The water resources of the united Arab emirates: a comprehensive empirical appraisal of their status and management

Uqba, Khaled Ali

How to cite:
Uqba, Khaled Ali (1991) The water resources of the united Arab emirates: a comprehensive empirical appraisal of their status and management, Durham theses, Durham University. Available at Durham E-Theses Online: http://etheses.dur.ac.uk/6299/

Use policy
The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a link is made to the metadata record in Durham E-Theses
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.
Please consult the full Durham E-Theses policy for further details.
THE WATER RESOURCES OF THE UNITED ARAB EMIRATES: A COMPREHENSIVE EMPIRICAL APPRAISAL OF THEIR STATUS AND MANAGEMENT

By

KHALED ALI UQBA

The copyright of this thesis rests with the author. No quotation from it should be published without his prior written consent and information derived from it should be acknowledged.

A thesis submitted to the Faculty of Science, University of Durham, for the Degree of Doctor of Philosophy

April, 1991

Vol. I
Thesis
1901/1108
ABSTRACT

The expansion in the cultivated area since the mid-1970s, and the eventual high demand for water, have taxed the groundwater resources of the Emirates to the limit. The annual groundwater abstraction by agriculture, based on average discharge measurements for the present study, is put at 2556 MCM/a. While the overall groundwater volume abstracted by all sectors is 3359 MCM/a; the total output from all the desalination plants at 300 MCM/a, and that from the wastewater recycling plants at 80 MCM/a. With the population for 1989 standing at 1.8 million, the per capita consumption is 2116 m³/a, which is close to that for the United States of America (2300 m³/a).

The water resource problem is common to all the Gulf Cooperation Council states. In the Emirates, as in all the neighbouring countries, the problem is embodied in the paradox of expansion in extensive agriculture despite the depleting groundwater resources. There is also the absence of a water policy, a plan or coherent water resource management. For the last aspect, there is a lack of indigenous expertise with the necessary knowledge to monitor water resources and guide their development.

The 8-fold increase in the cultivated acreage from 12,894 ha. in 1973 to 96,704 ha. in 1988, the 10-fold increase in population from 179,100 in 1968 to 1,748,804 in 1988, the continuously stable high cost of food imports during the past decade of above 3.0 billion dirhams ($ US 0.8 billion) a year and the 22-fold increase in water consumption from 172 MCM/a in 1968 to 3659 MCM/a in 1989, sum up the water resource problem of the Emirates. As a result, water-tables have been receding continuously, groundwater salinity rising both in inland and coastal aquifers, and the shallow fresh water aquifer in the Quaternary deposits has been depleted in many parts of the piedmont (gravel) plains.

Given this critical state of the groundwater resources, the preclusive cost of desalinated water to its application to agriculture and the ill-advised outlets to which every possible water resource developed is put, an urgent rethinking of water policies and development is vital. Such rethinking should set water-related priorities right, should resist all temptations, for reasons of national security, to imports of foreign water, and should be within the context of well-intentioned efforts towards achieving food security, through specialized agriculture, as much as is naturally possible.

I
ACKNOWLEDGEMENTS

The present study owes a great deal to a number of conscious individuals in the private and public water-related institutions in the Emirates for their unfailing assistance, continuous tips and discussions simply because of their sincere belief in the worthy cause of this research.

I am grateful to the late Professor William Bayne Fisher for accepting me to read for Ph.D. in the Faculty of Science, University of Durham; to Dr. Peter Collins, Dean of the Faculty of Science for his understanding regarding registration, and to Dr. Ewan W. Anderson, my supervisor, for his helpful comments on the style of the thesis text and his friendly cooperation during the period of research.

The following persons are especially acknowledged for their overwhelming support that alleviated hardship in the difficult final stages of the research programme:

Nadeem Hussain Ali (brother-in-law), Abdulla Ali Uqba (brother), Muhammad Ahmad Al Murr (Chairman of the managing committee of the Cultural and Scientific Association), Muhammad Bin Khalifah Bin Hadher, Abdul Aziz Bin Ali Al Owais, Muhammad Bin Hamad Abdulla Al Owais, Ali Ahmad Al Shurafa (Director of the President's Court), Sayyah Moosa Al Qubaisi (Undersecretary, WED Abu Dhabi), Dr. Darweesh Muhammad Khamees Al Qubaisi (Director of the President's Court, WED Abu Dhabi), Muhammad Uthman Abbas (Legal Advisor, WED Abu Dhabi), Basharah Makkawi Ahmad, Dr. Ezzeddin Ibraheem (Cultural Advisor to the President), Abdul Raheem Ahmad Al Marri (Cultural Attaché, UAE Embassy in London), Dr. Sam'an Al Asmar, Ibraheem Askar, Vijay Malhutra, Ibraheem Qassem Babel, Muhammad Saeed Al Husaini, Ibraheem Sayed, Mallika Karunaratne, P.M. Abdul Khadir, Joaehem Fernandes and Dr. Jum'ah Khalfan Abu Al Hoal (Director of the Dubai Health Department).

Finally, my deepest and most sincere gratitude is reserved for my beloved late father, Ali Omer Uqba, who passed away before seeing the completion of this work; and to my beloved wife Fawziyyah and daughters Rehab and Buthainah for their perseverance throughout the challenging period of what seemed at some stage a never-ending 'jihad'. I am equally indebted to the moral and financial support from relatives and friends that has kept this strictly personal endeavour going.

II
Dedicated to:

my wife Fawziyyah
and daughters,
Rehab and Buthainah,

for their unwaning encouragement, support and forbearance
without which this study would not have been possible
And We send from the sky water in measure, and We give it residence in the earth, and We certainly are able to drain it off.

"And We send from the sky water in measure, and We give it residence in the earth, and We certainly are able to drain it off."

THE HOLY QUR'AN
Verse 18.
Surat Al Mu'minoon
Chapter 18

Say, "See ye? If your water some day is lost by receding deeply underground (and turns saline), Who then can supply you with clear-flowing water?"

THE HOLY QUR'AN
Verse 30.
Surat Al Mulk
Chapter 29

(1) Muhammad Marmaduke Pickthall: "The meaning of the Glorious Qur'an".
(2) Abdulla Ali Yousuf: "The Holy Qur'an", page 877
### TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>I</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>II</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>III</td>
</tr>
<tr>
<td>RELEVANT VERSES FROM THE HOLY QUR'AN</td>
<td>IV</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>V</td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>XXXIV</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>XXXV</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>LI</td>
</tr>
<tr>
<td>ABBREVIATIONS</td>
<td>LXXIII</td>
</tr>
<tr>
<td>GLOSSARY</td>
<td>LXXIV</td>
</tr>
<tr>
<td>COPYRIGHT</td>
<td>LXXV</td>
</tr>
<tr>
<td>CHAPTER 1: INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>APPENDICES</td>
<td>963</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>985</td>
</tr>
</tbody>
</table>
# THE BACKGROUND PART

## CHAPTER 1: INTRODUCTION

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.</td>
<td>The water resource problem on the global, Middle East, Gulf Cooperation Council States and national (Emirates) levels</td>
<td>1</td>
</tr>
<tr>
<td>1.1.1.</td>
<td>General</td>
<td>1</td>
</tr>
<tr>
<td>1.1.2.</td>
<td>The water resource problem on the global level</td>
<td>2</td>
</tr>
<tr>
<td>1.1.3.</td>
<td>The water resource problem on the Middle East level</td>
<td>7</td>
</tr>
<tr>
<td>1.1.4.</td>
<td>The water resource problem on the Gulf Cooperation Council States (GCC) level</td>
<td>10</td>
</tr>
<tr>
<td>1.1.5.</td>
<td>The water resource problem on the national level: The United Arab Emirates</td>
<td>14</td>
</tr>
<tr>
<td>1.2.</td>
<td>The objectives, scope and method of the study</td>
<td>18</td>
</tr>
<tr>
<td>1.3.</td>
<td>Thesis plan and justification for a detailed study</td>
<td>21</td>
</tr>
<tr>
<td>1.3.1.</td>
<td>Justification for a detailed study</td>
<td>21</td>
</tr>
<tr>
<td>1.3.2.</td>
<td>Thesis plan</td>
<td>23</td>
</tr>
<tr>
<td>1.4.</td>
<td>The unique aspects of the study</td>
<td>27</td>
</tr>
<tr>
<td>1.5.</td>
<td>Synopsis</td>
<td>37</td>
</tr>
</tbody>
</table>
# CHAPTER 2: GEOLOGY, TOPOGRAPHY AND SOILS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.</td>
<td>Introduction</td>
<td>38</td>
</tr>
<tr>
<td>2.2.</td>
<td><strong>Geology</strong></td>
<td></td>
</tr>
<tr>
<td>2.2.1.</td>
<td>The regional geological setting</td>
<td>41</td>
</tr>
<tr>
<td>2.2.2.</td>
<td>Structural features</td>
<td>43</td>
</tr>
<tr>
<td>2.2.3.</td>
<td>Stratigraphic succession</td>
<td>47</td>
</tr>
<tr>
<td>2.2.4.</td>
<td>The geology of the mountains</td>
<td>49</td>
</tr>
<tr>
<td>2.2.4.1.</td>
<td>The carbonate massif of Ru‘us Al Jibal</td>
<td>50</td>
</tr>
<tr>
<td>2.2.4.2.</td>
<td>The Dibba–Idhn zone (The Dibba ‘Corridor’)</td>
<td>52</td>
</tr>
<tr>
<td>2.2.4.3.</td>
<td>The Semail Ophiolites Zone</td>
<td>54</td>
</tr>
<tr>
<td>2.2.5.</td>
<td>Water-bearing sedimentary stratigraphy</td>
<td>57</td>
</tr>
<tr>
<td>2.2.5.1.</td>
<td>The Upper Cretaceous-Tertiary sedimentary stratigraphy</td>
<td>58</td>
</tr>
<tr>
<td>2.2.5.1.1.</td>
<td>The Upper Cretaceous stratigraphy</td>
<td>58</td>
</tr>
<tr>
<td>2.2.5.1.2.</td>
<td>The Tertiary Formations</td>
<td>60</td>
</tr>
<tr>
<td>2.2.5.1.2.1.</td>
<td>Um Er Radhmah Formation</td>
<td>61</td>
</tr>
<tr>
<td>2.2.5.1.2.2.</td>
<td>Upper Tertiary Formations</td>
<td>63</td>
</tr>
<tr>
<td>2.2.6.</td>
<td>The Quaternary stratigraphy</td>
<td>64</td>
</tr>
<tr>
<td>2.2.7.</td>
<td>The stratigraphy of the piedmont plains and the desert foreland</td>
<td>66</td>
</tr>
</tbody>
</table>
2.2.8. Quaternary sea-level and tectonic land-level changes

2.3. Topography

2.3.1. General

2.3.2. Topographic divisions

2.3.2.1. The highland zone

2.3.2.1.1. The Hajar Limestone Mountains of Ru’us Al Jibal

2.3.2.1.2. The Dibba-Idhn Corridor

2.3.2.1.3. The Central Mountains

2.3.2.2. Geomorphology of the highland zone

2.3.2.2.1. Mountain slopes

2.3.2.2.2. Mountain wadis

2.3.3. The Lowland zone

2.3.3.1. The eastern piedmont plains (Al Batinah)

2.3.3.2. The western piedmont plains

2.3.3.3. The desert foreland

2.3.4. Geomorphology of the desert foreland

2.4. Soils

2.4.1. Introduction
2.4.2. Soil characteristics.................................................95
2.4.3. Mechanical characteristics of soils.................................96
2.4.3.1 Soils of the mountain wadis, outwash fans and piedmont plains.................................................96
2.4.3.2. Soils of the desert foreland......................................100
2.4.3.3. Other fine alluvial soils........................................101
2.4.4. Chemical composition of soils......................................101
2.4.5. Soil-water relationship................................................105
2.4.5.1. Infiltration tests................................................105
2.4.5.1.1. The principle of the experiments............................105
2.4.5.1.2. Infiltration tests in the various terrains of the Emirates................................................106
2.4.5.1.3. Simulation of infiltration under flood conditions.....111
2.4.6. Soil-water-vegetation relationship...................................113
2.5. Synopsis........................................................................114

CHAPTER 3: CLIMATE..............................................................115
3.1. Introduction.......................................................................115
3.2. The state of the meteorological network..............................116
3.3. Atmospheric circulation: Air masses and wind systems........125
3.4. Climatic elements ........................................ 133
  3.4.1. Radiation .............................................. 133
  3.4.2. Temperature .......................................... 134
  3.4.3. Wind .................................................. 140
  3.4.4. Relative humidity .................................... 141
3.5. Rainfall .................................................. 143
  3.5.1. Introduction .......................................... 143
  3.5.2. Rainfall measurement network .......................... 144
  3.5.3. Long-term rainfall characteristics ..................... 148
  3.5.4. Annual rainfall ....................................... 152
  3.5.5. Variability of annual rainfall .......................... 158
  3.5.6. Seasonality and type of rainfall ....................... 159
  3.5.7. Annual rainfall probabilities .......................... 159
   3.5.7.1. Rainfall return periods ............................ 161
  3.5.8. Monthly rainfall ...................................... 165
  3.5.9. Daily rainfall ........................................ 167
   3.5.9.1. Daily winter rainfall ............................... 170
   3.5.9.2. Daily summer rainfall ............................... 172
  3.5.10. The monsoon rainfall of the east coast ................ 175
3.5.11. The convectional storms in the mountains and the piedmont plains..........................177

3.5.12. Rainfall (storm) intensity.................................180

3.5.12.1. General.........................................................180

3.5.12.2. Analysis of available rainstorm intensity data for selected stations by region.........................181

3.5.12.3. Storm intensities of the winter rainstorms........182

3.5.12.3.1. Rainstorm intensities in the mountains..............182

3.5.12.3.1.1. Masafi......................................................182

3.5.12.3.1.2. Masfut....................................................185

3.5.12.4. Rainstorm intensities in the piedmont plains........186

3.5.12.4.1. Digdaga......................................................186

3.5.12.4.2. Filli..........................................................186

3.5.12.5. Rainstorm intensities in the east (Batinah) coast ..187

3.5.12.5.1. Dibba.........................................................187

3.5.12.5.2. Khor Fakkan.................................................188

3.5.12.6. Rainstorm intensities in the west coast..............189

3.5.12.6.1. Dubai and Sharjah.........................................189

3.5.12.6.2. Sha’am.........................................................189

3.5.12.7. Intensities of the summer convectional rainstorms..191
3.5.12.8. Intensities of the late ‘winter’ rainstorms of 30/4 and 1/5/1981.................................193

3.6. Evaporation.........................................................194

3.6.1. Estimation of potential evapotranspiration..........197

3.6.2. Evaporation from sabkha..................................199

3.7. General summary...............................................201

3.8. Synopsis............................................................202

---

THE MAIN PART

CHAPTER 4: SURFACE HYDROLOGY.................................203

4.1. Introduction.....................................................203

4.2. Drainage and catchments.....................................205

4.3. Physiographic characteristics of catchments..........207

4.4. Surface flow measurement....................................211

4.5. Wadis...............................................................214

4.6. Runoff characteristics.........................................216

4.7. Base-flow.........................................................239

4.8. Loss of runoff to the sea and inland/coastal sabkhas...........................................239

4.9. Catchment yields and actual runoff volumes..........242

XII
4.9.1. Actual annual runoff volumes.........................242
4.9.2. Catchment yields........................................243
4.10. The aflaj....................................................249
4.10.1. The aflaj of Al Ain....................................258
4.10.2. Discharge from the aflaj...............................259
4.10.3. Total discharge from the aflaj of the Emirates.....261
4.11. Synopsis....................................................262

CHAPTER 5: HYDROGEOLOGY.....................................263

5.1. Introduction...................................................263

5.2. Definitions of nomenclature of groundwater occurrence, aquifer types and aquifer hydraulic properties........................................267
5.2.1. Groundwater in the lithosphere........................267
5.2.2. Aquifers and aquifer system, aquiclude, aquitard and aquifuge.............................................270
5.2.3. Hydraulic properties of water-bearing strata:
Aquifer porosity, permeability, transmissivity and storage........................................275
5.2.4. Reliability of pumping-test and aquifer characteristic data in the Emirates..................282

5.3. Groundwater occurrence: The aquifer systems........285
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3.1.</td>
<td>General</td>
<td>285</td>
</tr>
<tr>
<td>5.3.2.</td>
<td>The Aquifer System</td>
<td>286</td>
</tr>
<tr>
<td>5.3.2.1.</td>
<td>The pre-Permian to Upper Cretaceous fractured bedrock aquifers of the Hawasina Metasediments and the Semail Ophiolite Suite</td>
<td>288</td>
</tr>
<tr>
<td>5.3.2.2.</td>
<td>The Hajar Carbonate Aquifer</td>
<td>295</td>
</tr>
<tr>
<td>5.3.2.2.1.</td>
<td>The characteristics of the Hajar aquifer</td>
<td>299</td>
</tr>
<tr>
<td>5.3.2.3.</td>
<td>The Mesozoic (Upper Cretaceous) and the Tertiary (Palaeocene-Eocene) aquifer system</td>
<td>303</td>
</tr>
<tr>
<td>5.3.2.3.1.</td>
<td>The Upper Cretaceous and Tertiary Formation aquifers in the Northern Emirates</td>
<td>303</td>
</tr>
<tr>
<td>5.3.2.3.2.</td>
<td>The Upper Cretaceous and Tertiary aquifers of Abu Dhabi</td>
<td>307</td>
</tr>
<tr>
<td>5.3.2.3.2.1.</td>
<td>General</td>
<td>307</td>
</tr>
<tr>
<td>5.3.2.3.2.2.</td>
<td>The deep carbonate Simsima Formation (Upper Cretaceous) Aquifer</td>
<td>309</td>
</tr>
<tr>
<td>5.3.2.3.2.3.</td>
<td>The deep carbonate Um Er Radhmah (UER) Formation (Palaeocene-Lower Tertiary) Aquifer</td>
<td>312</td>
</tr>
<tr>
<td>5.3.2.3.2.4.</td>
<td>The deep carbonate Dammam Formation (Middle to Upper Eocene) Aquifer</td>
<td>315</td>
</tr>
<tr>
<td>5.3.2.3.2.5.</td>
<td>The Simsima, UER and Dammam deep carbonate aquifer system of the eastern region of Abu Dhabi (Al Ain)</td>
<td>315</td>
</tr>
<tr>
<td>5.3.2.3.2.6.</td>
<td>The Upper Tertiary (Oligo-Miocene) aquifer system of Abu Dhabi: The 'Sahil Clastics' and Miocene</td>
<td>316</td>
</tr>
</tbody>
</table>

XIV
5.3.2.3.2.6.1. The Oligo-Miocene Sahil Clastics Formation........316
5.3.2.3.2.6.2. The Lower Miocene Gachsaran (Lower Fars) Evaporites
Formation aquifer..................................................318
5.3.2.4. The Quaternary alluvial and aeolian aquifer system.319
5.3.2.4.1. The Quaternary alluvial and aeolian aquifer system
of the western piedmont plains and the desert
foreland.................................................................319
5.3.2.4.2. Hydrogeology and aquifer system of the western
piedmont plains.......................................................324
5.3.2.4.3. The Quaternary alluvial-aeolian and the Tertiary
Miocene evaporites aquifer systems of Abu Dhabi....329
5.3.2.4.3.1. General.........................................................329
5.3.2.4.3.2. The Quaternary alluvial-aeolian and the Tertiary
Lower Fars evaporites aquifer system of the Al Ain
region.................................................................330
5.3.2.4.3.3. The Quaternary alluvial and aeolian, and the
Tertiary Miocene evaporites aquifer systems of
central, southern and western Abu Dhabi emirate....339
5.3.2.4.3.4. The sand dune aquifer in Asab, Bu Hasa, Shah
and Liwa...............................................................341
5.3.2.5. The alluvial aquifers of the mountain wadis and
intermontane basins..................................................347
5.3.2.5.1. The alluvial aquifers of the mountain wadis........347
5.3.2.5.1.1. The alluvial aquifers of the wadis of the northern
limestone mountains of Ru’us Al Jibal.................349
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3.2.5.1.2</td>
<td>The alluvial aquifers of the wadis of the ophiolite central mountains</td>
<td>351</td>
</tr>
<tr>
<td>5.3.2.5.1.2.1</td>
<td>The alluvial aquifer of Wadi Ham and its outwash fan</td>
<td>351</td>
</tr>
<tr>
<td>5.3.2.5.1.2.2</td>
<td>The alluvial aquifers of wadi Al Baseerah</td>
<td>354</td>
</tr>
<tr>
<td>5.3.2.5.2</td>
<td>The alluvial aquifers of the intermontane basins</td>
<td>358</td>
</tr>
<tr>
<td>5.3.2.6</td>
<td>Coastal aquifers</td>
<td>361</td>
</tr>
<tr>
<td>5.3.2.6.1</td>
<td>General</td>
<td>361</td>
</tr>
<tr>
<td>5.3.2.6.2</td>
<td>Coastal aquifers of the western (Gulf) coast</td>
<td>361</td>
</tr>
<tr>
<td>5.3.2.6.3</td>
<td>Coastal aquifers of the east (Batinah) coast of the Emirates</td>
<td>362</td>
</tr>
<tr>
<td>5.3.2.6.4</td>
<td>Seawater intrusion</td>
<td>369</td>
</tr>
<tr>
<td>5.4</td>
<td>Groundwater flow</td>
<td>372</td>
</tr>
<tr>
<td>5.4.1</td>
<td>General</td>
<td>372</td>
</tr>
<tr>
<td>5.4.2</td>
<td>Groundwater flow regimes of the Emirates</td>
<td>374</td>
</tr>
<tr>
<td>5.4.2.1</td>
<td>Groundwater flow in the Northern Emirates</td>
<td>377</td>
</tr>
<tr>
<td>5.4.2.2</td>
<td>Groundwater flow south of Al Madam Plain: The eastern region of Abu Dhabi (Al Ain) from Al Shuwaib in the north to Mazyad in the south</td>
<td>382</td>
</tr>
<tr>
<td>5.4.2.3</td>
<td>Groundwater flow in Liwa and central Abu Dhabi</td>
<td>385</td>
</tr>
<tr>
<td>5.4.2.4</td>
<td>Groundwater flow in mountain wadis</td>
<td>387</td>
</tr>
<tr>
<td>5.4.2.4.1</td>
<td>Groundwater movement in Wadi Al Beeh</td>
<td>387</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>5.4.2.4.2. Groundwater movement in Wadi Ham and its outwash fan.</td>
<td>389</td>
<td></td>
</tr>
<tr>
<td>5.4.2.4.3. Groundwater movement in Wadi Al Baseerah.</td>
<td>391</td>
<td></td>
</tr>
<tr>
<td>5.5. Groundwater levels and their fluctuation trends</td>
<td>395</td>
<td></td>
</tr>
<tr>
<td>5.5.1. Groundwater levels</td>
<td>395</td>
<td></td>
</tr>
<tr>
<td>5.5.1.1. General</td>
<td>395</td>
<td></td>
</tr>
<tr>
<td>5.5.1.2. Groundwater levels in the mountain wadis</td>
<td>396</td>
<td></td>
</tr>
<tr>
<td>5.5.1.3. Groundwater levels in the piedmont plains</td>
<td>401</td>
<td></td>
</tr>
<tr>
<td>5.5.1.4. Groundwater levels in the desert foreland</td>
<td>403</td>
<td></td>
</tr>
<tr>
<td>5.5.2. Groundwater level fluctuation trends</td>
<td>408</td>
<td></td>
</tr>
<tr>
<td>5.5.2.1. General</td>
<td>408</td>
<td></td>
</tr>
<tr>
<td>5.5.2.2. Long-term fluctuation of groundwater levels</td>
<td>409</td>
<td></td>
</tr>
<tr>
<td>5.5.2.3. Short-term fluctuation of groundwater levels</td>
<td>413</td>
<td></td>
</tr>
<tr>
<td>5.6. Synopsis</td>
<td>417</td>
<td></td>
</tr>
</tbody>
</table>

**CHAPTER 6: HYDROCHEMISTRY**  451

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1. Introduction</td>
<td>451</td>
</tr>
<tr>
<td>6.2. Water chemical analysis and presentation of the results</td>
<td>452</td>
</tr>
<tr>
<td>6.3. Water quality</td>
<td>455</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>6.4.</td>
<td>Water quality data in the Emirates</td>
</tr>
<tr>
<td>6.4.1.</td>
<td>Water chemistry and quality data for the present study</td>
</tr>
<tr>
<td>6.5.</td>
<td>Groundwater chemistry and quality of the Emirates by region</td>
</tr>
<tr>
<td>6.5.1.</td>
<td>The mountain zone</td>
</tr>
<tr>
<td>6.5.1.1.</td>
<td>The ophiolite gabbro zone</td>
</tr>
<tr>
<td>6.5.1.2.</td>
<td>The ophiolite peridotite zone</td>
</tr>
<tr>
<td>6.5.1.3.</td>
<td>The ophiolite peridotite and Hawasina metamorphics zone of the Masfut-Hatta-Muzeirea' intermontane basin</td>
</tr>
<tr>
<td>6.5.1.4.</td>
<td>The Hawasina metamorphics and volcanics Dibba Corridor zone</td>
</tr>
<tr>
<td>6.5.1.5.</td>
<td>The Hajar Limestone Massif of Ru'us Al Jibal zone</td>
</tr>
<tr>
<td>6.5.1.5.1.</td>
<td>Groundwater quality in the Deep Wells Project wells RK-5, RK-6 and RK-9 in the northern limestone massif of Ru'us Al Jibal</td>
</tr>
<tr>
<td>6.5.2.</td>
<td>The Lowland Zone</td>
</tr>
<tr>
<td>6.5.2.1.</td>
<td>General</td>
</tr>
<tr>
<td>6.5.2.2.</td>
<td>The northern part of the western alluvial piedmont plains (from Falaj Al Mualla to Al Jiri Plain)</td>
</tr>
<tr>
<td>6.5.2.3.</td>
<td>The central part of the western alluvial piedmont plains (from Falaj Al Mualla to Al Madam)</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>6.5.2.3.1</td>
<td>Water chemistry and quality of wells of the Deep Wells Project in the piedmont plains (1982-86)</td>
</tr>
<tr>
<td>6.5.2.4.</td>
<td>The southern part of the alluvial piedmont plains: Al Ain region from Wadi Ma’aisheq to Um Ghafah</td>
</tr>
<tr>
<td>6.5.2.4.1</td>
<td>General</td>
</tr>
<tr>
<td>6.5.2.4.2</td>
<td>The quality of the recharge waters in Al Ain</td>
</tr>
<tr>
<td>6.5.2.4.3</td>
<td>The chemistry of the waters of the Al Ain region</td>
</tr>
<tr>
<td>6.5.2.4.4</td>
<td>Increase of groundwater salinity with depth and distance from the foothills</td>
</tr>
<tr>
<td>6.5.2.4.5</td>
<td>Long-term fluctuation in groundwater quality in the Al Ain region</td>
</tr>
<tr>
<td>6.5.2.4.6</td>
<td>Short-term fluctuation in water quality in the Al Ain region</td>
</tr>
<tr>
<td>6.5.2.4.7</td>
<td>The relationship between the drop in groundwater levels and the deterioration in groundwater quality</td>
</tr>
<tr>
<td>6.5.2.4.8</td>
<td>Suitability of groundwater for domestic use in the Al Ain region</td>
</tr>
<tr>
<td>6.5.2.4.9</td>
<td>Suitability of groundwater for agriculture in the Al Ain region</td>
</tr>
<tr>
<td>6.5.2.5.</td>
<td>The chemistry and quality of the waters of the east coast (the eastern piedmont plains)</td>
</tr>
<tr>
<td>6.5.2.5.1</td>
<td>General</td>
</tr>
<tr>
<td>6.5.2.5.2</td>
<td>Groundwater chemistry and quality in the two sections of the east coast to the north and south of Khor Fakkan</td>
</tr>
</tbody>
</table>
6.5.2.5.3. Groundwater chemistry and quality in Wadi Al Baseerah Basin...........................................560

6.5.2.5.3.1. Groundwater quality in the coastal aquifer of Wadi Al Baseerah at Dibba..............................562

6.5.2.5.3.2. Groundwater quality in the central channel of Wadi Al Baseerah......................................565

6.5.2.5.3.3. Groundwater quality in the eastern and western flanks of Wadi Al Baseerah.......................565

6.5.2.5.3.4. The quality of the old 'stagnant' wadi-terrace groundwater............................................571

6.5.2.5.4. Groundwater chemistry and quality of the Wadi Ham-Fujairah alluvial outwash fan....................573

6.5.3. The Desert Foreland...........................................579

6.5.3.1. Groundwater chemistry and quality in the desert foreland of the Northern Emirates...................582

6.5.3.2. Groundwater quality in the desert foreland south of Tawi Nazwa as far as Al Ain......................588

6.5.3.3. Groundwater quality in the desert foreland zone extending from Al Ain to Bu Remramah, Bu Heeran and Al Ya’eeiliyyah in the west, and Um Ez Zemoool in the south...........................................589

6.5.3.4. Groundwater quality in the desert foreland zone of central Abu Dhabi...................................594

6.5.3.5. Groundwater quality of the shallow and deep water wells of the Abu Dhabi Company for Onshore Operations (ADCO) in the areas of the oilfields in the desert foreland of central Abu Dhabi........602
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5.3.6</td>
<td>Groundwater chemistry and quality in Eastern and Western Liwa</td>
</tr>
<tr>
<td>6.5.3.7</td>
<td>Groundwater chemistry and quality of the deep Tertiary carbonate aquifer system</td>
</tr>
<tr>
<td>6.5.4.</td>
<td>Groundwater quality in the western (Gulf) coastal zone</td>
</tr>
<tr>
<td>6.6.</td>
<td>Synopsis</td>
</tr>
</tbody>
</table>

**CHAPTER 7: ENVIRONMENTAL ISOTOPES**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1.</td>
<td>Introduction</td>
</tr>
<tr>
<td>7.2.</td>
<td>Principles of isotope techniques</td>
</tr>
<tr>
<td>7.3.</td>
<td>Tritium ($^3$H)</td>
</tr>
<tr>
<td>7.4.</td>
<td>Carbon isotopes</td>
</tr>
<tr>
<td>7.5.</td>
<td>Sulphur-34 ($^{34}$S)</td>
</tr>
<tr>
<td>7.6.</td>
<td>Application of isotope techniques</td>
</tr>
<tr>
<td>7.7.</td>
<td>Summary of the results of isotopic studies carried out in the United Arab Emirates (1980-1989)</td>
</tr>
<tr>
<td>7.7.1.</td>
<td>Environmental isotope measurements in Wadi Al Baseerah (Al Shimal) by the Japan International Cooperation Agency (JICA), 1980-81</td>
</tr>
<tr>
<td>7.7.2.</td>
<td>Isotopic measurements by Geoconsult as part of the Deep Wells Project, 1982-86</td>
</tr>
</tbody>
</table>
7.7.3. Summary of the isotope investigations by the International Atomic Energy Agency (IAEA), (1984-). 637
7.7.3.1. Results of the stable isotopes of Oxygen-18 and Deuterium ($^2$H). 637
7.7.3.2. Tritium results. 644
7.7.3.3. Carbon-14 ($^{14}$C) of TDIC (Total Dissolved Inorganic Carbon). 647
7.7.3.4. Origins of groundwater from isotopic deductions. 651
7.8. General conclusions. 656
7.9. Synopsis. 660

CHAPTER 8: WATER PRODUCTION, USE AND COST. 661

8.1. Introduction. 661
8.2. Groundwater production for domestic use. 665
8.2.1. General. 665
8.2.2. Regional wellfields of the MEW in the Northern Emirates. 668
8.2.2.1. Ras Al Khaimah groundwater public supply. 668
8.2.2.2. Groundwater public supply for Um Al Qaiwain. 671
8.2.2.3. Groundwater public supply for Ajman. 672
8.2.2.4. Groundwater public supply for Al Dhaid. 672

XXII
8.2.2.5. Groundwater public supply for the east coast........673
8.2.2.5.1. Groundwater public supply for Dibba and Zikt........673
8.2.2.5.2. Groundwater public supply for Khor Fakkan...........674
8.2.2.5.3. Groundwater public supply for Fujairah...............674
8.2.2.5.4. Groundwater public supply for Kalba.................675
8.2.2.6 Total groundwater production for domestic use from
MEW wells in the Northern Emirates.........................675
8.2.3. Sharjah groundwater public supply.........................675
8.2.4. Dubai groundwater public supply..........................681
8.2.5. Abu Dhabi groundwater public supply.......................684
8.2.5.1. Groundwater public supply of the eastern region of
Abu Dhabi: Al Ain..................................684
8.2.5.2. Groundwater public supply in central and western
Abu Dhabi.........................................690
8.3. Groundwater production for agricultural use..............694
8.3.1. General.........................................694
8.3.2. Groundwater abstraction by agriculture in western
and southern Abu Dhabi emirate..............................696
8.3.3. Groundwater abstraction by forestry in both the
western and eastern (Al Ain) regions of Abu Dhabi
emirate...........................................697
8.3.4. Groundwater production for agriculture in the
Al Ain region........................................704
8.3.4.1. Groundwater abstraction for agriculture in the Al Ain town vicinity and the Al Jaww Plain.........704

8.3.4.2. Groundwater abstraction for agricultural use in the northern and western dune areas of the Al Ain region706

8.3.4.3. Groundwater abstraction for agriculture in the southern desert of the Al Ain region..............707

8.3.5. Groundwater abstraction for agricultural use in the Northern Emirates.................................708

8.3.6. Natural falaj discharge of the aflaj of the Emirates709

8.4. Quantification of groundwater abstraction for agricultural use..............................................711

8.4.1. General.................................................................711

8.4.2. Irrigation water requirements.............................................712

8.4.2.1. Potential evapotranspiration and irrigated crop water requirements.................................712

8.4.2.2. Quantifying groundwater abstraction for agricultural use by the gross crop irrigation requirements.....714

8.4.3. Quantifying groundwater abstraction by agriculture by borehole discharge measurement...............720

8.5. Desalinated water production and use......................724

8.5.1. General.................................................................724

8.5.2. Desalinated water production and use in Abu Dhabi emirate.............................................724

8.5.2.1. Small desalination plants in the emirate of Abu Dhabi................................................728

XXIV
8.7.4. Cost of water in Sharjah.........................766
8.7.5. Cost of sewage treated water in the Emirates......766
8.7.6. The average cost of water in the Emirates..........768
8.8. General summary......................................773
8.9. Synopsis............................................776

CHAPTER 9: THE SHARED WATER RESOURCES..............777

9.1. Introduction.........................................777
9.2. The regional shared water resources..................778
9.3. The local shared water resources......................780
  9.3.1. Ru‘us Al Jibal peninsula........................780
  9.3.2. Al Shumailiyah mountain enclave of Madhah........780
  9.3.3. The area of brackish to saline water: South of
         Jabal Hafeet as far as Um Ez Zemool, and westwards
         of this line........................................781
  9.3.4. The fresh water zone of Al Ain-Al Buraimi........782
        9.3.4.1. Recharge potential and groundwater availability on
                    the Omani side of the border in the Al Buraimi
                    region...........................................786
        9.3.4.2. The hydrogeology of the Emirates side of the border
                    in the Al Ain region............................798
9.4. The groundwater balance in the Al Ain region(1988)..803
CHAPTER 19: RECHARGE POTENTIAL, GROUNDWATER RESERVES
AND THE GROUNDWATER BALANCE

10.1. Introduction.........................................................806
10.2. Groundwater reserves............................................808
10.3. Previous groundwater recharge and balance estimates.813
  10.3.1 General..........................................................813
  10.3.2 Recharge and balance estimates of the 'Water
        Resources of the Trucial States' Study (William
        Halcrow), 1966-69..............................................814
  10.3.3 Recharge and balance estimates of the 'Water
        Resources Survey of Abu Dhabi' study, (Alexander
        Gibb), 1969-70..................................................816
  10.3.4 Recharge estimates of the 'Development of Water
        Resources in the Emirate of Dubai' study by
        Wellfield Services Ltd. (1976)..................................819
  10.3.5 Recharge and balance estimates of the 'Preliminary
        Appraisal of Water Resources Report' of the FAO
        (Carr and Barber)..............................................820
  10.3.6 Recharge estimates of the 'Water Resources and Rural
        Development in the UAE' study by the International
        Development Centre of Japan (IDCJ), 1978.................821
| 10.3.7 | Recharge and balance estimates by the 'Reconnaissance Report on Abu Dhabi, the Eastern Region: Water Resources and Development Proposals' study by Hydroconsult, 1978 | 822 |
| 10.3.7.1 | Recharge from local rainfall | 824 |
| 10.3.7.2 | Recharge from surface flow | 825 |
| 10.3.7.3 | Recharge from irrigation return | 825 |
| 10.3.7.4 | Recharge in the Northern Dune Area | 827 |
| 10.3.8 | Omani recharge and balance estimates related to the Al Ain region (1982-87) | 830 |
| 10.3.8.1 | Estimates of groundwater recharge and balance of the 'Soil and Groundwater Survey for Buraimi Area - Groundwater Resources Development' by Groundwater Development Consultants (GDC), 1982 | 830 |
| 10.3.8.2 | Estimates of groundwater recharge and balance by the Oman Regional Development Council (RDC), 1987 | 834 |
| 10.3.9 | Recharge and balance estimates of the 'Wadi Al Baseerah Basin Water Resources Development Project' by the International Cooperation Agency (JICA), 1981 | 836 |
| 10.3.10 | Recharge and balance estimates of the Ministry of Agriculture and Fisheries (MAF) (1982) | 837 |
| 10.3.11 | Recharge and balance estimates of the 'Master Plan for the Al Ain Region (Public Utilities part) by Edworthy and Brandt, 1983-85 (the so-called Al Ain 2000 Master Plan) | 839 |
| 10.3.12 | Recharge and balance estimates of the Deep Wells Project (MAF-GEOCONSULT-IWACO) (1982-86) | 841 |
10.4. Recharge and balance estimates of the present study.846

10.4.1. General.................................................................846

10.4.2. Recharge from surface runoff.................................846

10.4.3. Recharge from subsurface flow...............................851

10.4.4. Recharge from direct rainfall.................................852

10.4.4.1. Recharge from direct rainfall in the piedmont plains........................................852

10.4.4.2. Recharge from direct rainfall in the desert foreland........................................853

10.5. The general groundwater recharge/discharge balance of the Emirates (1988)......................856

10.5. Synopsis.................................................................859

THE CONCLUDING PART

CHAPTER 11: WATER RESOURCE MANAGEMENT 860

11.1. Introduction.........................................................860

11.2. Management considerations of the hydrometeorological networks.....................................862

11.3. Water resource development and related problems.........................................................866

11.3.1. Trends in water resource development in the Emirates...................................................866

11.3.2. Management problems related to the development of the conventional and non-conventional water resources.........................................................868

11.3.2.1. General.............................................................868
11.3.2.2. Management problems of the conventional water resources: Groundwater.................................869

11.3.2.2.1. The siting of water wells.................................869

11.3.2.2.1.1. The Sha’arah and Kidnah wellfields of Wadi Ham and Wadi Kidnah on the east (Batinah) coast............870

11.3.2.2.1.2. The Kashoonah-Al Shuwaib wellfield north of Al Ain..872

11.3.2.2.2. Management aspects related to well development in the Emirates.................................875

11.3.2.2.3. Management problems related to the maintenance of water supply equipment..............................878

11.3.2.2.4. Management problems related to groundwater level monitoring........................................879

11.3.2.2.5. Water management considerations of groundwater resource development in the Northern Emirates......880

11.3.2.2.5.1. Water supply shortages........................................880

11.3.2.2.6. Water management problems in Al Ain.........................882

11.3.2.3. Management problems in the non-conventional water resources: Desalinated water and recycled wastewater883

11.3.2.3.1. Desalinated sea-and ground-water.................................883

11.3.2.3.2. Development problems related to desalinated brackish water........................................885

11.3.2.3.3. Development problems related to recycled wastewater.886

11.3.2.3.4. The problem of water losses (leakage) in the supply systems of the towns.................................888

XXX
11.4. Water legislation, policy and the water-managing organizations: the existing water management infrastructure...........................889
11.4.1. Water legislation and water policy......................889
11.4.1.1. Public ownership of water resources....................890
11.4.1.2. The General Water Resource Authority (1981).........891
11.4.2. Institutional issues.......................................892
11.4.3. Water-managing organizations............................894
11.4.3.1. Aptitude and efficiency of the staff of the water organizations..............................896
11.5. Water resource planning..................................896
11.5.1. Requirements of a water resource management plan....897
11.5.1.1. Institutional requirements for the water resource plan............................................897
11.5.1.2. Data assembly.............................................898
11.5.2. Objectives of a water resource plan.......................901
11.5.3. The water resource planning process.......................902
11.5.3.1. The area of responsibility most likely to assume the task of formulating and implementing a water resource management plan in the Emirates.............904
11.6. Environmental considerations...............................906
11.6.1. Introduction.................................................906
11.6.2. Water quality issues.......................................906

XXXI
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.6.2.1</td>
<td>General</td>
<td>906</td>
</tr>
<tr>
<td>11.6.2.2</td>
<td>Management problems in water quality monitoring</td>
<td>907</td>
</tr>
<tr>
<td>11.6.2.2.1</td>
<td>Pollution hazards of water supply in the towns</td>
<td>909</td>
</tr>
<tr>
<td>11.6.2.2.2</td>
<td>Contamination hazards of groundwater outside the towns: Nitrate (NO₃), fluoride (F) and Sulphate (SO₄) monitoring</td>
<td>911</td>
</tr>
<tr>
<td>11.6.3</td>
<td>Water quantity issues</td>
<td>916</td>
</tr>
<tr>
<td>11.6.3.1</td>
<td>General</td>
<td>916</td>
</tr>
<tr>
<td>11.6.3.2</td>
<td>The problem of seawater intrusion</td>
<td>916</td>
</tr>
<tr>
<td>11.6.3.3</td>
<td>Land subsidence as a result of groundwater level decline and aquifer depletion</td>
<td>918</td>
</tr>
<tr>
<td>11.7</td>
<td>Conservation and augmentation of water resources</td>
<td>920</td>
</tr>
<tr>
<td>11.7.1</td>
<td>General</td>
<td>920</td>
</tr>
<tr>
<td>11.7.2</td>
<td>Modern irrigation techniques versus water consumption</td>
<td>921</td>
</tr>
<tr>
<td>11.7.3</td>
<td>Methods of conserving and augmenting domestic water supplies</td>
<td>925</td>
</tr>
<tr>
<td>11.7.3.1</td>
<td>Urban storm runoff</td>
<td>926</td>
</tr>
<tr>
<td>11.7.3.2</td>
<td>Recycled wastewater for recreational use</td>
<td>926</td>
</tr>
<tr>
<td>11.7.3.3</td>
<td>Weather modification to augment water resources</td>
<td>927</td>
</tr>
<tr>
<td>11.7.4</td>
<td>Ways of conserving and augmenting agricultural water supplies</td>
<td>927</td>
</tr>
<tr>
<td>11.7.4.1</td>
<td>General</td>
<td>927</td>
</tr>
</tbody>
</table>
CHAPTER 12: CONCLUSIONS AND RECOMMENDATIONS

12.1. Introduction.................................................940

12.2. Conclusions..................................................940

12.3. Recommendations............................................945

12.3.1. General recommendations of key institutional aspects of water resource management in the Emirates.........945

12.3.2. Specific recommendations of the conventional and non-conventional water resources of the Emirates....953

12.3.2.1. Groundwater.............................................953

12.3.2.2. Desalinated water......................................958

12.3.2.3. Treated sewage water.................................960

XXXIII
APPENDICES

APPENDIX 1  Interemirate boundaries of the seven emirates of the UAE.................................963

APPENDIX 2  Examples of malfunctioning of rain-recorders.................964

APPENDIX 3  Return periods of 38 rainfall stations......................968

APPENDIX 4  Crop water requirements in the Emirates (Prashar and Thanki), 1978.................................973

APPENDIX 5  Example of the presentation of water chemical analysis results by the Al Ain Groundwater Department..............974

APPENDIX 6  Examples of bacteriological contamination of groundwater.........................................................975

APPENDIX 7  Translation of the General Water Resource Authority Law (1981).........................................................979


APPENDIX 9  Map of the direct EC measurements of the present study, 1988.................................................................983

References......................................................................................985
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIG.</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.</td>
<td>4</td>
</tr>
<tr>
<td>1.2.</td>
<td>13</td>
</tr>
<tr>
<td>2.1.</td>
<td>42</td>
</tr>
<tr>
<td>2.2.</td>
<td>45</td>
</tr>
<tr>
<td>2.3.</td>
<td>46</td>
</tr>
<tr>
<td>2.4.</td>
<td>48</td>
</tr>
<tr>
<td>2.5.</td>
<td>51</td>
</tr>
<tr>
<td>2.6.</td>
<td>53</td>
</tr>
<tr>
<td>2.7.</td>
<td>55</td>
</tr>
<tr>
<td>2.8.</td>
<td>59</td>
</tr>
<tr>
<td>2.9.</td>
<td>62</td>
</tr>
</tbody>
</table>

The 4-fold increase in total world water consumption since 1950

Comparison between the per capita water consumption of the residents of the U.S.A., Saudi Arabia and the Emirates

The structural features of the Arabian Peninsula

Generalized stratigraphic sequence of the Emirates

Generalized geological cross-section of the sediments in the northern parts of the Emirates

The Hajar Super Group, the Sumeini Group, the Hawasina Nappes and the Semail Nappe

The geology of the Hajar Mountains to the north of the Dibba-Idhn Fault Line

The complex geology of the Dibba-Idhn Corridor

The geology of the catchments of the Emirates and adjacent areas

Lithostratigraphic-hydrogeological correlations of the sedimentary water-bearing stratigraphy in the Emirates

The Upper Cretaceous to Middle Tertiary deep carbonate aquifer system of central Abu Dhabi
2.10. Location of the oil wells in Sharjah and Um Al Qaiwain......68

2.11. Lithological variation of the same rock sequences in drill cuttings of selected oil wells in the piedmont plains and desert foreland in the emirates of Sharjah and Um Al Qaiwain in the Northern Emirates.........................69

2.12. Topographical subdivisions of the Highland Zone............77

2.13. Long wadi profiles of Wadis Al Naqab and Al Fayy.............83

2.14. Long wadi profiles of Wadis Al Wurai'ah and Ashwani........84

2.15. Topographical subdivisions of the Lowland Zone.............88

3.1. The distribution of the comprehensive meteorological stations in the Emirates.................................117

3.2. Atmospheric conditions in the Emirates during the period October to May.....................................................128

3.2. The median location of the Subtropical Jetstream in winter..129

3.4. The main tracks of the cyclones associated with the Subtropical Jetstream and areas of intense cyclonic activity in the Middle East in winter.....................129

3.5. The distribution of the mid-level atmospheric pressure in summer (July)......................................................130

3.6. The distribution of the mid-level atmospheric pressure in winter (January)....................................................130

3.7. (A and B) Mid-level atmospheric conditions over the Emirates during the summer monsoon storm of 20-07-1988......131

3.8. (A and B) Mid-level atmospheric conditions over the Emirates during the widespread winter rainstorms of 17-02-1988......131

XXXVI
3.9. (A to C) Isothermal maps of the mean monthly minimum temperature for January, the mean monthly maximum temperature for July and the mean annual temperature, for the whole Emirates.................................139

3.10. The distribution of rain gauges/recorders of the Emirates (1990).......................................................146

3.11. (A to E) Long-term annual rainfall of Sharjah, Fujairah, Al Aweer, Masfut and Mileiha............................149

3.12. Rainfall frequency graphs at 20mm thresholds for Masafi and Masfut in the mountains, Mileiha in the piedmont plains, Fujairah on the east coast, Al Aweer in the desert foreland, Sharjah on the west coast and the mean for the UAE....................................................153

3.13. Annual rainfall of the Emirates (combined graph for representative climatological stations)....................155


3.15. Annual mean rainfall values for 38 stations set against the period mean for the UAE, and against the period mean of the mountains, the piedmont plains, east and west coasts and the desert foreland........................................162

3.16. Daily summer (convectional) rainfall of 10/11-08-1983.......176

3.17. Comparison of the number of rainstorms reaching the different duration thresholds for selected stations by region........184

3.18. Relationship between radiation, temperature, wind, relative humidity and open pan evaporation.............200

4.1. The catchments of the Emirates.................................................208
4.2. Combined flood hydrograph for Wadis Siji, Ham, Sfini, Sfini-Ashwani, Qawr East, Ashwani, Al Wurai'ah and Naqab for the floods of 17/18, February, 1988.............224

4.3. Flood hydrograph for the floods of 17/18-02-1988 for the west-flowing Wadi Siji in the ophiolite central mountains...225

4.4. Flood hydrograph for the floods of 17/18-02-1988 for the west-flowing Wadis Sfini-Ashwani downstream of their confluence..................225

4.5. Flood hydrograph for the floods of 17/18-02-1988 for the east flowing Wadi Ham in the ophiolite central mountains........................................226

4.6. Flood hydrograph for the floods of 17/18-02-1988 for the west-flowing Wadi Sfini, upstream of its confluence with Wadi Ashwani, in the ophiolite central mountains........226

4.7. Flood hydrograph for the floods of 17/18-02-1988 for the west-flowing Wadi Ashwani, upstream of its confluence with Wadi Sfini, in the ophiolite central mountains..........227

4.8. Flood hydrograph for the floods of 17/18-02-1988 for the east-flowing Wadi Al Qawr East in the ophiolite central mountains.................................227

4.9. Flood hydrograph for the floods of 17/18-02-1988 for the west-flowing Wadi Al Naqab in the northern limestone mountains of Ru’us Al Jibal..................228

4.10. Flood hydrograph for the floods of 17/18-02-1988 for the east-flowing Wadi Al Wurai’ah in the ophiolite central mountains.................................228

(Commentary for Figs 4.2 to 4.10 after Fig. 4.10)......229

4.11. Long section of a ‘daudi’ falaj..................253

XXXVIII
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.12.</td>
<td>Cross-section of a 'daudi' falaj</td>
<td>253</td>
</tr>
<tr>
<td>4.13.</td>
<td>The aflaj of the Emirates (1990)</td>
<td>257</td>
</tr>
<tr>
<td>5.1.</td>
<td>The hydrogeological zones of the United Arab Emirates: (1) The Northern Emirates</td>
<td>265</td>
</tr>
<tr>
<td>5.2.</td>
<td>The hydrogeological zones of the United Arab Emirates: (2) Western and southern Abu Dhabi emirate</td>
<td>266</td>
</tr>
<tr>
<td>5.3.</td>
<td>The occurrence of groundwater in the lithosphere</td>
<td>269</td>
</tr>
<tr>
<td>5.4.</td>
<td>The different types of aquifers down to the fractured baserock</td>
<td>272</td>
</tr>
<tr>
<td>5.5.</td>
<td>Types of aquifers in water-bearing material other than the fractured baserock</td>
<td>274</td>
</tr>
<tr>
<td>5.6.</td>
<td>The relative permeabilities in the different rock types, including porosity, well-yield and type of the water-bearing unit</td>
<td>277</td>
</tr>
<tr>
<td>5.7.</td>
<td>The relationship between grain size, porosity, specific retention and specific yield</td>
<td>281</td>
</tr>
<tr>
<td>5.8.</td>
<td>(A and B) Drill cuttings of the Deep Wells Project Wells RK-10 in Wadi Haqeel and MF-1 in Masfut</td>
<td>290</td>
</tr>
<tr>
<td>5.9.</td>
<td>(A to D) Drill cuttings of wells drilled by JICA in the Wadi Al Baseerah basin (1981)</td>
<td>292</td>
</tr>
<tr>
<td>5.10.</td>
<td>(A to C) Drill cuttings of wells drilled by JICA in the Wadi Al Baseerah basin (1981)</td>
<td>293</td>
</tr>
<tr>
<td>5.11.</td>
<td>(A to C) Drill cuttings of wells drilled by JICA in the Wadi Al Baseerah basin (1981)</td>
<td>294</td>
</tr>
</tbody>
</table>

XXXIX
5.12. (A and B) Drill cuttings of the Deep Wells Project Wells GP-3 (Manama) and GP-13 (Tawi Suhailah) drilled by Geoconsult (1983) ........................................296

5.13. (A and B) Drill cuttings of the Deep Wells Project Wells BHF-11 and BHF-12 in the Wadi Ham outwash fan on the east coast (1984-85) ........................................297


5.15. (A to C) Drill cuttings of the Deep Wells Project Wells RK-14, RK-15 and RK-16 drilled in the carbonate aquifer in Ras Al Khaimah (1985-86) ........................................302


5.17. Location of the main onshore oilfields of central Abu Dhabi .................................................................310

5.18. (A and B) Isopach maps of the Simsima and Um Er Radhmah deep carbonate aquifers ........................................311

5.19. (A and B) Isopach maps of the Dammam and Sahil deep carbonate aquifers ...........................................317

5.20. (A and B) Drill cuttings of two wells drilled for Fujairah Government in the Wadi Siji outwash fan on the western foothills (1978) .....................................................326


5.22. Drill cuttings of boreholes of the old Al Za’alah wellfield, west of Al Ain (1980) ..........................................334

5.23. Drill cuttings of selected wells in the Al Ain region ........338

XL
5.24. The Quaternary aeolian and Tertiary Lower Fars evaporites aquifer in Asab in the desert foreland of central Abu Dhabi. 342

5.25. Multi-layered perched aquifers in Um Al Rudoom oasis in Western Liwa. .................................................. 346


5.27. Cross-section in a typical mountain wadi in the central ophiolite mountains ............................................. 357

5.28. Locations of JICA's observation wells in the Wadi Al Baseerah Basin (1981) ................................................. 359

5.29. Location of the Deep Wells Project observatory wells ...... 365

5.30. The Tertiary 15m. coastline in Fujairah ................................................. 368

5.31. Isoresistivity profile of the geophysical investigation by Geoconsult in the Fujairah coastal zone (1983) ........ 371

5.32. The 'Sabkha Line' or 'sink' of the Arabian Peninsula ....... 375

5.33. Tectonic map of the Arabian Peninsula .......................... 376

5.34. (A and B) Representation of groundwater flow by Halcrow (1969) and Mar'ee (1978) ........................................... 379

5.35. Groundwater flow in the Northern Emirates from Al Madam to Sha'am ...................................................... 381

5.36. Groundwater flow in the land front south of Al Madam in the Al Ain region (from Al Madam to 'Ajran) ................. 384

5.38. Groundwater flow in the Ras Al Khaimah limestone mountain mass and the narrow wadi outwash fan piedmont plains (the coastal zone to the north of Seih Al Fahlain) .......... 388

5.39. Groundwater flow in Wadi Ham and its outwash fan ........... 390

5.40. Groundwater flow in the Wadi Al Baseerah basin .............. 392

5.41. The seawater intrusion tongue in the Wadi Al Baseerah coastal zone ................................................. 394

5.42. Groundwater-level recorders of the Emirates (1990) ............ 418

5.43. Groundwater-level recorders in the lower Wadi Ham (the Fujairah outwash fan) and Kalba (1990) ......................... 419

5.44. Groundwater-level recorders of the Wadi Al Baseerah basin (1990) .......................................................... 420

5.45. (A to H) Groundwater level hydrographs of wells in the western piedmont plains (1983-88) ................................. 421

5.46. (A to C) Groundwater level hydrographs for the southern part of the western piedmont plains (the Al Ain region (1979-88) 422

5.47. (A to F) Groundwater level hydrographs for wells in the Um Ghafah public supply wellfield of Al Ain in southern Al Jaww Plain ......................................................... 423

5.48. (A to D) Groundwater level hydrographs for Kalba, Al Madam, Muzeirea‘ and Idhn .................................................. 424

5.49. (A to C) Groundwater level hydrographs of general groundwater level decline for Al Hamraniyyah, Al Dhaid and Al Madam in the northern, central and southern parts of the Plains .... 425

5.50. (A to C) Groundwater level hydrographs for the three Dubai public supply wellfields of Al Hibab, Al Wuhoosh and Al Aweer in the desert foreland ......................... 426

XLII
5.51. (A to C) Groundwater level hydrographs for Mohayyer East and Suwaihan Road public supply wells of the northern dune area of Al Ain (1978-88) ...................... 427

5.52. (A to D) Groundwater level hydrographs for Bida' Bint Ahmad and Al Kara' public supply wells of the northern dune area of Al Ain (1977-88) ...................... 428

5.53. (A to D) Groundwater level hydrographs for Al Kara' North, Al Hayer North and Jubaita (Bida' Bint Saud) public supply wells of the northern dune area of Al Ain (1981-88) .......... 429

5.54. (A to D) Groundwater level hydrographs for Bida' Bint Saud (East and West) and Al Hamam, public supply wells of Al Ain (1979-88) ...................... 430

5.55. (A to E) Groundwater level hydrographs of MEW wellfields in the desert foreland and piedmont plains of the Northern Emirates: Wadi Fareekh, Tawis Shunuf and Rashed, Tawi Sirrah, Al Dhaid and Idhn (1984-88) ...................... 431

5.56. Average groundwater level fluctuation in the MEW Sahwat wellfield in Wadi Ghaleelah in Ras Al Khaimah, 3km. from the coast at Mina Saqr in Khawr Khuwair (1980-87) .......... 432

5.57. (A to C) Groundwater level hydrographs for Wells GG-8, 9 and 10 (upstream) and GG-1 and 3 (downstream) in Wadi Al Baseerah, and a well in Kalba on the coastal end of the Wadi Ham outwash fan ...................... 433

5.58. (A and B) Groundwater level hydrographs showing monthly groundwater fluctuation in Dhuhuriyyeen and Kidnah MEW wellfields for the two consecutive years 1987-88 .......... 434

5.59. (A to C) Groundwater level hydrographs for Habhab, Siji and Tawi Jaheeli on the western edge of the northern part of the piedmont plains ...................... 435
5.60. (A and B) Groundwater level hydrographs for Al Burairat and Idhn in the northern carbonate mountains (1988).............436

5.61. (A to C) Groundwater level hydrographs for Wells GP-15 and GWR-4 in upstream locations in wadis in the piedmont plains; and GWR-2 in Falaj Al Mualla on the sandy western fringe of the piedmont plains (1987).................................437

5.62. (A to F) Groundwater level hydrographs showing monthly groundwater level fluctuation in Well GWR-2 in Falaj Al Mualla for years with least rainfall (1980 and 1984), years of moderate rainfall (1981 and 1987) and years of exceptionally high rainfall (1982 and 1988).................................438

5.63. Groundwater level hydrograph for the observation well BHF-15 at Sha'arah showing monthly groundwater level fluctuation for the two consecutive years 1987-88.................................439

5.64. (A to D) Groundwater level hydrographs for Al Madam and Mileiha in the Ghareef Plain in the south-central part of the western piedmont plains (1988).................................440

5.65. (A to C) Groundwater level hydrographs for Masfut, Gulfa and Muzeirea' in the Masfut-Hatta-Muzeirea' intermontane basin (1988).........................................................441

5.66. (A to E) Groundwater level hydrographs for the observation wells GG-9, 2, 6, 4 and 1 in Wadi Al Baseerah (1988)........442

5.67. Configuration of the water-table along Wadi Al Baseerah between the observation well GG-9 (upstream) and the observation well GG-1 on the Dibba coastal strip (1988).....443

5.68. (A to C) Groundwater level hydrographs for well BHF-15 at Sha'arah, downstream of Wadi Ham Dam, Well BHF-12 at Fujairah and Well GWR-5 at Al Saff in Kalba (1988)........444

XLIV
5.69. Cross-section along the three observation wells BHF-15 at Sha'arah, BHF-12 at Fujairah airport and GWR-5 at Kalba showing the configuration of the water-table in the Wadi Ham outwash fan.................................445

5.70. (A to E) Groundwater level hydrographs of MEW wellfields in the northern limestone mountains (A and B), in the central ophiolite mountains (E), in the piedmont plains (C) and in the desert foreland (D) (1987-88).................................446

5.71. Chart from the groundwater level recorder of Well GP-15, SE of Al Dhaid, showing the daily groundwater level fluctuation for February-March 1987.................................447

5.72. Chart from the groundwater level recorder of Well GP-15, SE of Al Dhaid, showing the daily groundwater level fluctuation for July 1987.................................448

5.73. Chart from the groundwater level recorder of Well GP-15, SE of Al Dhaid, showing the daily groundwater level fluctuation for November 1988.................................449

5.74. Chart from the groundwater level recorder of Well GWR-7 in Al Ain for July 1983.................................450

6.1. Subdivisions of the mountain area and the northern and central parts of the piedmont plains and the east coast (the eastern piedmont plains) of the Emirates for which detailed water sampling was carried out and water quality is described in the text.................................462

6.2. Area 1 of the mountain zone: the ophiolite gabbro zone........464

6.3. Irrigation water class of the waters of the mountain AREA 1 (the ophiolite gabbro zone).................................469

6.4. Area 2 of the mountain zone: the ophiolite peridotite zone...471
6.5. Irrigation water class of the waters of the mountain
AREA 2 (the ophiolite peridotite zone).................................475

6.6. AREA 3 of the mountain zone: the ophiolite peridotite
and Hawasina metamorphics zone of the Masfut-Hatta-
Muzeirea' intermontane basin........................................477

6.7. Irrigation water class of the waters of the mountain
AREA 3 (the ophiolite peridotite and Hawasina metamorphics
zone of the Masfut-Hatta-Muzeirea' intermontane basin)......482

6.8. AREA 4 of the mountain zone: the Hawasina metamorphics
and volcanics Dibba Corridor Zone.................................484

6.9. Irrigation water class of the waters of the Hawasina
metamorphics and volcanics Dibba Corridor....................488

6.10 AREA 5 of the mountain zone: the Hajar carbonate
massif of Ru‘us Al Jibal..............................................490

6.11. Irrigation water class of the waters of the Hajar
carbonate massif of Ru‘us Al Jibal zone...........................495

6.12. Delineation of the northern part of the piedmont plains
from Falaj Al Mualla to Al Jiri Plain..............................499

6.13. Irrigation water class of the waters of the northern part of
the piedmont plains from Falaj Al Mualla to Al Jiri Plain...502

6.14. Delineation of the central part of the piedmont plains
from Falaj Al Mualla to Al Madam.................................504

6.15. Irrigation water class of the waters of the central part
of the piedmont plains from Falaj Al Mualla to Al Madam....507

6.16. Location map of the Al Ain region showing the southern
part of the piedmont plains, the northern dune area to
the north of Al Ain and the western and southern
deserts.................................................................514

XLVI
6.17. (A to C) The relationship between the drop in groundwater levels and the deterioration in groundwater quality in the Al Ain region (1981-87).................................544

6.18. The irrigation water class of the waters of the Al Ain region.................................................................552

6.19. The eastern alluvial embayments of the east coast from Sur Kalba in the south to Dibba in the north...........555

6.20. Irrigation water class of the waters of the alluvial embayments of the section of the east coast to the north of Khor Fakkan.................................................................558

6.21. Irrigation water class of the waters of the alluvial embayments of the section of the east coast to the south of Khor Fakkan.................................................................559

6.22. Locations of water samples analyzed for the Wadi Al Baseerah basin on the east coast: the coastal aquifer, the central wadi channel and the eastern and western flanks of the wadi basin........................................561

6.23. Irrigation water class of waters of the coastal aquifer of Wadi Al Baseerah on the east coast.........................568

6.24. Irrigation water class of the waters of the central Wadi Al Baseerah flow channel........................................569

6.25. Irrigation water class of the waters of the eastern and western flanks of Wadi Al Baseerah on the east coast...........570

6.26. Locations of water samples analyzed for the Wadi Ham-Fujairah alluvial outwash fan and some points upstream......574

6.27. Irrigation water class of the waters of the Wadi Ham-Fujairah outwash fan on the east coast.........................578

XLVII
Subdivisions of the lowland zone of the Emirates showing the subzones of the desert foreland (8 A to E), the southern part of the piedmont plains (Al Ain, 6 C) and the western coastal zone (9) from where water samples were collected and groundwater quality described in the text........580

Irrigation water class of waters in the desert foreland zone in the Northern Emirates.........................587

Irrigation water class in the forestry wells of the desert foreland zones 8 B and C (the desert foreland to the west of Al Ain as far as 10km west of Al Khaznah.........................591

Irrigation water class for selected analyses in Tables 6.40 and 6.41 of wells in the desert foreland zone 8 D........600

Irrigation water class in the desert foreland zone of central Abu Dhabi (Zones 8 D and E).........................601

Irrigation water class of the waters of Eastern Liwa in the desert foreland 8 E zone.................................610

Irrigation water class of the waters of Western Liwa in the desert foreland 8 E zone.................................611

Irrigation water class of waters in the western (Gulf) coastal zone (marked 9 in Fig. 6.28).................................616

Groundwater movement and age from isotopic deductions by Geoconsult (1985).................................636

Regional and local wellfields, dual and single wells of the public supply of the MEW, Dubai, Sharjah and Ras Al Khaimah in the Northern Emirates.................................669

The public supply wellfields of WED Al Ain (1990).................................685
8.3. The public supply wellfields of WED Abu Dhabi and the oil companies in central, western and southern Abu Dhabi (1990)........ 692

8.4. Graphical representation of the daily production of desalinated water in the 6 power and desalination plants of Abu Dhabi for 1987 and 1988.............................. 727

8.5. The desalination plants of the Emirates (1990)...................... 731

8.6. Development of desalinated and groundwater production in Sharjah (1981-89)................................. 739

9.1. Fresh, brackish and saline groundwater resources shared with Oman and the countries of the Arabian Peninsula........ 779

9.2. Estimates of groundwater from Omani catchments underflowing the Oman-UAE border into the Al Ain region in the land front from Al Madam to Al Wagn......................... 784

9.3. Groundwater abstraction points on the Emirates side of the international border with Oman in the Al Ain-Al Buraimi shared fresh groundwater front.............................. 785

9.4. Location map of the wells of the Buraimi region of Oman of the Groundwater Development Consultants (GDC) (1982)........... 790

9.5. Location map of the ZG series of wells in the Zarub Basin and Gap area........................................... 796

9.6. The geology of the Al Ain region and adjacent hardrock catchment areas in Oman................................. 799

10.1. The water balance regions of Iwaco, 1986......................... 842
11.1. The ill-advised siting of wells (or wellfields) along the whole groundwater flow profile in the lower Wadi Ham and its outwash fan.................................871

11.2. The intensively developed wellfields of Al Shuwaib-Kashoonah-Al Khadher of the recharge zone in the northern alluvial-aeolian area of Al Ain.................................874

11.3. The main water resource developing and managing organizations of the Emirates (1990-91).........................895

11.4. The broad stages of the water resource plan process.........903
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.</td>
<td>The distribution of water sources in the world</td>
<td>2</td>
</tr>
<tr>
<td>1.2.</td>
<td>Total annual production of desalinated water of the AGCC states for 1989</td>
<td>13</td>
</tr>
<tr>
<td>1.3.</td>
<td>The increase in the 4 related sectors: water, agricultural land, population and foreign food imports</td>
<td>16</td>
</tr>
<tr>
<td>2.1.</td>
<td>The mechanical composition of the different types of soils by weight from pits dug in wadi-piedmont alluvium and sandy-sabkha soils</td>
<td>98</td>
</tr>
<tr>
<td>2.2.</td>
<td>The increase in soil salinity in the Dibba fruit farm between 1982 and 1989</td>
<td>98</td>
</tr>
<tr>
<td>2.3.</td>
<td>Analysis of the mechanical composition of azonal soils through which recharge from rain and flood water is taking place</td>
<td>99</td>
</tr>
<tr>
<td>2.4.</td>
<td>A typical sabkha soil profile at Seih (Sabkhat) Mussannad in Sharjah</td>
<td>100</td>
</tr>
<tr>
<td>2.5.</td>
<td>A typical soil profile of the fine alluvial deposits in the flood plain of Wadi Al Baseerah</td>
<td>101</td>
</tr>
<tr>
<td>2.6.</td>
<td>Chemical analysis of the soil paste extract and both the ECe of the soil and the EC of the water (bracketed) that is being used on such soils in different alluvial and sandy localities in the piedmont plains and desert foreland</td>
<td>103</td>
</tr>
<tr>
<td>2.7.</td>
<td>The salinity and carbonate content of the soils in the agricultural areas of the Al Ain region</td>
<td>104</td>
</tr>
</tbody>
</table>
2.8. Increase in soil salinity in the Al Sa'adiyah forestry project in Al Dhafrah in Abu Dhabi (1987-1989)..........................104

2.9. Individual infiltration tests in locations of different types of deposits in a variety of terrains in the Emirates to show the variation in infiltration rates using a double-ring infiltrometer (1988)..........................107

2.10. Summary of the infiltration tests in the aeolian deposits of the desert foreland (giant, medium and low dunes) and in the sabkha deposits of the 'seihs' (1988)...............108

2.11. Summary of the infiltration tests in the alluvial deposits of the mountain wadis, piedmont plains and adjacent areas of the desert foreland (1988)..........................109

3.1. The meteorological stations of the Western (Abu Dhabi) and Central (Dubai) Military Commands (1989)..................120

3.2. Rain-gauges in Al Ain (Al Ain Department of Agriculture) 1989..........................................................122

3.3. Solar radiation: 24-hour mean and maximum values for Abu Dhabi Airport Meteorological Station (in Cal/cm²)...........132

3.4. Surface wind in km/d for stations in all the topographical zones (for the hydrological year Oct.-Sept.)...............132

3.5. Mean monthly temperature, annual mean for each station and the annual mean for the area (topographic region)........135

3.6. Mean monthly maximum and mean monthly minimum temperature and the annual mean maximum and minimum for the Emirates...136

3.7. Absolute maximum and minimum monthly temperature and their range..........................138
3.8. Relative humidity (%): Monthly mean, mean maximum, mean minimum, absolute maximum, absolute minimum, monthly mean for the whole Emirates, annual mean for each station and the general annual for the whole Emirates


3.10. Annual rainfall totals for the period of records (1967-68 to 1987-88) for 38 stations in the different topographical zones of the Emirates

3.11. The relationship between the mean annual rainfall and annual runoff totals (1981-88)

3.12. The seasonality of rainfall: the main winter rainfall and the convectional and monsoonal rainfall in the summer, and the percentage of the amount of each type out of the annual totals

3.13. Frequency of rainfall amounts of selected thresholds (totals) in percentages of the total number of years of rainfall records, and also in the years of recurrence (or return)

3.14. Rainfall return periods of the Sharjah long-term rainfall record (1934-88), with the return periods of selected thresholds of rainfall totals

3.15. The long-term Sharjah monthly rainfall record (1934-88), monthly and annual totals and the period mean, with the annual rainfall totals arranged in ascending order

3.16. The mean monthly rainfall for the period of rainfall records for stations in the various topographical regions

3.17. Daily winter rainfall in the piedmont plains for Falaj Al Mualla, Digdaga and Mileiha
3.18. Daily winter rain: the number of rain days of more than 2.0mm. in the rainy month of February in the exceptionally rainy year 1988 for selected stations in each of the topographical regions. .................................174

3.19. Rainfall totals in the various mountain stations illustrating the extent of the convectional rainstorms of the 10th. of August, 1983. .........................................................175

3.20. Convectional rainstorms originating in the mountains but extending eastwards into the east coast, or westwards into the piedmont plains; convectional storms originating within the piedmont plains and extending eastwards into the mountains; east coast monsoon rainstorms extending westwards into the mountains and the piedmont plains; and localized convectional rainstorms in limited areas within either the mountains or the piedmont plains. ..............................178

3.21. The available unpublished rainstorm intensity data and the duration of their records for stations that have storm intensity records (1979-83). .................................................182

3.22. The range of rainfall intensity rates: comparison of the storm intensity rates in the 10-min., 20-min., 30-min. and the 1-hr., 2-hr., 3-hr., 4-hr., 12-hr. and 24-hr. duration for most of the stations for which rainstorm intensity records exist for the period 1979-83. ............................183

3.23. Moderate rain peaks (12-40mm) in Sha‘am separated by intervals of 1-2 days during the rainy months (1982-83). ....190

3.24. Rainstorm intensity data for the summer convectional rains. .................................................................192

3.25. The range of rainfall totals and intensity rates of the summer convectional storms for the period of record (1979-83) .................................................................193
3.26. Rainstorm intensity records of the late 'winter' rainfall events of 30th. April to 2nd. May 1981

3.27. Mean monthly class 'A' open pan evaporation rates

4.1. Runoff volumes of the gauged catchments of the Emirates for the hydrological years 1975-76 to 1987-88

4.2. The main physiographic characteristics of the wadi catchments of the Emirates

4.3. Runoff characteristics for main flood events for selected wadis in both the limestone and ophiolite parts of the mountains of the Emirates for flood events in 1979, 1982, 1983 and 1988

4.4. Average annual runoff ratio for selected wadis in the limestone and ophiolite gauged catchments

4.5. The flood-gauging stations of the Emirates (1990)

4.6. Localized rainfall in the Ashwani and Sfini wadi catchments giving rise to greater runoff volumes in the smaller Wadi Ashwani than the larger Wadi Sfini (Tables A and B)

4.7. Runoff characteristics for a high runoff year (1988), a medium runoff year (1983) and a low runoff year (1987)

4.8. Runoff characteristics: the duration of runoff from start to peak for selected wadis for low (1979), moderate (1983) and high (1988) runoff years

4.9. Flood peaks in a moderate runoff year (1987) for selected wadis

LV
4.10. Flood peaks, the total daily runoff volume of the flood event and the total annual flood volume for selected wadis in the limestone and ophiolite parts of the mountains for the medium (1983), low (1987) and high (1988) rainfall years (Tables A to E)..............................231

4.11. Comparison of the total annual runoff volumes, runoff ratios and effective rainfall for the gauged catchments of the Emirates for a high rainfall (1987-88) and a comparatively moderate rainfall (1986-87) year, and the median for the period of rainfall records (7-13 years).........................238


4.13. Outflow to the sea from submarine springs on either coast of the Emirates (1981)........................................242

4.14. Mean annual runoff yields and estimated effective groundwater recharge from them for both the gauged and ungauged catchments of the Emirates.................................246

4.15. Comparison of total catchment yields for high-rainfall years (1982 and 1988), a medium-rainfall year (1983) and a relatively low-rainfall year (1987)...............................247

4.16. Runoff volumes for east- and west-flowing wadis in both the limestone and ophiolite parts of the mountains north and south of the Dibba-Idhn Fault Line.................................248

4.17. Hydrological and physiographical data of all the aflaj and hot springs of the Emirates, and the mean annual natural discharge of the aflaj whose flows are still unaugmented.......252

4.18. Average annual falaj discharge rates of Falaj Buraimi and Falaj Sa’arah in Oman based on several measurements taken during the year (1982-1988)..............................260
5.1. Representative porosity ranges for selected rocks .............. 278
5.2. Specific yield of important water-bearing rock material ....... 278
5.3. Classification of the aquifers of the Emirates according to transmissivity ranges and productivity rating .............. 279
5.4. Average aquifer characteristics of the deep carbonate formation aquifers of the Simsima, Um Er Radhmah and Dammam (1981-83) ................................................................. 313
5.5. The hydraulic properties of the aquifers in the piedmont plains as given by the Deep Wells Project (1985) .............. 321
5.6. Transmissivity and permeability values of aquifers in important groundwater abstraction locations in the piedmont plains and the desert foreland ...................... 323
5.7. Variation with depth of strata thickness with water-bearing properties in Al Jaww Plain in Al Ain.
5.8. The characteristics of the shallow Asab aquifer in southern Abu Dhabi ................................................................. 344
5.9. The characteristics of the Shah shallow aquifer .............. 344
5.10. Variation in permeability in the wadi aquifer in the indurated Tertiary alluvium in Wadi Ham ...................... 353
5.11. The well-discharge rates in MEW wellfields of the east coast ................................................................. 356
5.12. Transmissivity and specific capacity values of the coastal aquifer in Fujairah up to 3 km. from the shoreline .............. 356
5.13. The hydraulic characteristics of the alluvial aquifers of Wadi Al Baseerah (1981) ................................................................. 364
5.14. Results of the pumping tests of some wells in the different alluvial aquifers of Wadi Al Baseerah

5.15. Static water levels in the northern limestone aquifers (1984-86)

5.16. The static water levels are below MSL in MEW wellfields in the lower parts of the northern mountain wadis of Ras Al Khaimah (1988)

5.17. Groundwater level fluctuation in Wadi Al Beeh, 1984-87

5.18. Groundwater level fluctuation in Dhuhuriyyeen, 1984-87

5.19. Static water levels in wadi terraces and flood plains for some mountain wadis

5.20. Static water levels in the Juweiza Formation in the wells of the Deep Wells Project in the piedmont plains (1982-86)

5.21. The continuous recession of groundwater levels in Al Dhaid in the central part of the piedmont plains

5.22. The boreholes of Al Badea’ North wellfield of Sharjah showing pump-levels below MSL (1988)

5.23. SWLs in the Al Wuhoosh Wellfield of Dubai (1988)

5.24. Groundwater levels in selected points in the desert foreland within Dubai emirate (1988)

6.1. The main ions in water and their mineral sources in the different rock types

6.2. Arbitrary classification of groundwater in the Emirates on the basis of the Total Dissolved Solids content

6.3. International water quality standards for the various uses
6.4. Water chemical analyses of AREA 1 of the ophiolite gabbro mountain zone.......................................................... 465

6.5. Water chemical analyses of AREA 2 of the ophiolite peridotite mountain zone...................................................... 473

6.6. Water chemical analyses of AREA 3 of the ophiolite peridotite and Hawasina metamorphics zone of the Masfut-Hatta-Muzeirea' intermontane basin.............................................. 479

6.7. Water chemical analyses of AREA 4 of the Hawasina metamorphics and volcanics zone of the Dibba Corridor....... 487

6.8. Water chemical analyses of AREA 5 of the part of the limestone mountain block of Ru'us Al Jibal zone that lies within the Emirates, including analyses of the three deep wells RK-5, RK-6 and RK-9 of the Deep Wells Project.............................. 492

6.9. Water chemical analyses of AREA 6 (A) of the northern part of the western piedmont plains from Falaj Al Mualla to Al Jiri Plain................................................................. 501

6.10. Water chemical analyses of AREA 6 (B) of the central part of the western piedmont plains from Falaj Al Mualla to Al Madam................................................................. 506

6.11. Seasonal variation in groundwater quality in Al Dhaid (April-June 1982).............................................................. 509

6.12. Water chemical analyses of the wells of the Deep Wells Project in the western piedmont plains from Al Manama to Um Ghafah.. 512

6.13. Water chemical analyses of the recharge waters of the Zarub (Musaileq) catchment in Oman to the east of the southern part of the western piedmont plains: the Al Ain region from Ghashabah to Um Ghafah.................................................. 517

LIX
6.14. Water chemical analyses of the recharge waters of the Mahdhah catchment and outwash fan in Oman to the east of Al Ain (from Musaileq to Ghashabah)..........................518

6.15. Chemical analyses of the waters of the Al Ain region: northern, central, eastern and southern Al Jaww Plain; the Al Ain vicinity and the northern alluvial and dune area (2 tables)........................................523

6.16. Chemical analyses of waters in the Al Jaww Plain showing the increase in groundwater salinity with depth and distance from the foothills.................................527

6.17. Chemical analyses of irrigation water in the gravel and sabkha areas of western, southwestern and southern Al Ain region...528

6.18. Long-term change in water quality in some areas in Al Ain (1975-1988)........................................530

6.19. Short-term variation in groundwater quality in some of the wells of the Um Ghafah public supply wellfield in the Al Ain region (1987-88).......................................533

6.20. Short-term variation in groundwater quality in some of the wells of the Al Hayer North public supply wellfield in the Al Ain region (1987-88).................................534

6.21. Short-term variation in groundwater quality in some of the wells of the Ghashabah public supply wellfield in the Al Ain region (1987-88).......................................536

6.22. Short-term variation in groundwater quality in some wells of the public supply wellfields of Al Kara’, Jubaita and Bida’ Bint Ahmad in the Al Ain region (1987-88)........537

6.23. Short-term variation in groundwater quality in some of the wells of the public supply wellfield of Al Khadher Nassas in the Al Ain region (1987).................................539
6.24. Short-term variation in groundwater quality in some of the wells of the Suwaihan Road public supply wellfield of the Al Ain region (1987-88).................................541

6.25. Short-term variation in groundwater quality in some of the wells of the outlying villages of Al Ain (1987-1988)..............542

6.26. Irrigation water quality in the Al Ain region by the percentage of groundwater samples analyzed according to the various salinity groups (1987-88).................................547

6.27. Salinity (ECe), calcium-carbonate (CaCO₃) content and alkalinity (pHs) of the saturated soil extract of the soils of the Al Ain region (1988).................................549

6.28. Water chemical analyses and classes of the irrigation water in the various agricultural locations in the Al Ain region (1989).........................................................551

6.29. The increase in the EC and SAR and the deterioration in the irrigation water class westwards along the Al Ain-Abu Dhabi highway.........................................................553

6.30. Water chemistry and quality of the two sections of the east coast to the north and south of Khor Fakkan (1988)..............557


6.32. Chemical analyses of groundwater in the central channel of Wadi Al Baseerah (1988).........................................................566

6.33. Chemical analyses of groundwater in the eastern and western flanks of Wadi Al Baseerah (1988).........................................................567

6.34. Water chemical analysis of a water sample from a well in an old indurated wadi terrace alluvium at the confluence of Wadi Al Halah and Wadi Al 'Uyainah in upper Wadi Al Baseerah.....572
6.35. Chemical analyses of the groundwater of the Wadi Ham-Fujairah alluvial outwash fan (1988) ........................................576


6.38. Comparison of the water chemistry of a well in Al Faqa for 1969 and 1988 .................................................................589

6.39. Chemical analyses of groundwater used in the forestry areas of the Al Ain region of Abu Dhabi in the desert foreland AREAS 8 B and C as far as Al Khaznah in the west and Um Ez Zemool in the south (1988)(2 Tables) ......................592

6.40. Chemical analyses of groundwater used for irrigation in the agricultural and forestry locations in central and western Abu Dhabi in AREA 8 D of the desert foreland (1988) (2 Tables) .................................................................595

6.41. Chemical analyses of groundwater in AREA 8 D of the desert foreland of central and western Abu Dhabi to show the spatial variation in the chemistry of brackish and saline groundwater in whole aquifers or parts of them (1988) (2 Tables) .................................................................597

6.42. Chemical analyses of potable and agricultural groundwater in AREAS 8 D and E of the desert foreland of central and western Abu Dhabi (1988) .................................................................599

6.43. Bu Hasa Well BU-229 in the Bu Hasa/Shuaiba-Thamama Group of Lower Cretaceous aquifers (of 2601m depth) illustrating stratification of groundwater salinity with continued pumping .................................................................603

LXII
6.44. Groundwater salinity stratification in other shallow and deep aquifers in the oilfield areas of central Abu Dhabi for Asab Wells-136 and 132, BU Hasa Well 252, Sahil Well-29 and Shah Well-9.................................603

6.45. Chemical analyses of potable and rig groundwater from shallow and deep boreholes in the vicinities of the oilfields of the Abu Dhabi Company for Onshore Operations (ADCO) in the desert foreland of central Abu Dhabi..........................604

6.46. The range in salinities in ADCO’s water wells in the oilfield areas of central Abu Dhabi..............................................605

6.47. Comparison of Cl and SO₄ content in groundwater of some boreholes in Liwa..........................................................607

6.48. Chemical analyses of groundwater in the oases of Eastern Liwa in AREA 8 E in the southern part of the desert foreland of Abu Dhabi.................................................608

6.49. Chemical analyses of groundwater in Western Liwa oases in AREA 8 E in the southern part of the desert foreland in Abu Dhabi...............................................609

6.50. Water chemistry of the Upper Cretaceous and Tertiary deep carbonate system aquifers of the Simsima, Um Er Radhmah and Dammam (1983)...............................................613

6.51. Chemistry of the groundwater of other deep wells in Al Sila’ (in northwest Abu Dhabi) and Al Maida’ah (near the Abu Dhabi-Dubai interemirate border) 1983-88..............614

6.52. Chemical analyses of groundwater in the western (Gulf) coastal zone from Sha’am in the north to Al Sila’ in the west........615

7.1. Isotope content of rain events in the Emirates (1984-88)....622
7.2. Tritium content in rainfall at the WMO/IAEA station at Bahrain............................624

7.3. $^{13}$C values of carbon sources in groundwater......................626

7.4. Summary of the results of the environmental isotope study in Wadi Al Baseerah by the Japan International Cooperation Agency (JICA), 1981........................631

7.5. Results of the isotope analyses of the Deep Wells Project by Geoconsult (1982-86)..................................633

7.6. Selected results of isotopic investigations in the Emirates by the International Atomic Energy Agency (IAEA), 1984-88...639

7.7. The range of mean values of the stable and radioactive isotopes in the 5 topographic regions of the Emirates (1984-88)........................................641

7.8. Salinization (in situ) in Well No. 3 in Dhuhuriyyeen wellfield (1984-86)..........................643

7.9. Salinization of groundwater due to seawater intrusion in Well No. 4 in Sahwat wellfield (1985-86)..................643

7.10. Carbon-14 ($^{14}$C) determinations in pmc and groundwater age in years (1984-88)..........................650

7.11. Groundwater age in locations in the central desert foreland of Abu Dhabi..................................656


8.2. Hamlets in the remote areas of the Northern Emirates receiving water supply by road-tankers hired by the MEW (1988)........667

LXIV
8.3. The daily production of potable groundwater from the public supply wellfields, dual and single wells of the MEW in the Northern Emirates (1989).................................676

8.4. Decrease of production and number of boreholes (by depletion) in Al Wushah wellfield of Sharjah between 1986 and 1988.....679

8.5. Decline in borehole production in Hamdah wellfield (1986-88).679

8.6. Development in groundwater production from the Sharjah wellfields (1965-88)..................................................680

8.7. Comparison of the total daily production of all the Sharjah wellfields for the two years 1987 and 1988..............680

8.8. Development in the total daily production of groundwater from the public supply wellfields of Dubai (1961-1988)......682


8.10. Alternating lead in groundwater production in the three Dubai public supply wellfields (1981-1988).....................683

8.11. Groundwater production from the public supply wellfields of Al Ain (1989)......................................................687


8.13. The potable and brackish groundwater public supply wellfields of WED Abu Dhabi and the oil companies in central, western and southern Abu Dhabi emirate.........................691


8.15. The development of acreage under forest in both the western and eastern (Al Ain) regions of Abu Dhabi 1981-1988........698
8.16. The development of acreage under landscaping in and around the town of Abu Dhabi (1974-1989)..............................700

8.17. The development of acreage under trees of various kinds, date palms, vegetable and fodder outside Abu Dhabi town managed by the Agriculture Section of Abu Dhabi Municipality (1974-89).700

8.18. The forested areas managed by the Private Department of the Diwan of Abu Dhabi, their areas, the total number and type of trees grown in them and the type of irrigation water used (1988)....................................................701

8.19. The actual amounts of desalinated and groundwater used for irrigating forest trees on Sir Bani Yas Island (1988)............703

8.20. The quantities and sources of the types of irrigation water used by the Al Ain Municipality for landscaping (1988)......703

8.21. Shrinkage in agricultural acreage because of groundwater shortage in the Northern and Eastern Agricultural Regions...710

8.22. Dwindling natural falaj flow in some of the aflaj of the Northern Emirates that still have natural flow (1985-88)....710

8.23. Fluctuation of falaj discharge volumes in the aflaj of the Northern Emirates still with natural flow (1977-88)..........716

8.24. Quantifying the total annual volumes of groundwater used by agriculture in the Emirates on the basis of the gross crop water requirements (1988)......................................................716

8.25. Quantifying the crop water requirements by the traditional open basin (inundation), and the modern sprinkler and drip irrigation methods on the basis of the actual land area under each type of crop grown in the Al Ain region (1987-88)......717

LXVI
8.26. The percentage of the cultivated and uncultivated area out of the total agricultural acreage in the agricultural regions of the Emirates (1987-88).......................... 719

8.27. Results of the well-discharge tests from irrigation wells in different agricultural regions of the Emirates (1988)...... 723

8.28. The development of the installed desalinated water production capacity in Abu Dhabi (1970-1989)......................... 726

8.29. The daily production of desalinated water of the 6 plants in Abu Dhabi, and the percentage of each from the total daily output for 1987 and 1988................................. 727

8.30. The desalinated water production in Abu Dhabi (1973-88)..... 729

8.31. All the existing and proposed desalination plants in the Emirate of Abu Dhabi, their units, the installed capacity, the manufacturer, the type of desalination process and the total daily output of each (1990)................................. 730

8.32. Percentage of the daily desalinated water produced by either DEC or DUBAL out of the total daily desalinated water production and that of the gross daily water production (including groundwater) in Dubai for 1987 and 1988............ 736

8.33. The average daily production of desalinated water by DEC and DUBAL for 1987 and 1988................................. 736

8.34. The average daily production of desalinated and ground water and the daily total output of both on a monthly basis for Sharjah town for 1989................................. 738

8.35. Small desalination plants in the Northern Emirates (1990).... 743

8.36. The design capacity of the Al Mafraq Sewage Treatment Plant of Abu Dhabi................................. 746

LXVII
8.37. The physical and chemical specifications of the raw influent and the treated affluent of the Al Mafraq Sewage Treatment Plant of Abu Dhabi

8.38. The cost of MEW water boreholes (1975-1988)


8.40. The cost of the various types of pumps installed on boreholes in the Emirates for 1982 and 1987

8.41. The high-output/low-cost and the low-output/high-cost desalination plants of Abu Dhabi, 1988-89

8.42. Breakdown of elements of the production cost of each desalination plant in Abu Dhabi (1988)

8.43. Breakdown of the components of the production cost of all the desalination plants of Abu Dhabi town, 1980-88

8.44. The development of desalination plants in association with power stations in the Dubai Electricity Company (DEC) site at Jabal Ali, 1979-1993

8.45. (A) Breakdown of the estimated production cost components of desalinated water produced by Dubai Electricity Company for 1988 and 1989

8.45. (B) The actual cost of the desalinated water produced by DUBAL in 1988 as invoiced to the Dubai Water Department (1988)

8.46. The average production unit cost of the 3 sources of water in Dubai (groundwater and the two sources of desalinated water), on the basis of apportionment of water volume produced from each source (1988)
8.47. Breakdown of the production unit cost of the desalinated water produced at Al Layyah plant in Sharjah (1988)...........767

8.48. The production and selling unit costs of desalinated and ground water, and of both combined, as well as the cost per 1000 gallons reaching the consumer in Sharjah, for 1987 and 1988........................................767

8.49. Breakdown of the cost of the expected production of recycled sewage water from the New Dubai Sewage Treatment Plant at Al Aweer, which has commenced operation at the end of 1989..769

8.50. Summary of the production unit cost of ground, desalinated and recycled water by emirate or region, and the combined production unit cost of each type of water for the whole Emirates (1988)........................................770

8.51. The combined unit cost per 1000 gallons of both the produced water and that reaching the consumer for the whole Emirates (1988)..............................772


9.2. Groundwater recharge and net inflow balance remaining for the Emirates from the Omani catchments of the Buraimi region from Al Madam to Sunainah according to estimates of the Regional Development Council of Oman (1987).......................788

9.3. Variation in the saturated thickness and well-discharge rates in the cemented alluvium of the 'Ajran Gap............793

9.4. Water-bearing units and their hydrogeological properties in the Zarub basin and Gap area...............................794

LXIX
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5.</td>
<td>Results of the pumping tests from the different water-bearing strata in the inland basin of Zarub (Musaileq) and the Zarub Gap areas in Oman adjoining the Al Ain region of the Emirates (1985)</td>
</tr>
<tr>
<td>10.2.</td>
<td>The groundwater balance of Carr and Barber (1976)</td>
</tr>
<tr>
<td>10.3.</td>
<td>Annual runoff volume of the catchments in the limestone and ophiolite parts of the central mountains, by the International Development Centre of Japan (IDCJ) (1978)</td>
</tr>
<tr>
<td>10.4.</td>
<td>Allocation of the annual rainfall and runoff totals to each hydrological (topographical) zone in the Al Ain region by Hydroconsult (1978)</td>
</tr>
<tr>
<td>10.5.</td>
<td>The groundwater balance of the Al Ain region by Hydroconsult (1978)</td>
</tr>
<tr>
<td>10.6.</td>
<td>Consultants and the wadi basins for which they prepared groundwater recharge balance estimates in Oman (to the east of the common border with the Emirates) responsible for replenishing the aquifers of the Al Ain region in the Emirates</td>
</tr>
<tr>
<td>10.7.</td>
<td>Previous groundwater recharge estimates for the Sumaini-‘Ajran land front of the Al Ain region in the Emirates</td>
</tr>
<tr>
<td>10.10.</td>
<td>The groundwater balance estimates of the MAF (1982)</td>
</tr>
</tbody>
</table>
10.11. The groundwater balance estimates of the Al Ain region by the Al Ain 2000 Master Plan by Edworthy-Brandt (1985)........840


10.15. The combined groundwater balance of the main agricultural areas by Iwaco, 1986.................................................845

10.16. Comparative summaries of groundwater balance estimates for previous studies in the Emirates and the areas covered by each study................................................847

10.17. Estimates of natural outflow to the sea through submarine springs in both the west and east coasts of the Emirates (Lavalin, 1980).................................................851

10.18. Breakdown of the localities in the desert foreland and their total area for which recharge from direct rainfall has been calculated for the present study (1988)........857

10.19. The general groundwater recharge/discharge balance of the Emirates (1989)................................................858

11.1. The total volume of water produced in the four main towns of Abu Dhabi, Dubai, Sharjah and Al Ain; the gross and actual daily per capita consumption; percentage of the recycled wastewater to the gross water produced and that actually used domestically (1989)................................................887

11.2. Fluoride and sulphate content in the waters of the wellfields of WED Abu Dhabi in central Abu Dhabi and Liwa (1987)......913

LXXI
11.3. Results of water analysis showing Nitrate (NO₃), Fluoride (F⁻) and Sulphate (SO₄) occurrences in selected locations in the Emirates (June, 1989)

11.4. Ratio of irrigated land by modern and traditional irrigation methods to the total irrigated land (1988)
ABBREVIATIONS

BOD : = Biochemical Oxygen Demand
°C : = Celcius
Dhs. (dhs.) : = Emirates dirhams (currency) = 3.65 US$
EC : = Electrical conductivity of the water
ECe : = Electrical conductivity of the soil extract
gals./hr. : = Gallons per hour
ha. : = Hectare
km/d : = Kilometre per day
l/s : = Litres per second
lch : = Low cost housing (estate)
lpd : = Litre per capita per day
m/h : = Metre per hour
m/s : = Metre per second
m³/d/m : = Cubic metre per day per metre
m³/h : = Cubic metre per hour
m³/ha/m : = Cubic metre per hectare per metre
m³/m²/d : = Cubic metre per square metre per day
m³/s : = Cubic metre per second
MAF : = Ministry of Agriculture and Fisheries
MCM/a : = Million Cubic Metres per annum
meq/l : = Milli equivalent per litre
MEW : = Ministry of Electricity and Water
mg/l : = Milligram per litre
MGD. (mgd.) : = Million gallons per day
mmhos/cm : = Micromhos per centimetre (at 25°C)
MSL : = Mean Sea Level
pH (moles/litre): = Alkalinity of water
ppm : = Parts per million
SAR : = Sodium Adsorption Ratio
SS (TSS) : = Suspended Solids (Total Suspended Solids)
SWL : = Static Water Level
TDS : = Total Dissolved Solids (in parts per million)
WED : = Water and Electricity Department
x10⁶ : = Million
GLOSSARY

Abu = Father of (Abu Dhabi= Father of the gazelle (oryx)).
ADCO = Abu Dhabi Company for Onshore Operations.
ADNOC = Abu Dhabi National Oil Company.
Bidar (bedar) = Farm worker (of Hindi origin).
Bida' = Town, village or any habitation.
Bin = Son of (Seih bin Ammar).
Bint = Daughter of (Bida’ bint Saud).
Coliform = Disease-producing rod-shaped bacteria in human and animal waste present in raw sewage.
DEC = Dubai Electricity Company.
Depocentre = Centre of deposition (deepest part of a geosyncline).
Diwan = A shiekh’s (ruler’s) local government house.
DUBAL = Dubai Aluminium Company.
DWD = Dubai Water Department.
Falaj (pl. aflaj)= Traditional irrigation tunnel/channel (qanat).
Jabal = Mountain, hill, hillock or even a mound (Jabal Ali).
Khawr = An estuary, a lagoon or any inlet of the sea.
Misyal = A seasonally flowing wadi channel.
Qarn = Horn, to describe a hillock detached from a mountain block.
Ras = Headland (promontory).
Rol (Rul) = Flat coastal plain (outwash fan) (Rul Dibba); or related to a local broad-leaved tree called ‘rolla’ that once grew on the east coast but is still found on the west coast (the ‘Rolla’ of Sharjah refers to the famous tree that was a gathering spot in central Sharjah town.
Ru’us = Summits of mountains (Ru’us Al Jibal).
Sabkha = Mud flat, salt flat, playa.
Seih = Any wide, flat land (plain) (Seih Al ‘Aqareb).
Shamal (Shimal) = North(also describing the prevalent northerly winds)
Um = Mother of (Um el Zemool= mother of the giant dunes).
Wadi = An ephemeral or dry valley; also the flowing stream.
Wali = Area chief, usually a tribal leader.
Wilayah = Governorate (managed in Oman by a wali).
(pl. Wilayat)
"The copyright of this thesis rests with the author. No quotation from it should be published without his prior written consent and information derived from it should be acknowledged."
1. INTRODUCTION

1.1. The water resource problem on the global, Middle East, Gulf Cooperation Council States and national (Emirates) levels

1.1.1. General

In arid regions, more than elsewhere, water assumes great importance as the basic prerequisite of life. Surface water sources have guided civilizations since the dawn of mankind and have continued to do so since the Industrial Revolution. The heavily industrialized advanced countries, in both the East and West, are those that possess secure supplies of suitable surface or groundwater. Although surface water sources are cheaper to exploit than those of groundwater, they only make up 2% of the world's fresh water supplies and, in most cases, they have reached an advanced stage of overdevelopment and pollution in the industrialized countries. 98% of the fresh water of the Earth is stored as groundwater which has also been so heavily developed in the past few decades that water shortages have become a worldwide phenomenon. This is why the United Nations (UN), recognizing the importance of water and its ready availability to the betterment of standards of living around the world, declared the years 1981-1990 as the International Drinking Water Supply and Sanitation Decade (UN General Assembly Resolution 35/18, 10-12-1980).

While surface water sources (rivers, lakes, springs) are localized in occurrence, groundwater is more widely distributed beyond surface water bodies. Groundwater development offers the better option in terms of the possibility of development in stages, according to the increase in demand, than is the case with surface water sources that lose a substantial part of their flow to sea, and are also becoming increasingly polluted. However, this advantage of groundwater development is conditional on the availability of the resource and the principle that natural or artificial discharge should not exceed the
natural or artificial recharge, an ideal situation that is hard to attain.

The water resource situation is discussed in this introductory chapter on the global, the Middle East, the Gulf Cooperation Council States (GCC) and the national (Emirates) levels. Although the deterioration in water quality and quantity is a global problem, it intensifies as the circle narrows down to the regional (Middle East) and the Gulf levels as both regions lie within the hot semi-arid and arid belt. As the water resources are examined in detail on the national level, either with official data or that acquired in the field, the problem deepens further owing to inhospitable physical limitations and human misuse.

This brief review of the water resource problem on the various geographical levels is aimed at providing the background against which is set the same problem on the national level discussed in detail throughout the present study.

1.1.2. The water resource problem on the global level

The World Resources Institute (1988-89) estimated the annual available water from precipitation on all the land mass, after losses by evapotranspiration and outflow to the sea, as 9.0 billion km$^3$, which is enough for a population three times the present total of the world inhabitants (5.1 billion, 1988). Table 1.1. shows the quantitative and geographical distribution of water on the globe.

<table>
<thead>
<tr>
<th>Source</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water in the Oceans</td>
<td>97.41%</td>
</tr>
<tr>
<td>Water on the land:</td>
<td>2.59%</td>
</tr>
<tr>
<td>a) Ice caps and glaciers</td>
<td>1.920%</td>
</tr>
<tr>
<td>b) Groundwater</td>
<td>0.956%</td>
</tr>
<tr>
<td>c) Lakes, rivers and moisture in the soil, vegetation and atmosphere</td>
<td>0.014%</td>
</tr>
</tbody>
</table>

Table: 1.1

The distribution of water sources in the world.
As this great volume of water from precipitation is unevenly distributed in the world, there are water-rich countries and others that are water-deficient. The following example of the two island states of Iceland and Bahrain clearly illustrates this: while the former has available water from natural sources at the rate of 68,500 m³/annum/per capita, the latter has nearly exhausted its groundwater sources from the Dammam aquifer and relies almost totally on desalinated water (37mgd.). Again, the average resident of the United States uses up to 70 times (2,300m³/annum/per capita) more than the Ghanaian resident (33m³/annum/per capita), more than 4 times the amount used by the Swiss resident (500m³/annum/per capita) or 14 times that of the Jordanian (170m³/annum/per capita) resident. Furthermore, whereas the American per capita consumption can be explained by an economically viable agriculture in that country, the virtually equally high consumption of water-deficient countries in the arid zone, such as Saudi Arabia and the Emirates of 1785 m³ and 2151 m³/annum/per capita, respectively, is for economically unviable agriculture. This is evident from the cost of imports of foodstuff, as in the case of the Emirates, which has not shown any decline in the total annual cost of food imports in the past decade as will be discussed later.

The global increase in water consumption in the past three decades has been phenomenal as shown in Fig. 1.1. Countries such as the United States, the Soviet Union, Australia and South Africa, with parts of their territories lying within semi-arid or arid zones, have developed technologies of water augmentation (dams, artificial recharge) and abstraction that have enabled them to draw on their groundwater resources heavily. The commendable work of the UN in introducing such technologies to the poorer countries of the world, with the intention of bettering their standards of living, has led to more quantities of water being utilized from previous poorly exploited surface sources, but also has led to heavy abstraction from groundwater sources. The overall development in agriculture worldwide, whether leading to successful results and food self sufficiency, or just the greening of large tracts of land without a clear policy towards the goal of food security, has meant that agriculture uses up to 73% of the usable water available in the world. This percentage can be as high as 95% on the local or national level and is not necessarily paying off in terms of agricultural productivity or economic viability in most countries of
Figure: 1.1.

The four-fold increase of the consumption of water in the world since 1950.
the world. The global agricultural land under continuous irrigation is estimated at 3 million km\(^2\) and is increasing annually at a rate of 8% (Scientific American, September, 1989).

Depleting groundwater resources are widespread in many parts of the world, such as the United States, India, Australia, China and the Soviet Union. As population increases, the nations less endowed with mineral resources take to agriculture to enhance their economies. As a result, the pressure on groundwater increases leading to the acute depletion of aquifers. Even the oil-rich nations are looking to agriculture, either for diversifying their economies or for trying to reach the seemingly unattainable goal of food self-sufficiency (as most of these countries are situated in the arid zone of the world). Water shortages in such countries become even more critical when it is realized that they are neither well endowed with surface and ground water reserves nor are the soils of acceptable quality to sustain a successful agriculture.

The reduction in quantity of water reserves in many parts of the globe has also been accompanied by a worsening in quality, which can limit tremendously the usability of water despite its possible abundance in places in the form of brackish or saline groundwater. Furthermore, surface and groundwater contaminated, whether by natural or industrial means, can be deadlier than no water at all. Thus, while in Third World countries biological pollution continues, the increasing awareness by the masses makes it only a matter of time before the situation improves. In the technologically advanced countries of the world, though administrative measures concerning pollution have been effective of late, rivers, lakes, ground and sea water are still being contaminated with industrial waste. The global 'green house' phenomenon has been brought into prominence recently by human activities in the industrially advanced countries such as the production of waste gases.

However, the most widely occurring contamination in world water is salinization. This takes place in three ways:

a) by overpumping of coastal aquifers causing cones of depression and the overriding of the seawater front over the retreating fresh water front;

b) by overpumping in inland locations causing the depletion of fresh
water aquifers and ultimately attracting saline water from deeper salty formations, and;

c) by the artificial increase in the total dissolved solids because of the heavy application of fertilizers and the use of marginal to brackish irrigation water.

With regard to groundwater salinization due to seawater intrusion in coastal areas, scientists believe that the 'green house' effect might cause, in the next 100 years, a rise in the level of ocean water by 0.5 to 1.5m. (Scientific American, September, 1989). Apart from the inundation of low lying coastal areas of the globe, this rise would cause enough pressure to push the ground/seawater zone inland and therefore increase the volume and area of salinization. In the United States 20% of the agricultural land is already salinized to an intolerable level and 1 million hectares are thus affected annually worldwide.

In the field of non-conventional sources of water, desalination technology, invented and developed in the developed Western countries, has been exported to rich developing countries, such as the Gulf states, where the shortage of potable water is acute. The producing capacity of desalinated plants in the Gulf is about 60% of the global total. (US State Department, Memo on Water Resources in the Middle East and the United States Foreign Policy, US Embassy, Riyadh, June, 1989).

With regard to sewage recycling, the reuse of such treated waste-water has been more effective in the advanced countries than in the developing countries because of the wider coverage of areas of domestic consumption by sewage networks. However, the use of such water resource is still limited to agriculture and artificial recharge in the developed countries. Although the trend of waste-water treatment is gaining momentum in developing countries, such as the Gulf states that can afford the setting up of expensive sewage treatment plants, the end product is used solely for municipal irrigation.

Water resource management, both the technical (developing the resources and monitoring their quality and quantity) and the administrative (requiring specialized personnel with the adequate knowledge to manage the water related establishments effectively) aspects, is beginning to
make its mark in many developing countries. Although most developed countries are more capable of managing their water resources than the developing countries, they are still confronted with the difficult task of providing enough good quality water to meet the ever-increasing demand. The situation is more acute in the developing countries where disciplined conservation is still far from being realized.

1.1.3. The water resource problem on the Middle East level

In the vast area of the Arab world (a total of 1.41 billion km².) there are only 3 rivers of international standards on the basis of the volume of water they discharge. These are the River Nile, the River Euphrates and the River Tigris. All are sources of water shared by several countries and all pose dangers of strife for water rights in the near future. The upper sections of the Tigris-Euphrates are in Turkey which has ambitious plans in southeast Anatolia involving the construction of 21 dams across the Tigris-Euphrates to enhance the generation of electricity and provide irrigation water that would increase the agricultural productivity in that part of Turkey by 17 times by the year 2001. Such multi-damming of the two rivers would reduce markedly their flow into both Syria and Iraq, with the flow into Iraq, estimated at present (1989) at 30 billion m³/annum, is being reduced to only 11 billion m³/annum\(^1\). This would result in a water deficit as even the minimum irrigation requirements of Iraq (13 billion m³/annum) would not be met. The situation could worsen for Iraq should Syria also go ahead with its equally ambitious plans to exploit the Euphrates, which could leave Iraq with an immense water shortage in the coming few years that might put an end to the age-long dream of transporting 300 mgd. (1.4 MCM/d) from the Shatt al Arab in Iraq to Kuwait, although the pipeline for that was opened in 1990\(^1\).

Israel, which at present (1989) uses 98% of its water resource potential and faces an annual water deficit of 500 MCM (Lesley Schmidt, Pennsylvania University, 1988), as well as the growing problem of

\(^1\) Starr, J.R. and Stoll, D.C., United States foreign policy on water resources in the Middle East, Centre for Strategic and International Studies, Washington DC, 1987.)
salinization of groundwater resources because of heavy abstraction, has 40% of the available fresh water resources in the occupied Arab territories of the West Bank (Likud Party manifesto, 1989). By the year 2000 the shortage of water in Israel, if the present rate of consumption continues, would be 800 MCM/a, and only a reduction in agricultural consumption would provide the solution to the shortage problem (Water and Israeli Expansion Strategy, Joy Snork, 1988). However, as agricultural interests are a dominant force in Israeli politics, the possibility of conserving water use appears remote. By 1987 Israel had cut a canal to divert the waters of the Wazzani River in the occupied zone of southern Lebanon and connected the lower section of the Khardali River to the Huwleh Plain. The insistence of the Israelis on a 'security zone' (even of United Nations peace keeping forces) in the occupied southern part of Lebanon, is thought to be to secure accessibility to the waters of the Litani River which, when its waters are totally diverted by Israel, would provide that country with 500 MCM/a (Ramzy Musallam, Gulf Centre for Strategic Studies, London, 1989).

Israel is also drilling deep wells in the occupied Arab West Bank and in the Negev desert. The latter region is practically on the border with Egypt and draws water from the common aquifer within Egypt's Sinai desert. A volume of nearly 11 MCM/a is expected to be extracted from the Jarafi Wadi (A. Shinawi, former Egyptian irrigation minister, Al Khaleej, October, 1987).

Egypt relies largely on surface water provided by the River Nile for its irrigation needs. The population at present (1989) is 50 million and with the annual increases of 2.7% will reach 70 million by the year 2000. Egypt's agriculture is based on extensive farming and is not satisfying the food needs of the country as is evident from the cost of food imports of $4.0 billion for 1987-88 (Financial Times, 30/11/1987). By 1990 Egypt's total water demand reached 73 billion m$^3$/annum but the annual available flow from the Nile is only 68.9 billion m$^3$/annum, which is also by no means of a safe quality to use for human consumption due to contamination (Waterbury, J., Princeton University, USA, 1989; also Ramzy Musallam, Gulf Centre for Strategic Studies, London, 1989).

The Nile itself is also a shared watercourse. It flows across 9 states
with 82% of its flow rising in Ethiopia (*The Hydraulic System of the Nile Valley*, Waterbury, J., (1979). The problem of drought in the East African highlands in the past few years has posed a great threat to water supplies from the Nile to both Sudan and Egypt leading to an alarming drop in flows, as judged from the levels in Lake Nasser. In 1984-85 the water level reached 150m. above the dangerous limit and the total volume of flow dropped to 38 billion m$^3$/annum (the lowest ‘dangerous’ volume of flow is 30 billion m$^3$/annum).

Egyptian and American food experts envisage that the provision of 12 billion m$^3$/annum of water for agriculture would solve Egypt’s food deficit. Realizing such a need for water, Egypt has helped finance the Jonglei Canal in the marshlands of the Sudan. It has also tried to ensure Sudan’s political stability so as to drain about 10 billion m$^3$/annum of water from the marshlands into the main river flow of the Nile, to eventually reach Lake Nasser. The Jonglei Canal project has been shelved for the time being because of the civil war in the south of Sudan. Furthermore, any plans to dam the upper reaches of the Nile within Ethiopia would aggravate the water shortages in both the Sudan and Egypt and impose an explosive political and military situation in the region.

Data concerning groundwater availability, extraction and use in the Arab World as a whole, and the Arab countries in the Middle East in particular, are unavailable and the estimate, put forward by the Arab Food Organization in 1978, of the actual groundwater volume extracted in all the Arab countries as being 12 billion m$^3$/annum, is still being referred to by several authorities in the region, including the Arab Centre for Arid and Semi Arid Lands (of the Arab League) as late as 1986 (*Al Bayan*, 11-2-1986). The limited credibility of such statistics becomes apparent when water resource estimates for some Arab countries, that have become recently available, are considered.

Groundwater abstraction has intensified in the 1980s and the leading countries in groundwater abstraction are Saudi Arabia, Syria and Libya. In 1989 the annual abstraction of groundwater in Saudi Arabia alone was 20.5 billion m$^3$, making up 25% of the estimated total Arab World groundwater output (more than 80 billion m$^3$/annum). With Syria and Libya (20% each out of the total Arab World abstraction ), the three
countries use up more than 60% of the entire groundwater abstraction of the Arab World. Yet, all the three countries are water-deficit areas and, despite using more than 85% of this groundwater for agricultural applications, they are large importers of food. Most of the Arab states lack the capital necessary to finance the exploration and development of groundwater resources.

Waste water recycling has only developed in the towns of the Gulf Cooperation Council States and the use of the recycled produce is limited only to municipal landscaping irrigation. As yet, there is hardly any surplus from this water resource nor are there any plans to use this water to irrigate even non-edible crops (tobacco, sisal anato and cotton) or for artificial recharge of aquifers.

1.1.4. The water resource problem on the Gulf Cooperation Council States (GCC) level

When the water resources are studied in detail in the regional (Gulf) context, the shortage in water supplies is clear despite the big strides taken by the countries of the region in developing the non-conventional sources of desalination and wastewater recycling. Political tension over water resources does not exist between the member states of the Gulf Cooperation Council, as it does between some other states in the Middle East. The common water deficit as well as trends in water overabstraction and use are characteristic features of the whole region. The only areas in need of possible mutual agreement are the common Dammam aquifer between Saudi Arabia, Kuwait, Bahrain and Qatar; and the shared groundwater zone of Al Buraimi-Al Ain-Al Madam and Mussandam between the Emirates and the Sultanate of Oman.

Data for groundwater abstraction in general, and those exclusively concerning agricultural use in particular, are not available for two reasons. The first is the reluctance by the GCC member states to announce water resource estimates, if they actually exist; the second is that, in the majority of cases, groundwater abstraction is not quantified due to: a) the unplanned provision of water for hastily developed agriculture; b) the fragmented responsibility of the groundwater development and supply establishments; and c) the limited knowledge of actual monitoring of groundwater storage and abstraction.
Such a lack of information on the actual groundwater abstraction was one of the incentives to embark on the present study.

It has been disclosed (June, 1989) that Saudi Arabia is abstracting groundwater in excess of 20.5 billion m$^3$/annum of which only 12% (2.5 billion m$^3$/annum) is from replenishable groundwater sources, the remaining 88% (18 billion m$^3$/annum) is mined from fossil groundwater in deep formations (US State Department, Memo on Water Resources in the Middle East and the United States Foreign Policy, US Embassy, Riyadh, June, 1989). Groundwater reserves of Saudi Arabia were estimated in 1988 to be 337.5 billion m$^3$, with a possible additional 160 billion m$^3$ from deeper aquifers. Given the present rate of groundwater abstraction, total exhaustion of these largely fossil groundwater reserves could take place before the year 2006. Saudi Arabia is drawing groundwater from the upgradient parts of the same Dammam/Um Er Radhmah aquifers that stretch into Kuwait, Bahrain and Qatar. In all these three countries the groundwater imbalance is critical. There is, therefore, a hydropolitical situation between these four countries that has not yet been addressed bilaterally or through the aegis of the GCC.

Bahrain in 1987 withdrew 180 MCM/a from the Dammam aquifer when the recommended safe yield should have been 83-90 MCM/a. In Qatar, the groundwater deficit reached 84.6 MCM/a (1985) while most drinking water is being supplied at present (1990) from a 37 mgd. (62.0 MCM/a) desalination plant. In Qatar, as in the neighbouring countries, there are hardly any emergency measures in case of total plant breakdown. The breakdown of the desalination plant in Doha during May-June 1987 revived shelved plans for an additional desalination plant to meet such an emergency. Kuwait's total groundwater abstraction is from brackish sources and amounts to 109.4 MCM/a (1987). There were plans for the transfer of 300mgd. (1.4 MCM/d) of water from the Shatt Al Arab in a 160-km. pipeline (actually opened in mid-1990), but these are not likely to be implemented in view of the negative political and security situation created by Iraq's aborted invasion and annexation of Kuwait in August 1990 (which was ended in February 1991).

Since the early 1970s the Gulf countries turned to desalination to solve their drinking water shortage. By 1989 the domestic needs of the towns in all the GCC countries were being met from desalination plants,
mostly attached to power generation stations. The annual output from the desalination plants in the GCC countries totals 1242.0 MCM/a (3.4 MCM/d, 1989) of which 42% is produced in Saudi Arabia alone (525 MCM/a). Table 1.2 shows the production of desalinated water for domestic use for the GCC countries in 1989, and Figure 1.2 compares the per capita quotas, for all types of water produced, for residents in Saudi Arabia, the United Arab Emirates and the United States of America.

It was hoped in the early 1970s, when oil and gas prices were 10 times lower than at present, that desalinated water would solve the shortage problem in the agricultural sector. The huge desalination projects that were initially envisaged for some of the GCC countries had to be shelved or reduced to insignificant alternatives. The present cost of oil and gas precludes the use of desalinated water for irrigation. It is estimated that the cost of desalinated water needed to irrigate a ton of wheat in Saudi Arabia is about $3,625 (U.S. State Department Memo, Riyadh, 1989).

All this propaganda is timed to improve the official and public atmosphere for the acceptance of the latest of the proposed solutions to the water shortage problem in the Gulf, namely the twin-pronged pipeline from southeast Turkey running along the Hijaz and the Gulf coasts of the Arabian Peninsula, the so-called 'Peace Pipeline', that might ultimately pump 3.5 MCM/d. Though such a project has its own political problems, involving the possibility of bringing Israel into a largely Arabian financed venture, the basic principle of import of water touches upon the matter of both water and national security and should be completely ruled.

The attempts by Turkey to sell water to Arab Middle Eastern countries (it is already shipping water to Israel, 1991), with the cost of the installation of such a 'Peace Pipeline' to be borne by the Arab countries as noted earlier, would be as dangerous for their national security as would be an invasion. Dependence on water supplies from a foreign country conceals bigger and far-reaching threats to national security and existence than naked military hegemony. Attempts to sell the idea to the Arab countries in peace time a few years ago did not meet with success. Turkey is making the same attempts to sell water again (Turgat Ozal's proposal for a summit of the head of states of
<table>
<thead>
<tr>
<th>Saudi Arabia</th>
<th>Kuwait</th>
<th>Emirates</th>
<th>Qatar</th>
<th>Oman</th>
<th>Bahrain</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>525.0</td>
<td>200.0</td>
<td>300.0</td>
<td>114.0</td>
<td>41.0</td>
<td>62.0</td>
<td>1242</td>
</tr>
</tbody>
</table>

Source: Departmental statistics of the respective countries.

Table: 1.2.

The total annual production of desalinated water in the member states of the Gulf Cooperation Council for 1989.

Saudi Arabia and the Emirates produce 66% of the total desalinated water output of the GCC states.

Figure: 1.2.

Comparison between the overall per capita consumption of the resident of the self-sufficient food-exporting United States and those of either Saudi Arabia and the Emirates which import most of their food needs.
the Gulf countries to meet with the Turkish leadership, Reuters, February, 1991). The war in the upper Gulf, and the huge oil slick created by military action and its pollution threat to the Gulf region's desalination plants, have now created the psychological conditions under which the 'Peace Pipeline' idea may be considered. On the contrary, the idea should be even more vigorously resisted, whatever are the declared 'diplomatic' intentions of Ankara. Furthermore, Turkey has a recent history of political instability and military dictatorships and it is very likely that such instability may recur, which may compromise the needs of the Arab consumers of Turkish water at the other end of the 'Peace Pipeline'. Turkey is also part of a military and economic block (NATO and the EEC) that aims at global dominance in the wake of the military and economic eclipse of the Communist block, and there can be no guarantees to the Arab countries from Turkey or its partners against future pressure for economic and political domination. This stance should help convince the squanderers of water in the region to consider seriously conservation policies strictly based on the economic viability and absolute necessity of agriculture.

1.1.5. The water resource problem on the national level: the United Arab Emirates

The problem of water resources in the Emirates is embodied in the paradox of a continued ambitious expansion in extensive farming, similar to that in all GCC countries, despite the depleting groundwater resources. The present situation is clearly expressed in Table 1.3. which presents the four related economic aspects: water, agriculture, population and food imports. Given the ratio of groundwater abstraction for domestic consumption to that for agriculture as 1:19 (or 5% for domestic and 95% for agricultural use, of the total groundwater volume abstracted), a ratio maintained since the Trucial States Survey of 1966-69, then the population, most of whom are urban dwellers, can provide little explanation for the big surge in groundwater abstraction. Most of the needs of the large towns at present (1990) are being provided by desalinated water, the output of which is larger than that actually used domestically. For example, the total daily output of desalinated water of Abu Dhabi throughout 1989 was 83 mgd. of which only 29 mgd. (35% of the total) were actually consumed by the population of the town. 18% of the total daily production was pumped to Al Ain (14-15
mgd.), while the rest (47%) was lost between the irrigation of municipal reserves, 'unaccounted for' leakages and clandestine connections.

As shown in Table 1.3., population in the Emirates increased 10-fold between 1968 and 1988, agricultural land more than 3-fold, but water consumption (both groundwater and desalinated) by 22 times. The striking feature is that the cost of food imports has consistently maintained the high level of above 3.0 billion dirhams\(^1\) per annum since 1980 (this is the cost of foreign food imports from which has been deducted the cost of food items that have been re-exported), which points to the inability of the 'expanded' agriculture to contribute effectively to food security. Agricultural land can generally be described as more of the recreational 'private garden' type than that of the farming.

Groundwater reserves are already in the stage of overdevelopment and abstraction in the past decade and a half has been, in effect, the mining of the aquifer system. Brackish water aquifers are also overdeveloped, while the fresh groundwater in the Quaternary deposits is almost depleted. Pump intake levels in most parts of the country have sunk from an average depth of 60-100m. less than 10 years ago to 300-1500m. (in 1989). This has resulted in the exhaustion of the highly transmissive alluvium and abstraction is now from the less transmissive flysch (U. Cretaceous clastics and shales) of the Juweiza Formation, as is the case in the Northern Emirates, or the even less transmissive clay-marl-anhydrites sequence of the Fars Formation, as is the case in most of Abu Dhabi emirate to the west and south of Al Ain.

Only the desalinated water production of the main coastal towns and the potable groundwater output of the towns of Dubai, Sharjah and Al Ain are monitored; the whole of the agricultural abstraction, that for domestic use in the villages in the Northern Emirates and that of the desert foreland, is unmonitored. Added to this, agricultural water use is absolutely uncontrolled. The agricultural sector itself is highly subsidized and is not based on a successful economic system that takes into account the cost of the various input components, foremost among which is the cost of water; nor is it protected against foreign imports of the same items it is growing.

\(^1\) 1 US$ = 3.65 UAE dirhams (permanent official rate).
Table: 1.3.


The concurrent increase in the four related sectors of water resources, expansion of agricultural land, population growth and the high cost of foreign food imports sum up the water resource problem on the national (UAE) level. The salient feature in these interrelated economic aspects is the paradox of expanding the agricultural land despite the depleting groundwater resources, and maintaining the high level of foreign food imports despite the continuous expansion in agriculture.
A natural consequence of the overabstraction of groundwater is the encroachment of the seawater front in coastal areas (as far as 20km inland in Al Badea' and Al Aweer) and the upconing of brackish to supersaline deeper waters (in places also in shallow anhydrite strata in the western areas of Abu Dhabi emirate, as in Al Za'alah in Al Ain). When such waters are used on non-saline sandy soils in the desert foreland (such as in the areas of the forestry projects), they lead to the salinization of these soils and the recirculating irrigation water becomes more saline.

Recycling of sewerage is limited to only the 4 towns of Abu Dhabi, Dubai, Sharjah and Al Ain and the annual volume is nearly 80 MCM. This is wholly dedicated to irrigating the landscaping schemes in these towns.

Despite the imbalance of the water resources in the Emirates having reached an advanced stage, conservation is still far from even being considered in practical terms. As will be discussed in this study, modern irrigation methods hardly save more than 20% of the water normally applied by the traditional inundation method. Nor is recycled wastewater, which is treated in all the plants of the Emirates to a high quality, used for irrigating even non-edible crops. In view of the unrestricted and unlicensed drilling, the unmonitored flow of water at the borehead and the continuing allocation, reclamation and allotment of agricultural land in total indifference to the real deteriorating groundwater situation, conservation appears to be a remote possibility.

The key water resource problems at the national level can be summarized as follows:

i) The high cost of desalinated water renders its use for irrigation prohibitive;

ii) the depletion of groundwater reserves appears irremediable;

iii) the import of foreign water is unacceptable both politically and from the point of view of 'water security';

iv) the ambitious greening of the desert is unstoppable;

v) the existing conventional and non-conventional water supplies lack emergency plans;

vi) water resource management is fragmented;
vii) there is no national water grid system;
viii) the life of desalination plants is limited and,
ix) the total absence of water legislation and planning.

The remedy could be sought in the conservation of water resources. No party is more capable of implementing this than the government itself. In a society where agriculture is heavily subsidized by the government, such subsidies could be tied to meeting certain qualifications of proper water use by the beneficiary of these subsidies; but the government does not appear willing to pursue such an approach.

Desalination is by now an established source of water production and is definitely going to become more important in the 1990s. The country has been handling this non-conventional water source for nearly two decades and the potable water produced in this way is 4 times that extracted from groundwater sources for drinking purposes. Yet, no technical self-sufficiency, for manufacturing and maintaining the desalination plants, has been contemplated. Nationally-based technical and administrative management traditions for water resources must be established if production costs are to be made more economical than those at present to meet the expected big demand of the 1990s.

1.2. The objectives, scope and method of the study

The main objectives of the study are:

1) to make a comprehensive appraisal of the conventional and non-conventional water resources of the Emirates and to investigate their present status, within the single geographical and political unit of the United Arab Emirates (UAE).

These subsume the following objectives:

i) to provide a data-base for a field of study that is little studied and for which data are increasingly being rendered intentionally unavailable as a result of confidentiality.
ii) to identify the areas of responsibility for the deteriorating groundwater resources and the rapid escalation in the production of the non-conventional water resources.

iii) to answer several vital questions that have always bewildered officials, consultants and the interested public relating to the actual state of the water resources, particularly the question of quantification of groundwater abstraction by agriculture. (no private, local government or federal water-related organization keeps an inventory of the development and total volume of groundwater from agricultural wells).

2) To recommend:

i) realistic procedures for water resource planning, policy and legislation and,

ii) a water system for the whole country to prevent the exhaustion of both the replenishable and non-replenishable groundwater resources.

Points (i) and (ii) require nationally self-reliant water resource management.

To accomplish these objectives, it was necessary to research into every aspect (physical, economic, social and political) of water resources.

The scope of the study thus involved determining the following:

i) the overall interplay of the climatic elements affecting water resources through precipitation and evaporation;

ii) the importance of the chemical and mechanical composition of the soils in relation to recharge water in terms of infiltration and water quality;

iii) the geology and hydrogeology of the whole Emirates and their relation to water resources;
iv) the surface runoff and its actual contribution as recharge to groundwater;

v) the volumes of water involved in the recharge of the groundwater system from direct rainfall, surface runoff and subsurface flow;

vi) the types of water currently used by agriculture, forestry and town landscaping;

vii) the present state of the aflaj;

viii) the quality of the water (by sampling from all parts of the Emirates and expressing results in a standardized form (in milliequivalent per litre (meq./l), including the sodium adsorption ratio (SAR) and irrigation water class);

ix) the age of groundwater (by means of environmental isotopes to draw attention to the overabstraction of non-replenishable groundwater resources);

x) the unit production and delivery cost, which is at present unknown for all the three types of water: ground, desalinated and recycled (to highlight the impracticability of using desalinated water for large-scale irrigation);

xi) the actual volumes involved in the shared water resource area of the Al Ain-Buraimi (in terms of surface flow and inflow and look into the present abstraction rates as well as future plans for further abstraction on the Omani side of the border that will have a grave impact on the groundwater inflow into the Emirates side of the border);

xii) the recharge potential, groundwater reserves and the groundwater balance.

xiii) the problems in water resource development and management and the technical and administrative aptitudes of the staff of the water-managing organizations.
1.3. Thesis plan and justification for a detailed study

1.3.1. Justification for a detailed study

Such an ambitiously comprehensive study, involving the thorough appraisal of the ground, desalinated and recycled water resources, was bound to assume sizeable dimensions. The study thus developed into a full-fledged survey of the water resources of the Emirates. In any assessment of the groundwater resource, all the elements of the hydrological cycle are considered. These include rainfall, evaporation, surface runoff, recharge, groundwater storage fluctuation or continuous depletion and the balance of the groundwater in the whole aquifer system. Research into all previous estimates of recharge and the water balance was undertaken and these estimates were examined and were upheld or disputed. Estimates of both recharge and abstraction are presented to indicate the volume of water involved in the input and output groundwater relationship. Previous estimates, including official estimates of recharge and water balance by the Ministry of Agriculture and Fisheries (MAF) of 1982, offered little or no explanation to how they were derived; this study, on the other hand, explains in detail how its estimates have been calculated.

The detailed rainfall analysis, stratigraphic description and the discussion of the azonal soils (the latter as the medium through which recharge is taking place), are all important and relevant to the study of the groundwater resources to explain groundwater storage, movement and quality. Similarly, the detailed explanatory descriptions of the water quality, by region and subregion, are necessary for obtaining an up-to-date picture of water quality as well as trends in deterioration concurrent with the groundwater overabstraction of the past few years.

The problem of the groundwater resources is more than a mere shortage of water supply. A shortage in the available water must be seen in the context of the outlets to which that water is applied and in particular if they are necessary and are based on a well-planned productive agriculture that aims at the definite goal of food security. However, as agricultural land is largely recreational, more often in the form of private gardens rather than economically productive farms, with more water being consumed by the former than the latter, the shortage in
supplies is thus imposed by man through the extensive greening that the limited groundwater resources cannot sustain. The detailed chapters on hydrogeology, hydrochemistry and water production and use are the result of personal research into the various aspects of groundwater occurrence, its quality and its various uses.

Desalinated water production is rapidly growing in importance, though limited in location to the three major Gulf coast towns of Abu Dhabi, Dubai and Sharjah. The large daily output is consumed within these towns, and the only quantity transferred outside these towns is that from Abu Dhabi to Al Ain (15 mgd.). The daily output of desalinated water in the three towns would have been more than enough for human consumption, which actually accounts for between 40-50% of the volume produced at present (1989-90), had it not been for a great deal of it being used to supplement treated sewage water for irrigating town amenities. An investigation into the production and consumption in this sector was essential to illuminate the various uses within the towns, and also to highlight the uneconomic use of desalinated irrigation water for large-scale agriculture to supplement or substitute for groundwater in areas where the latter is heavily depleted.

With regard to wastewater recycling, research in the four major towns of Abu Dhabi, Dubai, Sharjah and Al Ain, where partial sewerage treatment is taking place, was essential to find out the possibility of the use of this non-conventional water source for recharge or for the irrigation of non-edible crops in agricultural farms. Both possibilities appear remote at present because water from this resource is totally dedicated, together with brackish and desalinated water, to watering town amenities.

An appraisal of the water resources of the Emirates can only be safely tackled if there was an understanding of all the physical and human topics related to the conventional and non-conventional water resources that this study undertakes. Hence the empirical approach that characterizes the thesis, not for its own sake but as a natural consequence of the detailed field investigations on which the whole study has depended. The detailed analyses are, therefore, a necessary development of the comprehensive survey, and are included to substantiate the points expounded throughout the thesis. This last
point is stressed, not only for the sake of scientific truth but, since water is a controversial field of study, to provide evidence of mismanagement practices.

1.3.2. Thesis plan

The thesis treats the topic of the water resources of the Emirates in 12 chapters grouped in 3 main parts. These are:

A. The background part: 3 chapters
   The introduction and physical factors.

B. The main part: 7 chapters
   The water resources of the Emirates.

C. The concluding part: 2 chapters
   Water resource management, conclusions and recommendations.

Synopses

As many of the chapters are long and detailed, a synopsis is given at the end of each to emphasize the continuity of the argument and provide a clear link with the following chapters.

A. The background part:

Chapter 1: Introduction

This chapter discusses the background to the water resource problem on the global, Middle Eastern, regional (the Gulf Cooperation Council States) and the national (Emirates) levels to put the detailed main subject of the thesis in the broader water resource context. It defines the objectives and scope of the study, justifies the need for a detailed study, and outlines the thesis plan and its unique aspects.
Chapter 2: Geology, topography and soils

These 3 physical aspects are discussed in relation to water: geology in as far as lithologies and their textural and mineralogical composition are concerned; topography, the landforms in which groundwater occurs; and soils with regard to their chemical and mechanical composition focusing on porosity as governed by the content of the coarse material, and salt content as governed by natural and man-made concentrations. Both are important factors affecting infiltration rates and quality of recharge water. Infiltration tests relate to the soil-water relationship and selected vegetation types relate to the soil-water-vegetation relationship, both of which are briefly discussed.

Chapter 3: Climate

Although more attention in this chapter is given to rainfall, the other climatic elements are briefly discussed to understand the precipitation-evaporation-recharge relationship. Available rainfall data, including those for rainstorm intensity up to 1983, were studied, and the detailed rainfall analysis is aimed at developing a clear picture of the distribution and characteristics of rainfall to provide the necessary background to the volumes and characteristics of surface runoff discussed in Chapter 4 on surface hydrology.

B. The main part

Chapter 4: Surface Hydrology

This chapter discusses the drainage system and physiographic characteristics of the catchments, the flood gauging network in the mountain wadis, runoff characteristics, base-flow and the aflaj. Available surface runoff data were used to calculate the mean runoff volume for the gauged wadi catchments, the runoff coefficient and the possible ultimate recharge from surface flow. Runoff volumes were also calculated for the ungauged catchments.
Chapter 5: Hydrogeology

Groundwater occurrence in the Quaternary, Tertiary and pre-Tertiary aquifer systems is identified. The chapter also discusses groundwater flow. The section on groundwater level fluctuation deals comprehensively with all the boreholes with water level records presenting hydrographs covering the different hydrogeological zones providing a comprehensive testimony to the consistently receding groundwater levels in all the abstraction areas.

Chapter 6: Hydrochemistry

Water chemistry data were obtained from analysis of water samples collected for the study. The treatment of the subject is by region and subregion. Explanation of the chemical composition of the waters is sought in the mineralogical composition of the rocks on which water flows and in which water resides. Long and short term fluctuation in water quality is discussed for the Al Ain region. The chemistry of the waters of the deep carbonate aquifers is also discussed to show its brine nature and therefore its use limited only to the injection process in oil operations.

Chapter 7: Environmental Isotopes

This chapter reviews the three limited isotope investigations carried out by the Japan International Cooperation Agency (JICA) in Wadi Al Baseerah (1981), Geoconsult in the piedmont plains as part of the Deep Wells Project (1982-86) and the International Atomic Energy Agency mainly in the Northern Emirates (IAEA, 1984-), and summarizes their findings. The chapter also examines the substance and method of the IAEA investigation and assesses its role in understanding groundwater resources. Environmental isotope investigations are insufficient on their own and only offer back-up information to traditional hydrogeological investigations. While the Carbon-14 dating can be a once and all survey identifying the age of groundwater at the sample points, tritium detection is an interesting technique that can be repeated on a regular basis to trace groundwater flow and recharge.
Chapter 8: Water production, use and cost

This chapter discusses water production according to use. It presents data for domestic consumption by emirate, and agricultural abstraction by agricultural region. The latter is based on actual discharge measurements carried out specifically for this study. It also includes statistics on actual volumes of groundwater abstracted by the forestry activities based on data from the respective departments.

The chapter also discusses desalinated and recycled water production and presents exact figures of the quantities produced.

The unit production and consumption cost is calculated for each emirate and the combined cost of all types of water for the whole country is presented.

In all the 3 sectors of water production (ground, desalinated and recycled), the data presented in this study are made available for the first time.

Chapter 9: The shared water resources

In this chapter the water resources shared between the Emirates and the Sultanate of Oman in the Mussandam, Al Madam, Al Ain-Al Buraimi, Madhah and Milaha regions (the last 2 on the east coast) are examined. Attention is focused on the Al Ain-Al Buraimi area, for which hydrogeological, groundwater production and balance data, for either side of the international border, are presented to portray the serious groundwater situation in this area that can only be addressed by decisions at the highest political level.

Chapter 10: Recharge potential, groundwater reserves and the groundwater balance

This chapter examines previous recharge and balance estimates of other studies since the Parsons Report (1963). It disputes previous calculations concerning effective rainfall and runoff-recharge estimates. It puts forward estimates for recharge
from direct rainfall, surface runoff and irrigation return, and explains in detail how they were derived. Finally, it presents all the input and output components of the groundwater system in the overall groundwater balance of the Emirates.

C. The concluding part:

Chapter 11 Water resource management

Using selected examples of technical and administrative mismanagement practices as the underlying theme, this chapter emphasizes the critical state of water resources and their management in the Emirates to complete the argument in favour of a radical overhauling of the management of the water resource sector. The chapter discusses water planning, development, policy legislation and conservation and presents the vision of the present study concerning all these aspects in relation to the Emirates.

Chapter 12: Conclusions and recommendations

This chapter sums up the findings of the study in a resume and conclusions. It also offers a set of recommendations for the ground, desalinated and recycled water resources of the Emirates. These are practical recommendations, addressing the overall ill-conceived water resource development and its mismanagement, intended as a contribution towards salvaging a fast deteriorating groundwater situation.

1.4. The unique aspects of the thesis

The scope, substance and method of the thesis, which evolved pragmatically from extensive field work, earned the study its original qualities and unique aspects. These aspects can be outlined as follows:
1. The thesis is a geographical reference on the whole of the United Arab Emirates. The marshalling and analysis of the data in the thesis are an important achievement in a field in which either the scanty data are classified or the activities are undocumented. The task of acquiring such data was arduous, if obtained by field work, or extremely difficult and frustrating, if sought from official sources.

2. The comprehensive nature of the study which treats all aspects related to water resources within the single geographical and political unit of the Emirates. This is important in view of the absence of such a country-wide methodological study.

3. It is an action study that was from the beginning informally associated with ongoing water surveys and its plan of action evolved along the following lines:

   a) The collection and collation of all available data on the water resources of the Emirates. These were mostly concerned with groundwater, were general in approach and were of a fragmented nature. Nearly all available written work on the subject was acquired and a library was gradually built up.

   b) As most of the previous studies were outdated and dealt with limited aspects of groundwater on a localized scale, and data, if available, were not easily forthcoming from official water departments, current data were sought in the field through the personal involvement of the author in a number of water projects that were being conducted in several parts of the country. In this way, first hand knowledge was obtained with regard to drilling, logging of boreholes and discharge tests. The most significant involvement was with the Deep Wells Project (Project 21/81 of the Ministry of Agriculture and Fisheries, 1982-86) from the first seismic sounding at Masfut (August, 1982) during the main phase of the project undertaken by Geoconsult.

   This practical participation provided good training and insight into the manifold water resource problem. However, the main
difficulty of the paucity of data still remained owing to the sparse and specialized nature of these projects.

c) It was realized earlier in the long association of the author with the field of water resources that simple details, such as infiltration rate and well discharge rate tests, which always appeared insurmountable to consultants and contractors for differences on cost issues with the official commissioning establishments, could be carried out. This was eventually done for the present study. Thus, the study relies a great deal on its own programme of field work to obtain non-extant data through experiment and extensive field investigation.

4. Place-names have been well represented by a careful transliteration into English preserving as much as possible the pronunciation preferred by the local inhabitants. As not all the places visited by the author appear on available maps, they have been included in the maps of this study with approximate locations. Such locations are precisely described in the text in relation to well-known places by distance and direction so as to enable the reader to pinpoint them.

5. Case studies

Most of the study is the result of field work. A number of key case studies were completed:

i) The state of the meteorological network (Chapter 3, Climate)

The parts of the meteorological network belonging to the Ministry of Agriculture and Fisheries (MAF), the Ministry of Electricity and Water (MEW), Al Ain Department of Agriculture, the Western and Central Military Commands, the Airports and the Petroleum Companies, were inspected to observe the state of the equipment. Rainfall and evaporation measurement are particularly important in the assessment
of water resources, although monitoring other climatic elements is also important.

Evaporation ceased to be measured in 1984 while rainfall recorders require regular maintenance, limited at present due to undermanning in the MAF, the main source of climatic data in the Emirates.

The state of the meteorological network reflects the level of efficiency of the managing establishments and, therefore, the reliability of the climatic data.

ii) **Soil chemical and mechanical analyses**

*(Chapter 2: Geology, topography and soils)*

Soil samples were collected from the various terrains and analyzed for their chemical and mechanical composition to determine their permeability by percentage of their content of coarse material; and also their salinity. The former affects infiltration of recharge waters; the latter, the quality of the infiltrated water.

iii) a) **Infiltration tests** *(Chapter 2: Geology, topography and soils)*

 Comprehensive infiltration rate measurements for soils in all the different areas of the Emirates do not exist. Infiltration tests, using a double-ring infiltrometer, were carried out on various typical soil types in the different terrains. While acknowledging that more frequent and specialized infiltration tests must be carried out in future studies to determine the exact rainfall-infiltration relationship for specific thresholds of rainfall totals and/or duration, the approximate infiltration tests of the present study suffice to achieve two objectives:
(1) to provide a reference or data-base for infiltration rates in the different soil types; and,

(2) to serve as an indicator of the capacity of these soils as mediums of recharge for both rain and flood waters.

b) Flood simulation: to study infiltration on a more realistic scale (Chapter 2, Geology, Section 2.4.5.1.3)

A flood simulation experiment was carried out in Wadi Ham (near the dam). Although it was in many ways unrepresentative of real conditions of sustained flooding, it was intended to demonstrate the feasibility of carrying such experiments repetitively and on a large-scale by the concerned water-managing bodies so that the rainfall-recharge-soil relationship can be understood. No such experiments in the field of hydrology have been carried out by any of the Faculties of the UAE University or the concerned water-related departments.

iv) Interpretations of rainfall, surface runoff and recharge volumes: (Chapter 3, Climate; Chapter 4, Surface Hydrology)

All available rainfall and surface runoff data were analyzed to derive a mean runoff-recharge volume. The interpretations of the spatial distribution of rainfall and runoff revealed that there is more surface runoff in the east-flowing wadis, where the recharge potential is less, due to the limited horizontal and vertical extent of the eastern piedmont plains (of the Batinah coast) alluvial deposits. On the other hand, there is less surface flow in the west-flowing wadis where the recharge potential is large in the extensive western piedmont plains and the desert foreland beyond them. The most important conclusion of this case study is that the expected mean annual recharge into the groundwater system along the whole front from Ras Al Khaimah to Al Ain is only 34.32 MCM/a. All previous guestimates put this volume at 100-175 MCM/a. (Halcrow, (1966-69); Carr and Barber, (1976)).
v) **Hydrochemistry (Chapter 6)**

This study of the detailed chemistry and quality of the waters of the various regions of the Emirates was instigated to overcome the paucity of water quality data and the varied (in the form and expression of results) partial water chemistry data that previously existed. More than 750 water samples were collected for chemical analysis with the objective of standardizing water quality data. In addition, more than 800 direct measurements of electrical conductance (EC) of groundwater were simultaneously made with a direct EC-TDS (Total Dissolved Solids) meter that automatically compensated for the difference in water temperature and gave a digital reading of the EC value at 25°C.

The presentation of the results includes both the sodium adsorption ratio (SAR), the ratio of replacement of the calcium and magnesium ions by sodium, and the irrigation water class according to the US Department of Agriculture classification. The objective for this is to highlight the quality of the water in any particular place, and the use to which it is put, thereby demonstrating the confused priorities in water use. An example, is the use of groundwater of prime quality, or even desalinated water, for irrigating salt-resistant plants, while marginal quality water is used for food crop irrigation or for drinking.

vi) **Environmental Isotopes (Chapter 7)**

Data from the 3 environmental isotope investigations, carried out in the Emirates to date, were reviewed and collated and a summary of each is presented in the study with the objective of proving the age and 'fossil' nature of most of the fresh-to-brackish groundwater that is being mined and depleted at present.

The inclusion of environmental isotope data complements this study on water resources as it confirms the state of
overdevelopment of the groundwater resources by the haphazard exhaustion of deeper aquifers of non-renewable sources. It is conceived by this study that such specialized information, as that of the isotopes, would help convince those involved with water misuse of the finite nature of groundwater.

vii) Groundwater pollution investigation (Chapter 11)

Water contamination tests for the present study were initiated as a result of the knowledge that:

(1) the water chemistry analyses for all parts of the Emirates, but mostly for the waters in central Abu Dhabi emirate where the sulphate and fluoride contents in some waters are known to be extremely high (above 1000mg/l);

(2) fertilizers (chemical and organic) are being applied to cultivated farms in the country at a rate of 4-5 tons per hectare per year; and also,

(3) infiltration rates in the sandy soils on which most farms are located are high. As a consequence it was worth attempting to detect nitrate (NO$_3$) in the groundwater beneath such farms.

The stated maximum limit for nitrate (NO$_3$) in groundwater for human consumption is 50mg/l. At present there is concern over this in the countries of the European Community, but there are places in the Emirates with NO$_3$ values exceeding this limit. This fact could be determined in only a few cases as sampling was constrained by the unavailability of the nitrate electrode in nearly all the local laboratories approached, and also by the time-consuming nature of the analysis if done by the titration process.
viii) **Groundwater discharge tests and groundwater level fluctuation (Chapter 6)**

Previous groundwater abstraction rates, particularly those for agriculture, were guestimates that were not based on large-scale discharge tests and little or no explanation was offered as to how they were derived. With the absence also of flow-metering of agricultural groundwater abstraction, it was essential to quantify the consumption of this sector, the least known of all groundwater uses. Such quantification was a prerequisite for calculating the groundwater balance. This was done for the present study by means of a widespread well discharge test programme. The discharge rate was measured using 3in. and 4in. Kent flow-meters (to fit the two sizes of pipes at the borehead normally used in the Emirates) that were screwed onto the end of the threaded pipe at the borehead. If there was no thread, the flow was measured by filling a plastic 44-gallon barrel. This latter measurement was repeated several times and the results were added together and then averaged to derive the mean time taken to fill the barrel.

ix) **Production unit cost (Chapter 8, Water production, use and cost)**

The only officially published production unit cost is that of the Abu Dhabi Power and Desalination Department in its annual statistical abstract. This study calculated the production unit costs for ground, desalinated and recycled water resources in each emirate and the overall production and consumption unit cost (reaching the consumer) for the whole Emirates derived. During the search for data concerning the cost input, the present study influenced the Dubai Water Department to calculate the cost of its combined ground and desalinated water. The Department had not had a detailed production and consumption cost breakdown before 1989.

Both low production and that from several plants of different makes leads to high cost desalinated water as is
the case with Sharjah and Abu Dhabi respectively. In Dubai, the Dubai Aluminium plant produces desalinated water at double the cost of that produced by Dubai Electricity despite the use by the former of free waste heat to produce water. The research into the production unit cost revealed discrepancies in the cost of water between the various producers of desalinated water in the Emirates.

x) The shared water resources (Chapter 9)

Water legislation on the local scale exists in some Arab countries. Groundwater rights concerning shared resources of common aquifers (both confined and unconfined) have yet to be realized. Acknowledging this legal deficiency in organizing water sources common to two countries, as well as being aware of the particularly difficult situation of the water resources shared between the UAE and Oman, since the territories of Oman lie, in all cases in the upgradient (or the recharge) part of groundwater flow, it was considered necessary to undertake this case study of the Al Ain-Al Buraimi region. The treatment of the water resources covers the hydrogeology, the volumes of groundwater exploited on either side of the border and the groundwater balance in the Al Ain region.

Groundwater is heavily extracted on both sides of the border. While Oman draws groundwater from renewable sources above the mountain gaps, the Emirates draws groundwater from reserves that have accumulated over decades and, in the case of water abstracted from deep wells, from fossil groundwater that has accumulated over centuries. Agriculture is extensively developed on the UAE side of the border, where also there is the heaviest pressure on the groundwater resources. Oman is in the process of undertaking ambitious agricultural schemes that will lead to large-scale interception of groundwater flow into the UAE. Groundwater studies carried out in Oman in the past decade have been explicitly aimed at quantifying what remains of underflow below the gaps and using it to
meet the proposed expansion in agriculture before it reaches
the UAE. This is why it was important to research into the
groundwater situation in this region in order to know the
groundwater potential and the actual volumes abstracted on
both sides with the objective of establishing better
understanding by both countries of the limited groundwater
resources. The UAE fresh groundwater reserves cannot last
for a long time at the present rate of overabstraction, nor
can Oman hope for opulent supplies from a zone so close to
the mountain front and known for its limited groundwater
storage capacity.

xi) **Aptitude and efficiency survey of the staff of the water
organizations (Chapter 11)**

It is held by this study that among the most important of
the manifold problems of water resources is the poor
performance of the bureaucracy throughout the hierarchies
of the water-related organizations. Having closely observed
the detailed day-to-day workings of these institutions,
mainly during the course of this study, a monitoring
programme of the staff was carried out. This survey
included an assessment of technical knowledge, field
performance, familiarization with the areas and places and
ability to tackle water resource problems. The results of
this survey, summarized in this chapter, confirmed the
the conviction of this study by emphasizing the low
aptitudinal, technical and administrative performance of the
staff of the water resource institutions.

xii) **Actual per capita consumption survey (1989) (Chapter 11)**

'Domestic consumption' is a broad, largely misleading
categorization of water use in urban areas in the Emirates.
For example, the daily output of desalinated water in the
town of Abu Dhabi is 83 mgd., the maximum sewerage inflow
into the town’s sewerage plant at Al Mafraq is 25 mgd.
(114,000 m³/d) from an 85% sewage-connected area in the
town. 15 mgd. are pumped to Al Ain. 29 mgd. are officially
estimated (by the Abu Dhabi Water Department) as the volume pumped to properties in the town area. This accounts for 43% of the remaining 68 mgd. output of desalinated water after Al Ain gets its daily share.

A survey was conducted specifically for this study to determine the actual per capita consumption of occupants of several categories of households in a number of urban centres. The results are given in Chapter 11. In the case of Abu Dhabi, the leakage in the water distribution network is the least of all the towns of the Emirates, simply because nearly all the town's pipe system is new and the equipment is of good quality. The 'loss' then is in the 'unaccounted for' for which agricultural applications, of one kind or another in the town, are largely responsible.

1.5. Synopsis
This study presents a comprehensive description and appraisal in its physical, economic, social and political context of the water system of the United Arab Emirates. Water resources are viewed as comprising interlocking physical and socio-economic systems. A complete collection of existing data has been made, complemented by a wide range of physical and economic studies made by the author specifically for this research programme. The results obtained are therefore the most definitive available and allow the most accurate assessment to be made of the national water balance. As a result, the key water problems have been identified and scientifically-based recommendations for the future management of water resources have been made.
2. GEOLOGY, TOPOGRAPHY AND SOILS

2.1. Introduction

In any country, where there has been a comparatively modest amount of earth science research, there are bound to be controversies. In the case of the Emirates, with neighbouring Oman, in which there is much related geology, this holds true. It is only in recent decades, with the development of the oil industry, the accelerated population growth and the resulting need for water, that serious geological work has taken place. Previously, the region was viewed only in the general pattern of world orogenies, the movement of tectonic plates and the formation of large-scale features. The need now is for a very much more specific and detailed appraisal over limited areas; and it is true to say that work on this scale is only just beginning. Thus, geological mapping has been very limited; the most important resulting from the work of Glennie et al (1974). There is virtually no large-scale geological mapping. The nearest approach to local mapping, by no means comprehensive, has developed as a result of the activities of the oil companies.

Drilling records allow certain generalizations to be made. However, it must be remembered that the siting of oil wells is related to the potential for oil rather than for the explanation of geology. As a result, the first few hundred, or even thousand, metres from the surface, are not logged, though these strata may be important for groundwater potential. Furthermore, any geological interpretations from the drilling for oil, tend to occur almost exclusively in official documents, many of which are classified as confidential. These historical and technical problems have to be seen in the context of the extremely complicated geology of the Emirates.

The Emirates is in a world zone, which has undergone in the recent geological past, and is still undergoing, large-scale changes. These
changes have produced, particularly in the mountain zone, an extremely complicated arrangement of outcrops, resulting in many features which still lack satisfactory explanation. Best known in this connection are the ophiolites and the Oman 'exotics', which arouse considerable controversy about their origin and age.

The dominant feature, apart from the sand dune of the desert foreland, is the mountain wadi. This appears as a generally deeply-cut dry valley, that experiences only occasional flow. The wadi forms part of a drainage system etched on what is predominantly a limestone highland, where the wadi is wide; and on an ophiolite highland, where it is narrow, except where a wadi occupies a fault-line. This brings into consideration past pluvial and drier periods, together with sea-level changes. The relationship between the cutting of wadis, the formation of their extensive alluvial fans and the presence of obvious erosion surfaces, await detailed investigation.

Of particular significance for water research, is the development of the alluvial terraces. Wadi terrace gravels provide a particularly suitable aquifer and knowledge of their chronology and formation sequence would be an asset in attempting to locate preferred flow routes. However, there is still controversy about the basic factors concerning the environments in which the gravels were laid and in which they were subsequently dissected. The higher rainfall of a more temperate period might be thought to be the obvious cause of erosion, but it would also result in a more luxuriant vegetation and greater soil development, with the result that flows might be diminished and therefore there would be less erosion.

Geology is directly related to surface and ground water by governing its flow, residence and quality. The geology is discussed in this chapter with emphasis on lithostratigraphic characteristics in the various rock types, a requisite necessary to understand the aquifer systems, their continuous or dislocated vertical and horizontal extent, as in the western piedmont plains, the transmissivity governing both water movement and quality and also the storage capacity.

The mountain wadi alluvial fill, with its loose and permeable cobbles,
gravel and sand, is a highly transmissive conduit of recharge water, but its limited vertical and lateral extent reduces its groundwater storage capacity. The sandy desert foreland, with its thick deposits of fine to coarse sand, possesses both high transmissivity and large groundwater storage potential. The western alluvial piedmont plains, in between these two rock types, are a transition of the gravelly deposits of the mountain wadis and the sandy deposits of the desert foreland. Although the recharge capabilities of the western piedmont plains are high, their content of sand and silt and their heavily faulted stratigraphy, on the local scale, have given rise to discontinuous groundwater bodies. Very little has been done to unravel the geological jigsaw beneath the plains apart from the limited geophysical prospecting, carried out by Geoconsult as part of the Deep Wells Project (1982-86). This confirmed the heterogeneity of the lithologies and their lateral discontinuity beneath the plains, but was inconclusive about the thickness of the alluvial deposits down to the ophiolite bedrock.

The lithologies to the west of Al Ain are described here as far as geological information from boreholes permits. A knowledge of the anhydrite-gypsum-clay-marl lithologies of the Fars Formation helps explain the longer groundwater residence owing to the low permeability of this sequence, and the reaction of the resident water with the minerals in the rocks leading to intense mineralization and, therefore, to high salinity in the waters.

The geology of the deep Upper Cretaceous to Tertiary carbonate aquifer system of the Simsima, Um Er Radhmah and Dammam, is also significant in this study of the water resources of the Emirates as these aquifers, though their waters are brines several times the salinity of Gulf seawater, are heavily tapped groundwater reserves by the oil industry at a rate of 63 mgd. (105 MCM/a.).

A description of the mineral composition of the various rock types, with which water comes into contact, is relevant for understanding the chemistry of the waters dealt with in Chapter 6 on Hydrochemistry.

The section on topography contributes to the clear perception of the physical setting of the water resources. In particular the sand
dunes of the desert foreland, emphasized in the present study for being important fresh water-bearing features of noticeable groundwater recharge value, have either been ignored or underestimated by previous studies. This groundwater potential of the dune sands was confirmed during well-discharge measurement carried out for the present study (Chapter 8); it is also discussed in the context of the recharge potential and the groundwater balance estimates (Chapter 10).

Finally, soils are discussed in as much as they are a medium of recharge. Hence the azonal or geologic soils are given more attention than the agricultural or biologic soils, with the interest in either case being in the effect of salinity on the infiltrating recharge waters as determined from chemical analyses of soil samples collected and analyzed for the present study.

2.2. GEOLOGY

2.2.1. The regional geological setting

The two main geological provinces in the Arabian Peninsula are:

a) The Precambrian igneous and metamorphic block of the Arabian Shield to the west, which has remained a geologically positive region since the Cambrian.

b) The Arabian Platform, occupying the vast area to the east of the Shield that includes the Emirates, has undergone successive subsidence and inundation that have resulted in the accumulation of a sedimentary sequence ranging in age from Cambrian to Recent.

Although the Platform in general remained tectonically stable, it was subjected to basement-activated epirogenic settlement causing upwarping and subsequent downwarping. The latter led to the formation of the two important basins of the Falaaha Syncline, to the east of Dubai, and the Ras Al Khaimah Syncline, off the coast of Ras Al Khaimah (Fig. 2.1.).
Figure: 2.1.

The structural features of the Arabian Peninsula.

The two main geological provinces in the Arabian Peninsula are the Precambrian igneous and metamorphic Arabian Shield, and the Arabian Platform. The latter has accumulated from the former a sedimentary rock sequence ranging in age from Cambrian to recent. Structural and geological development in the Emirates has been influenced by two major regional geological features: the Central Arabian Arc and the Rub' Al Khali Basin.
The structural evolution of the Platform strongly influenced the sedimentation sequence in the Emirates. From the Hercynian (Upper Palaeozoic) to the Eocene (Lower Tertiary), deposition changed from the clastics of the deep, to the carbonates of the shallow, marine environments. The following is the broad sequence that took place:

i) **Permian-Triassic**: dolomites with evaporites or anhydrites, which included clastics in the upper layers.

ii) **Jurassic**: shallow-marine limestones with subordinate dolomites and extensive thick deposits of anhydrites such as those of the Hith Formation of the Late Jurassic.

iii) **Cretaceous**: mostly shallow-marine limestones, without evaporites, but with lenses of clastics of Albian/Turonian age (Middle Cretaceous).

iv) **Palaeocene-Eocene**: shallow-marine limestones with subordinate gypsum/anhydrite in the Lower-Eocene.

Deposition was actively resumed in the late phases of the Mio-Pliocene Alpine Orogeny with the deposition of clastics and subordinate carbonates.

2.2.2. **Structural features** (Fig. 2.1.)

The structural geological development in the Emirates was influenced by two major regional geological features:

i) The Central Arabian Arc; and,

ii) The Rub' Al Khali Basin.

Both structural features dip gently towards the northeast with a corresponding thickening of sediments in that direction. Several small folds, of 5° dip of the periclinal type, occur in the substrata in central and western Abu Dhabi trending N-S, E-W, NE-SW and NW-SE. The most important of these are the 'Arabian Folds', which were caused by basement-related tectonics. The oilfields of Shah, Asab and Sahil lie
on NE-SW trending folds, while the offshore oilfield of Zakum lies on a fold trending E-W (Schlumberger, Well Evaluation Conference, 1981).

The uplift of the Zagros Mountains during the Tertiary led to volcanic intrusions from deep-seated sources in the Precambrian, as salt diapirism, that forms the cores of most of the offshore islands and that of onshore Jabal Addhannah, which was later surrounded by Tertiary and Quaternary deposits. The two important Falahaa and Ras Al Khaimah synclines, noted earlier, collected strata from Upper Permian to Lower Cretaceous times, variations being caused by alternations of sea transgressions and periods of stability. A transgression that occurred during the Lower Cretaceous deposited the shales of Um Annahr Formation, while a subsidence during the Middle Cretaceous deposited the shales of the Shilaif and Mishref formations of the Wasia Group (Figs. 2.2. and 2.3.).

The rising of the deep-seated Cambrian salt-plugs, at the end of the Middle Cretaceous, disrupted the lithostratigraphic sequence by dislocating the layering, causing faults and localized folding. Subsequent sediments, that were laid down in Upper Cretaceous times, thin out towards the northeast in Dubai.

As an aftermath to the disruption caused by the upsurge of the salt domes, subsidence took place during the Upper Cretaceous leading to the deposition of the Aruma Group of four alternating shale-marl-limestone formations of which the uppermost is the Maastrichtian Simsima aquifer. The four formations make up the lowermost of the deep carbonate aquifer system in central Abu Dhabi that will be discussed in detail later in this chapter and also in Chapter 5. The most violent period of instability, however, accompanied and followed the Zagros Orogeny, which began in Middle Cretaceous times.

From the Upper Cretaceous to the Miocene times, the whole of the Northern Emirates was part of a Tertiary basin and the Oman Mountains, which had started to rise in Oligo-Miocene times, continued to do so, with the salt domes, which, during the Upper Miocene, succeeded in piercing the lithologies and forming the islands of offshore Abu Dhabi.
Figure: 2.2.

Generalized stratigraphic sequence of the Emirates.
Figure: 2.3.

Generalized geological cross-section of the sediments in the northern part of the Emirates.

Shown in Figure 2.3. is the sedimentary sequence deposited from Lower Cretaceous to present times in the basin of deposition between the Qatar Arc and the Oman Mountains anticline. The Tertiary Um Er Radhmah, Rus and Dammam formations of Abu Dhabi are represented in the Northern Emirates by the Pabdeh basinal shales. Shelf carbonates similar to those of Um Er Radhmah of Abu Dhabi have been recognized in onshore Um Al Qaiwain on the eastern fringes of the depositional basin. The 'massive salt' is the Oligo-Miocene evaporites sequence at whose closing depositional phases the Miocene Lower Fars or Gachsaran sequence was deposited.
2.2.3. Stratigraphic succession

According to Glennie et al (1974) (Fig. 2.4.), there are three main sedimentary rock formations in the Emirates:

1) The Hajar Super Group (Middle-Permian to Middle-Cretaceous): These are autochthonous (rocks that were formed in situ) limestones and dolomites that were laid down in a shallow-marine environment on the Arabian continental margin. They are, in turn, overlain in parts of the mountains and their fringes, by the Aruma Group limestones, shales, marls and clastics of the Upper Cretaceous.

To the west of the Oman Mountains, the Hajar Super Group is represented by the shales and marls of the Senonian to Maastrichtian Fiqa' Formation (Upper Cretaceous). Towards the mountains, the Fiqa' marls become limestone conglomerates, turbidites and cherts of the Coniacian to late Campanian Muti Formation (also of Upper Cretaceous). The Muti Formation is overlain by the Hawasina and Semail Nappes. To the west of the mountains, these nappes are in turn overlain by the youngest of the Hajar Super Group formations, the Campanian or Maastrichtian Juweiza Formation. The Juweiza is a flysch sequence of carbonate clastics ranging in age from lower Jurassic to lower Cretaceous in a silicified shale matrix of Campanian (Upper Cretaceous) age. The Juweiza is an important, though less transmissive, aquifer in most of the piedmont plains in the Northern Emirates.

2) The Sumaini Group (Permian to Cenomanian of the Middle-Cretaceous): These comprise carbonate sequences of paraautochthonous rocks (rocks formed at a place far from where they are located) ranging in composition from reefal facies to shallow marine marls with an abundance of conglomerates deposited on the continental edge at the foot of the continental slope.
The Hajar Super-Group, the Sumeini Group, the Hawasina Nappes and the Semai Nappe.

The Hajar Super Group (Middle Permian to Middle Cretaceous) are limestones and dolomites that are overlain by the Aruma Group limestones shales, marls and clastics of the Upper Cretaceous. The Sumeini (Sumeini) Group (Permian to Middle Cretaceous) consists of marls and conglomerates, the Hawasina Group (Permian to Middle Cretaceous) comprises folded nappes consisting of limestone and sandstone. In their higher nappes there are the Oman Exotics, which comprise limestones and cherts. They are intruded by dykes, sills and pillow lava. Finally the Semai (Samayel) Nappe, which forms the central mountains of the Emirates to the south of the Dibba-Idhn Fault Line, comprises ophiolites that are made up of peridotite, gabbro, diabase dykes and spillatic pillow lavas.


Figure: 2.4.
3) **The Hawasina Group (Permian to Middle-Cretaceous):** These are allochthonous rock units (rocks transported to the site of deposition from their original location), which were deposited on the continental rise and ocean basin that lay to the northeast of the Emirates. They comprise several thin folded nappes (folds in which the axial plane is horizontal), each of which is a sequence on its own.

The Hawasina largely consist of limestone and sandstone turbidite sequences transported mainly from the northeast. The higher nappes of the Hawasina Group, the Oman Exotics, comprise limestones and cherts that were laid down under shallow marine conditions with a high coral content. Their age span from the Middle/Late Permian to the Late-Triassic and they were laid down over substrata of basaltic pillow lavas. They are intruded by dykes, sills and pillow-lava.

The *Semail Nappe*, which forms the central mountains of the Emirates to the south of the Dibba-Idhn Fault line, was originally a Mesozoic ocean crust, which, with the Hawasina and Sumaini Groups, was tectonically emplaced above the carbonates of the Hajar Super Group. The *Semail Nappe* consists mostly of ophiolites, which comprise peridotites, gabbros, diabase dykes and spillatic pillow lavas. The thick peridotites are sheared and serpentinized along the basal contact of the nappe, with a magmatic transition zone separating the peridotites from the overlying gabbros. The gabbros are layered and include diabases and porphyrites as well as magmatic intrusions of vertical dykes.

2.2.4. **The geology of the mountains**  
(Figs. 2.4, 2.5, 2.6 and 2.7)

The mountains of the Emirates are the northern extension of the 700kms. long Oman Mountain range. Within the Emirates, they stretch for about 150kms. from the extreme north of Ras Al Khaimah emirate to Jabals Al Aghbar and Hatta, south of the village of Hatta in Dubai emirate, in the south. Further south, in the Al Ain region, the only parts of the Oman Mountains included within the Emirates are the small
Palaeocene-Eocene massive limestone of Jabal Malaqet and the ultrabasic, Maastrichtian and Eocene western slopes of Jabal Mundassah. The outlying anticline of Jabal Hafeet in the Al Ain region in the south is similar to the Fayah-Mileiha anticline further north in the Northern Emirates, both of which are made up of Maastrichtian limestone.

The major structural Dibba-Idhn Fault Line divides the mountain zone of the Emirates into two geologically distinct provinces; while the Dibba-Idhn 'grabben' forms a transitional 'corridor' of a melange (mixture) of rock formations. The two hardrock regions to the north and south of the Dibba-Idhn Line are:

a) The Carbonate Massif of Ru‘us Al Jibal, to the north of the Line, stretching for about 60kms. from north to south.

b) The Semail Ophiolite central mountain block, to the south of the Line, stretching for 90kms. from north to south.

While only 15kms. of the northern carbonate massif lie within the Emirates, limited by the international border with Oman to the east of the Ras Al Khaimah coastline, the ophiolite block forms the main part of the highland. It stretches for about 30kms. at its widest between Idhn and Sharm (this is the Sharm of the east coast north of Khor Fakkan), and for only 20kms. at its narrowest along the Masfut axis.

As the mountains are the only source of the rock material deposited in the wadis and the piedmont plains, where aquifers of potable to tolerable groundwater occur, an understanding of the geology and the mineralogical composition of these deposits is essential to explain the effects these deposits have on the quantity and quality of the resident groundwater in them.

2.2.4.1. The Carbonate Massif of Ru‘us Al Jibal (Fig. 2.5.)

As noted earlier in this chapter, the autochthonous limestones of the massif to the north of the Dibba-Idhn Line belong to the Hajar Super Group of Middle Permian to Middle Cretaceous (Cenomanian). They are made up of three formations:
The geology of the Hajar Mountains to the north of the Dibba-Idhn Fault Line (the carbonate massif of Ru’us Al Jibal).

The mountains of Ru’us Al Jibal are made up of three limestone formations: the Ru’us Al Jibal Group, the Elphinstone Group and the Mussandam Group spanning in age from the Middle Permian to the Lower Cretaceous times. All the three groups consist of limestone, dolomite, shale, sandstone, cherts, conglomerates and oolitic, fossiliferous limestone. The whole limestone sequence is about 3000m thick and the strata dip sharply towards the west and south. In texture the limestone of the three groups is massive. In the southern part of the mountains there are Hawasina volcanics and metamorphics that form the geology of the Dibba Corridor. The Tertiary-Quaternary alluvium of the outwash fans of Wadis Sha’am, Ghaleelah, Al Beeh and Naqab occupies most of the coastal strip between the limestone mountains and the Ras Al Khaimah shoreline.
i) Ru'us Al Jibal Group (Middle Permian to Triassic): consists of dolomites, dolomitic and argillaceous limestones with some shale.

ii) Elphinstone Group (Middle Permian to Triassic): consists of limestone, dolomitic limestone, dolomite, shale, marl, siltstone, sandstone, cherts and conglomerates.

iii) Mussandam Group (Lower Jurassic to Lower Cretaceous): consists of grey massive to well-bedded limestone, locally oolitic, fossiliferous, dolomitic with chert.

The whole sequence is about 3000m. thick and was laid down in shallow or supratidal environment over the basic rocks of the Arabian Platform (Glennie et al, 1974). In Wadi Al Naqab, the strata of the Mussandam Group dip sharply towards the south and, in places, they are thin and contain beds of chert. The carbonate massif is heavily faulted and karstification is less developed as evident from drillings that struck planes in the thick carbonate strata, where trapped groundwater demonstrated large drawdown and extremely quick recovery. The Mussandam Group itself comprises 60m-thick layers of Lower Cretaceous limemudstones and conglomerates. Both the Mussandam and the Elphinstone Groups are exposed on either side of Wadis Sha'am and Ghaleelah; while in Wadi Al Beeh, especially along the southern wadi side, all the three carbonate groups are exposed. The limestone in all the three formations can be considered as massive.

2.2.4.2. The Dibba-Idhn Zone (the Dibba 'Corridor') (Figs. 2.4, 2.5 and 2.6.)

The Dibba zone comprises a complex Permo-Triassic to Upper Cretaceous rock associations that are heavily faulted and folded. These include 152m. thick shallow continental shelf-edge strata of the Mayha Formation in the form of nappes made up of limestone and conglomerates. Deep marine sediments of the Hawasina series, which are generally made up of turbidites, cherts, oolitic limestones, radiolarian chert and volcanics as well as green cherts and grey mudstones, overlie the Hajar Mayha series. Within the Hawasina series, are interbedded volcanic layers of pillowed basalts up to 30m. thick.
The complex geology of the Dibba-Idhn Corridor.

The Dibba zone comprises a complex Permo-Triassic To Upper Cretaceous rock associations that are heavily faulted and folded. The most important rocks are the Hawasina volcanics and metamorphics, blocks of Oman Exotics (limestones and cherts of Permo-Triassic age) and the Oman Melange, which is a varied mixture of Hawasina sediments, greenschist, Maastrichtian Juweiza sandstones, volcanics and metamorphics in either a sedimentary or serpentinite matrix.


Figure: 2.6.
Other volcanics include agglomeratic flows of glassy lava, pyroxinite, green schist and metamorphics. Blocks of the Oman Exotics, of up to 4 or 5km. across, such as the whole mass of Jabal Qamar (North and South) near Idhn are also found within the Corridor. As noted earlier, the Oman Exotics are made up of limestones and cherts of Permo-Triassic age. The widespread Oman Melange of the Dibba Corridor is made up of a varied mixture of Hawasina sediments and greenschist, Maastrichtian Juweiza sandstones, volcanics and metamorphics in either a sedimentary or serpentinite matrix of varying thicknesses. The melange outcrops are in places separated by thrust sheets of Hawasina sediments, and the whole melange (mixture) is totally or partially transformed by metamorphism (Fig.2.4).

The metamorphics, which occupy large tracts in the central parts of the Dibba Corridor, with a wedge-like extension as far as Masafi in the midst of the ultrabasic peridotite ophiolite highland block to the south, are largely composed of amphibolite and greenschist, which assume great thicknesses. The greenschist and quartz mica schists predominate and are usually mixed with impure marble. The amphibolite metamorphics comprise mafic amphibolites (rocks of ferro-magnesium minerals), quartz-rich schists, hornblende, epidote, plagioclase, biotite and muscovite. Dykes of dolomite, rich in hornblende, intrude the greenschist and metamorphics. In Wadi Al Fayy, in the Al Baseerah wadi basin, the Hawasina limestone is densely intruded with dolomite dykes.

2.2.4.3. The Semail Ophiolites Zone (Fig. 2.7)

The mountain block to the south of the Dibba-Idhn Fault Line forms the northern section of the largest Semail Ophiolite complex in the world. The ophiolites consist of:

"tectonized harzburgites, . . . and dunites at the base passing up into layered peridotites and gabbros, a sheeted dyke complex and extrusive pillow lavas"

(Anon, 1972 / Smewing et al, 1982)

The whole block is a Mesozoic oceanic lithosphere emplaced and thrust
Permo-Triassic to Upper Cretaceous Carbonates:
Limestones, dolomites - fossiliferous and dolomitic, in places with marl, shale, sandstone, chert and conglomerate.

Pre-Permian to Upper Cretaceous Hawasina Metamorphics (Lst, Quartz, Schist and Marble) and volcanics (Basic and intermediate lavas)

Pre-Permian to U. Cretaceous ultrabasic Peridotite and Serpentinite.

Pre-Permian to U. Cretaceous coarse-grained gabbro, Pegmatite and Serpentinite.

Quaternary Fluvial deposits: Boulders gravels and sand in terrace and piedmont beds

Inland Sabkha: Muddy and silty evaporitic soft or hard-crusted playas or seiks.

Coastal Sabkha: Salt-crusted calcareous silt and mud flats seasonally inundated by sea

Quaternary Eolian Sand: Sheet, ripple high and low dunes.

Key to the geological map (Fig. 2.7.) on page 55.
The geology of the catchments of the Emirates and adjacent areas.

The ophiolite Central Mountains block to the south of the Dibba–Idhn Line is of Middle Cretaceous age and it consists of two sections: an ultrabasic peridotite northern and northeastern half and a basic gabbro southern and southwestern half. The whole mountain block has been subjected to faulting that has divided it into distinct relief zones.
over the older carbonates of the Hajar Super Group of Ru’us Al Jibal. It is therefore an allochthonous unit and the emplacement took place during Upper Cretaceous times producing a unique mixture of rock masses that underlies the ophiolite unit. These rock masses were then heavily and repeatedly tectonized, severely serpentinized under stable conditions and subjected to hydrothermal alteration. The Samail Ophiolites have been subdivided by Reinhardt (1969) into seven units, in a superimposed sequence, as follows:

1) Pillow lavas and interbedded umbers (ironstones).
2) Diabase dykes.
3) Massive gabbros with brecciated metagabbros and plagiogranite.
4) Layered gabbros rich in plagioclase with various proportions of clinopyroxene, olivine and orthopyroxene.
5) A transition zone with alternating dark bands of olivine and clinopyroxene and light ones of anorthosites, tractolites, gabbros and norites.
6) Serpentine peridotite of a large extent consisting mostly of harzburgite, olivine and orthopyroxene.
7) Metamorphics of Hawasina series consisting mainly of melange units of quartzite, marble, schist and amphibolite.

The age of the Ophiolites is considered to be of Cenomanian to Turonian (both of which belong to the late phases of the Middle Cretaceous) and the overthrust of the whole unit over the Arabian Platform is considered to have taken place during the Coniacian to Campanian times (of Upper Cretaceous). According to Graham (1981), the Samail Ophiolite Suite was initiated above a northeast-dipping subduction zone. In the early stages of emplacement it was moved by continental underthrusting and, in its final stages, by gravitational processes. During thrusting, the Samail Ophiolite unit partially overrode the Hawasina series and incorporated the Sumaini thrust sheet. The initial Ophiolite slab was broken into blocks and plates, either simultaneously as emplacement was taking place, or later during the Tertiary times. The major fractures within the Ophiolite block, like the Dibba-Idhn, the Ham and the Hatta fault-lines, are related to basement dislocation. Faults that were not of a deep-seated Arabian foreland origin, must have occurred as a result of stresses accompanying the emplacement of such a slab that was 3000-4000m.
thick. Tertiary folding, coupled with mild thrusting, resettlement and subsequent erosion, shaped the Ophiolites mass into separate blocks.

The formation of the Oman Mountains accompanied major tectonic events, which were marked by deep faulting, that dislocated the mountain zone into the following regional blocks:

a) The Carbonate Massif of Ru‘us Al Jibal.

b) The Dibba Corridor, which is a grabben of broken hills in its upper and middle sections but is occupied in its central and lower sections by the flat flood plain of Wadi Al Baseerah down to the shoreline at Dibba.

c) The Central Ophiolite mountain block, which is subdivided by the Wadi Ham Fault, into the eastern Shumailiyah block (of mostly ultrabasic peridotite), and the western Hajarain block (of mostly basic gabbro).

It is believed (Geoconsult, 1985) that the Dibba-Idhn Fault continues further southwest from Idhn, under the central piedmont plains, taking an offshore course to the west of Dubai. Other major fault-lines dissect the piedmont plains to the west of the mountains trending N-S from Ras Al Khaimah in the north to Al Ain in the south. Such a fault system was "inferred from the geology and also by magnetic survey" (The Deep Wells Project, Final Report, Geoconsult, 1985).

The faulting pattern in the central piedmont plains suggests that the sedimentary formations are in 'echelon' with the fractured rocks in the mountains to the east, having been affected by their instability during the rising and settlement geological processes. The result has been a complicated hydrogeological situation relating to groundwater occurrence and exploitation due to differences in groundwater levels and lateral extent of groundwater bodies.

2.2.5. **Water-bearing sedimentary stratigraphy** (Fig. 2.8.)

Stratigraphically, the important sedimentary sequences in relation to groundwater resources are those that span in age from Upper Cretaceous
to Recent. The older deeper formations hold great volumes of extremely saline fossil water, put solely to industrial use by the oil industry for injection purposes to pressurize oil extraction. The most in use for this end is the deep carbonate aquifer system of Upper Cretaceous to Upper Tertiary, from the Simsima to the Lower Fars and Miocene clastics, marls and shales (Figs. 2.2, 2.8 and 2.9).

In Abu Dhabi, the Upper Cretaceous Aruma Group (from bottom to top: Laffan, Halul, Fiqa' and Simsima (Figs. 2.8 and 2.9)), is deep and thick consisting mostly of limestone-marl-shale series that forms the deepest section of the carbonate aquifer system under central Abu Dhabi. In the northern emirates, especially in areas adjacent to the mountains from Al Dhaid northwards, they are represented by the Juweiza flysch described earlier. They underlie the Quaternary alluvium and are in places not far from the surface, depending on the thickness of the overlying Quaternary deposits. Their clayey matrix renders them poorly transmissive holding groundwater of marginal quality that is hydraulically connected with the fresh groundwater of the overlying highly permeable Quaternary alluvium.

The water-bearing stratigraphy, from the Upper Cretaceous to the Recent, is discussed in this chapter for the desert foreland, the piedmont plains and the mountain wadis to provide the geological background that relates to the origins and composition of these water-bearing strata, which are treated in detail in chapter 5 (Hydrogeology).

2.2.5.1. The Upper Cretaceous-Tertiary sedimentary stratigraphy: (Figs. 2.2, 2.3, 2.8, 2.9 and 2.10.)

2.2.5.1.1. The Upper Cretaceous stratigraphy

Upper Cretaceous: Aruma Group (Halul, Fiqa' and Simsima Formations): This group was formed in the depocentre of central Abu Dhabi in two marine transgressive cycles of deposition. The first cycle was that of the Laffan and Halul formations, the second cycle was that of the Fiqa' and Simsima formations. The first two formations are made up of shales and argillaceous limestones; the second two formations are made up of marls, shales, argillaceous limestones and wackestones.
<table>
<thead>
<tr>
<th>Era</th>
<th>Age</th>
<th>Formation</th>
<th>Aquifer Name and Thickness</th>
<th>Aquifer Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Holocene</td>
<td>Quaternary (40-100m.)</td>
<td>Unconfined. Productive in the alluvium of the piedmont plains and mountain wash and the aeolian deposits of the desert foreland.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pleistocene</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tertiary</td>
<td>Pliocene</td>
<td>Upper Fars</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td></td>
<td>Middle Fars</td>
<td>Unknown</td>
<td>Lower Fars (900-1150m.)</td>
<td>Semi-unconfined. Poor transmissivity. Brackish to saline water.</td>
</tr>
<tr>
<td></td>
<td>Lower Sahil Clastics</td>
<td>Asmar (300m.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oligocene</td>
<td>Sahil Clastics</td>
<td>Asmar (300m.)</td>
<td>Confined. Varied productivity depending on the presence of silt and clay and hydraulic connection with underlying aquifers.</td>
</tr>
<tr>
<td>Eocene</td>
<td>Upper</td>
<td>Damama</td>
<td>Damama (850m.)</td>
<td>Limestone and marl Aquifer. Confined. Poor permeability. Containing in Liwa brackish water if in hydraulic contact with the aeolian aquifer above it.</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>Rus</td>
<td>Rus (150m.)</td>
<td>Aquiclude. Very saline water.</td>
</tr>
<tr>
<td>Paleocene</td>
<td>Eocene</td>
<td>Salmaya</td>
<td>Salmaya (200-400m.)</td>
<td>Limestone. Confined. Poor permeability.</td>
</tr>
<tr>
<td>Cretaceous</td>
<td>Maastrichtian</td>
<td>Fisa'</td>
<td>Fisa' (100-350m.)</td>
<td>Shale and Marl. Aquiclude.</td>
</tr>
<tr>
<td>Upper</td>
<td>Upper Campanian</td>
<td>Fila</td>
<td>Fila (100-350m.)</td>
<td>Limestone. Unknown. Shale aquiclude.</td>
</tr>
<tr>
<td></td>
<td>Lower Campanian</td>
<td>Halul</td>
<td>Halul (100m.)</td>
<td>Limestone. Unknown. Shale aquiclude.</td>
</tr>
<tr>
<td></td>
<td>Santonian</td>
<td>Laffan</td>
<td>Laffan (100m.)</td>
<td>Limestone. Unknown. Shale aquiclude.</td>
</tr>
<tr>
<td></td>
<td>Coniacian</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Turonian</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure: 2.8.

Lithostratigraphical-hydrogeological correlations of the sedimentary water-bearing stratigraphy in the Emirates.

The Quaternary to Recent alluvial-aeolian strata and the underlying old ophiolite fractured bedrock hold fresh groundwater; the compact Tertiary alluvium of the wadi terraces and intermontane basins holds marginal groundwater; the Tertiary clastics-in-shale (Juweiza Formation) and evaporites (Lower Fars Formation) hold marginal to saline groundwater, while the deeper Tertiary and Upper Cretaceous massive limestones and dolomites are holders of brines up to five times the salinity of Gulf sea water.
(mud-supported carbonate particles). All the four strata are deep, open marine-shelf environment formations reaching a thickness of 335m. in offshore Abu Dhabi. The Simsima, which overlies the Halul, represents a marine regressive phase. It consists of limestones, mainly wackestones, and dolomites of a shallow water origin. In offshore Abu Dhabi, it is 183m. thick, while in the northeastern parts of Abu Dhabi emirate, it is 366m. thick.

The Ilam limestone in Dubai, the equivalent of the Halul in central Abu Dhabi, was deposited in a very shallow-marine environment consisting mainly of wackestone that thins out in the east and south. In the Northern Emirates, downwarping led to the deposition of the deep-marine environment Aruma shales. The Ilam is thin or absent in the Northern Emirates beyond Dubai, while the Aruma shales are interbedded or, in places, replaced by the Juweiza flysch sequence of eroded carbonates and shales in areas adjacent to the foothills north of Dhaid (Fig. 2.3).

The significant uplift that took place along the western fringe of the Oman Mountains towards the end of the Campanian (Upper Cretaceous) led to the deposition of the Maastrichtian limestone, which is similar in character to the Simsima of the shelf areas of Abu Dhabi. The anticlinal ridges of Jabals Fayah-Mileiha in the northern emirates, and Jabal Hafeet in Al Ain in the south, presumably overlying the ophiolite bedrock, belong to this age.

2.2.5.1.2. The Tertiary Formations

Two basins of deposition existed during the Lower Tertiary. These were:

a) The Rub' Al Khali Basin in the south, and

b) The Pabdeh-Gurpi Basin centered in the Northern Emirates.

In the western parts of Abu Dhabi, the Lower Tertiary consists of a group of three formations known collectively as the Hasa Group, which, in sequence from bottom to top, are: Umm Er Radhmah, Rus and Dammam formations. They diminish in eastern and northeastern Abu Dhabi
towards Dubai, and are replaced by the Pabdeh Formation in the Northern Emirates, which formed the depocentre of the Tertiary Basin.

2.2.5.1.2.1. Um Er Radhmah Formation (Palaeocene-Lower Eocene):

This rock formation ranges in thickness from 351m. in the northwest to 457m. in the south, to more than 701m. in the east, of Abu Dhabi emirate. These thicknesses indicate the depositional environment of a widespread marine transgression in the beginning of the Palaeocene. The base of Um Er Radhmah comprises shales but the bulk of the formation consists of shaly and bioclastic limestones and dolomites, argillaceous in parts, indicating shallow-water depositional conditions. In parts of the formation, as at Zakum and Um Al Shaif, the shales are alternating with sabkha cycles and each phase is marked by a thin anhydrite layer. Towards the Lower Eocene, wide evaporitic platforms existed over most of Abu Dhabi and the Northern Emirates in which were deposited the evaporites and carbonates of the Rus Formation. This latter formation varies in thickness from 656m. in the north, to more than 256m. in the south of central Abu Dhabi. Its composition is dominated by a massive anhydrite sequence formed under subaerial supratidal conditions. The minor presence of argillaceous limestone at the base of the formation represents lagoonal conditions.

A large marine transgressive phase took place during the Middle Eocene, with less saline water, providing normal shallow-shelf marine conditions for the widespread deposition of the nummulitic carbonates of the Dammam Formation. The Dammam, the uppermost of the deep carbonate formations, consists of calcareous shales and argillaceous limestones in the lower part of the formation, succeeded by wackestones and finally topped by limestones, dolomites and subordinate shales.

The continental-shelf, shallow-marine deposited sequence of the Um Er Radhmah, Rus and Dammam of central Abu Dhabi is represented in the Northern Emirates by the Pabdeh basinal shales reflecting the continuing basinal depositional environment that commenced in the Upper Cretaceous. Shelf carbonates, similar to those of Um Er Radhmah, have been encountered by oil drillings in offshore Um Al Qaiwain,
<table>
<thead>
<tr>
<th>Time Unit</th>
<th>Rock Unit</th>
<th>Current Terminology</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miocene</td>
<td>Lower Fars Formation</td>
<td>Lower Fars</td>
<td>Evaporites</td>
</tr>
<tr>
<td></td>
<td>Clastics (Sahil)</td>
<td>Miocene Clastics</td>
<td>Sands and Clays</td>
</tr>
<tr>
<td></td>
<td>Dammam Formation</td>
<td>* Dammam Dammam Basal Shales</td>
<td>Limestone Marl</td>
</tr>
<tr>
<td>Oligo/Miocene</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle/Upper Eocene</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower Eocene</td>
<td>Rus Formation</td>
<td>Rus</td>
<td>Anhydrite and Limestone</td>
</tr>
<tr>
<td></td>
<td>Um Er Radhmah Formation</td>
<td>* Um Er Radhmah Um Er Radhmah Basal Shale</td>
<td>Limestone Shale</td>
</tr>
<tr>
<td>Palaeocene</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Cretaceous</td>
<td>Aruma Group</td>
<td>* Simsima Fiqa' Halul Laffan</td>
<td>Limestone Shale and Marl Limestone Shale</td>
</tr>
</tbody>
</table>

* Producing aquifers

Source: Abu Dhabi Company for Onshore Operations (ADCO), 1981; PARTEX, Fig. 2, 1982.

Figure: 2.9.

The Upper Cretaceous to Middle Tertiary deep carbonate aquifer system of central Abu Dhabi.

The deep formation aquifer system of the Emirates span in age from the Upper Cretaceous Halul, Fiqa' and Simsima of the Aruma Group to the Oligo-Miocene Lower Fars Evaporites. Of the deep water-bearing formations, those of the Simsima (Upper Cretaceous), Um Er Radhmah (Tertiary (Palaeocene)) and Dammam (Middle/Upper Eocene) are the productive ones and are in use for pressurizing oil by injection into oil wells in central Abu Dhabi. Groundwater in the Oligo-Miocene Sahil clastics and Lower Fars Evaporites are widely exploited throughout Abu Dhabi because of nearness to the surface despite their brackish to saline waters.
which marked the periphery of the Pabdeh depositional basin.

2.2.5.1.2.2. Upper Tertiary Formations

During the Upper Eocene and Lower Oligocene, uplift of the land and active erosion were underway. The uplift was pronounced to the west of Abu Dhabi in the rising of the Qatar Dome (Fig. 2.1.), while in the western parts of Abu Dhabi emirate the uplift affected the Eocene platform by active erosion. Again, a sea transgression took place and the Asmari Formation (limestones and clastics of Oligocene age overlying the Dammam; they are similar to the Miocene clastics of the Sahil Formation of central Abu Dhabi), was laid down in the extreme east of Abu Dhabi and offshore Northern Emirates. The Asmari is a shallow-marine fossiliferous limestone, partly dolomitic, laid down on the continental shelf.

In early Miocene, the Gachsaran Formation was deposited. Its thickness varies from 122m. in western Abu Dhabi to 850m. in the extreme east of the emirate. The Lower-Middle Miocene Gachsaran (or Fars) Formation consists of three units:

a) An upper unit of interbedded anhydrites, shales, marls and carbonates.

b) A middle unit of dolomites and limestones.

c) A lower unit of anhydrites with dolomites and clastics.

The land was uplifted again during the Upper Miocene with subsequent enhanced erosion taking place throughout Abu Dhabi and the Northern Emirates caused by the Alpine Orogeny. This last event shaped present-day landscape with great volumes of water-borne boulders, cobbles, gravels and sand being deposited on either side of the mountains of the Emirates, that form the groundwater recharge zone. The Zagros Mountains continued to rise to the east of the Gulf, while the Oman Mountains on this side of the Gulf were gradually taking shape. The active erosion in the Oligocene exposed the series of anticlines of Jabals Fayah-Mileiha-Hafeet, 20km. off the main Oman Mountain range.
During the Upper Tertiary (Miocene), a deep marine salt section of the Oligo-Miocene, known as 'massive salt', was deposited in the remnant Pabdeh Basin, while the Red Sea was being opened. During the Miocene times also, Hormuz Strait was periodically being closed setting the scene for a marine environment in which deep marine salts were precipitated from the supersaline remnants of the Pabdeh Basin waters.

Simultaneously, the evaporites of the Gachsaran of the Lower Fars were being deposited. On to these evaporites, were added gravels, sands and conglomerates that were washed down from the higher ground that extended as far as Qatar. The Gachsaran evaporites represent the end phase of the filling of the Pabdeh Basin that was marked with the deposition of halite and anhydrite with occasional dolomites and terrigenous clastics. This last sequence is water-bearing throughout Abu Dhabi below the Quaternary and is in places close to the surface in large areas of the Emirates. Its salty composition has a profound effect on the quality of the groundwater it is holding (Figs. 2.3., 2.8 and 2.9.)

2.2.6. The Quaternary Stratigraphy:

The Quaternary stratigraphy, which is the main container and recharge conductor of the fresh groundwater resources of the Emirates, as it has been since the Pleistocene, is a sequence of reordered alluvial and aeolian material from older sources. An example of this is the recarving, since the Pleistocene, of the older well-cemented Tertiary wadi alluvium, which forms present-day terraces on either side of wadis, and the depositing of these sediments in outwash fans at the point where the wadis debouch on to the lowlands. Numerous such alluvial outwash fans coalesced at the western mountain front to form the piedmont plains.

The sequence of deposition of the Quaternary strata was influenced by the following physical factors:

a) A major sea regression during the Pleistocene, down to 120m. below present-day sea-level (Fairbridge, 1961). The whole Gulf sea floor was exposed and the climate was wetter, thus activating heavy runoff. Downcutting in the mountain hardrock
parts, and in the well-cemented Tertiary wadi alluvium, resulted in the deposition of gravel and sand at the foothills.

b) A sea transgression phase, which started 20,000 years ago and is still continuing, characterized by the existing aridity, in which wind action is playing a leading depositional role.

Of direct relation to groundwater resources, the Quaternary deposits are of three types:

i) The alluvial deposits of the wadis and the piedmont plains:

These are the most important fresh water-bearing deposits. They have an average thickness of between 40m. and 50m. in most localities in the Emirates and are only thicker where they overlie older well-cemented Tertiary alluvium as in Wadis Ham, Al Wurai’ah and Al Baseerah. The composition of their rounded rock material, which ranges from boulders to fine gravel, also containing poorly sorted medium- to coarse-grained sand, enables them to absorb flood water rapidly. This is particularly so in the active wadi and braided outwash fan channels, where high infiltration occurs. The material is derived from parent rocks in the mountains, that range in age from Pre-Permian to Recent. North of the Dibba-Idhn Line, the gravels are mostly of a carbonate source from the same sequences that make up the Ru’us Al Jibal limestone massif; to the south of the Line, they are mostly basic and ultrabasic gabbros, peridotites and serpentinites derived from the basic and ultrabasic central mountain block. In the middle part of the Dibba Corridor, in both west- and east-flowing wadis, the most important of which is Wadi Al Baseerah, the boulders, gravels and sands are of the Hawasina metamorphics and volcanics, with quartz and cherts dominating the deposits. There is also a substantial contribution of material from the serpentinites of the upper reaches of the wadis that flow into the Dibba Corridor.
ii) The aeolian deposits of the desert foreland:

These comprise low to high, and even giant dunes, as in Liwa, where such dunes reach heights of more than 200m. Sand deposits in the desert foreland close to the western Gulf coast, as at Al Aweer and Sirrah, are of a carbonate base; while the inland sands, as at Al Hayer and Liwa, are of a quartzitic base.

Apart from the stable older giant dunes, this aeolian formation is wind-blown and unstable and is continuously resurfacing sabkha tracts that occur between the dunes. It is an important, highly permeable deposit, demonstrating the highest infiltration rates, as will be shown later in this chapter (section 2.3.5.), and contributing substantially to the fresh groundwater resources.

iii) The inland sabkhas:

These are made up of silt and muddy sand, continually being inundated either by wadi flows or rising groundwater levels. Sabkhas are tracts where evaporites are continuously being formed and where, naturally, the waters they contain are highly saline. The so-called 'seis' of Sabrah, Gharabah and Al Miyah in Al Ain, which contain brackish to saline groundwater, are sabkhas between elongated dunes.

2.2.7. The stratigraphy of the piedmont plains and the desert foreland

On the local scale, there are no detailed studies relating to the thickness of the Quaternary deposits that underlie the piedmont plains. Comprehensive lithostratigraphic data of lithologies beneath the Quaternary are available from oil companies operating in the emirates of Sharjah, Um Al Qaiwain and Ras Al Khaimah, but such geological material falls under corporation confidentiality. Some information from several wells drilled by these oil companies was, however, obtained besides that from very limited geophysical investigations carried out by Geoconsult between 1982 and 1984.
At the start of the Deep Wells Project (1982-86) it was hoped that such a study, particularly the geophysical part of it, would determine the thickness of the Quaternary alluvial mantle of the piedmont plains. It was hoped also that the stratigraphy of the geosyncline between the Fayah-Mileiha anticline and the main mountain block, an area occupied by the Ghareef Plain, would be clarified more decisively and the occurrence of groundwater would be determined both quantitatively and qualitatively. Little was added by the results of this MAF-Geoconsult-Iwaco study than what had already been known and the hydrogeological situation, particularly in the Ghareef geosyncline, remains unclear. The exploratory wells drilled by the Deep Wells Project in the piedmont plains, however, confirmed the heterogeneity of the lithologies and the abrupt alteration in their vertical extent, which are attributed to change in facies caused by vertical dislocation due to faulting.

Examples of this lithological unconformity are found in some oil wells drilled in the area to the west of the mountains in the Northern Emirates (Figure 2.10). In the oil well Mu'ayyed-1, the Lower Miocene Fars anhydrites are twice as thick as in the oil well Saja'ah-2. In well Mussannad-1, the Miocene evaporites are missing and the Quaternary directly overlies the Maastrichtian (Late Cretaceous) clastics, shales and clays of the Juweiza Formation. In well Al Ali-2, the Quaternary rests on a thinner Maastrichtian Juweiza flysch, which in turn rests on the Pre-Permian to Upper Cretaceous Hawasina metasediments that do not appear to exist in the drill cuttings of the other oil wells (Fig. 2.11). The Hawasina series reaches a thickness of 3000m. Pabdeh shales, which in the Northern Emirates are the equivalent of the Um Er Radhmah, Rus and Dammam in central Abu Dhabi, are represented in wells Mu'ayyed-1 and Saja'ah-2 but are absent in wells Mussannad-1 and Al Ali-2 (Fig.2.11).

These differences in lithologies are echoed by similar differences in composition. The Um Er Radhmah, Rus and Dammam of the west are limestones and wackestones in the east; and their equivalent, the Pabdeh in the north, are shales. The Miocene carbonates and shales
Figure: 2.10.
Location of the oil wells in Sharjah and Um Al Qaiwain.
Lithological variation of the same rock sequences in drill cuttings of selected oil wells in the piedmont plains and desert foreland in the emirates of Sharjah and Um Al Qaiwain in the Northern Emirates.

Lithological unconformity in the strata of the piedmont and desert plains of the Northern Emirates is illustrated by these drill cuttings of oil wells. In the oil well Mu’ayyed-1, the Lower Miocene Fars anhydrites are twice as thick as in the oil well Saja’ah-2, while in Mussannad-1 the Miocene evaporites are missing. In Al Ali-2 the Quaternary alluvium rests on a thinner Maastrichtian Juweiza Flysch, which in turn rests on the Pre-Permian to Upper Cretaceous Hawasina metasediments that do not appear to exist in the drill cuttings of the other oil wells. The Pabdeh shales, which in the Northern Emirates are the equivalent of the Um Er Radhmah, Rus and Dammam in central Abu Dhabi, are represented in wells Mu’ayyed-1 and Saja’ah-2 but are absent in wells Mussannad-1 and Al Ali-2 (see Fig. 2.10 for the location of these oil wells).
encountered in the wells of the Deep Wells Project, that were drilled in the Maastrichtian Juweiza (the Aruma Formation in the Northern Emirates) are lacking in the east, but reappear in the southern plains as anhydrites.

The Fayah-Mileiha hills are folded anticlines of Maastrichtian age resting on the Semail Ophiolites. The 20km-gap between them and the main mountain block is a syncline filled with a thin mantle of Quaternary gravel and sand that overlies the Maastrichtian limestone as revealed by the limited number of drillings in the vicinity. Borehole GP-14 (Deep Wells Project well, Fig. 5.21, Chapter 5; see also Fig. 5.29 for the location of the wells of the Deep Wells Project), at the point Wadi Siji enters the piedmont plains, was drilled to a depth of 106m. It cut through 42m. of Quaternary alluvium, and then through the Upper Cretaceous Juweiza flysch down to the total depth of the well of 106m. without reaching the contact zone with the Semail Ophiolite, which appears to lie deep below the surface, even at this point near the foothills of the ophiolite mountain block, lying 10km. to the east.

Evidence of a post-sedimentation fault is apparent in the difference in levels between the general topography and that of the ophiolite outcrop. A fault brought the interface between the terrestrial gravels and the Semail Ophiolite to about 147m. from the general surface of the land.

The thickness of the Quaternary deposits in the alluvial outwash fans in the northern parts of the piedmont plains, as in Hamraniiyyah or even further north of it in the outwash fans of Wadis Ghaleelah and Rahbah, varies from 50m. to 100m.

On the east (Batinah) coast (Chapter 5, Sections 5.3.2.5.1.2.1 and 5.3.2.5.1.2.2), the alluvial deposits of Wadi Ham outwash fan average 40m. in thickness before the fractured ophiolite zone is reached. In the smaller embayments of the coast, softer sediments of sands and silts overlie the gravels. In the large Wadi Al Baseerah, the Quaternary alluvial deposits of boulders, gravels, sands and silts, which fill the lower part of the wide wadi basin, are about 20-50m. thick as far upstream as 15km. from the shoreline at Dibba. Underneath
these alluvial deposits, the Hawasina-Ophiolite bedrock follows a graded sequence due to block-faulting in the grabben of the Dibba-Idhn Fault Line that forms Wadi Al Baseerah basin.

In Al Jaww Plain in Al Ain, which is the southern section of the western piedmont plains, the Quaternary deposits, of mainly coarse pebbles and sandy gravels (Fig. 2.11), have an average thickness of 40m., but the deposits thin out towards the mountain gaps to the east. Recent drillings (June, 1989, as part of the NDC-US Geological Survey Study) have shown that the Oligo-Miocene clays and marls predominate the drill-profiles, while the Quaternary alluvium is hardly 30m. thick and of that, only 4m. are saturated. The alluvium thickens towards the west, and at the eastern foothills of Jabal Hafeet, it reaches a thickness of 150m. Immediately beneath the Quaternary alluvial deposits is the evaporites-clays-shales-marls sequence of the Lower Fars Gachsaran (Lower/Middle Miocene), which locally acts as an aquitard, but is, over large areas, a thick brackish to saline water-bearing sequence, in hydraulic connection with the overlying Quaternary alluvium (Chapter 5, Section 5.3.2.4.3.2; also Chapter 9, Section 9.3.4.). Eocene-Oligocene limestone underlies the Fars evaporites, and this is also in hydraulic continuity with the other two sequences above it (the Lower Fars evaporites and the Quaternary alluvium).

The Oligo-Miocene Lower Fars sequence in Al Jaww Plain is composed of evaporites, anhydrite-halite, marls, clays and conglomerates. The sequence is close to the surface at Sa‘ah near the Zarub Gap, where it intercalates with gravel from ground level down to more than 200m. At Kashoonah and Al Shuwaib further north, the sequence appears at levels between 50m. and 55m. below the surface. At Um Ghafah, in southern Al Jaww, the clay and marl lithologies intercalate with coarse sand and gravel down to 20m. from the surface below which, the Lower Fars evaporites sequence predominates. To the west of Jabal Hafeet clay, marl and gypsum start at depths between 190m. and 220m. below the surface, and continue so to depths of below 1200m. from the surface. All these hydrogeological data have been deduced from interpretations of drill cuttings in the records of the Groundwater Department of the Diwan of Al Ain.
Further west, in central and western Abu Dhabi, wherever the Quaternary alluvial mantle is thin, the Oligo-Miocene Lower Fars (Gachsaran) evaporites are close to the surface. Apart from having very low transmissivities, the anhydrite and gypsum give rise to brackish/saline groundwater. The Upper Eocene Dammam Formation normally occurs at depths below 1100m. below the surface in central Abu Dhabi, but outcrops in northwestern Abu Dhabi, in the Sila’ area, where it is in hydraulic continuity with coastal waters and thus contains extremely saline groundwater (Chapter 6, Hydrochemistry, Sections 6.5.3.7).

In Liwa, the Lower Palaeocene to Lower Eocene (both of the Tertiary) limestones and evaporites of the Rus Formation are overlain by the Dammam nummulitic carbonates. These are in turn overlain by clastics of coarse limestones, gravels, calcareous sands, muds, silts and finally aeolian sands and sabkha evaporites.

The surficial sands, such as those of the giant dunes of Liwa, can reach heights of up to 200m. above the deflation basin (sabkha) floor, but thin out northwards towards Bu Hasa and Bida’ Zayed. In Bu Hasa, surface sand dune accumulations of 100m. in height have been reported from boreholes tapping fresh groundwater in the dune sand aquifer in Al Qafa and Bu Hasa. These thick sands are the fresh water-bearing strata in this area, and the groundwater they contain practically floats over the denser saline waters of the Oligo-Miocene Lower Fars (Gachsaran) evaporites. Further north and northeast the Quaternary sand cover is thinnest and saline groundwater is abstracted from the salty Oligo-Miocene evaporites and gypsum strata from shallow levels.

In the Shah oilfield area within Liwa, the Recent aeolian dune sands and the Sabkha evaporites, gypsum, silts and sheet sands make up a 170m-thick water-bearing sequence before reaching the underlying calcareous Pleistocene sandstone. The Oligo-Miocene limestone and sandstone are about 100m. thick, followed by 305m. of limestones and marls of the Eocene Dammam Formation. Gravels are almost absent in the vast heartland of Abu Dhabi, but in Sila’, in the extreme northwestern end of the emirate of Abu Dhabi, the Quaternary deposits comprise a mantle of 60m. thick quartzitic sands, cherts and pebbles with a
calcareaeous matrix. On the whole, gypsum, evaporites and accumulated anhydrite-halite (still forming in the many sabkhas that interspace all types of dune formations) are widespread in the whole region covered by the desert foreland of Abu Dhabi.

2.2.8. Quaternary sea-level and tectonic land-level changes:

The present Gulf is a remnant of a once more extensive sea that included the Rub‘ Al Khali (Empty Quarter) desert and the whole of eastern Arabia. Its present average depth is 35m. and is only 100m. in its deepest parts. Three main sea-level changes took place during Quaternary times. These were:

i) A transgression took place during the Late Pliocene-Early Pleistocene with a rise of 150m. above present-day sea-level (Fairbridge, 1961). Lees (1928) put this rise at 370m. based on the presence of wave-cut platforms along the Batinah coast of Oman at this level. According to this, the whole land below that level was inundated and only the eastern mountains and the Fayah-Hafeet hills, above 370m., remained above that sea-level.

This great difference between the two levels is confusing as the 150m. level of Fairbridge’s does not conform with the geological end of the Pliocene and the beginning of the Pleistocene, but conforms with a later date in the Pleistocene of a time scale of 500,000 years. Lees’s 370m. level coincides with the end of the Pleistocene. The 150m. level is, therefore, of a later date in the Pleistocene; the 370m. level could possibly be of a tectonic origin.

ii) A regression of Gulf waters took place during the Pleistocene Ice Age, reaching its lowest level of 120m. below present-day Gulf sea-level about 20,000-70,000 years ago. Accordingly, the whole Gulf floor was dry down to Hormuz Strait where present-day sea-floor is below 120m. After this sea transgression, a damper climate followed, activating surface runoff, with subsequent enhanced erosion and deposition taking place, leading to the accumulation of gravels and sands.
and the building of the outwash fans at the foothills of the Oman Mountains.

iii) **Renewed regression** of the sea started 20,000 years ago and has continued to the present day (present-day sea-level was reached 5000 years ago during the Holocene). The climate turned drier and has acquired its present aridity.

The fluctuation in sea-level is important in explaining most of the geomorphological events in the Emirates because of their relation to changes in climate, erosion and deposition processes, whether these processes were the result of more humid or more arid conditions. These changes in sea-level produced various surface levels on the coastal plains of the Emirates, like the 'qurs' or wave-cut platforms, such as those at Khatt in Ras Al Khaimah, occurring in three levels and stretching for up to 9km. in length. The sea-level changes also left behind the raised wadi terraces of the older and more compact Tertiary alluvium into which present-day wadis are cutting their courses.

Equally important are the tectonic movements and the rise of 60m. of the whole mountain block in the last 10,000 years, especially in the limestone massif of Ru’us Al Jibal and the ophiolite block of Al Shumailiyyah Mountains overlooking the east coast, that has left a series of raised beaches seen clearly between Fujairah and Dhahnanah (Vita-Vinzi, 1973).

Apart from these levels on dry land, scientists have distinguished six different levels or steps on the Gulf sea-floor below present-day sea-level. The inundation of a gently sloping sea-floor, and the subsequent retreat of the sea, has given rise to the coastal sabkhas. It also explains the origin of inland sabkhas or seihs in the extreme southeast of the Emirates, such as the sabkhas of Um Ez Zemool and Um Assameem (the latter is in Omani territory), which are relics of a surface once covered by an extensive ancient sea. This agrees with the view that relates these internal sabkhas to a former high sea-level (Lees, 1928; Holme, 1960; Glennie, 1970), before they were separated topographically from the shoreline by sand dunes and sand sheets during the gradual retreat of the sea.

74
2.3. **TOPOGRAPHY**

2.3.1. **General**

Mountain and plain relief characterizes the topography, particularly in the Northern Emirates. To the west and south of the western piedmont plains, in nearly the whole area of Abu Dhabi emirate, is a vast expanse of flat to slightly undulating desert as far west as Sabkhat Matti and south, beyond the Liwa oases, merging with the 'sand sea' of the Empty Quarter. The mountains, covering only 8% of the total land area of the Emirates, occupy a narrow zone in the north-eastern part of the country, while the remaining 92% is occupied by a desert of sand dunes interspersed with gravel and sabkha (playa) tracts. The mountains trend generally N-S with a NW-SE axis in their southern part to the east of Al Ain. They form the northern extremity of the Oman Mountain chain.

Within the Emirates, the mountains are dissected by two main structural fault lines: the Dibba-Idhn and the Ham-Masafi. The eastern flank of the mountains is close to the sea and the coastal strip, described in this study as the 'Eastern Gravel Plains', is narrow, varying in width from 1 to 5 km., and consists of a series of alluvial-filled embayments separated by rocky promontories.

The lowland to the west of the mountains, on the other hand, grades from nearly flat alluvial piedmont plains immediately to the west of the mountains, to the undulating sand dunes of the desert foreland, which are of limited extent in the Northern Emirates but are extensive to the west and southwest of Al Ain, to low coastal dunes and finally to a sabkha littoral.

Both the highland and lowland zones need to be subdivided and described so that locations of significance for water resources can be identified. The mountains, the piedmont plains on either side of them, and the desert foreland are potentially important groundwater resource areas, but both littorals are only included in the present description in the appropriate sections for completeness as they are areas of natural outflow of groundwater through seepage and evaporation.
The landforms of the hardrock catchment areas, and those of the alluvial and aeolian deposits in the different topographic regions, are described here to highlight their role as transmitting mediums of recharge water from direct rainfall and runoff. These landforms may be in the form of barren catchments, wadi terraces and flood plains, piedmont outwash fans and wadi channels as well as desert foreland sand dunes, which in the south and southeast of the Emirates, attain heights exceeding 200m. and form important sources of fresh groundwater in the desert heartland of Abu Dhabi.

2.3.2. Topographic divisions

2.3.2.1. The Highland Zone (Fig. 2.12)

The total length of the highland zone, which lies wholly within the Northern Emirates, is 150 km. from the extreme northern point in Jabal Assadmah north of Wadi Tayyebat, across the limestone mountains of Ru’us Al Jibal, through the hills of the Dibba Corridor and the Central Mountains south of them, to the vicinity of Hatta near the Omani border at Hadf. It reaches a maximum width of 35 km. in the east-west axis of Masfut but has an average width of 25-30 km. to the east of Al Dhaid. The total area of the mountain zone, which contains the 27 wadi catchments, is 2,750 km².

The highland zone can be subdivided as follows:

1) The Hajar limestone mountains of Ru’us Al Jibal (M-1, Fig.2.12)

2) The Dibba Corridor (Hills of Hawasina volcanics, metamorphics, limestones and dolomites) (M-2, Fig. 2.12).

3) The Central Ophiolite Mountains, which can be subdivided into the following two sections:

   a) The peridotite section in the west, north and northwest. (M-3A, Fig. 2.12).
Topographical subdivisions of the Highland Zone: The limestone mountains of Ru’us Al Jibal (M-1) to the north of the metamorphic and volcanic hills of the Dibba Corridor (M-2) and the ultrabasic peridotite (M-3A) and basic gabbro (M-3B) sections of the ophiolite Central Mountains.

Also shown are the topographical subdivisions of the Lowland Zone of the northern part (G-1A), the central part (G-1B) and the southern (G-1C) of the Western Piedmont Plains; and the Eastern Piedmont Plains of the east (Batinah) coast (G-2).
b) The gabbro section in the centre, south and east.
(M-3B, Fig. 2.12).

2.3.2.1.1. The Hajar limestone mountains of Ru‘us Al Jibal (M-1, in Fig. 2.12)

The larger part of this mountain block lies within Oman and only a 15 km. stretch is within the Emirates to the west of the common border. The southern part of the limestone block, immediately to the north of the Dibba Corridor, is about 24 km. across between Habhab in the west and Wadi Khabb in the east. Peaks in the northern part of Ru‘us Al Jibal are above 1500m., such as Jabal Rahbah (1500m.) and Jabal Yabir (1527m.), while peaks in the southern parts, such as Jabal Qamar (556m.) to the east of Idhn are much lower. Wadis are steep-sided with broad floors. The smaller wadis, such as Wadi Sha‘am (8km.long), vary in length from 8 to 16 km.; the larger wadis, such as Wadi Al Beeh (47km.long) and Wadi Tuwaiyyain (37km.long), vary in length from 16-47 km..

2.3.2.1.2. The Dibba-Idhn Corridor (M-2 in Fig. 2.12)

Intense faulting has given rise to jagged relief in all the volcanic and metamorphic rock types, which form the geology of this intermediate part of the highland. Elevations are much lower than those of Ru‘us Al Jibal to the north or the Central Mountains to the south, and average 200-600m. The ‘Corridor’ is in essence a hilly region of complex and varied geology and relief in its upper half, but is a flat flood plain in its lower half. It is about 20 km. wide and 30 km. long.

Wadi Al Baseerah occupies the lower north-eastern part between Hawasina volcanics and metamorphics in the west and northwest and the peridotites of the Semail Ophiolite Suite of the Central Mountains in the east and south. The wadi is wide with a near flat flood plain below Qarn Al Rakhrn filled with boulders, cobbles, gravel and coarse sand deposited by the main wadi and its tributaries from the different surrounding rocks. The wide flat wadi floor warrants the description of ‘Seih Dibba’. The Arabic term ‘seih’ is used indiscriminately to describe a wide, flat plain regardless of its location whether it is
in an open desert, piedmont plain or wadi basin such as that of Wadi Al Baseerah. The wadi floor at Addhaba’ah (17 km. upstream from Dibba) is about 2km. wide, but in its lower course, at Waam, Wadi Al Baseerah is 5.5 km. wide.

A main central channel of flow is more distinguishable from measurements of electrical conductivity of groundwater than from actual surface channels of flow. During runoff the wadi floor is braided by numerous central and tributary channels. Tributary wadis flowing from the volcanic and metamorphic highland to the west have cut less ravine-like courses than those tributaries flowing from the ophiolite highland to the east. In the south of the 'corridor' is the elevated mountain basin of 'Asimah-Tayyibah, which is bounded in the north and east by hills of Hawasina metamorphics and in the west and south by hills of peridotites, from which is derived the alluvial fill of the mountain basin.

2.3.2.1.3. The Central Mountains (M-3A and M-3B, Fig. 2.12)

The mountains to the south of the Dibba-Idhn line, as far as the border with Oman at Hadf beyond the Masfut-Hatta mountain basin, are made up of the Semail Ophiolite Suite, which comprises two distinct rock types: (see Figs. 2.7 and 2.12).

3a) The ultrabasic peridotites outcropping in the west, north and northwest (M-3A, Fig 2.12).

3b) The basic gabbros outcropping in the centre, east and south.
(M-3B, Fig. 2.12)

Each of these rock types has an influence on the quality of the waters flowing across them or occurring in their wadi deposits (Chapter 6).

The whole mountain block averages 25km. in width, though in the axis of Filli-Milaha in the south it reaches 40km. in width. It is about 70km. long from Al Khubus near Dibba in the north to Hadf in the extreme south. Regardless of the two different geological halves noted above, this ophiolite mountain block is divided by the major NW-SE Wadi Ham structural fault into two highland relief areas with the
watershed running N-S in the centre of both topographical areas, crossing the fault-line near Masafi between the sources of Wadi Ham and Wadi Siji.

Apart from the middle and lower courses of Wadi Al Baseerah and Wadi Ham, wadis flowing westwards from this ophiolite zone have broader wadi basins than those wadis flowing eastwards. Of the wadis flowing to the west, the main ones are Wadi Siji, Wadi Sfini-Ashwani, Wadi Al Dhaid and Wadi Shawkah. Of those wadis flowing to the east, the main ones are Wadi Ham, Wadi Al Wurai'ah (Al Shamah), Wadi Madhah, Wadi Zikt and Wadi Al Baseerah.

Elevations are relatively lower than those of the Hajar carbonate mountains to the north, but higher than those of the hills of the Dibba Corridor immediately to the north of this ophiolite highland block. The general range of the elevation is between 700-1200m. Summits in the northern peridotite half of the block range between 730m. and 880m., with Jabal Samah reaching a peak of 1034m. In the central parts elevations are between 817m. and 992m.; while in the southern parts, in gabbro outcrops, the general elevation is much lower, ranging between 316m. and 680m. but with isolated peaks, like those of Jabal Da'ad and Jabal Masafi, reaching heights of 1018m. and 1153m. respectively.

2.3.2.2. The Geomorphology of the highland zone.

2.3.2.2.1. Mountain slopes

There are marked differences in the geomorphological features between the limestone (Ru‘us Al Jibal), the metamorphic (Dibba Corridor) and the ophiolite (Central Mountains) sections of the highland zone. In Ru‘us Al Jibal, where lithologies are either of limestone, dolomitic limestone or sandstone, the summits are generally flat as a result of the slightly tilted horizontal sedimentary strata. Wadi sides stand vertically with overhanging upper parts, which detach in large blocks, a process facilitated by the bedding planes common to limestone and sandstone geology, as can be observed on the sides of Wadi Al Beeh and Wadi Ghaleelah. The limestone helps to absorb water rather than allow it to overflow its sides or slopes, and the detachment of large parts
of the cliffs of the wadi sides by rockfall is more widespread than the development of cones of scree.

In the impervious ophiolite rocks of the Central Mountains the basic gabbros and the ultrabasic peridotites appear to give rise to two different surfaces. While the basic gabbros give rise to rounded summits, covered with a veneer of darkened weathered debris, and rounded wadi catchments (Wadi Al Wurai'ah, Wadi Madhah and Wadi Zikt); the ultrabasic peridotites give rise to sharp summits and rectangular watersheds (Wadi Siji, Wadi Idhn, Wadi Khabb and Wadi Ashwani). Slopes are steeper in the peridotite highland (40°-60°) than in that of the gabbro (40°-45°).

Although both rock types in the ophiolite section of the highland zone are resistant to weathering, they are deeply incised by wadis the courses of which follow fissures, which in some areas are filled with granite dykes as in the northeast between Wadi Zikt and Wadi Al Wurai'ah. The intensive dissection by the main wadis and their tributaries has given the Central Mountains the appearance of a 'badland' landscape, but of hard rock. Peridotite appears to be relatively more susceptible to weathering than gabbro as evident in the amount of scree on either side of wadis traversing hardrock areas of the former. Equally susceptible are the metamorphosed rocks of the Dibba Corridor which are intruded with schist and similar constituents that form points of weakness reacted upon by chemical weathering.

As running water is a rarity in the Emirates, subaerial weathering assumes great importance in the preparation of the disintegrated debris, which collects as scree on wadi sides and is eventually transported by a subsequent flood. Floods, though occurring on average once a year or two years, have a greater impact on the landscape than subaerial weathering by the volume of sediments they transport and continually unload on wadi flood plains, outwash fans and piedmont plains. Such rock material, held in suspension by the flood waters, are estimated to make up between 0.5-3.6% of the total volume of flood water (FAO, MAF, Halcrow (1982)).
2.3.2.2.2. **Mountain wadis**

Most of the courses of wadis are in barren highland in steep-sided ravine-like channels. In their middle courses and part of the lower, wadis are incised in old compact gravel with gorge-like vertical sides, which in some cases, as in Wadi Al Baseerah (Al Shimal), are about 60m high. The gradients of wadi profiles vary from 0.5 to 4.0% and gradients for the lower courses of wadis are about 1% (Figs. 2.13 and 2.14).

There is great variation in the geomorphology from wadi to wadi in the same rock type or in other parts with different rock types. Wadis of the eastern side of the ophiolite Central Mountains have steeper gradients than those flowing westwards. On the whole, there are more wadis on the eastern side with total lengths of between 10-30km. than on the western side, where the bulk of the wadis are with total lengths of 10-20km. each.

Figs. 2.13 A-B and 2.14 A-B present the long profiles of Wadi Naqab in the limestones of Ru’us Al Jibal, Wadi Al Fayy in the metamorphics and volcanics of the Dibba Corridor, the east-flowing Wadi Al Wurai‘ah and the west-flowing Wadi Ashwani in the ophiolites of the Central Mountains. The long profile for Wadi Al Naqab is typical of wadis in the limestone highland. It is steep in its upper course and the whole profile drops 580m. in 18km. It is the steepest among the four profiles shown in the diagrams in the two figures (with a gradient of 3%). The profile for Wadi Al Fayy, a main tributary of Wadi Al Baseerah, shows a slightly irregular but symmetrical profile, and the drop in level, between the source of the wadi and the outfall on the coast, a distance of 18 km., is 220m. (gradient of 1%). The profiles for Wadi Al Wurai‘ah and Wadi Ashwani appear to be similar, except for the steep part in the upper reaches of Wadi Al Wurai‘ah. Both the east-flowing Wadi Al Wurai‘ah and the west-flowing Wadi Ashwani drop in similarly gentle and uniform profiles: Wadi Al Wurai‘ah drops 380m. in 30kms. (a gradient of 1%); Wadi Ashwani drops 300m. in 22kms. (a gradient of 1%). Thus, apart from Wadi Naqab, all the wadis have similar very gentle gradients.
Figure: 2.13. (A and B)

Long wadi profiles of Wadi Al Naqab in the limestone highland of Ru'us Al Jibal (A) and Wadi Al Fayy, the main tributary of Wadi Al Baseerah, in the metamorphic-volcanic Dibba Corridor.

The long profile for Wadi Al Naqab is typical of wadis in limestone upland characterized by a steep upper course. The wadi drops 580m. in 18km. (a gradient of 3%). It is the steepest wadi profile among the 4 profiles shown in both Figs. 2.13.(A and B) and 2.14.(A and B).

The long profile for Wadi Al Fayy is slightly irregular but is generally symmetrical; the wadi drops 220m. in 18km. (a gradient of 1%).
Long wadi profiles of Wadi Al Wurai'ah (A) and Wadi Ashwani (B) in the ophiolite central mountains.

Both the east-flowing Wadi Al Wurai'ah and the west-flowing Wadi Ashwani have gentle and uniform profiles: Wadi Al Wurai'ah drops 380m. in 30km. (a gradient of 1%); Wadi Ashwani drops 300m. in 22km. (a gradient of 1%).
The lower courses of all the wadis that flow westwards from the Central Mountains into the western piedmont plains, collect into the two main flow channels of Wadi Yadai’ah-Sumaini and Wadi Lamhah, both of which possess gentle gradients averaging 0.1%. Sediments carried by the wadis start settling in their middle courses where they help to slow down flood flows considerably. The lower courses of wadis are largely in the coalesced outwash fans that form the western piedmont plains, or in single outwash fans making the embayments on the east (Batinah) coast. In either case wadi flows fan out in braided channels, a few of which actually maintain overland flow beyond the western edge of the piedmont plains (10-15km. from the mountain front) or retain their identity in clearly identifiable wadi courses.

Tertiary boulders, cobbles, gravel and sand of varying sizes and composition, held by a matrix of calcareous fines, stand as raised terraces that once made up the old wadi flood plain. This has been cut into by existing rejuvenated wadis as a result of the tectonic rise of the land by 60m. during the Holocene (Section 2.2.8.). Such incisions into old wadi deposits are found in Wadi Al Wurai’ah and wadi Ham among the east-flowing wadis, and in Wadi Sfini and Siji among the west-flowing wadis. These terraces stand generally at levels of between 10–40m. in Wadi Al Wurai’ah in the east, but are between 11–23m. in Wadi Sfini in the west.

There are generally two levels of wadi terraces, an older terrace where the boulders are large and compact, and an upper younger terrace of gravels of smaller size, which are less compact. Both can hold groundwater but with varying productivity and quality as discussed for Wadi Al Baseerah in Chapter 5, Section 5.3.2.5.1.2.2; and Chapter 6, Section 6.5.2.5.3.

Drainage in the highland zone is closely related to geology. Large wadis, such as Wadi Ham, Wadi Al Baseerah and Wadi Al Munai’ee, and also most of the smaller wadis and their tributaries, follow structural lines and the drainage is superimposed, with active erosion taking place causing the recession of wadi sources. The sources of Wadi Ham and Wadi Siji are only a short distance apart at Masafi where Wadi Ham is in the process of capturing Wadi Siji. A similar situation
exists between Wadi Hatta and Wadi Humfariyyah-Yudai’ah in the south in favour of Wadi Hatta.

2.3.3. The Lowland Zone (Fig. 2.15)

The important areas with regard to groundwater transmission and storage in the lowland zone are the piedmont (gravel) plains, on either side of the highland, and the desert foreland. Both regions receive recharge from direct rainfall through their highly permeable alluvial and aeolian landforms, but recharge from runoff mostly infiltrates into the former (the piedmont plains) and is transmitted as underflow into the latter (the desert foreland).

The Sabkhas of both the eastern and western littorals are related to groundwater resources by being areas of natural discharge through evaporation and outflow to the sea. Neither the volume of water discharged in the coastal sabkhas, nor the sabkha soils are favourable for any exploitation of the water. Furthermore, fresh water mixes with seawater rendering sabkha waters extremely saline. However, the emphasis in this discussion of the key landscape elements is on the alluvial piedmont plains, wadis, and the aeolian dune sands as the important desert landscape features in relation to groundwater. The sand dunes have been least attended to by previous studies, and their contribution to groundwater has either been ignored or underestimated.

In the alluvial areas there are the western (sometimes called central) and the eastern, piedmont (gravel) plains. The former are wide plains that grade into the desert foreland, which offers a vast groundwater storage capability. The latter are narrow plains, occurring in limited embayments that are unable to sustain all their input from recharge, thus allowing some of the groundwater to escape to the sea as overland (during floods) or subterranean (all the year round) flow.

In the desert foreland, areas of low, high and giant dunes are important sources of fresh to marginal groundwater. The higher the dune is, the better are the chances of a thick fresh water-bearing layer occurring in it. Inland sabkhas occur everywhere, interspersing all types of dunes, and providing points where brackish to supersaline groundwater is near or at the surface, as in the Liwa troughs.
The lowland zone can be subdivided as follows: (Fig. 2.15)

1) **The piedmont (gravel) plains** (G1 and G2 in Fig. 2.15)
   i) The eastern piedmont plains (Al Batinah coast) (G-2, Figs. 2.12 and 2.15.)
   (ii) The western piedmont plains (G-1A, G-1B and G-1C, Fig. 2.12)
       (which include the northern (Hamraniyyah), the central (Al Dhaid) and the southern (Al Jaww in Al Ain) sections).

2) **The desert foreland** (D-1, D-2 and D-3 in Fig. 2.15)
   (which includes areas of low, high and giant dunes).

2.3.3.1. **The eastern piedmont plains (Al Batinah coast)**
   (G-2, Fig. 2.12).

The eastern piedmont plains are not only limited in extent by nearness to the shoreline, but also by a sabkha littoral, especially in the stretch of the coastline between Kalba and Khorfakkan. With the exception of the outwash fan of Wadi Ham at Fujairah and the outwash fans of Wadi Al Wurai‘ah at Badyah-Zubarah, Wadi Zikt at Dhadhnah and Wadi Al Baseerah at Dibba, all wadis have direct outflow to the Gulf of Oman. Of these, Wadi Al Wurai‘ah recorded the largest volume of 18,740 m$^3$/d in 1980 (Lavalin, 1980). The larger outwash fans, such as that of Wadi Al Baseerah, absorb most of the surface runoff, as evident by their low runoff coefficient (Chapter 4). Wadi gradients in general are gentle; the slope at Seih Dibba is about 1%.

2.3.3.2. **The western piedmont plains** (G-1 A to C in Fig. 2.12)

The western piedmont plains are essentially a series of alluvial outwash fans formed by the wadis that debouch from the mountains to the east and deposit their sediments of boulder, cobbles, gravel and sand. These outwash fans have coalesced to form the flat piedmont plains extending westwards for 15-20km. from the mountain front.
Topographical subdivisions of the Lowland Zone: the Desert Foreland; on the basis of sand-dune height:

D-1 = Low sand dunes of below 100m. in height interspersed with gravel floor.
D-2 = High sand dunes of 100-200m. interspersed with inland sabkhas or 'seihs'.
D-3 = Giant sand dunes of more than 200m. in height interspersed with inland sabkhas.

The higher the dune, the larger is the recharge potential of fresh groundwater storage as in the Al Qafa region north of Liwa (D-3).
The western piedmont plains are recognized as subplains by local names. These are, from north to south:

a) Al Seer Plain at Shamal (in Ras Al Khaimah)
b) Al Jiri Plain around Digdaga and Hamraniyyah (in Ras Al Khaimah)
c) Al Dhaid Plain around Dhaid (in Sharjah)
d) Al Ghareef Plain around Filli (in Sharjah)
e) Al Madam Plain of Madam-Shuwaib-Mahdhah (Sharjah, Dubai, Abu Dhabi and Oman).
f) Al Jaww Plain east of Al Ain (Abu Dhabi)

The plains are narrow in the north, where in Al Seer and Al Jiri subplains they are between 5-10km. wide; while in Al Dhaid-Ghareef-Madam subplains they are 15-20km. wide. Gradients can be monotonously near flat; the slope across the Al Dhaid subplain, between the foothills in the east and the dunes in the west, being only 50m. in 16km. or 0.3%.

Al Jaww subplain in Al Ain is about 20 X 20 km. in area. There are two different slopes, one to the north and the other to the south, separated by an E-W trending long col in the centre. Hence the flow of Wadi Al Ain is to the north-west towards Al Ain and that of Wadi Shik towards Mazyad in the southwest.

The drainage of the wadis in the plains is basically internal. After crossing the plains in a westerly direction, the wadis then change course to a northerly direction guided in this by the dune barrier on the western fringe of the plains. There are the two main wadi channels, Lamhah and Yudai‘ah-Sumaini, into which flow all the west flowing wadis. While Wadi Lamhah does reach the coast through Bathat Al Ali in years of exceptionally high rainfall, Wadi Yudai‘ah, even in years of exceptional rainfall, never reaches the sea despite its longer course and larger surface-flow collecting capacity. It loses its way in Bathat Mussannad near Saja‘ah in Sharjah, where a large lake develops for a few weeks after the rains have ended, drying up to leave behind a 20-30cm. veneer of fines (e.g. after the February 1988 rains). Bathat Mussannad is a large inland sabkha.
2.3.3.3. **The desert foreland** (D-1, D-2 and D-3 in Fig. 2.15)

The desert foreland covers 70% of the total land area of the Emirates, extending into the Rub' Al Khali (Empty Quarter) in the southeast and into eastern Saudi Arabia in the west, southwest and south. The main topographic characteristics are the low altitude ranging between 100-300m. above mean sea level and the fact that the landforms are aeolian. The only exceptions are a number of limestone/sandstone hillocks or 'qurun' (sing. 'qarn', meaning hill in Arabic) such as those of Qarn Bint Sa'ud (325m.) and Qarn Sa'abah (298m.), both north of Al Ain, and Qarn Nazwa (238m.) in southern Dubai emirate.

Apart from these eminences of hardrock, the whole vast expanse to the west, south and southwest of the piedmont plains is an undulating desert with elevations rising from 10-30m. in the coastal dunes to about 150-200m. in Al Khatm, Manader Arrabbadh and Al Hamrah. In the deep interior of the desert foreland in the south, the dunes reach their highest, in excess of 250m. in Al Qafa in Liwa. In the extreme west of the Emirates, extending beyond the international border into Saudi Arabia, is the largest continuous inland sabkha in eastern Arabia, Sabkhat Matti of Al Majn. In Al Bateen, or the "depression" south of the Liwa arc of oases, ground surface elevations are 75-100m. while in Al Dhafrah 'plateau' to the north of the Liwa arc, surface elevations are between 150-200m.

The landscape of the desert foreland is characterized by the alternating dune-and-deflation basin (sabkha) topography. The deflation basins are inland sabkhas with actively forming muddy evaporites, continually being resurfaced by thin sheets of wind-blown sand. The dunes assume importance from the point of view of groundwater in that they are sand aquifers of fresh water, which effectively floats on the saline waters of the underlying sabkha (Chapters 5 and 6). The sabkhas are normally elongated in shape though some are sufficiently extensive to deserve the local description of seih. The seihes of Al Khatm, Al Rabbadh, and those to the southwest of Al Ain, as well as the 'troughs' of Liwa, are all low-lying flat inland sabkhas (playas) containing brackish to supersaline groundwater near or at the surface. The desert foreland can be subdivided into three areas on the basis of sand-dune form and height:
1) **Low dunes, sabkha and gravel desert floor (of below 100m. height) zone:** (D-1 in Fig. 2.15)

This is the most extensive of the three types of desert topography, stretching from Digdaga in Ras Al Khaimah in the Northern Emirates across Al Khatm, Addhafran, Bida’ Al ‘Areedh, and Ghayathy as far as Al Maghreb in the extreme west of the country for a distance of 450km.; and is 60-70km. wide. Sand dune heights range from 50-100m. with some of the elongated dunes reaching heights of 120m., separated by sabkhas or seihs 1-5km. across. The main seihs in this zone are Seih Maida’ah, Seih Bu Muraikha and Seih Al Reef and all the seihs of southwest Al Ain, such as Seih Gharabah, Seih Al Miyah and Seih Shabak and also those in Al Khatm between Abu Dhabi and Al Ain, such as Seih Busitmah, Seih Bu Hafeefah, Seih Haleebah, Seih Thaqeebah and Seih A’ttagah.

In the Northern Emirates, the dunes between Falah and Al Dhaid, and those of Al Aweer, Sirrah and Minhad, lie within this zone. The main inland sabkhas in the Northern Emirates are those of Seih Mussannad, Bathat Al Ali and Seih Al Fahlain. Dunes and sabkhas, such as those of Seih Shu’aib and Seih Al Reef near the Abu Dhabi-Dubai interemirate border, run for many kilometres inland.

2) **The High dune (100-150m.) and sabkha zone** (D-2 in Fig. 2.15)

This is the zone of high dunes of up to 150m., which occupies the south central part of the desert foreland in Al Dhafrah and Manader Arrabbadh proper, where the zone reaches its widest extent of 110km. The zone stretches north of Al Qafa in Liwa to Al ‘Ajeer (to the south of Al Ain) and then along the common border with Oman down to Al Wagn. The alternating elongated dune-and-sabkha (seih) topography is dominant. The important sabkhas here are Seih Al Ruqai’at and Seih Fai’ah. The dunes rise up to 50-75m. from the surface of the sabkhas. The sabkhas are extensive and are covered with sand ripples. They are locally called ‘sawareeq’ (Arabic sing. = sarooq, meaning a sabkha with a thin veneer of rippled sand).
3) The giant dune (up to 250m) and sabkha zone (D-3 in Fig. 2.15)

This sand dune zone is in the southern and southeastern parts of the desert foreland encompassing the whole of Liwa, Al Qafa to the north, and Al Bateen to the south, of Liwa, where the zone is at its widest (55km.). It stretches as far as Um ez Zemool on the border with Oman, and then northwards in a stretch 30km. wide west of the border with Oman as far north as Al Wagn. The dunes reach heights of 200m. in Shah and Al Bateen, and exceed 250m. in Al Qafa and Qasyoorah. In the southeast, from the easternmost tip of Eastern Liwa to 'Uruq Ashaibah; and in the southwest, from the westernmost extremity of Western Liwa at Shuduq Al Jawwan in 'Aradah, to the Saudi border, the whole area is a continuous 'sand-sea' region of giant dunes. In all the dunes here, and also the high dune area to the north (No. 2 (D-2) in this section), there are fresh water reservoirs. There is a particular concentration of fresh groundwater in a zone in Al Qafa proper (dealt with in detail in Chapters 5, Section 5.3.2.4.3.4; and Chapter 6, Section 6.5.3.6).

2.3.4. Geomorphology of the desert foreland

Fluvial action is largely responsible for the formation of the piedmont alluvial plains by the deposition of gravel and sand eroded from the hardrock catchment areas. Wind, on the other hand, is the chief architect responsible for the details of the aeolian landforms of the desert foreland, the types and geographical extent of which have been outlined in the preceding subsections. Wind activity is facilitated by a mean annual rainfall for the desert foreland of 91.71mm. (period mean, see Chapter 3), potential evaporation rates exceeding the annual mean rainfall by more than 25 times, the lack of a continuous vegetation cover and strong winds all the year round with little impediment to their movement. The wind action involves abrasion, deflation, transportation and accumulation of sediments ranging from small grits and sand to silt and clay fines.

The dominant aeolian landform in the desert foreland of the Emirates is the continental dune, which occurs in various forms, together with
sand sheets or sheet beds laid down over the sabkha surface between the dunes. All forms of sand dunes: straight; accumulative; irregular; oval; crescent-shaped (barchan); star-shaped; complex; multi-directional and flat-topped, are represented in the desert foreland of the Emirates. Within this variety in dune types, the crescent-shaped barchan (or barkhan) dune is the dominant land form. It is locally known in Arabic as ‘Al naqa’ (pl. Al anqa).

The barchan occurs in two main types: a) the single or isolated naqa and, b) the compound or complex anqa. The single type is widespread in the northern parts of the desert foreland of Abu Dhabi south of Al Taff, getting denser and larger towards Addhafrah and Liwa in the southern and east central parts. The orientation of the dune clearly indicates the prevailing direction of the winds (from the north and northwest). The windward side, which is known as ‘Al Qafa’, points towards the north and northwest. The leeward side, which is known as ‘Al Hayl’, dips at 30°.

The second type of barchan, the complex type, is found in marked concentration in the southeast, in Liwa and Ramlat Zararah, where the dunes merge into the vast sand-sea of the Empty Quarter. The dunes here develop in clusters or chains collectively called ‘Addamghah’ or ‘Al Zumool’. Hence the name of the border village of Um ez Zumool (the village of the giant dunes).

Dunes amalgamating diagonal to the direction of the wind, with smaller dunes climbing over larger ones forming a cluster, are locally known as ‘digdaga’. Some dunes join laterally as well as axially in all directions, giving an outline of sharp crescents, fully joined arcs and hollows between them. These hollows are called ‘ghuroofah’ (sing. ghareef) if they are small, and ‘al batn’ or ‘al bateen’, if they are large. The area enclosed by the Liwa arc of oases, in which are located the series of the troughs of the Liwa oases, is known as Al Bateen. When the ‘ghareef’ takes a longitudinal shape, it is known as ‘al dakhlah’ (the ‘entrance’ or the ‘pass’), and when it is oval in shape, it is called ‘al sahn’ (the plate).

Longitudinal dunes, regardless of size, are known by several local names, such as ‘al hibal’, ‘al hafeef’, ‘al dira’, ‘al silsila’, ‘al...
saif', 'al taweel' and 'al 'irq', all of which describe the thread-like form. The 'irq' dune (pl. 'uruq') can develop in complicated formations joining together in a chain up to 50km. long and assuming heights of up to 50m. in the Northern Emirates and Al Khatm, and to more than 100m. in height in Um ez Zemool.

2.4. **SOILS**

2.4.1. **Introduction**

The aridity, high temperatures and the unstable nature of the deposits (because of continued wind action) have led to the mechanical disintegration of desert material. These physical factors combine to limit the development of soils in the arid environment of the Emirates ensuring their azonal state.

According to Aubert (1962) soils of the arid environment can be divided into two groups: soils of deflation and soils of deposition. The former are soils from which the finer material has been blown away to other locations, such as the soils of the hardrock (catchment) areas of the Northern Emirates and the carbonate anticlinal ridges of Hafeet-Fayah-Mileiha as well as the piedmont plains (the gravel plains) on either side of the highland. The latter, are soils that have been deposited by wind and running water and these form the aeolian and fluviatile soils of the vast desert foreland of the Emirates. Soils deposited by wind include the sands of the dunes of all forms and sizes and also the veneer, which covers the fringes of the piedmont plains and wadi courses that reach out to the desert foreland from the mountains; those deposited by running water include the equally dominant desert foreland feature, the sabkhas (seihs) or playas. Whereas the sands of the dunes are highly permeable and demonstrate the highest infiltration rates of any soil type in the Emirates, the sabkhas are of extremely low permeability. In all cases, therefore, the soils are more geologic (inorganic) than biologic (organic) in nature.

Soils are discussed in the present study with regard to their mechanical and chemical composition, especially their porosity as
governed by their content of coarse material and salt, and the effect these have on groundwater during recharge or residence. Interest is focused on azonal soils rather than those under cultivation although some reference is given to the increasing salinity in the latter soils caused by a few seasons of cultivation. Salts accumulated in cultivated soils are eventually leached down by both rain and irrigation water into the groundwater system.

Recharge takes place through all kinds of soil. Whether natural recharge from direct rainfall over all the terrains, or from surface runoff limited to wadi channels, their outwash fans or the open piedmont plains in parent deposits, or these two methods of recharge plus irrigation water return through reclaimed and cultivated soil, the factor of salinity of these soils as a medium through which recharge is taking place, is important and should be taken seriously in the existing situation of depleting groundwater resources. Hence the discussion of this physical aspect that directly relates to water.

2.4.2. Soil characteristics

The soils of the Emirates may be broadly classified, according to their extent of occurrence, into the following three types:

i) Aeolian coarse, medium and fine sands in the dunes and sand sheets.

ii) Wadi floor/terrace, outwash fan and piedmont plains cobbles, gravels and sand.

iii) Mud, clay, silt and fine sand of the inland sabkhas.

Soil samples were collected for the present study from various locations in the above rock types and analyzed for their mechanical and chemical composition and the results have been used in the descriptions in this section.
2.4.3. **Mechanical Characteristics of the soils of the Emirates**

2.4.3.1. **Soils of the mountain wadis, outwash fans and piedmont plains: the main groundwater recharge areas.**

The soils in these areas of groundwater recharge are virtually unmodified alluvial deposits of Quaternary materials washed down continually by floods and reflect the geological rock types that form the wadi catchment. The material consists of sub-angular and/or sub-rounded cobbles and gravels and sand. Being continually added to with fresh or reworked material by floods, these soils exhibit no features of pedogenesis. They are virgin and in the active wadi channel (i.e. experiencing frequent flows during floods) they are unstable due to continual shifting of the upper layers by flood flows. The only differentiation in their 'profile' is in the form of platiness denoting deposition of material of finer texture.

Textures generally range from pure cobbles and gravels (of between 2.0 to 75.0mm. diameter) on the surface of the active wadi channel and in most of the flood plain to a depth of 50cm. or even 100 cm., to mainly sandy and loamy sand textures (of sand particles of less than 2.0mm. in diameter). On the fringes of the flood plain and in those parts between the braided wadi channels on the piedmont plains and outwash fans, the sand content becomes higher and the soils range from sandy loams to loamy sands to coarse unsorted sand towards the desert foreland.

If the 2.0mm. particle size is considered, then coarse sand is the dominant constituent, which is modified in scattered patches especially in shallow depressions where flood waters stagnate, by variable amounts of clay, silt and fine sand. The unstable material of the active wadi channel ranges from medium/coarse sand to gravel and cobbles of large sizes. Because of the amount of sand, which increases downstream, slight stratification occurs, especially below 50cm. Stratification, though not strictly the horizons of developed soils, increases away from the active wadi channel. These strata are made up of fine silt, sand and clay but also of calcareous material (CaCO₃) washed down from the surface by successive floods. Such calcium carbonate strata are neither thick nor totally impermeable to impede
vertical infiltration.

Cobbles and gravel content in the mountain wadis, outwash fans and the piedmont plains is visually high. The higher the content of these large constituents, the greater is the porosity of the deposits through which recharge is taking place. To determine the volume of the various particles making up the soil, by percentage, the content from a pit 25cm. X 25cm. X 25cm. was weighed and then sieved in two stages: a 2-mm. mesh to let through the finer particles, and a 75-mm. mesh to trap the larger boulders, cobbles and gravel. Each of the grades of the deposits was then weighed separately. Table 2.1. gives the percentages of the various particles of a number of pits dug in different locations in the Emirates.

In the piedmont plains (the gravel plains), away from the foothills, sand and silt content increases westwards. Predominantly gravelly soils of the piedmont plains of the heavy texture contain up to 35% silt and 10% sand, as in parts of Hamraniyyah in the Jiri Plain of Ras Al Khaimah. In the light-textured gravelly soils the clay/silt content is 12% and the coarse sand content is high. Gravels are found throughout the soil profile but become more concentrated 50cm. below the surface.

The gravel content at Al Manama, to the east of Al Dhaid, may reach between 50% to 80% of the total volume of the soil (Table 2.3), whereas it is less in Al Dhaid where sandy clay loams characterize the upper layer of the soil profile, becoming sandy loams at 20cm. below the surface. The gravel content dominates the profile below that depth where it forms 60% of the soil volume. North of Al Dhaid, around Tawi Akhai (analysis 2, Table 2.3), the soils were found to contain more sand than those at Al Manama and Al Dhaid. In Falaj Al Mualla the sand content in the soil was 60%, superseding that of gravel (Table 2.1).

In Mileiha, further south, nearness to sand dunes has affected soil composition providing the soils here with a high sand content of up to 70% with the general texture being sandy clay loam (Table 2.3).
Table: 2.1.

The mechanical composition of the different types of soils by weight from pits dug in wadi-piedmont alluvium and sandy-sabkha soils.

Percentage of the mechanical composition of soils by weight from pits excavated in wadi and piedmont plain alluvium, sandy and sabkha locations, to illustrate the ratio of coarse deposits to the total weight of the deposits of the sample. The higher percentage of coarse particles in the soil is in the mountain wadis, outwash fans, piedmont plains and high sand dunes where infiltration is highest.

Table: 2.2.

The increase in soil salinity in the Dibba fruit farm between 1982 and 1989.

The soils of the fruit farm are of the gravally-sandy type, characteristic of the Wadi Al Baseerah flood plain alluvium. Sodium (Na) and chloride (Cl) increased by 4 times between 1982 and 1989, an increase facilitated by the high permeability of the soils of more than 70% gravel content (gravels of sizes of between 0.2-75mm.) in which salts can easily be leached down the soil profile and may even reach the wadi aquifer.
<table>
<thead>
<tr>
<th>Location</th>
<th>Gravel 2.0-75.0mm</th>
<th>Coarse Sand &gt;0.2mm</th>
<th>Fine Sand &lt;0.2mm</th>
<th>Silt</th>
<th>Clay</th>
<th>Carbonate</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEOLIAN SOILS IN THE DESERT FORELAND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Wagn (1)</td>
<td>21.10</td>
<td>41.10</td>
<td>3.80</td>
<td>6.70</td>
<td>27.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Khaznah</td>
<td>42.10</td>
<td>24.30</td>
<td>2.70</td>
<td>1.50</td>
<td>29.40</td>
<td></td>
</tr>
<tr>
<td>Suwaihan</td>
<td>4.60</td>
<td>33.60</td>
<td>16.10</td>
<td>4.30</td>
<td>41.40</td>
<td></td>
</tr>
<tr>
<td>Dhafeer(Liwa)</td>
<td>52.20</td>
<td>41.20</td>
<td>0.0</td>
<td>3.00</td>
<td>3.60</td>
<td></td>
</tr>
<tr>
<td>Qutuf (Liwa)</td>
<td>77.10</td>
<td>18.60</td>
<td>0.0</td>
<td>2.00</td>
<td>2.30</td>
<td></td>
</tr>
<tr>
<td>Hisan (Liwa)</td>
<td>68.80</td>
<td>23.20</td>
<td>2.0</td>
<td>4.00</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>Khanoor(Liwa)</td>
<td>63.20</td>
<td>24.80</td>
<td>6.00</td>
<td>4.00</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>Bida Mubarak(Liwa)</td>
<td>75.00</td>
<td>19.00</td>
<td>0.0</td>
<td>3.00</td>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td>Mariyah (Liwa)</td>
<td>70.00</td>
<td>24.00</td>
<td>0.0</td>
<td>4.00</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>Al Aweer</td>
<td>45.10</td>
<td>38.80</td>
<td>6.10</td>
<td>10.00</td>
<td>36.00</td>
<td></td>
</tr>
<tr>
<td>Khawaneej</td>
<td>40.20</td>
<td>33.20</td>
<td>18.20</td>
<td>8.40</td>
<td>30.60</td>
<td></td>
</tr>
<tr>
<td>ALLUVIAL SOILS IN MOUNTAIN WADIS, OUTWASH FANS AND PIEDMONT PLAINS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Manamah</td>
<td>55.70</td>
<td>42.40</td>
<td>39.30</td>
<td>2.80</td>
<td>15.50</td>
<td>28.40</td>
</tr>
<tr>
<td>Al Dhaid (1)</td>
<td>60.20</td>
<td>53.80</td>
<td>31.20</td>
<td>2.40</td>
<td>13.10</td>
<td>14.10</td>
</tr>
<tr>
<td></td>
<td>(2)</td>
<td>61.70</td>
<td>66.80</td>
<td>19.80</td>
<td>1.60</td>
<td>11.80</td>
</tr>
<tr>
<td>Nebebig</td>
<td>36.00</td>
<td>45.70</td>
<td>38.80</td>
<td>2.20</td>
<td>13.30</td>
<td>21.60</td>
</tr>
<tr>
<td>Wushah</td>
<td>17.00</td>
<td>42.40</td>
<td>42.10</td>
<td>2.10</td>
<td>13.40</td>
<td>17.00</td>
</tr>
<tr>
<td>Miletha</td>
<td>79.10</td>
<td>67.70</td>
<td>11.40</td>
<td>3.40</td>
<td>17.50</td>
<td>32.20</td>
</tr>
<tr>
<td>Al Munai'ee</td>
<td>60.00</td>
<td>55.00</td>
<td>21.00</td>
<td>8.00</td>
<td>16.00</td>
<td>4.13</td>
</tr>
<tr>
<td>Masfut (1)</td>
<td>65.00</td>
<td>60.00</td>
<td>24.00</td>
<td>12.00</td>
<td>4.00</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>(2)</td>
<td>80.00</td>
<td>70.00</td>
<td>20.00</td>
<td>2.00</td>
<td>8.00</td>
</tr>
<tr>
<td>Hamraniyyah</td>
<td>87.00</td>
<td>77.00</td>
<td>17.00</td>
<td>3.50</td>
<td>1.70</td>
<td>9.50</td>
</tr>
<tr>
<td>Dibba(Fruit Farm)</td>
<td>90.00</td>
<td>80.00</td>
<td>17.10</td>
<td>1.00</td>
<td>1.90</td>
<td>7.30</td>
</tr>
<tr>
<td>Sha'arah</td>
<td>92.00</td>
<td>85.00</td>
<td>10.00</td>
<td>4.00</td>
<td>1.00</td>
<td>8.00</td>
</tr>
<tr>
<td>Um Ghafah</td>
<td>85.00</td>
<td>70.00</td>
<td>20.00</td>
<td>2.50</td>
<td>7.50</td>
<td>32.00</td>
</tr>
<tr>
<td>Al Awha</td>
<td>80.00</td>
<td>55.00</td>
<td>25.00</td>
<td>8.00</td>
<td>12.00</td>
<td>35.00</td>
</tr>
<tr>
<td>SABKHA SOILS IN THE DESERT FORELAND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mussannad</td>
<td>-</td>
<td>-</td>
<td>47.00</td>
<td>44.00</td>
<td>6.00</td>
<td>25.80</td>
</tr>
<tr>
<td>Al Khatm</td>
<td>-</td>
<td>-</td>
<td>18.00</td>
<td>50.00</td>
<td>27.00</td>
<td>20.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.00</td>
</tr>
</tbody>
</table>

* Gypsum in the sabkha soils only.
Period of sample collection April-October 1989.

Table: 2.3.

Analysis of the mechanical composition of azonal soils through which recharge from rain and flood water is taking place.

The higher the content of coarse material, the higher is the soil permeability. Such a soil condition is present in the loose alluvium of the active wadi channels. Even such azonal soils develop substantial content of silt and fine sand that forms a film 3-6cm thick in some wadi flood plain and piedmont locations where natural or artificial ponding of flood water occurs, as was observed behind the retention dam on the Wadi Ham flood plain after the floods had receded (1988). Such surficial or subsoil fine deposits hamper infiltration and cause high losses to evaporation from ponded waters.

99
In the southern part of the Ghareef Plain and the whole of Al Madam Plain, gravel content again dominates soils making up between 60% and 80% of the volume (Table 2.1). In the Al Ain region, on the other hand, the gravel and coarse sand content to the west of Jabal Hafeet is lower (35-55%) than that at Um Ghafah in Al Jaww Plain to the east of it (up to 70%). Table 2.3. shows examples of the mechanical composition of wadi, outwash fan and piedmont plains soils.

2.4.3.2. Soils of the desert foreland

The aeolian deposits of the dunes, that cover most of the desert foreland, are uniform medium to fine sands. Nearer the Gulf coast the sands are made up of carbonate grains, and such deposits form the low coastal dunes. Further inland the sands are made up of silica grains and assume a greater thickness, reaching 200m. in the dunes of Liwa. The sands exhibit dune bedding and may rest on the clay and mud of the sabkha underneath (the halosols or saline sabkha soils).

The Sabkha is the depositional soil of the deflation basins interspacing all types of sand dunes in the desert foreland. It has developed fine textured sediments, mostly of clay. Because they are associated with high water-tables that are near or at ground surface, the sabkha soils are continuously water-logged. Besides their being saturated, their compact clayey textures render them of poor permeability. The surface is usually made up of a salt-gypsum crust, which may extend down to 20cm. A typical sabkha soil profile at Seih Mussannad is given in Table 2.4.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10 cm.</td>
<td>Loose salt puff</td>
</tr>
<tr>
<td>10-20 cm.</td>
<td>Gypsum and silt</td>
</tr>
<tr>
<td>20-25 cm.</td>
<td>Light brown silty clay</td>
</tr>
<tr>
<td>25-50 cm.</td>
<td>Brown loam</td>
</tr>
<tr>
<td>50-120 cm.</td>
<td>Silty clay with fine sand at the bottom</td>
</tr>
<tr>
<td>120 cm. +</td>
<td>Fine sand</td>
</tr>
</tbody>
</table>

Table: 2.4.
A typical sabkha soil profile at Seih (Sabkhat) Mussannad in Sharjah.
2.4.3.3. Other fine alluvial soils

These are pockets of silty outwash soils, either surficial or in places relatively deep, and made up of fine textured soil occupying shallow deflation basins or old wadi channels. These soil patches are found in mountain wadi flood plains or in the more extensive piedmont plains on either side of the mountains. The fine material of these deposits is of aeolian or fluviatile origin. The composition is characterized by up to 50mm. thickness of fines (silt, clay and fine sand). Such pockets of fine soil are also found behind retention dams and are exposed after the impounded flood waters have dried up, as well as at various isolated localities in the flood plains of mountain wadis and in the piedmont plains, rendering the patches in which they occur of extremely low permeability as proved by infiltration tests (see section 2.4.5.). A typical soil profile of this type of deposit is given in Table 2.5.

Table 2.5.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>Light brown fine sand, finely laminated</td>
</tr>
<tr>
<td>5-10</td>
<td>Silty fine sand with laminations of silt</td>
</tr>
<tr>
<td>10-15</td>
<td>Silty loam with medium grain sand</td>
</tr>
<tr>
<td>15-20</td>
<td>Medium grain sand with silt and grit</td>
</tr>
<tr>
<td>20+</td>
<td>Gravel and coarse sand of the wadi flood plain</td>
</tr>
</tbody>
</table>

A typical soil profile of the fine alluvial deposits in the flood plain of Wadi Al Baseerah.

2.4.4. Chemical composition of soils

An examination of the chemical analyses of soil paste extract, presented in Table 2.6, reveals the following salient characteristics:

1) Most of the desert foreland aeolian soils, which contain small amounts of clay, are non-saline non-sodic (i.e., with low total dissolved solids and exchangeable sodium of less than 15.00 meq/l)
2) Soils in the clayey sabkhas, or those containing a reasonable percentage of silt and clay (10-20%), as at Al Wagn (sample 1, Table 2.3.), are saline sodic (i.e., with exchangeable sodium content of more than 15.00 meq/l. and electrical conductivity values of over 4000 mmhos/cm).

3) The total salinity (the total dissolved solids (TDS)), as indicated by the electrical conductivity of the soil extract (ECe), is relatively high even in the non-saline non-sodic soils. When those soils are cultivated, the accumulation of all the soluble salts intensifies after several seasons of cultivation as seen in Tables 2.7 and 2.8.

Table 2.2. shows the increase in the salt content in the alluvial (gravelly) soils of the flood plain of Wadi Al Baseerah. The sodium chloride content increased by four times between 1982 (when the Dibba Government Fruit Farm was established) and 1989. The high permeability of the wadi alluvium facilitates the leaching of salts down the gravelly deposits.

It was observed during soil sample collection that salt accumulation owing to drip irrigation may occur in the top 10-30cm. of the soil, but in the case of the continuous application of irrigation water by the sprinkler system the salt accumulation zone may extend down the profile as far as 60cm. from the surface, besides having a horizontal extent.

Salinity increases with depth and values of the total soluble salts (measured as soil electrical conductance (ECe)) range from 500 to 55,000 mmhos/cm. Specific salt content, as represented by the chloride ions, is dominant in soils with electrical conductivities of above 8000 mmhos/cm. The relatively high presence of soluble salts in the soils of the Emirates is the result of the long dry spells between rainfall events as well as the failure of the rainfall to exceed potential evapotranspiration.

4) The presence of substantial quantities of calcium carbonate is
### Table 2.6.

Chemical analysis of the soil paste extract and both the ECe of the soil and the EC of the irrigation water (bracketed) that is being used on such soils in different alluvial and sandy localities in the piedmont plains and desert foreland (period of sampling: April-October, 1988).

The long-term effect of using such irrigation water on these soils would be the accumulation of salts in the soil and their eventual leaching into the aquifer.
Table: 2.7.

The salinity and carbonate content of the soils in the agricultural areas of the Al Ain region.

Salts already present in these soils, in addition to further accumulations from irrigation water, fertilizers and leached dry surficial salts deposited by evaporation, are continuously being washed down by the generous application of irrigation water, and also by rain water, into the aquifer, rendering groundwater more saline with time.

Table: 2.8.

Increase in soil salinity in the Al Sa'adiyah forestry project in Al Dhafrah in Abu Dhabi (1987-1989).

The application of brackish sabkha water on previously non-saline non-sodic desert foreland sands has turned these soils into saline sodic soils within a short time. In this case of the Al Sa'adiyah forest project, soil salinity almost doubled in 2 years between 1987 and 1989.
clear especially from the percentages present in the soils of Al Ain (shown in Table 2.7.) as analyzed by the Al Ain Department of Agriculture. When the calcium carbonate (CaCO₃) develops into a thick layer, it impedes drainage.

5) With electrical conductivity values of the saturated soil paste (ECₑ) of less than 4000 mmhos/cm, sodium and calcium form the dominant cations, the single domination of either being governed by the amount of gypsum in the soil, especially in those soils close to sabkhas such as at Seih Bin Ammar and Al Khaznah (Table 2.7.).

6) The high sodium content can mostly be absorbed by the halophytes (salt resistant plants) found naturally growing in the desert areas, but also cultivated in the extensive afforestation projects, is put into the relatively non-saline non-sodic sandy soils by the highly brackish irrigation water. A substantial amount of the sodium chloride accumulates in the soil from the soluble salts left unabsorbed by the plants. This is clear from the electrical conductivity values of the specimens of the forestry sites in Table 2.8. referred to earlier in this section.

7) The pHs values (the measure of alkalinity) of the soils range from 7.5 to 8.5 (moles per litre), which places the soils of the Emirates in the normal to medium alkalinity range.

2.4.5. Soil-water relationship

2.4.5.1. Infiltration tests (Tables: 2.9; 2.10 and 2.11)

2.4.5.1.1. The principle of the experiments

A number of infiltration tests were carried out for the present study during the period January-April 1988 to establish the accumulated and terminal infiltration rates in the various fluviatile and aeolian deposits. A standard double-ring flooding type infiltrometer was used in these tests. It consisted of two concentric circles that were both graduated in centimetres on the inside. The outer ring had a diameter
of 50 cms., the inner ring 30 cms. and the height was 50 cms. The infiltrometer was installed 25 cms. in the ground and the protruding 25 cms. part was filled with water, which was continually being topped up at every 1 cm. lowering of the water head inside both rings. Readings on the graduated inner ring, indicated directly the rates and amount of water absorbed by the soil, and the time taken to achieve that absorption. This was read from the inner ring from which the percolation of the water is usually maintained in the vertical plane by the lateral saturation of the surrounding earth with water from the outer ring.

Infiltration usually has a high initial rate that gradually diminishes until it maintains a nearly constant lower rate with the saturation of the soil. The infiltration tests performed for this study were simple and the results approximate. Results of the average infiltration rates, a description of the texture of the soil (as the medium of recharge) and the location of the experiments are given in Tables 2.9, 2.10 and 2.11.

2.4.5.1.2. **Infiltration tests in the various terrains of the Emirates.**

These tests revealed that infiltration rates in the well-sorted, but shifting dune sands of the desert foreland were about two times greater than those of the highest rates in the loose gravels and sands of the active wadi channels where the proportion of gravel of all sizes forms more than 70% (by weight) of the total volume of these alluvial deposits (No. 5 in Table 2.9; Nos. 14 and 15 in Table 2.10).

Infiltration rates in the quartzitic sands of the desert foreland, such as at Al Hayer, Liwa and Qasyoorah (Nos. 3 and 10-15 in Table 2.10), were higher than the rates in the carbonate sands nearer the coast, such as at Al Aweer and Seih Al 'Aqareb near Fayah, despite the medium texture of the latter (Nos. 1 and 2 in Table 2.10). Infiltration rates are lower in the sandy textures at Al Jarf and 'Ajban, which have substantial proportions of calcareous sandstone particles and are in many places well-cemented (No. 4 in Table 2.10). These last two areas contain beneath the dune sands brackish
Selection of individual infiltration tests in the various terrains showing the range of rates

<table>
<thead>
<tr>
<th>DESCRIPTION OF DEPOSITS</th>
<th>MEAN INFILTRATION RATE IN $m^3/m^2/d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Loose gravel and sand of varying size in mountain wadis, at the foothills, mountain basins and active wadi channels in the gravel plains. The degree of infiltration is governed by the amount of fines available.</td>
<td>6.8 4.8 3.4 3.3 1.4 0.9</td>
</tr>
<tr>
<td>2. Fine sand and gravel loosely cemented</td>
<td>3.5 2.9 1.5 0.8</td>
</tr>
<tr>
<td>3. Medium to coarse sand and gravel, well-cemented.</td>
<td>1.6 0.4 0.2</td>
</tr>
<tr>
<td>4. Well cemented gravel</td>
<td>1.6</td>
</tr>
<tr>
<td>5. Sand, gravel and cobbles in active wadi channel. The lowest rate is where mud and silt has been left behind by the floods as in Wadi Ham above the dam after the Feb. 1988 rains.</td>
<td>7.6 5.2 4.3 1.6 1.0</td>
</tr>
<tr>
<td>6. Silt on top of gravel and sand</td>
<td>0.2</td>
</tr>
<tr>
<td>7. Silty soil near the foothills</td>
<td>0.9</td>
</tr>
<tr>
<td>8. Gravelly/silty agricultural soil in Dhaid</td>
<td>2.2</td>
</tr>
<tr>
<td>9. Gravelly agricultural soil in Sa’ah in Zarub Gap</td>
<td>3.4</td>
</tr>
<tr>
<td>10. Gravelly/sandy/silty agricultural soil in Um Ghafah in southern Al Jaw</td>
<td>4.5</td>
</tr>
<tr>
<td>11. Sandy agricultural soil in Sulaimat</td>
<td>17.9</td>
</tr>
<tr>
<td>12. Sandy-loam agricultural soil in Al Khawaneej</td>
<td>5.5</td>
</tr>
<tr>
<td>13. &quot; &quot; &quot; &quot; in Al Diglasa</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table: 2.9.

Individual infiltration tests in locations of different types of deposits in a variety of terrains in the Emirates to show the variation in infiltration rates using a double-ring infiltrometer, 1988. (The infiltration tests were carried out during the period January-April, 1988)

The variation in the infiltration rate is governed by the content of finer material (fine sand, silt and clay) in the deposits in which the infiltration tests were carried out. The highest infiltration rates are in alluvial deposits with a high content of gravel and coarse sand and almost devoid in silt (analyses 1, 5 and 11). The lowest infiltration rates are in all the alluvial deposits that have a high silt content (analyses 3, 6 and 7).
<table>
<thead>
<tr>
<th>LOCATION</th>
<th>COMPOSITION OF THE DEPOSITS</th>
<th>MEAN INFILTRATION RATE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m3/h m2/s d</td>
</tr>
<tr>
<td>1. Seih Al 'Aqreb (near Feyah)</td>
<td>Carbonate medium to coarse sands in high dunes</td>
<td>584 14.0</td>
</tr>
<tr>
<td>2. Al 'Aweer (near the wellfield)</td>
<td>Carbonate medium to coarse sands in dunes of medium height</td>
<td>478 11.5</td>
</tr>
<tr>
<td>3. Al Hayar (40km, north of Al Ain)</td>
<td>Quartzitic coarse to medium well sorted sands in medium to high dunes</td>
<td>824 19.8</td>
</tr>
<tr>
<td>4. Al Jasf (near President's palace)</td>
<td>Coarse to fine sands in low dunes with particles of calcareous sandstone, shaly limestone and calcrete</td>
<td>408 9.8</td>
</tr>
<tr>
<td>5. Al Khazneh (60km, from Al Ain)</td>
<td>Quartzitic medium to coarse sands in medium to high dunes</td>
<td>668 16.5</td>
</tr>
<tr>
<td>6. Al Hakeem (in Al Qafa, 30km west of Huzeirah)</td>
<td>Quartzitic medium to coarse sands in high dunes</td>
<td>756 18.1</td>
</tr>
<tr>
<td>7. Sida' Rashid (near Bu Hasa)</td>
<td>Quartzitic medium to coarse sands in high dunes</td>
<td>728 17.5</td>
</tr>
<tr>
<td>8. Sida' Khalifan (30km, north of Huzeirah)</td>
<td>Quartzitic medium to coarse sands in high to giant dunes</td>
<td>632 15.2</td>
</tr>
<tr>
<td>9. Sida' Maharak (in Al Gafa in Liwa, 22km, SW of Asab oilfield)</td>
<td>Quartzitic medium to coarse sands in high to giant dunes</td>
<td>917 22.0</td>
</tr>
<tr>
<td>10. Bujair (near the wellfield)</td>
<td>Quartzitic medium to coarse sands in high dunes</td>
<td>850 20.4</td>
</tr>
<tr>
<td>11. Kayyah (in western Liwa)</td>
<td>Quartzitic well sorted medium to coarse sands in high to giant dunes</td>
<td>808 19.4</td>
</tr>
<tr>
<td>12. Qutuf (in western Liwa)</td>
<td>&quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot;</td>
<td>780 18.7</td>
</tr>
<tr>
<td>13. Al Maziyah (in western Liwa)</td>
<td>&quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot;</td>
<td>788 18.9</td>
</tr>
<tr>
<td>14. Qasr Yorah (30km, SW of im ez Ramool)</td>
<td>&quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot;</td>
<td>864 20.7</td>
</tr>
<tr>
<td>15. Bu Arba'e'en (30km east of Jusairah in eastern Liwa)</td>
<td>&quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot;</td>
<td>880 21.1</td>
</tr>
<tr>
<td>16. Al Dha'il (4km, west of Dha'il)</td>
<td>Carbonate and quartzitic well sorted medium to fine sands in low dunes</td>
<td>568 13.6</td>
</tr>
<tr>
<td>17. Falah (1) near Sharjah airport</td>
<td>Carbonate coarse to fine sands with some clay in low dunes</td>
<td>632 15.2</td>
</tr>
<tr>
<td>18. Falah (2)</td>
<td>Carbonate coarse to fine sands with more clay content than (1) in low dunes</td>
<td>248 6.0</td>
</tr>
<tr>
<td>19. Seih Husanmad (near Saja'ah oilfield)</td>
<td>Carbonate fine sands with gypsum in sheet dunes</td>
<td>421 10.1</td>
</tr>
</tbody>
</table>

Table: 2.10.

Summary of the infiltration tests in the aeolian deposits of the desert foreland (giant, medium and low dunes) and in the sabkha deposits of the 'seis', 1988. (The infiltration tests were carried out during the period January-April, 1988).

Using a double-ring infiltrometer, these infiltration results were for tests carried out mostly in aeolian deposits in localities in the desert foreland with both recharge potential and groundwater abstraction. Fresh water aquifers exist in the thick sands of the high dunes periodically being recharged by rain water by direct infiltration. Infiltration rates in quartzitic sands are higher (results 1-15) than those in the carbonate sands (results 16-18) or the clayey sabkhas (result 19).
**Table: 2.11.**

Summary of the infiltration tests in the alluvial deposits of the mountain wadis, piedmont plains and adjacent areas of the desert foreland, 1988. (The infiltration tests were carried out during the period January-April, 1988).

Using a double-ring infiltrometer, the highest infiltration rates were in the mountain wadi fill, of both carbonate (results 1 and 2) and ophiolite (results 3 to 7) boulders, gravels and sands. The medium infiltration rates were in the alluvial gravels and sands of the piedmont plains with varying clay and/or silt content or calcrete cementing (results 15, 17 and 20). The lowest infiltration rates were in alluvial localities with surficial silt patches or subsurface calcrete cementing (results 8 to 10).

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>COMPOSITION OF THE DEPOSITS</th>
<th>MEAN INFILTRATION RATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Al Beeh (near wellfield)</td>
<td>Gravels, from boulder size to fine. Sands from coarse to medium (Limestone)</td>
<td>333</td>
</tr>
<tr>
<td>2. Al Burairat (near wellfield)</td>
<td>Gravels, medium to fine. Sands, coarse to fine (Limestone)</td>
<td>300</td>
</tr>
<tr>
<td>3. Wadi Siği (near village)</td>
<td>Medium to fine gravel. Coarse to medium sand. Becoming finer with silt lower in the profile (Ophiolites)</td>
<td>350</td>
</tr>
<tr>
<td>4. Wadi Siği (DS near rain-recorder)</td>
<td>Large to medium gravel. Medium to coarse sand (Ophiolites)</td>
<td>383</td>
</tr>
<tr>
<td>5. Wadi Al Hana'e (near Awailat)</td>
<td>Loose gravels from large to fine but rounded. Coarse to medium sands (Ophiolites)</td>
<td>396</td>
</tr>
<tr>
<td>6. Wadi Al Wurai'ah (5km d/s from spring)</td>
<td>Boulders and gravels of all sizes. Coarse sands. (gabbros and ultrabasics)</td>
<td>358</td>
</tr>
<tr>
<td>7. Wadi Ham (below the dam)</td>
<td>Boulders, cobbles and gravels of all sizes. Coarse to medium sands (Ophiolites)</td>
<td>317</td>
</tr>
<tr>
<td>8. Wadi Ham (above the dam)</td>
<td>Boulders, cobbles and gravels of all sizes. Coarse to fine sand. Top silt (Ophiolites)</td>
<td>67</td>
</tr>
<tr>
<td>9. Wadi Al Baseerah (near fruit farm)</td>
<td>Rounded and sub-angular gravels and cobbles of all sizes with coarse well sorted sands. (Ophiolites and Hameene exotics)</td>
<td>383</td>
</tr>
<tr>
<td>10. Wadi Al Baseerah (further d/s)</td>
<td>Rounded and subangular boulders and gravels with coarse to fine sand and silt</td>
<td>50</td>
</tr>
<tr>
<td>11. Wadi Lamsa (near F. Al Nualla)</td>
<td>Medium to fine gravels with more than 40% content of coarse to fine sands of fluvial and eolian sources.</td>
<td>345</td>
</tr>
<tr>
<td>12. Wadi Sumaini (near Um Attarateeth)</td>
<td>Loose boulders and gravels with medium to fine sand and some silt (Ophiolites)</td>
<td>275</td>
</tr>
<tr>
<td>13. Wadi Khadhrah (near Dhaiid)</td>
<td>Loose boulders and gravels with medium to fine sands and silt patches.</td>
<td>271</td>
</tr>
<tr>
<td>14. Seih Al Fahlain (near village)</td>
<td>Coarse gravels and sands of dolomites with carbonate cementing.</td>
<td>217</td>
</tr>
<tr>
<td>15. Al Jirri Plain (Hamraniyah)</td>
<td>Coarse gravels and sands with patches of crystalline limestone and silt becoming finer down the profile.</td>
<td>200</td>
</tr>
<tr>
<td>16. Al Dhaid Plain (near block fort)</td>
<td>Gravels and sands of all sizes with the medium gravels increasing down the profile.</td>
<td>254</td>
</tr>
<tr>
<td>17. Al Ghareef Plain (near T.Mandah)</td>
<td>Coarse to medium gravels and sands. 20% medium to fine sand with some silt</td>
<td>167</td>
</tr>
<tr>
<td>18. Mahdah Fan (in Ghashabah wellfield)</td>
<td>Medium to fine gravels and sands with 20% silt.</td>
<td>258</td>
</tr>
<tr>
<td>19. Al Jaw Plain (Hamid Bin Jawail)</td>
<td>Cemented coarse to fine sands and gravels. Cementing is medium to hard.</td>
<td>104</td>
</tr>
<tr>
<td>20. Zikt (30km NW of Dhaadhurh village)</td>
<td>Coarse to medium gravels and sands with some silt content.</td>
<td>233</td>
</tr>
</tbody>
</table>
groundwater resources that supply the villages and forestry projects along the Abu Dhabi-Dubai highway.

The lowest infiltration rates in the aeolian sands were found in the sands of Falah near Sharjah airport (No. 18 in Table 2.10), where there was a high percentage of fines; but high rates were also measured in Falah in the higher parts of the sand dunes away from the gardens (No. 17 in Table 2.10) because of their distance from irrigated land. The highest infiltration rates were found in the giant dunes of Al Qafa in the Liwa region, in Bida' Mubarak, to the north of Huwailah, lying in an elevated depression within the high dunes, but well above the general level of the Liwa oases to the south (No. 9 in Table 2.10). The wells in this area are 30-40m. deep and the groundwater has an EC of below 1000 mmhos/cm. This is the part of the sand dune fresh groundwater belt from which the wellfields of Bujair (I, II and III), Bida' Khalfan and Al Hilew tap their water.

Other spots of high infiltration rates, similar to those for Bida' Mubarak, were at Bu 'Arba'een and Qasyoorah near Um Ez Zemool, where fresh groundwater has been known to exist in the lower parts of the high dunes, floating over the very saline waters of the extensive Qasyoorah inland sabkhas of the interdunal deflation basins extending through Um Ez Zemool into Oman and Saudi Arabia (H.C. Harding: Confidential internal memorandum of a visit to Party 19 in Um Ez Zemool in southeast Abu Dhabi, April 1969).

In more important areas of recharge potential, the alluvium-filled mountain wadis, the piedmont alluvial outwash fans and plains, as well as those 'protrusions' of gravel-filled wadi courses penetrating into the dune sands of the desert foreland, such as those of Wadi Lamhah and Wadi Yudai'ah, infiltration rates ranged from 0.20 m3/m2/d (8.4 mm/h) in the silty or silt-capped wadi gravels especially in the higher ground within the wadi flood plain and old terraces (No. 6 in Table 2.9), to over 9.0 m3/m2/d (375 mm/h) in freshly laid down loose boulders-gravels-sands in the active wadi channels (Nos. 5, 6, and 7 in Table 2.11). Two extreme infiltration rates were obtained in the same locality in Wadi Ham: the high rate of 7.6 m3/m2/d (317 mm/h) in the active wadi channel before the major floods of 17/2/1988 in boulders-gravels-coarse sand; while the low rate of 1.6 m3/m2/d
(66mm/h) was obtained in the top veneer of 350 mm of very fine silt and mud left behind the impounded flood waters upstream of the dam. Both tests were carried out in the reservoir bed 100 m. behind the dam: the first on 2/2/1988 before the floods, the second on 23/3/1988 four weeks after the last February floods of 22/2/1988. For the latter case, the actual infiltration rates varied from 0.05 to 2.20 m$^3$/m$^2$/d (Nos. 7 and 8 in Table 2.11).

Infiltration rates were found in general to be less in the sands and gravels of the piedmont plains (the main recharge zone in the Emirates) than those in the loose renewable deposits of similar composition in the active wadi channels (Nos. 1-7 and Nos. 10-20 in Table 2.11). Even in these places, not all active wadi channels exhibited high infiltration rates (Nos. 8 and 10 in Table 2.11). Silt and other fines in the piedmont plains of Dhaid, Ghareef, but mostly in the Jiri Plain in Ras Al Khaimah, as well as the pockets of silt in small depressions in the active wadi channels, were found to retard vertical movement of water (Nos. 13-20 in Table 2.11). Elsewhere, as in Al Jaww Plain, compaction of the alluvium by calcrite cementing (CaCO$_3$) and the presence of fines of clay and silt in thin interbeds, gave comparatively low infiltration rates (2.5 m$^3$/m$^2$/d) compared with those for gravel and sands of the wadi courses and outwash fans, as in Al Jaww (No. 19 in Table 2.11).

Finally, infiltration tests carried out in newly prepared agricultural land, revealed relatively lower rates for some sites in Dhaid with a high silt and clay content or calcrite cementing (2.2 m$^3$/m$^2$/d or 92 mm/h as in No. 8 in Table 2.9), medium infiltration rates in Zarub, Um Ghafah, Digdaga and Khawaneej (3.4, 4.4, 5.0 and 5.5 m$^3$/m$^2$/d in Nos. 9, 10, 12 and 13 in Table 2.9), but extremely high rates in the predominantly medium-grained sandy soils at Al Sulaimat and Al Sad in Al Ain (17.9 m$^3$/m$^2$/d or 746 mm/h, as in No. 11 in Table 2.9).

2.4.5.1.3. **Simulation of infiltration under flood conditions**

The basic national pattern of infiltration rates has been described by results obtained using standard equipment. However, the double-ring infiltrometer provides a reading specific to one point and in no way
replicates the mode of application of water during wadi floods. Under natural conditions, the wadi water would be virtually saturated with material in states of a solution, suspension, saltation and traction along the wadi bed. During the passage of the flood hydrograph, its depth would also become on average, far greater than that within the infiltrometer. However, from the viewpoint of infiltration potential, the most important point is that the water would be mobile and would thereby churn up the surface. In the standard infiltration test, the water column is static and is applied to the wadi bed on which layers of fine material have settled as flow has ceased.

The simulation involves the application of a reasonably large volume of mobile water to an area of wadi bed below the Wadi Ham earth flood retention dam. To control the flow and achieve a depth well in excess of that in the infiltrometer, a trench 5m. long and 2m. wide was excavated to a depth of 0.5m. The down valley half of the trench was then excavated a further 0.5m. and covered with a heavy duty plastic sheet so that the remaining water from the simulated overland flow in the upper 5m. stretch would collect into it. Two bowsers of capacity 8m$^3$ and 10m$^3$ were employed to provide water, which was poured into the upvalley end of the trench to a depth of approximately 0.5m. When the complete volume had been used, that retained in the lower half of the trench was measured. The difference between the volume applied and that finally measured in the trench gave a figure for the volume which had infiltrated into the wadi gravel.

Any such large-scale simulation is likely to appear somewhat unsophisticated. For example the rate of flow down the trench may not have matched that of a wadi in spate and there would have been infiltration losses, probably over the time period comparatively small, into the sides of the trench. However, despite these problems, the conditions remain nearer those of a wadi flood than those that obtain with standard infiltration measurement. Therefore, it is not surprising that the infiltration rate (recharge coefficient or ratio) measured, which in this case amounted to 70%, accords well with that which has been given by GDC (65% for catchments in Oman with a surface area of more than 150km$^2$ and 75% for catchments of a surface area each of less than 100km$^2$; see Chapter 10, Section 10.4.). Thus, it can be concluded that, while such a simulation is in a
measure unrealistic, it does offer guidance on the approximate order of infiltration rates. As such, it is considered that this simulation, perhaps improved in some details, could be repeated to advantage in other wadis of the Emirates.

2.4.6. Soil-water-vegetation relationship

Various salt bushes, such as the Zygophylum spp. (Arabic: Al Harm), Halopeplis perfoliata (Arabic: Al Khurrayz) and Haloxylo salicornia (Arabic: Al Ramth), grow on coastal sand dunes and the fringes of both coastal and inland sabkhas, as in Tareef, where the salinity of the sandy soil is 23,000 parts per million (ppm). In Habshan, 25 km. to the southwest of Tareef, Zygophylum spp. grow on relatively 'sweeter' sands of salinities of 12,500 ppm. 40 km. inland from the coast. Other halophytes (salt-tolerant plants), such as Dipterigium glaucum (Arabic: Al 'Arfaj) and Tribulus longipetalus (Arabic: Al Zahr) grow on sandy soils near agricultural land where water is plentiful.

On the sand dunes further inland is found the large bush Calligonum comosum (Arabic: Al 'Arta), as in Liwa, indicating lower soil salinity, while the Calotropis procera (Arabic: Al 'Ushar) grows in dry water courses where fine deposits have collected.

With regard to plants as indicators of fresh groundwater, the Acacia tortolis (Arabic: Al Sumar) indicates both good non-saline soil and fresh groundwater, as in the piedmont plains on either side of the mountains, where this tree is found more than in any other region. The roots of the Acacia tortolis can reach 15m. in depth in search of fresh water. The Prosopis spicigera (Arabic: Al Ghaf), the largest tree in the Emirates growing up to 12m., can grow both on sandy and gravelly soils, but mostly on the former. The roots of this plant can reach down to 20m. to tap fresh water aquifers.

Finally, Leptadenia pyrotechnica (Arabic: Al Markh), a large bush used in Liwa for stabilizing the high sand dunes, is another indicator of fresh groundwater. In a recent study (Ecology and flora of Qatar, K. Batanooni, 1986), it was observed that the Al Markh plant can grow up to 1.60m. in height and its roots can reach 12m. in depth. Its root
system can occupy up to 850 m$^3$ of sandy soil and the plant may consume up to 6 tons (6 m$^3$) of water per year. It can survive drought up to 4 consecutive years, and it is able to achieve that because the 850 m$^3$ of earth its roots occupy store up to 24 tons (24 m$^3$) of moisture.

2.5. Synopsis

In this chapter the major structural features of the Emirates have been identified and the key elements in the stratigraphy described in detail. The geology of the main physical elements, such as the mountain wadis, the piedmont plains and the desert foreland has been described in detail in the context of water resources. The significant topographical divisions of the landscape have been identified and the geomorphological features important for water resource analysis, such as wadis and dunes, have been discussed. The physical and chemical characteristics of the other basic landscape component, soil, have been examined particularly in the light of their influence upon water.
3. CLIMATE

3.1. Introduction

Climate in general and rainfall in particular, are the dominant physical factor affecting water resources. An understanding of their characteristics and spatial variation, is essential for evaluating, planning and managing conventional water resources.

Most of the annual precipitation is lost in evaporation. Research in identical hot arid desert environments in the United States has concluded that up to 75% of the annual precipitation is lost in this way. Thus, the climatic elements of temperature, radiation, wind and humidity are described in this chapter to show the effect the interaction of these elements has on the rate of evaporation.

Effective precipitation is also limited in amount and extent by a subsiding warm air in the southern Gulf region obstructing the eastward movement of the Sub-Tropical Jetstream with which is associated most of the rainfall of the Emirates in winter. A discussion of atmospheric circulation provides the necessary background to the climatic conditions, especially those affecting rainfall.

As rainfall is the most important single factor in water resources, the detailed analysis in this chapter with regard to its type, characteristics and spatial distribution is relevant for explaining runoff characteristics and volumes, which are discussed in detail in the chapters on surface hydrology and the water balance (Chapters 4 and 10.).

All the available daily rainfall data have been used in this analysis of the rainfall of the Emirates. Rainfall intensity data (for 10, 20 and 30 minutes and the 1, 2, 3, 4, 6, 12 and 24 hours duration), which are only
available with the Ministry of Agriculture and Fisheries for the period 1979-83, have been extensively used to develop a clear picture of the concentrated and localized incidence of rainstorms, which are responsible for the runoff from the catchments.

The discussion on the state of the meteorological network based on official information concerning location, but verified in field visits to most of the meteorological sites belonging to the various organizations, aims at portraying the actual level of efficiency of managing this sector of climatic observation vital to water resources. The purpose of this is to demonstrate the limitations of meteorological observation pursued further in the chapter on the management of water resources (Chapter 11).

3.2. The state of the meteorological network (Figs. 3.1. and 3.10.)

With the exception of the long rainfall record of Sharjah, which goes back to 1934, with only a 6-month gap in 1949, meteorological observation in the Emirates is recent. The Trucial States Water Resources Survey (1966-69) made full use of the Sharjah climatic data but found it necessary to set up 16 standard rain gauges and 5 evaporation pans for the purpose of that study. The results from these instruments were published in hydrological year books. The meteorological sites were continuously manned throughout the duration of the survey after which the information gradually became unreliable with time due to neglect of the instruments until 1975 when a modernization programme of the meteorological network was started by the Ministry of Agriculture and Fisheries (MAF) with the help of the Food and Agriculture Organization of the United Nations (FAO).

Reliability of the data from the existing meteorological network of the Ministry of Agriculture and Fisheries (MAF) improved during the period 1978-82, yet only the rainfall and temperature data can be taken as sufficiently reliable at present as the instruments for their measurement are the only components of the network that are functioning. Measurement of evaporation had never been accurate prior to 1982, owing to the evaporation pans being unprotected against birds; and has never been reliable since that date owing to the total neglect of the
Figure: 3.1.

The Distribution of the comprehensive meteorological stations in the Emirates.

These comprehensive meteorological stations include those of the MAF, the MEW, the Airports, the Western and Central Military Commands, the Al Ain Department of Agriculture and the UAE University.
instruments. There has been no evaporation measurement in any of the MAF meteorological stations since 1982.

In a field visit on 13-08-1988 to the meteorological station at Falaj Al Mualla (belonging to the MAF), the pan was observed to be full of dirt, the water in the pan contained a thick growth of algae and the hinged mesh cover of the pan was ajar and held so by a stick. A 16mm. hose-pipe continuously filled the pan with water from a tap outside the enclosure of the station. The Stevenson Screen was blown from its support and all its contents totally destroyed. The anemometer, which was hardly 60cm. from ground level, was obstructed on one side by a well-established Calotropis procera ('ushar') plant about 2m. wide and 2m. high.

Although automatic wind recorders have been installed in stations like Digdaga, Um Al Qaiwain, Burairat, Dibba, Masafi, Al Awha and Al Hibab since 1982, and despite the full information available on their charts, wind speed readings only are extracted and included in the unpublished meteorological data of the MAF. Radiation is not measured by the MAF and the only data on solar radiation are available from the meteorological sections in the three airports of Abu Dhabi, Dubai and Sharjah.

The rainfall recorders are of the automatic type with 6-month charts and are basically accurate, yet the percentage failure of these recorders due to the non-replacement of charts, the sticking of the pen, the blockage of the funnel by rubbish and the failure of the battery, is high (see Appendix 2). Only two people are designated the task of monitoring the whole meteorological network of the MAF. The total number of the MAF rain gauge/recorders, for the whole country, is 53, 11 of which are installed within comprehensive meteorological stations.

The Ministry of Electricity and Water (MEW) set up its own hydrometeorological network in 1984. The network is looked after by one person and consists of 13 automatic rain recorders, mostly with monthly charts, 5 thermohygrographs (temperature and humidity), 3 hygrographs (humidity), 3 barographs (pressure), 3 wind recorders, 3 evaporation balance instruments, 3 sunshine recorders and 5 actinographs (radiation). Of these instruments, as observed in July 1989, the sunshine recorders, actinographs, evaporation balances and wind...
recorders were not functioning. This seemed to have been the case for a long time.

The most striking observation concerning the MEW meteorological network, set up well after the upgrading of the MAF network, is that a number of the sites are near or even at MAF stations. Of the 13 rain recorders of the MEW, 7 coincided with those of the MAF and in Khatt, in Ras Al Khaimah, the rain recorders of both official organisations were found to be side by side. (1990). The recorders are of the automatic type, but the charts of 10 out of 13 are monthly, while the remaining 3 are weekly. Unlike MAF rain-recorders with the 6-monthly charts, the shorter duration of the MEW charts tends to lead to many of their charts not being replaced on time. However, it should be pointed out that the monthly and weekly charts have an advantage over the 6-monthly charts in that short duration rain events of 10 minutes or so can be plotted conveniently in the more widely spaced intervals of the charts; but this is irrelevant to the MEW as it is only a body supplying water to the rural settlements; while the MAF stopped preparing intensity data in 1983. Neither establishment puts these data to practical applications and their role is strictly limited to collecting observation records.

The two MAF staff in charge of the meteorological stations are professional meteorologists while the one in charge of the MEW network is not. The duplication in siting, does little to make the meteorological data of the various regions more representative.

The military has its own network which is shown in Table 3.1. All the meteorological stations of the military are of the Milos type and, apart from the Dhafrah station, are operational during daytime only (all the automatic instruments are switched off at dusk). The Minhad station has been in existence for only 5 years, the Dhafrah since 1982, and the other out-stations under the Dhafrah command, since 1986. None of these military stations observe evaporation or radiation.

In the Al Ain region, in addition to the 2 military stations at Al Ain town and Suwaihan and also the 2 MAF stations at Kuwaitat and the central laboratory at Al Awha, the Al Ain Department of Agriculture maintains the meteorological stations/rain recorders shown in Table 3.2.
A. Under the Western Region Military Command (Abu Dhabi)

Al Dhafrah air-base
Tareef
Delma Island
Al Hamrah
Al Sila’
Al Ain
Suwaihan
Al Rudoom
Khorfakkan

B. Under the Central Military Command (Dubai)

Minhad air-base.

Table: 3.1.

The meteorological stations of the Western (Abu Dhabi) and Central (Dubai) Military Commands (1989).

Only the two stations at Al Dafrah and Minhad air-bases are in full operation. The rest are in disuse, though a standard rain-gauge is maintained in each. The majority of the rain-gauges were set up in the early part of 1989.

The UAE University in Al Ain recently (1988) set up two complete meteorological stations on its experimental farm at Al Awha. These are shared by both the Faculties of Agriculture and Engineering.

Two more full meteorological stations are planned to be set up by the UAE University (by the Geography Department in both the Men’s and Girls’ colleges). Also the current NDC-US Geological Survey Project is planning to set up 10 full meteorological stations in the Al Ain area. All these planned stations are going to be sited alongside the already existing full stations or rain-gauges of the Al Ain Department of Agriculture. Thus, the same situation of duplicated siting of meteorological stations of the MAF-MEW, that exists in the Northern Emirates, will be repeated.
in the Al Ain region. There will be little value in such a density of meteorological equipment with the same meteorological measurement offered by more than one station in the same location.

The petroleum companies in Abu Dhabi and Dubai have meteorological stations at Jabal Addhannah, Bu Hasa, Asab and Shah (Abu Dhabi Company for Onshore Operations (ADCO)), on Das Island and Jaseerah Island (Abu Dhabi Marine Operating Company), in Arzanah, Zarcoah Islands (Zakum Development Company), Mubarraz Island (Abu Dhabi Oil Company Limited-Japan) and at K-3 Station in Fateh offshore oilfield in Dubai (Dubai Petroleum Company).

Data from these stations are collected by non-meteorologists. Most are reported instantaneously from a radio room to various interested sources and linked to marine operations in the oilfields. Rainfall is reported as 'rain', with no totals given.

Finally, there are the meteorological stations of the main airports of Abu Dhabi, Dubai, Sharjah and Ras Al Khaimah, which come administratively under the local civil aviation authorities in the respective emirates, but are technically run by International Aeradio Limited by contract. The meteorological service in Fujairah airport is similarly operated by Pan Am and, as the airport has just opened, little is observed there apart from temperature and wind. The airports observe meteorology primarily for aviation applications. The Dubai airport station no longer maintains evaporation measurements. The Abu Dhabi airport meteorological station uses a Class 'A' pan and the Sharjah meteorological station a piché•(1), so that the two methods are totally irreconcilable for comparative purposes. All three airports present data for all their observations.

(1) The piché' evaporimeter consists of a long narrow glass tube, graduated in cubic centimetres, one end of which is closed and the other open and ground flat. The flat end is covered with a circular filter paper held in position with a small disc and a metal clip. In use, the tube is filled with distilled water, closed with the filter paper and then inverted. Water soaks the filter paper and then evaporates from it; the amount of water which evaporates in any given time can be measured by making two consecutive readings of the level of water in the tube. The difference will give the volume of water evaporated.
<table>
<thead>
<tr>
<th>Location</th>
<th>Starting date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al Ain (Meteorological Station)</td>
<td>1971</td>
</tr>
<tr>
<td>Al Hayer</td>
<td>1982</td>
</tr>
<tr>
<td>Al Sulaimat</td>
<td>1977</td>
</tr>
<tr>
<td>Abu Samrah</td>
<td>1989</td>
</tr>
<tr>
<td>Al Wagn</td>
<td>1979</td>
</tr>
<tr>
<td>Al Faqa'</td>
<td>1989</td>
</tr>
<tr>
<td>Al Shuwaib</td>
<td>1989</td>
</tr>
<tr>
<td>Al 'Ushoosh</td>
<td>1989</td>
</tr>
<tr>
<td>Ghamdh</td>
<td>1989</td>
</tr>
<tr>
<td>Suwaihan</td>
<td>1989</td>
</tr>
<tr>
<td>Al Awha</td>
<td>1980</td>
</tr>
<tr>
<td>Al Sad</td>
<td>1989</td>
</tr>
<tr>
<td>Abu Samrah</td>
<td>1989</td>
</tr>
<tr>
<td>Al Khaznah</td>
<td>1989</td>
</tr>
<tr>
<td>Seih Al Miyah</td>
<td>1989</td>
</tr>
<tr>
<td>Seih Bin Ammar</td>
<td>1980</td>
</tr>
<tr>
<td>Al Qattarah</td>
<td>1980</td>
</tr>
<tr>
<td>Department of Agriculture main office</td>
<td>1986</td>
</tr>
<tr>
<td>Um Ghafah</td>
<td>1989</td>
</tr>
<tr>
<td>Jabal Hafeet</td>
<td>1986</td>
</tr>
<tr>
<td>Al 'Arrad</td>
<td>1989</td>
</tr>
<tr>
<td>Al 'Aqeer</td>
<td>1989</td>
</tr>
<tr>
<td>Al Qoa'</td>
<td>1989</td>
</tr>
</tbody>
</table>

Table: 3.2. The rain-gauges of the Al Ain region and their installation dates (Al Ain Department of Agriculture), 1989.

Thus, there are different organizations in charge of meteorological observations with no coordination between them apart from the negotiated bilateral exchange of limited data. Published data are scarce. The Abu Dhabi Civil Aviation Department (Abu Dhabi Airport Meteorological Office) has been issuing an annual meteorological summary which includes results from the Dubai and Sharjah stations, but this has been possible only because the same company is managing the meteorological offices in all the three airports. Dubai airport started to issue an annual summary...
in 1987. The last published meteorological report of the Ministry of Agriculture and Fisheries was in 1979. MAF data are not always readily available, while the MEW makes known none of its data and few people, including official circles, are aware of the existence of its meteorological network. The other organizations, military or civilian, do not divulge any of their meteorological information.

The Emirates, therefore, does not have a national meteorological network nor, in its existing fragmented state, is standardization possible. Attempts by the Ministry of Communications (MC) to take over the aviation meteorological divisions of the airports would merely add another authority rather than unite the existing ones. The Emirates became a member of the World Meteorological Organization (WMO) in 1987 and the Organization is assisting the MC in setting up a 'national' meteorological body.

The official reiterated view that the MAF network is also an agrometeorological one, with regard to the very nature of the work of the MAF, is not wholly true. Only soil temperature is measured (in Dgada, Dibba, Masfut, and Masafi) and no soil moisture measurements are carried out. The same is the case at the two main experimental stations of the Department of Agriculture in Al Ain. The MEW is not concerned with such measurement as it is purely a well-drilling and water-supplying authority providing water for domestic use in the rural areas. For the remaining networks, those of the military and the petroleum companies, operation of the meteorological facilities is either for part of the day only or is strictly specialized in what is measured. It is clear that:

"the network of stations in support of meteorological activities in the UAE is inadequate to ensure the maintenance of a high standard of service"


There exists no coordination between the civilian and military meteorological establishments nor is the quality of the observations of the petroleum companies satisfactory. Furthermore, dissemination of their data is limited.
Basic weather forecasting is carried out by the airports and only the military station at Dhafrah has a storm warning radar facility with a 480km. range. This started operating in October, 1988. It is intended, as this is going to remain the only such facility in the Emirates, to announce storm warnings to the various weather related bodies and the public.

As far as data management is concerned, the airports publish their observations regularly in monthly and annual reports that are easily available. None of the other authorities lends available data except on request and, even in that case, the data given are very limited. Even the MC is concentrating on taking meteorological responsibilities from the airports, avoiding those of the MAF and the Military. The aim of the MC is to collect aviation meteorological data under its 'centralized' authority. The reservation about this is whether the meteorological data under its control would be accessible to those who need them or whether they would be made confidential, an established characteristic of most government establishments.

From all this, the appropriate meteorological organization envisaged by the present study, would be a central national meteorological department, similar to the British or Indian Meteorological Office, responsible for all the meteorological, agrometeorological, aviation and marine data as well as weather forecasting. Technically, for ease of operation, the airports could have a certain degree of autonomy, but even these would acquire regular information from the would be central meteorological office. This central meteorological authority should be independent from any other government establishment, and its basic interest should be wide, embracing the whole spectrum of meteorological observation. Not only should this meteorological authority standardize observation procedures and the storing and presentation of data, but it should also be reinforced with qualified staff in the field of meteorology and related sciences who would be expected to carry out studies of regular and rare weather phenomena.

Meteorology in the Emirates is a field almost totally devoid of indigenous staff. The exception is the Dhafrah Air Base where national officers are being trained as meteorologists. If the MC is to take over and be a mere replacement for some or all of the existing
meteorological establishments, then little new will have been achieved in this vital sector that is intimately related to water resources.

3.3. Atmospheric circulation: Air masses and wind systems

The Emirates lies within the arid, hot desert belt of the northern hemisphere. The rainfall is sporadic derived mostly from Mediterranean depressions that reach the southern Gulf in winter after crossing northern Arabia and the upper Gulf, from monsoonal air incursions from the south during early and mid-summer and also from localized convection in the interior.

In the winter, the whole Gulf is under the influence of warm subsiding air. The Mediterranean becomes a region of reduced pressure owing to the influence of the Azores 'high' to the south and the Alpine 'high' over central Europe in the north. The Mediterranean thus becomes a route for depressions moving eastwards from the Atlantic (Figs. 3.2D and 3.4.). These depressions continue their journey across northern Arabia retaining enough energy to reach the Gulf. They are aided in their movement eastwards by cyclones associated with the Sub-Tropical Jetstream. The Subtropical Jetstream is defined by the World Meteorological Organization as a "strong narrow current in the upper troposphere or in the stratosphere, characterized by strong vertical and lateral wind sheers" with speeds of up to 110km./h. (60 knots), though they may exceed this limit by several times. Winds of the jetstream strike at right angle to the thermal gradient, found between the cold (northern) and the warm (southern) regions and therefore follow east-west paths.

The Subtropical Jetstream is at a level in the atmosphere of 300-350 millibar or 9000-11000m. (over the Emirates) with its core in the summer over Turkey and in the winter over the northern parts of the Red Sea (Figs. 3.3, 3.7A and 3.8A). In winter, the southernmost flank of the Jetstream pushes southwards as far as the southern coasts of Oman (Fig. 3.3 and 3.8A). Thus, the Emirates lies within the southern limits of this continuous wind system below the 200mb. surface. The Jetstream is known to have a velocity over the Emirates, during the period from November to April, of between 150km./h. and 270km./h. (90 knots to 160 knots).
The system originates in the Atlantic and crosses the northern parts of Africa and northern Arabia and, when it reaches Iraq, it turns southwards along the eastern shores of the Gulf to continue eastwards towards India at about the latitude 22°N (W.B. Fisher, The Middle East, 1978).

The air whipped up by the Jetstream from its sources in the Atlantic is in fact the maritime air which is partly polar and partly tropical, and as the Jetstream moves eastwards with it, it sucks in air of different sources developing a series of depressions or 'lows' along its path as far as the middle Gulf. These conditions last from October until May. The maximum rain falls in the eastern Mediterranean in December and January and, if they maintain their journey, the depressions reach the southern Gulf a month later causing rain in the Emirates, mostly during February and March. (Figs. 3.2.A., 3.4 and 3.8.A-B.).

When reaching the southern Gulf, the Jetstream has already lost most of its velocity resulting in the transformation of its kinetic energy into potential energy with a consequent increase in atmospheric pressure. At this time of the year also, the Emirates is under the influence of the descending warm air that hampers the movement of the Mediterranean depressions and limits the possibility of widespread and sustained precipitation by inhibiting violent convections of moist air from Gulf waters. When occasionally some of the depressions do reach the Emirates, the resulting rain is intense and is of short duration. Figures 3.7.B and 3.8.B show the synoptic atmospheric situation over the Emirates in summer and winter while Figures 3.7.A. and 3.8.A. show the location of the Subtropical Jetstream in summer and winter.

During the same October to May period the flow of the maritime air with the Jetstream is sometimes interrupted. Two different air masses are responsible for disruptions in its flow. One, is the Tropical Continental Air (Fig. 3.2. C.), the other the Polar Continental Air (Fig. 3.2. B and D). The former blows into the region from the vast desert heartland of Africa and Arabia, to the west, and is dry and hot causing temperatures to rise suddenly by 6-12°C. within 6 hours in May or even earlier (W.B. Fisher, The Middle East, 1978). In the Emirates, the strong local wind associated with the Tropical Continental Air is the dust-raising 'Khamseen' of the late spring and early summer. These
westerly or south-westerly winds rise when tropical air is sucked into the area at the same time as a fast moving warm depression is forming within the maritime air mass. The winds may be of short duration but are accompanied by intolerably hot and sandy conditions. (Fig. 3.2.C.).

The second air mass, the Polar Continental (Fig. 3.2.B and D), is responsible in winter and spring for the waves of cold air from interior Eurasia, which blow south and westwards across Iran in the form of anticyclonic waves originating in the Siberian anticyclone. Furthermore, the cold moist air which forms over central and eastern Europe is drawn into the region by the east moving Jetstream depressions noted earlier and may reach the Emirates as early as December and as late as May (Fig. 3.4.). During the winter rains of 1988 this kind of frontal rain occurred on 26-27 April, while the heavy downpours of February 17th. and 19th. were caused by the combination of three air masses which included, besides the above 2 air masses, maritime air from the Indian ocean as well. (Fig. 3.2. A, B and D., and Fig. 3.8.A and B.)

In summer, the monsoon air current from the Indian Ocean, flowing from the south, is at levels in the atmosphere of about 5000m. Above it, at levels of 9000-11000m. (north of latitudes 27°-30°N) is the westerly Subtropical Jetstream, which, though present all the year round with its core seasonally shifting north and south over the Gulf, is prevalent over the southern Gulf between November and March. Between April and October, on the other hand, an easterly Jetstream is present over the Emirates, above the monsoon air, at the usual Jetstream atmospheric level of 9000-11000m. (south of latitudes 27°-30°N). This easterly summer Jetstream is weaker than the 'winter' westerly Jetstream (which is present all the year round) and the two are separated in summer by the so-called 'Subtropical Ridge' at latitudes 27°-30°N (Fig. 3.7.A.). These 3 levels of atmospheric activity over the Emirates induce vorticity and mixing of air currents in the middle atmosphere (3000-6000m.) attracting moist air from the Indian ocean from the south in an anticlockwise direction causing the rains largely experienced on the east (Batinah) coast of the Emirates in the summer (see Figs. 3.5. and 3.7.A-B.).

From June to September the monsoon 'low', which rests over northwest India and Pakistan (Fig. 3.5.), is at a low level in the atmosphere
Atmospheric conditions in the Middle East during the period October to May.

A. **Maritime Air** (October to May): Originating over the Atlantic, partly tropical and partly polar; crosses the Mediterranean and northern Arabia into the Gulf. Its eastward movement is enhanced by the Subtropical Jetstream. Small, low-level 'Lows' (3,000m.) develop along its path to the lower Gulf.

B. **Polar Continental Air** (December to April): South- and west-flowing cold air from Eurasia. The west-flowing cold and stable air originates over south-central Asia. It blows over the Gulf after descending the Zagros mountain range and becomes adiabatically warmed. It is accompanied by anticyclonic disturbances (D).

D. **Polar Continental Air** (January to March): South-flowing air originating over central and eastern Europe. It is cooled maritime air aided in its southerly movement by anticyclonic conditions and east-moving depressions associated with the Subtropical Jetstream (A) into northern Arabia and the Gulf. Its lower layers are heated by its overriding the warm maritime air but its higher levels remain cold. The incursions of the anticyclonic southerly waves (B) are responsible for the winter rain in the Emirates.

C. **Tropical Continental Air** (October to May): Strong westerly and southerly air flows from Africa and Arabia giving rise to hot dusty surface winds.
The median location of the Subtropical Jetstream in winter.

It is common that velocities within the Subtropical Jetstream may exceed 200 knots over the Emirates, but the median location of the Jetstream is over the upper Gulf.

Intermittent southerly advances of the Polar Front and the resulting deviations in the easterly flow of the Subtropical Jetstream cause the atmospheric disturbances that bring rain to the Emirates between December and May.

(Both maps were compiled from information obtained from the following sources: WMO; W.B. Fisher; Iran Islamic Republic Meteorological Organization; P. Beaumont; UAE Civil Aviation Authorities (the Airports Met. Offices); 'Winter Shamal in the Arabian/Persian Gulf': Naval Environmental Prediction Research Facility, T. Perrone, USA.)
The distribution of the mid-level (3000-6000m.) atmospheric pressure in summer (July).

Notice the position of the Inter-Tropical Convergence Zone (ITC) above which the violent Westerlies give rise to the monsoon 'cell' in the northern Indian Ocean, which is the source of rain in mid-summer on the east (Batinah) coast of the Emirates.

The distribution of the mid-level (3000-6000m.) atmospheric pressure in winter (January).

Notice the median location of the Cold Polar Front whose incursions southwards into the Gulf disrupts the easterly flow of the Subtropical Jetstream giving rise to disturbed weather conditions that greatly help in causing the winter frontal Mediterranean type of rainfall in the Emirates.

(Basic data for both maps were obtained from: Deutsches Hydrographisches Institut, Nachtrag Nr 1, pages 30 and 32, Hamburg, 1985, Ungenhemigter Nachdruck).
Figure: 3.7. A and B

Mid-level (3000-6000m.) atmospheric conditions over the Emirates during the summer monsoon storm of 20th., July, 1988.

Notice the weaker velocities of the Subtropical Jetstream and its location further north, but also the presence of an easterly Jetstream. The two Jetstream systems are separated by the so-called 'Subtropical Ridge' at latitudes 27°-30° North.

Figure: 3.8. A and B

Mid-level (3000-6000m.) atmospheric conditions over the Emirates during the widespread winter rainstorms of 17th., February, 1988.

Notice the location of the Subtropical Jetstream with its core (shaded) over the upper Gulf. Incursions of air from the cold moist Polar Front from the north, the warm moist monsoons from the south, interacting with the usual Mediterranean cyclones from the west and northwest caused the continuous 24-hour rainstorms of the 17th. of February, 1988.

(Both maps were drawn from information contained in synoptic weather charts obtained from Abu Dhabi Airport Meteorological Office)
Solar radiation: 24-hour mean and maximum values for Abu Dhabi Airport Meteorological Station (in Cal/cm²).

The high values from April to September coincide with the high temperature and evaporation values.

Table: 3.3.

<table>
<thead>
<tr>
<th>Station</th>
<th>O</th>
<th>N</th>
<th>D</th>
<th>J</th>
<th>F</th>
<th>M</th>
<th>A</th>
<th>M</th>
<th>J</th>
<th>Ju</th>
<th>A</th>
<th>S</th>
<th>Daily mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharjah</td>
<td>130</td>
<td>142</td>
<td>126</td>
<td>137</td>
<td>152</td>
<td>167</td>
<td>165</td>
<td>182</td>
<td>190</td>
<td>170</td>
<td>160</td>
<td>125</td>
<td>154 km/d</td>
</tr>
<tr>
<td>Abu Dhabi</td>
<td>355</td>
<td>355</td>
<td>266</td>
<td>312</td>
<td>355</td>
<td>444</td>
<td>401</td>
<td>401</td>
<td>401</td>
<td>341</td>
<td>418</td>
<td>305</td>
<td>362 km/d</td>
</tr>
<tr>
<td>Al Hibab</td>
<td>146</td>
<td>222</td>
<td>134</td>
<td>131</td>
<td>138</td>
<td>191</td>
<td>151</td>
<td>188</td>
<td>161</td>
<td>151</td>
<td>203</td>
<td>117</td>
<td>161 km/d</td>
</tr>
<tr>
<td>Falaj Al Mualla</td>
<td>73</td>
<td>66</td>
<td>61</td>
<td>70</td>
<td>92</td>
<td>102</td>
<td>106</td>
<td>108</td>
<td>110</td>
<td>100</td>
<td>87</td>
<td>69</td>
<td>87 km/d</td>
</tr>
<tr>
<td>Mileha</td>
<td>95</td>
<td>92</td>
<td>87</td>
<td>85</td>
<td>96</td>
<td>99</td>
<td>115</td>
<td>125</td>
<td>124</td>
<td>129</td>
<td>112</td>
<td>90</td>
<td>104 km/d</td>
</tr>
<tr>
<td>Masafi</td>
<td>153</td>
<td>149</td>
<td>149</td>
<td>167</td>
<td>150</td>
<td>196</td>
<td>165</td>
<td>177</td>
<td>151</td>
<td>201</td>
<td>218</td>
<td>180</td>
<td>171 km/d</td>
</tr>
<tr>
<td>Masfut</td>
<td>139</td>
<td>169</td>
<td>169</td>
<td>175</td>
<td>134</td>
<td>180</td>
<td>204</td>
<td>166</td>
<td>122</td>
<td>137</td>
<td>104</td>
<td>154</td>
<td>154 km/d</td>
</tr>
<tr>
<td>Kalba</td>
<td>67</td>
<td>96</td>
<td>109</td>
<td>119</td>
<td>118</td>
<td>125</td>
<td>75</td>
<td>157</td>
<td>105</td>
<td>80</td>
<td>88</td>
<td>66</td>
<td>100 km/d</td>
</tr>
<tr>
<td>Dibba</td>
<td>130</td>
<td>189</td>
<td>189</td>
<td>190</td>
<td>173</td>
<td>274</td>
<td>271</td>
<td>357</td>
<td>188</td>
<td>178</td>
<td>192</td>
<td>165</td>
<td>208 km/d</td>
</tr>
<tr>
<td>Monthly mean</td>
<td>143</td>
<td>164</td>
<td>143</td>
<td>154</td>
<td>156</td>
<td>198</td>
<td>178</td>
<td>211</td>
<td>177</td>
<td>164</td>
<td>179</td>
<td>136</td>
<td>167 km/d</td>
</tr>
</tbody>
</table>

Table: 3.4.

Surface wind in km/d for stations in all the topographical zones (for the hydrological year October-September).

The strongest winds are on the west and east coasts, followed by the mountains and desert foreland.
(3000-5000m.) and extends to Oman and the Gulf. With it is associated a strong wind system that affects the Emirates during these months. The weaker summer Subtropical Jetstream blows from the east at heights of about 9000 to 11000m. (Fig. 3.7.A-B.). The wind system that develops in the lower atmosphere (3000m.) is the Trade Winds of the southern hemisphere, which cross the equatorial zone to be deflected north of the Equator as the south-westerlies. Two more dry and low level wind systems blow during the same period from June to September from the north and north-east. These two winds, together with the moisture-laden south-westerlies blowing from the Indian Ocean and the Arabian Sea, converge in the so-called Inter-Tropical Convergence Zone (ITC) (Fig. 3.5.). Above this zone, in the middle atmosphere, are the violent easterlies that give rise to the monsoon 'cell' (5000m.) of the northern Indian Ocean, which is the source of rain on the east coast of Oman and the Emirates in mid-summer. (Fig. 3.5.).

3.4. Climatic elements

This discussion illustrates the aridity of the Emirates and the limited contribution to recharge from precipitation effected by the climatic elements. Solar radiation and the resulting temperature, humidity, wind and evaporation are all factors directly affecting water resources.

Precipitation requires detailed research, as little is known of its distribution and actual contribution to recharge in the Emirates. This provides the background to the analysis of the uneven distribution of precipitation and the actual contribution to recharge from surface runoff put forward in the chapters on 'Surface Hydrology' (Chapter 4) and the 'Recharge Potential, Groundwater Reserves and the Groundwater Balance' (Chapter 10.).

3.4.1. Radiation

Solar radiation may be defined as the sum of direct and diffused radiation falling on a unit horizontal surface for the day. It is measured only at Abu Dhabi and Sharjah airports. As may be expected from such a location as that of the Emirates, solar radiation is high and
intense all the year round. Table 3.3. gives the 24 hour mean and 24 hour maximum radiation as measured at Abu Dhabi airport. As seen in Table 3.3., the intensity of radiation varies from the hourly maximum of 436 cal/cm² in December to 732 cal/cm² in July, while the yearly mean is 543 cal/cm². (hour). These high values of radiation provide intense heating of the land surface, producing high temperatures and inducing high potential evaporation rates.

3.4.2. Temperature

Table 3.5. shows the mean monthly and mean annual temperature. The mean monthly summer temperature is above 30°C in all the topographical regions between the months of May and September, with the highest summer temperature occurring in July and August when the mean monthly is between 34°C and 36°C. There is little variation in the summer monthly mean temperature between coastal and interior stations, whether in the desert foreland, the piedmont plains or the mountains. Winter monthly means for January and February also show minimal variation, with the mean temperature in January being between 18°C and 20°C. While the west coast, the desert foreland and the piedmont plains show similarity of mean temperature in January, some mountain stations such as Burairat and Masfut, and also stations on the east coast, such as Dibba, show slightly higher temperatures, with the east coast having relatively the warmest values in January (Masfut 21.5°C, (in the mountains) Dibba 21.6°C (on the east coast)).

The mean annual temperature also shows little variation for all the topographic regions, being between 26°C and 29°C, with the lowest means being for the stations on the Gulf coast of Dubai, Sharjah and Jabal Addhannah (26°C to 26.5°C). Annual mean values are higher by 1°C to 2°C occur in the piedmont plains, mountains and east coast. Dibba, on the east coast, has the highest annual mean of 28.6°C, while in Al Burairat, in the northern mountains, the annual mean temperature is 27.9°C.

Table 3.6. presents the mean monthly maximum and minimum temperatures. The mean maximum values range from 31°C to 37°C, with the higher values...
<table>
<thead>
<tr>
<th>Station</th>
<th>J</th>
<th>F</th>
<th>M</th>
<th>A</th>
<th>M</th>
<th>J</th>
<th>Ju</th>
<th>A</th>
<th>S</th>
<th>O</th>
<th>N</th>
<th>D</th>
<th>Ann. Mean</th>
<th>Area Ann. Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WEST COAST</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dubai</td>
<td>18.0</td>
<td>18.0</td>
<td>19.7</td>
<td>23.9</td>
<td>30.7</td>
<td>32.2</td>
<td>34.0</td>
<td>34.8</td>
<td>31.8</td>
<td>29.2</td>
<td>23.0</td>
<td>18.9</td>
<td>26.2</td>
<td></td>
</tr>
<tr>
<td>Sharjah</td>
<td>19.3</td>
<td>19.4</td>
<td>22.7</td>
<td>27.2</td>
<td>29.1</td>
<td>31.7</td>
<td>34.4</td>
<td>34.2</td>
<td>31.5</td>
<td>27.7</td>
<td>22.5</td>
<td>19.7</td>
<td>26.6</td>
<td></td>
</tr>
<tr>
<td>Abu Dhabi</td>
<td>20.4</td>
<td>20.0</td>
<td>23.2</td>
<td>27.7</td>
<td>30.0</td>
<td>32.1</td>
<td>34.2</td>
<td>34.4</td>
<td>32.2</td>
<td>28.8</td>
<td>24.1</td>
<td>21.1</td>
<td>27.4</td>
<td></td>
</tr>
<tr>
<td>Jabal Addannah</td>
<td>18.5</td>
<td>19.8</td>
<td>21.5</td>
<td>24.8</td>
<td>27.5</td>
<td>31.0</td>
<td>32.2</td>
<td>33.1</td>
<td>32.2</td>
<td>29.8</td>
<td>24.2</td>
<td>23.4</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td><strong>DESERT FORELAND</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Hibab</td>
<td>19.2</td>
<td>19.7</td>
<td>22.6</td>
<td>28.0</td>
<td>29.8</td>
<td>32.3</td>
<td>35.3</td>
<td>35.1</td>
<td>31.1</td>
<td>27.7</td>
<td>22.0</td>
<td>19.3</td>
<td>26.0</td>
<td></td>
</tr>
<tr>
<td>Madinet Zayed</td>
<td>16.5</td>
<td>20.1</td>
<td>23.9</td>
<td>28.6</td>
<td>32.1</td>
<td>33.9</td>
<td>35.1</td>
<td>35.8</td>
<td>33.3</td>
<td>30.0</td>
<td>24.1</td>
<td>21.1</td>
<td>27.9</td>
<td></td>
</tr>
<tr>
<td>Bu Hesa</td>
<td>21.0</td>
<td>22.5</td>
<td>22.5</td>
<td>28.5</td>
<td>33.0</td>
<td>35.3</td>
<td>35.8</td>
<td>36.0</td>
<td>34.5</td>
<td>30.5</td>
<td>25.0</td>
<td>21.4</td>
<td>28.3</td>
<td></td>
</tr>
<tr>
<td>Asab</td>
<td>14.8</td>
<td>15.4</td>
<td>22.5</td>
<td>28.2</td>
<td>30.4</td>
<td>32.0</td>
<td>35.6</td>
<td>36.6</td>
<td>34.1</td>
<td>30.1</td>
<td>21.1</td>
<td>16.6</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td><strong>PIEDMONT PLAINS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digdaga</td>
<td>18.8</td>
<td>19.4</td>
<td>22.5</td>
<td>26.9</td>
<td>29.4</td>
<td>32.3</td>
<td>35.4</td>
<td>34.1</td>
<td>31.0</td>
<td>27.0</td>
<td>22.1</td>
<td>19.6</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td>Hamraniyyah</td>
<td>19.9</td>
<td>20.1</td>
<td>22.9</td>
<td>27.8</td>
<td>29.1</td>
<td>32.9</td>
<td>35.6</td>
<td>34.9</td>
<td>32.0</td>
<td>27.9</td>
<td>22.1</td>
<td>20.1</td>
<td>27.0</td>
<td></td>
</tr>
<tr>
<td>Falaj Al Mualla</td>
<td>19.6</td>
<td>20.9</td>
<td>23.0</td>
<td>28.5</td>
<td>29.7</td>
<td>31.5</td>
<td>34.3</td>
<td>33.6</td>
<td>30.5</td>
<td>26.1</td>
<td>22.7</td>
<td>19.9</td>
<td>26.7</td>
<td></td>
</tr>
<tr>
<td>Al Ain</td>
<td>19.5</td>
<td>19.8</td>
<td>22.9</td>
<td>28.7</td>
<td>31.9</td>
<td>31.9</td>
<td>36.1</td>
<td>35.9</td>
<td>32.8</td>
<td>30.4</td>
<td>22.7</td>
<td>19.1</td>
<td>27.3</td>
<td></td>
</tr>
<tr>
<td><strong>MOUNTAINS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burairat</td>
<td>20.9</td>
<td>21.3</td>
<td>23.6</td>
<td>28.9</td>
<td>31.2</td>
<td>33.7</td>
<td>35.6</td>
<td>35.4</td>
<td>32.3</td>
<td>27.1</td>
<td>23.9</td>
<td>21.1</td>
<td>27.9</td>
<td></td>
</tr>
<tr>
<td>Masafi</td>
<td>19.5</td>
<td>19.4</td>
<td>22.3</td>
<td>29.9</td>
<td>31.2</td>
<td>34.8</td>
<td>35.7</td>
<td>34.8</td>
<td>31.8</td>
<td>27.4</td>
<td>22.8</td>
<td>19.6</td>
<td>27.0</td>
<td></td>
</tr>
<tr>
<td>Masfut</td>
<td>21.5</td>
<td>19.5</td>
<td>23.0</td>
<td>29.3</td>
<td>31.1</td>
<td>34.1</td>
<td>35.7</td>
<td>35.8</td>
<td>32.0</td>
<td>27.4</td>
<td>23.0</td>
<td>20.5</td>
<td>27.7</td>
<td></td>
</tr>
<tr>
<td><strong>EAST COAST</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dibba</td>
<td>21.6</td>
<td>22.5</td>
<td>24.1</td>
<td>29.7</td>
<td>31.7</td>
<td>35.2</td>
<td>34.4</td>
<td>34.3</td>
<td>32.5</td>
<td>29.2</td>
<td>24.8</td>
<td>22.3</td>
<td>28.6</td>
<td></td>
</tr>
<tr>
<td>Kalba</td>
<td>21.5</td>
<td>21.6</td>
<td>24.0</td>
<td>29.2</td>
<td>31.4</td>
<td>34.8</td>
<td>35.5</td>
<td>34.3</td>
<td>31.9</td>
<td>28.4</td>
<td>24.3</td>
<td>22.5</td>
<td>26.3</td>
<td></td>
</tr>
</tbody>
</table>

Table: 3.5.

Mean monthly temperature, annual mean for each station and the annual mean for the area (topographic region) (° Celsius).

The highest area annual mean temperature is in the mountains and east coast, while the lowest is on the west coast where the relative humidity is highest causing relative cooling of air temperature.
### Table: 3.6.

Mean monthly maximum and mean monthly minimum temperature and the annual mean maximum and minimum for the Emirates.

The relatively higher and lower mean monthly maximum and minimum temperatures occur in the piedmont (gravel) plains and the desert foreland.
being in desert foreland and piedmont plain locations (33°C to 37°C). The mean annual minimum values range from 14°C to 24°C, with the lowest values being in the same regions of the desert foreland and the piedmont plains; and the higher values on the western and eastern coasts (21°C to 24°C), with the eastern coast having the higher values of the two coasts.

In Table 3.7. are given the absolute maximum and absolute minimum temperatures and the range between them. Absolute maximum values of over 40°C occur in all regions between May and October, while maxima of over 45°C occur in all regions between June and August. The highest absolute maximum temperatures that occur in the piedmont plains range from 48°C to 49°C, values that are reached in places like Falaj Al Mualla, Mileiha and Al Ain. Absolute maximum values of up to 50°C are reached in July in places, such as Asab, in the heartland of the desert foreland. In the latter place, absolute maxima of over 48°C are recorded throughout June, July and August. Such high temperatures cause most of the rainfall from convectional and monsoon storms in the summer in the mountains to evaporate; hence they least benefit recharge during this season.

The lowest temperatures occur between December and February and the lowest absolute minimum values are measured in the piedmont plains and the desert foreland reaching 1°C in Asab and Liwa. The lowest absolute minimum temperature recorded was -6°C at Digdaga in 1967 (Trucial States Water Resources Survey, 1966-69). The east coast has the highest absolute minimum temperatures of any region in the country followed by the west coast (16.6°C and 9.9°C respectively).

Such low winter temperatures and the cloudy conditions help to minimize evaporation (although the high winds maintain relatively high evaporation, especially after the rains have stopped) and maximize surface flows and recharge from them.

Figure 3.9. A to C shows the isotherms for the mean monthly minimum temperature for January, the mean monthly maximum temperature for July and the mean annual temperature for the period of records.
<table>
<thead>
<tr>
<th>Station/ Region</th>
<th>J</th>
<th>F</th>
<th>M</th>
<th>A</th>
<th>M</th>
<th>J</th>
<th>Ju</th>
<th>A</th>
<th>S</th>
<th>O</th>
<th>N</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>West Coast</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dubai</td>
<td>30.2</td>
<td>32.2</td>
<td>30.4</td>
<td>34.7</td>
<td>42.6</td>
<td>43.4</td>
<td>47.0</td>
<td>44.7</td>
<td>41.2</td>
<td>40.0</td>
<td>35.1</td>
<td>28.4</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>10.4</td>
<td>9.9</td>
<td>11.6</td>
<td>14.8</td>
<td>20.4</td>
<td>23.3</td>
<td>25.4</td>
<td>28.4</td>
<td>23.4</td>
<td>19.8</td>
<td>13.1</td>
<td>9.4</td>
</tr>
<tr>
<td>Range</td>
<td>19.8</td>
<td>22.3</td>
<td>18.8</td>
<td>19.9</td>
<td>22.2</td>
<td>20.1</td>
<td>22.4</td>
<td>16.3</td>
<td>17.8</td>
<td>20.2</td>
<td>22.0</td>
<td>19.0</td>
</tr>
<tr>
<td><strong>Desert Foreland</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Hibab</td>
<td>30.0</td>
<td>31.2</td>
<td>32.6</td>
<td>37.8</td>
<td>44.4</td>
<td>46.6</td>
<td>48.2</td>
<td>46.2</td>
<td>44.6</td>
<td>40.4</td>
<td>35.0</td>
<td>30.6</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>6.8</td>
<td>6.4</td>
<td>8.8</td>
<td>10.4</td>
<td>16.4</td>
<td>18.8</td>
<td>22.2</td>
<td>26.2</td>
<td>25.6</td>
<td>29.4</td>
<td>23.6</td>
<td>16.7</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>23.2</td>
<td>24.8</td>
<td>23.8</td>
<td>27.4</td>
<td>28.0</td>
<td>27.8</td>
<td>26.0</td>
<td>20.2</td>
<td>25.0</td>
<td>25.5</td>
<td>24.6</td>
<td>23.9</td>
</tr>
<tr>
<td>Aseb</td>
<td>31.0</td>
<td>34.0</td>
<td>33.7</td>
<td>41.0</td>
<td>45.0</td>
<td>48.0</td>
<td>50.0</td>
<td>48.0</td>
<td>46.0</td>
<td>42.0</td>
<td>37.0</td>
<td>29.0</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>4.0</td>
<td>14.0</td>
<td>18.0</td>
<td>20.0</td>
<td>13.0</td>
<td>12.0</td>
<td>11.0</td>
<td>5.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>30.0</td>
<td>33.0</td>
<td>32.7</td>
<td>37.0</td>
<td>31.0</td>
<td>30.0</td>
<td>30.0</td>
<td>35.0</td>
<td>34.0</td>
<td>31.0</td>
<td>32.0</td>
<td>27.0</td>
</tr>
<tr>
<td><strong>Piedmont Plains</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Falaj Al Mualla</td>
<td>30.6</td>
<td>32.8</td>
<td>32.0</td>
<td>39.0</td>
<td>45.0</td>
<td>47.5</td>
<td>49.0</td>
<td>45.5</td>
<td>44.5</td>
<td>41.5</td>
<td>36.0</td>
<td>31.9</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>2.4</td>
<td>2.8</td>
<td>6.0</td>
<td>8.8</td>
<td>11.4</td>
<td>18.4</td>
<td>21.2</td>
<td>25.0</td>
<td>18.0</td>
<td>17.8</td>
<td>4.8</td>
<td>6.5</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>28.2</td>
<td>30.0</td>
<td>26.0</td>
<td>30.2</td>
<td>33.6</td>
<td>29.2</td>
<td>28.2</td>
<td>20.0</td>
<td>26.5</td>
<td>23.7</td>
<td>31.2</td>
<td>25.4</td>
</tr>
<tr>
<td>Range</td>
<td>25.8</td>
<td>28.0</td>
<td>20.0</td>
<td>30.0</td>
<td>34.0</td>
<td>32.0</td>
<td>32.0</td>
<td>34.0</td>
<td>30.0</td>
<td>37.2</td>
<td>37.2</td>
<td>28.8</td>
</tr>
<tr>
<td>Mleiha</td>
<td>30.4</td>
<td>31.0</td>
<td>32.0</td>
<td>39.0</td>
<td>45.5</td>
<td>47.6</td>
<td>49.0</td>
<td>46.0</td>
<td>44.5</td>
<td>44.4</td>
<td>35.0</td>
<td>29.6</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>5.0</td>
<td>2.0</td>
<td>5.0</td>
<td>8.0</td>
<td>14.0</td>
<td>14.8</td>
<td>19.0</td>
<td>24.8</td>
<td>21.0</td>
<td>17.2</td>
<td>8.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>25.2</td>
<td>29.0</td>
<td>27.0</td>
<td>30.6</td>
<td>40.5</td>
<td>32.8</td>
<td>30.0</td>
<td>22.8</td>
<td>23.5</td>
<td>27.2</td>
<td>27.0</td>
<td>23.6</td>
</tr>
<tr>
<td>Range</td>
<td>23.0</td>
<td>29.5</td>
<td>28.0</td>
<td>30.0</td>
<td>40.0</td>
<td>35.0</td>
<td>30.0</td>
<td>22.0</td>
<td>28.0</td>
<td>27.0</td>
<td>25.0</td>
<td>22.5</td>
</tr>
<tr>
<td>Al Ain</td>
<td>31.0</td>
<td>32.0</td>
<td>32.5</td>
<td>40.0</td>
<td>44.0</td>
<td>48.0</td>
<td>48.5</td>
<td>46.5</td>
<td>45.5</td>
<td>43.0</td>
<td>34.5</td>
<td>29.0</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>6.0</td>
<td>4.5</td>
<td>4.5</td>
<td>13.0</td>
<td>15.0</td>
<td>15.5</td>
<td>22.0</td>
<td>24.0</td>
<td>18.5</td>
<td>15.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>25.0</td>
<td>27.5</td>
<td>28.0</td>
<td>27.0</td>
<td>31.5</td>
<td>26.5</td>
<td>22.5</td>
<td>27.0</td>
<td>27.5</td>
<td>28.0</td>
<td>28.0</td>
<td>22.5</td>
</tr>
<tr>
<td><strong>Mountains</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Masafi</td>
<td>29.8</td>
<td>29.2</td>
<td>28.1</td>
<td>36.0</td>
<td>41.2</td>
<td>44.6</td>
<td>45.2</td>
<td>43.0</td>
<td>40.4</td>
<td>39.0</td>
<td>31.0</td>
<td>26.7</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>8.0</td>
<td>7.0</td>
<td>9.1</td>
<td>12.1</td>
<td>19.1</td>
<td>20.4</td>
<td>25.2</td>
<td>24.6</td>
<td>25.0</td>
<td>29.0</td>
<td>12.2</td>
<td>11.3</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>21.8</td>
<td>21.0</td>
<td>19.0</td>
<td>23.9</td>
<td>22.1</td>
<td>22.2</td>
<td>22.0</td>
<td>19.6</td>
<td>15.4</td>
<td>19.0</td>
<td>18.8</td>
<td>15.4</td>
</tr>
<tr>
<td>Range</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>East Coast</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dirba</td>
<td>30.0</td>
<td>30.0</td>
<td>28.0</td>
<td>40.2</td>
<td>45.2</td>
<td>46.8</td>
<td>46.0</td>
<td>41.0</td>
<td>42.0</td>
<td>40.1</td>
<td>32.0</td>
<td>31.0</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>13.2</td>
<td>14.0</td>
<td>12.0</td>
<td>16.0</td>
<td>22.0</td>
<td>25.2</td>
<td>29.0</td>
<td>26.0</td>
<td>24.0</td>
<td>20.0</td>
<td>16.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>17.0</td>
<td>16.0</td>
<td>16.0</td>
<td>24.2</td>
<td>23.2</td>
<td>21.8</td>
<td>17.0</td>
<td>15.0</td>
<td>18.0</td>
<td>20.1</td>
<td>16.0</td>
<td>18.0</td>
</tr>
</tbody>
</table>

Source of data is the Ministry of Agriculture and Fisheries.

Table: 3.7.

Absolute maximum and minimum monthly temperature and their range.

The highest temperature range occurs in the piedmont plains and the desert foreland, while the lowest temperature range occurs in the mountains.
Figure: 3.9. (A – C)

Isothermal maps of the mean monthly minimum temperature for January (A), the mean monthly maximum temperature for July (B) and the mean annual temperature for the whole Emirates (C).

The heart of the desert foreland (central Abu Dhabi and Liwa) experiences the highest and lowest temperatures in summer and winter; the mountains, situated in the narrow peninsula of the Northern Emirates, have their temperatures ameliorated during both seasons by proximity to both the Gulf and Arabian Sea waters.
The range between the absolute maximum and absolute minimum varies between 16°C and 41°C but is generally between 20°C and 41°C in the piedmont plains with the widest range being at Mileiha (reaching 40.5°C in the month of May) (Table 3.7.).

3.4.3. Wind

The cumulative monthly wind run, expressed in km/d, varies from a mean of 96 km/d in the piedmont plains to 258 km/d on the west coast. The mean wind speed for the mountains is 163 km/d. The highest mean wind run values are for Dibba on the east coast (208 km/d.) and Abu Dhabi on the west coast 362 km/d.) followed by Masafi in the mountains (171 km/d.). (Table 3.4.).

On the Gulf coast surface winds are mostly southerly and south-easterly at night and early morning, changing to westerly and north-westerly by mid-day as the sea breeze becomes established. Higher wind runs coincide with the incidence of rainfall in winter and are associated with the 'frontal' movement of the cold moist air aided across the Gulf from the Mediterranean by the Subtropical Jetstream between December and March. High wind runs also induce high evaporation rates (see Table 3.27 and Fig. 3.18.).

Sandstorms occur frequently in January, March and April, while thick dust in suspension is prevalent during June, July and August. Gale force north-easterly winds, known as the 'Nashi', develop around November, while during the summer the northerly 'Shamal' (in June-July), lasting for about 40 days, causes haze and reduces visibility. Both are dry winds enhancing the potential evaporation rate.

On the Gulf coast, besides the major winds as part of the low level atmospheric circulation, land and sea breezes govern the general wind pattern. Table 3.4. gives the daily mean surface winds for stations in the mountains, the piedmont plains, the desert foreland and the east and west coasts.

The stronger the wind the higher the evaporation rate. Even during the rainy season, when rain is falling, evaporation is taking
All evaporation measurement is of the open pan type and, as the instruments do not work during the period of rain due to the flooding, and also because of the general state of disrepair of the pans, measurement of losses of water due to evaporation during the rainy/cloudy conditions has never been possible in the Emirates.

3.4.4. Relative Humidity

The mean annual relative humidity is everywhere above 50% indicating conditions of high humidity throughout the year. Both the east and west coasts have the highest relative humidity means of 61% and 59% respectively, followed by the piedmont plains and the desert foreland where the relative humidity values are less by only 13% (Table 3.8.). May is the least humid month, with the mean relative humidity being below 50% in all the regions. There is an abrupt increase of relative humidity in June, particularly on both the Gulf and Batinah coasts, to over 60%, persisting at that level for four months. The absolute maximum humidity rises to well over 90% and may reach 100% especially before dawn for the greater part of the year. There is usually a high diurnal variation in relative humidity as shown in Table 3.8. by the absolute maximum and absolute minimum values which may vary from 1% to 100% in all the regions. This humidity range is wider during the summer than the winter months on the west (Gulf) coast, but is as wide as 1% to 100% for most of the months from February to November in all the other regions.

The higher the humidity in the lower atmosphere, the less the evaporation. It is usual before dawn in coastal areas for the relative humidity to reach 100% and dew is important for sustaining halophyte grass and small bushes growing on the sand dunes.
<table>
<thead>
<tr>
<th>Station/Region</th>
<th>J</th>
<th>F</th>
<th>M</th>
<th>A</th>
<th>M</th>
<th>J</th>
<th>Ju</th>
<th>A</th>
<th>S</th>
<th>O</th>
<th>N</th>
<th>D</th>
<th>Ann. Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>West Coast</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dubai</td>
<td>65</td>
<td>70</td>
<td>66</td>
<td>59</td>
<td>47</td>
<td>51</td>
<td>58</td>
<td>53</td>
<td>64</td>
<td>61</td>
<td>60</td>
<td>68</td>
<td>61</td>
</tr>
<tr>
<td>Mean Max.</td>
<td>83</td>
<td>89</td>
<td>85</td>
<td>62</td>
<td>69</td>
<td>65</td>
<td>82</td>
<td>71</td>
<td>84</td>
<td>82</td>
<td>79</td>
<td>83</td>
<td>81</td>
</tr>
<tr>
<td>Mean Min.</td>
<td>45</td>
<td>49</td>
<td>44</td>
<td>33</td>
<td>25</td>
<td>31</td>
<td>29</td>
<td>32</td>
<td>35</td>
<td>33</td>
<td>32</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>100</td>
<td>99</td>
<td>100</td>
<td>99</td>
<td>90</td>
<td>99</td>
<td>100</td>
<td>88</td>
<td>100</td>
<td>100</td>
<td>97</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>19</td>
<td>19</td>
<td>15</td>
<td>11</td>
<td>12</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>1</td>
<td>11</td>
<td>17</td>
<td>26</td>
<td>14</td>
</tr>
<tr>
<td><strong>Desert Foreland</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Htibab</td>
<td>60</td>
<td>56</td>
<td>50</td>
<td>46</td>
<td>51</td>
<td>47</td>
<td>49</td>
<td>47</td>
<td>49</td>
<td>49</td>
<td>53</td>
<td>55</td>
<td>51</td>
</tr>
<tr>
<td>Mean Max.</td>
<td>89</td>
<td>93</td>
<td>87</td>
<td>85</td>
<td>94</td>
<td>96</td>
<td>86</td>
<td>85</td>
<td>96</td>
<td>90</td>
<td>87</td>
<td>86</td>
<td>90</td>
</tr>
<tr>
<td>Mean Min.</td>
<td>31</td>
<td>19</td>
<td>13</td>
<td>7</td>
<td>9</td>
<td>4</td>
<td>13</td>
<td>8</td>
<td>3</td>
<td>7</td>
<td>20</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>96</td>
<td>99</td>
<td>98</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>99</td>
<td>97</td>
<td>98</td>
<td>99</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td><strong>Piedmont plains</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Falaj Al</td>
<td>63</td>
<td>64</td>
<td>62</td>
<td>55</td>
<td>44</td>
<td>49</td>
<td>50</td>
<td>48</td>
<td>50</td>
<td>56</td>
<td>62</td>
<td>68</td>
<td>56</td>
</tr>
<tr>
<td>Mean Max.</td>
<td>99</td>
<td>98</td>
<td>98</td>
<td>96</td>
<td>83</td>
<td>94</td>
<td>90</td>
<td>81</td>
<td>93</td>
<td>97</td>
<td>96</td>
<td>99</td>
<td>94</td>
</tr>
<tr>
<td>Mean Min.</td>
<td>28</td>
<td>29</td>
<td>25</td>
<td>14</td>
<td>5</td>
<td>3</td>
<td>9</td>
<td>15</td>
<td>9</td>
<td>14</td>
<td>27</td>
<td>37</td>
<td>18</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Al Ain</td>
<td>62</td>
<td>63</td>
<td>57</td>
<td>52</td>
<td>39</td>
<td>41</td>
<td>43</td>
<td>45</td>
<td>36</td>
<td>50</td>
<td>72</td>
<td>72</td>
<td>70</td>
</tr>
<tr>
<td>Mean Max.</td>
<td>93</td>
<td>92</td>
<td>91</td>
<td>85</td>
<td>78</td>
<td>80</td>
<td>76</td>
<td>73</td>
<td>83</td>
<td>56</td>
<td>90</td>
<td>93</td>
<td>83</td>
</tr>
<tr>
<td>Mean Min.</td>
<td>31</td>
<td>28</td>
<td>23</td>
<td>21</td>
<td>18</td>
<td>10</td>
<td>13</td>
<td>23</td>
<td>13</td>
<td>16</td>
<td>27</td>
<td>41</td>
<td>22</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>96</td>
<td>97</td>
<td>96</td>
<td>97</td>
<td>93</td>
<td>95</td>
<td>93</td>
<td>100</td>
<td>93</td>
<td>97</td>
<td>95</td>
<td>97</td>
<td>96</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>12</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td><strong>Mountains</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hasefl</td>
<td>64</td>
<td>64</td>
<td>58</td>
<td>47</td>
<td>37</td>
<td>42</td>
<td>45</td>
<td>58</td>
<td>44</td>
<td>47</td>
<td>54</td>
<td>67</td>
<td>52</td>
</tr>
<tr>
<td>Mean Max.</td>
<td>95</td>
<td>94</td>
<td>91</td>
<td>77</td>
<td>64</td>
<td>69</td>
<td>72</td>
<td>62</td>
<td>69</td>
<td>79</td>
<td>85</td>
<td>94</td>
<td>81</td>
</tr>
<tr>
<td>Mean Min.</td>
<td>34</td>
<td>34</td>
<td>25</td>
<td>17</td>
<td>11</td>
<td>14</td>
<td>17</td>
<td>33</td>
<td>28</td>
<td>43</td>
<td>46</td>
<td>52</td>
<td>31</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>96</td>
<td>85</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>East Coast</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DJIBBA</td>
<td>58</td>
<td>60</td>
<td>55</td>
<td>52</td>
<td>43</td>
<td>64</td>
<td>69</td>
<td>69</td>
<td>62</td>
<td>54</td>
<td>55</td>
<td>62</td>
<td>59</td>
</tr>
<tr>
<td>Mean Max.</td>
<td>85</td>
<td>86</td>
<td>86</td>
<td>83</td>
<td>78</td>
<td>92</td>
<td>94</td>
<td>86</td>
<td>84</td>
<td>83</td>
<td>81</td>
<td>84</td>
<td>85</td>
</tr>
<tr>
<td>Mean Min.</td>
<td>32</td>
<td>33</td>
<td>35</td>
<td>36</td>
<td>33</td>
<td>44</td>
<td>52</td>
<td>40</td>
<td>26</td>
<td>39</td>
<td>40</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Abs. Max.</td>
<td>100</td>
<td>96</td>
<td>100</td>
<td>100</td>
<td>96</td>
<td>91</td>
<td>86</td>
<td>91</td>
<td>98</td>
<td>100</td>
<td>98</td>
<td>100</td>
<td>97</td>
</tr>
<tr>
<td>Abs. Min.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>Monthly mean for the UAE</td>
<td>62</td>
<td>63</td>
<td>58</td>
<td>52</td>
<td>44</td>
<td>51</td>
<td>52</td>
<td>53</td>
<td>52</td>
<td>51</td>
<td>57</td>
<td>65</td>
<td>55</td>
</tr>
</tbody>
</table>

Source of data is the Ministry of Agriculture and Fisheries.

Table: 3.8.

Relative humidity (%): Monthly mean, mean maximum, mean minimum, absolute maximum, absolute minimum, monthly mean for each station and the general annual mean for the whole Emirates.

The highest mean relative humidity is in the east and west coasts (60%) and the lowest is in the desert foreland and the mountains (51%).
3.5. Rainfall

3.5.1. Introduction

Rainfall is the only source of fresh water available for recharge in the Emirates. An understanding of its amount, incidence, variability and distribution is essential in the assessment of the water resources of the country. There are two main rainfall regimes: the Mediterranean type, which is confined to the winter half of the year associated with fronts moving east with the Subtropical Jetstream; and the monsoon type occurring in the late spring and summer. The Mediterranean type is the more widespread of the two rainfall types causing rain all over the country which may occur as early as December and as late as May, but with a definite concentration during the period January to March. It accounts for most of the annual rainfall total. The monsoon type is limited to the east coast and is received mostly in early and mid summer, varying from year to year according to the spread of monsoon conditions westwards and northwards from the Gulf of Oman. In normal years, rainfall is limited to the coastal fringes of the east coast between Kalba and Dibba, while in rare and unusual years, as happened on 20th July 1988, the monsoon conditions occur as far north in eastern Arabia as Dhahran. During this time even stations in the heartland of Abu Dhabi received substantial amounts of rainfall.

Incursions of moist monsoon air also occur during the winter as happened in the exceptionally heavy rainstorms of the 17th and 19th of February 1988 caused by a combination of the usual high level cold Mediterranean fronts from the north and northwest, the mid level westerlies from the west and the incursion of the low level moist monsoon air from the northern Indian Ocean from the south and south-east.

A third, limited and more localized type of rainfall, is the convectional type occurring typically in the mountain basins, as in Masafi and Masfut, and in parts of the piedmont plains, as in Al Ain, between May and November. This is helped by both convectional currents and relief.
The mean total rainfall varies from region to region. In the mountains, where the heaviest rainfall occurs, it may be as little as 1.2mm. (1970-71) and as much as 207.0mm. in only 24 hours, as at Huwailat (16-17, February, 1988). However, the period mean (that is for the whole period of available rainfall records) for mountain stations varies from 129.0mm. (‘Asimah) and 208.0mm. (Marbadh in the mountains); between 46.0mm. (Jabal Addhannah) and 147.0mm. (Sha‘am) with only 84.0mm. for Dubai on the west coast; 114.0mm. (Dibba) and 175.0mm. (Khor Fakkan) for the east coast; 96.0mm. (Al Ain) to 144.0mm. (Filli) for the piedmont plains and 69.0mm. (Ain Busukhnah) and 109.0mm. (Al Hibab) in the desert foreland (Table 3.10).

3.5.2. Rainfall measurement network

The state of the rain recording equipment in the Emirates is discussed separately since most rainfall recorders are sited as single instruments rather than in fully equipped meteorological stations. This section provides the necessary background to allow the assessment of the reliability of rainfall measurement and of the overall state of the rain gauges and recorders. It complements section 3.2. of this chapter dealing with state of the meteorological network in general in the Emirates.

The only long-term rainfall data available are for Sharjah (55 years). The 3-year gap in the Sharjah data, which appeared in the Trucial States Water Resources Report (the Halcrow report) of 1969 and in all other subsequent studies, was filled from the archives at Bracknell in Britain (the so-called Ashfield Files) except for a 6-month gap (May to August 1949) for which no data could be traced. The Sharjah rainfall data (1934-88) are given in Table 3.15.

For the rest of the Emirates, the number of rainfall stations, including that of Sharjah, total 104 of which some are parts of complete meteorological stations, but the majority are just monitoring rainfall. They vary in the length of their records from 21 years for the oldest to only 7 years for the latest (1989). More are still being set up such as those in Al Ain (Al Ain Department of Agriculture). Table 3.9. gives
the distribution of rain gauge/recorders by region (the distribution of these rain gauge/recorders is shown in Fig. 3.10).

Rain gauges/recorders by region (1989)

Mountains 27
Piedmont Plains 19
East Coast 6
West Coast 18
Desert Foreland 34

Total: 104

Table: 3.9 Rain gauges/recorders in the Emirates by region (1989)

There are 8 establishments running comprehensive meteorological or rain gauge/recorder sites. These are:

1) The Ministry of Agriculture and Fisheries (MAF)
2) The Ministry of Electricity and Water (MEW)
3) The Airports:
   Abu Dhabi
   Dubai
   Sharjah
   Ras Al Khaimah
   Fujairah
4) The Ministry of Defence (Western Region, Abu Dhabi)
5) The Ministry of Defence (Central Region, Dubai)
6) The Department of Agriculture, Al Ain
7) The Petroleum Companies (ADCO, ADNOC and others)
8) The University of the Emirates (Faculties of Science, Agriculture and Arts).

Figure 3.10. shows the distribution of the rain gauges/recorders in the Emirates (1989). Most of the MAF rain recorders are of the automatic type with the six- or one- month charts, but there are still some stations with rain-gauges of the standard daily type (127mm. tipping bucket) such as the one still in use in Dhaid. 10 of the 13 MEW rain
Figure: 3.10.

The distribution of the rain gauges/recorders of the Emirates (1990).

The map shows all the standard and automatic rain gauges and recorders belonging to the following organizations:

- The Ministry of Agriculture and Fisheries (MAF)
- The Ministry of Electricity and Water (MEW)
- Al Ain Department of Agriculture
- The Airports
- The Western and Central Military Commands.
- The Petroleum Companies.
- The UAE University.
Annual rainfall totals for the period of records (1967-68 to 1987-88) for 38 stations in the different topographical zones of the Emirates (Also shown: the mean period (i.e., for the period of rainfall records) for each station, the area (or zone) mean and the country (UAE) mean).

The highest area mean is for the mountains (154.61mm.), followed by the east coast (142.59mm.), the piedmont plains (127.41mm.), the west coast (94.51mm.) and finally the desert foreland (91.71mm.). The highest period rainfall mean is for Marhah (207.74mm.). The lowest period rainfall mean is for Jebel Addannah (45.60mm.) on the west coast.

<table>
<thead>
<tr>
<th>Station</th>
<th>Area Mean</th>
<th>Zone Mean</th>
<th>Country Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>passenger</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table: 3.10.
recorders (Fig. 3.10.) are automatic with one-month record charts, the other 3 are of the standard daily type and are mostly neglected due to the lack of regular daily attendance. The rain recorders of the airports, and those belonging to the Emirates University in Al Ain, are all of the automatic one-month-chart type. All the rain recorders of the Military and the Al Ain Department of Agriculture are of the standard daily type. (Fig. 3.10.).

Rainfall records from 38 stations have been used in this study: 15 in the mountain region; 9 in the piedmont plains; 5 on the east coast; 6 on the west coast; and 3 in the desert foreland. Table 3.10. shows the mean annual rainfall values for all these stations, the period mean (for the whole period of available records) for each station, the area mean (that is for the zone in which the station is situated, for example, the mountain region) and the country period mean (that is for the whole Emirates). The length of rainfall record for each station is clear from Table 10.

3.5.3. Long-term rainfall characteristics

The long-term rainfall record for Sharjah (Table 3.15.) in particular was examined for trends and return periods, although the west coast in which Sharjah is situated, has less rainfall than the other regions, with the exception of the desert foreland, and cannot be taken as representative of the whole country. Selected stations, one from each zone, with records extending to 21 years, were also used for comparison with Sharjah for long-term trends and characteristics of the rainfall (Fig. 3.11. A-E).

The main long-term characteristic of the rainfall of the Emirates is its irregularity and unreliability. As seen in Table 3.10., Table 3.15. and also in Figure 3.11. A-E, which graphically illustrate the long-term annual rainfall of Sharjah, Masfut, Mileiha, Al Aweer and Fujairah, the following long-term rainfall characteristics can be detected:

1) The recurrence of two high peaks separated by a lower one (Sharjah, Figure 3.11.A years 1934-40, 1943-46, 1955-58, 1963-66), or two high peaks in consecutive years (Sharjah...
Figure: 3.11. (A to E)

(See commentary overleaf)

The graph for the Sharjah longest rainfall record shows a recurrence of 2 high peaks separated by a lower one, or two high peaks in consecutive years separated by 2-5 less rainy years. In the mountains (Masfut) rainfall peaks of 200mm. are separated by 2-4 years; in the piedmont plains (Mileiha) the same 200mm. peaks are separated by 2-5 years, on the east coast (Fujairah) by 6-7 years and on the west coast (Sharjah) they are separated by 2-3 years.
1975-76, 1981-88 / Masfut 1981-83 / Mileiha 1981-83 / Aweer 1981-83 / Fujairah 1981-83) separated by 2-3 less rainy years (Fig. 3.11 A-E).

2) In the mountains, peaks with 200mm. and more are separated by 2-4 years of much reduced totals. In the piedmont plains and the desert foreland these peaks are separated by 2-5 years of least rainfall, and on the east and west coasts by between 6-7 years and 2-3 years respectively. (Fig. 3.11. A-E).

The long term rainfall record for Sharjah was studied for long-term rainfall characteristics, and also to calculate the return periods of selected rainfall thresholds. Table 3.15 presents the mean rainfall for Sharjah for 55 years (1934-88), the annual total for each year, the period mean and also the annual total, arranged in ascending order; while Figure 3.11-A graphically represents the same data.

As seen from the Sharjah graph (Fig. 3.11.A), there are 3 types of peaks: the 260.0mm. peak attained in 1956-57, the medium peaks between 200-250mm. (1981-82) and the lower peaks between 100-150mm. (1958-59). The erratic nature of the rainfall is clear but, despite this irregularity, there seem to be intervals of 4-6 years between the low peaks of 100-150mm., and 8-10 years between the medium peaks of 200-250mm. It is not uncommon that rain of similar peaks might occur in two consecutive years, such as happened in 1974-75 and 1975-76 (167.4mm. and 168.1mm.), 1981-82 and 1982-83 (241.5mm. and 189.5mm.) and 1986-87 and 1987-88 (141.6mm. and 170.2mm.). As can also be seen in the graph, a year of least rainfall separates two peaks such, as the year 1935-36 with only 58.0mm. separating 1934-35 (154.0mm.) and 1936-37 (218.0mm.) Again, the year 1955-56 with 85.7mm. separating 1954-55 with 208.3mm. and 1956-57 with 260.2mm.

With regard to the frequency of selected rainfall thresholds (annual totals) during the period of the Sharjah rain record (Figure 3.12. E), rainfall of 50mm. recurred almost every year, that of 100mm. every 2 1/2 years, 150mm. nearly once every 5 years, the 200mm once every 11 years while the 250mm. (actually 260.2mm.) happened only once throughout the
period of record and has not recurred in any of the hydrological years since (the hydrological year is from October to the following September).

The return periods of rainfall totals for all the 38 rainfall stations made use of in the present study are given in Appendix 3. Table 3.13 is a summary of the data contained in the tables in Appendix 3.

3.5.4. Annual Rainfall

The annual rainfall pattern is similar in all the topographical regions and the only effect topography has on rainfall is in the localized increased totals in the highlands. Fig. 3.13 illustrates this in a combined diagram of the annual rainfall for stations in the mountains (Masfut), piedmont plains (Mileiha), desert foreland (Aweer) and the east (Fujairah) and west (Sharjah) coasts. The higher limb, shown in the graph for Fujairah (1981-82) is because this station is backed by high mountains and also that more rain was contributed by a monsoon incursion from the east besides the incursion from the frontal Mediterranean type from the west. There are hardly any differences in the overall rainfall pattern in all the regions as is evident in the combined graph (Fig. 3.13.), which shows coincidence in the limbs of graphs for stations in all the topographical regions. The only general striking feature is the increase of rainfall totals eastwards towards the east coast, as is seen in the increase in totals for the stations as given in the diagram (Sharjah on the west coast, Mileiha in the piedmont plains, Masfut in the mountains and Fujairah on the east coast).

Long-term rainfall averages for hill stations such as Masafi (166.6mm.) and Masfut (159.3mm.) are higher than averages elsewhere in the country. Averages for east coast stations such as Khorfakkan (175.0mm.), are in turn higher than those for the west coast, except for Sha'am (147.4mm.), which, though on the west coast, is backed by high relief enhancing its rainfall (147.4mm.); while Dubai and Abu Dhabi, also on the west coast backed by low-lying relief, have low averages (77.0mm. and 97.8mm. respectively) (refer also to Table 3.10).
Figure: 3.12. (A to G)
(See commentary overleaf)
Rainfall frequency graphs at 20mm thresholds for Masafi and Masfut in the mountains (B and F), Mileiha in the piedmont plains (A), Fujairah on the east coast (C), Al Aweer in the desert foreland (D), Sharjah on the west coast (E) and the mean for the UAE (G).

The graph for the long-term rainfall record of Sharjah illustrates that 50mm. of rainfall occurred in more than 70% of the years of records, or almost every year. 100mm. of rainfall fell in 40% of the period of records, or once every 2.5 years; 150mm., in 20% of the cases, or once every 5 years and 200mm. in 5% of the cases or once every 20 years (E). In the mountain station of Masfut (F) rainfall of 250-300mm. occurred in 25% of the cases or with a frequency of once in 4 years, while rainfall of over 350mm. occurred in 5% of the recorded years or once in 20 years. Rainfall of 250mm. in the piedmont plains and the desert foreland occurred in 20% of the cases in Mileiha (A) and Al Aweer (D) or once in 20 years. Rainfall of over 300mm. occurred on the east coast in Fujairah (C) and the mountains in Masafi (B) and Masfut (F) in 7-12% of the recorded cases, or once in 8-14 years.

The frequency graph for the mean rainfall of the UAE shows that the bulk of the rainfall was from 0-80mm. falling in 80% of the recorded years or nearly every year. 100-200mm. made 20-40% of the cases or once in 2.5 years. Taken for the whole UAE, rainfall totals of 300mm. hardly made up 3% of the recorded cases or nearly occurring once in 20-30 years.
Figure: 3.13.
Annual rainfall of the Emirates.

(Combined graph for comparison of the annual rainfall trends in selected stations in each of the topographical regions: Masfut (mountains), Fujairah (east coast), Mileiha (piedmont plains), Al Aweer (desert foreland) and Sharjah (west coast).

The high limb in the graph for Fujairah (1981-82) is due to the fact that this station receives more rainfall as it is backed by high relief and also receives a substantial contribution of its annual rainfall from the monsoons from the Indian Ocean. Otherwise, the general annual rainfall trend appears similar in all the stations, regardless of topographical differences. This suggests the widespread rainstorm conditions engulfing the larger part, if not the whole, of the Emirates.
Maximum rainfall seems to be concentrated in a cell in the central part of the ophiolite central mountain block between Fujairah and Zubarah on the east coast, ‘Asimah in the north-west, Siji in the west and Farā‘ah in the south-east, where the mean annual rainfall is over 160.0mm. The centre of high concentration is towards the north-western part of this cell encompassing the high rainfall stations of Masafi (166.6mm.), Jabal Sharmah (192.0mm.) and Marbadh (207.7mm.). The last station has the highest period rainfall mean in the Emirates. This is clearly illustrated in the isohyetal map (Figure 3.14), which is based on the annual totals of the various stations as given in Table 3.10.

A second area of high rainfall concentration is in the southern parts of the central mountains around Masfut and Hatta where the mean annual rainfall is between 140.0mm. and 160.0mm., with Masfut measuring the highest mean value of 159.3mm. A zone of similar concentration along the east coast is from Khawr Kalba in the south to Marbah in the north, and from Zubarah to Dhadhnah.

Catchments in this zone of concentration of rainfall have high runoff volumes, with east flowing wadis developing greater volumes than those flowing to the west as discussed in detail in Chapters 4 and 10.

The minimum annual rainfall means are measured along the west coast up to Sila‘, in the interior of the desert foreland from Al Wagn in the east to Sabkhat Matti in the west and Shah in Al Bateen in Liwa in the south. Although continuous rainfall data for the heartland of Abu Dhabi are rare, from the inconsistent rainfall data for Asab, Bu Hasa and Al Rudoom the annual mean rainfall can be estimated to be as low as 47.0mm. in Al Sila‘ (the westernmost station along the Gulf coast of the Emirates) and 60.0mm. in Al Rudoom in Liwa in the south. Only in years of exceptionally high rainfall, such as 1981-82, 1982-83 and 1987-88, when widespread rainy conditions prevailed over the whole Emirates, did such inland stations receive high rainfall totals: Asab (214.0mm. and 240.0mm. in 1981-82 and 1982-83), Al Wagn (385.6mm. in 1981-82), Al Dhafrah (249.1mm. and 165.5mm. in 1981-82 and 1987-88), Al Rudoom (93.0mm. in 1987-88) and Al Sila‘ (98.8mm. in 1987-88).
Figure: 3.14.

Isohyetal map of the long-term rainfall means of the Emirates.

The cell of highest rainfall is in the central part of the mountains bounded by the locations of the following settlements: Fara'ah, Khor Fakkan, Siji, 'Asimah, Marbach and Jabal Sharman; the last two stations receive the highest mean rainfall (207 mm and 192 mm respectively). The remaining parts of the Emirates, to the west and south of the areas covered by this map (i.e., the whole of the desert foreland in Abu Dhabi emirate) lies below the 100 mm isohyet with stations such as Abu Dhabi (81 mm), Al Rudooom (80 mm) and Silla (47 mm) receiving the least rainfall in the whole Emirates.
3.5.5. Variability of annual rainfall

Variability of annual rainfall, common to all arid regions, can be very extreme in the Emirates. The long-term Sharjah rainfall record shows an annual total of only 0.3mm. on the west (Gulf) coast in 1961-62 (Table 3.14) and for Bithnah in the mountains of 0.3mm. in 1970-71 (Table 3.10); but records also show 260.2mm. (1956-57) and 350.0mm. (1981-82) for these two stations, respectively.

From available rainfall records of mountain stations it appears that 1970-71 was a year of least rainfall, but the years 1983 through to 1986 were the three consecutive years of least rainfall particularly the first two years. The long term Sharjah record confirms the low rainfall of these years (Tables 3.14. and 3.15.). The variability in the annual totals is naturally reflected on the volumes of surface runoff (see Chapter 4 on Surface Hydrology).

The rainfall during the period 1983-86 averaged 29.7-73.0mm. a year, which was reflected on surface flow from the catchments as shown in Table 3.11.

<table>
<thead>
<tr>
<th></th>
<th>81-82</th>
<th>82-83</th>
<th>83-84</th>
<th>84-85</th>
<th>85-86</th>
<th>86-87</th>
<th>87-88</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean annual rainfall in mm.</td>
<td>310.9</td>
<td>266.4</td>
<td>42.7</td>
<td>29.7</td>
<td>73.0</td>
<td>180.5</td>
<td>227.20</td>
</tr>
<tr>
<td>Total runoff volume in million cubic meters (MCM)</td>
<td>47.65</td>
<td>34.98</td>
<td>0.49</td>
<td>0.13</td>
<td>0.11</td>
<td>16.41</td>
<td>68.51</td>
</tr>
</tbody>
</table>

Note: The mean annual total rainfall is for stations in the mountains and the piedmont plains (only) where surface runoff originates and mostly flows.

Table: 3.11.

The Relationship between the mean annual rainfall and annual runoff totals (1981-88).

1984-86 was a low rainfall period as reflected on the low runoff volumes.
3.5.6. **Seasonality and type of rainfall**

Table 3.12. presents the types of rainfall by season and their ratio to the annual total. Most of the annual total is from the winter Mediterranean frontal type of rainfall falling between December and March, with the highest percentage of such rainfall type being on the east coast (86%), the west coast (86%) and the desert foreland (83%). It is slightly less in the piedmont plains (79%) and the mountains (77%) where, in both areas, there are summer rains from local convectional and monsoonal types. Of the two latter types of localized rainfall, the highest in occurrence is the convectional type in the mountains (23%) and the piedmont plains (21%) where convectional rains occur during July and August. All the three types of rainfall are discussed separately in detail in sections 3.5.9.1., 3.5.9.2., 3.5.10. and 3.5.11.

3.5.7. **Annual rainfall probabilities**

For the planning of water resources, especially for design purposes, it is more useful to consider the probable rainfall than to rely on the mean rainfall, which can sometimes be misleading in quantifying the probable amounts. Rainfall probabilities or return periods were calculated by applying the formula given below to the available annual rainfall totals for all the 38 rainfall stations (Table 3.10, and Appendix 3) in ascending order:

\[
R = \frac{1}{m} - \frac{1}{N + 1}
\]

where, 
- \( R \) = Return period
- \( m \) = Rank in ascending order
- \( N \) = Total number of observations in the record in ascending order.
### Table: 3.12.

The seasonality of rainfall: the main winter rainfall and the convective and monsoonal rainfall in the summer, and the percentage of the amount of each type out of the annual total.

In the mountains the winter rainfall, the main type of rainfall in the Emirates, makes up more than 77% of the annual total, while the convective and monsoonal rains make up 22% and 21% of the annual total in the mountains and piedmont plains, respectively.

<table>
<thead>
<tr>
<th>STATION/REGION</th>
<th>Winter Rainfall to March</th>
<th>Monthly Rainfall to November</th>
<th>Period Mean Rainfall</th>
<th>Area Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount (mm)</td>
<td>January, February, March</td>
<td>Mean for Station</td>
<td>Mean mm</td>
</tr>
<tr>
<td><strong>MOUNTAINS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Ain</td>
<td>121.2</td>
<td>77.7</td>
<td>21.0</td>
<td>16.3</td>
</tr>
<tr>
<td>Al Jazirah</td>
<td>191.5</td>
<td>91.3</td>
<td>29.0</td>
<td>14.3</td>
</tr>
<tr>
<td>Al Ain</td>
<td>119.4</td>
<td>91.3</td>
<td>29.0</td>
<td>8.7</td>
</tr>
<tr>
<td>Al Ain</td>
<td>119.4</td>
<td>91.3</td>
<td>29.0</td>
<td>130.8</td>
</tr>
<tr>
<td>Al Ain</td>
<td>119.4</td>
<td>91.3</td>
<td>29.0</td>
<td>130.8</td>
</tr>
<tr>
<td>Al Ain</td>
<td>119.4</td>
<td>91.3</td>
<td>29.0</td>
<td>130.8</td>
</tr>
<tr>
<td>Al Ain</td>
<td>119.4</td>
<td>91.3</td>
<td>29.0</td>
<td>130.8</td>
</tr>
<tr>
<td>Al Ain</td>
<td>119.4</td>
<td>91.3</td>
<td>29.0</td>
<td>130.8</td>
</tr>
<tr>
<td><strong>PIEDMONT PLAINS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dibba</td>
<td>103.7</td>
<td>88.9</td>
<td>21.0</td>
<td>11.1</td>
</tr>
<tr>
<td>Dibba</td>
<td>103.7</td>
<td>88.9</td>
<td>21.0</td>
<td>11.1</td>
</tr>
<tr>
<td>Dibba</td>
<td>103.7</td>
<td>88.9</td>
<td>21.0</td>
<td>11.1</td>
</tr>
<tr>
<td>Dibba</td>
<td>103.7</td>
<td>88.9</td>
<td>21.0</td>
<td>11.1</td>
</tr>
<tr>
<td><strong>DESSERT FORELAND</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Khut</td>
<td>99.3</td>
<td>87.4</td>
<td>21.0</td>
<td>11.1</td>
</tr>
<tr>
<td>Khut</td>
<td>99.3</td>
<td>87.4</td>
<td>21.0</td>
<td>11.1</td>
</tr>
<tr>
<td>Khut</td>
<td>99.3</td>
<td>87.4</td>
<td>21.0</td>
<td>11.1</td>
</tr>
<tr>
<td>Khut</td>
<td>99.3</td>
<td>87.4</td>
<td>21.0</td>
<td>11.1</td>
</tr>
<tr>
<td><strong>WEST COAST</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dibba</td>
<td>72.3</td>
<td>87.1</td>
<td>21.0</td>
<td>17.9</td>
</tr>
<tr>
<td>Dibba</td>
<td>72.3</td>
<td>87.1</td>
<td>21.0</td>
<td>17.9</td>
</tr>
<tr>
<td>Dibba</td>
<td>72.3</td>
<td>87.1</td>
<td>21.0</td>
<td>17.9</td>
</tr>
<tr>
<td>Dibba</td>
<td>72.3</td>
<td>87.1</td>
<td>21.0</td>
<td>17.9</td>
</tr>
<tr>
<td><strong>EAST COAST</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dibba</td>
<td>59.3</td>
<td>87.1</td>
<td>21.0</td>
<td>17.9</td>
</tr>
<tr>
<td>Dibba</td>
<td>59.3</td>
<td>87.1</td>
<td>21.0</td>
<td>17.9</td>
</tr>
<tr>
<td>Dibba</td>
<td>59.3</td>
<td>87.1</td>
<td>21.0</td>
<td>17.9</td>
</tr>
<tr>
<td>Dibba</td>
<td>59.3</td>
<td>87.1</td>
<td>21.0</td>
<td>17.9</td>
</tr>
</tbody>
</table>

* Percentages in bold type refer to averages of the percentage for the stations of a region, usually in the column to the left.

Source of rainfall data are the Ministry of Agriculture and Fisheries unpublished daily and rainfall intensity records.
Table 3.13. shows the return periods of selected rainfall thresholds (or totals) for all the 38 stations by geomorphological region. For completeness the return periods for the Sharjah long rainfall record of 55 years (up to 1988) was also used and the results are given in Table 3.14.

3.5.7.1. Rainfall return periods

(Tables 1 to 38 in Appendix 3; Table 3.13 in this section; the Sharjah Table 3.14. and Fig. 3.15)

In the mountains rainfall of up to 120.00mm. may recur every year, or at the most every 2 years, at all the stations except Bithnah, where the total is reduced to 104.00mm.; and Munai’ee, where it is 106.00mm. On the east coast the total is reduced to 90-100mm., except in Zikt and Khor Fakkan, which both have return periods for the same amounts as for the mountain stations (Tables 1-38, Appendix 3).

In the piedmont plains, the values are less in the northern parts, as at Khatt and Digdaga (100.0mm.) than in the central parts as at Mileiha, Dhaid and Filli (120.0mm.). In Falaj Al Mualla, in the western extremity of the central part of the piedmont plains, the total rainfall recurring every year is 80.0mm. and at Al Ain, the value is even less (70.0mm.). Hamraniyyah in the northern part of the plains, due to its proximity to the mountains, has a high value of the amount of rainfall recurring every year (120.0mm.). The yearly value is further reduced in the desert foreland to the west, as at Al Aweer (80.0mm.) and Ain Busukhnah (40.0mm.). On the west coast, apart from Ras Al Khaimah and Sha’am (120.0mm.), the rest of the stations have lower values. Examples are, Dubai with 77.0mm. recurring every 2 years: Abu Dhabi 38.0mm. and Jabal Addhnannah 43.5mm., both with the possibility of repetition every 2 years.

Figure 3.15. depicts the period mean rainfall for all the 38 stations for the period of records set against the long-term means for the whole country (UAE) and also for the mountains, piedmont plains, desert foreland and east and west coasts zones separately. In relation to the UAE period mean (132.13mm.), nearly 70% of the stations in the
Figure: 3.15.

Annual mean rainfall values for 38 rainfall stations (Table 3.10) set against the period mean (mean for the period of record) for the UAE, and against the period mean of the mountains, the piedmont plains, east and west coasts and the desert foreland.

The positive and negative percentages refer to the number of stations (of the total number in a topographic zone) above or below the period mean for the UAE. In relation to the UAE period rainfall mean (132.13mm), nearly 70% of the mountain rainfall stations, 60% of those on the east coast, 22% in the piedmont plains and 17% on the west coast, exceed this mean. No rainfall station in the desert foreland exceeds this long-term UAE mean.
mountains, 60% of those on the east coast, 22% in the piedmont plains and 17% on the west coast, exceed this mean. No station in the desert foreland exceeds the long-term UAE rainfall mean.

The mean for the mountain zone (154.6mm) is surpassed by the means of 7 of the 15 rainfall stations of the mountain zone, but it is only surpassed by Khor Fakkan on the east coast.

As far as the high rainfall totals on the local scale are concerned, relief has a marked influence on the totals. Thus, although Masafi is only a few kilometres from Jabal Sharmah and Marbadh, its highest total of 357.1mm. (1975-76) can recur once in 21 years. The high total of 411.4mm. of Jabal Sharmah (1981-82), and the even higher total of 454.2mm. of Marbadh (1981-82) can recur once every 8 years. The total of 316.2mm. of Sfini (1981-82), which has a return period of 13 years, appears to occur once every 4 years at Marbadh, whereas such a total is not likely to fall on Munai’ee further south in even 15 years. The very high Masfut total of 475.8mm. (1974-75), the highest that has fallen in any rainfall station in the Emirates to date (1990), may occur once in 22 years. (Appendix 3) (also Table 3.10).

Conditions prevailing during extensive storms may cover the whole mountain zone or even the whole Emirates, but higher relief and aspect in relation to the rain-bearing winds are responsible for the higher totals. Stations in the western foothills such as Idhn and Siji (329.7mm. in 1981-82, and 334.5mm. in 1975-76, respectively) receive equal or sometimes more rainfall than stations within the mountains such as Munai’ee (305.6mm. in 1987-88) and ‘Asimah (332.0mm. in 1981-82) (Table 3.10.).

Table 3.13. shows the probabilities of selected thresholds. It appears that the probability of a fall of more than 100mm in the desert foreland is between 2 to 5 years. In the mountains the probability of occurrence of such a total, is between 1 and 2 years, and in the piedmont plains and the east coast it is once in 1 1/2 to 2 1/2 years. Rainfall of more than 200mm. may occur on the plains, desert foreland and the west coast once in 3 to 10 years, on the east coast once in 2 1/2 to 5 years and in the mountains once in 3 years. Totals of over 300mm. are likely to
Table 3.13.

Frequency of rainfall amounts of selected thresholds (totals) in percentages of the total number of years of rainfall records, and also in the years of recurrence (or return).

50mm and 100mm of rainfall recur in 1-2 years in all the regions, except for 100mm recurring in 2-3 years in the desert forest; 200mm in 2-3 years in the mountains and the piedmont plains, but in 2-6 years elsewhere; 300mm totals recur in 4-17 years in the mountains, east coast and the piedmont plains, but once in 16 years in the desert forest. The 400mm rainfall threshold is reached once in 8-19 years in the mountains and in 12-17 years on the east coast and none elsewhere.

<table>
<thead>
<tr>
<th>Station</th>
<th>50mm</th>
<th>Freq. 100mm</th>
<th>Freq. 150mm</th>
<th>Freq. 200mm</th>
<th>Freq. 250mm</th>
<th>Freq. 300mm</th>
<th>Freq. 350mm</th>
<th>Freq. 400mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>years</td>
<td>in years</td>
<td>in years</td>
<td>in years</td>
<td>in years</td>
<td>in years</td>
<td>in years</td>
<td>in years</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOUNTAINS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abu Dhabi</td>
<td>62%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ras Al Khaima</td>
<td>71%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dubai</td>
<td>71%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sharjah</td>
<td>60%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fujairah</td>
<td>32%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hatta</td>
<td>42%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Ain</td>
<td>28%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huqayratan</td>
<td>27%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fitrai</td>
<td>25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dhaid</td>
<td>24%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Jazirah</td>
<td>23%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EAST COAST</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duba</td>
<td>90%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fujairah</td>
<td>57%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kalba</td>
<td>37%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Umm Al Quwain</td>
<td>26%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Umm Al Quwain</td>
<td>25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WEST COAST</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doha</td>
<td>77%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qatar</td>
<td>56%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abu Dhabi</td>
<td>40%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Aamah</td>
<td>30%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIUD FOREST</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al-Ain</td>
<td>30%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Khat</td>
<td>25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shagha</td>
<td>20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jabel Althamah</td>
<td>15%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on rainfall data from the Ministry of Agriculture and Fisheries, the airports and local agriculture departments.
happen once in 17 years on the west coast and desert foreland, once in 7 years on the east coast and once in 3 to 9 years in the mountains.

The Sharjah rainfall data are not representative of the rainfall data for the whole Emirates as they are for a station on the western Gulf coast, a zone of below average rainfall. There are even differences in rainfall totals between Sharjah and Dubai that are only about 5km. from each other on the same Gulf coastline. In Sharjah (Table 3.14.), up to 83.0mm. of rainfall can occur once a year, 125.0mm. once in 2-3 years; 150.0mm. in 3-4 years; 160.0mm. in 5 years; 170.0mm. in 7 years and over 200.0mm. once in 10 years. The highest total of 260.2mm., reached in 1956-57, may probably occur once in 56 years, whereas the 170.2mm. of 1987-88, which includes the 24-hour fall of the 17th of February of 115.5mm., may recur once in 7 years. In Dubai the 226.5mm. total of the same year (1987-88), which includes the 24-hour rainfall of the 17th of February of 171.1mm., which was the highest daily rainfall as well as the highest annual total for Dubai since rainfall records started in Dubai in 1967, may probably occur again in 22 years (Table 3.13).

3.5.8. Monthly Rainfall (Tables: 3.15. and 3.16.)

Monthly rainfall totals can be the outcome of a single storm, as happened on February 17th 1988. However, the MAF details of monthly rainfall are not readily available though they are kept in unpublished records.

Most of the rainfall is concentrated in the winter months of the year, with February being the rainiest month (Table 3.16.). Convectional and monsoonal rainfall occurs between May and October particularly in the mountains, the piedmont plains and the east coast. Winter rains may start as early as November and may occur as late as May in all the zones. The early November rains can in some years be heavy, as took place in Khatt in 1982-83 when 82.1mm. fell during that month, and was only slightly surpassed by the February total of that year of 90.6mm. This also happened at Masafi in 1976-77 when 84.0mm. fell as early as October, after which rainfall occurred in every subsequent month until June (Table 3.16).
<table>
<thead>
<tr>
<th>Year</th>
<th>Annual rainfall mean in ascending order</th>
<th>Return period in years</th>
</tr>
</thead>
<tbody>
<tr>
<td>61-62</td>
<td>0.3</td>
<td>1.018182</td>
</tr>
<tr>
<td>73-74</td>
<td>3.1</td>
<td>1.037037</td>
</tr>
<tr>
<td>45-46</td>
<td>9.0</td>
<td>1.056040</td>
</tr>
<tr>
<td>70-71</td>
<td>10.8</td>
<td>1.076923</td>
</tr>
<tr>
<td>66-67</td>
<td>11.5</td>
<td>1.098039</td>
</tr>
<tr>
<td>83-84</td>
<td>12.0</td>
<td>1.120000</td>
</tr>
<tr>
<td>84-85</td>
<td>17.6</td>
<td>1.142857</td>
</tr>
<tr>
<td>48-49</td>
<td>30.7</td>
<td>1.166667</td>
</tr>
<tr>
<td>50-51</td>
<td>33.1</td>
<td>1.191489</td>
</tr>
<tr>
<td>41-42</td>
<td>42.0</td>
<td>1.217391</td>
</tr>
<tr>
<td>69-70</td>
<td>45.4</td>
<td>1.244444</td>
</tr>
<tr>
<td>59-60</td>
<td>47.6</td>
<td>1.272727</td>
</tr>
<tr>
<td>72-73</td>
<td>51.0</td>
<td>1.302326</td>
</tr>
<tr>
<td>85-86</td>
<td>55.1</td>
<td>1.333333</td>
</tr>
<tr>
<td>35-36</td>
<td>58.0</td>
<td>1.365854</td>
</tr>
<tr>
<td>46-47</td>
<td>58.0</td>
<td>1.400000</td>
</tr>
<tr>
<td>0-34</td>
<td>58.0</td>
<td>1.439898</td>
</tr>
<tr>
<td>65-66</td>
<td>60.8</td>
<td>1.473684</td>
</tr>
<tr>
<td>39-40</td>
<td>61.0</td>
<td>1.513514</td>
</tr>
<tr>
<td>37-38</td>
<td>70.0</td>
<td>1.555556</td>
</tr>
<tr>
<td>78-79</td>
<td>72.2</td>
<td>1.600000</td>
</tr>
<tr>
<td>40-41</td>
<td>78.0</td>
<td>1.647059</td>
</tr>
<tr>
<td>47-48</td>
<td>80.0</td>
<td>1.696970</td>
</tr>
<tr>
<td>53-54</td>
<td>81.5</td>
<td>1.750000</td>
</tr>
<tr>
<td>67-68</td>
<td>81.8</td>
<td>1.806452</td>
</tr>
<tr>
<td>80-81</td>
<td>82.1</td>
<td>1.866667</td>
</tr>
<tr>
<td>52-53</td>
<td>83.2</td>
<td>1.931035</td>
</tr>
<tr>
<td>55-56</td>
<td>85.7</td>
<td>2.076843</td>
</tr>
<tr>
<td>77-78</td>
<td>86.2</td>
<td>2.100000</td>
</tr>
<tr>
<td>49-50</td>
<td>87.2</td>
<td>2.130000</td>
</tr>
<tr>
<td>60-61</td>
<td>89.3</td>
<td>2.153846</td>
</tr>
<tr>
<td>43-44</td>
<td>93.0</td>
<td>2.240000</td>
</tr>
<tr>
<td>76-77</td>
<td>93.8</td>
<td>2.333334</td>
</tr>
<tr>
<td>63-64</td>
<td>95.6</td>
<td>2.434783</td>
</tr>
<tr>
<td>51-52</td>
<td>104.5</td>
<td>2.666667</td>
</tr>
<tr>
<td>57-58</td>
<td>108.0</td>
<td>2.800000</td>
</tr>
<tr>
<td>79-80</td>
<td>125.1</td>
<td>2.947369</td>
</tr>
<tr>
<td>38-39</td>
<td>129.0</td>
<td>3.111111</td>
</tr>
<tr>
<td>86-87</td>
<td>141.6</td>
<td>3.294118</td>
</tr>
<tr>
<td>58-59</td>
<td>141.7</td>
<td>3.500000</td>
</tr>
<tr>
<td>42-43</td>
<td>149.0</td>
<td>3.733333</td>
</tr>
<tr>
<td>64-65</td>
<td>152.9</td>
<td>4.000000</td>
</tr>
<tr>
<td>34-35</td>
<td>154.0</td>
<td>4.307692</td>
</tr>
<tr>
<td>68-69</td>
<td>154.7</td>
<td>4.666667</td>
</tr>
<tr>
<td>62-63</td>
<td>160.4</td>
<td>5.090909</td>
</tr>
<tr>
<td>74-75</td>
<td>167.4</td>
<td>5.600001</td>
</tr>
<tr>
<td>75-76</td>
<td>168.1</td>
<td>6.222223</td>
</tr>
<tr>
<td>87-88</td>
<td>170.2</td>
<td>7.000001</td>
</tr>
<tr>
<td>71-72</td>
<td>174.4</td>
<td>8.000000</td>
</tr>
<tr>
<td>82-83</td>
<td>189.5</td>
<td>9.322700</td>
</tr>
<tr>
<td>54-55</td>
<td>208.3</td>
<td>11.200000</td>
</tr>
<tr>
<td>44-45</td>
<td>214.0</td>
<td>14.000000</td>
</tr>
<tr>
<td>36-37</td>
<td>218.0</td>
<td>18.666668</td>
</tr>
<tr>
<td>81-82</td>
<td>241.5</td>
<td>26.000000</td>
</tr>
<tr>
<td>56-57</td>
<td>260.2</td>
<td>56.000003</td>
</tr>
</tbody>
</table>

Table: 3.14.

Rainfall return periods of the Sharjah long-term rainfall record (1934-88), with the return periods of selected thresholds of rainfall totals.

Up to 33mm of rainfall can recur in Sharjah every year, up to 83mm every 2 years, up to 125mm every 3 years, up to 152mm every 4 years, while the highest total of 260.2mm (1956-57) may occur once every 56 years.
February and March are the months with the highest rainfall. When the winter rains start in November, as shown in Table 3.16. for Sinnah, the annual total is spread over several months up to May or June, but with sometimes a higher total in March than in February. When the winter rains arrive suddenly in February, as happened in February 1988, most of the rain falls during that month (168.9mm. for Masafi), with some falling in March (2.6mm. for Masafi), or, as was the case in the mountain stations when March (1988) was relatively dry, April had some rainfall (29.5mm. for Masafi).

The months from May/June to September/October are months of localized convectional or monsoonal rainfall. The former is more frequent in the mountains and the piedmont plains, the latter on the east coast.

Referring to the monthly means in Table 3.16., there is rainfall in all the months, even if only a trace in some stations. In most stations June is the driest month, and in others it is July. In the plains, May can also be a dry month in addition to June or July. In the mountains, at 55% of the stations, there is rain in all the months, with September as the month with least rainfall. 80% of the stations on the east coast have rain every month; it is only in Zikt, that September, and in Dibba, that July, have no rainfall. On the west coast, June and July are the driest months in all the stations along the west coast. In Sharjah the dry period is from July to September (Tables 3.15 and 3.16), and in Sha'am it is in the months of July, September and October. Despite the long rainfall record of Sharjah (Table 3.15) its location on the west (Gulf) coast makes it unrepresentative of other regions or the whole of the Emirates. The monthly rainfall of Sharjah varies from none at all in the rainiest months of January and February to 156.4mm (Table 3.15). Finally, in the desert foreland, in all the months of the long-term average, there is rain, though with least amounts, during the period of July to October (Table 3.16).

3.5.9. Daily Rainfall

Daily rainfall data are prepared by the MAF but have not been published since the Ministry's Hydrology Book of 1979 (which presented data for the years 1976-79). The daily rainfall data used in this analysis are those contained in unpublished rainfall intensity sheets for the period
The 3-year gap in the rainfall record that appeared in the Trucial States Water Resources Study (the Halcrow Report) of 1969, and in every subsequent study, has been filled from the so-called Ashfield Archives, except for the period March-August 1949 for which data were unavailable.

Table: 3.15.

The long-term Sharjah monthly rainfall record (1934-88), monthly and annual totals and the period monthly mean, with the annual rainfall totals arranged in ascending order.

The extreme variability in the monthly rainfall is evident in the monthly rainfall totals for the rainiest months of January and February. The monthly totals vary from no rain at all to 156.4 mm. Although Sharjah is the only rainfall station in the Emirates to have such a long record, its location on the west coast makes it unrepresentative of the other regions or the whole of the Emirates.
The mean monthly rainfall for the period of rainfall records for the stations in the various topographical regions (as given in Table 3.10).

There is rainfall in all the months, even if only a trace in some stations. In most stations June is the driest month and in others it is July. In more than half the stations in the mountains there is rain in all the months, with September being the month with least rainfall.

(1) The mean monthly rainfall for Sharjah in this Table is for the period 1967-88 and not for the 55-year period. For the rest of the stations the monthly mean is for what is available of rainfall records for the respective stations.
1976 to 1983 (when the preparation of rainstorm intensity data by the MAF ceased) and daily rainfall totals in monthly sheets from 1983 to 1988 (both of the MAF). 2 years were chosen for comparison: 1982-83 (moderate rainfall year) and 1981-82 (heavy rainfall year) (Table 3.17 A-C).

3.5.9.1. Daily winter rainfall (Tables 3.17 A-C and 3.18.)

If rain events of more than 2.0mm. are considered, then the daily winter rainfall can start as early as October, although October may still experience convectional activity, especially around Masfut (1974-75, 1976-77 and 1979-80) (Table 3.16).

In 1980-81 there was no rain in October in any of the hill stations. In 1982-83, a relatively medium rainfall year, there was rainfall above 4.0mm. in both October and November in Masfut with 16.8mm. and 20.2mm. in December and January, and then 3 peaks in February, March and April of 68.2mm., 54.2mm., and 62.2mm. In Masafi, there were 4.0mm. in October and 31.2mm. in November, 28.6mm. in December and 21.6mm. in January and the much reduced peaks (compared with those for Masafi) of 48.0mm., 41.9mm. and 35.8mm. for February, March and April, respectively. For the exceptionally rainy year of 1981-82, a total of 7.8mm. fell in January in Masfut and 6.8mm. in Masafi, but there were then two major peaks in February and March of 176.2mm. and 150.6mm. in Masfut, and 168.2mm. in Masafi.

Winter rainfall peaks can therefore be either 3 peaks, in years of moderate rainfall occurring as late as April or 2 peaks, in the months of February and March. Daily rain events may occur on as many as 15 days in the rainy months, as in March in Masfut in 1981-82, or 14 days of the month as in Masafi in the same year. However, the rainfall is not evenly distributed in these rainy days of the month and most of the monthly total may fall in 1, 2 or 3 daily storms. In Masfut, on the 13th of February 1981-82, 129.0mm. fell out of a monthly total of 176.2mm., whereas in the following month (March) 135.0mm., out of the monthly total of 150.6mm., fell in 5 days.

In Masafi, 151.6mm. fell in 4 daily rain events out of a total of 168.2mm. for February 1981-82, and 153.8mm. fell in 5 daily rain events
in March of the same year out of a total for the month of 165.6mm. By comparison, although the February 1988 rains were elsewhere of the highest daily intensities, this was not the case in Masafi where rainfall of more than 2.0mm. occurred in 5 events within a single day totalling in amount 127mm. (17/2/88) out of the total for the same month of 152mm. (Table 3.18.)

In Masfut (1987-88) there were 7 rain days of more than 2.0mm., 4 of which were of more than 15.0mm. with a single day fall of 155mm. (17/2/88) out of the February total of 266mm. The rainfall was more spread out in Masfut than in Masafi. There was a single major peak of 127m. in Masafi preceded by 12.0mm. the previous day and followed a week later by another peak of 15mm; while in Masfut there were 3 peaks on 17th, 18th and 19th February 1988 of 155mm., 31.2mm., and 34mm, with 2 lower peaks of 15.0mm. and 18.0mm. separated by 1 or 2 days (on 21st and 24th February 1988) (Table 3.18).

The main characteristic of the winter daily rainfall of normal rain years (moderate rainfall years) in the piedmont plains is its occurrence over a number of days during the period from December to May that may total up to 20 rain days in the year unlike the daily summer rainfall which may occur as a thunderstorm during part of a day or a few isolated rain days. Most of the winter rain days occur in February and March, the rainiest months, although January in some years can also be equally important in the number of rain days and in the monthly total. In exceptionally rainy years, when storm conditions are widespread all over the country, all locations may receive rain on the same days and even the trend, described above for the normal rain year may be altered, with Falaj Al Mualla receiving rain in as many as, or even more days than, Digdaga. Under such conditions Mileiha may receive rain in more days than the rest (Table 3.18).

In normal rain years, the number of rain days in Digdaga in the northern part of the piedmont plains is more than that for Falaj Al Mualla in the centre of the plains and Mileiha and Al Ain in the southern parts. In Digdaga, during the rainy months in normal years, there may be 2 or 3 peaks on different days separated by up to 3 weeks (Table 3.18), whereas in Falaj Al Mualla and Mileiha there is normally one peak occurring either in the middle of a series of rain days, in consecutive days or at
the end of the series (Table 3.17 A and C). This pattern may change in exceptionally rainy years to rain occurring on several consecutive days in the month such as happened during February 1988 (Table 3.17.). In Mileiha in February 1983 there were 2 peaks in 2 consecutive days providing 85% of the monthly total (Table 3.17. C). The rainfall amounts falling in the daily winter peaks in the northern plains (Digdaga) may make up between 60% to more than 90% of the monthly total, but the amounts falling in the daily peaks in the central and southern plains (Falaj Al Mualla and Mileiha) may make up between 35% and 95% of the monthly total (Table 3.12.).

In the desert foreland, the number of rain days is less and the rainfall is more concentrated in the few daily rain events which may occur in 2 or 4 days during the rainy months in normal (moderate) rainfall years. In the desert foreland, in exceptionally rainy years (1988) the occurrence of rain days in the rainy month may follow the overall general trend as elsewhere in the Emirates (as for Al Aweer, Table 3.18).

3.5.9.2. Daily summer rainfall

Daily summer rains are limited to only 1, 2 or 3 events as in Masafi in August 1983: 10/8/83 (25.8mm.), 11/8/83 (12.0mm.) and 13/8/83 (0.6mm.), which were local convectional storms centring on Masafi in the mountains, but extending also to Fujairah (which received 0.9mm. on 10/8/83) in the east and Idhn in the west (which received 1.4mm. on 10-11/8/83).

If summer daily rainfall on the east coast is not of monsoon origin, as happened in the 3 years, 1980-83, during which no monsoon rains were recorded, it is either of an extended mountain or piedmont plains convectional type. In the mountains, this can be of extremely localized incidence limited to a small locality, such as Masfut, Masafi or 'Asimah, or extending to the adjoining parts of the plains as in Idhn (adjoining Masafi) and Filli (adjoining Masfut).

The convectional or orographic rainstorms can also be extensive covering the length and breadth of the mountain zone from Mussandam in the north to Hatta in the south. The rainfall totals of the 10th. and 11th. of
Table: 3.17. (A – C)

Daily winter rainfall in the piedmont plains for Falaj Al Mualla (A), Digdaga (B) and Mileiha (C).

The number of rain days in Digdaga in the northern parts of the piedmont plains is more than at Falaj Al Mualla in the central parts and Mileiha in the southern parts. In Digdaga there are usually 2-3 rainfall peak days during the rainy month (in this case February 1982 for Digdaga and February and March 1983 for Mileiha) separated by up to 3 weeks. In Falaj Al Mualla there is usually one peak occurring either in the middle of a series of rainfall days or in 2 consecutive days, or in a single day at the end of the series for the rainy month. In Mileiha, there appears to be 2 peaks in consecutive days responsible for most of the rainfall for the month.
|       | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
|-------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Masafi|   |   |   |   |   |   |   |   |   | 5  | 12 | 127| 3  | 15 | 18 |    |    |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Masfut|   |   |   |   | 7 | 6  | 155| 31| 34 | 15 | 18 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Khor Fakkan|9  | 6  | 67 | 5 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Fujairah|16 | 6  | 14 | 14| 170| 20 | 4  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Digdaga|   | 6  | 13 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Falaj Al Mualla|2 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Mileiha|   |    |    |    | 3 | 6  | 2  | 13| 50 | 16 | 24 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Al Aweer|   |    |    |    |    | 8  | 28 | 141| 3  | 7  | 4  | 6  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Dubai |   |    |    |    |    |    |    |    |    |    |    |    | 6  | 150| 5  | 8  | 4  | 6  |    |    |    |    |    |    |    |    |    |    |    |    |

Source: MAF unpublished daily rainfall records (1987-88)

Table: 3.18.

Daily winter rain: the number of rain days of more than 2.0mm in the rainy month of February in the exceptionally rainy year 1988 for selected stations in each of the topographical regions.

When rainfall conditions are widespread, as happened in February 1988, a year of exceptional rainfall, rain days may occur simultaneously in most stations in several peaks in consecutive days. Stations in the northern parts (Digdaga), the central (Falaj Al Mualla) and the southern (Mileiha and Al Ain) parts of the piedmont plains, receive rainfall in as many days as, or even the southern stations receive rainfall in more days than, the rest of the stations.
August 1983, shown in Figure 3.16., illustrate the extent of the same convectional conditions in the mountain zone. The area of concentration was in the vicinity of Masafi (Jabal Sharmah and Siji) and the higher totals received, especially on the 10th of August, were in localities with higher relief than others in relatively lower relief nearby. Hence, the totals received as shown in Table 3.19.

<table>
<thead>
<tr>
<th>Station</th>
<th>Date of storm</th>
<th>Rainfall total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinnah (North)</td>
<td>10/08/83</td>
<td>29.0 mm.</td>
</tr>
<tr>
<td>Marbadh (North)</td>
<td>10/08/83</td>
<td>25.8 mm.</td>
</tr>
<tr>
<td>'Asimah (North)</td>
<td>10/08/83</td>
<td>21.4 mm.</td>
</tr>
<tr>
<td>Jabal Sharmah (Centre)</td>
<td>10/08/83</td>
<td>30.6 mm.</td>
</tr>
<tr>
<td>Masafi (Centre)</td>
<td>10/08/83</td>
<td>23.2 mm.</td>
</tr>
<tr>
<td>Munai'ee (South)</td>
<td>10/08/83</td>
<td>25.2 mm.</td>
</tr>
<tr>
<td>Huwailat (South)</td>
<td>10/08/83</td>
<td>20.4 mm.</td>
</tr>
</tbody>
</table>

Masfut, in the extreme south of the mountains within the Emirates, received on 10/08/83 18.6mm.

Table: 3.19

Rainfall totals in the various mountain stations illustrating the extent of the convectional rainstorm of the 10th. of August, 1983.

3.5.10. The monsoon rainfall of the east coast

Monsoon rains may occur on the east coast between May and September, but mostly in July and August. They do not seem to take place every year, but only once in 5 or 10 years, concentrated mostly in these two months. From the available MAF unpublished rainfall records of between 14 and 19 years for east coast stations, the monsoon rains tended to occur whenever there was heavy winter rain in two consecutive years, with the monsoons on the east coast occurring in the second of the two rainy years. The monsoon rain years themselves appear to be separated by 1 to 4 less rainy monsoon rain years.
Figure: 3.16.

Daily summer (convectional) rainfall of the 10th./11th./08/1983.

Sketch map showing the extent of the same convectional storm in the mountains centered around Sinnah-Masafi-Siji (26-30mm) but extended as far south as Masfut and Hatta (19-20mm).
Although there appears to be no connection, the summer monsoons of the east coast tend to occur in a year of heavy winter rainfall with an annual total of more than 120.0mm. There are no clear cut trends in the totals of the monsoon rains: whereas Khor Fakkan has the highest total of annual rainfall for any station on the east coast, being in the area of the mountains and east coast receiving the highest rainfall (see isohyetal map Figure 3.14.), Dibba receives most of its rainfall from the monsoons in exceptionally rainy years. Dibba is in the path of the monsoon storms, the effect of which is felt deeper to the west of Dibba by the funnelling of their course by the Dibba Corridor as happened on the 20th of July 1988 when 42.5mm. of rain fell over Dibba and the south-facing sides of the Waam Mountains. Sinnah, 18km. inland, received 21.5mm., while Idhn, 35km. further west at the other end of Dibba Corridor, received 9.0mm.

In the mountains, nearly 5% of the annual total for 1987-88 was from the single monsoon storm of 20/07/88. From the annual mean for all the mountain stations of 250.8mm. for the same year, this amounted to 12.5mm. In the piedmont plains about 3% was from the same storm out of an annual total of 188.5mm., while on the east coast the percentage was 7% out of 275.9mm., with Dibba receiving in 3 hours 20% of its 1987-88 annual total of 213.4mm. from the single monsoon storm of 20/07/88.

3.5.11. The convectional storms in the mountains and the piedmont plains

Convectional rainstorms in the mountains are localized in incidence, although storms of wider occurrence are more common with their conditions felt farther to the west in the plains or to the east on the Batinah coast. Convectional conditions may occur at the same time as the monsoons on the east coast during the period June to September, and some of the monthly rainfall totals mentioned in the preceding section for stations on the east coast may also be the result of extended convectional activity centred in the mountains. Table 3.20. shows the convectional storms in the mountains, of which are those of a localized nature, those that extend to the piedmont plains to the west and those that extend to the Batinah coast to the east. The arrows in Table 3.20
Convectional rainstorms originating in the mountains but extending eastwards into the east coast (1) or westwards into the piedmont (gravel) plains (2); convectional storms originating within the piedmont plains and extending eastwards into the mountains (3); east coast monsoon rainstorms extending westwards into the mountains and the piedmont plains (4); and localized convectional rainstorms in limited areas within either the mountains or the piedmont plains (5 and 6).

Masfut and Masafi are the two mountain localities with extensive convectional activity reaching out to the western (gravel) and eastern (east coast) piedmont plains. Mileiha (near Filli), and even Al Awha (near Al Ain) are the two localities in the plains with extensive convectional effects reaching eastwards into the mountains and the east coast. East coast summer monsoon rainstorms occur in narrow paths, as was the case with the July 20th., 1988 rainstorm that was limited to Wadi Al Baseerah basin, with the rain-shadow effect of Ru'us Al Jibal being evident in the 1.0mm received by Sha'am on the leeward Gulf coast, as compared to the 42.2mm for Dibba on the east windward coast.

Table: 3.20.

Convectional rainstorms originating in the mountains but extending eastwards into the east coast (1) or westwards into the piedmont (gravel) plains (2); convectional storms originating within the piedmont plains and extending eastwards into the mountains (3); east coast monsoon rainstorms extending westwards into the mountains and the piedmont plains (4); and localized convectional rainstorms in limited areas within either the mountains or the piedmont plains (5 and 6).

Masfut and Masafi are the two mountain localities with extensive convectional activity reaching out to the western (gravel) and eastern (east coast) piedmont plains. Mileiha (near Filli), and even Al Awha (near Al Ain) are the two localities in the plains with extensive convectional effects reaching eastwards into the mountains and the east coast. East coast summer monsoon rainstorms occur in narrow paths, as was the case with the July 20th., 1988 rainstorm that was limited to Wadi Al Baseerah basin, with the rain-shadow effect of Ru'us Al Jibal being evident in the 1.0mm received by Sha'am on the leeward Gulf coast, as compared to the 42.2mm for Dibba on the east windward coast.
denote the direction and extent the convectional storms spread on either side of the mountains.

From the enumeration of the storm events in Table 3.20., it is clear that storms with effects felt eastwards in the Batinah coast are of higher frequency of occurrence than those extending westwards onto the western piedmont plains. This is mainly because the plains themselves are a region of convectional rainfall activity. Localized convectional storms in the piedmont plains are concentrated in the southern part. Those storms that occur in July or September have higher rainfall totals than those occurring in August. This is clearly seen in Table 3.20 in groups 3 and 6 for Mileiha, Filli, Al Awha and Al Ain.

The mountain zone is the area of most convectional activity, both on a localized and an extended scale.

Group 1 in Table 3.20. shows the rainstorms originating in certain localities within the mountains but with extended effects reaching adjoining localities on the east (Batinah) coast, in most cases along the same east-west axis. From the rainfall totals shown in the Table 3.20, there is more rain in the northern parts of the mountains around Masafi (70-80mm.) than the southern parts around Masfut (20-40mm.). This conforms with the period means (of all the rainfall types: winter frontal, summer monsoonal and convectional) for the northern stations, which show them to be points of heaviest rainfall (Fig. 3.14).

Masafi and Masfut are important centres of convectional activity extending westwards onto the plains. Masafi was the centre of a convectional storm on 17/09/80 when 24.0mm. were received. The same storm extended to Falaj Al Mualla to the west, where 12.0mm. were received. The same situation also occurred on 1/08/87 when Masafi received 56.6mm. and Al Ghail to the west 8.3mm. and Idhn further west 4.0mm. Masfut, on the other hand, had 23.6mm., and Mileiha to the west had 3.4mm., in August 1986. In August 1987 Masfut received 38.6mm. from a convectional storm which extended to Mileiha giving it 4.2mm., while Filli had 16.4mm.
From the available unpublished rainstorm records, all the extended, interrelated or strictly localized convectional storm events are included in Table 3.20.

3.5.12. **Rainfall (storm) intensity**

3.5.12.1. **General**

Rainfall or storm intensity data are of significance in studying rainfall-runoff-recharge relationships. Storm intensities, especially their rates of incidence, illustrate the characteristics of the heavy, short duration rainfall typical of an arid environment such as that of the Emirates. The intensities also govern surface runoff, its amount and duration of flow. Storm intensity data are only available for some stations, the oldest start in 1975 and 1976 (Masafi and Masfut) but all such vital data ceased to be prepared by the MAF in 1983 because of severe undermanning in the meteorological section.

Although storm intensity measurements have been enhanced by the introduction of the automatic rain recorders, the 6-month charts in most of these recorders have the disadvantage of not being able to accommodate the details of intensities of 10 or 20 minute duration because the intervals on the chart are too close. In this context, the monthly, or even better, the weekly, charts have an advantage. It does not seem feasible for the MAF to adopt monthly and weekly charts as a result of labour considerations. The recorders themselves may fail frequently, in most cases, generally during the critical time of the rainstorms (see the sample storm intensity sheets illustrating the failure of the automatic rain-recorder in Appendix 2). The stations used in this study, for which intensity data were available, together with the duration of their records, are given in Table 3.21.
3.5.12.2. Analysis of available rainstorm intensity data for selected stations by region
(Fig. 3.17. and Tables 3.21 and 3.22)

This section analyzes the rainstorm intensity data available for selected stations in all the topographic regions. Such data are only available for the stations shown in Table 3.21. between 1979 and 1983 when the MAF, the only source of comprehensive rainfall data, stopped preparing this important presentation of rainfall data. Only Masfut and Masafi have intensity data going back intermittently to 1975. Intensity data for 9 stations started in 1978 and ended in 1983. For the rest of the stations the records started in 1979, 1980, 1981 and even 1982 and terminated in 1983 (see Table 3.21.).

A discussion of the rainstorm intensities should help to illustrate the occurrence of the rainstorms in the various localities, as the rainstorm intensities vary greatly from one zone to another, and even within the same locality in a particular zone, as is the case within the mountains. It should also help clarify the rainfall characteristics, trends and distribution, both seasonally and geographically, outlined in the preceding sections of this chapter. The analysis should also provide the background to surface runoff from the various catchments responsible for recharge to the groundwater system described in Chapters 4 and 10.

All available data have been used in this rainstorm intensity analysis and the range of the intensity rates are presented in Table 3.22. for all the rainstorm intensity records between 1979 and 1983. As seen in Table 3.22, rainstorm intensities vary widely, not only from one topographic region to another, but also within the same region. Their duration ranges from 1 minute to 24 hours, but in all recorded rainstorm intensities, those lasting up to 1 hour, regardless of the amount produced, occur in almost all rainstorms (Fig. 3.17.).
<table>
<thead>
<tr>
<th>Station</th>
<th>Duration of record</th>
<th>Station</th>
<th>Duration of record</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masafi</td>
<td>30/10/79 to 11/8/83</td>
<td>Wahlah</td>
<td>3/3/82 to 10/4/83</td>
</tr>
<tr>
<td>Sinnah</td>
<td>17/2/79 to 11/8/83</td>
<td>Dibba</td>
<td>4/12/78 to 10/8/83</td>
</tr>
<tr>
<td>Bithnah</td>
<td>14/4/78 to 11/8/83</td>
<td>Zikt</td>
<td>30/11/80 to 10/8/83</td>
</tr>
<tr>
<td>'Asimah</td>
<td>20/12/79 to 11/8/83</td>
<td>Khor Fakkan</td>
<td>16/11/78 to 10/4/83</td>
</tr>
<tr>
<td>J.Sharmah</td>
<td>17/1/82 to 11/8/83</td>
<td>Kalba</td>
<td>4/12/78 to 10/8/83</td>
</tr>
<tr>
<td>Marbadh</td>
<td>11/2/81 to 11/8/83</td>
<td>Digdaga</td>
<td>27/12/79 to 10/4/83</td>
</tr>
<tr>
<td>Sfini</td>
<td>9/9/78 to 23/8/83</td>
<td>Filli</td>
<td>6/8/79 to 30/8/83</td>
</tr>
<tr>
<td>Al Ghail</td>
<td>12/2/79 to 29/9/83</td>
<td>Mileiha</td>
<td>24/2/82 to 28/8/83</td>
</tr>
<tr>
<td>Tuwaiyyain</td>
<td>29/10/82 to 10/8/83</td>
<td>Al Ain</td>
<td>12/8/87 to 8/9/83</td>
</tr>
<tr>
<td>Idhn</td>
<td>31/7/78 to 29/9/83</td>
<td>Aweer II</td>
<td>31/4/81 to 10/4/83</td>
</tr>
<tr>
<td>Munai'ee</td>
<td>4/7/78 to 15/5/83</td>
<td>Ain Sukhnah</td>
<td>4/7/78 to 12/4/83</td>
</tr>
<tr>
<td>Huwailat</td>
<td>24/1/79 to 11/8/83</td>
<td>Sharjah</td>
<td>3/3/81 to 12/4/83</td>
</tr>
<tr>
<td>Masfut</td>
<td>1/2/75 to 11/8/83</td>
<td>Sha'am</td>
<td>20/12/79 to 10/8/83</td>
</tr>
<tr>
<td>Fara'ah</td>
<td>2/1/82 to 11/8/83</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: MAF storm intensity sheets, 1975-83 (unpublished)

Table: 3.21.

The available (unpublished) MAF rainstorm intensity data and the duration for their records for stations that have storm intensity records up to 1983.

3.5.12.3. Storm intensities of the winter rainstorms:

3.5.12.3.1. Rainstorm intensities in the mountains
   (Table 3.22 and Fig. 3.17.)

3.5.12.3.1.1. Masafi

Out of 83 rainstorm intensity events recorded for Masafi between 1975 and 1983, 89% lasted up to 1 hour, 78% up to 2 hours, 70% 3 hours, 59% 6 hours, 42% 12 hours and 30% up to 24 hours.
The range of rainstorm intensity rates (in mm/hr.): comparison of the storm intensity rates in the 10-min., 20-min., 30-min. and the 1-hr., 2-hr., 3-hr., 4-hr., 6-hr., 12-hr., and 24-hr. duration for most of the stations for which rainstorm intensity records exist for the period 1979-83.

The highest intensity rates occur within the first 30 min. to 1 hr. of the beginning of the storm with the highest rates experienced being in the mountains and the piedmont (gravel) plains.

Source of intensity data: Unpublished records of the Ministry of Agriculture and Fisheries for the period 1979-83.
The figure to the left denotes the number of rainstorms, the figure to the right the duration of the storm in hours.

Figure: 3.17.

Comparison of the number of rainstorms reaching the different duration thresholds for selected stations by region.

There are more rainstorms reaching the 24-hr. duration in the piedmont (gravel) plains and the east coast than in the mountains. The larger number of rainstorms reach the 1-, 2- and 3-hr. duration in all the regions.
30% of the recorded storms had rainstorms with rainfall of over 5.0mm. within 10 minutes of the start of the storm, while those of the same order, within 30 minutes, amounted to 43%. Hourly intensity rates ranged from 0.4mm/hr. to 144.0mm/hr. and rainfall of up to 30.0mm. in 10 minutes is not uncommon in the northern parts of the central mountains.

About half the amount of rainfall for 24 hours fell within the first 6 hours; as occurred in the heavy rainstorm of 13/02/1982. The intensity rate during this storm ranged from 42.0mm./hr. to 3.8mm./hr. Of the 24-hour total for the storm of 28/03/1982 of 79.8mm., nearly 50% fell in the first 30 minutes and more than 97% in 12 hours.

3.5.12.3.1.2. Masfut

Masfut recorded the highest 24-hour total of 129.4mm. within 23 hours and 40 minutes on 13/02/1982, but very much less on 20/03/1983 (74.4mm.), which was less than that recorded at Huwailat and Munai'ee, 10 and 15km. to the northeast respectively. However, the striking characteristic in the Masfut area is the occurrence of high intensities within the first 30 minutes, but more so within the first 10 minutes, of the start of the rainstorm. The intensity rates varied from 0.6mm./hr. to 110.4mm./hr. in 23 out of the 50 rainstorms recorded, with high totals of above 50.0mm. attained in a 12-hour period. On 13/02/1982, about 50% of the total of 129.4mm. fell in the first 12 hours. On 25/03/1976 about 70% fell by the first 3 hours, and 95% by 12 hours, out of the total of 86.6mm. in 17 hours 30 minutes. Again, the 129.4mm. total fell in about 24 hours (13/02/82) and the 50.0mm. total of 11/02/1983 also fell in an equal period. Storm intensities of over 10.0mm./hr. occurred in 40 out of the 50 rainstorm events recorded for Masfut, but it is the intense, short-lived high amounts that are the striking feature in the Masfut region. A total of 26.8mm., with intensity rates ranging from 26.8mm./hr. to 84.0mm./hr. fell in only 40 minutes (2/11/76).

In Munai'ee, to the northeast of Masfut, rainstorm intensity rates ranged from 0.3mm./hr. to 95.0mm./hr. but with a marked occurrence of intensity rates of between 20.0mm./hr. and 94.8mm./hr. within the first 10 minutes out of the recorded 45 rain events in 18 rainstorms (1975-83). In Huwailat, also to the northeast of Masfut, the intensity
rates ranged from 0.3mm./hr. to 120.0mm./hr. and the rates were between 20.0mm./hr. and 120.0mm./hr. occurring in 20 out of the 40 recorded rainstorm events (1979-83) (Table 3.22).

3.5.12.4. Rainstorm intensities in the piedmont plains
(Table 3.22. and Fig. 3.17.)

3.5.12.4.1. Diqdaqa

Rainfall in the piedmont plains varies in occurrence between the northern, central and southern parts. Stations like Diqdaqa in the north have less rainfall than Falaj Al Mualla and Dhaid in the centre; and stations further south like Al Ain have the least rainfall. Although Falaj Al Mualla has higher rainfall totals than Filli, the storms are not as intense in incidence as in the latter. Storms exceeding 12 hours make-up 18% of those measured for rain intensities (1979-83). Rainstorm intensity rates of over 10.0mm./hr. in the first 10 minutes of a storm occur in 50% of the rainstorms recorded, in 38% of cases in the first 20 minute, in 30% in the first 30 minute and in 21% in the first 1 hour (60-min) duration.

The heavy rains of 13/02/1982 gave Diqdaqa only 34.6mm. over a 20-hour duration with low rainstorm intensity rates ranging from 6.0mm./hr. to 1.4mm./hr. Storms lasting for 1 hour are normally characterized by totals ranging from 2.4mm. to 9.4mm. Rainstorm intensity rates are also low, although in some cases, such as the storm of 24/02/82 when 10.6mm. of rain fell in 35 minutes, including 10.4mm. in the first 20 minutes, the intensity rates varied from 40.8mm./hr. to 10.6mm./hr.

3.5.12.4.2. Filli

Rainfall events in Filli do not have strikingly high totals. The highest (in the intensity records) was 87.0mm. that fell in 9 hours on 1/05/1981 with high storm intensity rates ranging from 138.0mm./hr. to 7.3mm./hr. A long rainstorm like that of 13/02/1982 in Filli, which lasted for 20 hours, produced only 18.8mm. of rain. Rain, however, continued on 14th. and 15th. of the same month with totals of 57.6mm. and 45.6mm., respectively. The total for these 3 days of rainfall was high but, having been spread over 68 hours, resulted in a lower total
with low intensity rates. The rain dwindled gradually to the final amount with no sudden increases.

The other rain event of 28/03/1982, on the other hand, gave 50.0mm. in 17 hours but with high intensity rates ranging from 51.6mm./hr. to 2.1mm./hr. compared with the rates of the rainstorms of the 3 days in February 1982 which ranged from 0.2mm./hr. to 3.6mm./hr. only.

Rainstorms continuing in Filli beyond 12 hours made up 13% of those events recorded. 93% of the rainstorms continued beyond 1 hour. Intensity rates of about 10.0mm./hr. accounted for 67% of the rain in the first 10 minutes, 56% in the first 20 minutes, 42% in the first 30 minutes and 20% in the first 1 hour. A total of only 2.8mm. may fall in 45 minutes (9/04/83) while a total of 7.6mm. may fall in 18 hours (20/12/79) (Table 3.22).

3.5.12.5. Rainstorm intensities in the east (Batinah) coast
(Table 3.22 and Fig. 3.17.)

3.5.12.5.1. Dibba

The incidence of rainstorms exceeding 12 hours in duration occurred in about 23% of the events recorded for Dibba (56 events from December 1978 to August 1983). The rain recorder failed only once in 1979 and the records available for Dibba for the period are the best for any station. Intensity rates of 10.0mm./hr. and more in the first 10 minutes occurred in more than 73% of the events, in 52% of cases for the first 20 minutes, 43% for the 30 minutes and 14% for the 1 hour duration. Storms exceeding the 12-hour duration produced totals of more than 10.0mm. but there were cases when as little as 7.2mm. rainfall was spread over 14 hours (26/03/82). The heavy rains of 13/02/82 produced only 46.0mm. in Dibba and this was due to its being in the rain shadow of Ru'us Al Jibal since the winter rains are carried to the area by the prevailing north-westerly winds.

On 28/03/1982 a rainstorm gave Dibba 95.8mm. of rain in 18 hours. Such a rainstorm usually happens when enough moisture laden air is picked up in the circulation from the northern Indian Ocean and the Arabian Sea to enhance the amount of rainfall giving higher totals to Dibba than it
would normally get from frontal rains from the west. Intensity rates of the latter case (28/03/82) were higher than those of the former (13/03/82). Intensity rates during the first 10 minutes of the storm reached 115.2mm./hr. and 13.2mm./hr., respectively. Of the total at the end of the storm of 115.2mm. and 46.0mm., 38% and 19% respectively fell within 1 hour of the commencement of the storm. In both cases the amount dwindled normally without sudden increments until the end of the rainstorm. In both cases the storm duration was 18 hours.

There are rainstorms with totals as low as 2.6mm., starting with an intensity rate of 13.2mm./hr. falling in 1 hour; and other rainstorms of 26.0mm. falling in 35 minutes with intensity rates at the beginning of the storm of 60.0mm./hr. and at the end of the storm, of 26.6mm./hr. Intensity rates in Dibba, in general, ranged from 0.3mm./hr. to 115.2mm./hr. and the 24-hour rainfall totals ranged from 7.2mm. to 95.8mm.

3.5.12.5.2. Khor Fakkan

Khor Fakkan registers the highest rainfall totals among the stations of the east coast. There were two pronounced peaks on 13/02/1982 with 123.4mm. and 11/02/1983 with 138.0mm. in storms lasting for 24 hours in both cases. During both events intensity rates were well distributed ranging from 15.6mm./hr. to 5.1mm./hr. for the former, and from 30.0mm./hr. to 5.8mm./hr. for the latter. The heavier intensity rates were recorded for storms of up to 1 hour duration, such as the rainstorm of 4/11/1982 with a fall of 32.4mm. in 55 minutes with intensity rates starting with 90.0mm./hr. and ending with 32.4mm./hr. The same heavy intensity occurred in the rainstorms of 1/02/1982 and 30/11/1980 with totals of 18.8mm. and 11.0mm. respectively. The intensity rate range was 87.6mm./hr. to 18.8mm./hr. for the former and 56.4mm./hr. to 11.0mm./hr. for the latter (Table 3.22).

Rainstorms exceeding the 12 hour duration made up 21% of the measured events, while the majority of the rainstorms lasted for 1 or 2 hours. (Fig. 3.17.).
3.5.12.6. **Rainstorm intensities on the west coast**

(Table 3.22.)

3.5.12.6.1. **Dubai and Sharjah**

MAF rainstorm intensity observation for stations on the west (Gulf) coast, are very limited. A sensitive rain recorder was offered by the MAF to Dubai Airport and was installed on 1/12/1982 after the major rain events of 13/02/1982. The only intensity record is from December 1982 to April 1983. The second important rain events of February/March 1983 did not give Dubai and Sharjah spectacular totals as they did for stations inland. During that time stations, such as Al Hibab and Falaj Al Mualla, received slightly more rainfall than Dubai and Sharjah (Dubai 17.4mm. on 11/02/1983 and Al Hibab 27.6mm. on the same day).

Rainstorm intensity rates are generally of medium magnitude and are rarely high; more than half the total of rainfall of more than 1 hour characterizes falls in the first 10 minutes. An example was the intensity rate of 109.2mm./hr for a fall in 10 minutes of 18.2mm., which was more than half the total of 35.2mm. that fell in 10 hours (30/04/1981). Another case was the short duration total of 11.6mm., which fell in 1 hour 40 minutes on 10/04/1983 with an intensity rate of 60.0mm./hr. for the first 10 minutes during which 86% of the total of 11.6mm. fell.

3.5.12.6.2. **Sha'am**

Sha'am is considered by the staff of the meteorological section of the MAF to be one of the mountain stations on the basis of its relatively high rainfall. Although there may be some resemblance in totals to mountain stations such as Burairat, 'Asimah, Siji and Munai'ee, it does not share with such mountain stations their summer rainfall and its coastal location. The latter factor indicates that it should be included with west coast stations rather than with those of the mountains. Its high rainfall is due to orographic effects as it is backed by the high mountains of Ru'us Al Jibal.

The totals for the rainfall peaks of February and March 1982 were not as high as those for other west coast stations, although the west coast did
not receive high rainfall as did the mountain region. The highest rainstorm intensity rate recorded was 127.2mm./hr. in a storm on 24/02/1982, which lasted for 20 minutes giving a total rainfall of 21.4mm. of which 21.2mm. fell within the first 10 minutes.

Of the 42 intensity measurements made for Sha'am between December 1979 and August 1983, 25 were of intensity rates of over 10.0mm./hr., occurred in 60% of the storms of 10-minute duration, in 41% of the storms of 20-minute, in 33% of the storms of 30-minute and in 24% of the storms of 1-hour duration. During the rainy season, peaks of moderate totals (12-40mm.) appear to occur with 1 or 2 days intervals as shown in Table 3.23.

Table: 3.23

<table>
<thead>
<tr>
<th>Rainfall</th>
<th>Date</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.4mm.</td>
<td>27/3/82</td>
<td>1-day</td>
</tr>
<tr>
<td>36.6mm.</td>
<td>29/3/82</td>
<td>1-day</td>
</tr>
<tr>
<td>18.2mm.</td>
<td>12/3/83</td>
<td>2-day</td>
</tr>
<tr>
<td>13.0mm.</td>
<td>15/3/83</td>
<td>2-day</td>
</tr>
</tbody>
</table>

Moderate rain peaks (12-40mm.) in Sha'am separated by intervals of 1-2 days during the rainy months (1982-83).

Storms of over 12-hour duration made up 26% of the total recorded events. Even in this, variation is wide as demonstrated by the following two storms: the one on 12/02/80 when 58.6mm. fell in 13 hours with intensity rates of between 66.0mm./hr. and 2.4mm./hr., and the storm of 1/01/1981, which lasted for 22 hours with fine drizzle totalling 3.0mm. with intensity rates of between 4.8mm./hr. and 0.1mm./hr.
3.5.12.7. **Intensities of the summer convectional rainstorms**  
*(Table 3.24)*

Storm intensity data for the summer convectional rain events are shown in Table 3.24. As seen in Table 3.24, 13 out of 31 recorded rainstorms, or (41% of the total) recorded, took place within the first 1 hour of the rainstorm. Up to 50% usually fell within the first 2 hours and 65% within the first 3 hours. The maximum intensity rate during the period of rainstorm record was 94.2mm./hr. at Munai'ee (15/07/1980) and the minimum was 1.2mm./hr. at Fara'ah (11/08/1983).

The wide variation in the rainfall intensity is evident in the following example. In Munai'ee (15/07/80), 33.2mm. fell in 40 minutes with intensity rates starting in the first 10 minutes at 94.8mm./hr. when also nearly half of the total amount of rainfall of the whole storm had already fallen, declining to 33.2mm./hr. at the end of the storm. On the other hand, 3.0mm. fell on Al Ghail in 2 hours and 40 minutes with intensity rates of between 13.2mm./hr. and 1.0mm./hr. (19/09/1983). Again, in Masafi, 25.8mm. (10/08/1983) fell in 8 hours and 20 minutes with intensity rates ranging from 28.8mm./hr. to 2.2mm./hr., while in Fara'ah 3.0mm. fell in 17 hours (11/08/83) with rates of between 1.1mm./hr. and 0.3mm./hr. (Table 3.24).

Intensity rates of the summer convectional rainstorms generally vary from 1.2mm./hr to 94.8mm./hr in the first 10 minutes or 0.4mm./hr to 33.7mm./hr in the first 1 hour, to 0.3mm./hr and 2.4mm./hr in the first 12 hours or 0.8mm./hr in storms extending 24 hours in duration (Table 3.25.).

If the storm continued for more than 6 hours, though in most cases up to 50% of its rain may have fallen within the first 3 hours, the amount increased gradually, not in sudden increments, until the end of the storm. The only exception was 'Asimah (10/8/83) when in 6 hours 12.6mm. fell out of a total of 23.2mm. in 9 hours (Table 3.24.). Convectional storms, though violent and thundery, have rainfall totals lower than the winter frontal storms, even of the totals of those late 'winter' rainstorms that may occur as late as May, which are discussed next.
Nearly 42% of the 31 rainstorms shown in Table 3.24 above took place within the first 1 hr., 50% within the first 2 hrs. and 65% within the first 3 hrs. The maximum rainstorm intensity rate was 94.2 mm/hr. at Munai'ee on 15/07/1980 and the minimum was 1.2 mm/hr. at Fara'ah on 11/08/1983.

Table: 3.24.

Rainstorm intensity data for the summer convectional rains.
### Table 3.25

The range of rainfall totals and intensity rates of the summer convectional storms for the period of record (1979-83).

<table>
<thead>
<tr>
<th>Rainfall Amount mm.</th>
<th>Intensity Rate mm./hr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mins. 0.6 - 15.8</td>
<td>1.2 - 94.8</td>
</tr>
<tr>
<td>20 mins. 0.2 - 19.0</td>
<td>0.6 - 64.8</td>
</tr>
<tr>
<td>30 mins. 0.2 - 28.8</td>
<td>0.4 - 57.6</td>
</tr>
<tr>
<td>1 hour 0.4 - 33.2</td>
<td>0.4 - 33.2</td>
</tr>
<tr>
<td>2 hours 0.8 - 14.8</td>
<td>0.4 - 6.7</td>
</tr>
<tr>
<td>4 hours 1.2 - 17.2</td>
<td>0.3 - 5.8</td>
</tr>
<tr>
<td>6 hours 1.2 - 23.8</td>
<td>0.3 - 4.0</td>
</tr>
<tr>
<td>12 hours 3.0 - 25.8</td>
<td>0.3 - 2.4</td>
</tr>
<tr>
<td>24 hours 18.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Source: MAF rainstorm intensity sheets, 1979-83, (unpublished)

3.5.12.8. **Intensities of the late 'winter' rainstorms of 30/04 and 1/05/1981 (Table 3.26.)**

The late 'winter' storms of 30/04-1/05/1981 were concentrated around Filli in the central parts of the piedmont plains where 134.2mm. fell on 1-2/05/1981. 87.0mm. fell on the 1/05/1981 (or 65% of the total for May) in only 9 hours with intensity rates above 126.0mm./hr. for the first 30 minutes reaching a maximum of 138.0mm./hr. during the first 10 minutes. 72.6mm. fell within 1 hour (or 88% of the 9-hour total) (Table 3.26).

In Masafi, on 1/05/81, all the 22.8mm. fell in 1 hour with intensity rates ranging from 75.6mm./hr. to 22.8mm./hr. (Table 3.26). In Sinnah, on 30/4/81, the 41.0mm. fell in 20 hours and 13 minutes, although 24.8mm. (or 61% of this amount) fell in 1 hour with high intensity rates
of 122.4mm./hr. and 24.8mm./hr., reduced to 1.7mm./hr. at the end of the rainstorm, after 20 hours (Table 3.26).

East coast stations, such as Kalba, had medium duration and intensity rate rainstorms. 44.2mm. fell on 30/04/81 in 5 hours 40 minutes, although 32.0mm. (or 72% of the total) fell in 1 hour, with intensity rates ranging from 42.0mm./hr. to 10.5mm./hr (Table 3.26).

3.6. Evaporation

The greater part of the annual precipitation of the Emirates is lost in evaporation. Such losses form an important factor in the evaluation of the water resources and the calculation of the water balance. The climatic factors affecting evaporation are: solar radiation, temperature, wind, atmospheric pressure, soluble solids, available open or soil water source and vegetation cover.

The source of the energy available to provide the latent heat for the process of evaporation is solar radiation. Evaporation also depends on the variation between the actual vapour pressure and the saturated vapour (humidity), which is a function of the air temperature. Wind enhances evaporation by the removal of moistened air. All the prerequisites of evaporation from low lying, open, largely unvegetated and wind swept terrains, discussed in the section on topography, to the meteorological elements of temperature, humidity, radiation and wind, discussed in the preceding subsections of this chapter, indicate a high evaporation potential in the Emirates.

In the Emirates, evaporation was measured by the American Class 'A' open pan, supported by a slatted wooden stand to allow ventilation, until 1984 when nearly all measurement of evaporation was abandoned. A metal cup container is used to refill the pan every morning to the level of the needle pointer gauge; each cupful is equivalent to 1.27mm. The circular, galvanized (or stainless steel), pan has a diameter of 122cm. and a depth of 25.4cm. As the area of the open pan is smaller than that of any natural open water body, the results obtained are usually exaggerated. A correction factor, the pan coefficient, which is between
### Table 3.26.

Rainstorm intensity records of the late 'winter' rainfall events of 30th. April to 2nd., May 1981.

Rainfall amounts varied from 22.8mm. in 1hr. to 41.0mm. in 20hrs. 38mins. to 87.0mm. in 9hrs. Rainstorm intensity rates varied from 7.0mm/hr. to 138.0mm/hr. in the first 10mins. to 22.8mm/hr. and 76.0mm/hr. in the first 1hr.

<table>
<thead>
<tr>
<th>Station</th>
<th>10-min</th>
<th>20-min</th>
<th>30-min</th>
<th>1-hr</th>
<th>2-hr</th>
<th>3-hr</th>
<th>4-hr</th>
<th>6-hr</th>
<th>12-hr</th>
<th>Total mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rate mm/hr</td>
</tr>
<tr>
<td>Masafi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22.8mm</td>
</tr>
<tr>
<td>(1/5/81)</td>
<td>Amount/mm</td>
<td>12.6</td>
<td>22.2</td>
<td>22.6</td>
<td>22.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rate:mm/hr</td>
<td>75.6</td>
<td>66.6</td>
<td>45.2</td>
<td>22.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Sinnah</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>41.0mm</td>
</tr>
<tr>
<td>(30/4/81)</td>
<td>Amount/mm</td>
<td>20.4</td>
<td>23.2</td>
<td>24.8</td>
<td>24.8</td>
<td>25.0</td>
<td>25.0</td>
<td>25.0</td>
<td>40.0</td>
<td>41.0</td>
</tr>
<tr>
<td></td>
<td>Rate:mm/hr</td>
<td>122.4</td>
<td>69.6</td>
<td>49.6</td>
<td>24.8</td>
<td>12.5</td>
<td>8.3</td>
<td>6.3</td>
<td>4.2</td>
<td>3.3</td>
</tr>
<tr>
<td>Kalba</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>44.20mm</td>
</tr>
<tr>
<td>(30/4/81)</td>
<td>Amount/mm</td>
<td>7.0</td>
<td>13.0</td>
<td>16.8</td>
<td>32.0</td>
<td>41.2</td>
<td>41.6</td>
<td>41.8</td>
<td>44.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rate:mm/hr</td>
<td>42.0</td>
<td>39.0</td>
<td>33.6</td>
<td>32.0</td>
<td>20.6</td>
<td>13.9</td>
<td>10.5</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Fili</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.40 mins</td>
</tr>
<tr>
<td>(1/5/81)</td>
<td>Amount/mm</td>
<td>23.0</td>
<td>44.0</td>
<td>54.0</td>
<td>76.2</td>
<td>77.0</td>
<td>77.0</td>
<td>86.8</td>
<td>87.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rate:mm/hr</td>
<td>138.0</td>
<td>132.0</td>
<td>108.0</td>
<td>76.0</td>
<td>38.5</td>
<td>25.7</td>
<td>19.3</td>
<td>14.5</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>(2/5/81)</td>
<td>Amount/mm</td>
<td>11.0</td>
<td>16.6</td>
<td>21.6</td>
<td>25.2</td>
<td>37.2</td>
<td>43.8</td>
<td>45.6</td>
<td>47.2</td>
</tr>
<tr>
<td></td>
<td>Rate:mm/hr</td>
<td>66.0</td>
<td>49.8</td>
<td>43.2</td>
<td>25.2</td>
<td>18.6</td>
<td>14.6</td>
<td>11.4</td>
<td>7.9</td>
<td></td>
</tr>
</tbody>
</table>

Source of data: Ministry of Agriculture and Fisheries rainfall intensity records (unpublished).
and 0.8, was introduced in 1964 by Ven Te Chow (Handbook of Applied Hydrology, McGraw Hill, New York, 1964).

Besides their being inadequately representative of natural evaporation conditions, the open pan measurements are liable to errors due to wind, animals and the heating of the metal of the pan itself. However, the most important failing that renders measurement totally impossible during that critical time is the liability of the water to overflow the pan uncontrollably during rainstorms. No reliable evaporation measurement data exist to date, nor did they exist in a satisfactory form even during the period when evaporation measurements were carried out between 1978 and 1984. The data provided in Table 3.27 are included for illustration and have been carefully used because of their tentative quality and the short duration of the measurements.

Evaporation in reality takes place from both surficial open water bodies and also from vegetated and unvegetated surfaces; the process is known as evapotranspiration. This is defined as the amount of water lost from both vegetated and bare ground surfaces under normal climatic conditions. The value is difficult to determine in arid environments because it is greatly influenced by soil characteristics and moisture content. Potential evapotranspiration measurement, on the other hand, involves the rate of evaporation and transpiration from an actively growing vegetated surface of a short green crop of uniform height (grass) for which a consistent supply of water is assumed. Actual evapotranspiration can be less than, or equal to the potential evapotranspiration depending on the amount of soil moisture available.

Besides being outside the scope of this study, to warrant a detailed discussion of the empirical formulae in the calculations of potential evapotranspiration (e.g. Thornthwaite, Blaney-Criddle and Penman), such calculations require accurate meteorological information. In turn, such information in the Emirates has never been available in an adequate form, and is becoming increasingly less available with time due to neglect caused by both staff and budgetary constraints.

Radiation data, which is the most important meteorological prerequisite for potential evaporation calculations, is only available in the west coast airport meteorological stations of Abu Dhabi, Dubai and Sharjah.
but no evaporation data exist for inland stations where evaporation is known to be taking place at higher rates than on the Gulf coast.

3.6.1. Estimation of potential evapotranspiration

It is not easy, or even perhaps feasible, to measure the losses of water across the wide range of evapotranspiration sources. Quantifying the amounts of water lost through evapotranspiration is usually based on estimation. In arid regions, annual water losses by evapotranspiration are very high. Studies in similar environments in the United States estimated precipitation loss to evapotranspiration as 75%. In a very arid region like that of the Emirates, this could be as high as 100% (Harold, L.L. 'Evapotranspiration: A factor with plant, soil and water economy', 1969, New York, John Wiley).

As only open pan evaporation measurements are available for some locations in the Emirates (up to 1982), the recommendation by the FAO (1977) of a coefficient of 0.55 for converting pan evaporation to potential evapotranspiration, is used here merely to illustrate the rate of water loss in the various topographic regions. Table 3.27 shows the mean monthly and the mean annual Class 'A' open pan evaporation rates as well as the rates calculated with the 0.55 coefficient factor.

The overall daily evaporation rate for the Emirates is 9.4mm./d, but the highest daily rate is 10.1mm./d for stations in the desert foreland, followed by the mountain region and the piedmont plains (9.6mm./d. each), the east coast (9.4mm./d.) and the west coast (9.0mm./d.). The highest evaporation rates occur during the hot months from May to October, with the highest cumulative monthly mean of 13.8mm./d. occurring in July.

The annual mean evaporation for the Emirates is 3433.6mm. per annum (9.4mm./d) or 26 times the period mean annual rainfall of the UAE of 132.13mm. The corrected value, using the coefficient 0.55 to approximate it with the potential evapotranspiration rate, is 1888.5mm. per annum (5.2mm./d) or 14 times the period annual mean rainfall. This mean potential evapotranspiration value is close to the mean values for most stations and is surpassed slightly by values for the mountain stations (5.6mm./d), Al Hibab in the desert foreland (5.5mm./d) and
Table: 3.27.

Mean monthly Class 'A' open pan evaporation rates in mm./month. Included also: total annual evaporation in mm./a, the 0.55 evapotranspiration coefficient in mm./a, mean monthly evaporation for the whole Emirates in mm./month, mean daily evaporation in mm./d and the overall daily mean evapotranspiration rate (5.2mm/d).

The highest evaporation rates are in the desert foreland, the piedmont (gravel) plains and the mountains, while the lowest are on the west coast.
Mileiha in the western piedmont plains (6.1 mm./d). Mileiha registers the highest potential evapotranspiration values, a reflection of its low relative humidity and therefore high evaporation potential, and Abu Dhabi (on the west coast) the lowest potential evapotranspiration values (4.3 mm./d), a reflection of its higher relative humidity values.

Figure 3.18. shows the relationship between open pan evaporation, temperature, radiation, wind and relative humidity. There is a close relationship between evaporation, temperature and radiation with the curves of these three climatic elements showing a downward trend for lower evaporation, radiation and temperature between December and February, but showing an upward trend for high evaporation between May and September. The upward trend in the curve for relative humidity coincides with the period of lower evaporation owing to high humidity in the air, which may reach maximum values of near saturation between November and February, while the downward trend in the curve between April and September coincides with the period of highest evaporation owing to relatively less humidity available in the air.

Although the curve for wind shows fluctuation and is not as smooth as the other curves, it retains the overall trend of low wind velocities during low evaporation between December and February, while between March and September the strong winds help enhance evaporation by the removal of moisture from the air continually.

3.6.2. Evaporation from sabkha

Inland and coastal sabkhas are evaporitic 'sinks' for both deep groundwater rising by capillary action and also by lateral flow following the surface gradient above phreatic (water-table) aquifers. Pike (Evaporation of groundwater from coastal playas in the Arabian Gulf, Journal of Hydrology, 11, 1970) estimated the evaporation rate from sabkhas near Dhahran in eastern Saudi Arabia to be in the order of 7000 mm. per year.
Figure: 3.18.

Relationship between radiation, temperature, wind, relative humidity and open pan evaporation.

There is a clear relationship between radiation, temperature, wind and open pan evaporation with the upper and lower limbs of their graphs coinciding with higher or lower activity (or values). The trend of the graph for relative humidity, with its limbs running contrary to those of the rest, represents higher evaporation during periods of lower relative humidity and vice versa.
3.7. General summary

Meteorological observation, which is a key prerequisite in the assessment of groundwater resources, is fragmented in management, the rain recorders are not appropriately sited and evaporation has ceased to be measured.

Rainfall is limited in amount, is seasonal and erratic. Most of it falls in the cooler months between December and April and it is largely of the Mediterranean frontal type associated with the Subtropical Jetstream. Except in years of unusually high rainfall, rainfall is localized, intense and of short duration. The same is equally true of the convective and monsoonal types of rainfall, which are experienced in the mountains, piedmont plains and on the east coast. There is a close relationship between rainfall and the resulting runoff though, owing to the existing siting of the rain recorders and the localized incidence of rainfall, a substantial surface flow may occur in a wadi, which cannot be explained by the amounts of rainfall measured by the surrounding stations. Normally, about 50mm. of rainfall may cause surface runoff.

As is shown later (Chapter 4), the mean annual volume of runoff and the expected recharge from it is less than hitherto guesstimated, and is certainly far less than recharge from infiltrating direct rainfall. As the widespread rain-causing conditions in winter reach the Emirates from the north and northwest over the lowlands to the west of the mountain range, the recharge potential of the highly permeable dune sands appear favourable to recharge from direct rainfall. The rainy season is also a time of the year when evaporation is relatively less owing to the cooler temperatures and high relative humidity.

The incidence of the monsoonal and the convectional rains in the hot summer months, on the other hand, leads to the greater part of the rainfall evaporating after months of the heating of the soil. The limited amount falling and the short duration does not allow discernible changes in the water-table even in mountain wadis after the heavy abstraction and lowering of groundwater levels in the months preceding the summer rains.
3.8. Synopsis

This chapter has been introduced by a complete description and critique of the meteorological measurement network. Following this, a basic consideration of the role and aspects of the atmospheric circulation has been included as the background to a very detailed treatment of the main climatic elements. The major characteristics of radiation, temperature, wind, rainfall, evaporation and evapotranspiration have all been described. The focus, as would be expected in such a study, has been upon rainfall, the key variable in the entire water resource system. An analysis of all the major systematic and regional aspects of rainfall has been provided.
4. SURFACE HYDROLOGY

4.1. Introduction

In this chapter catchment and runoff characteristics are discussed, together with the existing situation of the aflaj that were once substantial contributors of irrigation water, but have recently dwindled in output with the receding water-table. Quantification of the actual contribution to groundwater recharge from surface runoff is made for this study on the basis of yields from the gauged catchments and calculating the expected recharge volumes from the ungauged catchments.

As the present study is focussed upon the understanding of water resources in their entirety and not limited to only engineering design aspects, runoff characteristics and volumes are discussed for years of exceptional, medium and least rainfall to illustrate the point that the median of all the runoff volumes for the period of flood records can be accepted as the reasonable annual recharge volume to the groundwater system. Only when the comparatively large volume of surface runoff of a particular rainy year (e.g., 68.51 MCM. for the gauged catchments for 1987-1988 (Table 4.1.)) is set against that obtained during years of very small flow (only 1.01 MCM. for the period of the three dry years 1983-84 to 1985-86 for the gauged catchments (Table 4.1.)), can the actual mean annual contribution to groundwater recharge from surface runoff be identified. Taken as a whole for the gauged catchments based on available surface runoff data, the average runoff volume for these catchments is 23.67 MCM/a, of which a part only ends up as recharge to the groundwater system.

Immediate effects of recharge on groundwater levels, and thus storage, are experienced in mountain wadis and their alluvial fans at the point where the wadis debouch on to the plains. Further west in the piedmont plains and the desert foreland beyond them, such rapid responses of the water-table are gradually reduced to indiscernible levels. The movement
### Table 4.1

Runoff volumes of the gauged catchments of the Emirates (for the hydrological years 1975-76 to 1987-88).

Only when the comparatively large volume of surface runoff for the exceptionally rainy year of 1987-88 of 68.51 MCM for the gauged catchments is set against the runoff volume obtained during a year of very small flow (of 1.01 MCM for the whole dry period 1983-84 to 1985-86) can the mean annual contribution to groundwater recharge be realized. Based on available surface runoff data, the average annual runoff volume for these catchments is 23.67 MCM/a of which only a part ends up as recharge to the groundwater system.

<table>
<thead>
<tr>
<th>Wadi Catchment</th>
<th>75-76</th>
<th>76-77</th>
<th>77-78</th>
<th>78-79</th>
<th>79-80</th>
<th>80-81</th>
<th>81-82</th>
<th>82-83</th>
<th>83-84</th>
<th>84-85</th>
<th>85-86</th>
<th>86-87</th>
<th>87-88</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wadi Al Reesh (Qayfass Road)</td>
<td>2.87</td>
<td>1.17</td>
<td>Nil</td>
<td>2.23</td>
<td>0.47</td>
<td>0.11</td>
<td>0.11</td>
<td>0.41</td>
<td>0.41</td>
<td>0.41</td>
<td>0.41</td>
<td>0.41</td>
<td>0.41</td>
<td>0.41</td>
</tr>
<tr>
<td>Wadi Al Reesh (At Burairat)</td>
<td>2.27</td>
<td>1.60</td>
<td>0.04</td>
<td>0.10</td>
<td>4.77</td>
<td>0.04</td>
<td>2.27</td>
<td>0.98</td>
<td>0.11</td>
<td>0.08</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Wadi Naqqab (At Outflow)</td>
<td>3.60</td>
<td>0.84</td>
<td>0.63</td>
<td>1.66</td>
<td>2.72</td>
<td>0.22</td>
<td>0.93</td>
<td>1.57</td>
<td>0.11</td>
<td>0.02</td>
<td>0.02</td>
<td>0.54</td>
<td>1.21</td>
<td>1.10</td>
</tr>
<tr>
<td>Wadi Lamba (At Falaj Al Musila)</td>
<td>0.57</td>
<td>0.16</td>
<td>0.03</td>
<td>0.09</td>
<td>2.16</td>
<td>2.03</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Wadi Siyi U/S of Siji Village</td>
<td>0.29</td>
<td>3.27</td>
<td>0.07</td>
<td>0.31</td>
<td>0.80</td>
<td>0.26</td>
<td>7.05</td>
<td>1.18</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Wadi Siyi U/S of Ashwani Junction</td>
<td>1.55</td>
<td>1.90</td>
<td>0.29</td>
<td>2.35</td>
<td>0.21</td>
<td>1.47</td>
<td>4.09</td>
<td>3.18</td>
<td>0.43</td>
<td>0.10</td>
<td>1.25</td>
<td>6.08</td>
<td>1.93</td>
<td></td>
</tr>
<tr>
<td>Ashwani U/S of Siyi Junction</td>
<td>NA</td>
<td>NA</td>
<td>0.21</td>
<td>0.74</td>
<td>0.43</td>
<td>0.29</td>
<td>4.46</td>
<td>3.59</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Wadi Ham (At Bithna Weir)</td>
<td>2.15</td>
<td>0.79</td>
<td>0.26</td>
<td>0.27</td>
<td>0.32</td>
<td>0.06</td>
<td>13.06</td>
<td>3.67</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Wadi Al Qawr - East (At Huila)</td>
<td>NA</td>
<td>NA</td>
<td>0.14</td>
<td>1.76</td>
<td>4.58</td>
<td>4.67</td>
<td>13.99</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Wadi Al Qawr - West (At Jebel Fayah)</td>
<td>0.81</td>
<td>0.15</td>
<td>0.02</td>
<td>0.14</td>
<td>0.15</td>
<td>0.22</td>
<td>4.70</td>
<td>0.51</td>
<td>0.42</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Wadi Al Wulal (At Spring)</td>
<td>NA</td>
<td>NA</td>
<td>0.19</td>
<td>0.95</td>
<td>1.83</td>
<td>1.89</td>
<td>6.78</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Wadi Al Bateer (At Dibba)</td>
<td>N N</td>
<td>R E C O R D</td>
<td>0.16</td>
<td>0.15</td>
<td>0.96</td>
<td>0.17</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Wadi Shik (At Al Ain)</td>
<td>N N</td>
<td>R E C O R D</td>
<td>0.53</td>
<td>0.46</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Totals</td>
<td>16.01</td>
<td>9.88</td>
<td>2.01</td>
<td>5.19</td>
<td>12.45</td>
<td>15.56</td>
<td>47.87</td>
<td>36.00</td>
<td>0.76</td>
<td>0.11</td>
<td>0.11</td>
<td>16.41</td>
<td>68.21</td>
<td>23.67</td>
</tr>
</tbody>
</table>

* Volume includes the dammed water at Al Beeh Dam for 20-07-1988 accrued from surrounding hills upstream of the flood gauges at Al Burairat. Source of runoff data: Ministry of Agriculture and Fisheries (MAF/S).

---

204
of groundwater in the vast plains and sandy desert is extremely slow and the contribution to this inflow from a particular rainy year may not reach a point some kilometres away from the recharge zone at the foothills for several years. The actual expected contribution to groundwater recharge from surface flow is derived for all the catchments within the Emirates (i.e., for those catchments lying within the Northern Emirates), and also for those catchments south of Al Madam in Oman but contributing to groundwater recharge into the southern piedmont plains in the Al Ain region. This quantification is put in context later in the study in the groundwater recharge and balance estimates as the annual volume of input into the aquifer system from runoff, which, together with recharge from other input contributors (direct rainfall and through-flow), is set against the annual volume of the abstracted groundwater (Chapter 10).

4.2. Drainage and catchments

Surface flow in the Emirates is seasonal occurring as spate floods that result from isolated, intense rainstorms with the torrential flow taking place in the mountainous hardrock areas draining to the east and west of the N-S trending watershed. The mountain divide is heavily dissected by v-shaped wadis with very steep slopes that are devoid of vegetation. More than 3,800 tributaries and main streams (dry for most of the year) drain a hard rock mountain area of 3515 km². Most of these streams are fissure-controlled.

Major wadis, like Wadi Al Baseerah (also known as Wadi Al Shimal) and Wadi Ham, occupy the two major structural faults of Dibba-Idhn and Wadi Ham, respectively. As discussed in Chapter 2, the mountainous area within the Emirates is thus divided by these major fault-guided wadis into two main highland blocks:

a) The carbonate upland massif of Ru‘us Al Jibal, to the north of Wadi Al Baseerah, with west-flowing wadis. Whether small wadis, like Wadis Sha‘am and Ghaleelah, or large wadis, like Wadis Al Beeh and Al Naqab, they tend to have wide gravel-filled floors that are dry for several years.
b) To the south of Wadi Al Baseerah, the mainly ophiolite mountain block is divided by Wadi Ham into a smaller ultrabasic (mainly peridotite) eastern block between Fujairah, Dibba and Masafi, and a larger block of basic (mainly gabbro) rocks in the west between Hatta, Wahlah and Tawi Nassas in the south and Kub (north of 'Asimah), in the north. Blocks of each type of rocks are found in the area of the other and the whole area is dissected by fractures that form the basic lines of the drainage system.

Wadis flowing to the east are generally shorter than wadis flowing to the west, but among the eastern wadis are some of the longest, such as Wadis Al Baseerah, Wahlah, Wurai'ah and Qawr (East). With regard to wadis of the length of the main stream of 10km. or more, the number on either side of the watershed is equal (Table 4.2.).

The west-flowing wadis, whether they rise in limestone upland in the north or the basic and ultrabasic gabbros and peridotites in the south, have a general direction of flow towards the west and northwest. The east-flowing wadis, crossing both gabbro and peridotite highland, have a general direction of flow towards the east with the exception of Wadi Al Baseerah and Wadi Ham, which flow to the northeast and southeast, respectively.

The drainage of the Emirates is governed by the elongated mountain zone, which contains 27 wadi catchments whose west-flowing wadis group in the western piedmont plains into three main overland flow channels:

a) Al Beeh and Naqab in the north;

b) Lamhah in the centre; and,

c) Sumaini-Yudai'ah in the south central part of the piedmont plains.

No such groupings of wadi flow channels occur on the east (Batinah) coast where wadis flow separately towards the shoreline.

The west-flowing wadis of the eastern region of Abu Dhabi (Al Ain),
originate in Oman with some of their flow channels crossing the international border to the Al Ain region south of Sumaini, such as Wadis Al Jabeeb, Al Khabb, Ma'aisheq and Kahal (Bathat bin Hilal or Wadi Tuwaiyyah). The last two wadis are a continuation of Wadi Mahdah. The rest of the wadis, flowing into Al Ain from the mountains in Oman, are Wadis Shik, Al Ain (called in Oman Wadi Al Wadiyyain) and Hamad, all of which flow across the Al Jaww plain.

The compactness of the mountain divide, especially within the Emirates (35kms. at its widest between Khorfakkan and Jabal Mu'taredh in the Northern Emirates) and the steep-sided barren slopes, induce intense runoff despite the modest rainfall. Of the 27 catchments, 13 drain westwards into the piedmont (gravel) plains and 14 eastwards into the narrow embayments of the Batinah coast on the Gulf of Oman. The catchments vary in size from only 6km$^2$, in the case of Wadi Al Ghail, to 474km$^2$, in the case of Wadi Al Beeh. (see Fig. 4.1. and Table 4.2).

4.3. Physiographic characteristics of the wadi catchments (Table 4.2.)

The mountains of the Emirates have an area of approximately 3500km$^2$ containing 27 drainage basins (Fig. 4.1, and Table 4.2), of which 19 catchments have an area of less than 100km$^2$ each. Besides Wadi Al Beeh, which has the longest main stream (47kms.), 20 of the wadis have main streams of a length of less than 20 kms. each. Only the two catchments of Wadi Al Ghail and Wadi Gulfa have less than 30 tributaries each, while 14 of the catchments have more than 100 tributaries each. Drainage density varies from 1 to 8, with 23 basins (85% of the total number of catchments) have a density of below 3. The average slope varies from 2%, for Wadi Al Qawr (East) and Wadi Ashwani, to 18% for Wadi Sha'am. The compactness of the catchments, with the exception of that of Wadi Al Beeh, gives rise to torrential floods, as the contribution of the short tributaries to the main stream-flow takes place within an hour of the beginning of the storm. The runoff coefficient (the percentage of the volume of annual runoff to the total volume of catchment precipitation), in wadis in the limestone highland, varies from 3% for the long-term mean runoff to 4-7% for a year with exceptionally high rainfall (Wadi Al Beeh (1982) (Table 4.3.)), while it is higher in the catchments in the ophiolite (serpentinite) highland where the runoff coefficient ranges from 12% for the period runoff mean
The catchments of the Emirates.

The mountainous part, and thus the wadi catchments, of the Emirates lies in the northeastern tip of the country. There are 27 catchments, of which 11 are gauged. Of the 27 catchments 13 are feeding west-flowing wadis, and 14 are feeding east-flowing wadis. In the northern part of the mountains, Wadi Al Beeh is fed by a catchment that lies mostly within the Mussandam territory of Oman. In the southern part to the east of Al Ain, the Kahal, Mahdhah and Mussaileq catchments, also in Oman, recharge the groundwater system of the Al Ain region.
Qawr and Wahlah, have gentler slopes of 2 to 3°. The main physiographic characteristics of the wadi catchments of the Emirates have an area of less than 100 km² each. The catchments vary in size from only 6 km² (Wadi Al Ghail) to 474 km² (Wadi Al Beeh). The runoff coefficient or ratio (the total flood volume in relation to the total volume of catchment precipitation) for wadis in the limestone highland varies from 3% for the long-term mean to 9% for a year of exceptionally high rainfall (1982 or 1988). The runoff coefficient for wadis in the serpentinite highland is higher and ranges from 12% for the period mean to 22% for a year of exceptional rainfall. Wadis with short courses, such as the west-flowing wadis of Sha' am and Ghaleelah or the east-flowing wadis of Ramth, Safad and Shayy, have steep slopes ranging from 8 to 18°. Larger wadis, such as the west-flowing Al Beeh or the east-flowing Al Qawr and Wahlah, have gentler slopes of 2 to 3°. The average runoff coefficient (or ratio) is 6% for catchments in the limestone part and 12% for catchments in the serpentinite part, of the highland.

Table: 4.2.

The main physiographic characteristics of the wadi catchments of the Emirates.
### Table 4.3

Runoff characteristics for main flood events for selected wadis in both the limestone and ophiolite parts of the mountains of the Emirates for flood events in 1979, 1982, 1983 and 1988.

Flood duration in the wadis in the limestone hardrock areas (Wadis Al Beeh and Al Naqab) ranged from 5400 seconds (1hr. 30mins.) to 69000 seconds (19hrs. 20mins.), while in the ophiolite hardrock wadis (Wadis Siji, Sfini, Ham and Al Wurai'ah) the flood duration ranged from 7200 seconds (2hrs.) to 86400 seconds (24hrs.). Floods may continue for up to 120000 seconds (over 33hrs.) in years of heavy rainfall. The time for runoff concentration of a flow of more than 100m³/sec., before and after a flood peak flow, varied from 5100 seconds (5mins.) in Wadi Al Beeh (on 20-07-1988) to 51300 seconds (14hrs. 30mins.) in Wadi Sfini (on 12-02-1982), followed by Wadi Ham, where it varied from 18000-78000 seconds (5-8hrs.) (on 17/18-02-1988) to 86400 seconds (24hrs.) (on 15-02-1982), both being years of exceptional rainfall. Peak flows do not exceed 100m³/sec. in years of medium rainfall.

<table>
<thead>
<tr>
<th>WADI</th>
<th>CATCHMENT AREA KM²</th>
<th>FLOOD DATE</th>
<th>PEAK FLOW M³/SEC</th>
<th>AVERAGE FLOW M³/SEC</th>
<th>TIME OF CONCENTRATION SECONDS</th>
<th>FLOOD DURATION SECONDS</th>
<th>TOTAL RUNOFF MCN</th>
<th>AVERAGE RAINFALL RAINFALL MM</th>
<th>RUNOFF COEFFICIENT</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AL BEEH</strong> (HURABAT)</td>
<td>474</td>
<td>12-03-79</td>
<td>21.60</td>
<td>11.73</td>
<td>1800</td>
<td>5400</td>
<td>0.0633</td>
<td>30.60</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>13-03-79</td>
<td>5.40</td>
<td>5.50</td>
<td>4200</td>
<td>6900</td>
<td>0.0377</td>
<td>38.80</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-02-82</td>
<td>157.00</td>
<td>50.86</td>
<td>11700</td>
<td>33400</td>
<td>1.6480</td>
<td>50.20</td>
<td>7.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25-02-82</td>
<td>21.00</td>
<td>7.50</td>
<td>2300</td>
<td>10500</td>
<td>1.4600</td>
<td>50.60</td>
<td>14.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27-02-82</td>
<td>71.45</td>
<td>7.20</td>
<td>7800</td>
<td>40500</td>
<td>1.9040</td>
<td>64.60</td>
<td>16.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29-02-82</td>
<td>23.05</td>
<td>6.70</td>
<td>6200</td>
<td>50400</td>
<td>1.5400</td>
<td>66.20</td>
<td>51.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-01-83</td>
<td>23.20</td>
<td>11.16</td>
<td>6300</td>
<td>18000</td>
<td>0.2080</td>
<td>60.20</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27-04-88</td>
<td>56.80</td>
<td>13.19</td>
<td>2700</td>
<td>10800</td>
<td>0.1550</td>
<td>14.00</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27-04-88</td>
<td>186.88</td>
<td>51.24</td>
<td>5100</td>
<td>9600</td>
<td>0.4970</td>
<td>16.80</td>
<td>6.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AL NAQAB</strong></td>
<td>92</td>
<td>12-03-79</td>
<td>121.36</td>
<td>14.90</td>
<td>7680</td>
<td>69600</td>
<td>1.0372</td>
<td>28.20</td>
<td>40.0</td>
<td></td>
</tr>
<tr>
<td>13-03-79</td>
<td>26.89</td>
<td>12.20</td>
<td>3000</td>
<td>48200</td>
<td>0.5858</td>
<td>23.30</td>
<td>27.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-02-82</td>
<td>71.49</td>
<td>22.18</td>
<td>3600</td>
<td>7800</td>
<td>0.1730</td>
<td>88.80</td>
<td>9.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25-02-82</td>
<td>62.68</td>
<td>19.72</td>
<td>12500</td>
<td>27600</td>
<td>0.5444</td>
<td>17.40</td>
<td>34.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13-03-83</td>
<td>17.32</td>
<td>4.00</td>
<td>12600</td>
<td>31800</td>
<td>0.1820</td>
<td>11.00</td>
<td>9.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21-01-83</td>
<td>41.42</td>
<td>18.61</td>
<td>18600</td>
<td>35200</td>
<td>0.6190</td>
<td>25.80</td>
<td>17.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21-01-83</td>
<td>51.89</td>
<td>22.20</td>
<td>9000</td>
<td>21000</td>
<td>0.4662</td>
<td>19.80</td>
<td>26.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17-02-88</td>
<td>95.10</td>
<td>14.80</td>
<td>10800</td>
<td>51200</td>
<td>0.7550</td>
<td>77.00</td>
<td>11.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19-02-88</td>
<td>37.68</td>
<td>7.50</td>
<td>9000</td>
<td>7200</td>
<td>0.2703</td>
<td>22.60</td>
<td>13.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SIFNI</strong></td>
<td>86.6</td>
<td>12-03-79</td>
<td>23.86</td>
<td>6.60</td>
<td>5400</td>
<td>47400</td>
<td>0.3142</td>
<td>39.60</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>13-03-83</td>
<td>167.00</td>
<td>21.12</td>
<td>26100</td>
<td>77400</td>
<td>1.6356</td>
<td>108.70</td>
<td>17.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-02-82</td>
<td>15.00</td>
<td>4.60</td>
<td>5400</td>
<td>35100</td>
<td>0.3930</td>
<td>20.00</td>
<td>16.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17-02-88</td>
<td>272.30</td>
<td>80.60</td>
<td>43200</td>
<td>34300</td>
<td>0.4384</td>
<td>118.40</td>
<td>34.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18-02-88</td>
<td>47.25</td>
<td>11.28</td>
<td>28600</td>
<td>88400</td>
<td>0.9742</td>
<td>76.00</td>
<td>15.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HAM</strong></td>
<td>90</td>
<td>12-03-79</td>
<td>95.75</td>
<td>30.33</td>
<td>17700</td>
<td>77400</td>
<td>2.3478</td>
<td>29.00</td>
<td>57.1</td>
<td></td>
</tr>
<tr>
<td>14-02-82</td>
<td>199.32</td>
<td>25.68</td>
<td>36900</td>
<td>74700</td>
<td>1.0912</td>
<td>77.80</td>
<td>17.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-02-83</td>
<td>11.35</td>
<td>3.90</td>
<td>1800</td>
<td>86400</td>
<td>0.3362</td>
<td>43.60</td>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30-03-83</td>
<td>71.73</td>
<td>4.88</td>
<td>7200</td>
<td>86400</td>
<td>0.4212</td>
<td>37.80</td>
<td>8.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>05-04-83</td>
<td>49.16</td>
<td>4.06</td>
<td>6600</td>
<td>86400</td>
<td>0.3504</td>
<td>50.40</td>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17-02-88</td>
<td>403.76</td>
<td>49.94</td>
<td>51300</td>
<td>120600</td>
<td>5.9017</td>
<td>143.40</td>
<td>29.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18-02-88</td>
<td>36.45</td>
<td>3.36</td>
<td>7200</td>
<td>14400</td>
<td>0.1924</td>
<td>34.80</td>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AL MURAI'AH</strong></td>
<td>129</td>
<td>14-02-82</td>
<td>35.42</td>
<td>5.12</td>
<td>11700</td>
<td>86400</td>
<td>0.4427</td>
<td>47.20</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td>28-02-82</td>
<td>356.21</td>
<td>68.17</td>
<td>7200</td>
<td>23278</td>
<td>101.40</td>
<td>17.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-02-83</td>
<td>56.20</td>
<td>12.82</td>
<td>9900</td>
<td>26400</td>
<td>0.3384</td>
<td>33.60</td>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11-02-83</td>
<td>294.04</td>
<td>88.37</td>
<td>57600</td>
<td>61200</td>
<td>5.4000</td>
<td>171.60</td>
<td>34.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-02-83</td>
<td>16.50</td>
<td>3.47</td>
<td>4800</td>
<td>86100</td>
<td>0.1590</td>
<td>39.00</td>
<td>14.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16-02-88</td>
<td>12.62</td>
<td>3.54</td>
<td>1800</td>
<td>32400</td>
<td>0.1147</td>
<td>21.60</td>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17-02-88</td>
<td>313.60</td>
<td>23.84</td>
<td>22500</td>
<td>49400</td>
<td>1.9780</td>
<td>85.00</td>
<td>20.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18-02-88</td>
<td>673.14</td>
<td>17.90</td>
<td>9000</td>
<td>18000</td>
<td>1.3500</td>
<td>112.00</td>
<td>21.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Hourly rainfall preceding or coinciding the flood event of stations within or near catchments.(from recorder charts)
to 12-43% for a year of exceptional rainfall ((1982), Table 4.3)).

The average runoff coefficient, based on measured runoff in the gauged catchments, and also that calculated for the ungauged catchments, is 6% for wadis in the limestone, and 12% for wadis in the serpentinite (ophiolite), mountains. (see Table 4.4).

4.4. Surface flow measurement

Surface flow measurement was carried out on a limited scale for the first time during the ‘Trucial States Water Resources’ survey of 1966-69 when surface hydrology data were needed. 9 stations for the measurement of flood flow were established in Wadis Al Qawr, Ham, Siji, Lamha (2 gauges), Al Beeh (2 gauges), Dadssah and Sumaini. Six of these had autographic flood level recorders that registered the depth and duration of floods. Once the survey was over (1969), these stations were neglected until 1975 when the MAF, with the assistance of the United Nations Food and Agriculture Organization (FAO), embarked on the development of an updated network that used the same sites in addition to two new sites at Wadis Sfini and Naqab. By 1988 the MAF flood-gauging network included 14 permanent stations consisting of the Leopold and Stevens float-operated flood-recorders, which continuously register the long-term fluctuation in flood level on a six-month chart.

Spot measurement is occasionally carried out in Wadi Al Dhaid (where the road crosses Wadi Al Dhaid), in Wadi Tuwaiyyain (at the dam site), Wadi Al Ghail (by the weir) and under the bridge at Mileiha.

Base- and falaj-flow is measured by a vertical axis Pygmy-Ott current meter, while there is only one cable-way current meter in suspension across Wadi Siji (called SK-4 Cable), which is supposed to continuously measure flood flow, but has never come into operation since it was installed in 1982.

Problems concerning the surface flow measurement network involve the occasional washing away of flood-recorders by torrential floods, such as the one in Wadi Ham during the heavy storms of February 1988, or their being stolen, as happened to the one in Sfini (upstream of the junction with Wadi Ashwani) in April 1988. The washing away of the
### Table: 4.4.

Average annual runoff ratio (coefficient) for selected wadis in the limestone (Wadis Al Beeh and Naqab) and ophiolite (Wadis Siji, Sfini, Ham, Qawr (East) and Wurai'ah) gauged catchments.

The period (of flood records) mean runoff ratio for the limestone catchments is 6%, and for the ophiolite catchments 12%. The mean runoff ratio for Wadi Lamhah in the western piedmont plains (not included in the table), for what is available of its incomplete flood data, is 1.0%.

<table>
<thead>
<tr>
<th>Wadi Catchment (Area km²)</th>
<th>75-76</th>
<th>76-77</th>
<th>77-78</th>
<th>78-79</th>
<th>79-80</th>
<th>80-81</th>
<th>81-82</th>
<th>82-83</th>
<th>83-84</th>
<th>84-85</th>
<th>85-86</th>
<th>86-87</th>
<th>87-88</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al Beeh (474)</td>
<td>1.90</td>
<td>1.30</td>
<td>0.10</td>
<td>0.28</td>
<td>6.19</td>
<td>0.40</td>
<td>2.00</td>
<td>1.89</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>4.40</td>
<td>10.50</td>
<td>2.90</td>
</tr>
<tr>
<td>Al Naqab (92)</td>
<td>14.60</td>
<td>3.60</td>
<td>8.50</td>
<td>23.50</td>
<td>18.10</td>
<td>6.56</td>
<td>4.20</td>
<td>9.30</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>4.50</td>
<td>6.40</td>
<td>9.60</td>
</tr>
<tr>
<td>Siji (86.6)</td>
<td>9.50</td>
<td>14.30</td>
<td>0.60</td>
<td>4.00</td>
<td>5.51</td>
<td>6.81</td>
<td>19.64</td>
<td>6.30</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>4.24</td>
<td>34.50</td>
<td>10.54</td>
</tr>
<tr>
<td>Sfini (138)</td>
<td>9.90</td>
<td>10.30</td>
<td>2.20</td>
<td>25.30</td>
<td>1.92</td>
<td>15.82</td>
<td>12.26</td>
<td>11.41</td>
<td>2.50</td>
<td>D</td>
<td>D</td>
<td>4.86</td>
<td>18.20</td>
<td>10.42</td>
</tr>
<tr>
<td>Ham (90)</td>
<td>9.40</td>
<td>4.70</td>
<td>3.60</td>
<td>5.10</td>
<td>9.49</td>
<td>2.06</td>
<td>46.19</td>
<td>12.36</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>4.33</td>
<td>32.00</td>
<td>12.92</td>
</tr>
<tr>
<td>Qawr-East (303)</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>3.31</td>
<td>20.05</td>
<td>4.16</td>
<td>16.29</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>10.30</td>
<td>16.90</td>
<td>12.34</td>
</tr>
<tr>
<td>Wurai'ah (129)</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>24.54</td>
<td>7.13</td>
<td>13.88</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>-</td>
<td>17.80</td>
<td>15.84</td>
</tr>
</tbody>
</table>

NR = No records were yet available  D = Dry year
flood-recorders is the result of substandard workmanship in the installation of the otherwise sturdy flood-recorder, which is made to withstand strong flood currents.

Surface runoff data have become reliable only since 1978 after the upgrading of the flood-gauging network. Data are collected, computed and tabulated by the MAF with no change in their presentation form since 1976. The availability of such data in detailed form is always years overdue as all the hydrological computation is carried out by one person who prepares the data and checks them as well. A list of the flood-gauging stations is given in Table 4.5:

<table>
<thead>
<tr>
<th>No.</th>
<th>Wadi</th>
<th>Location</th>
<th>MAF Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al Beeh</td>
<td>Digdaga Road</td>
<td>WB-1</td>
</tr>
<tr>
<td>2</td>
<td>Al Beeh</td>
<td>Burairat</td>
<td>WB-2</td>
</tr>
<tr>
<td>3</td>
<td>Al Naqab</td>
<td>Foothills</td>
<td>WB-3</td>
</tr>
<tr>
<td>4</td>
<td>Lamha</td>
<td>Falaj Al Mualla</td>
<td>WL-1</td>
</tr>
<tr>
<td>5</td>
<td>Siji</td>
<td>U/S Siji village</td>
<td>WL-2</td>
</tr>
<tr>
<td>7</td>
<td>Sfini</td>
<td>D/S Ash. Junction.</td>
<td>WL-4</td>
</tr>
<tr>
<td>8</td>
<td>Ashwani</td>
<td>U/S Sfini Junction.</td>
<td>WL-5</td>
</tr>
<tr>
<td>9</td>
<td>Ham</td>
<td>D/S Bithnah weir</td>
<td>WH-1</td>
</tr>
<tr>
<td>10</td>
<td>Qawr (East)</td>
<td>D/S Huwailat-Munai'ee</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Junction.</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Qawr (West)</td>
<td>Jabal Fayah</td>
<td>WG-2</td>
</tr>
<tr>
<td>12</td>
<td>Shik</td>
<td>Al Ain</td>
<td>WS-1</td>
</tr>
<tr>
<td>13</td>
<td>Wurai'ah</td>
<td>East of Lulaiyyah</td>
<td>WW-1</td>
</tr>
<tr>
<td>14</td>
<td>Al Baseerah</td>
<td>'Abadillah</td>
<td>WAB-1</td>
</tr>
<tr>
<td>15</td>
<td>&quot;</td>
<td>'Uyainah</td>
<td>WAB-2</td>
</tr>
<tr>
<td>16</td>
<td>&quot;</td>
<td>Dam Site</td>
<td>WAB-3</td>
</tr>
<tr>
<td>17</td>
<td>&quot;</td>
<td>By the road</td>
<td>WAB-4</td>
</tr>
<tr>
<td>18</td>
<td>&quot;</td>
<td>Al Fayy/Danhah</td>
<td>WAB-5</td>
</tr>
<tr>
<td>19</td>
<td>&quot;</td>
<td>Dibba</td>
<td>WAB-6</td>
</tr>
</tbody>
</table>

Source: Ministry of Agriculture and Fisheries (MAF)

Table: 4.5.

Flood-gauging stations of the Emirates (1990)
The surface runoff data used in the present study are those obtained from unpublished records of the MAF. The only detailed reports available are for the years 1981-82, 1982-83 and 1987-88 with discharge computations for 15-, 30- and 60-minute intervals. Although 1986-87 is the ideal low runoff year for comparison purposes, no such detailed discharge data are available to allow close comparisons with other years. As rainfall intensity data are only available for some mountain stations up to 1983 (Chapter 3, Section 3.5.12), it was only possible to study in detail runoff characteristics, by relating flood development to rainfall intensity, for the runoff years 1981-82 and 1982-83. For 1986-87 and 1987-88, daily rainfall data were used for the same purpose to also try and obtain acceptable basin rainfall averages that might have been responsible for the runoff volumes as shown in Tables 4.3, 4.6 (A-B), 4.10 (A-E), 4.11,, 4.14, 4.15 and 4.16).

4.5. Wadis

The barren mountains, with steep-sided ravine-like wadis, offer the ideal physical conditions for intense short-lived runoff. This is further aided by the compactness of the catchments and the short wadi courses on either side of the water divide despite the limited and intermittent rainfall. East-flowing wadis, such as Wadis Al Baseerah and Ham, are the largest wadis in the Emirates among those wadis wholly within Emirates territory, developing large volumes of surface flow, especially in the case of Wadi Ham, but their recharge potential is limited by the low storage capacity of the outwash fan deposits and the narrowness of the eastern coastal plain. West-flowing wadis, of which Wadis Sfini and Siji are the largest, on the other hand, have greater recharge potential because of the availability of the wide western piedmont plains across which they spread their flows.

The eastern edge of the sand dunes of the desert foreland provides a barrier to the westward flow of runoff, added to the fact that rarely do flood flows exceed the westward limit of the western (central) piedmont plains in medium rainfall years. The dunes are breached at two points by Wadi Yudai'ah, a continuation of Wadi Sumaini, near Jabal Fayah, and Wadi Lamhah at Falaj Al Mualla. Wadi Sumaini-Yudai'ah funnels the wadis draining the catchments within Oman south of Seih Sulailiyah (the outwash fan of Wadi Sumaini east of Al Hayer in Al Ain), flowing across
the Al Madam Plain; Wadi Lamhah collects all the wadis that drain the catchments between Seih Sulailiyyah in the south and Ramlat Sheesa (near Al Ghail) in the north, flowing across Al Ghareef and Al Dhaid plains. Only in years of exceptionally high rainfall do floods reach the wadis in the extreme western parts of the plains and dune areas, and only in Wadi Lamhah may floods reach the coastline near Jazeerat Al Hamrah. Even in years of high rainfall, Wadi Yudai’ah loses its course about 30kms. northwest of Jabal Fayah in Batbat Mussannad. Wadi Lamhah has a smaller course in relation to the wide catchment front it is draining suggesting that much of the water flowing out of the mountains infiltrates into the alluvium of the plains.

Large wadis such as Wadis Ham, Al Wurai’ah and Al Baseerah on the east coast, have developed outwash fans that form wide, flat lower sections extending for more than 10kms., that of Wadi Ham extends from the Fujairah coastline up to the Ham flood retention dam; and Wadi Al Baseerah, the gravel-filled floor of which is about 6kms. at its widest and stretches for up to 17kms. from the date plantations at Dibba on the coast to a point midstream near the confluence of Wadi Al Baseerah with Wadi Addhaba’ah, (2kms. downstream from Al Halah). Such vast outwash fans or plains, also called ‘seihs’, help to absorb most of the flood waters. Similarly, all the west-flowing wadis of the serpentinite (ophiolite) block south of the Dibba-Idhn Line debouch on to the broad western piedmont plains and form the main source of recharge to the aquifer system. Smaller wadis on the east coast and in the northwestern Gulf coast (in Ras Al Khaimah) flow directly into the sea after ponding in the mud-flats of the littoral behind the beach by the embankment of the main road from Fujairah to Dibba.

The mountains may be divided into two sections on the basis of east- and west-flowing wadis:

a) a northern largely limestone section to the north of the Dibba-Idhn Line and,

b) a southern, largely ophiolite, section to the south of it.

73% (19 wadis) of the wadis and their catchments is in the southern serpentinite section of the mountains and 27% (8 wadis) is in the
northern limestone section. 13 wadis (48% of the total number) flow into the eastern piedmont plains of the east (Batinah) coast and 14 wadis (52% of the total number) flow into the western piedmont plains to the west. The east-flowing wadis together drain a total area of 1181km$^2$, which is smaller than that drained by the west-flowing wadis (1335.60km$^2$). In the hardrock serpentinite (ophiolite) part of the highland to the south of the Dibba-Idhn Line, which contributes 80% of the total runoff of the Emirates, the area drained by the east-flowing wadis (1061km$^2$) is more than 2 1/2 times that drained by the west-flowing wadis (408.6km$^2$). Of the total annual runoff volume of 29.25 MCM/a, produced by this southern part of the mountains, 70% (19.997 MCM/a) is produced by the part of the catchments to the east of the watershed and only 30% (9.25 MCM/a) by the western part, although the latter provides the larger, more important, recharge area in the western piedmont (gravel) plains (Table 4.16). The contribution from both the gauged and ungauged catchments is discussed later in the section on catchment yields (Section 4.10).

4.6. Runoff characteristics

The source of runoff data used in the study has already been mentioned (section 4.4). The information includes daily flood discharge data from the various flood-gauging stations, annual flood discharge and base-flow measurements.

Although runoff in the wadis is generally influenced by the size of the catchment, its shape and the amount of rainfall, it is also affected by the localized incidence of rainstorms. Whether most of the rain is caused by air flow from the west and northwest (Mediterranean type) striking the catchments to the west of the watershed, or from the east and southeast (Monsoon type) striking the catchments to the east of the watershed, the slope aspect, in most of the catchments or of individual wadi sides or their tributaries, is more important than the general rain-causing conditions (Table 4.6 A-B).

Catchment size is an important factor in the volume of runoff. When the rainfall is widespread, as was the case in 1982 in Wadi Sfini (area is 138km$^2$), which would naturally have a greater runoff volume than that of the adjacent, smaller, Wadi Ashwani (area 46km$^2$), the period mean
runoff of the former being nearly double that of the latter. The localized rainfall incidence in the northern part of the two basins, concentrated more over Wadi Ashwani than Sfini, gave rise to larger runoff volumes in the smaller catchment of Ashwani. An example of this was seen in the flood events of 28-29/3/82, which produced in the smaller Wadi Ashwani a runoff volume of 1.97 MCM and in the larger Wadi Sfini, 1.39 MCM. Although in both cases the duration of the floods was 32 hours, the rainstorm included a strong monsoon incursion from the Arabian Sea, its effect being felt more in the south facing slopes of the northern half of the Ashwani basin. After the storm passed over the summit of Jabal Najdain (888m.), the larger part of the Sfini basin lay on the leeward side (Table 4.6 A-B).

Wadi Ham catchment, further east, faced the full force of this southeasterly monsoon incursion and, during the same period of the storm, the volume of runoff in this wadi was 4.99 MCM (Table 4.3). Table 4.6 A-B shows the runoff events of Wadis Sfini and Ashwani for the same days (28-29/3/1982).

Referring to Table 4.7, the average rainfall of 250.82mm for eight southern mountain rain-recorders for the high runoff year (1988) was lower than that for the medium runoff year (1983) with an average annual rainfall of 289.58mm., although the runoff volume of the gauged catchments for 1988 was almost twice as much as that for 1983 (rainfall averages for the southern serpentinite (ophiolite) catchments). On the other hand, the rainfall for the high runoff year of 1988 was only more by 32% than that for the low runoff year of 1987 (191.84mm.); yet the runoff volume for 1988 was higher by more than 4 times than that for 1987.

As seen in Table 4.3 for the main flood events in two wadis in the limestone (Wadis Al Beeh and Al Naqab), and four wadis in the ophiolite (Wadis Siji, Sfini, Ham and Al Wurai'ah) hardrock areas, flood duration ranged in the limestone areas from 5400 seconds (1 hr. 30 min.) to 69600 seconds (19 hrs. 20 mins.), while in the ophiolite hardrock catchments the duration of floods ranged from 7200 seconds (2 hrs.) to 86400 seconds (24 hrs.). In the majority of cases the duration may continue up to 120,000 seconds (over 33 hrs.) as happens in years of heavy rainfall in Wadi Sfini (on 17/18-02-1988 (Table 4.3)).
<table>
<thead>
<tr>
<th>Runoff Event</th>
<th>Time</th>
<th>Discharge m³/sec.</th>
<th>Duration Seconds</th>
<th>Runoff Volume m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>28-03-82</td>
<td>16.00</td>
<td>0.052</td>
<td>57600</td>
<td>3995</td>
</tr>
<tr>
<td></td>
<td>16.30</td>
<td>8.01</td>
<td>100</td>
<td>7254</td>
</tr>
<tr>
<td></td>
<td>17.00</td>
<td>29.46</td>
<td>1800</td>
<td>33714</td>
</tr>
<tr>
<td></td>
<td>17.15</td>
<td>21.99</td>
<td>900</td>
<td>23148</td>
</tr>
<tr>
<td></td>
<td>17.30</td>
<td>29.46</td>
<td>900</td>
<td>23148</td>
</tr>
<tr>
<td></td>
<td>18.00</td>
<td>6.00</td>
<td>1800</td>
<td>32634</td>
</tr>
<tr>
<td></td>
<td>18.30</td>
<td>8.01</td>
<td>1800</td>
<td>33220</td>
</tr>
<tr>
<td></td>
<td>19.00</td>
<td>6.80</td>
<td>1800</td>
<td>33020</td>
</tr>
<tr>
<td></td>
<td>19.30</td>
<td>0.72</td>
<td>1800</td>
<td>6768</td>
</tr>
<tr>
<td></td>
<td>20.00</td>
<td>0.30</td>
<td>1800</td>
<td>918</td>
</tr>
<tr>
<td></td>
<td>20.15</td>
<td>151.94</td>
<td>900</td>
<td>68508</td>
</tr>
<tr>
<td></td>
<td>20.20</td>
<td>110.00</td>
<td>300</td>
<td>39291</td>
</tr>
<tr>
<td></td>
<td>20.30</td>
<td>79.96</td>
<td>600</td>
<td>56988</td>
</tr>
<tr>
<td></td>
<td>20.45</td>
<td>110.00</td>
<td>900</td>
<td>85482</td>
</tr>
<tr>
<td></td>
<td>21.00</td>
<td>62.50</td>
<td>900</td>
<td>77625</td>
</tr>
<tr>
<td></td>
<td>21.30</td>
<td>34.18</td>
<td>1800</td>
<td>87012</td>
</tr>
<tr>
<td></td>
<td>22.00</td>
<td>16.15</td>
<td>1800</td>
<td>45288</td>
</tr>
<tr>
<td></td>
<td>23.00</td>
<td>12.25</td>
<td>3600</td>
<td>51120</td>
</tr>
<tr>
<td></td>
<td>24.00</td>
<td>10.42</td>
<td>3600</td>
<td>49788</td>
</tr>
<tr>
<td>Total For 28-03-82</td>
<td>86400</td>
<td>709321</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29-03-82</td>
<td>00.30</td>
<td>12.45</td>
<td>1800</td>
<td>20412</td>
</tr>
<tr>
<td></td>
<td>01.00</td>
<td>9.53</td>
<td>1800</td>
<td>19062</td>
</tr>
<tr>
<td></td>
<td>01.30</td>
<td>13.88</td>
<td>1800</td>
<td>21078</td>
</tr>
<tr>
<td></td>
<td>02.00</td>
<td>9.53</td>
<td>1800</td>
<td>21078</td>
</tr>
<tr>
<td></td>
<td>02.10</td>
<td>34.18</td>
<td>600</td>
<td>13116</td>
</tr>
<tr>
<td></td>
<td>02.20</td>
<td>9.53</td>
<td>600</td>
<td>13116</td>
</tr>
<tr>
<td></td>
<td>02.30</td>
<td>38.26</td>
<td>600</td>
<td>14334</td>
</tr>
<tr>
<td></td>
<td>03.00</td>
<td>34.18</td>
<td>1800</td>
<td>65196</td>
</tr>
<tr>
<td></td>
<td>03.30</td>
<td>29.46</td>
<td>1800</td>
<td>57276</td>
</tr>
<tr>
<td></td>
<td>04.00</td>
<td>20.08</td>
<td>1800</td>
<td>44586</td>
</tr>
<tr>
<td></td>
<td>05.00</td>
<td>18.06</td>
<td>3600</td>
<td>66852</td>
</tr>
<tr>
<td></td>
<td>06.00</td>
<td>16.15</td>
<td>3600</td>
<td>61596</td>
</tr>
<tr>
<td></td>
<td>07.00</td>
<td>13.88</td>
<td>3600</td>
<td>54072</td>
</tr>
<tr>
<td></td>
<td>08.00</td>
<td>10.42</td>
<td>3600</td>
<td>43740</td>
</tr>
<tr>
<td></td>
<td>09.00</td>
<td>8.01</td>
<td>3600</td>
<td>33192</td>
</tr>
<tr>
<td></td>
<td>10.00</td>
<td>6.80</td>
<td>3600</td>
<td>26640</td>
</tr>
<tr>
<td></td>
<td>11.00</td>
<td>4.98</td>
<td>3600</td>
<td>21204</td>
</tr>
<tr>
<td></td>
<td>12.00</td>
<td>3.21</td>
<td>3600</td>
<td>15300</td>
</tr>
<tr>
<td></td>
<td>13.00</td>
<td>2.31</td>
<td>3600</td>
<td>10476</td>
</tr>
<tr>
<td></td>
<td>14.00</td>
<td>2.18</td>
<td>3600</td>
<td>8100</td>
</tr>
<tr>
<td></td>
<td>15.00</td>
<td>1.99</td>
<td>3600</td>
<td>7524</td>
</tr>
<tr>
<td></td>
<td>16.00</td>
<td>1.92</td>
<td>3600</td>
<td>7038</td>
</tr>
<tr>
<td></td>
<td>17.00</td>
<td>1.75</td>
<td>3600</td>
<td>6606</td>
</tr>
<tr>
<td></td>
<td>18.00</td>
<td>1.59</td>
<td>3600</td>
<td>6012</td>
</tr>
<tr>
<td></td>
<td>19.00</td>
<td>1.48</td>
<td>3600</td>
<td>5526</td>
</tr>
<tr>
<td></td>
<td>20.00</td>
<td>1.26</td>
<td>3600</td>
<td>4932</td>
</tr>
<tr>
<td></td>
<td>21.00</td>
<td>0.99</td>
<td>3600</td>
<td>4050</td>
</tr>
<tr>
<td></td>
<td>22.00</td>
<td>0.82</td>
<td>3600</td>
<td>3258</td>
</tr>
<tr>
<td></td>
<td>23.00</td>
<td>0.82</td>
<td>3600</td>
<td>2952</td>
</tr>
<tr>
<td></td>
<td>24.00</td>
<td>0.82</td>
<td>3600</td>
<td>2952</td>
</tr>
<tr>
<td>Total For 29-03-82</td>
<td>86400</td>
<td>683616</td>
<td></td>
<td>1392237</td>
</tr>
</tbody>
</table>

Table: 4.6 (A)
Localized rainfall in the Ashwani and Sfini wadi catchments giving rise to greater runoff volumes in the smaller Wadi Ashwani than the larger Wadi Sfini.

Although catchment size is important in governing the volume of runoff in a catchment, localized rainfall incidence in the northern (aspect factor of south-facing slopes) part of the catchments of Wadis Ashwani and Sfini gives rise to greater runoff volumes in the smaller catchment of Wadi Ashwani. The flood event of 28-29/03/1982 produced in the smaller Wadi Ashwani basin (46km²) a runoff volume of 1.97MCM, but only 1.39MCM in the larger Wadi Sfini basin (138km²).
### Table 4.7

Runoff characteristics for a high runoff year (1988), a medium runoff year (1983) and a low runoff year (1987).

For the high runoff year (1988), the general runoff ratio (the total flood volume in relation to the total volume of catchment precipitation) averaged 8% for the limestone, and 23% for the ophiolite, mountain catchments. For the medium (1983) and low (1987) runoff years, the runoff ratios were 1.2% for the limestone wadis and 11 and 6% for the ophiolite wadis respectively. For individual wadis, the runoff ratio varied from 17 to 35% for 1988 (Wadi Siji), from 3 to 18% for 1983 and from 3 to 13% for 1987 in the ophiolite mountain block. The average for the median runoff year of 13% was close to the mean runoff ratio for catchments in the ophiolite mountains (Tables 4.11 and 4.14). The percentage of the runoff produced out of the total runoff volume in both the limestone and ophiolite catchments remained the same: 7% and 93% (i.e., 93% of the total catchment runoff volume was raised by the wadis of the ophiolite mountains and 7% by wadis in the limestone mountains).

<table>
<thead>
<tr>
<th>Wadi/Group of Wadis</th>
<th>Total Annual Volume of Runoff for the gauged Catchments in MCM/a</th>
<th>Percentage of Overall Total Annual Volume %</th>
<th>Overall Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1988</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NORTHERN WADIS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beeth/Naqab</td>
<td>1.87 (1.8)</td>
<td>2.98</td>
<td>7.0 %</td>
</tr>
<tr>
<td>Baseerah</td>
<td>2.45 (11.0)</td>
<td>3.91</td>
<td></td>
</tr>
<tr>
<td><strong>SOUTHERN WADIS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siji</td>
<td>7.51 (35.0)</td>
<td>11.97</td>
<td></td>
</tr>
<tr>
<td>Sfini/Ashwani Ham</td>
<td>13.55 (25.0)</td>
<td>21.60</td>
<td></td>
</tr>
<tr>
<td>Ham</td>
<td>7.31 (12.0)</td>
<td>11.37</td>
<td></td>
</tr>
<tr>
<td>Qawr (East)</td>
<td>17.35 (23.0)</td>
<td>27.66</td>
<td></td>
</tr>
<tr>
<td>Qawr (West)</td>
<td>2.20 (19.0)</td>
<td>3.51</td>
<td></td>
</tr>
<tr>
<td>Wurai‘ah</td>
<td>5.55 (17.0)</td>
<td>8.85</td>
<td></td>
</tr>
<tr>
<td>Farfar</td>
<td>3.84 (23.0)</td>
<td>6.12</td>
<td></td>
</tr>
<tr>
<td>Shik</td>
<td>1.32 -</td>
<td>2.10</td>
<td></td>
</tr>
<tr>
<td><strong>1983</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NORTHERN WADIS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beeth/Naqab</td>
<td>2.10 (1.4)</td>
<td>5.8</td>
<td>7.0 %</td>
</tr>
<tr>
<td>Baseerah</td>
<td>0.295 (0.9)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>SOUTHERN WADIS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siji</td>
<td>1.184 (5.0)</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Sfini/Ashwani Ham</td>
<td>7.363 (22.0)</td>
<td>20.4</td>
<td></td>
</tr>
<tr>
<td>Ham</td>
<td>3.637 (14.0)</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>Qawr (East)</td>
<td>13.897 (16.0)</td>
<td>30.0</td>
<td></td>
</tr>
<tr>
<td>Qawr (West)</td>
<td>0.428 (3.0)</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Wurai‘ah</td>
<td>6.783 (18.0)</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td>Farfar</td>
<td>NA -</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Shik</td>
<td>0.463 -</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td><strong>1987</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NORTHERN WADIS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beeth/Naqab</td>
<td>0.697 (1.3)</td>
<td>4.20</td>
<td>6.0 %</td>
</tr>
<tr>
<td>Baseerah</td>
<td>0.105 (1.3)</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td><strong>SOUTHERN WADIS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siji</td>
<td>0.622 (4.0)</td>
<td>4.28</td>
<td></td>
</tr>
<tr>
<td>Sfini/Ashwani Ham</td>
<td>3.520 (9.0)</td>
<td>24.23</td>
<td></td>
</tr>
<tr>
<td>Ham</td>
<td>0.634 (4.0)</td>
<td>4.37</td>
<td></td>
</tr>
<tr>
<td>Qawr (East)</td>
<td>7.415 (13.0)</td>
<td>51.04</td>
<td>94.0 %</td>
</tr>
<tr>
<td>Qawr (West)</td>
<td>0.857 (1.0)</td>
<td>5.90</td>
<td></td>
</tr>
<tr>
<td>Wurai‘ah</td>
<td>0.262 (3.0)</td>
<td>1.80</td>
<td></td>
</tr>
<tr>
<td>Farfar</td>
<td>0.416 -</td>
<td>2.86</td>
<td></td>
</tr>
<tr>
<td>Shik</td>
<td>NIL -</td>
<td>NIL</td>
<td></td>
</tr>
</tbody>
</table>

Bracketed figures are runoff ratios in percentage.

Source of surface runoff data: the MAF.
The time of a runoff concentration of a flow of more than 10.00 m$^3$/sec. varies in the limestone hardrock catchments from 1800 seconds (30 mins.) to 18600 seconds (5 hrs.), while in the ophiolite catchments it varies from 1800 seconds (30 mins.) to 86400 seconds (24 hrs.) (Table 4.3).

Wadi Nagab in the limestone, and Wadi Ham in the ophiolite hardrock areas experience the longest time of concentration of runoff in years of medium to high rainfall, although in the ophiolite hardrock area Wadi Sfini experiences the highest time of concentration in the year of least rainfall (for 1979, in Table 4.8).

The time for runoff concentration of a flow of more than 100m$^3$/sec. before and after a flood peak flow varies from 5100 seconds (51 min.) in Wadi Al Beeh (on 20-07-88) to 51300 seconds (14 hrs. 30 mins.) in Wadi Sfini (on 17-02-88), followed by Wadi Ham, where it varies from 18000-28000 seconds (5-8 hrs.) on 17/18-2-1988 to 86,400 seconds (24 hrs.) on 15-2-1982, both being years of exceptional rainfall. Peak flows do not exceed 100m$^3$/sec. in years of moderate rainfall, as seen in Table 4.9. The two peaks for Wadis Sfini/Ashwani and the two for Wadi Al Qawr (East) (underlined figures in Table 4.9), can be explained as follows: for Wadis Sfini and Ashwani the figure was due to a combined runoff volume from both wadis though, as seen in Table 4.9, flood flows in the two wadis did not exceed a peak of 70m$^3$ in a medium rainfall year (1987). For Wadi Al Qawr (East), on the other hand, the figure was due to the fact that Al Qawr has a large drainage basin and also that the wadi flows for most of its course in bare hardrock ophiolite with hardly any alluvium to absorb the larger part of the runoff. Apart from these two exceptions the rule mentioned earlier, of peak flows not exceeding 100m$^3$ in years of medium rainfall, holds true for all the other wadis.

The time taken by floods to reach a peak, whatever the volume of the peak, varies from 45 mins. to 18 hrs. as summarized in Table 4.8 for runoff events detailed in Table 4.3. This is also graphically illustrated in the runoff (flood) hydrographs of 8 wadis (Figs. 4.2 to 4.10). Peaks in general occur within twelve hours from the start of the flood in all the wadi runoff events. The highest peaks in all the wadis, however, as shown in the combined hydrographs (Fig. 4.2) for Wadis Ham (number 3 in Fig. 4.2), Sfini (4), Qawr East (5), Ashwani (6)
Table 4.8.

Runoff characteristics: the duration of runoff from start to peak for selected wadis for low (1979), moderate (1983) and high (1988) runoff years.

There is clear correlation between the intensity and total of rainfall on the one hand and the duration of the floods on the other. As seen in Table 4.8 above, the higher the rainfall (February, 1988), the shorter is the duration of the floods from start to peak. The opposite is also true for the moderate (1983) and low (1979) rainfall years, in which the flood duration was longer.
Table: 4.9.

Flood peaks in a moderate runoff year (1987) for selected wadis.

Flood flow peaks do not exceed 100m³/sec in years of medium rainfall/runoff intensity (1987). The two flood peaks for Wadis Sfini and Ashwani, and the two peaks for Wadi Al Qawr East (the underlined figures in the Table 4.9) can be explained as follows: the two peaks for Wadis Sfini-Ashwani resulted from the combined runoff of both wadis as floods in neither wadi, separately, exceeded a 70m³/sec peak as can be seen in the same table; the two high peaks of 615m³/sec and 237m³/sec for Wadi Al Qawr resulted from the large size of the Al Qawr catchment but also, more importantly, due to the fact that the wadi flows for most of its course in bare ophiolite baserock with hardly any alluvium to absorb part of the runoff.
Figure 4.2.

Combined flood hydrograph for Wadis: Siji, Ham, Sfini, Sfini-Ashwani, Qawr East, Ashwani, Al Wurai'ah (in the ophiolite central mountains) and Naqab (in the northern limestone mountains) for the floods of 17-18, February, 1988.

(See commentary for Figs. 4.2. to 4.10. after Fig. 4.10)
Figure: 4.3.

Flood hydrograph for the floods of 17-18, February, 1988 for the west-flowing Wadi Siji in the ophiolite central mountains.

(See commentary for Figs. 4.2. to 4.10. after Fig. 4.10)

Figure: 4.4.

Flood hydrograph for the floods of 17-18, February, 1988 for the west-flowing Wadis Sfini-Ashwani downstream of their confluence.

(See commentary for Figs. 4.2. to 4.10. after Fig. 4.10)
Figure: 4.5.

Flood hydrograph for the floods of 17-18, February, 1988 for the east-flowing Wadi Ham in the ophiolite central mountains.

(See commentary for Figs. 4.2. to 4.10. after Fig. 4.10)

Figure: 4.6.

Flood hydrograph for the floods of 17-18, February, 1988 for the west-flowing Wadi Sfini, upstream of the its confluence with Wadi Ashwani, in the ophiolite central mountains.

(See commentary for Figs. 4.2. to 4.10. after Fig. 4.10)
Figure: 4.7.

Flood hydrograph for the floods of 17-18, February, 1988 for the west-flowing Wadi Ashwani, upstream of its confluence with Wadi Sfini, in the ophiolite central mountains.

(See commentary for Figs. 4.2. to 4.10. after Fig. 4.10)

Figure: 4.8.

Flood hydrograph for the floods of 17-18, February, 1988 for the east-flowing Wadi Al Qawr (East) in the ophiolite central mountains.

(See commentary for Figs. 4.2. to 4.10. after Fig. 4.10)
Figure: 4.9.

Flood hydrograph for the floods of 17-18, February, 1988 for the west-flowing Wadi Al Naqab in the northern limestone mountains of Ru’us Al Jibal.

(See commentary for Figs. 4.2. to 4.10. after Fig. 4.10)

Figure: 4.10.

Flood hydrograph for the floods of 17-18, February, 1988 for the east-flowing Wadi Al Wurai’ah in the ophiolite central mountains.
Flood peaks in general occur within twelve hours from the start of the flood in all the wadi runoff events. The highest peaks in all the eight wadis are shown in the combined hydrograph (Fig. 4.2) and all these peaks occurred within three hours from just before midnight on 17th. February to about 3.00 a.m. on the morning of the 18th. of February 1988. The peaks for Wadis Siji and Sfini-Ashwani (1 and 2 in Fig. 4.2) were reached four hours earlier, but such a tendency does not occur after the concentration of the peak of floods in the majority of wadis and the post-runoff period is shorter in duration. Thus, in the widespread winter rainfall conditions wadi floods appear to occur simultaneously, the difference is only in the lag period before runoff takes place as governed by the size of the catchment and the volume of wadi deposits required to be saturated before overland flow takes place. Whether east- or west-flowing wadis, the hydrographs clearly illustrate the coincidence of flood peaks within a period of three hours. All the floods of wadis in the ophiolite mountains had a single large peak flow of over 10m³/sec. lasting between 12hrs. and 18hrs., with the exception of Wadi Al Murai'ah, which had two main peaks because of an additional southerly monsoonal rainy incursion during the 17-18 February 1988 rains; and Wadi Al Qawr East, which had a large continuous peak for more than 20hrs. because of the large catchment of the wadi and also that the wadi runs in bare ophiolite bedrock in parts of its long course.
and Naqab (7) occurred within three hours from just before midnight on 17th. February to about 3.00 a.m. on the morning of the 18th. of February 1988. The peaks for Wadis Siji (1) and Sfini/Ashwani (2) were reached four hours earlier, but such a tendency does not occur after the highest peak concentration of the floods in the majority of wadis and the post-runoff peak period is shorter in duration than that from the start of the flood to reaching its highest flow peak.

There appears to be a correlation between the highest runoff peak and total runoff volume of the wadi catchments. This holds generally true, although there are a few exceptions, as seen in Table 4.3, where, in Wadi Naqab, in the runoff event of 21-01-1983 (moderate runoff year), the lower peak of 42.42m³/sec. of the former runoff event was related to the higher total runoff volume of 0.6198 MCM rather than the higher peak of 51.89m³/sec. of the latter runoff event with the lower total runoff volume of 0.4602 MCM. Similarly, in Wadi Ham (Table 4.3.), in the flood events of 13-02-1983 and 5-04-1983, the low flood peaks of 19.20m³/sec. and 17.71m³/sec. were associated with the low total flood volumes of 0.3164 MCM and 0.3494 MCM respectively. Conversely, also in Wadi Ham, during the two flood events of 17/18-02-1988 (high runoff year), the lower peak of 520.00m³/sec. was associated with the higher runoff total of 5.3557 MCM and the shorter flow duration of 9 hrs. than the higher peak of 823.13m³/sec. with the lower total runoff volume of 1.5488 MCM and the longer flow duration of 25 hrs. This is explicable by the flow for 5 hrs. of more than 100m³/sec. from the rising to the recession stages of the flood event in the former case (17th. of February), and of hardly 15 mins. duration of 100m³ peak for the latter (18th. February 1988) (Table 4.3 and Fig. 4.5.). For most of the longer flood duration in the latter case (18th. Feb. 1988), flow was minimal (of below 1.0m³/sec.), while nearly during the whole duration of floods of the former (17th. Feb. 1988), the flow was of 10.0m³/sec. for more than 9 hours.

The relationship between the peak and the total runoff volume appears to follow a logical trend in Wadi Al Wurai'ah (Table 4.10 (B) and Fig. 4.10), as for the flood of 16-02-1988 with a peak of 12.62m³/sec. and a total runoff volume of 0.1147 MCM; 17-02-1988 with a peak of 313.60m³/sec. and a total runoff volume of 2.193 MCM; and finally the runoff event of 18-02-1988 with a peak of 673.14m³/sec. and a total runoff volume of 3.195 MCM.

230
Flood peaks, the total daily runoff volume of the flood event and the total annual flood volume for selected wadis in the limestone massif of Ru'us Al Jibal (Wadis Al Beeh and Al Naqab), a wadi fed from both the northern limestone and the southern ophiolite uplands (Wadi Al Baseerah) and east- and west-flowing wadis in the ophiolite mountain block (Wadis Siji, Sfini, Ashwani; and Wadis Ham, Al Wurai'ah and Al Qawr East) for the years 1983 (medium rainfall year), 1987 (low rainfall year) and 1988 (high rainfall year).

<table>
<thead>
<tr>
<th>Flood date</th>
<th>Peak (m³/sec.)</th>
<th>Runoff Volume (m³/1000)</th>
<th>Total Annual Volume (m³/1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WADE AL BASERAH (Area= 520 km²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17-02-88</td>
<td>36.0</td>
<td>511.56</td>
<td>1600.716</td>
</tr>
<tr>
<td>17-02-88</td>
<td>15.50</td>
<td>75.888</td>
<td></td>
</tr>
<tr>
<td>17-02-88</td>
<td>71.50</td>
<td>394.14</td>
<td></td>
</tr>
<tr>
<td>20-07-88</td>
<td>10.50</td>
<td>54.959</td>
<td></td>
</tr>
<tr>
<td>WADE AL BEEH (Area= 474 km²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-01-88</td>
<td>10.00</td>
<td>20.00</td>
<td>105.00</td>
</tr>
<tr>
<td>20-01-88</td>
<td>15.00</td>
<td>45.00</td>
<td></td>
</tr>
<tr>
<td>20-01-88</td>
<td>14.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>WADE NAQAB (Area= 9.2 km²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11-02-83</td>
<td>13.7</td>
<td>100.10</td>
<td>100.10</td>
</tr>
<tr>
<td>11-02-83</td>
<td>15.00</td>
<td>112.20</td>
<td></td>
</tr>
<tr>
<td>11-02-83</td>
<td>16.00</td>
<td>122.20</td>
<td></td>
</tr>
<tr>
<td>11-02-83</td>
<td>17.00</td>
<td>132.20</td>
<td></td>
</tr>
<tr>
<td>11-02-83</td>
<td>18.00</td>
<td>142.20</td>
<td></td>
</tr>
<tr>
<td>11-02-83</td>
<td>19.00</td>
<td>152.20</td>
<td></td>
</tr>
</tbody>
</table>

Commentary on Table 4.10 (A):

Table 4.10 (A) shows the low flood peaks and small runoff volumes in the wadis of the limestone mountains of Ru'us Al Jibal because of the larger wadi floor area, greater thickness of the wadi-bed alluvial material and the surrounding and underlying limestone and therefore the larger absorbing capacity of the limestone base-rock and wadi sides.

Wadi Al Naqab (with an area of 92km²) has a larger flood volume by comparison to either Wadi Al Baseerah (area 520km²) or Wadi Al Beeh (area 474km²). These wadis of the northern mountains had less runoff on 17-18/02/1988 (year of exceptionally high rainfall) than mountain wadis elsewhere to the south of the Dibba-Idhn Line.
<table>
<thead>
<tr>
<th>Flood date</th>
<th>Peak (m³/sec.)</th>
<th>Runoff Volume (m³x1000)</th>
<th>Total Annual Volume (m³x1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WADI HAM</strong>&lt;br&gt;(Area= 90.00 km²)&lt;br&gt;Downstream of Bithnah Bridge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1988</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17-02-88</td>
<td>520.00</td>
<td>5355.72</td>
<td>7128.00</td>
</tr>
<tr>
<td>18-02-88</td>
<td>823.13</td>
<td>1548.802</td>
<td></td>
</tr>
<tr>
<td>19-02-88</td>
<td>0.18</td>
<td>12.960</td>
<td></td>
</tr>
<tr>
<td>20-02-88</td>
<td>0.12</td>
<td>9.504</td>
<td></td>
</tr>
<tr>
<td>21-02-88</td>
<td>0.10</td>
<td>6.48</td>
<td></td>
</tr>
<tr>
<td>22-02-88</td>
<td>0.05</td>
<td>2.16</td>
<td></td>
</tr>
<tr>
<td>27-04-88</td>
<td>36.54</td>
<td>192.375</td>
<td></td>
</tr>
<tr>
<td><strong>1987</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28-03-87</td>
<td>22.60</td>
<td>107.205</td>
<td>634.173</td>
</tr>
<tr>
<td>06-04-87</td>
<td>85.90</td>
<td>270.972</td>
<td></td>
</tr>
<tr>
<td>01-06-87</td>
<td>13.26</td>
<td>55.896</td>
<td></td>
</tr>
<tr>
<td><strong>1983</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-02-83</td>
<td>27.50</td>
<td>1078.388</td>
<td>3632.522</td>
</tr>
<tr>
<td>13-02-83</td>
<td>19.20</td>
<td>316.600</td>
<td></td>
</tr>
<tr>
<td>14-03-83</td>
<td>0.21</td>
<td>2.172</td>
<td></td>
</tr>
<tr>
<td>30-03-83</td>
<td>3.85</td>
<td>294.522</td>
<td></td>
</tr>
<tr>
<td>31-03-83</td>
<td>7.05</td>
<td>64.680</td>
<td></td>
</tr>
<tr>
<td>05-04-83</td>
<td>17.71</td>
<td>349.409</td>
<td></td>
</tr>
<tr>
<td>10-04-83</td>
<td>0.98</td>
<td>27.909</td>
<td></td>
</tr>
<tr>
<td><strong>WADI AL WURAI'AH</strong>&lt;br&gt;(Area 129.00 km²)&lt;br&gt;Downstream of the spring</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1988</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-02-88</td>
<td>23.20</td>
<td>46.915</td>
<td>5551.946</td>
</tr>
<tr>
<td>16-02-88</td>
<td>12.62</td>
<td>114.651</td>
<td></td>
</tr>
<tr>
<td>17-02-88</td>
<td>313.60</td>
<td>2193.452</td>
<td></td>
</tr>
<tr>
<td>18-02-88</td>
<td>673.14</td>
<td>3194.928</td>
<td></td>
</tr>
<tr>
<td><strong>1987</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28-03-87</td>
<td>16.89</td>
<td>67.173</td>
<td>261.966</td>
</tr>
<tr>
<td>30-03-87</td>
<td>28.75</td>
<td>164.34</td>
<td></td>
</tr>
<tr>
<td>31-03-87</td>
<td>0.055</td>
<td>0.789</td>
<td></td>
</tr>
<tr>
<td>05-04-87</td>
<td>28.10</td>
<td>29.70</td>
<td></td>
</tr>
<tr>
<td><strong>1983</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-02-83</td>
<td>56.20</td>
<td>388.352</td>
<td>6370.774</td>
</tr>
<tr>
<td>11-02-83</td>
<td>249.04</td>
<td>5407.956</td>
<td></td>
</tr>
<tr>
<td>12-02-83</td>
<td>16.50</td>
<td>213.684</td>
<td></td>
</tr>
<tr>
<td>13-02-83</td>
<td>1.95</td>
<td>88.740</td>
<td></td>
</tr>
<tr>
<td>05-04-83</td>
<td>16.50</td>
<td>109.689</td>
<td></td>
</tr>
<tr>
<td>06-04-83</td>
<td>0.745</td>
<td>46.224</td>
<td></td>
</tr>
</tbody>
</table>

Table: 4.10 (B)
Commentary on Table 4.10 (B and C)

Tables 4.10 (B and C) shows that the highest flood peaks in years of high rainfall/runoff occur more frequently in east-flowing wadis of the central ophiolite mountains, such as wadis Ham and Al Murai'ah, where the peaks are exceptionally high (Table 4.10 (B)). Examples are the flood peaks of 520.00 m^3/sec. and 823.13 m^3/sec. of Wadi Ham on 17/18-02/1988; and of 673.14 m^3/sec. on 18/02/1988 in Wadi Al Murai'ah (Table 4.10 (B)). Another example are the peaks of 403.76 m^3/sec. of 17-18/02/1988 of Wadi Sfini (upstream of its confluence with Wadi Ashwani), and the peak of 348.40 m^3/sec. of 18/02/1988 of Wadi Sfini also (downstream of its confluence with Wadi Ashwani) (Table 4.10. (C)).
The table below provides details on the flood dates, peak discharges, runoff volumes, and total annual volumes for Wadi Siji. The area is 86.6 km², and the upstream village is flooded with peak dates ranging from 17-2-88 to 28-4-88.

### Flood Data

<table>
<thead>
<tr>
<th>Date</th>
<th>Peak (m³/sec)</th>
<th>Runoff Volume (m³ x 1000)</th>
<th>Total Annual Volume (m³ x 1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17-2-88</td>
<td>272.34</td>
<td>3483.351</td>
<td>7447.255</td>
</tr>
<tr>
<td>18-2-88</td>
<td>47.25</td>
<td>974.42</td>
<td></td>
</tr>
<tr>
<td>19-2-88</td>
<td>0.123</td>
<td>8.389</td>
<td></td>
</tr>
<tr>
<td>20-2-88</td>
<td>0.08</td>
<td>4.14</td>
<td></td>
</tr>
<tr>
<td>21-2-88</td>
<td>0.73</td>
<td>3.28</td>
<td></td>
</tr>
<tr>
<td>22-2-88</td>
<td>0.32</td>
<td>2.85</td>
<td></td>
</tr>
<tr>
<td>23-2-88</td>
<td>0.71</td>
<td>2.59</td>
<td></td>
</tr>
<tr>
<td>24-2-88</td>
<td>49.0</td>
<td>867.731</td>
<td></td>
</tr>
<tr>
<td>25-2-88</td>
<td>52.95</td>
<td>1765.734</td>
<td></td>
</tr>
<tr>
<td>26-2-88</td>
<td>0.06</td>
<td>4.234</td>
<td></td>
</tr>
<tr>
<td>27-2-88</td>
<td>0.04</td>
<td>3.283</td>
<td></td>
</tr>
<tr>
<td>28-2-88</td>
<td>0.036</td>
<td>3.110</td>
<td></td>
</tr>
<tr>
<td>29-2-88</td>
<td>0.036</td>
<td>2.851</td>
<td></td>
</tr>
<tr>
<td>1-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>2-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>3-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>4-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>5-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>6-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>7-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>8-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>9-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>10-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>11-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>12-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>13-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>14-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>15-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>16-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>17-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>18-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>19-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>20-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>21-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>22-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>23-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>24-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>25-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>26-3-88</td>
<td>0.036</td>
<td>2.592</td>
<td></td>
</tr>
<tr>
<td>26-4-88</td>
<td>44.62</td>
<td>233.631</td>
<td></td>
</tr>
<tr>
<td>27-4-88</td>
<td>0.13</td>
<td>9.803</td>
<td></td>
</tr>
<tr>
<td>28-4-88</td>
<td>0.04</td>
<td>3.110</td>
<td></td>
</tr>
</tbody>
</table>

### Table: 4.10 (D)
Commentary on Table 4.10. (D and E)  Table: 4.10 (E)

Table 4.10 (D and E) illustrates the continuation of flood flows in the large wadis of the ophiolite central mountains, such as Wadis Siji and Qawr East, for up to 9 or 10 weeks after the last major runoff peak. For Wadi Siji this was so between 17/02/1988 and 28/04/1988, with a total runoff volume for the whole of 1988 of 7.5 MCM, all of which flowed during that period between February and April. For Wadi Al Qawr East the flows lasted between 17/02/1988 and 29/03/1988, with a total runoff volume of 17.4 MCM for the whole of 1988, all of which flowed during that February-March period.

In both wadis, one or two very high flood peaks of over 250m$^3$/sec. usually started the runoff: for Wadi Siji (272.34m$^3$/sec. on 17/02/1988); for Wadi Al Qawr East (597.6m$^3$/sec. or 385.0m$^3$/sec on 17-18/02/1988).
The highest flood peaks in years of high runoff occur more frequently in east-flowing wadis, such as Wadis Ham and Al Wurai'ah in the ophiolite part of the catchments, where the peaks are exceptionally high. Examples, are the flood peaks of 520.00m$^3$/sec. and 823.13m$^3$/sec. of Wadi Ham on the 17/18-02-1988 and of 673.14m$^3$/sec. on 18.02.88 in Wadi Al Wurai'ah (Table 4.10 (B); Figs. 4.5 and 4.10).

The flood peaks in west-flowing wadis, such as Wadis Sfini and Siji, in the ophiolite mountain block, are relatively moderate by comparison to those in east-flowing wadis, such as Wadis Ham and Al Wurai'ah. These latter two wadis rank third and fourth among the wadis in the recurrence of high peaks. Runoff peaks of more than 100m$^3$/sec. in the limestone wadis, such as Wadis Al Beeh and Naqab (Tables 4.3 and 4.10 (A)), occur occasionally and flood peaks never exceed 200m$^3$/sec. They may vary from 20.00 to 160.00m$^3$/sec. during winter flood flows, but can reach higher peaks during sudden, torrential summer monsoon floods. An example of the latter summer case was the peak of 186.88m$^3$/sec. during the runoff event of 20-07-1988 in Wadi Al Beeh (Tables 4.3 and 4.10 (A)), which was caused by a concentrated short-lived monsoon storm in an area of Ru’us Al Jibal which had, and still has, no rain-gauge. The rainfall measured in all the existing surrounding stations did not appear at that time to correlate with the torrential floods in Wadis Al Baseerah and Al Beeh that lasted for three and two hours, respectively.

Referring to Table 4.1, which presents the total annual runoff and the mean for the period of flood records for the gauged catchments since 1975, it is clear that the east-flowing wadis of the ophiolite mountain zone accrue the largest runoff volumes, with Wadi Al Qawr (East) having the highest runoff, followed by Wadi Ham (half the mean annual flow volume of Wadi Al Qawr), Wadi Al Wurai'ah and Wadi Al Baseerah.

Of the west-flowing wadis, Wadi Sfini experiences the largest volume of runoff, followed by Wadis Siji, Al Beeh and Naqab. The last two wadis had some flow in the dry year 1984-85 (one of three consecutive dry years 83-84 to 85-86) when all the other wadis in the ophiolite mountain block, with the exception of Wadi Sfini, had hardly any flow (Table 4.1). The runoff coefficient is highest in Wadi Ham where it ranges from 8% to 43%, and is lowest in Wadi Al Beeh, where it ranges from 0.2% to 6% (Table 4.3).
The runoff ratio appears to be closely related to the amount of basin rainfall and the resulting runoff volume; the higher the runoff volume, the higher is the runoff coefficient (Table 4.3).

The runoff coefficient is higher for wadis in the ophiolite mountain block than for those in the northern limestone mountain block. Higher values are also measured for the east-flowing than for the west-flowing wadis. This is shown in Table 4.4, which gives the annual runoff coefficient (ratio) values since the hydrological year 1975-76 and also the mean runoff coefficient for the period of flood records. Runoff coefficients are even lower in wadis of the piedmont plains as they debouch on to the gravels and sands of the plains, with their high absorption capacity and broader flow channels. The best example is Wadi Lamhah (not included in Table 4.4 because of incomplete data), where the annual runoff coefficient rarely exceeds 1.0% even in years of high rainfall/runoff, such as 1987-88 when the runoff ratio was only 0.3% despite the prevalent widespread high rainfall-runoff in the hardrock catchments to the east. The average annual runoff ratios are given in Table 4.4, and also in Table 10.4 Chapter 10 (for the Al Ain-Buraimi area). The general runoff ratios are 6% for wadis in the limestone, and 12% for wadis in the ophiolite catchments (see also Table 4.14).

The extreme variability in runoff volumes from year to year can clearly be seen in Table 4.11, which gives annual runoff totals for the gauged catchments for a year of exceptional (1987-88), a year of moderate (1986-87) rainfall and also the median annual runoff volume for the period of flood records (7-13 years). Wadis in the ophiolite mountain block (Wadis Ham, Qawr East and Siji) develop larger flood volumes than wadis in the limestone mountain block (Wadis Al Beeh and Naqab). Also, east-flowing wadis in the ophiolite catchments (Wadis Ham and Qawr East) develop larger runoff volumes than west-flowing wadis (Wadis Sfini and Ashwani) (Table 4.11). The average runoff volumes for a high rainfall year are about 4 times those for a moderate rainfall year (68.51 MCM/a (1987-88) against 16.41 (1986-87)), and are also three times the median runoff volume for the period of flood records (68.51 MCM/a (1987-88) against 21.42 MCM/a (median)).
<table>
<thead>
<tr>
<th>Catchment (Area km²)</th>
<th>Annual Rainfall mm</th>
<th>Basin Prec. mm</th>
<th>Actual Runoff Vol. MCM/a</th>
<th>Runoff Coef. %</th>
<th>Effective Rainfall mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wadi Beeh (474)</td>
<td>159.80</td>
<td>75.75</td>
<td>10.14</td>
<td>8</td>
<td>12.78</td>
</tr>
<tr>
<td></td>
<td>134.00</td>
<td>63.52</td>
<td>3.16</td>
<td>5</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>144.06</td>
<td>68.28</td>
<td>1.96</td>
<td>3</td>
<td>4.3</td>
</tr>
<tr>
<td>Wadi Naqab (92)</td>
<td>182.95</td>
<td>16.83</td>
<td>1.21</td>
<td>7</td>
<td>12.81</td>
</tr>
<tr>
<td></td>
<td>142.10</td>
<td>13.10</td>
<td>0.54</td>
<td>4</td>
<td>5.68</td>
</tr>
<tr>
<td></td>
<td>144.06</td>
<td>13.23</td>
<td>1.10</td>
<td>8</td>
<td>11.6</td>
</tr>
<tr>
<td>Wadi Siji (86.6)</td>
<td>228.25</td>
<td>19.77</td>
<td>7.45</td>
<td>38</td>
<td>86.74</td>
</tr>
<tr>
<td></td>
<td>178.95</td>
<td>15.50</td>
<td>0.62</td>
<td>4</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>179.89</td>
<td>15.58</td>
<td>1.64</td>
<td>11</td>
<td>20.00</td>
</tr>
<tr>
<td>Wadi Sfini</td>
<td>228.00</td>
<td>31.46</td>
<td>6.08</td>
<td>19</td>
<td>43.32</td>
</tr>
<tr>
<td>U/S Ashwani Junction (138)</td>
<td>195.60</td>
<td>26.99</td>
<td>1.25</td>
<td>5</td>
<td>10.00</td>
</tr>
<tr>
<td></td>
<td>156.30</td>
<td>21.57</td>
<td>1.93</td>
<td>9</td>
<td>14.00</td>
</tr>
<tr>
<td>Wadi Sfini</td>
<td>228.00</td>
<td>49.25</td>
<td>5.36</td>
<td>11</td>
<td>25.00</td>
</tr>
<tr>
<td>D/S Ashwani Junction (216)</td>
<td>210.40</td>
<td>45.45</td>
<td>2.01</td>
<td>4</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td>156.30</td>
<td>33.76</td>
<td>2.16</td>
<td>6</td>
<td>11.00</td>
</tr>
<tr>
<td>Wadi Ashwani (46)</td>
<td>228.00</td>
<td>10.49</td>
<td>2.15</td>
<td>20</td>
<td>45.60</td>
</tr>
<tr>
<td></td>
<td>210.40</td>
<td>9.68</td>
<td>0.25</td>
<td>3</td>
<td>6.00</td>
</tr>
<tr>
<td></td>
<td>156.30</td>
<td>7.19</td>
<td>1.10</td>
<td>15</td>
<td>24.00</td>
</tr>
<tr>
<td>Wadi Ham (90)</td>
<td>205.30</td>
<td>18.48</td>
<td>7.13</td>
<td>39</td>
<td>80.10</td>
</tr>
<tr>
<td></td>
<td>162.30</td>
<td>14.61</td>
<td>0.63</td>
<td>4</td>
<td>7.00</td>
</tr>
<tr>
<td></td>
<td>174.31</td>
<td>15.69</td>
<td>2.86</td>
<td>10</td>
<td>31.00</td>
</tr>
<tr>
<td>Wadi Qawr(E) (303)</td>
<td>338.50</td>
<td>102.57</td>
<td>17.35</td>
<td>17</td>
<td>57.57</td>
</tr>
<tr>
<td></td>
<td>241.95</td>
<td>73.31</td>
<td>7.42</td>
<td>10</td>
<td>24.00</td>
</tr>
<tr>
<td></td>
<td>146.68</td>
<td>44.44</td>
<td>5.50</td>
<td>12</td>
<td>18.00</td>
</tr>
<tr>
<td>Wadi Qawr(W)</td>
<td>296.00</td>
<td>13.62</td>
<td>2.20</td>
<td>6</td>
<td>18.00</td>
</tr>
<tr>
<td></td>
<td>237.85</td>
<td>10.94</td>
<td>0.87</td>
<td>8</td>
<td>19.00</td>
</tr>
<tr>
<td></td>
<td>146.68</td>
<td>6.75</td>
<td>0.81</td>
<td>12</td>
<td>18.00</td>
</tr>
<tr>
<td>Wadi Baseerah (129)</td>
<td>304.60</td>
<td>39.29</td>
<td>5.55</td>
<td>14</td>
<td>42.64</td>
</tr>
<tr>
<td></td>
<td>239.40</td>
<td>30.88</td>
<td>0.26</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>175.00</td>
<td>22.58</td>
<td>1.97</td>
<td>9</td>
<td>9.00</td>
</tr>
<tr>
<td>Wadi Baseerah (120)</td>
<td>213.65</td>
<td>25.64</td>
<td>1.60</td>
<td>6</td>
<td>12.82</td>
</tr>
<tr>
<td></td>
<td>99.50</td>
<td>11.94</td>
<td>0.42</td>
<td>4</td>
<td>4.00</td>
</tr>
<tr>
<td></td>
<td>132.98</td>
<td>15.96</td>
<td>0.39</td>
<td>3</td>
<td>3.30</td>
</tr>
</tbody>
</table>

Source of rainfall and runoff data: MAF

<table>
<thead>
<tr>
<th>Annual Averages/</th>
<th>68.51</th>
<th>17</th>
<th>40.00</th>
<th>87-88</th>
</tr>
</thead>
<tbody>
<tr>
<td>Totals:</td>
<td>16.41</td>
<td>5</td>
<td>10.00</td>
<td>86-87</td>
</tr>
<tr>
<td></td>
<td>21.42</td>
<td>10</td>
<td>15.00</td>
<td>Median</td>
</tr>
</tbody>
</table>

Table: 4.11.

Comparison of the total annual runoff volumes, runoff coefficients (ratios), and effective rainfall for the gauged catchments of the Emirates for a high rainfall (1987-88) and a comparatively moderate rainfall (1986-87) year, and the median for the period of rainfall and flood records (7-13 years).

The extreme variability in runoff volumes from year to year is clearly illustrated in Table 4.11. Wadis in the ophiolite mountain block (Wadis Ham, Qawr East and Siji) develop larger flood volumes than wadis in the limestone mountain block (Wadis Al Beeh and Naqab). Also, east-flowing wadis in the ophiolite catchments (Wadis Ham and Qawr East) develop larger runoff volumes than west-flowing wadis in the same ophiolite mountain block (Wadis Sfini and Ashwani). The average runoff volumes for a high rainfall year are about four times those for a moderate rainfall year (88.51MCM/a for 1987-88 against 16.41MCM/a for 1986-87), and are also three times the median runoff volume for the period of flood records (88.51 MCM/a against 21.42MCM/a). The median runoff volume is produced by an effective rainfall for all the catchments of 15mm.
4.7. Base-flow

Measurement of base-flow was carried out at random. It was started in the early 1980s but has been abandoned since 1984. The 1987-88 'Hydrology Year Book' of the MAF (unpublished) does not contain any base-flow measurements. An important reason for abandoning this practice is that base-flow is increasingly declining with overpumping from the gravels of the wadi floor. Base-flow does continue in some wadis long after the rains and floods have receded and in some of these wadis, in years of exceptionally heavy rainfall, base-flow may continue well into mid-June. For the hydrological year 1982-83 base-flow was observed in almost all the gauged wadis until April. Only in Wadi Sfini, upstream of its confluence with Wadi Ashwani, and in Wadi Al Farfar (near Fujairah), did base-flow remain until May and June respectively. The base-flow was 0.285 m³/sec. for Wadi Sfini and 0.05 m³/sec. for Wadi Al Farfar. In the preceding heavy rainfall year of 1981-82, base-flow continued in Wadis Ham and Al Farfar until May.

Wadi Siji is known to maintain the longest duration of base-flow, continuing for up to 2 or 3 months after the last heavy runoff. Wadi Ham recorded a flow of 0.02046 m³/sec. at the beginning of May 1982 or 32 days after the second highest runoff on 29-03-1982 (also refer to Table 4.10 (D) for 1987-88). The following year base-flow continued in the same wadi for more than three weeks after the last heavy runoff (in the beginning of April) but with the higher flow of 0.127 m³/sec. On 03-04-1982, Wadi Siji had a flow of 0.752 m³/sec. and at about the same time the following year it had a flow of 0.171 m³/sec. In the case of Wadi Ham, base-flow continued after the last heavy runoff at the end of March 1982 for nearly 105 days until mid-July, and for a similar period in the case of Wadi Siji, where the base-flows continued only until the end of May. Whatever the volume of base-flow, it is always included in the monthly or annual runoff total (Hydrology Reports for 1981-82 and 1982-83).

4.8. Loss of runoff to the sea and inland/coastal sabkhas

The narrowness of the alluvial embayments on the east coast more often allows spate-flows to reach the sea even in years of moderate rainfall. To the west of the mountain divide, owing to the greater distance
between the foothills and the coastline and also the high infiltration capacity of the western piedmont alluvial plains, only occasionally do large flood flows, during years of high rainfall and/or runoff, reach the sea through Wadi Lamhah.

In most cases, during years of low to moderate rainfall, flood waters end up in desert depressions or 'seihs' (playas) for days, or even weeks, before drying up leaving behind extensive areas of fine silt. Rarely does overland flow reach beyond the western limits of the western piedmont plains, but occasional ponding may take place if some degree of saturation of the alluvium of the plains has been effected by intermittent or continuous periods of rain shortly before a main storm. However, despite the fact that such ponded surface water bodies are exposed to high evaporation, some of this water infiltrates into the chloride- and sulphate-rich silts, gypsum and anhydrite-halite inland sabkha beds, becoming a contaminated brackish to saline groundwater source.

In order for the flood waters to reach the sea in a number of wadis on the east coast as well as Wadi Lamhah to the west of the mountain divide, the alluvium in wadi courses must first reach a degree of saturation, a process less effected by short-lived thundery downpours, than by widespread, consistent rainfall over a long period, in the form of light to medium raindrops. The perfect condition for violent overflow to reach longer distances from the mountains, occurs when there is a heavy rainstorm after this initial saturation of the wadi alluvium.

A.P. Gemmel, the FAO consultant who oversaw the modernization of the hydrometeorological network and the in-service training for MAF staff related to such fields of operation (Hydrometeorological data evaluation, processing and in-service training, A.P. Gemmel, FAO-MAF, 1975-78), maintained that floods that had a velocity of 90-110m³/sec. succeeded in reaching the sea from Wadis Al Beeh (west coast), Wurai'ah and Ham (east coast) (1978). However, no such documentation has since been continued by MAF staff. Therefore, the amount retained by saturation in the wadi alluvium, that is later released as base-flow, cannot be calculated.

Hassan and Maddrell (Halcrow: Dams and Recharge Facilities in the UAE, 240
1982), using infiltration rates for the sandy loam soils of the agricultural experimental station at Digdaga (the MAF Hydrological Year Book, 1979), varying from 100 to 190 mm/h., derived an average soil infiltration rate of 150 mm/h. (or 6 m³/m²/d). They applied this saturation rate to average areas of wadi beds and presented wadi alluvium saturation volumes for selected wadis, above which "all spates will be wasted to the undesirable areas" (implying inland/coastal sabkhas and the sea) (Table 4.12).

<table>
<thead>
<tr>
<th>Wadi</th>
<th>SATURATION VOLUME IN MCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuwaiyyain</td>
<td>0.42</td>
</tr>
<tr>
<td>Safad</td>
<td>0.05</td>
</tr>
<tr>
<td>Sfini</td>
<td>0.62</td>
</tr>
<tr>
<td>Zikt</td>
<td>0.15</td>
</tr>
<tr>
<td>Naqab</td>
<td>0.31</td>
</tr>
<tr>
<td>Wurai'ah</td>
<td>0.15</td>
</tr>
<tr>
<td>Al Farfar</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Source: Dams and recharge facilities in the UAE, Halcrow, 1982.

Table: 4.12.

Saturation volume of the alluvium of some mountain wadis in the Emirates (1982).

Saturation point of the wadi bed alluvium for selected wadis beyond which all spates will be 'wasted' to inland and coastal sabkhas and the sea.

When the actual overland flow or runoff has receded, water saturating the wadi alluvium is gradually released, first as base-flow and later as subsurface inflow. As noted in section 4.4., such a phenomenon is increasingly being intercepted by human interference by excessive pumping from the wadi gravels. On the east coast, overland flow to the sea does occur in years of moderate to exceptionally high rainfall, a process slightly slowed down by the road embankment of the
Fujairah-Dibba highway behind which water ponds for several weeks after the floods have receded.

Lavalin (1980), investigating by thermal imagery fresh water losses to the sea through submarine springs, delineated the four outlets of fresh water discharge into the sea and the volumes lost (Table 4.13):

<table>
<thead>
<tr>
<th>East Coast</th>
<th>Badiyah</th>
<th>Zubarah</th>
<th>Dhadhnah</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vol. m³/d</td>
<td>10,400</td>
<td>8,340</td>
<td>3,670</td>
<td>22,410</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>West Coast</th>
<th>Khawr Kuwair</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vol. m³/d</td>
<td>3,400</td>
</tr>
</tbody>
</table>

Grand total 25,810


Table: 4.13

Outflow to the sea from submarine springs on either coast of the Emirates (1980).

The total amount in 1980 according to the above estimates was 9.4 MCM/a. While such losses to the sea might still be continuing, at least during, and shortly after rain and runoff events, the widespread interception by excessive pumping that has accompanied the extensive agricultural development since the Lavalin survey, must have reduced this volume to half or even less (discussed further in Chapter 10).

4.9. Catchment yields and actual runoff volumes

4.9.1. Actual annual runoff volumes

As seen in Table 4.1, which gives the annual runoff volumes of the gauged catchments since the hydrological year 1975-76, the years 1984-85 to 1985-86 were the driest years on record with no flow in nearly all the wadis, except for minimal flows in Wadis Al Beeh, Naqab and Sfini.
Runoff volumes of more than 1.0 MCM seem to recur more frequently in Wadi Sfini, upstream of its confluence with Wadi Ashwani (8 out of 13 years) and in Wadi Al Qawr (East) (6 out of 9 years). Next in frequency are Wadis Al Naqab and Al Beeh (5 out of 13 years each). Wadis Siji and Ham, despite the long base-flows lasting for several weeks after the actual runoff has receded, show a frequency of surface flows of more than 1.0 MCM in 4 out of 13 years (Table 4.1). Runoff volumes of more than 2.0 MCM/year appear to be closely related to years of exceptionally heavy rainfall (1981-82 and 1987-88). This seems to occur in wadis in the ophiolite zone (Wadis Siji, Sfini, Ham and Qawr (East)) in 1 to 6-7 years and in wadis in the northern limestone zone (Wadis Al Beeh and Naqab) in 1 to 5-8 years (Table 4.1). Exceptionally heavy flows were recorded in 1981-82/1982-83 and 1987-88, with the largest runoff volumes being in Wadis Al Qawr (East), Ham, Siji and, to a lesser degree, in Wadi Sfini (Table 4.1). Again, such exceptionally heavy flows seem to occur once in 6-7 years. The runoff volumes of 1987-88 were the highest ever recorded for Wadis Qawr (East), Siji and Sfini although flood flows for Wadi Al Wurai’ah were higher for 1982-83 (Table 4.1). Similarly, the runoff volume for Wadi Ham in 1981-82 was twice that of 1987-88, both were years of heavy rainfall and runoff (Table 4.1).

4.9.2. Catchment yields

As shown in Table 4.16, the area of the ophiolite part of the catchments to the east of the watershed, which includes 12 wadis, is larger than that to the west containing 8 wadis. Together, the two areas produce 80% of the period mean annual runoff. Wadis of the limestone block to the north of the Dibba-Idhn Line contribute the remaining 20%.

The earliest measurements of surface flow, carried out by the ‘Trucial States’ Water Resources Study (Halcrow, 1966-69), had two shortcomings: i) the short period of only three years of surface flow observation; and, ii) the unusually dry period that coincided with the duration of that study. The Halcrow estimate of annual runoff for a mountain area, given as 3974 km², was based on a 26mm. effective rainfall (the amount out of the total catchment rainfall that actually causes runoff). The same value was also used by the FAO consultants Carr and Barber (1976), which in turn was the basis for runoff calculations for larger catchments in southwest Arabia (discussed further in Chapter 10).
runoff estimates of both these consultants were given as 157MCM (Halcrow), and 100 MCM (Carr and Barber) for the whole length of the western mountain front from Ras Al Khaimah to Al Ain. Both these estimates, however, are higher than the actual expected mean derived by the present study, for both the gauged and the ungauged catchments, as is shown in Table 4.14 (see also Chapter 10, Section 10.4).

Total annual catchment runoff yields vary from 35.72 MCM/a for a low rainfall/runoff year such as 1986-87 for both the gauged and ungauged catchments, to 88.38 MCM/a for an exceptionally high rainfall/runoff year such as 1987-88. The yield for 1982-83, which was a high-rainfall but medium-runoff year, was 65.20 MCM/a; whereas in the previous year (1981-82), which was another high rainfall/runoff year, the total catchment yield was 81.42 MCM/a which was close to the volume for 1987-88 (Table 4.15).

Besides presenting this comparative total annual catchment yield for the four years noted above, Table 4.15 also gives annual rainfall totals (averages for 15 mountain rainfall stations). As seen in Table 4.15, the rainfall average for 1988, which produced the highest runoff yield to date (88.38 MCM), was 250.82mm. which was less than that for 1982 (336.72mm.), yet the runoff yield for 1982 (81.42mm.) was only less by 2% than that for 1988. The average rainfall for 1988 was even less than that for 1983 (average rainfall 289.58mm.) which was also a moderate runoff year (the runoff volume was 65.20 MCM). This irregular relationship between rainfall and catchment runoff yield may be explained by two possible considerations:

a) that the rainfall for 1988 was more localized and of shorter duration than that for 1982, and,

b) that the rainfall that gave rise to such comparatively greater runoff crop could have been more, but was concentrated in parts of the catchments that have no rain gauge/recorders to offer rainfall totals.

When the annual catchment runoff volumes for the whole period of flood records (Table 4.1 and 4.14) are averaged, excluding years of no data but including those with no flow, the period mean annual runoff volume
for the gauged and ungauged catchments is in the order of 38.62 MCM/a (Tables 4.14 and 4.16), which is close to the 35.72 MCM/a total annual catchment yield for the low rainfall/runoff year 1986-87 (Table 4.15). Contrary to previous belief, it is now clear that most of the annual runoff, resulting from basin precipitation, flows into the east coast. This amounts to 20.49 MCM/a or 53% of the period mean annual runoff volume of all the catchments of the Emirates including those in the northern limestone massif of Ru‘us Al Jibal. Despite this, the whole east coast is a zone of water shortage. 47% of the mean annual runoff flows westwards into the western piedmont plains from Ras Al Khaimah to Al Ain (excluding the 5.35 MCM/a surface flow crossing the international border north of Al Ain from Oman (discussed later in Chapter 10) but including the 0.50 MCM flood volume generated in Wadi Shik in the Emirates), of which 57% is raised by east-flowing wadis in the ophiolite mountain block to the south of the Dibba-Idhn Line and 43% by the west-flowing wadis of the limestone mountain block to the north of the Line (Table 4.16). The coastal zone of Ras Al Khaimah and its wadis (with a mean annual runoff making up only 19% of the total for all the catchments), is an area of acute water shortage and sea-water intrusion, as at Sha’am, Ghaleelah and Sahwat. Furthermore, areas in the piedmont plains are drying up and the exhaustion of groundwater reserves is on the increase, as is evident in the increasing number of many gardens that are being abandoned (Al Dhaid) because of the drying of wells.

Of the 38.62 MCM/a total catchment runoff yield for both the gauged and ungauged catchments, using a 0.75 recharge factor, the expected mean annual groundwater recharge from this surface runoff is 28.97 MCM/a. The overall effective rainfall responsible for this ultimate recharge into the aquifers in both the limestone and ophiolite catchments, is 15mm. (Table 4.14)

Thus, the western piedmont plains, the main fresh water recharge zone in the Emirates with great recharge potential, receive less runoff than the narrow eastern coastal plain with limited recharge potential. These facts have put the whole situation of runoff, and the contribution to recharge expected from it, in a different but clearer perspective.
### Table: 4.14.

Mean annual runoff yields and estimated effective groundwater recharge from them for both the gauged and ungauged catchments of the Emirates.

Given in Table 4.14 are the total areas of the catchments and their rock types; the period mean rainfall and the total catchment precipitation accrued from it; the runoff coefficient or ratio for each catchment and the effective rainfall responsible for the surface runoff, the effective rainfall varies from 4mm. to 131mm. for catchments in the limestone, and from 11mm. to 31mm. for catchments in the ophiolite, mountains. The total mean annual runoff volume derived for the gauged catchments is 23.67 MCM/a, and that for the ungauged catchments 14.69 MCM/a, giving a total catchment runoff yield for all the catchments within the Emirates of 38.62 MCM/a. With a 75% (0.75) recharge factor, the expected mean annual groundwater recharge from surface runoff is 28.97 MCM/a from both the gauged and ungauged catchments of the Northern Emirates where all the UAE wadi catchments occur. The overall effective rainfall responsible for this recharge, for all the catchments, is 15mm.

<table>
<thead>
<tr>
<th>Wadi Catchment</th>
<th>Area km²</th>
<th>Rock Type</th>
<th>Period Mean Rainfall/mm</th>
<th>Total Catchment Precipitation/MCM</th>
<th>Gauged Period Mean runoff/MCM</th>
<th>Runoff Effective</th>
<th>Effective Rainfall/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gauged catchments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Abee</td>
<td>474</td>
<td>Limestone</td>
<td>144.06</td>
<td>68.38</td>
<td>2.99</td>
<td>3</td>
<td>4.3</td>
</tr>
<tr>
<td>Al Jaber</td>
<td>92</td>
<td>Limestone</td>
<td>144.06</td>
<td>13.25</td>
<td>1.10</td>
<td>0</td>
<td>11.6</td>
</tr>
<tr>
<td>Al Jum</td>
<td>88.6</td>
<td>Serpentinite</td>
<td>179.89</td>
<td>15.58</td>
<td>2.10*</td>
<td>11</td>
<td>20</td>
</tr>
<tr>
<td>Al Jum U/S Ashwan Junc.</td>
<td>238</td>
<td>Serpentinite</td>
<td>156.30</td>
<td>21.57</td>
<td>1.93</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>Al Jum U/S Ashwan Junc.</td>
<td>216</td>
<td>Serpentinite</td>
<td>156.30</td>
<td>33.76</td>
<td>2.58</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>Al Jum U/S Ashwan Junc.</td>
<td>46</td>
<td>Serpentinite</td>
<td>156.30</td>
<td>7.19</td>
<td>0.95</td>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td>Al Jum</td>
<td>90</td>
<td>Serpentinite</td>
<td>174.31</td>
<td>15.69</td>
<td>2.86</td>
<td>18</td>
<td>31</td>
</tr>
<tr>
<td>Qewr - East</td>
<td>303</td>
<td>Serpentinite</td>
<td>146.68</td>
<td>44.44</td>
<td>5.60</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>Qewr - West</td>
<td>46</td>
<td>Serpentinite</td>
<td>146.68</td>
<td>6.75</td>
<td>0.81</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>Musay'ah</td>
<td>279</td>
<td>Serpentinite</td>
<td>151.96</td>
<td>19.60</td>
<td>1.97</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Hobar ( Shimal )</td>
<td>120</td>
<td>Serpentinite</td>
<td>132.98</td>
<td>15.96</td>
<td>0.39</td>
<td>2.5</td>
<td>3.3</td>
</tr>
<tr>
<td>( Shik and Hamed/ Al Ain )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.39</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total Area</strong></td>
<td>1021.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>23.67</td>
<td>6 Let. &amp; 8 Let.</td>
<td>12 Serp. &amp; 19 Serp.</td>
</tr>
<tr>
<td><strong>Ungauged catchments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Abee</td>
<td>35</td>
<td>Limestone</td>
<td>147.30</td>
<td>5.16</td>
<td>0.209</td>
<td>6</td>
<td>13.3</td>
</tr>
<tr>
<td>Al Jum</td>
<td>198</td>
<td>Limestone</td>
<td>147.72</td>
<td>10.20</td>
<td>0.612</td>
<td>6</td>
<td>13.1</td>
</tr>
<tr>
<td>Al Jum U/S Ashwan Junc.</td>
<td>58</td>
<td>Limestone</td>
<td>131.13</td>
<td>26.16</td>
<td>1.570</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Qewr</td>
<td>38</td>
<td>Serpentinite</td>
<td>159.29</td>
<td>6.053</td>
<td>0.726</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Qewr</td>
<td>54</td>
<td>Serpentinite</td>
<td>156.30</td>
<td>8.440</td>
<td>1.023</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Qewr</td>
<td>7</td>
<td>Serpentinite</td>
<td>139.29</td>
<td>1.115</td>
<td>0.124</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Al Jum</td>
<td>6</td>
<td>Serpentinite</td>
<td>122.11</td>
<td>0.793</td>
<td>0.059</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Al Jum</td>
<td>61</td>
<td>Serpentinite</td>
<td>122.20</td>
<td>8.058</td>
<td>0.967</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Al Jum</td>
<td>185</td>
<td>Serpentinite</td>
<td>132.20</td>
<td>28.157</td>
<td>3.38</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Al Jum</td>
<td>73</td>
<td>Serpentinite</td>
<td>121.33</td>
<td>9.003</td>
<td>1.000</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Al Jum</td>
<td>31</td>
<td>Serpentinite</td>
<td>131.90</td>
<td>4.089</td>
<td>0.491</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Al Jum</td>
<td>26</td>
<td>Serpentinite</td>
<td>151.45</td>
<td>3.991</td>
<td>0.499</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Al Jum</td>
<td>68</td>
<td>Serpentinite</td>
<td>121.90</td>
<td>8.969</td>
<td>1.076</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Al Jum</td>
<td>17</td>
<td>Serpentinite</td>
<td>137.00</td>
<td>2.975</td>
<td>0.357</td>
<td>12</td>
<td>21</td>
</tr>
<tr>
<td>Al Jum</td>
<td>94</td>
<td>Serpentinite</td>
<td>170.60</td>
<td>16.036</td>
<td>1.934</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td><strong>Total Area</strong></td>
<td>1021.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>14.69</td>
<td>6 Let. &amp; 13 Let.</td>
<td>12 Serp. &amp; 17 Serp.</td>
</tr>
</tbody>
</table>

* Includes the mean annual runoff for Wadi Lulah (4.06 MCM/a)

* Source of rainfall and runoff data: WAF

With a 75% (0.75) recharge factor, the expected annual volume of replenishment is 28.97 MCM/a. The overall effective rainfall for both the limestone and serpentinite catchments is 15.00 mm.
Comparison of total catchment yields for high-rainfall years (1982 and 1988), a medium-rainfall year (1983) and a relatively low-rainfall year (1987) (in Million Cubic Metres (MCM)).

Despite the higher average annual rainfall for 1982 (336.7mm) than that for 1988 (250.8mm), the total runoff for both the gauged and ungauged catchments was almost equal for 1982 and 1988, both of which were high-rainfall years. Again, although the average annual rainfall for 1983 of 289.6mm was higher than that for 1988, the annual runoff total for 1983 was less than that for 1988. Furthermore, although the average annual rainfall for the low-rainfall year of 1987 was only 191.5mm, which was 76% of that for 1988, the annual runoff volume for 1987 was only 43% the runoff volume for 1988. The answer lies in whether the mountains or the rest of the Emirates receive the higher rainfall.

Table: 4.15.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauged Catchments</td>
<td>68.51</td>
<td>47.63</td>
<td>36.00</td>
<td>16.41</td>
</tr>
<tr>
<td>Ungauged Catchments</td>
<td>19.87</td>
<td>33.79</td>
<td>29.20</td>
<td>19.31</td>
</tr>
<tr>
<td>Total</td>
<td>88.38</td>
<td>81.42</td>
<td>65.20</td>
<td>35.72</td>
</tr>
<tr>
<td>Average Rainfall</td>
<td>(250.82mm)</td>
<td>(336.72mm)</td>
<td>(289.58mm)</td>
<td>(191.49mm)</td>
</tr>
</tbody>
</table>
Runoff volumes for east- and west-flowing wadis in both the limestone and ophiolite parts of the mountains north and south of the Dibba-Idhn Fault-Line.

The area east of the watershed drained by the east-flowing wadis (1750km$^2$) is larger than that to the west drained by the west-flowing wadis (1000km$^2$). The total mean annual runoff volume flowing into the east coast, which is an area of limited groundwater storage capacity, is 20.49MCM/a, and the total mean runoff volume flowing into the western piedmont plains and the desert foreland, which is an area of vast groundwater recharge capacity, is 18.13 MCM/a. In general, 80% of the total annual runoff occurs in the ophiolite mountain block south of the Dibba-Idhn Line (30.23 MCM/a out of 38.62 MCM/a), of which 70% flows into the east coast and only 30% flows into the extensive western piedmont and desert foreland plains.
4.10. **The Aflaj**

The falaj of the Emirates, similar to the 'qanat' in Iran and the 'khareez' in Pakistan and Afghanistan, is thought to have been introduced into eastern Saudi Arabia, the Emirates and Oman by the Persian invasion of the area in pre-Islamic times (Wilkinson, 1977). It provided a "musha'" (communal) irrigation system for all the consumers along its course, an adaptation to the scarcity of the resource and its limited occurrence. It delivered water continuously without the need for energy input, but with the problem of having to receive its waters at times when they were not required, such as during the winter months when reduced water quantities at wider intervals are needed for irrigation. The water also continues to flow unabated during the night in both winter and summer when there is no attendant to regularize its distribution or any need for it at that time by the users. The flow in some of the aflaj was so abundant that to save it in any form of storage was impracticable (Beaumont et al, 'The Middle East', 1978).

Thus, the aflaj, that do have natural flow, waste more water than is required by their users because of this drawback of the inability to regularize their flow. When sometimes the outlets of the aflaj are intentionally blocked with boulders and mud to hold back the flow temporarily, the result, when this blockage is removed, at times when water is needed, can be damaging to crops owing to the force of flow of the impounded water. Such temporary blocking of the outfall, aided by the extremely gentle gradient of the falaj tunnel floor, leads to the silting of the channel floor. For example, Falaj Dhaid has a difference in slope, from source to outfall, of 0.80m. in 3500m. or 1:4375.

The aflaj, found on either side of the mountains in the Emirates, in both the narrower east coast embayments as well as the wider piedmont plains to the west, are a feature of the mountain wadis, where there is an abundance of alluvial deposits in the wadi floor. They are also found in the piedmont plains, with cemented horizons lower down the profile, that are within the water-bearing strata, and are firm enough to support the sides and roof of the falaj tunnel. They are not found in the sand dune and desert foreland areas for two reasons: a) the depth of the water-table and the inhospitable sandy soils (to sustain agriculture at
the falaj outfall); and, b) the difficulty of supporting tunnels in soft sand. Even on the east coast, the aflaj are found well inland at the head of the outwash fans of the main wadis, such as the outwash fan of Wadi Ham. Falaj Farfar and Falaj Maduk are such aflaj.

The aflaj of the Emirates vary in length from 1 to 6 kms. The average width of the subterranean conduit is between 0.4m. and 1.0m., and the height varies from 1.5m. to 2.0m as was observed in Falaj Dhaid. Most of the falaj channels have these dimensions, although in some aflaj there are larger spans of up to 3m. or even 4.5m.. This was observed in the safely accessible sections of Falaj Filli, 16kms. south of Mileiha (1987), where the high vertical span of the tunnel was not original but resulted from the successive deepening of the tunnel floor in pursuit of the continuously receding water-table. Several such excavations took place before the 1950s since the falaj had been cut in the gravels of the plains a hundred years ago (Fig. 4.12)

The walls and roof of the tunnel of Falaj Filli are plastered with clay or mud and have no structural support. It is remarkable how they have withstood time, but this may only have been possible as long as water flowed in the channel and the air within the channel remained humid. When, however, the falaj began to dry or have intermittent flow, caving-in and peeling off of the plaster in the roof and walls must have taken place with the dilapidation happening so fast that some of the channels are now totally blocked. This was witnessed in Falaj Dhaid especially in the stretch of the falaj channel immediately downstream of the mother-well. By 1985 Falaj Dhaid had already dried up and had had its water augmented from boreholes drilled by Sharjah Municipality. Because of excessive collapse along the length of the channel and the resulting blockage, water had to be conducted overland to the outfall by plastic pipes, and from there distributed to the date gardens, a job completed by the Sharjah Water Department. This augmentation was not instigated by a desire for the conservation of traditional methods of irrigation, but rather as a result of the presence of old established date gardens downstream of the falaj outfall. It was also a cheap option to transfer irrigation water to the gardens.

As the falaj is a gravity fed system, it is only able to tap water from aquifers that are above the falaj channel floor. The tunnel is,
therefore, excavated well below the piezometric level so that groundwater seeps into the channel from both sides and flows over the channel floor, which is plastered to avoid seepage from the rest of the falaj course as the tunnel comes above the piezometric surface further down its course (Fig. 4.11).

The aflaj in the Emirates are of 3 types based on the source from which they tap their water:

1) **The Da’udi falaj**: Is a type the channel of which penetrates aquifers that in some places are found very deep below the surface. Examples of this falaj type are the aflaj of Al Ain, which are below 20m. and are of the large type that used to have high discharge, but were naturally prone to fluctuation in the water-table (Figs. 4.11 to 4.13).

2) **The Ghaili falaj**: is a wadi bed falaj with output depending on the seasonality of the base-flow in the wadi alluvium. The channel can be partially covered but in almost all cases it is an open ditch leading the water to nearby gardens, usually situated on the wadi side.

3) **Springs**: obtain their water from deep-seated sources and are usually warm and mostly associated with fissures in carbonate or ophiolite rock types. The Khatt springs are examples of the former and those of Madhab and Wurai’ah, the latter.

Table 4.17 presents all the data related to the aflaj of the Emirates with a description of their type and status todate. It should be noted that the local branding of irrigation channels as aflaj creates confusion, especially with the ‘ghaili’ type, springs and any form of seepage from wadi gravel. The diversion of a wadi bed base-flow by temporarily damming a braided channel or excavating a new one, is in fact the ‘ghaili’ type noted earlier. The meaning of the Arabic word ‘ghail’ is ‘brook’ or ‘rivulet’. The spring at Wurai’ah, which is an overflow from a saturated alluvium of a slightly elevated tributary wadi seeping onto the main wadi alluvium through a constriction in a sill about 5m. high, is also called a falaj and a ‘waterfall’.
Table: 4.17.

Hydrological and physiographical data of all the existing aflaj and hot springs of the Emirates, and the mean annual natural discharge of the aflaj whose flows are still unaugmented.

There is both official and public uncertainty about the present status of the aflaj concerning their natural or artificially augmented flow. Table 4.17 presents data based on observation and monitoring of most of the aflaj of the Emirates. The 'ghaili' aflaj is fast disappearing and a large number of the 'daudi' aflaj have dried up or have been neglected after having been washed away by floods or simply substituted by the electrical pump. The most affected of the aflaj are those of the western piedmont plains. The aflaj have either dried up or have transformed into concrete conduits transporting pumped borehole water. Natural falaj flow has been identified and all the aflaj of the Emirates together discharge only 10.64 MCM/a and, with the discharge of the fresh water spring of Al Wurai'ah (2.37 MCM/a), the total falaj discharge volume of the Emirates becomes 13.01 MCM/a.
Long section of a 'daudi' falaj.

There are two subterranean sections of the falaj: the active or supply section, which is excavated below the piezometric level, and the channelling or transporting section, which is from the point the falaj channel departs the piezometric surface to the outfall. The access wells (the ventilation shafts) have no hydrological role and are only there to facilitate maintenance operations. In the past the aflaj supplied both domestic and irrigation water. The uppermost access hole provided water for human consumption. Water for other domestic uses was taken from the outfall, after which came the use for irrigation.

Cross-section of a 'daudi' falaj tunnel.

The ceiling of the falaj tunnel is of a maximum height of 2m. except where large boulders were in the way and the tunnel had to negotiate its way during scouring in the alluvium. The walls were plastered with clay to minimize two-way seepage of groundwater into and from the tunnel. Only the floor of the tunnel was left unplastered to allow seepage from the saturated zone.
In the past, the falaj supplied both domestic and irrigation water. The uppermost ventilation or access hole was reserved for drawing water for human consumption. Ventilation holes were always protected from fouling. Water for other domestic uses was taken from the outfall, after which came the use for irrigation. The shafts themselves served the dual purpose of ventilation and points of access to the falaj channels for cleaning and maintenance. The aflaj controlled the siting of habitations with the villages clustering around the falaj outfall in places of agricultural potential. As the aflaj were important arteries of life in the old days, supplying the only source of water with minimum energy, they were regularly being maintained, and both the cultivated area and irrigation were under good communal management. The situation now, around most falaj locations, is that a number of allotments are sited on wadi terraces that could never have had, and can never have, natural water supply, had it not been for the powerful electric pump. As can be seen near Daftah, astride the Dhaid-Masafi-Fujairah highway, plastic pipes some of which are ordinary flexible hose-pipes, cross the wadi sides in all directions transporting pumped water from the gravels of the wadi bed to cultivated terraces high on the barren wadi sides.

Overabstraction of groundwater has led to the deterioration, and even dilapidation, of the aflaj. Continuously falling groundwater levels have rendered most of the aflaj ‘hanging’ over the ever receding water-table to a point of no return. Large investments have been spent in Al Ain on renovating the aflaj and augmenting, and for some totally substituting, their water flow. Regardless of the sentimentality attached to the aflaj concerning their past role, they have become nothing more than conduits for transporting mixed fresh, brackish and recycled irrigation water for the date gardens. The aflaj, and the once isolated oases they served, are now in the centre of Al Ain town engulfed by urban development.

The access wells (ventilation shafts) have no hydrological role and are only there to facilitate maintenance operations, especially as outlets for the removal of the excavated debris. These shafts vary in diameter from 1 to 2 m., and are usually uncemented, making them liable to continual caving-in. The spaces between these access shafts vary from 20-50m. as was observed in Falaj Filli. On the surface they do not follow a straight line, although they do lead directly into the falaj channels, which themselves follow crooked courses around hardrock.
sections, such as huge boulders, sills or cemented sections of the alluvial lithology. Excavating these tunnels must have been done by practically scouring the deposits as any vibration that might be caused by the use of heavy or noisy equipment would instigate collapse of the tunnel walls and roof. The feature common to all aflaj is the extremely gentle gradient averaging 1:1000 though, as mentioned earlier, Falaj Dhaid has a gentler gradient of 1:4000.

As seen in Fig. 4.11, there are two subterranean sections of any falaj, one is what is known as the active or supply section, which is excavated below the piezometric level as far upstream into the aquifer to be tapped as possible to ensure continuous safe yield draining into the channel from the sides and the floor by seepage; the second is the so-called channelling or transporting section which is from the point where the channel departs the piezometric surface to the outfall, running for the rest of its course in the unsaturated or vadose zone. As the floors of the aflaj were originally unplastered, a lot of water returned to the aquifer.

The excavation of the upper part of the falaj tunnel into the aquifer was a highly specialized and intricate process as the aim was to obtain a steady inflow of water into the channel. Should the channel be cut far upstream into the aquifer, it would lead to two undesirable consequences: the one, of increasing the volume of flow more than needed; the other, the depletion of the aquifer as a result, and the fast lowering of the water-table. As the loss of falaj water was largely from the tunnel floor, the tunnel walls and floor were gradually plastered with mud that became less watertight with time.

The renovation scheme of the aflaj of the Northern Emirates, carried out by the MAF from 1980 to 1984, led to the lining of most of the falaj channel with cement, thus minimizing lateral flow. Floods cause major disruptions in falaj courses by washing away large sections and dissecting some aflaj into several parts. Also, the sharp fall in groundwater levels in recent years slowed the momentum of renovation of the aflaj. Furthermore, the use of the dry falaj courses as conduits of artificial water supplies, does not warrant the cost of their renovation. If it is necessary to transport irrigation water to the gardens then the best option is by the drilling of boreholes and the
gardens then the best option is by the drilling of boreholes and the pumping the water directly to the gardens.

Figure 4.13 shows the location of the aflaj in the Emirates. Of these, the majority are of the 'ghaili' type, which are seasonal and their flow is closely related to that of base-flow in the wadi alluvium and, thus, to runoff and rainfall. The season of base-flow used to last longer in the past, but since the widespread introduction of the motor pumps and their negative impact was extended to the wadi floor and terraces, the amount of subsurface flow available to sustain falaj flow is becoming increasingly less and of a shorter duration.

Table 4.17 summarizes the important data concerning all the aflaj to date. Apart from some discharge values which have been obtained from MAF records, the rest of the information has been recorded during actual visits to falaj sites that included interviews with the local inhabitants and officials connected to this traditional water system (e.g., the Falaj Committee of Al Ain).

The renovation of the aflaj had started in the days of the Trucial States Council in the late 1960s long before the Emirates became a federated state. This was to maximize the efficiency of what was then the only source of both domestic and agricultural water at a time when the area under cultivation was limited and agricultural activity was of a subsistence nature. The use of irrigation water from the falaj was based on sharing. With the advent of the federal phase in the history of the Emirates, the development of lines of communication and the influx of cash into all areas, the predominance of mechanical groundwater abstraction and diverse job opportunities, reduced agriculture in the traditional areas to secondary importance, and even to a recreational level in spite of the apparent vast increase in the agricultural area. Farm owners resorted to private pumps, which led to individualism replacing the past well-knit system of communal sharing centred on the dying falaj.

All the aflaj were visited in the field and their existing state investigated. The 'ghaili' falaj is fast disappearing and a large number of the 'da'udi' aflaj have dried up or have been neglected after having been washed away by successive floods or simply substituted by the
Figure: 4.13.


The falaj is a man-made water scheme of the mountain wadis and the plains where its tunnel could safely be scoured in the firmer alluvial deposits than the aeolian deposits of the sandy desert foreland from where the falaj is markedly absent. Most of the falaj cluster of Al Ain is artificially augmented with fresh, brackish, desalinated and treated waste water, mainly because they happened to have traditional date gardens at the outfall. The aflaj of the Northern Emirates are dilapidating with time, very few of them are supplied with pumped water from boreholes and the falaj renovation scheme of the early 1980s came to a halt by 1984 and nothing has been pursued in that end since. Overabstraction of groundwater and the continuously falling groundwater levels have rendered most of the aflaj 'hanging' over the ever-receding water-table to a point of no return.

257
electric pump. The most affected are the aflaj of the western piedmont plains in the Northern Emirates. The renovation scheme of the MAF of the early 1980s came to a halt by 1984 and nothing has been pursued since.

4.10.1. The aflaj of Al Ain

Of the nine main aflaj of Al Ain, five ceased to have natural flow since the beginning of the 1980s. These are: Al Jimi, Al Qattarah, Al Hili, Al Muweij‘ee and Al Mu‘taredh. Falaj Al Aini has a reduced seasonal flow in winter but requires augmentation from external sources. Falaj Da‘udi still retains natural flow though its volume had so markedly dropped in the two winters of 1988 and 1989 that led its flow to be supplied from boreholes, at least to supplement its summer flow.

The aflaj of Al Ain have all been renovated and their tunnels are now totally lined by cement on the sides and floor. The falaj floor in Al Ain was once tapping aquifers the levels of which stood at 20-30m. Groundwater levels at present stand at 90-150m., and even as deep as 240m. The cement sealing of the tunnel walls and floor helps prevent recirculation of some of the mixed (augmented) water which the aflaj transport at present. This mixed water is made up of fresh water from WED Al Ain (fresh ground and desalinated water from the public supply), brackish water from Seih Al Miyah III wellfield and recycled wastewater. The total daily volume of this mixed falaj water is apportioned as follows:

1) Brackish water from Seih Al Miyah III = 1.75 mgd.
2) Fresh ground/desalinated water = 0.50 mgd.
3) Recycled wastewater = 0.50 mgd.

Total daily volume = 2.75 mgd.

Falaj Haza‘ and Falaj Mazyad have been dry for years, and since there are no date plantations at the outfall of these two aflaj, no water is pumped into them. The augmentation of the water of the Al Ain aflaj is governed by the historic location of the date plantations at their outfalls. These plantations were once scattered oases less than two decades ago but are now in the heart of the sprawling town of Al Ain. A.P.Gemmel (FAO Consultant working for the MAF (1975-78)) reported, as early as 1978, that the two aflaj of Al Mu‘taredh and Al Jimi had
already had their water flow augmented from boreholes, whereas Falaj Al Muwaj'ee had had no natural flow and was wholly reliant on pumped water.

In the early 1980s a falaj, to the north of Al Hilli in Al Awha, buried for decades, was unearthed and renovated. It is called Falaj Al Leem and at the time of its discovery, its channel floor had already been left 'hanging' above a much receded water-table. The falaj is located near the garden of Shaikh Saif bin Muhammed, where a 300 m³ reservoir collects water from boreholes in the area to supply the falaj.

The two remaining aflaj near Al Ain, Falaj Buraimi and Falaj Sa’arah, lie within Oman (in Al Buraimi). Both have natural flow that is also dwindling gradually as a result of the general depletion of groundwater in Al Jaww Plain in the Emirates, where the two aflaj have their sources. Falaj Buraimi had a discharge rate in January 1987 of 36.65 l/s., but in January 1988 it was 29.50 l/s. Similarly the flow in Falaj Sa’arah lessened from 48.40 l/s. to 37.59 l/s. for the same months. The continuous decline in falaj discharge is further illustrated by the averages of several readings in a single year for both aflaj (Table 4.18).

4.10.2. Discharge from the aflaj

The total annual discharge from the aflaj of the Emirates is presented in Table 4.17, which gives annual volumes (in million cubic metres (MCM)) from 1977 to 1987, except for the aflaj of Al Ain where values are available also for 1968 and are included from the ‘Water Resources Survey of Abu Dhabi’ (the Gibb Report, 1970). The values in Table 4.17 indicate a general decline in the volume of falaj discharge over the years, though fluctuations appear to occur in response to exceptionally high rainfall in some years with a slight increase especially in aflaj within the mountain wadis or in their outwash fans. Examples of this are the aflaj at Bithnah, Rafak and Wa’arah.

However, the most pronounced continuous decline has been in the aflaj of the western piedmont plains, which also include the Al Ain region, where the recession in groundwater levels has been particularly pronounced. Elsewhere, where the aflaj are in or near wadi courses, they have suffered in recent years from haphazard pumping from the wadi bed.
alluvium, either tremendously reducing or cutting off falaj water sources, in addition to the disruption of falaj flow by the dislocation of sections of the falaj courses by floods.

In the Northern Emirates, Falaj Dhaid and Falaj Al Mualla had already dried up by 1984 and 1985 respectively, and have had water pumped into them from boreholes since. Falaj Filli, reported in 1979 with a flow of 9 l/sec. or 0.32 MCM/a, had a flow of nearly half that in 1987 (5 l/sec.).

The most marked decline has been in the aflaj of Al Ain where, as noted in the preceding section (4.10.1), the four aflaj of Al Mu'taredh, Al Jimi, Al Muweij'ee and Mazyad were reported by A.P. Gemmel to have dried up and their natural flow had to be substituted from boreholes (1978). By 1980, Falaj Hili and Falaj Al Qattarah had joined the list of the drying aflaj. Only Falaj Da'udi remains with natural flow and, together with half the discharge of Falaj Al Aini, is considered in the present study in the total annual natural falaj discharge. The flow in Falaj Al Aini is artificially supplemented by 50% and thus an equal percentage is considered here as the natural flow. The aflaj of Al Buraimi and Sa'arah still maintain natural flow, although much reduced, and the flow in both aflaj is also becoming increasingly partially augmented (Table 4.18).

<table>
<thead>
<tr>
<th>Year</th>
<th>Falaj Buraimi l/sec.</th>
<th>Falaj Al Buraimi MCM/a</th>
<th>Falaj Sa'arah l/sec.</th>
<th>Falaj Sa'arah MCM/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982</td>
<td>59.83 (2.14)</td>
<td>63.50 (2.28)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1983</td>
<td>58.10 (2.10)</td>
<td>66.20 (2.37)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td>46.70 (1.67)</td>
<td>49.25 (1.77)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>49.40 (1.77)</td>
<td>56.42 (2.20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>36.55 (1.31)</td>
<td>47.35 (1.70)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1987</td>
<td>36.55 (1.31)</td>
<td>47.20 (1.69)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1988</td>
<td>26.30 (0.94)</td>
<td>35.50 (1.27)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Regional Development Council, Oman.

Note: The sharp drop in 1984 marks the start of a 3-year drought period in both Oman and the UAE.

Table: 4.18.

Average annual falaj discharge rates of Falaj Al Buraimi and Falaj Sa'arah in Oman based on several measurements taken during the year (1982-1988).
4.10.3. **Total discharge from the aflaj of the Emirates**

The falaj discharge data, which are prepared by the MAF, consist of total annual flow irrespective of whether it is natural, partially augmented or totally substituted from other sources. Taken at their face value, such data can be misleading. Their presentation in this form indicates that the MAF may be unaware of the real situation of the aflaj. Only in two minor aflaj is a reference made that the flow is from pumped water sources and these are Falaj Shafqa and Falaj Shariyyah (both in the Northern Emirates). Borehole water is pumped into these two aflaj at the outfall where the MAF is also taking falaj flow measurements; hence it is becoming aware of augmentation in these two particular cases. In most cases water is pumped into the falaj through one of the access holes. No notes are attached to the falaj discharge data of the MAF to draw attention to the artificially augmented flows of the aflaj. The augmented flows of the Al Ain aflaj, Falaj Dhaid and Falaj Al Mualla are not indicated, implying they are natural (MAF, Hydrology Report, 1987-88, (unpublished)).

The source of flow in each of the existing aflaj was determined during field investigation of all the sites as well as by discussions with local experts. Falaj flow sustained from external sources is not considered at this point as such an artificial contribution, whether from groundwater (domestic or agricultural boreholes) or recycled water, is considered later in the study, (Chapter 8 and Chapter 10).

Of the springs, that are also arbitrarily called aflaj, only that of Al Wurai'ah is included in the total falaj discharge volume as it is a fresh water source that, though not immediately used by gardens near it, adds to groundwater potential of the alluvium of Wadi Al Wurai'ah (Al Shamah). Its annual discharge is included in Table 4.17 separately at the end, since it is not mentioned at all in the MAF records. The other five are hot springs (such as Madhab and Khatt) of highly mineralized groundwater with low discharge volumes that have only a limited use in health pools but no suitability for drinking or agriculture. Their output is thus not considered in the water balance estimates (Chapter 10), though given in Table 4.17. Also left out from the water balance calculations for the Emirates is the output of Falaj Buraimi and Falaj Sa'arah as both aflaj lie within Oman, although, again, data about their
largely natural flow (only 2-5% is artificially augmented) are also included in Table 4.17.

According to the above clarifications, the mean annual natural flow in all the aflaj of the Emirates, including that from the Wurai'ah Spring, amounts to 13.01 MCM/a, of which 59% (7.65 MCM/a) is from the aflaj of the eastern and southern parts of the mountains of the Northern Emirates, 6% (0.82 MCM/a) from the aflaj of the western piedmont plains, 17% (1.17 MCM/a) from those of Al Ain and 18% (2.37 MCM/a) from the Wurai'ah spring (Table 4.17).

4.11. Synopsis

The key aspect of surface hydrology in an arid country such as the Emirates is runoff. In this chapter an analysis of the national pattern of catchments, a discussion on surface flow measurements and a detailed examination of wadis, have provided the background. The major focus has been on runoff, its main characteristics, the volumes measured and the yields. Finally, runoff channelled by man in a form characteristic of this region, the falaj, has been described and its operation illustrated with detailed examples from Al Ain.
5. HYDROGEOLOGY

5.1. Introduction

Hydrogeology may be defined as the study of groundwater occurrence with emphasis on the geological environment in which groundwater resides. This involves determining the various lithological characteristics of the water-bearing media to understand groundwater movement, whether by natural means in the form of vertical movement (infiltration) or lateral movement (gravitational and mechanical discharge).

Groundwater residence or flow in the lithosphere governs its quality, not only through the mineralogical composition of the lithologies, but also by the degree of its movement in shallow or deep strata. The chemistry of surface and groundwater is treated separately in Chapter 6, while the synthesis in this chapter treats groundwater occurrence in the various aquifer systems, its flow and level fluctuation. The detailed areal treatment in this chapter aims at unravelling the different geological conditions that govern groundwater availability and quality, with the objective of portraying a clear picture of the hydrogeologic environment to understand the complex physical setting of the groundwater resources and aid in the appraisal of their status and management.

Hydrogeological nomenclature is defined so as to comprehend the various values cited in the text that describe aquifer hydraulic characteristics. The aquifer systems of the Emirates are identified and the composition of the material in which they occur is described in detail in order to highlight the geological and chemical anomalies in groundwater occurrence so as to explain groundwater deficiency and underline the confused priorities in its abstraction and use. There exists no countrywide explanatory description of the hydrogeology of every region in the Emirates, and the detailed areal treatment presented in this chapter has been necessitated by the need to produce a
comprehensive appraisal of the water resources of the Emirates. Such
detailed synthesis would help provide a clearer picture of the existing
groundwater resources in relation to the adverse natural and man-made
conditions that limit their availability and usability.

The main hydrogeological units of the Emirates conform with the main
topographical regions. Such hydrogeological units have been recognized
by various previous studies since the Parsons Report (1963), and are
based on the two major mountain and lowland relief provinces discussed
in Chapter 2. The subdivisions into hydrogeological units within these
two major relief provinces may be outlined for the present study as
follows:

A. **Hydrogeological units within the mountain zone** (Fig. 5.1.)

i) The limestone massif of Ru‘us Al Jibal north of the Dibba-Idhn
fault-line.

ii) The Ophiolite block of the central mountains, to the south of the
Dibba-Idhn fault-line.

iii) The ‘melange’ zone of the Hawasina exotics of the Dibba Corridor,
between the two mountain blocks (i) and (ii).

iv) The alluvium-filled wadis within the three highland units (i),
(ii) and (iii).

(The units are marked 1A, 1B and 1C in Fig. 5.1.)

B. **Hydrogeological units within the lowland zone** (Fig. 5.2.)

v) The western piedmont plains (marked as 2 in Fig. 5.1.)

vi) The eastern piedmont plains of the east (Batinah) coast
(marked as 3 in Fig. 5.1.)

vii) The dune sands of the desert foreland
    (marked 4A to 4C in Fig. 5.2.)

viii) The coastal sand dune belt between (vii) and the Gulf littoral
    (marked 5 in Figs. 5.1. and 5.2.)
The hydrogeological zones of the United Arab Emirates:

1A The Hajar limestone aquifer system (marginal to brackish groundwater)
1B The Hawasina metamorphics and volcanics of the Dibba Corridor (fresh groundwater)
1C The serpentinite basic and ultrabasic wadi alluvium and fractured bedrock (fresh groundwater)
2 The western alluvial piedmont plains from Ras Al Khaimah to Al Ain (fresh to brackish groundwater)
3 The eastern alluvial piedmont plains (the east coast embayments) (fresh to brackish groundwater)
4A The desert foreland of the Northern Emirates - low/medium sand dunes (brackish to saline groundwater)
5 The sandy and sabkha coastal zone (brackish to saline groundwater)

Figure: 5.1.

The hydrogeological zones of the United Arab Emirates: (1) The Northern Emirates.
Figure: 5.2.
The hydrogeological zones of the United Arab Emirates:

(2) Western and southern Abu Dhabi Emirate.

- Desert Foreland—low/medium dunes (brackish groundwater)
- Desert Foreland—high/giant dunes (fresh to marginal groundwater)
- Desert Foreland—alternating low dunes and inland sabkhas (brackish to supersaline groundwater)
Of the hydrogeological units listed above, the dune sands of the desert foreland and the alluvium of the piedmont plains and the mountain wadis, contain the most important aquifers with groundwater potential for both domestic and agricultural use. The sand and alluvium aquifers of the desert foreland and the piedmont plains have been heavily exploited in the past two decades; the first for the supply of the large coastal towns of Dubai and Sharjah, the second for agriculture which has expanded enormously since 1972 (see Chapter 8).

The deep carbonate Upper Cretaceous to Upper Tertiary formation aquifers of the Simsima, Um Er Radhmah, Dammam and Sahil hold huge but supersaline groundwater reserves that are used industrially to pressurize oil extraction. On the other hand, the Mid-Permian to Lower-Cretaceous carbonate aquifer system of the Hajar Mountains in the north is yet undeveloped on a large-scale. While the quality of the waters of the piedmont plains and mountains is potable, that of the waters of the formation aquifers and the thick Miocene Fars Formation, which underlies most of the desert foreland in Abu Dhabi to the west and south of Al Ain, is highly saline.

This chapter identifies groundwater occurrence in the Quaternary, Tertiary and pre-Tertiary aquifer systems. It discusses aquifer characteristics using all available data to date with the aim of highlighting the negative natural factors that hamper proper development and management of the groundwater resources. The chapter also discusses groundwater levels and flow. The section on groundwater level fluctuation deals with all the boreholes in the Emirates for which groundwater level records exist presenting hydrographs for wells covering nearly all the hydrogeological areas of the Emirates.

5.2. Definitions of nomenclature of groundwater occurrence, aquifer types and aquifer hydraulic properties

5.2.1. Groundwater in the lithosphere

The main source of groundwater is meteoric water, that is precipitation, or water that has been recently involved in atmospheric circulation. The other source, though of secondary importance, is connate or fossil
water, that is water that has been out of contact with the atmosphere for thousands or even millions of years, and that has not necessarily remained static since the burial of the surrounding rocks but has migrated for many miles (Hydrogeology, Davis and De Wiest, 1966). The meteoric water source includes all replenishable groundwater in the Quaternary aquifers, while the connate water source includes the non-replenishable deep formation aquifers such as the Upper Cretaceous and Tertiary sequences of the Simsima, Um Er Radhmah and Dammam; or those aquifers that have already been reached by deep drilling in various parts of the Emirates, particularly the Tertiary Juweiza aquifers in the piedmont plains. In the last area, the groundwater that is being abstracted from the Pre-Tertiary carbonate, shale and clastics, or from the old conglomerates, for domestic and agricultural purposes alike, is more than 10,000 years old (see "Environmental Isotopes", Chapter 7).

The interstices in the zone of saturation (the aquifer) are filled with water, which is described as phreatic or groundwater. The top of this saturated zone is in effect the water-table. Above the water-table, up to ground surface, is the aeration or vadose zone, where the interstices of the soil particles are occupied by both air and water. This vadose zone is further subdivided into a capillary fringe, immediately above the water-table, an intermediate belt and that of the soil water belt. While water escapes from the soil water belt directly to the atmosphere by evapotranspiration, water is held by capillary action in the capillary fringe. The intermediate belt, on the other hand, occurs only when the water-table sinks far enough to allow a hydraulic continuity between the soil water and that of the capillary fringe.

In places where the water-table is high and is close to the surface, as in most inland sabkhas such as the Liwa troughs, these three subdivisions (of the subsurface above the water-table) do not exist and the whole subsurface horizon becomes saturated with water that is continually escaping directly to the atmosphere by evaporation. The intermediate zone is more pronounced in arid climates where the intervals between recharge events are wide.

The subsurface occurrence of groundwater in the different zones is shown in Fig. 5.3.
The occurrence of groundwater in the lithosphere.

The interstices of the zone of saturation (the aquifer) are filled with water, which is described as phreatic or groundwater. The top of this zone is the water-table. Above the water-table, up to ground surface, is the aeration or vadose zone in which the interstices of the soil are occupied by both air and water. The vadose zone is divided into a capillary fringe, which lies immediately above the saturated zone, an intermediate belt and that of the soil water belt.
Aquifer

An aquifer is a permeable geologic formation (a rock stratum or soil mass) that stores and transmits water that can be readily abstracted in significant quantities. The degree of transmission of water in an aquifer is governed by its permeability or hydraulic conductivity which should be in excess of 0.36 m/h. (8.6 m/d) to be productive. Aquifers are of the following types:

**Unconfined (or water-table) aquifer** (Figs. 5.4 and 5.5 (1))

An unconfined aquifer is a permeable stratum, partly filled with water, and overlying an impermeable layer. It is directly accessible to the atmosphere through the pores or fissures in the permeable material and its upper boundary is formed by a free water-table (or phreatic level) under atmospheric pressure. This water-table serves as the upper surface of the saturated zone. It fluctuates in form depending on a rise due to recharge, or recession due to discharge by gravity drainage or artificial pumpage. Such increase and decrease in the water-table relate to changes in the volume of water in storage in the unconfined aquifer.

A common phenomenon in unconfined aquifers that are made up of fine-grained material, as is the case with aquifers of the desert foreland in the Emirates, is the so-called delayed yield. This happens because gravity drainage of the interstices is not instantaneous and the water is released only sometime after the lowering of the water level. An example of this behaviour of the water-table occurs in the Za’alah wellfield west of Al Ain.

**Confined (artesian) aquifer** (Figs. 5.4 and 5.5 (2))

A confined aquifer is a saturated stratum bounded by an upper and lower impermeable layers. In theory, a confined aquifer is separated from the atmosphere by the upper impermeable layer. However, as a totally impermeable layer (i.e., an absolutely sealing layer) rarely exists in
nature, the confined aquifer is less common than previously envisaged. In reality, confined aquifers are linked to the atmosphere or to other unconfined aquifers through which they are recharged. As the pressure in a confined aquifer is greater than that of the atmosphere, the static water level (SWL), in wells that penetrate such aquifers, stands above the bottom of the upper impermeable confining layer (Fig. 5.5 (2)).

Confined aquifers exhibit minor changes in storage as changes in head in pumping wells result from changes in the pressure within the aquifer rather than in the water the aquifer is storing. Examples of confined aquifers are the Upper Cretaceous and Tertiary supersaline formation aquifers of the Simsima, Um Er Radhmah and the Dammam in central Abu Dhabi; in the Simsima formation that underlies the Quaternary alluvium and Tertiary conglomerates in the syncline between Jabal Fayah and the main mountain block, covered by the Ghareef Plain in the Northern Emirates.

**Semi-confined aquifer** (Fig. 5.5 (3))

A semi-confined aquifer is a fully saturated stratum bounded on top by a semi-permeable stratum and at the bottom by either a semi-permeable or a pervious stratum. The overlying semi-permeable layer has a low permeability yet allowing the vertical movement of water into the underlying main permeable aquifer. As the water level is lowered by pumpage from the main aquifer, vertical seepage from the overlying semi-pervious layer takes place; hence the description of this semi-confined aquifer as a 'leaky aquifer' as well. Examples of such an aquifer are found both in the western piedmont plains and the desert foreland where gravel, sand, silt and clay intercalate.

**Semi-unconfined aquifer** (Fig. 5.5 (4))

A semi-unconfined aquifer is essentially a semi-confined aquifer but where the permeability or hydraulic conductivity of the fine-grained saturated layer of the main aquifer is so great, and the drop in the water-table so pronounced, as to make the aquifer intermediate in characteristics between the traditional semi-confined and the unconfined aquifers. Examples of such aquifers occur within the multi-layered aquifer system in the piedmont plains and the desert foreland.
The different types of aquifers down to the fractured baserock: the perched, unconfined, confined and the fractured baserock zone; the aquiclude, aquitard and the impervious bedrock; the free water-table (the phreatic water level of the unconfined aquifers) and the trapped water level of the confined (artesian) aquifers.
Perched aquifer (Fig. 5.4.)

A perched groundwater body, which can also be described as a lens-shaped perched aquifer, is an unconfined aquifer, mostly of limited extent, and supported by a zone of low permeability. It is 'perched' in the vadose zone above the phreatic water with which it is not hydraulically connected. In many places in the piedmont plains and the desert foreland in the Emirates such aquifers are the first to be encountered during drilling and are mistaken for resourceful continuous unconfined aquifers until they are drained off by pumping within a short time. There can be more than one such perched layers before the water-table of the main unconfined aquifer is reached. The water-table of the perched water body is called the perched water-table.

Aquifer system

This is a heterogeneous succession of interrelated permeable and semipermeable strata of varying thickness that behave regionally as a single water-producing hydraulic unit. It may comprise one or more hydraulically connected main permeable aquifers separated by continuous or discontinuous aquitards yet not affecting the general hydraulic continuity of the system. Examples of such aquifer systems are found in the outwash fans of the western piedmont plains and also within the alluvial fill of some of the large mountain wadis, such as Wadi Al Baseerah on the east coast (Fig. 5.4.).

Aquiclude (Fig. 5.4.)

An aquiclude is a rock layer so impervious as to obstruct the vertical flow of groundwater, although it may itself be saturated with water, and has the ability to confine other permeable water-bearing strata with which it alternates. Aquicludes may have a permeability of less than 0.00086m/d. Shales or clays are aquicludes.

Aquitard (Fig. 5.4.)

An aquitard is a generally impervious and semiconfining stratum that transmits water at a very slow rate in comparison to the permeable
Figure: 5.5. (1-4)

Types of aquifers in water-bearing material other than the fractured base-rock: (1) the unconfined; (2) the confined; (3) the semi-confined; and, (4) the semi-unconfined.

The unconfined aquifer is a water-bearing stratum overlying an impervious layer; the confined (artesian) aquifer is bounded on top and below by impervious layers; the semi-confined aquifer is a fully saturated stratum bounded on top by a semi-pervious layer and at the bottom by either a semi-pervious or a pervious layer; and the semi-unconfined aquifer is essentially a semi-confined aquifer that exhibits the behaviour of both the confined and unconfined aquifers.
Aquifer it is confining. Over a large area of contact with aquifers, it may allow the passage of substantial amounts of water between adjacent aquifers that it may separate; but on the local scale, it may impede such seepage. Clay lenses with thin sandy interbeds, so common in the Quaternary alluvial and aeolian deposits in the piedmont plains and the desert foreland, are examples of aquitards.

The Juweiza flysch (see Chapter 2, and Section 5.3.3.2 in this chapter) and the Lower Fars evaporites, though both have the characteristics of aquitards with thick horizons of clay, shale and marl, function as important groundwater reservoirs in their own merit.

**Aquifuge** (Fig. 5.4.)

An aquifuge is a rock so massive as to contain no interconnected pores; it neither absorbs nor transmits water. Hard granite is an example.

5.2.3. **Hydraulic properties of water-bearing strata:**

Aquifer porosity, permeability, transmissivity and storage

Aquifer hydraulic properties are determined by well pumping tests. To calculate discharge and storage capacity of an aquifer, so as to obtain an accurate hydraulic data-base that would assist in monitoring future aquifer performance, particularly in the case of wellfield development, the parameters of aquifer transmissivity and storage must be determined.

Porosity and permeability of a water-bearing deposit are the two most important factors controlling the residence, distribution and flow of groundwater. They are not necessarily uniform in state and it is not uncommon to find variation in both within 1m. of depth of an aquifer below the surface.

The porosity of a deposit is defined as the percentage of pore space in the total volume of the deposit. It is therefore expressed as a percent by volume. Factors affecting the porosity of a deposit include particle size, shape and mineralogical composition; the degree of sorting, compaction and cementation; and the presence of fines, particularly clay particles. The highest porosities are obtained in deposits with
particles of the same size as in the dune sands in places like Al Hayer and Liwa (refer to infiltration rate tests, Chapter 2, Section 2.4.). The water content of a deposit is directly related to its porosity, but that does not necessarily give an indication of the volume of water that can be tapped from it. As the porosity of a rock is a measure of the interstitial space of the rock, it is expressed as the percentage of the total volume of the rock that contains the interstices (Meinzer, 1959). Table 5.1. gives the standard porosity values for selected rock types that comprise the main water-bearing strata in the Emirates. In general, a porosity value greater than 20% is regarded as high, that between 5-20% is considered medium, and the porosity of less than 5% is considered low.

Transmissivity is defined as the rate at which water is transmitted through a section of aquifer 1m. wide under a unit hydraulic gradient (a hydraulic gradient is the rate of change in total head per unit of distance of flow in a given direction). Transmissivity values are expressed as m³/d/m.

Transmissivity is directly related to aquifer permeability and thickness. Permeability in turn, is defined as the ability of a given rock type to allow the flow of water into or through it without diminishing its structure. The permeability or hydraulic conductivity of a certain water-bearing material is the flow of water through a unit cross-sectional area 1m² of the aquifer material in the prevailing temperature of the water. It is expressed in m/sec. or m/d.

Table 5.6. presents relative values of permeabilities in different rock types including porosity, well-yield and the type of water-bearing units; while Table 5.3. gives a general classification of aquifer types according to ranges of transmissivity coefficients of aquifers of the Emirates based on available data.

The coefficient of storage of an aquifer is defined as the volume of water the aquifer can release or take into storage per unit surface area of the aquifer per unit decline or rise in head normal to that surface. It is a dimensionless quantity. In an artesian (or confined) aquifer, the storage coefficient depends on the elasticity or compressibility of the aquifer material and of the water.
<table>
<thead>
<tr>
<th>Rock type</th>
<th>Porosity Primary (grain)</th>
<th>Porosity Secondary (fracture)*</th>
<th>Permeability (m/s)</th>
<th>Well yields</th>
<th>Type of water-bearing unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$10^0$</td>
<td>$10^{-2}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Sediments, unconsolidated</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel</td>
<td>30-40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse sand</td>
<td>30-40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium to fine sand</td>
<td>25-35</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>40-50</td>
<td>Occasional</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay, till</td>
<td>45-55</td>
<td>Often fissured</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediments, consolidated</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone, dolomite</td>
<td>1-50</td>
<td>Solutions joints</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>bedding planes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse, medium sandstone</td>
<td>&lt; 20</td>
<td>Joints and bedding planes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine sandstone</td>
<td>&lt; 10</td>
<td>Joints and bedding planes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shale, siltstone</td>
<td></td>
<td>Joints and bedding planes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volcanic rocks, e.g. basalt</td>
<td></td>
<td>Joints and bedding planes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plutonic and metamorphic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Rarely exceeds 10%


Figure: 5.6.

The relative permeabilities in the different rock types, including porosity, well-yield and type of the water-bearing rock unit (See Section 5.2.3).
Representative porosity ranges for selected rocks.

In general, a porosity of a rock of more than 20% is considered large, that between 5-20% is considered medium and that below 5% is considered small.

<table>
<thead>
<tr>
<th>Type of material</th>
<th>Specific yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse gravel</td>
<td>13-25</td>
</tr>
<tr>
<td>Medium gravel</td>
<td>17-44</td>
</tr>
<tr>
<td>Fine gravel</td>
<td>13-40</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>18-43</td>
</tr>
<tr>
<td>Medium sand</td>
<td>16-46</td>
</tr>
<tr>
<td>Fine sand</td>
<td>1-46</td>
</tr>
<tr>
<td>Silt</td>
<td>1-39</td>
</tr>
<tr>
<td>Clay</td>
<td>1-18</td>
</tr>
<tr>
<td>Loess</td>
<td>14-22</td>
</tr>
<tr>
<td>Aeolian sand</td>
<td>32-47</td>
</tr>
<tr>
<td>Tuff</td>
<td>2-47</td>
</tr>
<tr>
<td>Sandstone (fine)</td>
<td>2-40</td>
</tr>
<tr>
<td>Sandstone (medium)</td>
<td>12-41</td>
</tr>
<tr>
<td>Siltstone</td>
<td>1-33</td>
</tr>
</tbody>
</table>


Table: 5.2.

Specific yield of important water-bearing rock material.

The capacity of a deposit to yield water is more important than its capacity to hold water. Unconsolidated coarse material yields more water than consolidated finer material.
Table: 5.3.
Classification of the aquifers of the Emirates according to transmissivity ranges and productivity rating.

Aquifers with transmissivities of below 500 m³/d/m are poor: they include most of the aquifers in the Juweiza formation in the piedmont plains. Coastal aquifers in Quaternary deposits exhibit the highest transmissivities (1200-3000 m³/d/m); while those of the 'fossil' aquifers of the deep carbonate formations exhibit the lowest transmissivities (5-60 m³/d/m).
Although there are no rigid limits, the storage coefficients of confined aquifers range from 0.00001 to 0.001. The coefficients of storage of unconfined or water-table aquifers range from 0.02 to 0.30. For aquifers in dune sands, such as in the Al Qafa area north of Liwa, storage coefficients (the term is synonymous in American hydrogeological literature with the term specific yield) may be in the order of 0.1 to 0.2.

**Specific retention, specific yield and specific capacity**

From the point of view of groundwater supply, the capacity of a deposit to yield water is of greater importance than its capacity to store water. Not all the water in the interstices of a saturated layer can be withdrawn by gravity or pumpage; a part of this water is retained in the interstices. The amount of water retained in the aquifer depends on several factors, which include the temperature and mineral composition of groundwater. The amount of water retained also depends on the surface area and the space of the interstices. The surface area of a rock particle is controlled by its size and shape. As an example, a clay particle has a larger surface area than a sand particle by between 5000-10,000 times. As a result, a clay layer has a higher-specific retention capacity than a sandy layer.

Thus, specific retention is defined as the amount of water retained in a water-bearing stratum after water has been withdrawn from that stratum (i.e., aquifer) by gravity or pumpage. It is expressed as a percentage of the total volume of rock occupied by groundwater. Standard specific retention values in unconsolidated material, ranging from coarse sand to boulders, average 5%, while those for sandy clay average 30%.

Specific yield of an aquifer refers to the water yielding capacity by gravity or pumpage, such as when the water-table declines. It is expressed as the ratio of the water, after saturation, that can be drained by gravity or pumpage, to the total volume of the water stored in the aquifer. The values are given as percentages as shown in Table 5.2., which gives examples of estimated specific yield values for different rock material.

Fig. 5.7. presents the relationship between grain size, porosity,
The relationship between grain size, porosity, specific retention and specific yield.

Water-bearing characteristics in aquifer material are controlled by the proportion of available fine sediments which are greater in larger than smaller wadis. Alluvium in mountain wadis or active wadi channels is less compact than alluvium buried deeply in the wedge-like discrete channels beneath the sands of the desert foreland; it thus has larger storage capacity, but this is minimized by the limited vertical and horizontal area of the former than the latter. The amount of water retained in a water-bearing material (aquifer) depends on several factors, which include the temperature and mineral composition of groundwater. The amount of water retained in the deposits also depends on the surface area and space of the interstices. The surface area of a rock particle is controlled by its size and shape. For example, a clay particle has a larger surface area than a sand particle of between 5000 and 10000 times. As a result, a clay layer has a higher specific retention capacity than a sandy layer. Generally, water-bearing material would have porosities of between 5% and 60%, and specific yields from 2% to 40%.
specific retention and specific yield.

Specific capacity is a measure of the productivity of a production well, and is defined as the ratio of the pumping rate in m³/h. and that of the drawdown. Total drawdown in an aquifer is caused by several hydrogeologic and well abstraction conditions, and is expressed by the following equation:

\[ S_T = S + S_{WL} + S_p + S_d + S_b + S_r \]

When:

- \( S_T \) = Total drawdown
- \( S \) = Aquifer loss due to laminar flow of water within the aquifer towards the pump of the well.
- \( S_{WL} \) = Well loss due to the turbulent flow of water through the screen and inside the casing towards the pump.
- \( S_p \) = The partial penetration of the pumped well.
- \( S_d \) = The dewatering of a portion of an aquifer.
- \( S_b \) = The barrier boundaries of an aquifer.
- \( S_r \) = The recharge or input boundaries of an aquifer.

5.2.4. Reliability of pumping test and aquifer characteristic data in the Emirates

As aquifer coefficients or properties can only be determined by accurate and representative well pumping tests, a practice which hardly happens accurately in the Emirates, values relating to some or all of the aquifer properties cited in the present study are the best available from drilling projects that have been executed throughout the country. It ought to be pointed out that data concerning aquifer properties are sparse and are of a localized nature; and the quality of a great number of pumping tests is questionable. The majority of boreholes in the Emirates, both of the private and public sectors, are drilled without pilot wells prior to development and are not pump tested after their development. The main feature of well development is simply to strike groundwater and start pumping out from that source, however short-lived this source may turn out to be. The objectives of a well pumping test include the following:
1) To determine the hydraulic characteristics of an aquifer and the regional pattern of groundwater flow.

2) To investigate the effects of abstraction on the water-table in the aquifer.

Both these objectives require pumping tests for extended periods of time at a constant rate of discharge from the well.

3) To determine the aquifer loss, well loss and the efficiency of the well.

This objective would require a step drawdown pumping test by which the discharge from the well is increased at pre-selected time intervals. The step drawdown test helps to discover the most suitable pumping rate for a particular well.

4) To determine the perennial yield of the well which is done by varying the discharge from the well until the water level becomes steady (this procedure is only practical with aquifers with a short response time, i.e., in confined and semi-confined aquifers that exhibit quick drawdown within a short time of the start of pumping.

According to Kruseman and de Ridder (1970) and Anon (1977), the suggested duration of continuous pumping under average conditions for the different types of aquifers is as follows:

<table>
<thead>
<tr>
<th>Aquifer Type</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confined aquifers</td>
<td>24 hours</td>
</tr>
<tr>
<td>Semi-confined aquifers</td>
<td>15-20 hours</td>
</tr>
<tr>
<td>Unconfined aquifers</td>
<td>72 hours</td>
</tr>
</tbody>
</table>

Research for the present study into the technique and duration of well pumping tests, and related aquifer characteristics, of the Deep Wells Project (1982-86) has resulted with the following observations which are deemed relevant to illustrate the degree of reliability of aquifer data offered by that project (and similar projects):
1) Out of the 63 wells for which data were presented in the Final Report of the Deep Wells Project (IWACO, 1986), only 10 had observation holes drilled close to the test wells (i.e., 15% of the total number of wells). Only with such dual wells can the storage capacity of aquifers be determined.

2) The duration of pumping tests was short, ranging between 4-12 hours. Not a single step drawdown test was conducted for any of the wells.

3) The complex heterogeneous aquifer system of the piedmont plains, which contains all types of aquifers, but mostly that of the unconfined type, was assumed, for convenience, as semi-confined, in the absence of pumping tests of, and results for, the aquifer hydraulic properties of each aquifer.

4) The porosity of the different water-bearing lithologies was neither determined by the standard saturation method (by weighing samples extracted from each rock layer during drilling), nor by an air porosimeter, nor by gamma-gamma logging.(1)

5) As a result of the fragmented and inadequate pumping tests, no calculations were made of the storage capacity of all the aquifers penetrated by the project test wells.

Thus, the limited individual values of aquifer coefficients, that were obtained from several sources, have been used in this chapter to simply give indications of transmissivity, specific capacity and yield, permeability, porosity and storage capacity of the aquifers discussed in this synthesis of the hydrogeology of the Emirates.

(1) Gamma-gamma logging uses a source of gamma rays sent down the drill-hole walls where the rays collide with electrons in the rocks and lose energy. The returning gamma ray is recorded. The low electron density points to low formation density (or high porosity).
5.3. Groundwater occurrence: The aquifer systems of the Emirates

5.3.1. General

Although the aquifers of the Emirates can be described according to stratigraphic units, they are by no means homogeneous in extent, character and properties owing to local and regional geological dislocations by folding and faulting that cause changes in facies. This has resulted in a highly complex lithostratigraphic situation that negates correlation of a water-bearing strata with another one nearby. This fact should be borne in mind all the time as such dislocations are widespread and form a recurring feature in the aquifer system of the Emirates. This is especially true in the aquifers of the piedmont plains and desert foreland, which helps explain the anomalies that are encountered in boreholes within the same small area as will be discussed later in this chapter.

The main aquifer system of the Emirates underlies the piedmont plains to the west and east of the mountains (in the Northern Emirates and Al Ain) and also in the sand dunes of the desert foreland, especially in the area between Falaj Al Mualla and Al Aweer. The main water-bearing strata in the plains vary in dimensions, with some occurring in thick Quaternary deposits and others within the Oligo-Miocene carbonates, flysch (clastics) and anhydrites that underlie the Quaternary in both the piedmont plains and desert foreland. In the narrow embayments of the east coast, the Quaternary deposits are of limited horizontal and vertical extent; the fractured ophiolite bedrock is not far below the surface comprising a 2-4 m. thick zone of limited groundwater potential, though heavily exploited, as in Wadi Ham and its alluvial fan.

The desert foreland to the west and south-west of the western piedmont plains, largely covered by Quaternary deposits that range from gravel to aeolian sand, is underlain by a thick sequence of nearly 1500m. of shales, limestones, dolomites, anhydrites and sandstones of ages spanning from Upper Cretaceous to Upper Miocene. The water-bearing strata are the Quaternary sands and gravels in the Northern Emirates containing groundwater of fresh to marginal quality; and in both the Quaternary and Tertiary (limestone) in Abu Dhabi where the waters are saline to supersaline.
In the northern section of the mountain zone, in the limestone massif of Ru'us Al Jibal, the thick carbonate sequence has high storing and transmissive capabilities, becoming less so towards the west due to a change in facies caused by a major fault that causes the carbonate strata to end abruptly against less permeable clastics and shales.

In the ophiolite central mountain block to the south of the Dibba-Idhn Fault-Line, on the other hand, besides the wadis that traverse this upland block, deep structural fissures and fractured zones in the bedrock are the only places where groundwater occurs. The deep structural fissures can be found on the sides of wadis marking the fringes of structural basins; the fractured zones can be found mostly beneath the alluvial mantle in wadis, alluvial outwash fans and intermontane basins. The Wadi Ham structural fault, the outwash fan and the fractured bedrock, all have medium to high transmissivities.

5.3.2. The aquifer system

The aquifers of the Emirates may broadly be grouped as follows:

A. Pre-Permian to Upper Cretaceous fractured bedrock:

(i) The Semail Ophiolite Suite (Central Mountains).
(ii) The Hawasina metamorphics and volcanics (the Dibba Corridor and the Masfut-Hatta intermontane basin).

B. The Middle Permian to Lower Cretaceous aquifers:

(i) The Hajar (carbonate) aquifer system.

C.1. The Mesozoic Maastrichtian (Upper Cretaceous) aquifer system:

(i) The Simsima (Maastrichtian) deep carbonate aquifer.

C.2. The Tertiary (Palaeocene to Upper Miocene) aquifer system:

1- The deep carbonate aquifers (Palaeocene to Upper Eocene):

i) The Dammam (Middle to Upper Eocene) deep carbonate aquifer
ii) The Um Er Radhmah (Palaeocene to Lower Eocene) deep carbonate aquifer.

2- The Oligo-Miocene Clastics (Lower Fars Formation) aquifer.

3- The old wadi terrace deposits aquifers.

D. The Quaternary alluvial and aeolian aquifer system:

i) The alluvial deposits of the mountain wadis.

ii) The aeolian dune sands of the desert foreland.

iii) The alluvium of the piedmont plains to the east and west of the Oman Mountains.

iv) The coastal aquifers.

The Quaternary alluvium, both in areal extent and accessibility, comprises the main aquifer system of practical importance in terms of groundwater availability and potability. The aquifers that occur in it vary from alluvial and coarse sand deposits, as in the plains and the wadis, to fine sand, as in the western edge of the piedmont plains and the vast desert foreland. Porosities in both deposits are high, with the highest of 30-45% being in the aeolian sands at Al Aweer, Al Hayer and Al Qafa; the last place is in central Abu Dhabi north of Liwa.

Aquifers in the sandstones that underlie the Quaternary to the west and south of Al Ain as far as Sabkhat Matti, occur within indurated material with a substantial clay and silt content. The Oligo-Miocene Lower Fars, most extensive in Abu Dhabi, is a thick sequence of evaporites, anhydrites and halite. Although it contains aquifers, it is a producer of very saline water.

Of importance in some wadis are the old Tertiary terrace deposits which, unlike the recent Quaternary terrace deposits, are well-cemented and less permeable and, as in Wadi Al Baseerah near Dibba, hold near stagnant water bodies.

The Juweiza Formation (Campanian to Maastrichtian), which underlies the Quaternary in extensive areas to the west of the Oman Mountains,
especially in the Northern Emirates, is largely a clayey sequence of the Aruma Group which contains limestone clastics of Lower Jurassic to Lower Cretaceous age held by a shale matrix of Campanian-Maastrichtian age. Although in many places aquifers in this sequence are inseparable from those of the Quaternary above them, and are being heavily exploited in the piedmont plains, they are less productive and contain water of marginal quality.

The limestone Hajar aquifers of Ru'us Al Jibal are as yet undeveloped and are looked upon as the reservoir yet to be attended to. Evidence so far indicates to low permeability of less than 0.09 m/d. for the carbonate rocks, and water is trapped in enlarged bedding planes as evident by the extremely rapid recovery of the dynamic water levels during pumping tests, indicative of water occurrence in limited space (see Section 5.3.2.2.).

The deep carbonate aquifers of the Simsima, Um Er Radhmah and the Dammam have huge but deep reservoirs, their waters are extremely saline (3 to 6 times the salinity of Gulf seawater with 45,000 TDS) and are only tapped by the petroleum companies for oil operations.

Finally, the aquifers of the hardrock fractured zone in the Ophiolite and the Hawasina Metasediments, are of limited potential and are, in places, heavily tapped, as in the Fujairah (Wadi Ham) outwash fan (see Section 5.3.2.1.).

5.3.2.1. The Pre-Permian to Upper Cretaceous fractured bedrock aquifers of the Hawasina Metasediments and the Semail Ophiolite Suite:

In both these bedrock areas groundwater occurs in fissures, some of which are large and are of tectonic origin, and also in the fractured zone forming the topmost part of the bedrock which underlies the Quaternary alluvial mantle. The Hawasina 'melange' (see Chapter 2, Section 2.2.3) is found on a smaller scale in the Masfut-Hatta intermontane basin than in the Dibba Corridor in the north, a zone 20km. wide from north to south, where it comprises volcanic, sedimentary and ophiolite rocks in juxtaposition, with varying degree of textural transformation. The rocks themselves are impermeable, but tectonic
fissures, like the main Dibba-Idhn Fault-Line followed by courses of major wadis, such as Wadi Al Baseerah (Al Shimal), Wadi Al Sidr, Wadi Idhn, Wadi Tuwaiyyain, Wadi Al Fayy and Wadi Al ‘Uyainah, form limited sources of groundwater. This is particularly so in Tayyebah where the wells in the wadi near the village tap brackish groundwater from a tectonic fissure. The quality of the water deteriorates as pumping continues and the water becomes mineralized due to the exhaustion of the limited storage within the fissure. Hence, new sources of potable water have been developed higher up in the ‘Asimah intermontane basin to supply the village of Tayyebah.

There are small intermontane basins, such as that between ‘Asimah and Tayyebah, noted earlier, where both the older Tertiary and recent alluvial deposits hold groundwater of good quality in confined or semi-confined aquifers. A similar situation occurs in Al Mahrazah alluvial basin, an elevated gravel-filled basin from which the Masafi water bottling company taps its water from a twin-layered confined aquifer in Quaternary deposits (Geoconsult: Masafi Mineral Water Co. Groundwater Study, 1988). The aquifer here extends down to the fractured zone in the Semail Ophiolite Suite. The aquifer within the Quaternary alluvium had already been exhausted by 1986 and groundwater was being pumped out of the fractured bedrock zone, which locally exhibited high permeabilities that tended to decrease towards the northwest with the increase of silt. Transmissivity values of the fractured zone range between 60-200m²/d/m and the aquifer storage values range between 0.0032-0.0010, indicating a good unconfined aquifer.

There are many wells belonging to the MEW dotted all over the Dibba Corridor zone but these are not documented and hardly any basic well data exist for them. The two wells (part of the Deep Wells Project, 1982-86) that penetrated the Hawasina fractured bedrock, were wells RK-10 in Wadi Hageel (1985) and MF-1 in Masfut (1983)(Fig. 5.8 A and B) (also refer to Fig. 5.29 for location of the Deep Wells Project wells), both of which turned out to be unproductive. RK-10 encountered the fractured Hawasina bedrock at 57m. from the surface down to its total depth of 500m. The static water level (SWL) was at 38m. below the surface, transmissivity and specific yield were very low and the electric conductivity of the water was 1800 mmhos/cm. (Fig. 5.8. (A)).
Figure: 5.8.

Drill cuttings of the Deep Wells Project wells of: (A) Well RK-10 in Wadi Haqeel in Ras Al Khaimah; and, (B) Well MF-1 in Masfut.

Both deep wells penetrated the fractured bedrock of the Hawasina metasediments. RK-10 (1985) met the fractured Hawasina zone at 57m. below the surface; Well MF-1 met the same fractured zone at 42m. below the surface. The Hawasina fractured bedrock zone in both wells was unproductive despite the total penetration of 500m. (RK-10) and 410m. (MF-1).
Well MF-1 in Masfut, was drilled to 410m. It encountered the Hawasina fractured zone at 42m. the SWL was at 7.4m. beginning within the Quaternary alluvium. Transmissivity was 172m$^3$/d/m and the specific capacity was 5.6m$^3$/d/m. (Fig. 5.8. (B)).

Wells TW-6, TW-10, 3WR0058, and 3WR0064 (Fig. 5.9. A-D) drilled by the Japan International Cooperation Agency (JICA) in Wadi Al Baseerah in 1981 (refer to Fig. 5.28 for location of JICA's wells in Wadi Al Baseerah), penetrated the Hawasina schists, mica and quartz of the fractured zone. TW-10 (Fig. 5.9 (B)), with a total depth of 82m., met the Hawasina metasediments at 59m. The fractured zone of the bedrock contained clay in addition to fine quartz rendering permeability and transmissivity low by comparison to the wadi alluvial terraces (both the old Tertiary and new Quaternary, discussed in Section 5.3.2.5.). The transmissivity of the fractured aquifer was 229m$^3$/d/m. with the well drawing water from an aquifer in both the upper and lower terrace alluvium and also the fractured zone (26m. of saturated zone in the alluvium and about 3m. of fractured bedrock, as seen in Fig. 5.9. (B)).

However, several of JICA's Wadi Al Baseerah wells were drilled into the fractured serpentinite bedrock. In well TW-8 (Fig. 5.10 (B)), the fractured serpentinite zone was encountered at 75m. while in well OW-8, which was close to TW-8 (Fig. 5.10 (A)), the same fractured zone was met at 72m; in BH-13 (about 1.5km. downstream) it was met at 58m. (Fig. 5.10 (C)); in the Cement Plant No. 2 well (Fig.5.11 (A)), the fractured zone lay at 98m. In well 3WR002, on a wadi terrace, the ophiolite fractured base was met at 88m. while, finally, in well 3WR0052 it stood at 72m. below the surface (Fig. 5.11 (B and C)). The fractured ophiolite zone in all the boreholes was not clean but intermixed with greenish blue clay, through the whole horizon, rendering the contribution to discharge small owing to the reduced porosities and transmissivities (all the wells referred to were drilled in 1980).

The Deep Wells Project boreholes GP-3 and GP-13 (Fig. 5.12. (A and B)) at the foothills of the central mountains (in Manama and Tawi Sulailah respectively (1983)) penetrated the Semail ophiolite bedrock but were both unproductive. GP-13, which encountered the fractured bedrock at 96m. below the surface, was dry. On the other hand, a test well drilled in the lower course of Wadi Siji, where it fans out on the piedmont
Drill cuttings of wells drilled by the Japan International Cooperation Agency (JICA) in the Wadi Al Baseerah basin (1981)

The wells penetrated the Hawasina metasediments at levels varying from 59m. to 82m. Transmissivity in the fractured Hawasina bedrock aquifer was 229 m³/d/m, and the water in this zone was in hydraulic connection with the overlying indurated Tertiary wadi terrace alluvium.
Drill cuttings of wells drilled by the Japan International Cooperation Agency (JICA) in the Wadi Al Baseerah basin (1981)

These wells were drilled into the fractured ophiolite bedrock zone, in Wadi Al Baseerah, which varied in depth from 58m. (BH-13) to 75m. (TW-8 and OW-8). The fractured ophiolite bedrock zone was found to contain a high proportion of greenish-grey clay that gave low well-discharge rates.
Drill cuttings of wells drilled by the Japan International Cooperation Agency (JICA) in Wadi Al Baseerah (1981): (A) Well at the Cement Plant No.2; (B) Well 3WR002 and, (C) Well 3WR0052.

The depth of the fractured ophiolite bedrock varied in this middle section of Wadi Al Baseerah from 75m. (Well 3WR0052) to 98m. (in Well Cement Plant No.2). The fractured bedrock was not clean and contained greenish-blue clay rendering the contribution to recharge small because of the reduced porosity.
plains east of Dhaid (drilled for the government of Fujairah), pierced the fractured bedrock at 70m. The main aquifer occurred between 40-70m. in coarse and medium-grained gravels and continued into the fractured zone below, at levels from 69.5m. to 79.5m. below the surface (refer to Fig. 5.20). Transmissivity was 142m$^3$/d/m and the discharge rate was 35m$^3$/h.

Two wells were drilled in Fujairah in the ophiolite fractured bedrock of the Wadi Ham alluvial fan (as part of the Deep Wells Project, 1982-86) and showed high transmissivity values. Wells BHF-11 and BHF-12 (Fig. 5.13 (A and B)) had values of 386m$^3$/d/m. and 1340m$^3$/d/m. for transmissivity and 6.8m$^3$/h/m. and 47m$^3$/h/m. for specific capacity, respectively.

5.3.2.2. The Hajar Carbonate Aquifer

This is the aquifer system in the limestone massif of Ru’us Al Jibal, within the emirate of Ras Al Khaimah, but extending northwards and eastwards into the Omani territory of Mussandam. The mountain block has derived its name from the limestone formations of Ru’us Al Jibal, Elphinstone, Mussandam and Wasia Formations, all of which belong to the Hajar Super Group.

Stratigraphically, limestone predominates in the Hajar sequence although dolomite forms a substantial part. The limestone is occasionally siliceous grading into chert. It is stratified, fossiliferous, hard, compact and non-porous. There are signs suggesting to recrystallization maintaining its fine grain to massive or aphanitic (very fine-grained) character.

The whole sequence may reach several thousand metres thick and spans in age from Permian to Mid-Cretaceous. The sequence shows a general westward thrust with gentle 10° leeward eastern slopes and semi-vertical western slopes. Bedding planes have an E-W trend, having been dislocated by major N-S faults and subordinate E-W ones, which in places caused the reversal of the direction of the bedding planes. Besides tectonic dislocations, there are angular intraformational unconformities (conglomerates and cherts) within the limestone sequences.
Drill cuttings of the Deep Wells Project Wells GP-3 (Manama) and GP-13 (Tawi Suhailah) drilled by Geoconsult (1983).

The two deep wells penetrated the fractured ophiolite bedrock at the western foothills near Manama at depths below ground level varying between 70m. and 96m. In both wells the fractured zone was unproductive. At GP-13 transmissivity was 142m³/d/m and the well-discharge rate was 35m³/h. GP-3 was dry.
Figure: 5.13. (A and B)

Drill cuttings of the Deep Wells Project Wells BHF-11 and BHF-12 in the Wadi Ham outwash fan on the east coast (1984-85).

The fractured ophiolite bedrock was encountered at 42m. below the surface in Well BHF-11 (at Madhab) and at 94m. in Well BHF-12 (to the south of Jabal Al 'Uqaibat) for which the transmissivity values were 386 m³/d/m and 1340 m³/d/m respectively. The latter high value reflected the constricted and steep conditions of the fractured zone at the point where Wadi Ham opens to its outwash fan.
Before discussing the characteristics of the aquifer system in the Hajar carbonate mountain block, reservation must be expressed about the extent of karstification, which was emphasized by both Geoconsult and Iwaco, co-presenters of the Deep Wells Project Report (1982-86). This emphasis is conjectural as very little is known about karstification in the region and no geomorphological studies have been carried out to cast enough light on the subject. The view of the present study regarding karstification is in agreement with the view noted by Electrowatt (Wadi Al Beeh Recharge and Loss Prevention, 1980) and also that noted by the US Beareau of Reclamation (Water Supply Augmentation for the UAE, 1979).

The following factors point out to the limited, if not total lack of, karstification below the land surface in Ru‘us Al Jibal:

i) The N-S major faults along the western flank of the Hajar mountain massif and the minor folds in the block itself run at right angles to the westward groundwater gradient, a factor that does not favour dissolution of the carbonate of the rocks.

ii) The expected result of karstification would be the development of macroporosity that would hamper the hydrogeological pattern by the precipitation of fines that would impede groundwater flow either partially or totally within the limestone strata. No evidence of this exists.

iii) The rocks are resistant to erosion by surface flow and also by dry weathering as is evident from the absence of ravine-like wadis but the presence, instead, of vertical slopes on either side of broad wadis, such as those of Wadis Al Beeh and Naqab. Large blocks become separated by mechanical, rather than disintegrate by chemical, weathering. As a result, there are no cones of scree on the slopes but only large blocks and boulders at the foot of the slopes. Thus, chemical weathering plays a secondary role.

iv) The low runoff coefficient of Wadi Al Beeh (2%) points to active percolation of surface runoff into the thick loose gravelly deposits rather than by an underground karstic drainage system.

v) The fissures, which are in essence enlarged bedding planes, do not seem to penetrate deeper than 5m. from the surface. The widening
of the bedding planes takes place overland by slow mechanical weathering rather than by subterranean processes, groundwater appears to occupy structural bedding planes below the surface as will be discussed later in this section.

vi) The intraformational clayey cherty layers that occur within the limestone strata are so compact as to be impervious, a further hindrance to free percolation and undisturbed chemical reaction.

vii) Both the physical and chemical properties of groundwater within these limestone formations do not encourage widespread chemical dissolution. The high temperature of groundwater (39°C) reduces the effectiveness of chemical reaction of CaCO₃.

viii) Considering the several historical changes in sea level and the effect these might have had on groundwater levels, the part of the limestone rocks standing at present above sea level was once below it. This change would also have applied to the relative position of the groundwater levels at whose level or below it any form of karstification may usually take place. There is, however, no surface or subsurface evidence of large-scale karstification within the limestone formations.

5.3.2.2.1. The characteristics of the Hajar aquifer

The boreholes that penetrated the Hajar carbonate formations were those of the Deep Wells Project (1982-86) and these included the exploration wells: RK-5, RK-6, RK-9, and RK-11 (Fig. 5.14 A-D); RK-15, RK-16 and the production well RK-14 (Fig. 5.15 (A-C)) (also see location map of the Deep Wells Project Fig. 5.29). The last 3 wells were drilled in 1986 in the final stages of the project by Iwaco, the rest were drilled before that during the main phase of the project by Geoconsult (1982-85).

Well RK-5 (1985) (Fig. 5.14 A), in Wadi Sha'am, penetrated first 96m of wadi gravel and sands and encountered the carbonate aquifer of Triassic Lower Mussandam Formation from that level down to its total depth of 315m. In 2 hours of pumping, with a pumping rate of 36m³/h., there was a drawdown of 1.16m. that took subsequently 6 hours to
recover. Permeability was 2.8m/d.; transmissivity was calculated at 288m³/d/m. The quick recovery was thought by Iwaco to be due to hydraulic connection with the upper alluvial aquifer, but it is more likely to be because of water stored in the bedding planes of the limestone which leads to both fast drawdown and recovery.

Well RK-9 (1985) (Fig. 5.14 C), in Wadi Ghaleelah, passed first through 69m. of wadi alluvium and then through the Lower Mussandam Formation from that point down to its total depth of 216m. The SWL stood at 79.7m. below the surface and the discharge rate was 40m³/h. With this discharge rate, for 2 hours of pumping, the drawdown was 1.2m. and the recovery time was 1.5 hours. The thickness of the saturated layer was 133m. and the transmissivity was 253m³/d/m. The permeability was 1.9m/d.

Well RK-11 (1985) (Fig. 5.14 D), in Wadi Al Naqab, encountered the Jurassic Upper Mussandam Formation at 30m. from the surface after passing through wadi alluvium. Thus, from 30m. to 207m. (the total depth of the well) the borehole was in limestone rocks. With a pumping rate of 29m³/h. for a duration of 1 hour, a drawdown of 1.08m. was caused. The pump level was at 55m. depth and the SWL was at 44.50m. below ground level. Recovery took 16 minutes. The specific capacity was 27m³/h/m. and transmissivity 580m³/d/m. After 60 minutes of pumping the electrical conductivity rose from 2200 to 2450mmhos/cm.

Well RK-14 (1985) (Fig. 5.15 A), in Habhab-Khatt, met the limestone rocks of the Lower Cretaceous Upper Mussandam Formation at 24m. from the surface down to the total depth of the well of 321m. SWL stood at 20m. from the surface, the well discharge rate was 110m³/h., specific capacity 67m³/h/m. and transmissivity 2800m³/d/m. The well was drilled at the Hajar limestone foothills.

The Hajar aquifer occurs under the northern piedmont plains of Ras Al Khaimah, but at great depths reaching thousands of metres below the surface and the groundwater it contains is brackish (waters in wells RK-12 and RK-15 had conductivities above 3000mmhos/cm.(1986)). Only in RK-15 (1986) (Fig. 5.15 B) in the Jiri Plain (about 4km. northwest of Idhn) did the Hajar aquifer come relatively close to the surface (150m.). Its waters were plentiful but with electrical conductivities exceeding 3000mmhos/cm. Transmissivity was found to be 140m³/d/m. and
Drill cuttings of the Deep Wells Project Wells—RK-5, RK-6, RK-9 and RK-11 drilled into the Hajar carbonate aquifer of Ras Al Khaimah (all the wells were drilled in 1985).

The total depth of each of the four wells varied from 207m. to 315m. below the surface. All the four wells demonstrated large drawdowns and fast recoveries. In Well RK-11, in Wadi Al Naqab, there was a drawdown of more than 1m. after 1hr. of pumping that took only 16mins. to recover. Transmissivities ranged between 250 and 580m³/d/m.
Drill cuttings of the Deep Wells Project Wells—RK-14, RK-15 and RK-16 drilled in the Hajar carbonate aquifer in Ras Al Khaimah (1985-86)

All the three wells struck water in enlarged bedding planes as was evident from their sharp drawdowns and fast recoveries. In Well RK-16, drilled on the western edge of Wadi Tuwaiyyain (1986), after 11 hours of pumping at a discharge rate of 75m³/h., the drawdown was 7.0m. that took only 7mins. to recover to the level previous to pumping. This clearly demonstrated the occurrence of groundwater within limited spaces such as bedding planes.
the specific capacity was 26m³/h/m.

Nowhere was the effect of storage within the enlarged bedding planes in the carbonate aquifer more pronounced than in Well RK-16 (1986) (Fig. 5.15 (C)) which was drilled at the western edge of Wadi Tuwaiyyain, where groundwater storage was limited to fissures and the fractured bedrock. Specific capacity values were high (more than 10m³/h/m). After 11 hours of pumping at a rate of 75.3 m³/h (during the pumping test carried out on this well (located 7km. north of Idhn)), the drawdown was 7.0m. (the level dropped from 59.0m. to 66.0m.). This then took only 7 minutes to recover to the former level. This clearly demonstrated the occurrence of groundwater within limited spaces (bedding planes).

No information is available on the porosity of the Hajar aquifer. The UNESCO publication 'Guide to hydrology of carbonate rocks' (1985) gave values for porosity in such rocks ranging from 2-14% for poorly to medium fissured limestones. An estimated porosity value of 10% may be considered as a median for the Hajar carbonate aquifer.

5.3.2.3. The Mesozoic (Upper Cretaceous) and the Tertiary (Palaeocene-Eocene) aquifer system.

5.3.2.3.1. The Upper Cretaceous and Tertiary Formation aquifers in the Northern Emirates.

The Miocene Clastics (the Sahil Formation) of Abu Dhabi are represented in the Northern Emirates by the thick Oligo-Miocene deep marine "massive salt" of the Pabdeh shales (Fig. 2.3, Chapter 2). The Gachsaran or Lower Fars Formation, which marked the end phase of filling of the Pabdeh basin, is of the Middle and Late Miocene. It comprises a sequence of halite, anhydrite (with occasional dolomite) and terrigenous clastics. This thick sequence underlies the desert foreland of Abu Dhabi directly affecting the quality of groundwater drawn from its aquifers.

From Upper Cretaceous to Mid-Eocene, the large formation aquifers of the Simsima (Upper Cretaceous), Um Er Radhmah (Upper Palaeocene-Lower Eocene) and Dammam (Middle to Upper Eocene) were laid down. Although limestone outcrops, similar in composition to Um Er Radhmah, Rus and Dammam have been recognized in Um Al Qaiwain (on the periphery of the
The Pabdeh basin, the bulk of these formations is represented by the Pabdeh basinal shales of Upper Cretaceous to Lower Miocene. The deep formation aquifers of the Simsima, UER and the Dammam are of limited occurrence in the Northern Emirates, but are widespread under Abu Dhabi where they have been reasonably documented by the Abu Dhabi Company for Onshore Operations (ADCO).

The Upper Cretaceous formations (Campanian to Lower Maastrichtian) in the Northern Emirates are the Juweiza flysch (Campanian), which replace the Aruma shales of the Fiqa, Halul and Laffan formations of Abu Dhabi; and the Simsima, of the Lower Maastrichtian. From borehole cuttings available from the oil companies operating in the Northern Emirates (shown in Fig. 2.11, Chapter 2), it is clear that the Juweiza formation is thickest in the Mussannad-1 oilfield under Bathat Mussannad, but is very much less so in the Al Ali-2 oilfield on the Um Al Qaiwain coast. The Juweiza Formation is, however, totally absent in Saja’ah-2 and Mu’ayyed-1 oilfields, although the latter is on the same N-S axis as Mussannad-1 oilfield, and is only a few kilometres to the north of it (refer to location map of these oil wells in Fig. 2.10, Chapter 2). This is a clear indication of dislocation due to faulting to the west of the Oman Mountains.

The Pabdeh basinal shales (the equivalent of the UER, Rus and Dammam formations of Abu Dhabi), are represented in the oil wells Mu’ayyed-1 and Saja’ah-2 oilfields. The Juweiza flysch starts at 50m. below the surface in Bathat Mussannad, down to 650m. but in the Al Ali-2 oilfield on the Gulf coast, it is thin (60m.) and lies 190m. below the surface. The Pabdeh under Bathat Mussannad is encountered below 480m. The equivalent of these carbonate formation aquifers of the Northern Emirates occurs at greater depths in central Abu Dhabi as will be shown later in this chapter.

The Oligo-Miocene strata are the massive salt series belonging to the end of the Pabdeh phase and are made up of basinal evaporites that were laid down under supersaline conditions. Above that series was deposited the halite, evaporite and terrigenous clastics sequence, laid down in shallow marine conditions marking the close of the Pabdeh depositional phase, and known collectively as the Fars or Gachsaran formation.
It was reported by the Deep Wells Project (1986) that borehole GP-2 in Falaj Al Mualla (Fig. 5.16), penetrated the Lower Tertiary UER carbonates after passing through 270m. of Juweiza clastics and shales. Only 155m. of UER were penetrated. The UER in the Northern Emirates is made up of dolomites, limestone, marls and clays. GP-2 was the only project well to meet this rock sequence. Fig. 5.16 shows the start of the UER and Rus sequence at 300m. below the surface at Falaj al Mualla; while in the logs of the oil wells (Fig. 2.11, Chapter 2), a few kilometres to the west at Saja’ah and Bathat Mussannad, the UER and Rus Formations, start at 490m. and 530m. from the surface, respectively.

The Dammam aquifer, the nearest to the surface of the deep Tertiary carbonate aquifer series, is lithologically heterogeneous rendering the hydraulic properties of the aquifer very poor. The Juweiza flysch underlies the Quaternary in a large part of the piedmont plains north of Al Madam and in parts of the desert foreland to the west, although the extent of the sequence is greatly disturbed by faulting. Its flysch (clastics) content ranges in age from Lower Jurassic to Lower Cretaceous but its shale matrix is dated as Campanian (Upper cretaceous). The radiolarian, boulder and shale content renders the Juweiza sequence even poorer in transmissivity than the relatively more permeable limestones of the same Upper Cretaceous (Maastrichtian) Simsima. Discharge rates vary from low to medium with the low permeabilities occurring in the vicinity of Al Dhaid.

Wells drilled in the Juweiza aquifer showed varied transmissivity values. The part of the aquifer between Al Madam and Al Dhaid exhibited high transmissivities (during pumping tests of the Deep Wells Project, 1982-86), with the highest values being in the limestone of the Simsima in Mileiha, in Wells GP-11 and GP-6/6A (1983), where the values were 480m$^3$/d/m. and 1166m$^3$/d/m. (average) respectively. The Juweiza in the vicinity of Al Dhaid had transmissivities of less than 30m$^3$/d/m, and specific capacities less than 2m$^3$/h/m. (GP-1/1A, GP-4, (1983)) (Table 5.5).

The high clay content in the Juweiza in the Dhaid area is the cause of these low transmissivity values. Well GP-18 in Wushah (1983), south of Dhaid, was found to be unproductive; so were Wells GP-9 and GP-13 (Table 5.5).

GP-2 was the only deep well to penetrate the Upper Cretaceous Simsima and Lower Tertiary UER carbonate formations after passing through 270m. of the Upper Cretaceous Juweiza clastics and shales. The UER and Rus sequences start at 300m. from the surface at Falaj Al Mualla which, in the oil well logs (Fig. 2.11, Chapter 2), a few km. to the west at Saja'ah and Mussannad, start at 490m. and 530m. respectively.
The storage coefficient of the Juweiza ranges from 0.001 to 0.02, which indicates the semiconfined characteristic of the Juweiza aquifer, a condition confirmed by the drilling and pumping tests for different boreholes on the local scale in the piedmont plains (Table 5.5). On the regional scale, both the Quaternary and the Juweiza behave as a single aquifer system, with water drawn from the latter being of poor quality. The porosity of the Juweiza is estimated to be less than 5%. (Deep Wells Project, 1986).

As noted earlier, only one well pierced the Simsima in the piedmont plains in the Northern Emirates. The formation outcrops off the Oman Mountain front between Al Dhaid and Al Ain in the Fayah-Mileiha-Hafeet anticlines. The well concerned, GP-17 (1983), was drilled on the northwestern flank of Jabal Mileiha. Although the formation has 3 distinct layers: chalky, dolomitic and shaly limestones, the middle dolomitic one, is the relatively best aquifer. The top and bottom layers comprise shales. In addition, the lower layer contains interbeds of evaporites. Generally, the Simsima aquifer system has a poor hydraulic performance.

5.3.2.3.2. The Upper Cretaceous and Tertiary aquifers of Abu Dhabi
(Tables 5.4 and 5.5; Figures 5.17 to 5.19)

5.3.2.3.2.1. General

Most of the data in this synthesis of the deep carbonate aquifers is derived from the two main sources on the subject: "Tertiary and Upper Cretaceous Aquifers of Onshore Abu Dhabi", ADCO (1981); and "Regional Aquifer Simulation (Bu Hasa, Asab and Bab Fields)", Partex, which was contracted by ADCO (1983). The latter source relied principally on the former for its basic data. In addition to these two sources, there are a number of other ADCO studies referred to and cited in the references.

Although the 3 main deep carbonate aquifers of the Simsima (Maastrichtian, Upper Cretaceous age), the Um Er Radhmah (Palaeocene to Eocene) and the Dammam (Eocene), as well as the relatively shallow Sahil Clastics aquifer of the Miocene (Upper Tertiary), contain supersaline waters exceeding Gulf seawater salinity by between 3-5 times, their applicability for purely industrial use in supplying the huge amounts of
water necessary for the injection operations into the oil reservoirs to maintain pressure, is very important. Elsewhere in Saudi Arabia, Bahrain and Qatar, these formation aquifers are in the recharge zone, where they are sources of potable water. In the Emirates, on the other hand, the aquifers happen to be in the deepest section of the regional syncline, or the basin of deposition, where waters accumulate by gravity towards the depocentre (centre of basinal deposition) beneath the oilfields in central Abu Dhabi from upgradient sections of the formations all around.

Despite the unfitness of their waters for human consumption, they are aquifers in their own merit and are shared by the countries of the Arabian Peninsula. Based on the vast extent of their aquifer system and use of their waters by the oil companies, the largest single industrial user of groundwater in the Emirates (63mgd.), they are, therefore, dealt with here to complete the subject of groundwater occurrence and the aquifer system.

The Simsima aquifer is Maastrichtian in age belonging to the Aruma Group and dates from the Upper Cretaceous. The Um Er Radhmah (UER) and Dammam aquifers, on the other hand, belong to the Hasa Group of the Palaeocene and Eocene. The Rus Formation that separates the two aquifers belongs to the latter half of the Lower Eocene.

All the 3 aquifer systems consist largely of massive limestone sequences with dolomites, marls and shales interbedded in the main limestone. There is a general thickening of the strata towards the northeast of Abu Dhabi emirate where the depocentre for both the Simsima and UER underlies the area of the oilfields in central Abu Dhabi (refer to Fig. 5.17 for the location of the oilfields of central Abu Dhabi); while the depocentre for the Dammam underlies the Al Khatm-Al Jarf area to the northeast, coinciding with the depocentre for the overlying shallow Sahil Formation.

Each of the three aquifers has three distinct subunits of which the middle unit in each, the so called 'clean' zone, is the favourable hydraulic unit in porosity and permeability. Of the three systems of aquifers, the UER has relatively the best aquifer properties and contributes most of the 63 mgd. (105 MCM/a.) needed by the oil industry.
5.3.2.3.2.2. The deep carbonate Simsima Formation (Upper Cretaceous) aquifer (Table 5.4; Fig. 5.18 (A))

The Simsima was deposited in transgressive and regressive cycles during the latter (upper) half of the Aruma Group of formations under a shallow marine environment. There are three lithounits within this carbonate sequence:

**Units 1 and 2:**

*The upper and Middle Simsima* consist of dolomites, chalky wackestones \(^1\) forming the main aquifer stratum in the area of Shah oilfield.

**Unit 3:**

*The Lower Simsima* is made up of clean chalk, shaly wackestones with argillaceous limestones.

The whole formation offers good groundwater production potential with the middle unit having the best aquifer properties. The formation is separated from the overlying UER by the lowermost basal shale unit of the latter. The Simsima is thickest (366m.) in the Dhafrah-Falaaha area from where it thins out in all directions until it disappears totally in Manader Arrabbadh. The whole formation is 275m. thick under Bu Hasa, 260m. under Bab and 153m. under Asab oilfields. The thickness of the aquifer is about 183m. to the west of Bu Hasa, 153m. at Bida' Al Hamam-1 oilfields and the average thickness ranges from 130m. at Bu Hasa to 163m. at Asab oilfields (see isopach map, Fig. 5.18 (A)).

Porosity averages 15% in the upper unit and 12-15% in the lower unit in the Bu Hasa - Bab oilfields area, or 21-23% in the Asab-Sahil oilfields area. Porosities for the whole Simsima formation, therefore, range from 6% to 25% but in the middle unit, which has the best aquifer properties, porosity averages 24% under all the oilfields area (Fig. 5.17). Permeability varies from 0.1m/d. to 400m/d. and transmissivity 2m\(^3\)/d/m. to 54m\(^3\)/d/m. (Table 5.4).

---

\(^1\) Mud-supported carbonate rock with more than 10% grains.
Figure: 5.17.

Location of the main onshore oilfields of central Abu Dhabi referred to in the text in relation to the deep Upper Cretaceous-Tertiary carbonate aquifers.

Figure: 5.18. (A and B)

Isopach maps of: (A) the Simsima (Upper Cretaceous); and, 
(B) the Um Er Radhmah (Palaeocene (Lower Tertiary)),
depth carbonate aquifer system of central Abu Dhabi. Both formations are thickest in south-central Abu Dhabi, and both thin out towards the northeast.
The UER Formation is the lower member of the Tertiary Hasa Group. It is made up of four lithounits:

**Unit 1:**
The Upper UER limestone: consists of shaly limestones, wackestones and dolomites with traces of high organic content in its lower horizons.

**Unit 2:**
The Middle UER limestone: consists of limestones, clean packstones\( ^1 \) with grainstones\( ^2 \) and wackestones. Dolomitic cementing binds together streaks of marl in the lower parts of the unit. The whole unit forms the best reservoir of the whole formation.

**Unit 3:**
The Lower UER limestone: consists of dolomitic limestones and wackestones, with pure dolomite quite frequent.

**Unit 4:**
Consists of basal shales and marls forming a good 15-30m. thick seal between UER and the Simsima below it.

The top of the formation is in effect the base of the overlying anhydrite and limestone Rus Formation of the Lower Eocene. The UER Formation is thickest in its depocentre in the area of the oilfields in central Abu Dhabi, in the so-called Falaah Syncline, where it reaches 610m. From this area it gets thinner outwards in all directions. The average overall thickness in central Abu Dhabi is 300-600m.

\(^1\) Grain-supported carbonate rock with mud filling the interstices.

\(^2\) Mud-free carbonate rocks.
### Table 5.4.

Average aquifer characteristics of the deep carbonate formation aquifers of the Simsima, Um Er Radhmah and Dammam (1981-1983).

Of the three deep formation aquifers, the Um Er Radhmah exhibits the best aquifer characteristics in porosity, permeability, transmissivity and productivity; hence it contributes most of the daily requirements of the brine needed for injection into the oilfields to pressurize oil extraction (63 mgd.).

<table>
<thead>
<tr>
<th>Formation aquifer</th>
<th>Dammam</th>
<th>Um Er Radhmah</th>
<th>Simsima</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Characteristics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness (av. in m)</td>
<td>285</td>
<td>518</td>
<td>228</td>
</tr>
<tr>
<td>Porosity range (%)</td>
<td>22-28</td>
<td>22-32</td>
<td>15-25</td>
</tr>
<tr>
<td>Permeability range (m/d)</td>
<td>0.1-380</td>
<td>0.2-45</td>
<td>0.1-400</td>
</tr>
<tr>
<td>Transmissivity range (m³/d/m)</td>
<td>3-22</td>
<td>10-60</td>
<td>3-90</td>
</tr>
<tr>
<td>Productivity range (m³/d)</td>
<td>3-66</td>
<td>5-88</td>
<td>4-21</td>
</tr>
</tbody>
</table>

Regional Aquifer Simulation (Bu Has, Asab and Bab Fields), Partex, 1983.
The basal shales are thickest in the southeast of Abu Dhabi between Shah and Qasyoorah, while the thickness of the formation under the oilfields area is 534m. (Bu Hasa, Asab and Bab). The thickness of the water-bearing part of the formation varies from 220m under Bu Hasa to 260m under Shah and Bab (Fig. 5.17). There is a general deepening of the formation to the northeast (see isopach map Fig 5.18 (B)).

Porosity of the aquifer ranges from 15-35%, with the average being 27% at Bu Hasa, 32% at Bab and 30% at Asab. Permeability varies between 1-5m/d. with occasional permeabilities in isolated lithological sections within the formation of as low as 0.2m/d. and as high at 500m/d. Transmissivity averages 92m³/d/m (Table 5.4).

5.3.2.3.2.4. The deep carbonate Dammam Formation (Middle to Upper Eocene) aquifer (Table 5.4; Fig. 5.19 A).

Deposited in a shallow marine transgressive environment, the Dammam is made up of calcareous shales and argillaceous limestones at the bottom of the sequence, followed by foraminiferal packstones and grainstones (packstones and grainstones with fossilized protozoa) of a shallow environment higher up in the sequence. The top of the formation is a carbonate, often dolomite, sequence interbedded with anhydrite on which rests the Sahil Formation unconformably. The base of the unit is marked by a basal shale layer separating it from the clean limestone and anhydrites of the Rus Formation (Lower Eocene). Lithologically, the Dammam consists of three units:

**Unit 1:**
The *Upper Dammam*: is made up of foraminiferal wackestones, limemudstones, dolomites and anhydrites. The dolomite content is more in the eastern parts of Abu Dhabi, while marl is more in the western parts.

**Unit 2:**
The *lower Dammam*: is shaly with argillaceous limestone in its base followed upwards by a clean light grey fossiliferous chalky packstone with bioclastic interbeds. This unit forms the best aquifer in the Dammam.
Unit 3:
A basal shale unit with marly calcareous streaks.

As seen from the isopach map in Fig. 5.19 (A), the Dammam Formation ranges in thickness from 61m. in western Abu Dhabi to 488m. in Al Khatm (near Al Ain) in the east. Under the oilfields in central Abu Dhabi the thickness is between 244-336m. and the average aquifer thickness is 244m. (in Bu Hasa), 305m. (in Asab) and 336m. (in Sahil). The middle 'clean' stratum, the main aquifer, is estimated to be 122m. thick east of Sahil and Asab as far as Jarn Yafoor, while it is 73-76m. in Bu Hasa, 84-99m. in the Bab and 119-122m. in the Asab oilfields.

Porosities range from 22% to 25% in the area of the oilfields while permeabilities are low except in the vicinity of the Sahil oilfield. Transmissivity average 66m³/d/m. and productivity 7m³-15m³/d. The best porosity in the formation is at Asab (28%), and the lowest at Bu Hasa (24%) with the average porosity for the whole aquifer being 25% (Table 5.4)

5.3.2.3.2.5. The Simsima, UER and Dammam deep aquifer system of the eastern region of Abu Dhabi (Al Ain)

The properties of the three formation aquifers do not differ much in the eastern parts of Abu Dhabi from what has been outlined for the same deep formation aquifers in western Abu Dhabi. The exploration well LW-1 in Liwa (part of the Deep Wells Project), was drilled in the Dammam which was encountered at depths of 413-685m. from the surface. Transmissivity was found to be 10m³/d/m. and the specific capacity 0.4m³/h/m., which coincided with those measurements quoted above for the same aquifer in central Abu Dhabi (ADCO).

Well AA-2, in Mazyad on the eastern flank of the Jabal Hafeet anticline in Al Ain, was also drilled in the Dammam where it had a high clay content, and the well was, therefore, of poor productivity.

315
5.3.2.3.2.6. **The Upper Tertiary (Oligo-Miocene) aquifer system of Abu Dhabi: The 'Sahil Clastics' and Miocene Evaporites (Gachsaran) of the Lower Fars.** (Fig. 5.19 B)

5.3.2.3.2.6.1. **The Oligo-Miocene Sahil Clastics aquifer** (Fig. 5.19 (B))

The Tertiary 'Sahil Clastics' Formation ranges in thickness from 61m. in Al Maghreb in western Abu Dhabi to over 360m. in Al Jarf east of Ras Ghanadha (see isopach map Fig. 5.19 (B)). Lithostratigraphically, the formation has a thick upper layer of medium to coarse, subrounded sand grading downwards into thin, fine marls and subangular sandstone. The sequence is occasionally interbedded with greyish silt and siltstone as well as detritic sandy or silty limestone. The lower half of the sequence contains thick layers of sand with thinly bedded marls, marly shales, sandstones, siltstones and detrital limestone. The base of the Sahil, which separates it from the Dammam, is made up of green, brown and red marls and shale interbeds. The sand beds within the sequence offer the best water-bearing capabilities.

Although the Sahil formation rests unconformably on the Dammam, the marly and shaly lowest beds noted above form an impermeable zone. The Sahil extends all over central Abu Dhabi, but with variation in thickness and lithology. Whereas in Bab and Sahil oilfields (Fig. 5.17), the formation is made up of sand, light coloured sandstones interbedded with marls, shales, siltstones and limestones; in Al Jarf in the north, and in Asab and Shah oilfields area in Liwa in the south, the formation is calcareous, marly and evaporitic comprising chalk, limestone and anhydrite.

The centre of greatest thickness of the formation is around Jarn Yafoor where it attains 270m. but thins out towards Manader Arrabbadh and Um Ez Zemool in the southeast where it is 83m. thick, and also at Huwailah in Liwa to the southwest where it is 78m. thick.

Data relating to the aquifer characteristics of the Sahil formation are rare. Porosity is estimated to be 30% and permeability is deduced, from the unconsolidated nature of the clastics, to be good. Transmissivities of the Sahil aquifer average 2.5m³/d/m.
Isopach maps of: (A) the Dammam (Middle to Upper Eocene); and, (B) the Sahil (Oligo-Miocene).

deep carbonate aquifer system of central Abu Dhabi. Both formations are deepest in northeast Abu Dhabi in Al Jarf region. The Dammam is close to the surface in western Abu Dhabi in Sila', while the Sahil is the Lower Fars evaporites sequence in most of Abu Dhabi.
The waters of the Sahil aquifer have a high sulphate content rendering them incompatible for injection purposes if mingled with waters of the other formation aquifers. The friable sand can cause problems by plugging boreholes. Water salinities (TDS) are in excess of 150,000 (EC 203,000 mmhos/cm.). The waters of ADCO's Sahil Formation shallow wells, which supply the personnel camps, have salinities (TDS) ranging from 6000 to 18000 (EC 8000 to 24000 mmhos/cm.).

5.3.2.3.2.6.2. The Lower Miocene Gachsaran (Lower Fars) Evaporite formation aquifer

The Lower Fars Gachsaran Formation (Early Miocene) in western Abu Dhabi, thickens from 120m. in the western parts of the emirate to more than 850m. in the eastern parts. The sequence was laid down in an enclosed evaporitic basin in onshore Abu Dhabi. There are 3 distinct lithounits:

**Upper unit:**
Interbedded anhydrite, shales and marls with carbonates.

**Middle unit:**
Dolomite and limestone.

**Lower unit:**
Predominantly anhydrite with some dolomite and terrigenous clastics.

This predominantly anhydrite and shale sequence underlies the Quaternary alluvial and aeolian deposits in nearly the whole of Abu Dhabi, and in many areas it occurs close to the surface. The existing sabkha beds, where anhydrites are being actively laid down, form the topmost surficial sections of the sequence.

Transmissivities are either too high for the parts of the aquifer with a high sand or unconsolidated clastic content (50-200m²/d.), or too low for the parts of the aquifer with a high shale and marl content (10-15m²/d.). As a result, well discharge rates vary from 10m³/h. to 50m³/h., which was the range found during well discharge tests of boreholes carried out for this study in the desert foreland (for forestry wells drawing groundwater from this Lower Fars aquifer, 1988).
Specific capacity values ranged from 1-2m$^3$/h/m. in Al Za'alah wellfield south of Al Sad in Al Ain where wells were drilled in this aquifer (Al Za'alah Water Project Report, German Water Engineers, 1979).

5.3.2.4. The Quaternary alluvial and aeolian aquifer system

5.3.2.4.1. The Quaternary alluvial and aeolian aquifer system of the western piedmont plains and the desert foreland

The areal extent of the Quaternary deposits and the aquifers they contain make them the dominant aquifer system in the Emirates in terms of groundwater volume and quality for domestic and agricultural use. The deposits not only underlie the plains to the east and west of the mountain divide, but also fill wadi channels extending as discrete wedge-like aquifer systems under the sands of the desert foreland as far as the Gulf coast. The high permeability of the deposits in these wedge-like buried channels govern groundwater flow and quality, allowing inflow of fresh water into the desert foreland where groundwater is otherwise brackish or saline.

The Quaternary is the alluvial mantle formed under fluvial conditions by the deposition of boulders, gravel and sand by wadi floods, in wadi courses or in piedmont plains formed at the mountain front; the latter by the coalescence of detrital outwash fans. In the piedmont (also called 'gravel' or 'central') plains, these coalesced outwash fans form a zone 15km. at its widest. They are made up of wadi bed conglomerates, sands, silt and other fines, all of which are renewable with each successive flood. The changing braided wadi courses, caused by each flash flood, have resulted in a complex distribution of deposits of individual horizons in the soil that are difficult to correlate in horizontal and vertical occurrence. The gravels are generally well-cemented by a carbonate matrix, as in the Jiri Plain in Ras Al Khaimah.

The thickness of the alluvial deposits of the plains increases southwards where it ranges from 50m. in Tawi Jaheeli to 90m. in Tawi Assa'adi. In the Ghareef Plain, south of Filli, the composition of the detrital material is a polymict calcareous gravel with some marl
averaging 40-50m. in thickness.

Close to the foothills, there is variation in the composition of the deposits between the northern and the southern parts of the piedmont plains that lie within the Northern Emirates. The Quaternary deposits near Khatt in the north are composed of subangular and subrounded carbonate gravels with a sandy clay matrix; while around Manama, Siji and Tawi Suhailah, in the southern part of the piedmont plains, they are made up of gabbroic ophiolite gravel.

Except for the water it holds in the piedmont plains, in the dune sands in parts of the desert foreland in the Northern Emirates, and also in Al Qafa area north of Liwa in central Abu Dhabi, most of the water in the desert foreland is brackish to saline in quality. The latter is due to the Miocene Lower Fars Formation, made up of gypsum, evaporites and marls, which underlies the Quaternary deposits in the whole region to the west and south of Al Ain (Section 5.3.2.3.2.6.2.). Both the highly permeable Quaternary and the less so Miocene Lower Fars are hydraulically connected and form one aquifer in many localities; hence the contamination of groundwater resident in the Quaternary by the underlying gypsum and evaporite constituents of the Miocene Lower Fars.

Productivity of the Quaternary aquifer in many parts of the piedmont plains, especially in the part north of Al Dhaid, is low as can be seen in Wells GP-1, GP-2, GP-3 and GP-4 (Table 5.5). In Um Ghafah, in the southern Al Jaww Plain (in the Al Ain region), the specific capacity of Well AA-3A (1983) (Deep Wells Project well in Al Ain not included in Table 5.5) was found to be less than 0.2m³/h/m. (Deep Wells Project, Final Report, Geoconsult, 1985).

No exact measurements of porosity of the aquifers in the piedmont plains exist, but only tentative estimates made by previous studies giving porosity values of 10-20% for the aquifers in the northern part of the plains north of Dhaid (Mar‘ee, 1978), and 8% for the aquifers in the southern part of the plains in Al Jaww Plain in Al Ain (Brandt, Al Ain 2000 Master Plan, 1985). An average of 15% porosity value for the whole piedmont plains was suggested by the Deep Wells Project (1982-86).

In Al Badea‘-Al Aweer wellfields of the dune sands of the desert
Table: 5.5.

The hydraulic properties of the aquifers in the piedmont plains as given by the Deep Wells Project (1985).

Productivity in the Quaternary alluvial aquifer in many parts of the piedmont plains, especially to the north of Al Dhaid, is low as seen for wells GP-1, GP-2, GP-3 and GP-4. Transmissivities are high in the northern parts of the piedmont plains around Digdaga-Hamraniyah-Seih Al Fahlain, where they are generally above 700m³/d/m, while in the western margins of the piedmont plains in Falaj Al Mualla they range from 20-220m³/d/m. Discharge rates are all low because the wells are in the clayey Juweiza formation, except for wells GP-6 and GP-11 in Mileiha and Fayah which draw water mostly from the Maastrichtian limestone of the Ghareef geosyncline.
foreland, the most productive wellfields in the past three decades, the Quaternary aeolian sands are the dominant water-bearing deposits attaining thicknesses exceeding 90m. (at Al Aweer). Although the sands form the larger proportion of the deposits, they also contain marine silts, sandy silts, sabkha deposits of clay silt and silty sand, fine gravel lenses, formed either by the deflation action on dune sands or deposited by flash floods, and also silty sands of aeolian source. The material is uncompacted, with only irregular cementing by patches with a weak iron and carbonate matrix. This whole sequence overlies immediately the Tertiary sequence of boulder beds, dolomitic limestone and chert ending at the bottom with the Maastrichtian limestone (either the Simsima limestone or the Juweiza flysch), which rests directly on the Semail Ophiolite baserock.

The zone of saturation varies from 4m. to 40m. under Al Aweer and slightly less under Al Badea', with an overall average saturated thickness of 25-30m. for the whole aquifer. Transmissivities vary from 211m³/d/m. to 812m³/d/m., with the average transmissivity in a 25m-thick saturated zone in Al Aweer being 650m³/d/m. Permeability values range from 5.26m³/d/m. to 10.63m³/d/m. giving a well-yield of between 28m³-41m³/h. (Wellfield Services, Development of Water Resources in the Emirate of Dubai, 1976). Mean transmissivity values in various parts of the piedmont plains and desert foreland of the Northern Emirates are given in Table 5.6.

As seen in Table 5.6, transmissivity is high in the northern parts of the piedmont plains around Digdaga-Hamraniyyah-Seih Al Fahlain where the values are generally above 700m³/d/m. The aquifers in these parts of the plains are so heavily exploited for both domestic and agricultural purposes that an extensive depression cone has developed in the aquifer in the Al Hamraniyyah area.

Transmissivity values in the alluvial aquifer in Al Dhaid area range between 250m³-1000m³/d/m. In the western fringes of the piedmont plains, around Falaj Al Mualla, the full transmissivity range of between 20m³-2208m³/d/m. is exhibited indicating great variation in lithologies in this part of the plains (Table 5.6).

In the southern parts of the piedmont plains (within the Northern
### Table 5.6.

**Transmissivity and permeability values of aquifers in important groundwater abstraction locations in the piedmont plains and the desert foreland.**

Excluding the questionable exaggerated values of Seih Al Fahlain, high transmissivity and permeability values appear to be in wells in locations in predominantly alluvial aquifers in the piedmont plains, such as Al Hamraniyyah, Mileiha and Falaj Al Mualla; or those in the aquifers of the dune sands but also underlain by alluvial deposits, such as Al Wuhoosh, Al Badea' and Sirrah in the desert foreland.

<table>
<thead>
<tr>
<th>Location</th>
<th>Transmissivity $m^3/d/m$</th>
<th>Permeability $m^3/d/m$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Mean</td>
</tr>
<tr>
<td><strong>PIEDMONT PLAINS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seih Al Fahlain</td>
<td>3182-19865</td>
<td>7748</td>
</tr>
<tr>
<td>Al Hamraniyyah</td>
<td>622- 3019</td>
<td>1878</td>
</tr>
<tr>
<td>Al Manama</td>
<td>NA</td>
<td>61</td>
</tr>
<tr>
<td>Mileiha</td>
<td>235-2305</td>
<td>951</td>
</tr>
<tr>
<td>Falaj Al Mualla</td>
<td>20-2208</td>
<td>794</td>
</tr>
<tr>
<td><strong>DEESERT FORELAND</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Aweer</td>
<td>213- 770</td>
<td>411</td>
</tr>
<tr>
<td>Al Wuhoosh</td>
<td>406- 873</td>
<td>691</td>
</tr>
<tr>
<td>Al Badea'</td>
<td>741-2683</td>
<td>1193</td>
</tr>
<tr>
<td>Sirrah</td>
<td>NA</td>
<td>4760</td>
</tr>
<tr>
<td>Lamhah</td>
<td>46- 100</td>
<td>72</td>
</tr>
</tbody>
</table>

Source: Deep Wells Project(1986), Wellfields Services(1976) and various drilling reports from local water departments.
in the Mileiha-Fayah area, transmissivity is relatively lower with a range of between 235m$^3$-2305m$^3$/d/m (Mileiha, Table 5.6). Transmissivity values in the part of the aquifer to the east of the Jabal Fayah groundwater 'barrier' are higher than those for the part of the aquifer immediately to the west of the Jabal, but in either case they are normally below 250m$^3$/d/m.

There is also variation in transmissivity between Aweer-Wuhoosh in Dubai and Badea' in Sharjah in the desert foreland of the Northern Emirates, though both these groups of wellfields are situated on the same SE-NW trending wedge-like aquifer and are less than 15km. apart. In Al Aweer-Wuhoosh wellfields transmissivity values range between 200m$^3$-900m$^3$/d/m., with an average of between 400-700m$^3$/d/m.; while at Al Badea' they range from 700m$^3$-2700m$^3$/d/m., with an average of 1193m$^3$/d/m. (Table 5.6.).

In parts of the desert foreland with a thick aeolian cover, there is usually a twin-layered aquifer system. The first occurs in the gravels that underlie the dunes; the second, within the thick dune sands. The latter water-bearing unit is made up of a complex interbedded succession of well-sorted aeolian sand with occasional lagoonal silt and clay. At Al Wuhoosh, the gravels are highly permeable, whereas at Marghum they are cemented and are relatively less permeable (both localities are in the desert foreland of Dubai). Fine-grain sand leads to flood retention and causes delayed yields and drawdown when water is pumped out of the aquifer. The transmissivity at Marghum in Dubai averages 350m$^3$/d/m., which is nearly half that in Al Wuhoosh.

5.3.2.4.2. Hydrogeology and aquifer system of the western piedmont plains

The aquifers of the western piedmont plains are the most exploited in the Emirates. The plains are also the first region in the country where depletion of parts of the Quaternary and Tertiary aquifers has taken place. Despite recent drillings by the oil companies operating in the Northern Emirates, and also by the Deep Wells Project (1982-86), both of which attempted to describe in general terms the geological sequences the boreholes penetrated, the hydrogeology of the plains is still far from clear. However, these drillings revealed the presence of a
Quaternary alluvial mantle of varying thickness, depending on the underlying pre-Quaternary subsurface configuration, and ranging from 6-18m. in Al Manama and Dhaid and up to 50m. in Mileiha and the Wadi Siji outwash fan. Underlying the Quaternary in the eastern and central parts of the western piedmont plains are either Upper Cretaceous carbonate series or Upper Cretaceous shales and clastics of the Juweiza flysch (Maastrichtian) series. Underlying the Quaternary and aeolian cover in the western parts of the piedmont plains and in large parts of the desert foreland, is the Lower Miocene Fars evaporites (Gachsaran), followed underneath by the Upper Cretaceous clayey Juweiza flysch.

The Quaternary alluvial and aeolian aquifer system is the most extensive in the Emirates. The Quaternary deposits themselves are not homogenous as they are interbedded with clay and silt layers, varying in thickness from a few centimetres to more than 25m. In addition to this vertical variation in lithology, there is horizontal variation as well. This is clearly illustrated in the drill cuttings of the two Siji wells (Figure 5.20). The two wells (drilled by German Water Engineers for the Government of Fujairah, 1978) were only 700m. apart, yet Well No. 1 reached the ophiolites bedrock at 70m. depth from the surface; while Well No. 2A, despite the greater depth of 131m., it did not reach the ophiolite base but penetrated Upper Cretaceous limestone. Both wells were located about 8km. west of the ophiolites mountain block. The well logs show the vertical variation in lithology with silt and clay bands of 10-30m. thickness interbedding the outwash fan alluvium.

The SWL stood at between 16-17m. below the surface and the saturated zone, in the different strata, was down to the bedrock (1978). The main aquifer, however, lay in a gravel and coarse sand layer, below the clay and silt, in both wells. The saturated zone in Well No. 1 was 42m., 6m. of which were in the fractured ophiolite bedrock; while the saturated zone in Well No. 2 was 40m., 25m. of which were in the Upper Cretaceous Simsima limestone.

Besides the silt layers, there were intercalations of siliceous cementing which caused low permeabilities and gave reduced well discharge rates. Transmissivities in the main gravel and sand aquifer were found to range from 170m$^3$/d/m. to 350m$^3$/d/m. which is typical of aquifers within a mixed gravel, sand and silt strata. The storage
Drill cuttings of two wells (700m. apart) drilled for the Fujairah Government in the Wadi Siji outwash fan on the western foothills (1978).

The drill cuttings clearly show the heterogeneous hydrogeological situation in the Quaternary alluvium close to the ophiolite foothill recharge zone. Both cuttings illustrate the vertical variation in the lithology. Well No. 1 reached the ophiolite bedrock at 70m.; Well No. 2A did not reach the bedrock even at the total penetration of 131m. The recurring silt and clay intercalations are of 10-20m. thickness. Well No. 2A penetrated the Upper Cretaceous limestone. The saturated layer occurred in all the lithologies: gravel, sand, clay and silt, and finally in fractured ophiolite or limestone bedrock. The presence of clay and silt was responsible for the reduced permeabilities. Transmissivities ranged from 170m³/d/m to 350m³/d/m, typical of aquifers within a mixed gravel, sand and silt strata.
coefficient was below 0.05 which was made so by the substantial clay and silt interbedding, the siliceous cementing and the calcareous material in the water-bearing alluvial strata of the Wadi Siji outwash fan.

Well GP-14 (1983) (Deep Wells Project) was drilled 2km. closer to the mountain front than the two Fujairah Government wells 1 and 2. It penetrated 42m. of Quaternary gravel, sand and silt followed by the shales and clastics of the Juweiza Formation. The SWL stood at 17m. similar to the other two wells noted above. Transmissivity was 230m³/d/m. and the specific capacity was 6.2m³/d (that for the two Fujairah wells was 3.46m³/d) (Fig. 5.21).

Below the heterogeneous Quaternary deposits, the water-bearing strata in the compact Tertiary conglomerates (the Oligo-Miocene evaporites and the Maastrichtian shales and clastics of the Juweiza), are equally diversified, with clay and shale being the common component occurring with varying concentration. The Juweiza Formation is the dominant sequence underlying the Quaternary alluvium in the piedmont plains, while the Oligo-Miocene evaporites sequence is the dominant sequence that underlies the Quaternary alluvial and aeolian deposits in the western fringes of the plains and the whole of the desert foreland further west. In either case the saturated zone continues from the Quaternary alluvium into either underlying sequence.

Wherever the top layers of the Fars Formation contain a substantial proportion of sand, they appear to share with the overlying Quaternary alluvium some of its aquifer characteristics. Transmissivity in the shaly Juweiza under the plains ranges from over 200m³/d/m. in the vicinity of the Ghareef Plain, where the formation is underlain by the Upper Cretaceous carbonates, to between 100-200m³/d/m. in the vicinity of Al Dhaid, to the very low transmissivities of below 10m³/d/m. in the area north of Al Dhaid. Well GP-18 (1985) at Wushah (Table 5.5) exhibited a low transmissivity of below 5m³/d/m; and Well GP-19 at Falaj Al Mualla was totally dry (1986).

The hydrogeology of the piedmont plains is varied and is complicated further by faulting. The aquifer system appears, therefore, to be a continuous multi-aquifer system down to the base rock, whether this latter be a fractured ophiolite bedrock or a limestone one, as long as

This well was drilled 2km. closer to the ophiolite mountain foothills than the two Siji wells; it is thus about 6km. from the foothills and is separated from the two Fujairah wells (Fig. 5.21) by 6km. The well penetrated Quaternary gravel, sand and silt and also the Tertiary shales and clastics of the Juweiza formation. The aquifer lay mostly in the indurated Juweiza deposits; hence the transmissivity averaged 230m³/d/m.
all the strata are saturated from the SWL in the lower part of the Quaternary deposits downwards. The variation in storage capacity is governed by the proportion of clay and silt present in a particular sequence. While the Quaternary on the top of the series of strata may have a porosity of up to 10%, the Juweiza under the plains exhibits porosity values, from tentative pumping tests, of between 0.001 and 0.02%, pointing to the semi-confined characteristics of the aquifer (Deep Wells Project, 1982-86). As such, the saturated zone in all the strata appears hydraulically connected, and as most of this saturated zone is contained in the clayey strata of the Juweiza or the evaporites, the low to medium permeabilities and discharge rates of these two sequences appear to dominate the aquifer characteristics. The drill cuttings of selected wells of the Deep Wells Project presented in this chapter, although general and oversimplified, help illustrate the heterogeneity of the water-bearing strata that underlie the piedmont plains.

5.3.2.4.3. The Quaternary alluvial-aeolian and the Tertiary Miocene evaporites aquifer systems of Abu Dhabi

5.3.2.4.3.1. General

As the potable and marginal waters of the Quaternary alluvial and aeolian deposits in Abu Dhabi practically 'float' over the more saline waters of the Tertiary Miocene Lower Fars evaporites, with groundwater in either aquifer system in a delicate balance, the two aquifers may be regarded as hydraulically connected. Boreholes are so intensively developed in both the eastern and western regions of Abu Dhabi that a large proportion of them pierces all lithologies in both aquifer systems. As such, data of aquifer characteristics obtained from well pump tests may relate to both groundwater systems. The evaporites of the Lower Fars underlie the whole area within the emirate of Abu Dhabi to the west and south of Al Ain. While potable groundwater occurs in alluvial deposits in localities close to the mountains or in discrete alluvial channels extending westwards beneath the dune sands, such occurrence of potable groundwater is only limited to dune sand aquifers that cover the sabkha base, which in essence is the upper section of the evaporites sequence.
The two aquifer systems are, therefore, treated together in the ensuing sections for eastern and western Abu Dhabi. Such treatment, apart from being necessary because of the close relationship of the two aquifer systems, helps emphasize the unfavourable hydrogeological conditions: limited potable groundwater reserves in highly transmissive Quaternary strata, and opulent brackish to saline groundwater reserves in less transmissive shale and evaporite strata. Stratification of groundwater salinity is a common feature in both the eastern (Al Ain) and the western regions of Abu Dhabi (Chapter 6, Section 6.5.2.4). Overpumping from the Quaternary aquifer leads to salinization of the ever decreasing fresh groundwater reserves and also the attraction of denser and more saline water from the underlying evaporites sequence.

5.3.2.4.3.2. The Quaternary alluvial-aeolian and the Tertiary Lower Fars evaporites aquifer system of the Al Ain region

The Quaternary alluvial aquifer in the Al Ain region occurs in Al Jaww Plain and along the eastern foothills of the Oman Mountains in Ghashabah and Al Awha and further north in Al Shuwaib within UAE territory, where the alluvial deposits are covered by sand. It is also thought to occur within two discrete wedge-like wadi channels extending westwards to Al Khadher and Al Sad (A. Gibb, Water Resources Survey of Abu Dhabi, 1970).

Although the presence of clay layers in the Quaternary alluvium, in the region to the west of Jabal Hafeet, gives the aquifer the characteristics of a confined one, it is generally an unconfined (water-table) aquifer. In the Al Jaww Plain, to the east and southeast of Al Ain town, the alluvial aquifer is thinnest, especially in the vicinity of Malaqet near the Zarub Gab, but gets steadily thicker towards the north, west and south, where the thickness of the deposits averages 60m. The alluvium here is composed of coarse sand, pebbles and gravel with argillaceous limestone intercalations. The gravels are either rounded or subangular fragments of ophiolite, microgabbros and spillites of the Hawasina and Semail Ophiolite groups.

Two main wadi flow channels control the bulk of replenishment to the groundwater system in Al Jaww Plain. These are the channels followed by Wadis Shik and Al Ain emanating from the Zarub Gap in the north; and Wadis Hamad and Muraikhat emanating from the Ajran Gap in the south. The
deposits of these flow channels consist of carbonate-cemented ophiolite gravels and boulders. In the vicinity of Tawi Hamad Bin Jawwal, the fractured upper layer of the Upper Eocene limestone of the Dammam Formation lies at 300m. from the surface. Transmissivities in the water-bearing deposits of the wadi channels varies from moderate to high: in the Zarub Gap in Oman transmissivities are 3000-4000m$^3$/d/m (Results of drilling in Zarub Gap, Buraimi Region, Oman, by Nick Saines and Ansari, 1985), while at Hamad Bin Jawwal on the active channel of Wadi Al Ain, 9km. from the Zarub Gap, transmissivities are between 1000-2000m$^3$/d/m. The high transmissivities in the wadi channels are reflected in the low electrical conductivities which vary from 300-500mmhos/cm.

Nearer Al Ain, in the northwestern extremity of Al Jaww Plain, intercalated fossiliferous Oligocene limestone and marls block westward groundwater movement causing underground ponding in the water-bearing strata and, therefore, transmissivities are drastically reduced as in the Sarug district in the southeastern outskirts of Al Ain where transmissivities average 0.4m$^3$/d/m only.

At Mazyad, in the extreme southwest of Al Jaww Plain, the Quaternary deposits reach 100m. in thickness but the aquifer they contain is heterogeneous in composition consisting, besides gravels and sands, of conglomeratic limestone and clay interstratified with pure clay layers, with the latter assuming thicknesses of more than 3m. This naturally leads to reduced transmissivities. The availability of aquifers with water-bearing properties in the Al Ain region, varying with depth, was given by Gibb in 1970 (Water Resources Survey of Abu Dhabi) as shown in Table 5.7.

<table>
<thead>
<tr>
<th>Depth in m.</th>
<th>% of the aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20</td>
<td>10</td>
</tr>
<tr>
<td>20-40</td>
<td>18</td>
</tr>
<tr>
<td>40-60</td>
<td>44</td>
</tr>
<tr>
<td>60-80</td>
<td>31</td>
</tr>
<tr>
<td>80-100</td>
<td>30</td>
</tr>
</tbody>
</table>


Table: 5.7.

Variation with depth of strata thickness with water-bearing properties in Al Jaww Plain in Al Ain.
In the intermediate area between the northern recharge channel emanating from the Zarub Gap (represented by Wadis Shik and Al Ain) and the southern channel emanating from the Ajran Gap (represented by Wadis Hamad and Muraikhat) transmissivities are low, as in the vicinity of Tawi Mowafa in Al Niadat where the values are around 55m$^3$/d/m. and where also the groundwater salinities are high (1800-5000mmhos/cm).

In a zone of very permeable aquifer material between Al Hilli and Al Qattarah in the Al Ain vicinity, which is practically the continuation of the alluvial Zarub Gap flow channel, where the Quaternary gravels and sands are more than 100m. thick, the constituents of the water-bearing strata are conglomerates, limestone fragments and silt, holding an aquifer 5-10m. thick. Another limestone aquifer of poor permeability underlies the former zone separated from the Quaternary aquifer above it by a 5-10m. thick clay aquiclude. Transmissivities under Al Qattarah are 700-900m$^3$/d/m. in the Quaternary but are much reduced in the underlying limestone aquifer (3-34m$^3$/d/m in Mu’taredh and Bida’ Bint Saud).

The highly permeable wadi channel deposits are absent in the western parts of the Al Ain environs (in Al Mu’taredh and Al Muweij’ee) and the Oligo-Miocene limestones and clays interstratify nearer the surface giving extremely low transmissivities. Similarly under the northeastern parts of the town, in Al Hilli, the aquifer is hardly 10m. thick (1988) and is totally in conglomeratic limestone and gravel. Jabal Al Awha acts as an underground barrier, similar to Jabal Hafeet in the south and Jabal Fayah in the north, leading to groundwater ponding and choking of interstices with clay and silt, resulting in the salinization of the resident water, as is the case in Al Awha where the groundwater conductivities are 2000-3000mmhos/cm.

To the west of Al Ain, in Al Sad, Busamrah, Seih Al Miyah and Al Za’alah, limestones and clays are frequently present within the thick Quaternary aquifer deposits grading into the Miocene Lower Fars evaporites sequence proper, which under this area reaches 500m. in thickness. The heterogeneity of the lithology in the Quaternary has given the aquifer in it the low transmissivities, which range in the aforementioned four western localities from 100m$^3$ to 150m$^3$/d/m.

In Busamrah the water-bearing strata of the shallow aquifer is totally
in the upper fractured zone of the Eocene Dammam limestone with the SWL standing at 30-40m. below the surface. It was reported by the Water Resources Survey (Gibb, 1970) that the water-bearing horizon made up only 27% of the strata below the water-table. In Al Mu’taredh in Al Ain, and the area to the west and southwest of it, the aquifer is widely anisotropic (aquifer properties varying with direction) in characteristics that variation may be detected in wells only a few metres from each other. In Al Mu’taredh and Seih Bin Ammar, transmissivities can be as low as 20m$^3$/d/m. or as high as 210m$^3$/d/m., which are still within the low transmissivity range.

In Al Sad and Busamrah the aquifer that lies within the dune sands down to 25m. from the surface is the most productive. Below this dune sand aquifer immediately is a 20m. clayey aquitard, as is shown in Fig. 5.23 that presents borehole cuttings for Al Maqam, Seih Al Miyah, Seih Bin Ammar, Al Wagn and Al Markhaniyyah (compiled from information contained in the records of the Groundwater Department of Al Ain).

The wells of the old Al Za‘alah wellfield near Al Sulaimat (1979-80) were drilled in inland sabkhas or seihs between elongated sand dunes. The deposits in these seihs consist of evaporites containing carbonates and gypsum and also lenses of clay. These deposits are pervious with an infiltration rate of 1m/h. (Al Za‘alah Wellfield Report, German Water Engineers (GWE), 1980). As seen from the drill cuttings for all the wells of the old Al Za‘alah wellfield (Fig. 5.22), the stratigraphy is more complicated than that of Al Jaww plain. The broad sequence is made up of a succession of gravel and sand and lenses of clay followed by clay, soft white or red marl, then white chalk and limestone and finally sandy gravel and limestone. The sequence cannot be correlated in the various boreholes owing to the variation in thickness and depth of the different horizons, their discontinuous extent and their lens-shaped patchy occurrence.

Down to about 30m. from the surface is a layer of loose sand, which recurs frequently below 45m. from the surface. At a level of between 60-75m. below the surface clay predominates. This clay marly aquiclude does not form as continuous an aquifer base in these western areas of Al Ain as does the clay under the alluvium of the wellfields in the northern dune areas north of Al Ain. The aquiclude here is not of a
Drill cuttings of boreholes of the old Al Za’alah Wellfield, west of Al Ain (1980).

The drill cuttings illustrate the complicated stratigraphy in Seih Za’alah characterized by a succession of gravel, sand and lenses of clay, followed by clay, soft white or red marl, then white chalk and limestone and finally sandy gravel and limestone. The sequences cannot be correlated in the various boreholes owing to variation in thickness and depth of the different horizons, their discontinuous extent or lense-shaped patchy occurrence.
homogeneous character but can contain clay, marl, marly sand or marly limestones. It does not exist in all the boreholes but can only be matched in occurrence in a few of them. (Fig. 5.22).

The presence of carbonate cementing in the top Quaternary gravel and sand tends to give the strata rocky characteristics in addition to reducing their porosity and, with the already semi-permeable underlying fractured limestone zone and the alternating layers of porous sand and impermeable clay, leads to differential aquifer response. Such lithological heterogeneity allows the layers immediately below the water-table to exhibit the behaviour or response of a semi-confined or unconfined (water-table) aquifer.

With the semi-permeable marly clay lithologies, the aquifer exhibits the delayed yield behaviour during pumping (explained in Section 5.2.2.). This clay and marl layer is the aquiclude of the aquifer at Al Za‘alah. Permeable layers occur below this aquiclude indicating a water-bearing potential that was reached and has since been pumped out without adherence to the recommended safe yield during wellfield development and initial pump tests at the recommended rate of abstraction of 400-500 m$^3$/d (Al Za‘alah Water Project Report, GWE, 1980).

Transmissivity values range from 15 m$^3$/d to 200 m$^3$/d/m. The varied lithological setting gives rise to poor correlation between transmissivity and depth. However, the deeper boreholes that were drilled at Al Za‘alah to nearly 100 m below the top of the saturated zone indicated transmissivities lower than 60 m$^3$/d/m. on a localized scale. The water withdrawn from this depth was saline and the well discharge rates were lower than 8 m$^3$/h. per well (1980). Well discharge rates generally ranged from 18 to 47 m$^3$/h. with the average being 20 m$^3$/h. The specific capacity ranged from 0.61 m$^3$/h/m. to 15 m$^3$/h/m., with the median being between 1-2 m$^3$/h/m. The storage coefficient was estimated as 0.12.

The feature of well loss, quite common in wells drilled in the Miocene evaporites sequence, such as at Al Za‘alah and Seih Bin Ammar and Seih Al Miyah, is more an aquifer characteristic than a well drilling phenomenon effected by the rotary drilling process normally used in these areas. It is indicative of turbulent groundwater flow within the
aquifer. Wells in Al Sad, drilled with the cable-tool percussion method of drilling, which often resulted in the nominal flow disturbance of groundwater in the aquifer, also confirmed the low well-discharge efficiency to be due to the overall aquifer performance.

Deterioration, both in well efficiency and the quality of groundwater that is being drawn from the deeper aquifers by pumping in excess of safe yields, has resulted in a rapid worsening of groundwater salinities by more than 8-fold within two years (Chapter 6; Sections 6.5.2.4.3. and 6.5.2.4.4.). This has led to abandoning both the deep and deepened original boreholes in the old Za‘alah well field (which had reached depths of over 330m.) to higher levels in the shallow aquifer above. This is perhaps the only well field in the Emirates where the reverse action of withdrawal to shallower (higher) levels, after having tapped the lower deeper levels, has taken place.

In the region to the west of Jabal Hafeet, as far as the Al Ain-Abu Dhabi highway, groundwater lies in shallow depths close to the surface and transmissivities are quite low, ranging from 60m$^3$ to 100m$^3$/d/m; hence the extremely high salinities (EC 15,000 mmhos/cm. west of Ain Sakhinah). Groundwater occurs at different depths below 50m. under artesian conditions and, being confined, transmissivities are very low (below 30m$^3$/d/m.) and the groundwater is more saline than the brackish waters in the overlying unconfined alluvial aquifer. An interface separates the two groundwater bodies: that of the unconfined shallower aquifer (with ECs ranging from 3000-5000mmhos/cm.), and that of the confined highly saline deeper water (with ECs of +7000mmhos/cm.). This interface gets closer to the surface in the vicinity of Seih Bin Ammar where the lower more saline waters are encountered at depths of less than 50m. below the surface.

The Miocene Lower Fars gypsiferous aquitard is very close to the surface in large areas to the west of Al Ain. Its thickness varies from 1m. to nearly 12m. near the Zarub Gap in the eastern end of Al Jaww Plain. The gypsiferous clays of the Lower Fars are basinal deposits found on both sides of the Hafeet anticline; they are close to the surface in the east but are deeper in the west. There are, however, lenses or pockets of such evaporite deposits at various levels in the whole region. In Sa‘ah, in the vicinity of the Zarub Gap, the Lower Fars evaporites are only
20m. below the surface; while in Kashoonah, further north, the sequence occurs at 50m. below the surface, but within the water-bearing strata. At Al Jimi, within the Al Ain environs, the evaporites are 20m. below the surface. At Mazyad, in the southwestern part of Al Jaww, the evaporites are encountered at 200m. depth.

The gypsum aquitard has been studied from various drill cuttings and has been found to occur at different depths in the desert foreland of Abu Dhabi. In a deep well at Al Maqam (1300m.), Groundwater Department, 1985) this gypsum aquitard occurs as thin lenses starting from 20m., but as a thick layer on its own, or associated with marl and clay, at depths below 100m. from the surface. At Al Wagn (80km. south of Al Ain) the gypsum aquitard is usually found at 130m. and is part of the 500m. thick Oligo-Miocene sequence consisting of sands, gravels, gypsum, marls, evaporites, halite, shales and clays (Fig. 5.23).

Transmissivities of the gypsum are extremely low and vary between 20 and 30m³/d/m. The associated salinities, as indicated by the electrical conductivities of the groundwaters, vary in Al Jaww from 1000mmhos/cm. in the northwest to 6000mmhos/cm. in the centre, and to more than 9000mmhos/cm. east of Mazyad in the southeast.

The lower salinities in the northwest of Al Jaww are due to hydraulic connection, by lateral leakage, between the gypsum aquitard and the overlying Quaternary aquifer. This is particularly so in the lines of recharge (the wadi channels) where occasional input of fresh water helps dilute the concentrated salts in the strata. The very high salinities of the southern part of Al Jaww, on the other hand, are due to the occurrence of the gypsum aquitard in a confined state with extremely low transmissivities and, therefore, groundwater flow. The low well discharge rates of about 14m³/h. confirm the semi-pervious lithology of the gypsum aquitard.
Figure: 5.23.

Drill cuttings of selected wells in the Al Ain region.

The drill cuttings show the varied lithologies in the water-bearing strata to the west of Al Ain. The recurring alternation of gypsum, clay, shale and marl with sand, gravel and sandstone cause reduced permeabilities and longer groundwater residence in the salty strata.
Groundwater in Al Jarf, Al Dhafrah, Bida’ Zayed, Bida’ Rashed, Al Helew, Bujair, Bida’ Khalfan, Bu Hasa and Qurun Al Na’am, in the heart of the desert foreland of central Abu Dhabi, occurs in shallow Quaternary dune sand, and in Miocene evaporites of the Lower Fars, aquifers. The most productive and better quality water wells are those situated in the thick aeolian sands overlying the sabkha base. As overpumping takes place, saline water from the underlying evaporites and gypsum beds, is drawn up. Water quality may vary from potable in the sands (EC 1000-2000mmhos/cm.) to brackish and very saline in the sabkha (EC + 7000mmhos/cm.). Transmissivities in these central parts are low, ranging between 70-110m³/d/m., though in some cases they can even be as low as 40m³/d/m.

In Abu Assalf (north of Al Khatm) groundwater is pumped from levels of between 12-15m. from the sand dune aquifer. Sand dunes in Al Khatm are nearly 30m. thick, but in Bu Hasa and Liwa, further south, they may exceed 100m. (see Chapter 2, Section 2.2). The dune sands rest on the Miocene clastics, evaporites and clays, which are of low transmissivities, with groundwater in them in near stagnant condition and so acquiring high salinities (in Abu Assalf, the EC is 12,000-26,000mmhos/cm.).

In Bida’ Zayed, the SWL is between 20-40m. below ground level and the saturated zone is sandwiched between an upper sand and clay zone (0-25m.) and a lower zone of clastics, evaporites and clay of great thickness. There is hydraulic interchange between all the three layers as indicated by the high salinities in places such as Al Nakheel in Bida’ Zayed (EC, 9000-10,000mmhos/cm.), the New Gardens No. 101 (EC, 11,000mmhos/cm.) and the Defence Camp (EC, 9,000mmhos/cm.). In Bida’ Saif, on the other hand, the aquifer is totally in aeolian dune sands at levels of between 25-30m. below ground level; hence, transmissivities are relatively higher with values averaging 250m³/d/m. and the water conductivities are between 2000-3000mmhos/cm.
In northern Al Dhafrah, the water-bearing strata is also a sand layer 25m. thick sandwiched between two gypsum layers as shown below:

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>Gypsum</td>
</tr>
<tr>
<td>15-21</td>
<td>Sand</td>
</tr>
<tr>
<td>21-39</td>
<td>Red Sand</td>
</tr>
<tr>
<td>39-41</td>
<td>Gypsum</td>
</tr>
</tbody>
</table>

In some areas in Al Dhafrah, the sand cover can be as thick as 60m. but poor drainage or overpumping, leads to a deterioration in water quality. Such a situation is repeated all over central Abu Dhabi as at Bida' Zayed and Madinat Mohammed. Groundwater salinities are equally high in these areas (6000-12000mmhos/cm.).

In Wadi Al Riyoom, the top sand aquifer has already been exhausted of its water and the existing water-bearing strata are below 50m. in red sand and clay with the better producing aquifer occurring in a 30m. thick saturated layer in white/red sand and clay. In boreholes tapping groundwater from strata with less clay content, and therefore having relatively higher transmissivities (averaging 250m$^3$/d/m.), the EC of the water is between 2000-4000mmhos/cm.). In other boreholes, in strata with higher clay content and poor groundwater flow, the ECs are above 5000mmhos/cm. (Forestry wells of the Forestry and Agriculture sections of Abu Dhabi Municipality).

Again, in Bida' Al 'Areedh, the top white sand is dry (0-30m.) while the saturated layer lies between 30-50m. in red sand and is underlain by a clay aquiclude about 10m. thick. This aquiclude may have been an old sabkha bed of fine silt and clay. Transmissivities average 80-120m$^3$/d/m.

North of Bu Hasa, still in these central parts of the desert foreland of Abu Dhabi, the clay can be as thick as 10-20m. and the SWL is deeper than 40m. The high water conductivities, reaching 20,000mmhos/cm. in Bida' Al 'Areedh, can only be the result of hydraulic connection with waters in the clay and evaporite layers. Transmissivities are thought to be low but no actual data on them exist.
In Ghumaisah, clay is near the surface and the overlying sand cover is not thick. Clay is encountered at 18m. depth, followed by white and red sand. Water conductivities in the new wells range between 3000-4000mmhos/cm. and in the older wells they may reach 12,000mmhos/cm.

The aquifer in Qurun Al Na'am shows similar characteristics to the aquifer in Bida' Al 'Arreedh, both in lithological composition and quality of the water. Water salinities increase towards the north, west and northwest with a similar increase in the clay and gypsum content in the water-bearing strata.

In Bida' Al Matawa'ah and Ghayathy clay dominates the water-bearing horizons, in some places forming the deposits from the surface downwards. Transmissivities can be as low as 20m$^3$/d/m. and the water-table stands at 20m. from the surface. The high clay content retards groundwater movement; hence the high water conductivities of between 9000-15,000mmhos/cm.

5.3.2.4.3.4. The sand dune aquifer in Asab, Bu Hasa, Shah and Liwa

In Asab, there are at least 30m. of water-saturated sands. The dune aquifer is between the SWL and the top level of the underlying impermeable sabkha aquitard. The SWL stands at 24m. below ground level and the average total depth of the wells is 55m. The aquifer is within Quaternary aeolian fine- to medium-grained sands with silt and clay intercalations representing old sabkha beds. Below this sandy aquifer is a sequence of cemented sand, silt, clay and carbonates representing the Oligo-Miocene clastics of the Sahil and the Lower Fars evaporites of the Gachsaran (Figure 5.24). The high clay and silt content, compaction and cementation of the deposits are responsible for the low transmissivity, high specific capacity and low specific yield values due to a gentle drawdown in comparison to a moderately high well discharge rate of between 22m$^3$ and 63m$^3$/h. per well. Table 5.8. presents values for some of the Asab shallow aquifer characteristics.

In Bu Hasa the 'fresh' water of the thick dune sand aquifer practically floats over the highly saline and, therefore, denser waters of the
The Quaternary aeolian and Tertiary Lower Fars evaporites aquifer in Asab in the desert foreland of central Abu Dhabi.

In Asab, there are at least 30m. of water-saturated sands. The dune aquifer is between the SWL and the top level of the underlying impermeable sabkha aquitard. The SWL stands at 24m. below ground level and the average total depth of the wells is 55m. The aquifer is within Quaternary aeolian fine- to medium-grained sands with silt and clay intercalations representing old sabkha beds. Below this sandy aquifer is a sequence of cemented sand, silt, clay and carbonates representing the Oligo-Miocene clastics of the Sahil and the Lower Fars evaporites of the Gachsaran. The high clay and silt content, compaction and cementation of the deposits are responsible for the low transmissivity, high specific capacity and low specific yield values due to a gentle drawdown in comparison to a moderately high well discharge rate of between 22-63m³/h. per well.
Oligo-Miocene sabkha evaporites, clay, marl and gypsum that underlie the Quaternary aeolian deposits. No data on aquifer characteristics are available except for the well discharge rates that range from 18m$^3$ to 25m$^3$/h.

The sand cover in Bu Hasa may reach 100m. in thickness, and this explains the better quality groundwater obtained from these sands. The shallow aeolian Quaternary aquifer water wells in this area have relatively better quality waters than those of the other domestic water wells of the remaining oilfields of central Abu Dhabi (TDS range for Bu Hasa waters is 1000-7000 ppm.; that for the other wells in Asab, Bab, Sahil and Shah oilfields, is 3500-135,000 ppm., with the worst groundwater salinities occurring in the waters of Bab and Shah water wells). Groundwater salinity, however, increases within a short time of the start of pumping a new well (4-8 weeks), mostly due to saline water being drawn from the sabkha underneath.

In Shah, in Al Bateen of Liwa, the 6 ADCO water wells have been drilled in sand dunes to a maximum depth of 80m. each. The SWL stands between 15-59m. pointing to perched, confined or semiconfined groundwater occurrence where clay interbeds play a major role in this differential groundwater level situation. Below the 80m. level lie the Miocene evaporites and any deeper drilling would definitely abstract very saline water. Transmissivity and discharge rates of the aquifer are poor. The former range from 0.8m$^3$ to 41.0m$^3$/d/m.; the latter average 75m$^3$/d., although for the majority of wells the average discharge rate is 44m$^3$/d. These values put the aquifer here in the low range of aquifer transmissive capacity (Table 5.9).

The relatively higher transmissivities of the Asab aquifer are responsible for the lower water salinities than those of the lower transmissivities and higher water salinities of the Shah aquifer. The range of water salinities (TDS) in Asab and Shah aquifers are 2300-4400 and 15000-83000 respectively.

In Liwa, groundwater occurs close to the surface. In many places ditches are dug to expose pools of brackish to very saline water from which water is pumped to nearby gardens. Waters at or close to the surface are more saline than waters a few metres below the surface because of the
The characteristics of the shallow Asab aquifer in southern Abu Dhabi.

The clay and silt content and the compaction of the water-bearing strata are responsible for the low transmissivity, high specific capacity and low specific yield values due to a gentle drawdown in comparison to a moderately high well discharge rate range of 22-62 m³/d.

<table>
<thead>
<tr>
<th>Well</th>
<th>Transmissivity m³/d/m</th>
<th>Specific yield</th>
<th>Specific capacity m³/d/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NA</td>
<td>11</td>
<td>31.5</td>
</tr>
<tr>
<td>2</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>3</td>
<td>19.4</td>
<td>16</td>
<td>21.8</td>
</tr>
<tr>
<td>4</td>
<td>15.2</td>
<td>13</td>
<td>25.8</td>
</tr>
<tr>
<td>5</td>
<td>41.6</td>
<td>8</td>
<td>46.5</td>
</tr>
<tr>
<td>6</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>7</td>
<td>22.2</td>
<td>9.8</td>
<td>36.9</td>
</tr>
<tr>
<td>8</td>
<td>69.3</td>
<td>5.9</td>
<td>62.6</td>
</tr>
</tbody>
</table>

Source: Asab Water Wells Report, ADCO, 1987

Table: 5.8.

The characteristics of the Shah shallow aquifer.

The low transmissivity values indicate high clay, silt and anhydrite content (sabkha deposits) in the Shah aquifer. The average well discharge rate for all the wells is 75 m³/d, but for the majority of the wells the discharge rate is 44 m³/d.

<table>
<thead>
<tr>
<th>Well</th>
<th>Transmissivity m³/d/m</th>
<th>Constant discharge m³/d</th>
<th>SWL (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>28.1</td>
<td>163.6</td>
<td>56.2</td>
</tr>
<tr>
<td>7</td>
<td>4.9</td>
<td>33.6</td>
<td>58.1</td>
</tr>
<tr>
<td>8</td>
<td>2.2</td>
<td>98.4</td>
<td>52.2</td>
</tr>
<tr>
<td>9</td>
<td>2.8</td>
<td>55.2</td>
<td>44.6</td>
</tr>
<tr>
<td>10</td>
<td>0.8</td>
<td>14.4</td>
<td>15.3</td>
</tr>
<tr>
<td>11</td>
<td>2.2</td>
<td>33.6</td>
<td>56.0</td>
</tr>
<tr>
<td>12</td>
<td>2.5</td>
<td>7.2</td>
<td>58.7</td>
</tr>
<tr>
<td>13</td>
<td>36.3</td>
<td>229.0</td>
<td>56.0</td>
</tr>
<tr>
<td>14</td>
<td>40.8</td>
<td>91.2</td>
<td>53.7</td>
</tr>
<tr>
<td>15</td>
<td>1.6</td>
<td>19.2</td>
<td>57.4</td>
</tr>
</tbody>
</table>

Source: Shah Field Area Shallow Aquifers, Al Mardhi, ADCO, 1988

Table: 5.9.
concentration of salts by evaporation. Alternations of aeolian sands and clay (and also other sabkha fines) occur down to more than 100m. from the surface. In nearly all cases, the water-bearing stratum is a white sand-clay layer about 7-10m. thick.

Transmissivities are very low compared with those noted earlier for the Shah water wells some of which are located within the Liwa oases. The high content of clay and silt within the aquifer material, give transmissivity values lower than 1m$^3$/d/m. but near the base of the slip face of the high dunes transmissivity values may vary from 2m$^3$ to 25m$^3$/d/m.

The water-bearing strata in Liwa tend to occur as thin perched aquifers, which, as was observed in the oasis of Um Al Rudoom in Liwa, may alternate in several layers in close succession. In the case of the Um Al Rudoom example (Fig. 5.25), these alternating layers were observed exposed in a hand-dug well (2.0m. wide and 7.0m. deep), that cut through 4 'perched' water-bearing layers separated by 3 thin impervious clay layers. The water was observed cascading down the wall of the well above each clay aquiclude (Fig. 5.25.).

Water at a level of 2.3m. (the uppermost seepage) was found to have an EC of 20,000mmhos/cm. while water seeping at a level of 4.33m. (the third seepage level) had an EC of 8,000 mmhos/cm. Limited as they are in vertical and horizontal occurrence, the sand aquifers are mined at all levels. The wells of the Forestry and Agriculture sections of Abu Dhabi Municipality in the whole central Abu Dhabi region, draw water from shallower levels of between 5-15m. within the sands. The ECs of these waters range from 3000-14000mmhos/cm. The private wells in this area, and those belonging to ADCO, are deeper with average individual total depth of the wells ranging from 35m. to 50m. Wherever the penetrated horizons consist of alternating sand and clay, the water quality in these wells is similar to that quoted for the forestry wells; but where the gypsum and evaporites of the Miocene are penetrated, salinities can be extremely high, exceeding 20,000mmhos/cm.

In the far southeastern corner of the Emirates, in the sands of Rub' Al Khali within UAE territory (east of Um Ez Zemool), apart from the samples collected for chemical analysis and direct EC measurements
Figure: 5.25.

Multi-layered perched aquifers in Um Al Rudoom oasis in Western Liwa.

The water was observed cascading down the wall of the well above each clay aquiclude.
conducted for this study, the only other limited hydrogeological information is contained in a 'restricted' internal memorandum of the then Abu Dhabi Petroleum Company reporting a field visit to the area in 1969 (Visit to Party 19, Southeast Abu Dhabi, D.C. Harding, Engineering Department, Abu Dhabi Petroleum Company, 19/4/1969).

The memorandum described 16 boreholes that had been drilled in the three types of terrains that exist in the area (the Qasyoorah-Um Ez Zemool area): the sand dunes, the sabkha and the Miocene limestone and evaporites. The sabkha was the shallowest aquifer of the three in which the water levels varied between 3m and 10m. with all the wells in it producing saline water. Out of the 9 wells drilled in the sand dunes (usually in the lower part of the slip face of the dune), only 2 had potable water at depths of 6-12m. from the surface of the dune. The wells of the Miocene aquifer were deeper (12-16m.), but the quality of the water was brackish to saline.

The lowest discharge rates (as measured in 1969), were from wells in the sabkha aquifer (2.83m$^3$/h.) and the highest were in the limestone aquifer (4.5m$^3$/h.); while the discharge rates from the sand dune aquifer were slightly lower than the limestone aquifer (4.0m$^3$/h.). This latter discharge rate matched with the rate obtained by well discharge measurement, for the present study, by filling a 44-gallon barrel repeatedly until a steady filling time was maintained. It took 3 minutes to fill the barrel at a rate of 1.0 l/sec. or 3.6m$^3$/h. (as measured for the present study at Qasyoorah on 14/3/1988).

5.3.2.5. The alluvial aquifers of the mountain wadis and intermontane basins

5.3.2.5.1. The alluvial aquifers of the mountain wadis

Apart from the aquifers of the limestone rocks of Ru'us Al Jibal, the most important aquifer system within the mountain zone is that contained in the alluvium of wadi flood plains and wadi terraces, in both the limestone mountain zone to the north of the Dibba-Idhn Line and the Ophiolite zone to the south of it.

Mountain wadis vary in size from the small wadis, such as Wadis Sha'am
and Ghaleelah, to the large wadis, such as Wadis Al Beeh, Ham, Al Qawr and Al Baseerah. The alluvial fill in these wadis ranges in age from Tertiary to Recent conglomerates, gravels and sands. The thicker sediments are those of the Quaternary (dating from the Pleistocene), that overlie the older Tertiary wadi terrace deposits or the hard baserock.

The older Tertiary wadi terrace deposits are compact and well-cemented and have poor permeability. Present day wadis have been cutting into these older deposits since the Pleistocene, spreading their floors with materials from both these older terraces as well as recent material currently being washed down from the surrounding highlands. Within both the older (Tertiary) and the younger (Quaternary/Recent) deposits, are thin beds of calcrite of CaCO₃ and silica that help withhold water above a dry zone in the strata (perched water).

The older Tertiary deposits are darker, while the Recent deposits are lighter, in colour. They form the alluvial mantle of the flood plains on which flow the braided courses of wadis. The contact zone between the lower compact terrace conglomerates and the overlying less compact recent alluvium, as well as the contact zone between either deposit and the ophiolite baserock, are points of seepage in the central mountains. In the Hajar Mountains to the north, on the other hand, there is hydraulic continuity between the overlying wadi gravels and the underlying fissured limestone, where the bulk of the saturated zone is embodied.

The material of the wadi alluvial infill is identical in all the wadis, and the only broad difference is whether the main component of this infill is of an ophiolite (in the case of wadis in the central mountains) or a limestone (in the case of wadis in the Hajar Mountains of Ru‘us Al Jibal), source. The description of the aquifer holding material in this section uses information obtained from drill cuttings of the Deep Wells Project (MAF-Geoconsult-Iwaco, 1982-1986) and those of the Wadi Al Baseerah Water Resources Survey (JICA, 1981).
5.3.2.5.1.1. **The alluvial aquifers of the wadis of the northern limestone mountains of Ru‘us Al Jibal**

As seen in the drill cutting for Well RK-5 in Wadi Sha‘am (Fig. 5.14 (A)), the Quaternary alluvium is 96m. thick despite the small size of the wadi basin and the fact that the well was drilled in the middle course of the wadi. The SWL stood in 1985 (the year the well was drilled) at 55m. below the surface or 41m. above the contact zone with the Triassic Lower Mussandam limestone. After a drawdown of 0.92m. in 2 hours of pumping at a rate of 26m$^3$/h., recovery of the water-table to its position at the start of pumping took only 1.5 hours. Transmissivity was given by Geoconsult (1985) as 297.0m$^3$/d/m. and the specific capacity was 10.5m$^3$/d/m. Permeability was estimated as 6m/d, which is in the low permeability range (see Tables 5.2 and 5.3 and Fig. 5.6.); the EC of the water was determined as 800mmhos/cm.

In Well RK-9 in Wadi Al Ghaleelah (Fig. 5.14 (C)), the alluvial mantle is 69m. thick. Below that is the Triassic Lower Mussandam limestone formation. The SWL was reported in 1985 as standing at 80m. from the surface, that is within the underlying Mussandam limestone, but the whole alluvial zone was dry. The same was the case with RK-11 in Wadi Al Nagab (Fig. 5.14 (D)) where the alluvium was 30m. thick but the SWL lay at 44.6m. below the surface, that is within the underlying limestone (1985).

Transmissivities of the aquifer, in the grey Triassic massive to well-bedded limestone (locally oolitic, fossiliferous and dolomitic with cherts) of the Lower Mussandam in Wadi Al Ghaleelah and Wadi Al Naqab, range between 382m$^3$/d/m. (in Well RK-9) and 580m$^3$/d/m. (in Well RK-11).

In Wadi Al Beeh, the Quaternary alluvial infill is estimated to be about 120m. thick. Gravels and boulders are the dominant components of the deposits occurring in lenses about 1m. thick with individual boulders of 20-60cm. in size embodied in them. Within the active wadi channel the deposits are loose and well sorted, but away from the active wadi channels they are compact with a good degree of firm cementation. Below about 60cm. from the surface, the deposits are packed and contain sands and fines, grading to compact gravel at about 1m. depth. Below 2m. from the surface the gravels are firmly compacted, poorly sorted and grade
from notably spaced gravels to silty medium to fine sand. Oversize cobbles and boulders of up to 50cm. in size make up about 10-15% of the alluvial deposits at that depth.

The fines are a good cementing matrix but are non-plastic in character and make up 5% of the total volume of the deposits. The whole alluvial fill in these wadi channels is being repeatedly enhanced by occasional floods. The gravels are naturally of a carbonate base, because Wadi Al Beeh cuts through the limestones and dolomites of the Ru‘us Al Jibal limestone massif. Cherts make up 1% of the total volume of the deposits and are mostly of the Hawasina metasediments disintegrated from dykes within the hardrock upstream areas. Both the sands and fines become cohesive on drying.

Being underlain by the Permo-Triassic Lower limestone, which is itself a huge aquifer system, and with which the Quaternary wadi alluvium is in hydraulic contact, the water-table is deep, standing at between 110-120m. below ground level, or just a few metres above the contact zone between the Quaternary deposits and the underlying limestone. In Well RK-6 (Fig. 5.14 (B)), in the middle course of Wadi Al Beeh, where ground elevation is 140m AMSL, the Quaternary alluvial cover is 129m consisting of boulders and gravels that are held together by a cementing of calcite and silica. Unfortunately, no pumping test data were offered by the Deep Wells Project despite 3 hours of pumping. Transmissivity and specific capacity were reported as 'high' (Deep Wells Project, Final Report (Iwaco), Vol.4, p. 165). Generally, transmissivity is estimated to be 1000m³/d/m in the Burairat wellfield (Electrowatt, "Wadi Al Beeh Dam for groundwater recharge and loss prevention", 1980).

Porosity in Wadi Al Beeh alluvium is estimated to average 28% (Water Supply Augmentation for the UAE, US Bureau of Reclamation, Department of the Interior, 1979). The storage coefficient was estimated as ranging from 0.15 to 0.2, taking into consideration the possibility that the wadi alluvium may be well-packed below 50m. from the surface.

The aquifer of Wadi Al Beeh is unconfined in its main continuous part with a free water-table. It is hydraulically connected with the carbonate aquifer below it, and continues to be so down to the alluvial outwash fan at Al Burairat. However, the limited occurrence of

350
groundwater in perched lenses above the main water-table gives the Wadi Al Beeh aquifer a semi-confined character.

5.3.2.5.1.2. The alluvial aquifers of the wadis of the ophiolite central mountains

In both Wadi Ham and Wadi Al Baseerah, on the east coast, two or more water-bearing strata of different age, composition and hydraulic properties, exist within the wadi alluvial fill.

5.3.2.5.1.2.1. The alluvial aquifers of Wadi Ham and its outwash fan

The alluvium of Wadi Ham and its outwash fan is derived from the Semail Ophiolites across which the fault-guided Wadi Ham flows. More than 90% of the deposit is made up of basic and ultrabasic igneous rocks ranging in composition from diorite (both basic and ultrabasic rocks containing feldspar and olivines) to metamorphosed serpentinites. The remaining 10% of the alluvium is of the Hawasina metamorphics and volcanics consisting of quartz, quartzose, gneiss and schistose materials washed down from higher up the wadi course, where Hawasina outcrops occur in an area between Al Ghonah, Balaidah and Daftah, stretching northeastwards as far as the upper reaches of Wadi Madhah.

Three water-bearing layers are distinguishable in Wadi Ham and its outwash fan alluvium:

i) The old Tertiary gravels, left exposed in overhanging raised terraces.

ii) Recent Quaternary alluvium in the lower benches, essentially derived from the old alluvium by active downcutting.

iii) The current reworked alluvium in the active wadi channels, intermingled with Recent and Quaternary alluvial deposits.

The old Tertiary alluvium is compact and cemented by a variable degree of clay and carbonate matrix, but the actual gravels, that comprise most of the deposits, are weathered and are easily breakable. The cementing
is so binding that boreholes drilled into the wadi fill alluvium pierced large-sized boulders without shaking them off the surrounding cementing. The weathered serpentinite boulders make up 70% of the volume of the old terrace detrital material, with the large-size boulders of over 8 cm. forming 35% of the total weight of the material.

The fines are plastic and make up 5-10% of the total volume of the material. They are produced by the grinding of the same boulders and gravels that form the rest of the deposits. Firm cementing is evident in the fact that the raised terrace sides of the deeply incised wadi courses stand, as they have done for thousands of years, vertically.

The Quaternary deposits vary in thickness in relation to either the older Tertiary deposits or the bedrock. The Quaternary alluvium is thickest along the centre of Wadi Ham in the existing flow channel. Away from the channel, on either side up to the rocky wadi sides, the Quaternary alluvium thins out and is underlain by the old Tertiary talus. Transmissivities in the Tertiary alluvium are low in comparison with those in the Quaternary alluvium, particularly in the active wadi flow channels despite the presence of finer material. In a well drilled on the main Wadi Ham flow channel (in the gap between Jabal Nu‘aimat and Jabal Ahqab, at the point where the wadi opens on its outwash fan), transmissivities were found to range between 2000 and 4000 m³/d/m and permeabilities averaged 60 m/d (1983). The storage coefficient was estimated to be 0.00000041 (1983), which is more representative of a highly transmissive mountain wadi alluvial aquifer in a constricted gap in a recharge area where groundwater flow is fast, than of a confined aquifer as suggested by Geoconsult (Groundwater in Fujairah, Final Report, 1982). Transmissivities in the compact Tertiary alluvium range from 50m³ to 300 m³/d/m and permeabilities range from 5m. to 15 m/d.

There is wide variation in permeabilities in the old Tertiary terrace alluvium. The high permeability value of 50 m/d that was given by the Deep Wells Project (1982-86) for Well BHF-2 (in Muraished, 1984), which was even higher than permeability values for parts of coastal aquifers, can be explained by the fact that the well is located on a major NW-SE trending structural fault, which is water-holding with deposits within and above it, and the bedrock is well disintegrated and saturated. The much lower permeability of 10.0 m/d, that was given for
Well BHF-11 (1984) (in Madhab, Fig. 5.13 A), on the other hand, can be explained by the fact that, despite the location of this well also on a NW-SE trending tensional fault (though smaller and narrower than the Muraished one), the deposits are firmly cemented and, therefore, are less transmissive (Table 5.10).

<table>
<thead>
<tr>
<th>Well</th>
<th>Discharge m³/h</th>
<th>Transmissivity m³/d/m</th>
<th>Permeability m/d</th>
<th>EC mmhos/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>BHF-2</td>
<td>28.3</td>
<td>1500</td>
<td>50</td>
<td>840</td>
</tr>
<tr>
<td>BHF-11</td>
<td>29.0</td>
<td>306</td>
<td>10</td>
<td>2000</td>
</tr>
</tbody>
</table>


Table: 5.10.

Variation in permeability in the Deep Wells Project Wells BHF-2 (in Muraished) and BHF-11 (in Madhab) in the indurated Tertiary alluvium in the Wadi Ham outwash fan.

The high permeability value of 50m/d for Well BHF-2 (which is also within the coastal aquifer) is explicable by the fact that this well pierces a NW-SE trending saturated fault, which is water-holding in the Quaternary deposits within and above it and the bedrock is well-disentegrated and saturated. The much lower permeability value of 10.0m/d of Well BHF-11 can be explained by the fact that, despite the location of the well also in a NW-SE trending tensional fault (though smaller and narrower than the Muraished one on which is located BHF-2), the deposits in it are firmly cemented and compact and are, therefore, less transmissive.
5.3.2.5.1.2.2. The alluvial aquifers of Wadi Al Baseerah

The mountain wadi alluvial aquifers in Wadi Al Baseerah occur in three types of deposits as identified by JICA (1981):

i) The Recent wadi alluvium, which has an average thickness of 15m., although it reaches a thickness of up to 50m. in some localities. It consists of unconsolidated sand and gravel in the active wadi channels.

ii) The Quaternary (Pleistocene) well-cemented and compact alluvium of subrounded gravels held by a calcareous matrix, exposed in the middle course of Wadi Al Baseerah, reaching a thickness of 30m.

iii) The even more consolidated Tertiary talus terrace alluvium, similar to that in the Masafi intermontane basin (Section 5.3.2.5.2), reaching a maximum thickness of 35m. in the upper course of Wadi Al Baseerah.

(See Fig. 5.26. of the well logs of JICA's Wells TW-9, BH-4 and TW-5 and Fig. 5.27 for a cross-section in a mountain wadi)

Clay and silt intercalations occur in all the three alluvial deposits; the clay content increases with depth. The cementing by clay in the middle layer, and the even more consolidated compaction in the third and lower Tertiary talus layer, where clay consolidates into clear horizons, renders these two older terrace alluvial deposits less transmissive and, therefore, less productive than the more lithologically favourable overlying Recent alluvium. Furthermore, these two less permeable alluvial zones are the water-bearing strata in most of Wadi Al Baseerah basin. The Recent alluvium is dry in the upper and middle parts of the basin and the water-table appears in it in wells in the lower coastal part of the basin where it is considered as part of the coastal aquifers and discussed later (Section 5.3.2.6.3.). However, groundwater of potable quality at a good well-discharge rate is obtainable from a central zone beneath the main wadi flow channel. Away from this central channel, the quality and the rate of production of groundwater are poor (see Chapter 6, Section 6.5.2.5.3.2.). The aquifer hydraulic properties of the water-bearing strata in Wadi Al Baseerah are given in Tables...
Drill cuttings of three of the wells drilled by the Japan International Cooperation Agency in Wadi Al Baseerah: (A) TW-9 (upstream); (B) BH-4 (midstream); (C) TW-5 (downstream) (1981).

The three wells have been chosen to show the occurrence of the three alluvial deposits: the recent loose wadi channel, the well-cemented Quaternary (Pleistocene) and the indurated Tertiary talus terrace deposits. Notice the recent wadi deposits increasing in thickness downstream, but also there is an increase of the older alluvial deposits. Notice also that the water-table starts in Well BH-4 and TW-5 in the consolidated alluvium and the saturated zone is contained within such deposits.

The well discharge rates in MEW wellfields of the east coast.

Well-discharge rates differ widely according to the localized presence of clay in the coastal aquifer; they are all, however, relatively high (above 30 m³/d).

<table>
<thead>
<tr>
<th>Wellfield</th>
<th>SWL (m)</th>
<th>Well discharge rate range m³/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dibba</td>
<td>17.10</td>
<td>46-123</td>
</tr>
<tr>
<td>Khor Fakkan</td>
<td>20.65</td>
<td>23.59</td>
</tr>
<tr>
<td>Ahraj (Ahrai)</td>
<td>31.00</td>
<td>8-91</td>
</tr>
<tr>
<td>Qidfa'</td>
<td>-23.50 (1988)</td>
<td>50-90</td>
</tr>
<tr>
<td>Fujairah</td>
<td>-10.00</td>
<td>27-59</td>
</tr>
<tr>
<td>Tareef (Kalba)</td>
<td>-6.00</td>
<td>30-77</td>
</tr>
<tr>
<td>Sur Kalba</td>
<td>-12.00</td>
<td>90</td>
</tr>
</tbody>
</table>

Source: MEW/TEBODIN, 1983.

Table: 5.11.

Transmissivity and specific capacity values of the coastal aquifer in Fujairah up to 3 km. from the shoreline.

Both transmissivity and specific capacity values are very high in the Quaternary coastal aquifer at the shoreline end of the Wadi Ham outwash fan. Such high values are indicative of a high content of medium to coarse sand and gravel in the aquifer.

<table>
<thead>
<tr>
<th>Well</th>
<th>Aquifer</th>
<th>Sp. Capacity m³/d/m</th>
<th>Transmissivity m³/d/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>BHF-3/3A</td>
<td>Quaternary/Fractured</td>
<td>588</td>
<td>3450</td>
</tr>
<tr>
<td>BHF-4</td>
<td>Quaternary/Fractured</td>
<td>4248</td>
<td>8630</td>
</tr>
<tr>
<td>BHF-5</td>
<td>Quaternary</td>
<td>960</td>
<td>4347</td>
</tr>
<tr>
<td>BHF-10</td>
<td>Quaternary</td>
<td>336</td>
<td>1230</td>
</tr>
<tr>
<td>BHF-12</td>
<td>Quaternary</td>
<td>941</td>
<td>1867</td>
</tr>
</tbody>
</table>


Table: 5.12.
Cross-section in a typical mountain wadi in the central ophiolite mountains.

The succession of alluvial deposits in the mountain wadis (Wadis Al Wurai'ah and Ham) are repeated in the intermontane basins (Masafi and Muzeirea'-Hatta-Masfut). The unconsolidated boulders, gravel and sand deposits of the active wadi channels are being continuously carved from the indurated Tertiary alluvium that stands vertically on either side of wadis for up to 60m in height. In most wadis, and in all intermontane basins, such indurated alluvium also underlies the unconsolidated wadi alluvium. Whereas transmissivities in the recent wadi alluvium average 800-1000 m³/d/m, they average 300-450 m³/d/m in the less consolidated alluvium and are as low as 100-200 m³/d/m in the indurated alluvium of the wadi terraces. Well discharge rates average 30 m³/h in the unconsolidated wadi alluvium, 7-15 m³/h in the less consolidated alluvium and only 0.5-5.0 m³/h in the indurated Tertiary alluvium. Groundwater in the indurated Tertiary alluvium was found by JICA in Wadi Al Baseerah (1981) to be almost stagnant with a long residence of more than 100 years as detected by isotopic investigation.
5.11. and 5.12; while Fig. 5.26 A-C of the drill cuttings of Wells TW-9, BH-4 and TW-5 shows the three alluvial deposits and the fractured ophiolite bedrock (See also Figs. 5.27 for the cross-section in a mountain wadi, and Fig. 5.28 for well location of JICA’s wells in the Wadi Al Baseerah basin).

5.3.2.5.2. **The alluvial aquifers of the intermontane basins**

Intermontane basins (also called 'seihs') comprise Tertiary and Quaternary alluvial deposits similar to those described for the mountain wadis and their outwash fans (Section 5.3.2.5.1). The Masafi intermontane basin contains conglomerates belonging to the Tertiary (Pliocene) as well as the Quaternary (Pleistocene) eras noted earlier for Wadi Al Baseerah. The aquifer contained in the overlying Quaternary alluvium in the basin has almost been depleted and production at present is localized and minimal. The older hard and compact Tertiary alluvium is either very poor in storage or completely dry. No water sampling from deep wells in the basin was carried out by any authority to determine the residence of groundwater in the Tertiary aquifer. However, JICA (1981) found out from C-14 dating that groundwater held in similar compact Tertiary alluvium in Wadi Al Baseerah was more than 100 years old (see Environmental Isotopes, Chapter 7, Section 7.7.1).

In the nearby Mahrazah basin (where the Masafi Water Bottling Co. is operating) there are 25-40m. of alluvium overlying 2-4m. of fractured peridotites bedrock of the Semail Ophiolites. Groundwater in the part of the aquifer within the Quaternary alluvium has already been exhausted, leaving only a 12-m. saturated zone in the compact Tertiary alluvium and the fractured bedrock as the exploitable aquifer. A similar deterioration, though on a larger scale, must have taken place in the adjoining Masafi basin where the fractured bedrock provides the groundwater supply for Masafi village.

Intermontane basins repeat the same lithological succession as that which has already been discussed for the mountain wadis (Section 5.3.2.5.1). The basins had been subjected to the same general uplift of the mountains during the Middle Tertiary period and the subsequent erosion that took place has led to the deposition of the Tertiary (Pliocene) and the Quaternary (since the Pleistocene) alluvium in these
Figure: 5.28.

Locations of JICA's observation wells in the Wadi Al Baseerah Basin (1981).

nearly closed basins.

In the Muzeirea' basin (the Masfut-Hatta basin), the hard compact conglomeratic alluvial layer reaches, in some places, 10m. in thickness. Above that is a 15-m. thick less consolidated conglomerate, gravel and marl layer with CaCO$_3$ and silt cementing. On the surface are cobbles of gabbro and peridotites.

The productive aquifers are in the alluvial deposits which have an average thickness of 7m., but may reach a maximum thickness of 30m. in the centre of the basin (refer to identical environment in Fig. 5.27). The indurated and hard gravel is interbedded with silica and CaCO$_3$ layers that render permeabilities in these deposits low. Transmissivities in the Tertiary alluvium range from 100m$^3$/d/m to 200m$^3$/d/m with low well-discharge rates of between 0.5 and 5.0m$^3$/h.

In the less consolidated alluvium above the old Tertiary conglomerates, permeabilities are slightly better (300-450m$^3$/d/m) and the well-discharge rates are between 7m$^3$ and 15m$^3$/h.

Permeabilities in the unconsolidated wadi bed alluvium are even better. Transmissivities in the topmost wadi alluvium are above 800 m$^3$/d/m and the well-discharge rates are over 30m$^3$/h. This unconsolidated alluvium, therefore, offers the best 10-m. thick aquifer held in an assortment of roughly sorted boulders, cobbles, pebbles and gravels of all sizes, in addition to coarse sand. There are between 1-5 m. of recent alluvial deposits that have not yet been cemented by a matrix of fines.

Well MF-1 (1983) (Deep Wells Project well), in Masfut, penetrated the whole 42m. of alluvium in the basin (Fig. 5.8 (B)). The SWL stood at the shallow level of 4.7 m. below the surface (1983), the discharge rate of the well was 9.8 m$^3$/h., and transmissivity was 172m$^3$/d/m. The transmissivity value reflects the compactness of the water-bearing stratum, which, in this case, was Tertiary alluvium from which most of the pump intake was taking place.
5.3.2.6. Coastal aquifers

5.3.2.6.1. General

Lithologically, the coastal aquifers of the Emirates are made up of Quaternary deposits similar to those of the alluvial outwash fans, but with a higher proportion of fine sediments of clays and silts increasing progressively seawards. The deposition of the Quaternary to Recent material in coastal areas has been taking place from both the seaward and landward sides, and in both cases the deposited sand is of the carbonate type, forming the low coastal dunes. The littoral is fringed with active sabkhas, which in places extend inland for several km. Coastal sabkha lithologies consist of recent unconsolidated carbonate sediments which include quartz, evaporites, gypsum and halite. The top 1m. contains fine carbonate sand and silt largely derived from the coastal dunes that back the littoral, or by occasional floods that do reach the coast, particularly on the east coast. This top sandy layer is underlain by thick layers of clay deposits getting darker in colour with depth.

Sabkhas also exist inland as deflation basins (seih) interspersing longitudinal dunes, but these are old sabkhas marking the bed of a retreated ancient sea. Active coastal and inland dunes rest over crusted sabkha floors causing the dunes themselves to be humified by the sabkha saline water by capillary rise. Groundwater derived from shallow wells drilled in inland sabkhas is brackish to very saline. Coastal sabkhas are common to both coasts of the Emirates, although the closeness of the mountains to the shoreline on the east coast has led to the siting of producing wells very close to the sea.

5.3.2.6.2 Coastal aquifers of the western (Gulf) coast of the Emirates

Owing to the nearness of the Hajar Mountains to the Gulf coast of Ras Al Khaimah, the thick alluvial outwash fans of Wadi Sha'am and Wadi Ghaleelah reach out to the shoreline. The highly transmissive deposits of these coastal plains facilitate subsurface water movement to the sea, as well as a reverse intrusion of seawater effected by excessive abstraction from coastal wells.
There are fewer wells in coastal locations in the Northern Emirates than in the Baynoonnah coastal zone of Abu Dhabi, where many shallow wells have been drilled into the coastal aquifer to provide brackish water for the forestry projects. Coastal aquifers within the western Gulf coastal zone in Abu Dhabi are either in the carbonate Dammam Formation, as at Sila' where this formation appears on the surface covered only by a thin veneer of Quaternary to Recent sabkha deposits; or in the Miocene Lower Fars sabkha formations, as in Al Baynoonah between Tareef and Jabal Al Dhannah. Both the Lower Fars and the Dammam are carbonate formations; the latter partly gypsiferous while the former is a monotonous sequence of evaporites and halite. Aquifers in these two formations contain highly saline water. Even the shallow wells, with depths of between 0.5m. and 2.0m. below the surface, tap highly salt-contaminated waters from the sabkha evaporites and from seawater intrusion. West of Al Sila', aquifers in the Eocene Dammam limestone are of the confined type.

During field visits made to the region for this study to measure discharge rates of the forestry wells, it was found that there was a wide variation in well-discharge rates according to the lithological composition of the water-bearing deposits and the presence of fine material in these deposits. On average a 15m³/h well-discharge rate was found to be a credible median value. The low discharge rates in this part of the Gulf coast of Abu Dhabi are due to sabkha clayey water-bearing material with low permeabilities. This contrasts with the high discharge rates in the highly permeable coarse alluvial outwash fan material at Sha'am in Ras Al Khaimah in the Northern Emirates (50-100m³/h).

No data for aquifer properties exist for the western coast of Abu Dhabi, but transmissivities in the alluvial coastal aquifer in Sha'am range from 2000-4000m³/d/m and the storage coefficient ranges from 0.024 to 0.042 (Mar'ee, 1978).

5.3.2.6.3 Coastal aquifers of the east (Batinah) coast of the Emirates

East coast aquifers occur in alluvial deposits that fill the embayments, which are separated by promontories that end up in the sea (Fig. 6.19, Chapter 6). The coastal aquifer in Fujairah is characterized by a fine gravelly, sandy, silty lithology. The sequence is highly permeable.
despite the presence of silty horizons. The generous discharge from wells in this aquifer has led to overabstraction and an acute reduction in the fresh groundwater head, which has been pushed back inland by the encroaching seawater front. As a result, seawater incursion has become an increasing problem all along the east coast with groundwater salinities already averaging 5000 mmhos/cm. as in well BHF-4 (in Rughailat), BHF-3 (in Fujairah) and BHF-2 (in Muraished) (Deep Wells Project wells in the Fujairah area; refer to Fig. 5.29 for locations).

The coastal Quaternary aquifer on the east coast is underlain by consolidated Tertiary alluvium, which is in hydraulic contact with it through fissures in the latter. The Tertiary alluvial deposits are in turn underlain by the fractured bedrock, with which there is also hydraulic connection (Fig. 5.27). Seawater intrusion is, therefore, taking place through all these water-bearing strata (Fig. 5.31).

Transmissivities in Wells BHF-4 and BHF-5 at Rughailat and Kalba are high. They range from 4000 to 9000 m$^3$/d/m reflecting the highly permeable coarse alluvium that underlies the two main distributaries of Wadi Ham. Transmissivities in Wells BHF-3 and BHF-10 in Madhab, away from the permeable wadi channels, on the other hand, are relatively lower, ranging from 1000 to 3000 m$^3$/d/m, reflecting higher content of fine sediments in the water-bearing deposits (Table 5.12; Fig. 5.29).

Well-discharge rates differ widely according to the localized presence of clay in the coastal aquifer; but all discharge rates are generally very high and range between 30 and 123 m$^3$/h. Table 5.11. presents well discharge rates in MEW wellfields from Dibba to Kalba on the east coast.

Generally, there is an upper unconfined (water-table) aquifer with less saline water (2000 mmhos/cm), and a lower semi-confined aquifer with slightly more saline water (3000 mmhos/cm). The storage coefficient in the Fujairah coastal aquifer is 0.24 for the upper unconfined and 0.0025 for the lower semi-confined aquifer.

According to Geoconsult (1980), the Tertiary coastline in Fujairah is marked by the 15-m. contour line (Fig. 5.30). To the west of this
Aquifer Transmissivity Specific Storage
\( \text{m}^3/\text{d/m} \) yield

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>13,000</th>
<th>0.012</th>
<th>0.092</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent wadi-bed deposits (Quaternary)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower Terrace deposits (Quaternary)</td>
<td>1,800</td>
<td>0.005</td>
<td>NA</td>
</tr>
<tr>
<td>Upper terrace deposits (Tertiary)</td>
<td>200</td>
<td>0.003</td>
<td>0.021</td>
</tr>
<tr>
<td>Coastal sabkha deposits (Quaternary/Recent)</td>
<td>1,600</td>
<td>0.100</td>
<td>0.14</td>
</tr>
</tbody>
</table>


Table: 5.13.

The hydraulic characteristics of the alluvial aquifers of Wadi Al Baseerah (1981).

<table>
<thead>
<tr>
<th>Well</th>
<th>TW-3</th>
<th>TW-4</th>
<th>TW-5</th>
<th>TW-8</th>
<th>TW-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWL (m)</td>
<td>19</td>
<td>23</td>
<td>46</td>
<td>56</td>
<td>50</td>
</tr>
<tr>
<td>Transmissivity ( \text{m}^3/\text{d/m} )</td>
<td>13,400</td>
<td>13,700</td>
<td>1,840</td>
<td>19</td>
<td>229</td>
</tr>
<tr>
<td>Storage</td>
<td>0.092</td>
<td>0.14</td>
<td>0.021</td>
<td>0.022</td>
<td>0.032</td>
</tr>
<tr>
<td>Specific capacity ( \text{m}^2/\text{d} )</td>
<td>-</td>
<td>1,400</td>
<td>-</td>
<td>-</td>
<td>162</td>
</tr>
</tbody>
</table>


Table: 5.14.

Results of the pumping tests of some wells in the different alluvial aquifers of Wadi Al Baseerah.

(Commentary on both Table: 5.13 and 5.14.)

Transmissivities are higher in the unconsolidated Recent and Quaternary wadi alluvial aquifers than in the consolidated Tertiary alluvial aquifers. Well TW-5 is drawing groundwater from both Quaternary and Tertiary deposits; hence the intermediate transmissivity value between the high values for wells TW-3/TW-4 and the low values for wells TW-8/TW-10.

Figure: 5.29.

contour line is the generally compact and less permeable alluvium, higher up the Wadi Ham outwash fan, except along active wadi flow channels; to the east of the 15-m. contour line is the unconsolidated Quaternary water-bearing alluvium, which includes the coastal aquifers.

Although recently many gardens have sprung up on the Wadi Ham outwash fan to the west of the 15-m. contour line, the availability of groundwater in the less productive compact Tertiary alluvium is a limiting factor to agricultural development. Most of the cultivation in Wadi Ham and its outwash fan is to the east of the 15-m. contour line relying heavily on groundwater in the Quaternary alluvium, which is of high permeability but low storage capacity in this recharge area. This has resulted in the depletion of groundwater in the coastal aquifer and the extension of the cone of depression, which has, in turn, intensified seawater intrusion. The saline water tongue extends as far upstream as Madhab, 4km. inland, coinciding with the 15-m. Tertiary contour boundary (Falaj Madhab Study, Geoconsult, 1980).

Following the last uplift of the land during the Late Tertiary-Early Quaternary and subsequent enhanced erosion, newer sediments were deposited over the older consolidated Tertiary alluvium in a build-up of a new Wadi Ham outwash fan top alluvial mantle. Owing to their recent origin, the Quaternary alluvial deposits are less consolidated, but towards the coast the sand content increases and so, naturally, does that of other fine sediments. Even the gravels of the Quaternary are smaller in size than those of the Tertiary, which indicates the reduced energy involved in the deposition process compared to that which was involved in the deposition of the larger Tertiary boulders and gravels.

In Fujairah, the Quaternary aquifer below the 15-m. contour line, is recharged through the fractured ophiolite bedrock aquifer from sources higher up in Wadi Ham and its outwash fan. Besides this recharge, there is the contribution from recirculating irrigation water which may amount to 30% in the old-established, continuously irrigated area, between Fujairah and Khawr Kalba.

The Quaternary alluvial coastal aquifer is by no means lithologically homogeneous. Pumping tests carried out by the Deep Wells Project (Wells Nos. BHF-3/3a, BHF-4/4a, BHF-5 in Table 5.12.) confirmed the existence
of several thin impermeable horizons of clay and silt which help partially to confine the water-bearing strata. The undulating aspect of the drawdown curves produced by the pumping tests pointed to hydraulic connection between several water-bearing layers or subaquifers (Geoconsult, Deep Wells Project, Final Report, Volume IV on Fujairah, 1985). The supply of fresh water (or replenishment), that continually feeds the Quaternary aquifer, seems to be taking place through more than one vertically separated layers. This was confirmed by a salinity depth profile (fluid conductivity logging by geophysical, mainly geoelectrical, sounding) which indicated water conductivities of up to 5000mmhos/cm down to 40m from the surface. From 45m. downward there was an abrupt improvement in water conductivity to 1000mmhos/cm, which indicated fresh water lateral flow in relatively permeable semiconsolidated deposits within the Tertiary alluvium that normally predominates at this depth (Fig. 5.31).

Transmissivities in the Fujairah coastal aquifer range from 1230m$^3$/d/m (Well BHF-10) to 8630m$^3$/d/m (Well BHF-4) (Table 5.12). Transmissivity and discharge values of coastal wells of the Deep Wells Project in Fujairah are given in Tables 5.11 and 5.12.

In Dibba, the coastal aquifer produces good quality groundwater from wells in the date gardens of the coastal strip. This is due to the availability of enough fresh groundwater head, at least in three clearly marked outflow channels of Wadis Al Baseerah and Al Fayy to allow a fresh water zone to float over a denser more saline one below it in the older Tertiary alluvium (Figs. 5.40 and 5.41). Transmissivities in the coastal aquifer average 1600m$^3$/d/m, which is an intermediate value between the very high transmissivities of the recent unconsolidated wadi channel alluvium, averaging 13,000m$^3$/d/m, and the low transmissivities of the consolidated old Tertiary alluvium, averaging 200m$^3$/d/m (Tables 5.13 and 5.14). On the whole, coastal aquifers have porosities estimated at 20% owing to the unconsolidated texture of the water-bearing sediments.
The Tertiary 15m. coastline in Fujairah.

To the west of the 15m. contour line (Tertiary coastline) the alluvial deposits are generally compact and less permeable; to the east of the line the alluvial deposits are unconsolidated. The indurated nature of the material to the west (i.e., upstream in the Ham outwash fan) gives poor well-discharge rates that are unfavourable to cultivation, which is markedly concentrated on that part. On the other hand, the favourable well-discharge rates in the eastern coastal part has led to overpumping and subsequently to seawater intrusion.
5.3.2.6.4 Seawater intrusion

Under normal conditions fresh groundwater is discharged to the sea. When overpumping takes place, as it does in many coastal areas in the Emirates, the natural groundwater gradient is disturbed or even reversed, and the fresh groundwater head weakens before the seawater head. If overabstraction of groundwater in highly permeable outwash fans is continuous, as is the case in Wadi Sha‘am and Wadi Ghaleelah coastal plains in Ras Al Khaimah on the Gulf coast, or in the Fujairah and Dibba coastal plain (the Wadi Ham outwash fan and Seih Dibba) on the east coast, then seawater intrudes inland.

In the Emirates, the seawater intrusion phenomenon follows the Ghyben-Herzberg (1898-1901) hydrostatic theory whereby fresh groundwater practically 'floats' over the denser saline groundwater (Figs. 5.31 and 5.41). Continued overabstraction of groundwater leads to the upconing of brackish or saline groundwater from below, thus inducing the reversal flow head of seawater inland (Fig. 5.31).

In the Emirates, seawater intrusion is becoming a serious problem in nearly all important coastal groundwater abstraction centres. The increasing sodium chloride water in Al Aweer (Dubai) and Badea' (Sharjah) wellfields is attributed to the encroachment of the seawater front as far as 15-20km. inland in these two wellfields, where pump-levels in most of the wells in both wellfields are below MSL (see Chapters 6 and 8).

More serious, is the increasing salinities in the Sha‘am-Sahwat wellfields in northern Ras Al Khaimah. Isotopic analysis has confirmed that the increased chlorides in the groundwater in Sahwat (4-5km. from the coast) are due to seawater intrusion (Chapter 7, Section 7.7.3).

The phenomenon of seawater encroachment was investigated by geoelectrical sounding in the Fujairah coastal aquifers (Geoconsult, Groundwater in Fujairah, 1980-82). The isoresistivity profiles obtained as a result of these geophysical investigations did not exhibit the sharp parabolic-shaped fresh-saline groundwater interface typical of coastal aquifers. Instead, the profiles proved the presence of a transitional zone of mixed fresh and sea water (brackish) of varying
width extending inland for several kilometres. The presence of this wide
transitional zone is the result of intermittent but extensive pumping
from the shallow wells, which result in cyclic mixing of deeper seawater
seeping inland through the old intermediate Tertiary alluvium, and
fresher groundwater moving into this transitional groundwater zone
through fissures and old buried channels, but also through the overlying
Quaternary alluvium (see Fig. 5.31).

The fluctuation of this transitional zone is governed by the following
three physical factors:

(i) the steep gradient of the various alluvial deposits
influenced by an equally steep gradient of the underlying bedrock.

(ii) the occurrence of monsoonal rains in the summer breaking the
long dry periods between the winter rains, occasionally
producing enough fresh groundwater head that helps to push
back the seawater front, and, more importantly,

(iii) the extent of seawater intrusion is so basically controlled
by the rate of groundwater abstraction and recharge that the
transitional zone shifts markedly inland in the summer and
seaward in the winter because of the development or
shrinkage of a fresh water head that either pushes back the
saline water front or develops a substantially deep fresh
water zone on top of the saline seawater body. In both cases
there is active seepage to the sea of the mixed brackish
water of the transitional zone from the upper part of the
zone through the Quaternary alluvial and marine deposits
during the rainy season and shortly after it. (see Fig.
5.31 for the Fujairah; and Fig. 5.41 for the Dibba, coastal
zones and also Section 5.4.2.4.3. in this chapter and
Section 6.5.2.5.3.1. in Chapter 6).
It was found that there was a transitional groundwater zone of mixed fresh and seawater (i.e., of a highly brackish quality), of varying width, and extending inland for several kms. The presence of this wide transitional groundwater zone is the result of intermittent but extensive pumping from shallow coastal wells, which result in the cyclic mixing of deeper seawater seeping inland through the old indurated Tertiary deposits, and fresher groundwater moving into this transitional groundwater zone through fissures or old buried wadi channels, but also through the overlying Quaternary alluvium.
5.4 Groundwater flow

5.4.1. General

Groundwater flow is the result of both natural and man-made influences; the latter through widespread overabstraction and retention dams. The flow of groundwater through the soil and deeper rock material is controlled by three forms of energy: potential energy (from water height), pressure energy (water pressure in relation to atmospheric pressure) and kinetic energy (related to water velocity). The energy in water is expressed in terms of its head, i.e., its piezometric surface, which is the level to which a groundwater body would stand above a given datum.

Groundwater would flow in a zone of continuous saturation between a point of higher energy and another one of lower energy. The difference in head between the two points, the hydraulic gradient, maintains this flow. During its flow, groundwater loses energy due to friction resistance of the water-holding material, a loss greater in fine- than in coarse-grained deposits. The proportionality of the hydraulic gradient to groundwater velocity is known as the linear flow according to Darcy’s Law. This law states that "the flow rate through porous media is proportional to the head loss and inversely proportional to the length of flow path". It is expressed by the equation:

\[
Q_m = \frac{P (h_1 - h_2) A_d}{L_s}
\]

in which, \(Q_m\) = flow rate
\(P\) = coefficient of permeability
\(h_1 - h_2\) = head loss
\(L_s\) = distance in the direction of flow
\(A_d\) = cross-sectional area of the porous medium across which the flow occurs.

Darcy’s Law is valid in cases of laminar flow in water-bearing material of fine texture such as sand. The law does not represent turbulent flow owing to high velocities caused by highly permeable material, or flow in
highly porous but impermeable material owing to chemical and gaseous conditions within the rock material.

However, groundwater flow in nature is not smooth and uniform owing to the vertical and horizontal heterogeneity of the water-bearing media in the Emirates which, as has been discussed in this chapter and in Chapter 2 (Geology), is far from being uniform in composition and extent vertically and horizontally. The following factors influence groundwater flow in the Emirates:

1) The presence of water-bearing lithologies of alternating sequences of highly permeable Quaternary alluvium underlain by less permeable Tertiary conglomerates and clayey formations. The Quaternary alluvial mantle averages 40-60m. in thickness and is not itself homogeneous, even at the head of outwash fans such as that of Wadi Siji (Section 5.3.2.4.2). As a result of these lithological variations, porosities are also expected to be different and, therefore, groundwater velocities.

2) Topography and subsurface geology dip towards both the west and north, but more towards the latter. There is a difference in gradient between Al Ghareef Plain in the south of the piedmont plains and Al Seer Plain in the north (both in the Northern Emirates), of 140m., in a distance of 80km. This inclination in the land has influenced surface flow, as is evident in the major flow channels of Wadi Lamhah and Wadi Sumaini-Yuday'ah, which together collect nearly all the waters of the west-flowing wadis that emanate from the ophiolite central mountains. There is no westward surface flow north of Ramlat Unayq (north of Sharm in Oman) and Al Madam Plain, and all surface flow eventually joins the north-flowing Wadi Sumaini-Yuday'ah.

3) The occurrence of wedge-like highly permeable buried alluvial channels that may have been old west- and northwest- flowing ancient wadis or 'marine channels' that served as drainage lines during the three sea-level changes that have occurred since the Late-Pliocene (see Chapter 2, Section 2.2.8.). Such highly permeable buried wadi channels influence greatly the diffusion of recharge water from the catchment areas by vertical and lateral
seepage, and provide wedges of stronger groundwater head and therefore faster subsurface flow. The most important of such buried alluvial channels is the one on which are located the main wellfields of Dubai and Sharjah (Seih Al 'Aqareb, Al Hibab, Al Aweer, Al Wuhoosh and Al Badea').

4) Changes in groundwater hydraulic gradients effected by man through regionally extensive (such as the 50km. front of continuous wellfields north of Al Ain), but locally intensive, overabstraction centres that have caused the depletion of substantial parts of, or in some areas, whole aquifers in the Quaternary deposits, the main media of recharge and groundwater flow of potable water. This overabstraction must lead to the steepening of hydraulic gradients towards cones of depressions, or to the slowing down of groundwater flow as a result of interstitial compaction that is bound to reduce the transmissive and storage capabilities of the rock media through which groundwater moves.

5.4.2 Groundwater flow regimes of the Emirates

On the regional scale, groundwater movement in the Emirates, and the whole of eastern Arabia, is controlled by the so-called sabkha line (Fig. 5.32), which demarcates the low-lying areas, or the 'sink' of the Arabian Peninsula. To the west of this line are the recharge areas of Najd in Saudi Arabia; to the east and south are the recharge areas of Oman and the Yemen. Fig. 5.33 shows the structural (tectonic) contours of the Arabian Peninsula. The contours clearly portray the basinal section on which rests the whole of the Emirates. This is the large depositional basin in which the deep carbonate water-bearing strata were laid down. Present-day extensive inland sabkhas, of which the Liwa troughs and Sabkhat Matti are the most important, are the remnants of this depositional basin that has silted. The deep formation aquifer system of the Simsima, UER and Dammam (containing brines) is thickest and deepest in central Abu Dhabi. The upgradient (recharge) parts of the system are in west-central Saudi Arabia and the highlands of Oman and Yemen in southern Arabia. The regional groundwater flow regime is
The 'Sabkha Line' or 'sink' of the Arabian Peninsula.

On the regional scale, groundwater movement in the Emirates, and the whole of eastern Arabia, is controlled by the so-called 'Sabkha Line', which demarcates the low-lying areas, or the 'sink' of the Arabian Peninsula. To the west and south of the Line are the upgradient (recharge) areas of Najd, Oman and the Yemen. Regional groundwater flow is therefore through the deep carbonate formation aquifer system into the area below the Sabkha Line, on which is located the Emirates.
The structural contours of the Arabian Peninsula clearly show the basinal section on which rests the whole of the Emirates. This is the depositional basin in which the deep carbonate aquifer system of central Abu Dhabi was laid down. Present-day deep regional groundwater movement is directed from the west, south and east into this 'sink' of eastern Arabia (also see Fig. 5.32).
therefore in deep formations towards the lowest part in the Arabian Peninsula, which happens to be the southern half of the Emirates. Fig. 5.32 shows the assumed major lines of groundwater flow on the regional scale.

On the local scale, groundwater flow is to the coastline from the catchment (recharge) areas in the narrow mountain block that lies within the Northern Emirates where the travelling distance of groundwater is short (5-60km.); and from the catchments in the part of the same mountains to the east of Al Ain (in Oman) where the distance groundwater has to travel to the Abu Dhabi coastline is long (160km.). Both these groundwater flows are generally westward and northwestwards towards the Gulf coast. There is also an eastward groundwater flow from the catchments in the mountains in the Northern Emirates towards the Gulf of Oman, where the distances of groundwater flow in the alluvial embayments are very short (1-8 km.)

Groundwater movement on the local scale also occurs in inland areas such as in the Al Qafa 'plateau' where groundwater of the sand dune aquifer appears to move northwards into Al Baynoonah on the Gulf coast and southwards at the base of the dunes into the Liwa troughs.

5.4.2.1 Groundwater flow in the Northern Emirates (Figs. 5.34 and 5.35)

Halcrow (Water Resources of the Trucial States, 1966-69) and Mar’ee (1978) represented groundwater flow in the Northern Emirates by flow-nets (Fig. 5.34 (A) and (B)). A flow-net is made up of two types of lines or curves: the first, are the flow lines which are the paths followed by groundwater movement in the water-bearing strata; the second, are the equipotential lines, which are lines representing the subsurface contours of the piezometric surface or the free water-table.

Mar’ee (1978) relied on groundwater level measurements that had been made by Halcrow ten years earlier (1968). However, in the absence of accurate data on the thickness of the saturated zone, no credible quantitative assessment of groundwater storage and flow was possible. Mar’ee suggested that the wider downstream intervals between the groundwater contours were due to an increase in either, transmissivity and the saturated thickness, or both. It was concluded that in a
northern groundwater flow channel (may be the channel fed by Wadis: Sidr, Eiyaim and Idhn) transmissivity ranged from 0.4m$^3$ to 1.6m$^3$/d/m; and in a southern flow channel (possibly fed by Wadis: Shawkah, Khadhrah and Sfini) transmissivity ranged from 1m$^3$ to 6.7m$^3$/d/m. Hydraulic gradients for the whole part of the Northern Emirates to the west of the mountains were thought to vary between 0.001 and 0.005; groundwater velocity was estimated as 0.5m/d. In the northern parts of the piedmont plains (Al Hamraniyyah), groundwater gradients were thought to be so shallow (gentle) as to give a groundwater flow velocity of 0.15m/d, which would take 180 years for groundwater to flow under the Jiri Plain between Idhn and Hamraniyyah (20km.) (Mar’ee, Hydrogeology of the northern part of the UAE (Ph.D. thesis), University College, London, 1978).

According to Halcrow and Mar’ee (Fig. 5.34 (A) and (B)) groundwater contours run parallel to the mountain front in the central and southern parts of the piedmont plains (from Al Madam to Idhn); but the contours take a diagonal orientation to the mountain front from Idhn to Sha’am. For this same part of the piedmont plains to the north of Idhn, the Deep Wells Project (Geoconsult-Iwaco, 1982-86) suggested a northerly and a north-westerly groundwater flow, which meant that the groundwater contours ran almost at right angle to the Hajar mountain front. This surmise by the Deep Wells Project relied on new, though limited, data from the drilling of deep wells in the northern limestone mountain region. Thus, the main orientation of groundwater flow in the Jiri and Seer Plains is towards Khawr Ras Al Khaimah. This is included in Fig. 5.35 for the present study, which refines groundwater flow suggested by the three previous studies, of the part of the Emirates from Al Madam to Sha’am.

However, none of the previous studies recognized the possibility of the Jabal Fayah-Mileiha anticlinal ridges acting as barriers to groundwater flow. The flow-nets presented by Halcrow and Mar’ee for the Northern Emirates show uniformity in the groundwater contours and flow lines from the mountain front to the east, across the anticlinal ridges, and continuing uniformly westwards towards the coast (Fig. 5.34 A and B). The fact that present-day surface flow channels change to a northerly course immediately after debouching from the mountains (after taking a very short westerly course), and also the fact that such a northerly
Figure: 5.34.

Representation of groundwater flow by (A) Halcrow (1969) and (B) Mar'ee (1978).

Halcrow (1969) and Mar'ee (1978) represented groundwater flow in the Northern Emirates by flow-nets. Mar'ee relied on groundwater level measurements that had been made by Halcrow ten years earlier. In the absence of accurate data on the thickness of the saturated zone, no reasonable quantitative assessment of groundwater storage and flow was possible. According to Halcrow, groundwater contours ran parallel to the mountain front in the central and southern parts of the piedmont plains (from Al Madam to Idhn), but the contours took a diagonal orientation to the mountain front from Idhn to Sha'am.
course is found on either side of the Fayah-Mileiha anticlinal ridge (Fig. 5.35), attests to two strong physical possibilities. The first is the general westward but, also, most importantly, northward, dip of the topography which has a direct influence on the orientation of surface (and possibly subsurface) drainage and its gradient. The flow of the bulk of surface runoff in a northerly and northwesterly direction, following the general inclination of the land, is likely to develop a strong groundwater head in that direction rather than towards the west as has been surmised by most groundwater studies until now. This opens an interesting scope for investigation in future hydrogeological studies.

Although, generally, the highly permeable alluvium (mostly gravel) that underlies the piedmont plains and the desert foreland, provides a favourable transmitter of groundwater from the recharge zone at the foothills of the mountains in the east, its disposition is far from being simple. The water-bearing strata, on either side of the mountain divide, are made up of a multi-layered, lithostratigraphically complex sequences, of varying permeabilities, yet they are hydraulically connected. Even the generally unconsolidated Quaternary alluvial stratum is intercalated with less permeable layers and lenses of material of different degrees of texture. Consequently, this variation in the lithology is reflected in the different transmissivities which, in turn, affect the rate of vertical and, most importantly, that of laminar flow of groundwater. Wedge-like extensions of old buried, permeable wadi channels, have been recognized and confirmed by three decades of drilling in the Dubai and Sharjah wellfields and from the electrical conductivity of the groundwater. However, their exact extent is not known. Also unknown, is how far west, from the mountains and the piedmont plains, do the gravel deposits extend and what is their exact thickness, away from the wedge-like buried wadi channels.

The alarming proliferation of cones of depression, as a result of persistent large-scale and intensive overpumping over wide areas, deserves serious study as to how far this interception of groundwater flow by man is affecting the local or regional general groundwater movement. This is beyond the means and scope of the present study. Should it be argued that groundwater would still flow in the lower sequences if water ceases to flow in the overlying Quaternary sequence
Groundwater flow in the Northern Emirates from Al Madam Plain to Sha'am.

The general northerly dip of the topography and strata north of Al Madam guide groundwater flow more towards the north than the west. This is evident in the surface flow channels of Wadis Sumaini-Yudai'ah and Lamhah whose northerly overland flow and infiltration produces a groundwater head towards that direction. In the narrow plains north of Seih Al Fahlain, the flow is northerly. Thus the main groundwater flow in the Northern Emirates is northerly with a secondary diagonal nortwesterly flow into the vast desert foreland to the west of the piedmont plains.
owing to exhaustion, then it should be borne in mind that abstraction is already widely taking place in the less permeable Tertiary aquifer systems, and even from the older fractured base-rock.

5.4.2.2 Groundwater flow south of Al Madam Plain: the eastern region of Abu Dhabi (Al Ain) from Al Shuwaib in the north to Mazvad in the south (Fig. 5.36.)

South of Al Madam Plain, groundwater flow from the mountains to the east (within Oman) is also governed by similar wedge-like permeable alluvial buried extensions represented by Wadi Safwan, Wadi Ma'aisheq and Wadi Kahal which, with all the distributaries of Wadi Mahdhah crossing its outwash fan, join Bathat Bin Hilal and Wadi Masakin to take a NE-SW course towards Bu Samrah and Al Sad. It was surmised by Gibb (Water Resources Survey of Abu Dhabi, 1968-70), based on favourable electrical conductivity values for groundwater as far west as Al Sad, that old concealed wadi alluvial (mainly gravel) channels were responsible for fresh groundwater flow into the wellfields of the northern dune area between Ghashabah and Al Khadher Nassas.

The presence of gravel beneath the aeolian sands of the desert foreland is evident from well logs for locations as far west as Suwaihan and Al Khadher Nassas; the latter wellfield is 25km. from the mountain front at Seih Sulailiyyah (in Oman). The wellfields of the northern dune area of Al Ain are all situated on such old buried wadi channels. The Kara' Wellfield is situated on Wadi 'Athamiyyah; Bida' Bint Ahmad and Al Kara' North Wellfields are situated on Wadi Safwan; Mohayyer East Wellfield is situated on Wadi Sinabil; Suwaihan Road Wellfield is located on Wadi Khabb and Seih Al Baitar Wellfield is on Wadi Al Jabeel.

The lithologies in Al Khadher Wellfield consist of fine-grained reddish yellow sand, ranging from a thickness of 1.5m. to 15.0m. and overlie Pleistocene alluvium (mainly gravel and fine- to medium-grained sand and silt) 6-35m. thick. Below that is a Late Tertiary clay aquiclude assuming thicknesses of up to 40m. It is underlain in places, as in Suwaihan Road and Al Khadher Nassas wellfields, by white to pink hard limestone, also estimated to be about 40m. thick. The highly permeable alluvial sandwich seems to be wadi-laid and can be traced as far east as
the piedmont plains and the outwash fan of Mahdhah and Seih Sulailiyyah. It thus qualifies as the dominant transmitting medium and, therefore, main groundwater flow route. On the other hand, the marls under Mohayyer East wellfield, which are 6-24m. thick (comprising sandy, marly intercalations), are an indication of low permeability and, therefore, slow groundwater movement.

The average permeability in Al Khadher Nassas is 240.2m/d and the hydraulic gradient is 0.018 (1.8%). The velocity of groundwater flow is, therefore, 4.3m/d, which is higher than the velocity of groundwater flow within the Zarub Gap (discussed next) or any of the values given for the Northern Emirates. This means it would take groundwater 16 years to travel the 25km. distance between the foothills and Al Khadher wellfield in the buried alluvial channel (Al Khadher Groundwater Resources Survey, Final Report, 1977).

Groundwater flow in Al Jaww Plain, to the east and southeast of Al Ain, is controlled by both, the series of gaps in the hills at the eastern end of Al Jaww and also by the main overland east-west wadi channels of Wadis Al Ain and Shik in the northern part of the plain (emanating from the Zarub Gap) and Wadis Hamad and Muraikhat in the southern part (emanating from the Ajran Gap).

Most of the inflow into Al Jaww comes from the Zarub Gap where permeabilities within the constriction of the gap are high (212m/d) and groundwater gradients average 0.011 (1.1%). The velocity of groundwater flow is therefore high, averaging 2.33m/d (Gibb, 1970). Groundwater velocities in the Ajran Gap, most of whose over- and through-flow bypasses Al Jaww and flows back into Omani territory, are much lower (0.1-0.5m/d) due to the fact that the gap here is wider than that at Zarub and the through-flow is therefore spread over a wider path.

Groundwater flow velocities across Al Jaww are much reduced. Where unconsolidated alluvium occurs, such as in the flow channels of Wadis Shik and Al Ain, through-flow velocities range from 0.1m/d to 0.4m/d. Where, on the other hand, the lithologies are heterogeneous, such as in the areas between the wadi channels, where the water-bearing alluvium is well-cemented, such velocities can be as low as 0.04m/d. An example of such a low groundwater flow is at Mazyad (0.04m/d) where the Quaternary
Groundwater flow in the land front south of Al Madam in the Al Ain region (from Al Madam to 'Ajran).

In the northern part of this front, the bulk of groundwater flow is northerly into Al Madam Plain in the Northern Emirates, following the general northerly surface flow channel of Wadi Sumaini-Yudai'ah. In the central and southern parts of this front, the discrete wedge-like alluvial underground flow channels of Wadis Ma'aisheq, Safwan and Kahal guide groundwater flow in a westerly and southwesterly direction towards Bu Samrah and Al Sad. In the Al Jaww Plain in the southeastern part of this front, the Zarub Gap influences faster groundwater flow westwards with a particularly concentrated flow in the two well-marked wadi channels of Al Ain-Shik and Hamad where groundwater flow velocities are higher than further south in the Wadi Muraikhat flow channel emanating from the 'Ajran Gap. The slower groundwater velocities of the latter are due to the fact that the 'Ajran Gap is wider and therefore the inflow passing through it is spread over a wider front.
alluvium is thickest but where it is mostly composed of silt and clay. The groundwater flow velocities become even slower in the area immediately to the west of Jabal Hafeet (0.004m/d), which testify to the blocking effect the Jabal Hafeet anticlinal ridge is exercising on the westward groundwater movement (Fig. 5.36).

The unconsolidated alluvial deposits in the wadi channels in Al Jaww reach 100m. in thickness in the western end of the wadi channels of Wadis Shik and Al Ain (near Al Ain town), but generally average 20-40m. in the centre of the channels of these two wadis in the northern part of Al Jaww. The thickness of the permeable alluvium is less in the southern part of Al Jaww, where it is less than 20m. In the central area of Al Jaww, between the two main northern wadi channels of Wadis Al Ain and Shik and the two main southern channels of Wadis Hamad and Muraikhat, the permeable alluvium is thinnest. The thickness ranges from 1m. (in the vicinity of Um Ghafah village) to 10m. (in a zone stretching from Um Ghafah to Tawi Malagat near Zarub). Permeabilities in this zone are low, so are groundwater velocities (0.04m/d). Recharge into this intermediate area is also minimal as the bulk of the groundwater head is concentrated in the two main wadi flow channels (Fig. 5.36).

5.4.2.3 Groundwater flow in Liwa and central Abu Dhabi (Fig. 5.37)

Besides the deeper regional groundwater flow into Liwa from the west, south and east, to the region below the so-called 'sabkha line' (discussed in Section 5.4.2), there is also a local northerly and northwesterly groundwater flow, controlled by the Al Qafa plateau, from the Liwa oases towards the coast. This shallow fresh to marginal groundwater flow is superimposed over the deeper more saline regional flow into the sabkha 'sink' noted above. It appears to be guided by the inclination of the topography of Al Qafa towards the east and north. As these shallow waters are fresh sand dune waters, they are practically floating over the denser saline waters of the extensive sabkha that underlies the dunes in the whole central Abu Dhabi region.

Groundwater movement appears to be both to the north and northeast towards Qurun Al Na‘am, Bida’ Al ‘Areedh, Bida’ Zayed, Bujair and Al Hilew; and also in a more localized groundwater flow from the high dunes
Besides the deeper regional saline groundwater flow into Liwa from the west, south and east, into the region below the so-called 'Sabkha Line', there is a shallow flow superimposed on the deeper flow. The shallow fresh-to-brackish water flow is guided towards the north by the dip of the plateau of central Abu Dhabi into Qurun Al Na'am, Bida' Al 'Areedh, Bida' Zayed, Bujair and Al Hilew; as well as a more localized flow from the high dunes to the south of the Liwa arc of oases between Hadeebah in Western, and Jarrah in Eastern, Liwa, towards the troughs of the oases.
to the south of the Liwa arc of oases, between Hadeebah in western, and Jarrah in eastern, Liwa, towards the sabkhas or troughs of the oases to the north. The conductivities of the waters involved in this localized subsurface flow range between 900-2800mmhos/cm. Groundwater gradients average 0.014 (1.4%) and permeabilities average 250-450m/d, giving groundwater flow velocities of 3.6-6.3m/d, which reflect a highly transmissive sandy medium of groundwater flow (Fig. 5.37).

5.4.2.4 Groundwater movement in mountain wadis

5.4.2.4.1 Groundwater movement in Wadi Al Beeh (Fig. 5.38)

Groundwater levels are deep in Wadi Al Beeh and the other wadis of the Hajar limestone mountain massif of Ru‘us Al Jibal (SWLs are below 60m. (at or below MSL) from ground surface), despite the inland location of places of groundwater abstraction such as Al Burairat and Al Beeh wellfields (12-16km. from the coast). SWLs are either in the lower few metres of the alluvial stratum or they are mostly in the underlying limestone. Groundwater in the massive limestones and dolomites and the overlying alluvium is in hydraulic continuity. During drilling, up to 50m. of alluvial deposits can be dry.

Groundwater gradients average 0.005 (0.5%) and permeabilities average 400-500m/d, which give a groundwater flow velocity of about 2-2.5m/d. Groundwater movement in the limestone massif is controlled by the texture of the limestone itself, the bedding planes and the degree of their filling with fines and also the daily and seasonal tidal changes since the water contained in the limestone block may well be directly connected to the sea on either coast, where the larger part of the mountain massif is in direct interface with the sea. Although transmissivities in the carbonate massif are not high, pointing to their massive texture, they still act as a ‘sponge’ with the water level in the Hajar aquifer responding to tidal changes. The hydrogeology of the Hajar mountain block and the behaviour of the groundwater bodies it contains, have not been adequately studied and the region provides a good field for a systematic hydrogeological survey.

Further downstream, in the outwash fan of Wadi Al Beeh, below Al Burairat, groundwater movement westward is impeded by a tightly sealed
Groundwater flow in the Ras Al Khaimah limestone mountain mass and the narrow wadi outwash fan piedmont plains (the coastal zone to the north of Seih Al Fahlain).

The westward plane-guided groundwater movement in the massive limestones and dolomites of the Ru'us Al Jibal massif is impeded by a tightly sealed (with clay) structural fault along the foothills of the Hajar mountains. The coastal zone to the west of this fault is covered by permeable unconsolidated Quaternary alluvium (gravel and sand), underlain by the less permeable Maastrichtian clastics-in-shale of the Aruma Juweiza Formation that also help block the westward groundwater flow of the deeper waters in the Hajar limestone forcing these waters to rise and seep through the permeable Quaternary alluvium in addition to the localized groundwater flow within the Quaternary outwash fan alluvium emanating from the wadis to the east. In such geological juxtaposition, it may be surmized that during heavy rains or floods, the Hajar limestone aquifer is recharged from the Quaternary aquifer by a reverse downward groundwater flow eastwards.

Figure: 5.38.
(with clay) structural fault along the foothills of the Hajar massif. The coastal zone to the west of this fault is covered by a thin alluvial layer, which is underlain by the less permeable clays of the Maastrichtian Juweiza Formation that also help block the westward flow of the deeper waters in the Hajar limestone (to the east of the fault line) forcing these waters to rise and seep out through the permeable Quaternary alluvium. In such geological juxtaposition, it may be surmised that, during heavy rains or floods, the Hajar limestone aquifer is recharged from the Quaternary aquifer by a reverse downward groundwater flow eastwards (Fig. 5.38).

5.4.2.4.2. Groundwater movement in Wadi Ham and its outwash fan  
(Fig. 5.39.)

At the dam site in Wadi Ham (9km. from the coastline at Fujairah) groundwater gradients average 0.015 (1.5%), but downstream in the alluvial outwash fan, owing to the gentler topographical gradient and the slow release of groundwater stored in the old Tertiary terraces on the wadi sides, groundwater gradients flatten to about 0.001 (1 in 1000).

After leaving the narrow part of the wadi, just below the dam, groundwater spreads out in the outwash fan with a marked concentration of flow in a southeastern direction towards Kalba. This seems to coincide with the concentration of water head governed by the orientation of Wadi Ham itself that follows the major NW-SE structural Wadi Ham Fault. This concentration of flow to the southeast is further strengthened by an additional groundwater head (to the movement in the same direction) by flows from Wadi Al Hiyail and Wadi Al Buwaidhah, both of which flow into Tareef and Addiheyyat in Kalba (Fig. 5.39).

Permeability of the water-bearing strata below the Wadi Ham Dam (and also in the upper part of the outwash fan) averages 40m/d, and, with the water-table gradient of 0.015 noted earlier, groundwater flow velocity in the lower part of Wadi Ham and the upper part of its alluvial fan averages 0.6m/d. Elsewhere in the outwash fan, permeabilities average 30m/d and, with the shallow groundwater gradient of 0.001 noted earlier, the velocity of groundwater movement in the lower part of the outwash
Figure: 5.39.

Groundwater flow in Wadi Ham and its outwash fan.

The groundwater gradient in Wadi Ham near the retention dam is 0.015 (1.5%) and downstream in the outwash fan, it is 0.001 (or 1:1000). Groundwater flow velocity in the outwash fan averages 40m/d. and groundwater flow is concentrated in a southeasterly direction governed by the surface flow head of the main Wadi Ham distributary that flows towards Kalba. This concentrated southeasterly groundwater flow is further strengthened by an additional groundwater head to the movement in the same direction by flows from Wadis Al Hiyail and Buwaidhah, which both flow into Tareef and Addiheyyat in Kalba.
fan in the Fujairah area is 0.03m/d. With such a weak groundwater head at the point groundwater flow reaches the shoreline, any overpumping in the coastal aquifer weakens this groundwater head further and invites seawater in a reversal of movement (refer to Section 5.3.2.6.4.).

The whole of the Wadi Ham outwash fan (the Fujairah-Kalba coastal plain) is an area of heavy groundwater mining. As a result, fresh groundwater heads are systematically being weakened by such interception from the three types of water-bearing material: the unconsolidated Quaternary alluvium, the consolidated Tertiary alluvium and the fractured bedrock; resulting in establishing a long-term situation in favour of the seawater head along the coastal part of the Ham-Fujairah outwash fan.

5.4.2.4.3 Groundwater movement in Wadi Al Baseerah (Fig. 5.40)

There are two distinct groundwater flow regimes in Wadi Al Baseerah. The first, is a very slow groundwater flow in a low permeability, low storage upstream aquifer which is only in saturation during a period of heavy rain and which, owing to the steep gradient in upper Wadi Al Baseerah, drains off rapidly. The second groundwater flow regime, is downstream within thick alluvial deposits of more than 50m. saturated thickness and, unlike the upper aquifer, which has a low storage coefficient of 1%, this lower aquifer has a storage capacity of between 15-20% and extends for about 8km. inland from the coast. In addition, there are also the old Tertiary terrace alluvial deposits in which groundwater is almost stagnant and was proved by isotopic investigations to be more than 100 years old (JICA, 1980, Chapter 7, Section 7.7.1).

Groundwater flow is concentrated in a central path, coinciding with the main flow channel of Wadi Al Baseerah, as evident from the low groundwater conductivities along the whole length of the channel down to the shoreline (refer to Chapter 6, Section 6.5.2.5.3.). This channel occurs on the northeastern half of the wadi flood plain, towards Jabals Wa‘abain and Waam, guided by the presence of the structural Dibba-Idhn Fault Line along that side of the wadi basin, by the regional tilt of the land towards the north (noted earlier for the area to the west of the mountains (Section 5.4.2.1.) and also by the local dip of the strata within the wadi basin towards the same northern direction. As a result,
There are two distinct groundwater flow regimes in Wadi Al Baseerah:
(a) An upstream slow groundwater flow in a low permeability, low storage upstream aquifer, which is only in saturation during a period of heavy rain and, because of the steep strata and bedrock gradients in upper Wadi Al Baseerah, drains off rapidly; and, (b) A downstream flow within thick alluvial deposits, of more than 50m. saturated thickness, with a larger storage capacity than that in the upper part of the wadi.

Another minor extremely slow groundwater flow regime occurs in the indurated Tertiary wadi terrace alluvium.

Groundwater flow is concentrated in a central path coinciding with the main flow channel of Wadi Al Baseerah. This is evident from the low groundwater ECs down to the coastline. The concentrated groundwater flow in the northeastern half of the Wadi Al Baseerah flood plain, more towards Jabal Wa'abain and Waam, is guided by the presence of the Dibbe-Idhn structural fault along that side of the wadi basin, and also by the regional northern tilt of the topography and the northerly dip of the water-bearing strata. As a result, groundwater flows diagonally down the wadi towards the north and northeast.
groundwater moves diagonally down the wadi within these strata towards the north and northeast. (Fig. 5.40.).

Groundwater gradients in the upper section of the Wadi Al Baseerah flood plain average \(0.015\) (1.5%) and the permeabilities average 250m/d; while in the lower section of the flood plain the gradients are extremely flat, averaging \(0.0004\) (0.04%) and the permeabilities averaging 1750m/d. Thus, groundwater flow velocities, in the upper and lower sections of Wadi Al Baseerah, average 3.8m/d and 0.7m/d respectively.

Halcrow (1969) noted the fluctuation in groundwater levels in the Dibba coastal wells in response to tidal movement of up to 0.6m. as far upstream as 1.5km from the coast. The low groundwater flow velocities in the coastal end of Wadi Al Baseerah (6.5km wide coastal front) and the heavy abstraction in the date plantations of that coastal zone (about 8.5km\(^2\) of continuous date farming zone) weaken the fresh groundwater head in the coastal aquifer. As a result a seawater intrusion tongue is established as far as 1.5km inland beneath a thin mixed water front that is being continuously pumped and partially redressed by irrigation returns from the extensive date farming zone.

Unlike Halcrow, JICA (1980) carried out intensive geophysical investigations in Wadi Al Baseerah and succeeded with specific resistivity profiles (equi-depth electrical sounding at 10m. electrode intervals to a depth of 100m. in straight lines set perpendicular to the coastline; in this case of Wadi Al Baseerah, for a distance of 1000m. from the Dibba shoreline), which showed a wedge-like groundwater zone of resistivity values less than 5 ohms/m., clearly representing a seawater intrusion tongue (Fig. 5.41; refer also to Section 5.3.2.6.4.). However, the JICA study (Wadi Al Baseerah Basin Water Resources Development Project, JICA, 1980) was not decisive about the lenticular high resistant zone, that overrides the seawater intrusion tongue, as far as the shoreline, of whether it was a compacted hard sabkha or a fresh water lens.

On the other hand, Lavalin (1980), illustrated by aerial photography the occurrence of seepage from Al 'Akkamiyyah and Wadi Al Khasarah on the Dibba shoreline, but concluded that, on measuring the conductivities of this outflow, they did not differ significantly from those of seawater.
Unlike Halcrow (1966-69), who observed fluctuation in groundwater levels in coastal wells along the Dibba coast, JICA (1981) carried out intensive geophysical investigations that found out, with specific resistivity profiles, the presence of a wedge-like groundwater zone of resistivity values of less than 5 ohms/m, clearly representing a seawater intrusion tongue. However, JICA was not decisive about the lenticular high resistivity zone that overrode the seawater intrusion tongue, as far as the shoreline, of whether it was an old compacted hard sabkha or a fresh water lens.
The likely explanation for this phenomenon is that there is outflow of highly brackish groundwater, as shown by JICA's (1980) resistivity values of between 5-15 ohms/m which signify brackish water, in a thin outflow sheet to the sea where it mixes with seawater, obscuring its lower salinities and making them similar to those of seawater (Report on the 'Discovery of Submarine Springs Using Infrared Thermal Imagery', Lavalin, 1980).

5.5 Groundwater levels and their fluctuation trends
(Figs. 5.42 to 5.74; Tables 5.15 to 5.23)

5.5.1. Groundwater Levels
(Figs. 5.42 to 5.44 showing groundwater level recorders)
(Tables 5.15 to 5.23)

5.5.1.1. General

Since the aquifer systems of the Emirates are largely of the unconfined (free water-table) type, the changes in groundwater levels with time should affect both the transmissivity of the water-bearing strata and their storage capabilities. Groundwater levels have greatly changed in the past two decades since the two major water resource surveys were conducted in the country: The Trucial States Water Resources Survey by Halcrow (in what is now the Northern Emirates) (1966-69); and the Water Resources Survey of Abu Dhabi by Alexander Gibb (1968-70). Both surveys reported then groundwater levels that were close to the surface within the highly transmissive Quaternary alluvium. These groundwater levels have since receded deeply into less transmissive Tertiary clays and evaporites in the plains and desert foreland and also the fractured bedrock in the mountain wadis or in the foothill zone.

With groundwater flow disturbed and intercepted at nearly all points along its flow paths by excessive pumping, ground-water levels are sharply falling in centres of concentrated abstraction such as in most of the piedmont plains from Al Jaww Plain around Um Ghafah in the south, to Al Seer Plain around Seih Al Fahlain and Burairat in the north; in alluvial embayments, wadi flood plains and outwash fans along the east coast; and the desert foreland centres of Al Badea'-Al Aweer (in the Northern Emirates) Busamrah-Al Sad, the wellfields of the northern dune
area (in Al Ain) and also Bujair-Bida', Khalfan-Al Hilew wellfields (in central Abu Dhabi). Although there are limited positive fluctuations following the winter rains in some locations such as in the mountain wadis and the heads of outwash fans, or where semi- to confined aquifers exist, the overall trend on the larger areal scale over the longer term is that of consistent recession in groundwater levels.

Besides portraying a comprehensive picture of the groundwater levels in the various regions of the Emirates, the ensuing description focuses on groundwater and pump-levels that have already sunk below MSL, as in the desert foreland wellfields of Al Aweer and Al Badea'; those that have receded into clay and anhydrite formations, such as in the piedmont plains and Al Ain regions; and also those that differ widely in levels within the same locality. The aim of this is to cast light on consistently sinking groundwater levels, which form an important aspect in the groundwater resource appraisal undertaken by the present study, and provide the background to the discussion on 'Water Production and Use' (Chapter 8), the 'Shared Water Resources' (Chapter 9), 'Groundwater Recharge, Groundwater Reserves and the Groundwater Balance' (Chapter 10) and 'Water Resource Management' (Chapter 11).

5.5.1.2 Groundwater levels in the mountain wadis

The static water level (SWL) in the Burairat wellfield was reported in 1979 to be lying between 45-55m. below the surface or 0-10m. above mean sea level (MSL) (Water resources augmentation for the UAE, US Geological Survey, 1979). In 1987, the level was measured at 60m. below ground surface or -10m. below MSL (MEW, Groundwater level measurements in MEW wellfields, 1987). The SWL in the new Wadi Al Beeh wellfield, which is situated 5km. upstream of Al Burairat wellfield, measured 80m in 1979 below the surface (20m. above MSL) (Electrowatt, Wadi Al Beeh Dam for groundwater recharge and loss prevention, 1979); in 1987 it was 90m. below the surface (10m. above MSL) (MEW, 1987) (Table 5.16).

The SWLs in the limestone northern parts of the Emirates are deepest as was confirmed by wells of the Deep Wells Project (1982-86). The SWL in Well RK-6 in Wadi Al Beeh (1985) stood at 110m. below ground level. This is the case with nearly all boreholes in the carbonate massif of Ru‘us Al Jibal of the Northern Emirates. In Well RK-12 in Al Hamraniyah
Table: 5.15.

Static water levels (SWLs) in the northern limestone aquifers (1984-86).

The SWLs in the limestone aquifers of Ru'us Al Jibal are deep. The variation in the SWLs in the wells points to dislocation of the water-bearing limestone into blocks separated by fissures and bedding planes. Groundwater occurrence is semi-confined in bedding planes at different levels.

Table: 5.16.

The SWLs are below MSL in MEW wellfields in the lower parts of the northern mountain wadis of Ras Al Khaimah (1988).

The majority of the boreholes draw groundwater from below MSL. The most acute situation is in Al Beeh, Al Burairat, Sahwat, Seih Al Ghob and Seih Al Fahlain where groundwater salinities are rapidly increasing.
(1985), the SWL was 7m. below MSL (this well is located 20m. from the coastline of Ras Al Khaimah). Table 5.15 lists the wells of the Deep Wells Project drilled in the northern parts in Ras Al Khaimah, most of which were drilled away from the coast and penetrated deep into the carbonate formations. The variation in groundwater levels in these wells points to the dislocation of the limestone into blocks separated by fissures or bedding planes, in which is contained the water these wells are tapping, and where also the groundwater levels are different in some from others because the water bodies in them are being held in a semi- or totally confined state by the sealing effect of fines in the fissures.

The wellfields of the MEW in Ras Al Khaimah, which are close to the coast where the centres of consumption are located, exhibit an alarming groundwater level situation as is shown in Table 5.16. As seen in Table 5.16 the majority of the boreholes are below MSL, hence the widespread seawater intrusion into the coastal aquifers of Ras Al Khaimah. The worst cases of seawater intrusion are at Sahwat, where groundwater salinities are rising steadily; and also in Wadi Al Beeh, in both the Burairat and Al Beeh wellfields, where most of the boreholes are pumping groundwater from below MSL and the intrusion of seawater has advanced that far inland (12km).

Fluctuation in the groundwater levels in Wadi Al Beeh can be pronounced. There was a seasonal rise of up to 7.6m. after the 1987 winter rains, but there was a general fall of 1.65m. between 1984 and 1987 (Table 5.17).

In Dhuhuriyyeen, on the other hand, the dry period of 1984-86, particularly the year 1984-85, had a great impact on the water-table which dropped from 56.60m. in 1984 to 65.85m. in 1985. The drop continued until 1987 when it bettered slightly and the SWL stood at 65.05m. (Table 5.18.).

Elsewhere in mountain wadis, wadi alluvium is only saturated for a short time following the rains, but for most part of the year, the groundwater tapped is from the contact zones between either the Quaternary or Tertiary alluvium and the fractured bedrock. In most mountain wadis, especially those of the ophiolites central mountain block to the south
### Table: 5.17.

Groundwater level fluctuation in Wadi Al Beeh, 1984-87 (in metres below the surface).

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>1984</th>
<th>1985</th>
<th>1986</th>
<th>1987</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>85.64</td>
<td>88.18</td>
<td>-</td>
<td>89.28</td>
</tr>
<tr>
<td>February</td>
<td>86.04</td>
<td>88.20</td>
<td>88.39</td>
<td>88.58</td>
</tr>
<tr>
<td>March</td>
<td>86.20</td>
<td>88.38</td>
<td>88.09</td>
<td>88.65</td>
</tr>
<tr>
<td>April</td>
<td>86.31</td>
<td>88.44</td>
<td>87.55</td>
<td>81.07</td>
</tr>
<tr>
<td>May</td>
<td>86.74</td>
<td>88.49</td>
<td>-</td>
<td>87.39</td>
</tr>
<tr>
<td>June</td>
<td>86.83</td>
<td>-</td>
<td>-</td>
<td>87.44</td>
</tr>
<tr>
<td>July</td>
<td>87.13</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>August</td>
<td>87.29</td>
<td>-</td>
<td>88.06</td>
<td>88.60</td>
</tr>
<tr>
<td>September</td>
<td>87.49</td>
<td>-</td>
<td>-</td>
<td>88.88</td>
</tr>
<tr>
<td>October</td>
<td>87.67</td>
<td>-</td>
<td>89.70</td>
<td>89.24</td>
</tr>
<tr>
<td>November</td>
<td>87.98</td>
<td>-</td>
<td>89.92</td>
<td>88.94</td>
</tr>
<tr>
<td>December</td>
<td>87.98</td>
<td>88.40</td>
<td>89.78</td>
<td>89.54</td>
</tr>
</tbody>
</table>

Source: MEW unpublished records

### Table: 5.18.

Groundwater level fluctuation in Dhuhuriyyeen, 1984-87 (in metres below the surface).

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>1984</th>
<th>1985</th>
<th>1986</th>
<th>1987</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>63.17</td>
<td>66.96</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>February</td>
<td>63.37</td>
<td>66.09</td>
<td>65.55</td>
<td>-</td>
</tr>
<tr>
<td>March</td>
<td>63.23</td>
<td>66.03</td>
<td>65.58</td>
<td>-</td>
</tr>
<tr>
<td>April</td>
<td>63.67</td>
<td>65.96</td>
<td>65.72</td>
<td>63.07</td>
</tr>
<tr>
<td>May</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>63.17</td>
</tr>
<tr>
<td>June</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>63.17</td>
</tr>
<tr>
<td>July</td>
<td>65.19</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>August</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>64.94</td>
</tr>
<tr>
<td>September</td>
<td>65.49</td>
<td>-</td>
<td>-</td>
<td>65.21</td>
</tr>
<tr>
<td>October</td>
<td>65.82</td>
<td>-</td>
<td>-</td>
<td>65.16</td>
</tr>
<tr>
<td>November</td>
<td>65.68</td>
<td>-</td>
<td>-</td>
<td>65.22</td>
</tr>
<tr>
<td>December</td>
<td>56.60</td>
<td>65.85</td>
<td>-</td>
<td>65.05</td>
</tr>
</tbody>
</table>

Source: MEW unpublished records

The fluctuation in groundwater levels in Wadi Al Beeh can be pronounced. There was a rise of more than 8.0m. after the winter rains of 1987-88 (between December 1987 and April 1988), then there was a sudden drop in May 1988 by more than 6.0m.

The dry year 1984-85 had a great impact on the water-table in Dhuhuriyyeen where there was a drop of more than 9.0m. between December 1984 and December 1985.
<table>
<thead>
<tr>
<th>Location</th>
<th>SWL (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wadi Al Sidr</td>
<td>35</td>
</tr>
<tr>
<td>Dhuhooriyyeen</td>
<td>59-65</td>
</tr>
<tr>
<td>Fariyah</td>
<td>56</td>
</tr>
<tr>
<td>Al Eiyaim</td>
<td>14-54</td>
</tr>
<tr>
<td>Masafi</td>
<td>8-28</td>
</tr>
<tr>
<td>Marbadh</td>
<td>8-18</td>
</tr>
<tr>
<td>Sfini</td>
<td>11</td>
</tr>
<tr>
<td>Ashwani</td>
<td>6</td>
</tr>
<tr>
<td>Sukhaiber</td>
<td>10</td>
</tr>
<tr>
<td>Munai'ee</td>
<td>5</td>
</tr>
<tr>
<td>Wadi Al Qawr</td>
<td>4-12</td>
</tr>
<tr>
<td>Rafak</td>
<td>8</td>
</tr>
<tr>
<td>Fashgah</td>
<td>3</td>
</tr>
<tr>
<td>Balaidah</td>
<td>24</td>
</tr>
<tr>
<td>Riyamah</td>
<td>8</td>
</tr>
<tr>
<td>Al Gonah</td>
<td>24</td>
</tr>
<tr>
<td>Al Eiyais</td>
<td>17</td>
</tr>
<tr>
<td>Al Halah</td>
<td>20</td>
</tr>
<tr>
<td>Kidnah</td>
<td>16</td>
</tr>
</tbody>
</table>

Source: MEW and various drilling contractors.

Table: 5.19.

SWLs in wadi terraces and flood plains for some mountain wadis.

The variation in the groundwater levels in the mountain wadis is governed by the thickness of the alluvium in the wadi basins: where there are thick alluvial deposits, as in Wadi Sha'am (in Dhuhooriyyeen) the groundwater levels are deep; where the alluvial deposits are thin and the baserock is not far below ground surface, as at Rafak and Fashgah, the groundwater levels are not far below the surface.
of the Dibba-Idhn Line, water is pumped from a 2-4m. zone of fractured bed-rock, as at Sha’arah in Wadi Ham (below the dam) where the SWL is below 40m.; at Balaidah (24m.); Al Ghonah (24m.) and Wadi Al Sidr (35m.). SWLs are shallower in Fashqah (3m.), Rafak (8m.) and Wadi Al Qawr (4-12m.) in wadis on the east coast owing to the thin alluvial cover in the flood plains of these wadis. Wadi Al Qawr has a bare base-rock course near Al Qawr village. In Al Halah, in Wadi Al Baseerah, the SWL stands at 20m. from the surface (1990) (Table 5.19).

5.5.1.3 **Groundwater levels in the piedmont plains**

Groundwater levels in the western piedmont plains have been sinking in the past ten years into the clayey Tertiary Juweiza Formation that underlies the Quaternary alluvial deposits. There are now few wells tapping the Quaternary, and these are mostly tapping perched or lens-shaped semi-confined aquifers. As can be seen in Table 5.20, which shows the GP series of wells of the Deep Wells Project drilled in the piedmont plains, 16 out of the 18 wells draw water from the Tertiary Juweiza aquifer. The SWL starts in the lower part of the Quaternary alluvium while the saturated zone is mostly within the clayey Juweiza.

In Al Dhaid, the 8 wells of the old Dhaid Wellfield (MEW) had dried up by the summer of 1988 and the SWL, which stood in 1980-81 between 14-17m. below the surface, has been receding ever since until it has passed the whole depth of the boreholes (which varied from 48-68m.), and water in the water-bearing strata has almost been exhausted. This necessitated the drilling of a new wellfield of 7 wells at Al Bardi where the SWL now (1990) varies between 21-25m.

The deepening of boreholes in the piedmont plains, in pursuit of the ever-shrinking saturated zone as a result of the receding water-tables, has been a common practice in the past decade. This is particularly so in the Dhaid area in the central parts of the western plains, where part of aquifers (as at Wushah) have been exhausted. This practice has been investigated for the present study in Al Dhaid. The examples are numerous and the deepening of boreholes occurs in 9 out of 10 gardens. Two examples are included here for illustration (Table 5.21).

As seen in Table 5.21, the groundwater level dropped in Garden No. 1
Table: 5.20.

Static water levels (SWLs) in the Juweiza Formation in the wells of the Deep Wells Project in the piedmont plains (1982-86).

16 out of 18 wells drilled by the Deep Wells Project in the piedmont plains were in the clayey Juweiza formation, though their SWLs stood in the lower part of the overlying Quaternary alluvium. The variation in the levels may be due to the fact that some of the wells are in perched or lens-shaped semi-confined groundwater bodies, of varying levels of occurrence, that are quite common in the piedmont plains.

Table: 5.21.

The continuous recession of groundwater levels in Al Dhaid, in the central part of the piedmont plains.

The deepening of boreholes in the piedmont plains in pursuit of the ever-shrinking saturated zone as a result of the receding water-tables, has been common in the past decade. These two gardens started pumping water from the Quaternary and, when this strata became exhausted, they sank their wells deeper into the Juweiza clays, shales and clastics, which have low productivity.
from 24.4m. in 1974 to 183m. in 1988. In Garden No. 2 the level dropped from 61m. in 1978 to well below 200m. in 1988. In either case, the total depth of the wells was deepened from 40m. to 240m. (Garden 1) and from 76m. to 244m. (Garden 2). Water in the well in Garden 2 was already running dry at the 244m. depth by 1988, and there were plans to deepen the borehole yet again to 300m. Any levels below 20-40m. are certainly sinking into the Tertiary Juweiza Formation (Table 5.21).

The wellfields of Um Ghafah in Al Jaww Plain in Al Ain, those of the northern dune area from Ghashabah to Al Shuwaib, and also the remaining wellfields in the extreme western parts of the piedmont plains to the west of Mahdhah (all localities are in the Al Ain region), all have SWLs ranging from 20m. to 45m., with the deepest groundwater levels being in Um Ghafah (21-45m.). Levels in Ghashabah wellfield, which is located on the outward end of the Mahdhah outwash fan, are between 30-37m., in Bida' Bint Saud (west, east and Jubaita sections of the wellfield) the levels are between 20-36m. Of the 3 sections of the Bida' Bint Saud wellfield, the shallowest groundwater levels are found at Bida' Bint Saud West (13-20m.), and the deepest levels are at Jubaita (22-36m). Groundwater levels in Bida' Bint Ahmad (Al Hamam) are among the shallowest in this area of Al Ain (14-20m.), while the ever-sinking levels of Mohayyer East stand at 27-35m., Al Hayer North (21-35m.) and Al Kara' and Al Kara' North (33-43m.) (1988).

5.5.1.4 Groundwater levels in the desert foreland

SWLs in the wellfields of Al Aweer, Al Wuhoosh and Al Hibab (belonging to Dubai) and Al Badea' (belonging to Sharjah) have sunk below MSL. Since 1979, half of the boreholes of Al Badea' wellfield have had pump levels below MSL. By 1988 more than 22 out of the 24 boreholes that were in operation were pumping groundwater from below MSL, and there were indications of seawater intrusion with the increase in chlorides in the groundwater. Table 5.22 shows the boreholes in Al Badea' wellfield with levels below MSL for 1987. With the average ground level being 38m. above MSL, only 2 out of the 24 boreholes that were in operation in October 1987, were with pump-levels just above MSL. The rest of the boreholes had levels between 2-9m. below MSL.

In Al Aweer wellfield, a few kilometres to the southeast of Al Badea',
<table>
<thead>
<tr>
<th>Borehole</th>
<th>Pump-level (m)</th>
<th>SWL relative to MSL (in m)</th>
<th>EC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31.02</td>
<td>+ 6.98</td>
<td>2250</td>
</tr>
<tr>
<td>2</td>
<td>32.22</td>
<td>+ 5.78</td>
<td>2250</td>
</tr>
<tr>
<td>3</td>
<td>41.00</td>
<td>- 3.00</td>
<td>2300</td>
</tr>
<tr>
<td>4</td>
<td>44.64</td>
<td>- 6.64</td>
<td>2780</td>
</tr>
<tr>
<td>5</td>
<td>42.63</td>
<td>- 4.63</td>
<td>2800</td>
</tr>
<tr>
<td>6</td>
<td>46.62</td>
<td>- 8.62</td>
<td>2960</td>
</tr>
<tr>
<td>7</td>
<td>44.30</td>
<td>- 6.30</td>
<td>3000</td>
</tr>
<tr>
<td>8</td>
<td>44.08</td>
<td>- 6.08</td>
<td>2930</td>
</tr>
<tr>
<td>9</td>
<td>44.31</td>
<td>- 6.31</td>
<td>2950</td>
</tr>
<tr>
<td>10</td>
<td>44.09</td>
<td>- 6.09</td>
<td>3100</td>
</tr>
<tr>
<td>11</td>
<td>43.55</td>
<td>- 5.55</td>
<td>3050</td>
</tr>
<tr>
<td>12</td>
<td>44.41</td>
<td>- 6.41</td>
<td>2360</td>
</tr>
<tr>
<td>13</td>
<td>44.03</td>
<td>- 6.03</td>
<td>2850</td>
</tr>
<tr>
<td>14</td>
<td>42.21</td>
<td>- 4.21</td>
<td>2750</td>
</tr>
<tr>
<td>15</td>
<td>43.06</td>
<td>- 5.06</td>
<td>2800</td>
</tr>
<tr>
<td>16</td>
<td>45.45</td>
<td>- 7.45</td>
<td>2600</td>
</tr>
<tr>
<td>17</td>
<td>45.61</td>
<td>- 7.61</td>
<td>3000</td>
</tr>
<tr>
<td>18</td>
<td>46.08</td>
<td>- 8.08</td>
<td>2380</td>
</tr>
<tr>
<td>19</td>
<td>46.33</td>
<td>- 8.33</td>
<td>2700</td>
</tr>
<tr>
<td>20</td>
<td>45.25</td>
<td>- 7.25</td>
<td>2580</td>
</tr>
<tr>
<td>21</td>
<td>39.82</td>
<td>- 1.82</td>
<td>2350</td>
</tr>
<tr>
<td>22</td>
<td>45.12</td>
<td>- 7.12</td>
<td>2680</td>
</tr>
<tr>
<td>23</td>
<td>41.72</td>
<td>- 3.72</td>
<td>2800</td>
</tr>
<tr>
<td>24</td>
<td>38.07</td>
<td>- 0.07</td>
<td>2800</td>
</tr>
</tbody>
</table>

Source: Electricity and Water Dept., Sharjah

Table: 5.22.

The boreholes of Al Badea' North wellfield of Sharjah showing pump-levels below MSL, 1988.

With the average ground level standing at 38.0m. above MSL, 22 out of the 24 boreholes in operation in 1987-88 in Al Badea’ North wellfield of Sharjah were abstracting groundwater from pump-levels below MSL. Hence, the acute seawater intrusion that is taking place as far as the location of this wellfield inland (15kms. from the coast).
Table: 5.23.

SWLs in the Al Wuhoosh Wellfield of Dubai, 1988.

With the ground level standing at 40.0m. above MSL, 14 out of the 18 boreholes that were in operation in the Al Wuhoosh wellfield in 1987-88 were pumping groundwater from below MSL, and the groundwater levels in some wells stood at lower levels than those for wells in the downgradient Al Badea' wellfield. Al Wuhoosh is more than 30 km. from the coast.
Groundwater levels stood at between 46-50m (1988) below ground level, and boreholes are increasingly pumping from levels below MSL. This is despite the fact that there has been only a drop of 6-12m. in the past 26 years due to careful monitoring of extraction from this old wellfield, aided by desalinated water production that has met most the domestic requirements of Dubai since 1980. In Wuhoosh wellfield, the second of the 3 Dubai wellfields, ground level stood at 40m. above MSL and, as can be seen in Table 5.23, 14 out of 18 boreholes, that were in operation in 1987; were pumping groundwater from below MSL. This situation in Wuhoosh resembles that in Al Badea' in Sharjah, a few kilometres to the northwest. It should be noted that the groundwater levels given for these wellfields refer to pump-levels; the dynamic levels could be even deeper.

Groundwater levels for selected points in the rest of the desert foreland within Dubai emirate are given in Table 5.24.

In the new Seih Al ‘Aqareb wellfield (Sharjah), located upgradient of the same wedge-like groundwater flow channel on which the other Dubai and Sharjah wellfields are located, the SWL stands at between 16-20m. with the saturated layer being 60-130m. thick (1990).

<table>
<thead>
<tr>
<th>Locality</th>
<th>Depth in metres below ground level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al Masha’ar</td>
<td>26</td>
</tr>
<tr>
<td>Al Khawaneej</td>
<td>35</td>
</tr>
<tr>
<td>Nazwa</td>
<td>21</td>
</tr>
<tr>
<td>Marghum</td>
<td>23</td>
</tr>
<tr>
<td>Al Faww</td>
<td>25</td>
</tr>
<tr>
<td>Rimah</td>
<td>25</td>
</tr>
<tr>
<td>Al Faqa’</td>
<td>26</td>
</tr>
</tbody>
</table>

Source: Dubai Water Department

Table: 5.24.

Groundwater levels in selected points in the desert foreland within Dubai emirate (1988).

Levels do not differ much from each other in these localities that lie on the western fringes of the piedmont plains. The deeper groundwater level for Khawaneej is due to this locality being a heavy groundwater abstraction area.
Further south in the desert foreland, south of the interstate border between Abu Dhabi and Dubai, the SWL in Al Ushooosh, Al Khadher Nassas, Bida' Mughni and Suwaihan Road, varies from 40m to 70m. In Al Khadher Nassas the 50m. level was unproductive, while the 70m. level was productive, but with brackish water (Lahmayer, Al Khadher Wellfield Study, 1980).

Along the Al Ain-Abu Dhabi highway, apart from Al Sad, which is the oldest wellfield in the Al Ain region, groundwater levels vary between 20-60m. All the forestry wells along the highway are shallow wells that are highly brackish because they draw groundwater from the Miocene Lower Fars anhydrites, which are close to the surface in this region. At Abu Assalff, to the west of Suwaihan, the SWL stands at 12m; while at Al Khaznah it varies from 12-15m. In Al Za'alah, on the other hand, groundwater levels are mostly in the evaporites sequence and range from 50-110m.

In the desert foreland south of the Abu Dhabi-Al Ain highway, that is the area to the southwest of Al Ain, groundwater levels are controlled by the thickness of the saturated sand dune cover. Wherever the dunes are so thin or non-existent as to allow the sabkha floor to appear on the surface, groundwater levels can vary from 0.5m to 5.0m. as at Al Sila' in the extreme northwest and in Liwa in the extreme south of the Emirates. In Al Dhafrah, south of Al Khatm, groundwater levels vary from 40m to 50m., with groundwater levels in the wells at Al Numairiyah (at the end of the Dhafrah road) standing at 46m., although there are shallower levels (12m.).

In the Al Qafa region, to the north of the Liwa oases, where the potable water wellfields of Bujair, Al Hilew, Bida' Khalfan and Bida' Rashed are situated on sand dunes, groundwater levels range from 50m to 110m. In the domestic water wells of ADCO at Asab oilfield groundwater levels are at 102-106m; at Bida' Saif and Wadi Al Riyoom they range from 19m to 35m. In Bida' Zayed, which is situated in the northern edge of the dunes, the water levels stand between 21m and 65m.; while at Al Sa'eediyah and Al Yaheeliyah, on the sabkha, the levels are between 2m and 30m.

Further northwest in Qurun Al Na'am and Bida' Al 'Areedh the groundwater...
levels are between 20m and 44m., and at Ghayathy they are close to the surface (4m.) although there are wells where the levels stand at 18-35m. In Jaww Al Oad and Bida' Al Matawa'ah groundwater levels stand between 28-38m. and 18-22m. respectively.

In Liwa, groundwater levels nearer to the sabkha troughs vary between 0.5m and 11m., while in the dunes, as at Bida' Mubarak, the water levels are between 35m and 43m. from the surface. In ADCO's water wells in the Shah oilfield in Al Bateen, levels vary from 32m to 59m., and at Manader Al Rabbadh and Um Ez Zemool, where the wells are mostly in sabkha, groundwater levels stand at 1-3m. In this part of Abu Dhabi, as was observed at Qasyoorah, very saline water may occur at a level of 2m. from the surface with 1m. of fresh to brackish water floating over it in the thin dune sand cover.

5.5.2. Groundwater level fluctuation trends

5.5.2.1. General

Phreatic water levels occur generally within the Quaternary deposits on either side of the mountains and also within the Miocene clastics (Sahil Formation), which are made up of the Fars evaporites (gypsum, halite, calcite, and magnesium sulphate) and anhydrites (mostly calcium sulphate) that lie close to the surface in many parts in western Abu Dhabi. The groundwater surface conforms to the general topographic configuration, although it is slightly flatter in gradient. It is easily predictable in the desert foreland and coastal areas but is less so in the piedmont plains and near the foothills owing to the complex subsurface geology caused by excessive faulting and subsurface groundwater barriers in the baserock. Furthermore, variation in groundwater levels, which is common all over the Emirates, but more so within the piedmont plains and the desert foreland, is also attributed to the 'perched' groundwater bodies, or lens-shaped aquifers, which can be of limited extent, occurring in the thick wadi gravel deposits (Wadi Al Beeh in Ras Al Khaimah), or relatively extensive laterally, as in the western (central) piedmont plains and the vast desert foreland.

Apart from the alluvium of the wadis and their outwash fans (such as Wadis Ham and Al Beeh/Jiri, Dhaid, Ghareef, Madam, Ghashabah and Al Jaww
plains), where the deposits are highly permeable allowing fast infiltration, the distance to the water-table is generally too great to allow surface water to reach the aquifer except in occasional heavy run-off events. Silts and other fines, deposited during flash-floods, limit infiltration and thus lead to ponding, therefore intensifying losses by evaporation.

All available groundwater level records for wells in the various parts of the Emirates, kept by the MAF, WED Al Ain, WED Abu Dhabi, MEW, the water departments of Dubai and Sharjah, have been studied. The main groundwater level recorders of the Emirates are shown in Fig. 5.42 and the groundwater level recorders in the Wadi Ham-Fujairah outwash fan and Wadi Al Baseerah are shown in Figs. 5.43 and 5.44. Hydrographs have been prepared for most of these groundwater level measurement locations (Figs. 5.45 to 5.74).

5.5.2.2. **Long-term fluctuation of groundwater levels**

Long-term changes in the water-table are largely due to the seasonal and periodic fluctuation in the climate, especially long periods of relative drought. Recharge is occasional and limited in volume associated with intense short-lived rainstorms, while excessive mechanical discharge, on the other hand, is continuous all the year round, together with natural discharge, aided by the steep subsurface gradient as in the east coast. There are also the hydraulic factors of the aquifers concerning transmissivity, the storage coefficient and hydraulic gradient, largely governed by the configuration of subsurface hardrock, which is steep under the gravels of the east coast wadis and outwash fans and highly dislocated in the western plains. The result of the interplay of all these factors has been the general recession of the water-table everywhere as demonstrated by all the hydrographs (Figs. 5.45 to 5.74).

Extreme rises and falls in groundwater levels are an indication of limited storage capacity of aquifers. In vicinities where excessive groundwater abstraction is taking place, any recovery of the water level after the rains is only short-lived. The rapid lowering of the groundwater levels confirms this condition which eventually leads to depletion within short periods. Examples, are aquifers in the gravel deposits of the wadi basins, the alluvial outwash fans and parts of the
piedmont plains at the recharge zone near the foothills on either side of the mountains.

The hydrographs, Figs. 5.45 to 5.49 for observation wells in the piedmont plains from Al Hamraniyyah in Ras Al Khaimah in the north to Um Ghafah in the Al Jaww Plain (in Al Ain) in the south, and also for wells near the foothills where the mountain wadis debouch on to the plains such as Muzeirea' and Idhn, demonstrate clearly the general downward trend in almost the whole length of the piedmont plains (Fig. 5.48 C and D). This continuous groundwater level decline is more pronounced in localities where excessive groundwater abstraction has led to depression cones as in the Dhaid region, where the decline has been 13 to 14 m. since 1983 with an average annual drop of between 2.3 m. (GP-15) and 3.1 m. (GP-16), both south of Al Dhaid (Figs. 5.45 G and H).

In Well GWR-3 in Al Hamraniyyah (Fig. 5.49 A) the average annual drop has been 1.2 m. and the water level is well below MSL by nearly 18 m. (Al Hamraniyyah is 15 km from the Ras Al Khaimah coast). At Al Madam the annual drop has been 0.8 to 1.5 m. (Figs. 5.48 B and 5.49 C).

In the Ghashabah public supply wellfield, near the Al Awha government wheat farm in Al Ain, the average annual groundwater level drop has been about 1.3 m. in the public water supply wellfield of WED Al Ain (Fig. 5.46 A to C). The drop is much greater in the vicinity of the numerous wells used for irrigation in the Al Awha wheat fields, with an increasing number of the wells running dry. In Um Ghafah, in the southern part of Al Jaww Plain the groundwater level drop averages between 1.0 and 4.0 m. per year, with a large number of the wells demonstrating average annual drops of over 3.0 m. The most acute groundwater level drop has been in Well 401 (Um Ghafah) where it averages 3.8 m. a year (Fig. 5.47 B). A similar acute general drop in groundwater levels is also happening in mountain wadis close to the piedmont plains, as at Muzeirea' and Idhn where, in the former the average annual decline is 1.7 m., and in the latter it is 7.0 m., with recovery during the rainy years of 1982 and 1983 of up to 5.0 m. in Muzeirea' and 7.0 m. in Idhn, followed by a greater recession rate in the following two years (Fig. 5.48 C and D). The overall drop in the water level at Idhn between 1977 and 1988 was 36.0 m. (Fig. 5.48 D)

Fluctuation of levels in Wadi Al Baseerah, (Fig. 5.57 A to B) on the
east coast, reflects recharge from flood events as can be seen in Fig. 5.57 A for Wells GG-8, GG-9 and GG-10, with steep recovery limbs after the 1982 and 1983 heavy rains. Conversely, the years of least rainfall (1984 and 1985) were largely responsible for the equally sharp recession limbs. All three wells are located upstream of the dam site and GG-9 is 15kms. from the coastline at Dibba. The general recession of levels between 1983 and 1987 was 21.0 m. in Wells GG-10 and GG-8 and 16.0 m. in Well GG-9. The relatively smaller drop in the level in Well GG-9, despite its more upstream location than the other two wells, is less than would otherwise be expected due to the fact that the water-bearing deposits are made up of old and more compact terrace gravels with lower transmissivity than the recent gravels of Wells GG-10 and GG-8 (JICA, 1980).

Unlike the piedmont plains, the mountain wadis and the recharge zone at the foothills, where the storage capacity of aquifers is limited and where fluctuation in groundwater levels is more pronounced, changes in the groundwater levels in the desert foreland are less dramatic owing to the larger storage capacity and distance from recharge zones. The average yearly decline of the water-table in the three wellfields of Dubai ranges between 0.5 and 0.8 m., with the decline in Al Aweer wellfield between 1961 and 1988 being 16.0 m. As seen in Figure 5.50, the groundwater level changes in Al Hibab wellfield (Fig. 5.50 A) are more noticeable and the drop in levels is greater than those for Al Wuhoosh and Al Aweer wellfields further down owing to its upgradient location. In the wellfields of the northern dune area of Al Ain, careful monitoring, made possible by the large number of wells in each wellfield, and alternating abstraction with wells not in production being allowed to rest for long periods, groundwater levels recover, particularly in the immediate vicinity of the wells. The result is clearly demonstrated in the hydrographs Figs. 5.51 to 5.54 by the gentle decline, as in the Kara' wellfield, which is the oldest among this group of wellfields north of Al Ain (Figs. 5.52 C and D). The most acute continuous drop in the wellfields of the northern dune area has been in Mohayyer East (Fig. 5.51 A) and Al Hayer North (Fig. 5.53 C) wellfields where the average annual decline in the groundwater levels is about 1.0 and 0.5 m. respectively. Many wells have run dry in Mohayyer East and the rate of redrilling or deepening of wells in Mohayyer is the highest among the Al Ain wellfields.
In all the public supply wellfields of the desert foreland in Dubai and Al Ain, despite careful monitoring and the fact that, in the case of Dubai, the bulk of the demand is being met by desalinated water, the hydrographs still show the consistent downward trend (Fig. 5.50 A to C). The public supply wellfields of Sharjah, especially that of Al Badea’ (north and south), have groundwater levels in their production wells below MSL, even lower than the groundwater levels at Al Aweer and Al Wuhoosh of Dubai (Fig. 5.50 B and C). The observation wells in these wellfields have long been left 'hanging' above the continuously receding water-table.

Perhaps the clearest demonstration of depletion of aquifers in the alluvial deposits nearer to the recharge zone that have limited storage capacity, is that of Al Wushah and Hamdah wellfields situated between the Dhaid and the Ghareef plains south of the town of Al Dhaid. The former had run dry by 1987, less than two years after commissioning, while the latter is in the process of doing so, to be replaced by the new wellfield at Seih Al ‘Aqareb between Jabal Buhayes and Qarn Muleih, (to the west of Wadi Yudai‘ah and upgradient of the three Dubai wellfields).

Some coastal wellfields have levels standing below MSL. The MEW wellfield of Sahwat in Wadi Ghaleelah, in the extreme north of Ras Al Khaimah, has groundwater levels at 14.0 m. below MSL (Fig. 5.56). In the lower reaches of Wadi Al Baseerah, in the vicinity of Dibba, water is abstracted from Well GG-1 and Well GG-3, whose groundwater levels stand at 2.0 m. and 14.0 m. below MSL, respectively (Fig. 5.57 B). Similarly, at Kalba in the extreme southern part of the east coast, groundwater levels fluctuate between 2.0 and 4.0 m. below MSL (Fig. 5.57 C).

Other localities, where fast responses to recharge and abstraction are taking place, are those where groundwater is being drawn from 'perched' aquifers, which may be of a limited vertical thickness but are widespread laterally as at Manama in Wells GP-1 and GP-3 (Fig. 5.45 A and B) or within the thick deposits of large wadi basins, such as Wadi Al Beeh at Burairat, where such water bodies are perched at levels higher than that of the underlying main aquifer from which Al Burairat wellfield (50-60 m. below surface) is drawing its water. Perched water bodies may be found at various isolated pockets overlying the main
aquifer within large wadis or outwash fans, especially in the northern limestone mountains.

5.5.2.3. **Short-term fluctuation of groundwater levels:**

The steep gradient of the underlying bedrock, or that of the permeable water-bearing strata, may have a great influence on the rapid lowering of the water-table after recharge events by means of natural gravitational discharge to the sabkhas or directly to the sea. However, the most important factor in short-term water level fluctuation is that of pumpage or withdrawal from the aquifers. This is clear in localities where groundwater level observation wells are situated near farms where one or more motor-pumps are abstracting water for agricultural purposes. Figures 5.71 to 5.73 for the observation well GP-15 in Wadi Khadhrah, 8kms. south-east of Al Dhaid, show the effect of regular daily pumpage from two private wells in a nearby garden. Figure 5.71 illustrates the downward trend throughout February 1987 until the last week of the month when recharge water appeared to have reached the vicinity of the borehole. This recharge was from rainfall that had occurred previously in both December and early February, as represented by the upward limb of the plot in the chart. Figure 5.72 for the same well (GP-15), at the peak of the summer in July with no recharge having taken place since March, shows the continuous downward trend, but also the regular daily pumping with the flattening or widening of the limbs in the otherwise rhythmic succession coinciding with Thursday of the week. Figure 5.73 (also for Well GP-15) is for November 1988, again illustrating the regular fluctuation caused by the short-term daily pumping sessions, but with a long period in the centre of the chart when the pumps were laid off for a period of 11 days between the 15th. and the 26th. of the month. Figure 5.73, for Well GWR-7 in Al Ain (MAF) for July 1983, shows pronounced fluctuation due to daily pumping from nearby wells with differences between the start and the peak of operation of up to 5 metres or almost two-fold the fluctuations for the Dhaid region in GP-15 (Fig. 5.72).

In the hydrographs of water levels in the gravel-filled mountain wadis, foothill locations along recharge zones, gravel-filled wadi courses extending well into the sandy desert foreland and outwash fans, especially the narrow eastern coastal zone, the recession and recovery
limbs tend to be steep reflecting cycles of abstraction and recharge. This is well illustrated in the hydrographs for the piedmont plains observation wells from Al Hamraniyyah in the north (Fig. 5.49 A) through to Al Manama and Um Ghafah in the south (Figs. 5.45 to 5.55), foothill recharge zone locations such as Idhn (Figs. 5.48 D and 5.60 B), outwash fan locations in intermontane basins such as Muzeirea' (Figs. 5.48 C and 5.65 C), mountain wadis within the ophiolite zone such as Gulfa (Fig. 5.65 B) and Masfut (Fig. 5.65 A).

Water levels fluctuate more dramatically in mountain wadis cut into impervious volcanic bedrock (ophiolite) with relatively thin gravel and coarse sand mantle, than in wadis underlain by pervious carbonate rocks with thicker gravel and sand mantle, as is shown in Fig. 5.60 A and B for Al Burairat and Idhn, and Fig. 5.58 A and B for Dhuhuriyyeen and Kidnah. Dhuhuriyyeen in Wadi Al Sha’am and Al Burairat in Wadi Al Beeh are both situated in the northern limestone highland of Ru‘us Al Jibal (Fig.5.70 A, B and E). Water levels in both these wadis are deeper than for wadis in the ophiolite highland to the south, and the response to recharge and abstraction is milder due to the larger storage capacity caused by the surrounding and underlying pervious carbonate rocks. Kidnah (Fig. 5.58 B), Sha’arah (MAF Well BHF-15 Fig. 5.63), just downstream of the Wadi Ham dam, and GG-9 (Fig. 5.66 A), near Al Halah in upstream Wadi Al Baseerah, show groundwater levels in wadis underlain by impervious ophiolite rocks, with relatively less thickness of the alluvial mantle in addition to the narrow wadi basins; hence the steep recession and recovery limbs shown in their hydrographs in response to recharge from rains and subsequent abstraction.

Similarly, the four hydrographs for Al Madam Well GWR-1 (Fig. 5.64 A), Mileiha GP-6, GP-7 and GP-11 (Fig. 5.64 B to D) show levels in identical environment as that of Wadis Sha’am and Al Beeh underlain and surrounded on either side by carbonate rocks in a geosyncline where the Quaternary alluvial mantle, underlying the Ghareef Plain between Jabals Fayah-Mileiha and the main mountain block, is thought to be thin. The recession and recovery limbs are identical in all the four hydrographs despite the variation in the water level in each. The reservoir capacity could be large, as can be conjectured from the moderate fluctuation in the plots of the graphs.
The level at GP-11 (Fig. 5.64 D), which is higher by 9-10m. than GWR-1 at Al Madam (Fig. 5.64 A) 24 kms. to the south, and is about 12m. above GP-6 (Fig. 5.64 B) 10 kms. to the north, and 16m. above the level in GP-7 (Fig. 5.64 C) only 5 kms. to the north-east, may indicate perched water conditions. Identical conditions occur in Habhab-Khatt in Well RK-14 (Fig. 5.59 A).

The steepness of the recession and recovery limbs become less pronounced with distance from the mountains despite the presence of highly permeable deposits, though these deposits may be covered with the advancing sands from the west. This milder response is due to the fact that both the lateral and vertical extent of the deposits becomes greater and therefore the storage capacity larger. Examples of such a condition are GWR-1 at Al Madam (Fig. 5.48 B) as well as GWR-2 at Falaj Al Mualla (Fig. 5.61 B). The latter is illustrated by the series of hydrographs in Figure 5.62 A to F.

Wherever the permeable alluvium extends along the wadi courses into the sandy desert foreland, with its composition varying from coarse to medium sands and gravels, as in Wadi Al Dhaid and Wadi Khadhrah (Figs. 5.61 A and C), the steepness of the recovery limbs is maintained, a result of the funnelling of floods along the wadi channels and also of direct infiltration in the highly transmissive deposits. However, further from the piedmont plains in the sands of the desert foreland, the gentler limbs, as illustrated by the hydrographs of the various points noted earlier, are also clearly shown in the hydrographs for Falaj Al Mualla (Fig. 5.62 A to F), Sirrah (Figs. 5.55 C and 5.70 D), Wadi Fareekh (Fig. 5.70 C) and those for the three Dubai wellfields of Al Aweer, Al Wuhoosh and Al Hibab (Fig. 5.50 A to C).

The fluctuation of water levels in the desert foreland is between 1.0 and 2.0 m. and recovery is barely noticeable. This is clearly seen in the set of hydrographs for Falaj Al Mualla GWR-2 (Fig. 5.62 A to F), which shows the monthly fluctuation of the water-table for a year with least (1984), others with moderate (1980 and 1981) and years with exceptionally high rainfall (1982 and 1988). Falaj Al Mualla is situated on Wadi Lamhah, 18km. from the mountain front and rainfall in the vicinity of Falaj Al Mualla itself may not be as high as in the catchment area further east (e.g. the total rainfall for 1988 for Falaj
Al Mualla was 177.4mm., while for Filli in the upper Ghareef Plain it was 268.4mm., for Sfini it was 235.0mm. and for Masfut in the mountains it was 315.8mm). It may take a year or more for groundwater to reach Falaj Al Mualla from the foothills of the mountains (Mar’ee, 1978). Even the input of recharge water is hardly noticeable in the series of hydrographs owing to the greater lateral extent of the water-bearing strata and, naturally, the larger storage capacity in the vast desert foreland.

Wadis along the east coast exhibit, within short distances, the whole range of groundwater level fluctuation trends, from the sharp to the nearly flat, in response to recharge and abstraction as is demonstrated by the set of hydrographs for Wadi Al Baseerah GG wells (Fig. 5.66 A to E) and those for Wadi Ham (Fig. 5.68 A to C) and the corresponding long profiles Figures 5.67 and 5.69. In Figs. 5.67 and 5.69, the water-table in the lower coastal part of the outwash fans of wadis Al Baseerah and Ham is nearly flat and parallel to the equally flat ground level.

Well GG-9 is situated, as noted earlier, 15 kms. upstream of Wadi Al Baseerah near Al Halah, where the wadi is narrow, and where oscillations in groundwater levels due to recharge and recession are visible in the hydrograph in the steep limbs of the graph (Fig. 5.66 A). The limbs become less steep in Wells GG-2 and GG-6 (Fig. 5.66 B and C) downstream until they almost flatten out in Wells GG-4 and GG-1 where the groundwater levels are 20m. and 4m. below mean sea level respectively, and the actual levels are in delicate balance with, and floating over, saline water (Fig. 5.66 D and E).

It is clear from the preceding detailed discussion of this important aspect of water resource appraisal, groundwater levels, that the water-table (from official groundwater level measurement) is consistently receding in all the areas of the Emirates with groundwater potential, and with it the groundwater in storage is systematically shrinking. The persistent decline in the groundwater levels is clearly illustrated in all the groundwater level hydrographs Figs. 5.45 to 5.74, which all show, without exception, this advanced state of groundwater overdevelopment. This means that groundwater is being mined from both replenishable and non-replenishable reserves. This should be put in
context with all the adverse hydrogeological and other aspects treated in this chapter and Chapters 4, 6, 7, 9 and 10. The presentation and analysis of this variety of hydrographs, covering nearly every part of the Emirates where water levels are monitored, provide an embracing testimony to the critical state of the groundwater resources.

5.7. Synopsis

In this chapter the key terms needed for groundwater appraisal have been defined and discussed. Using them, detailed descriptions of the aquifers comprising the complete system of the Emirates have been provided. This comprehensive inventory, extending from the pre-Cambrian to the Quaternary ages, has furnished a definite structure within which the national water resources have been assessed throughout the remainder of the study. Bearing this structure in mind, the national pattern of groundwater flow, together with the levels and their fluctuation has then been described to demonstrate the consistently receding groundwater levels and the shrinking fresh groundwater resources in storage.
Groundwater level recorders in the Emirates

Sources: MAF; WED (AL AIN); MEW.

Figure: 5.42.

Figure: 5.43.

Groundwater-level recorders in the lower Wadi Ham (the Fujairah outwash fan) and Kalba, 1990.
Figure: 5.44.


(These observation wells were originally installed by the Japan International Cooperation Agency (JICA) in 1980)
Groundwater level hydrographs of wells in the western piedmont plains (1983-88).

The continuous groundwater level decline has been more pronounced in localities where excessive groundwater abstraction has led to the development of depression cones, as in the Dhaid region, where the decline in groundwater levels has been 13-14m. since 1983, and the average annual drop in levels has been 2.3m. (GP-15, (H)) and 3.1m (GP-16, (G)).
Groundwater level hydrographs for the southern part of the western piedmont plains (the Al Ain region (1979-88)).

The Ghashabah public supply wellfield is situated close to the Al Awha government wheat farm. The average annual groundwater level drop has been 1.3m. since 1979. The decline in groundwater levels has been greater in the vicinity of the numerous irrigation wells of the wheat farm, with an increasing number of these wells running dry.
Groundwater level hydrographs for wells in the Um Ghafah public supply wellfield of Al Ain in southern Al Jaww Plain (1982-88).

In Um Ghafah, in southern Al Jaww Plain in Al Ain where there is a marked density of groundwater abstraction points of several competing users, groundwater levels have been receding at an annual rate of between 1.0m. and 4.0m., with a large number of the public supply wellfield of Um Ghafah demonstrating average annual groundwater level drops of over 3.0m. The most acute recorded annual groundwater level drop of 3.8m. was in Um Ghafah Well-401.
Groundwater level fluctuations are pronounced in foothill locations such as Ibdn or Muzeirea' where the effects of recharge and subsequent heavy groundwater abstraction is noticeable. However, the general consistent groundwater level decline is maintained despite the seasonal fluctuations and the average annual groundwater level decline for Muzeirea' and Ibdn is 1.7m. and 7.0m. respectively. There was also a short-lived rise in levels caused by the heavy rains of February 1982 in the same two places of 5.0m. and 7.0m. respectively. The levels in the hydrographs for Kalba and Al Madam exhibit less dramatic fluctuations: the one for the foothill location of Al Madam could be for a confined (artesian) aquifer in which positive (recharge) and negative (discharge) effects are less pronounced because of the sealing effect of the top impervious layer; the one for the coastal location at Kalba is due to the softening of the level fluctuation by the shallowness of groundwater levels and the artificial rise of the levels caused by seawater intrusion.
Figure: 5.49. (A to C)

Groundwater level hydrographs of general groundwater level decline for: (A) Al Hamraniyyah in the northern part of the western piedmont plains; (B) Al Dhaid Plain in the central part of the western piedmont plains; and (C) Al Madam Plain in the southern part of the western piedmont plains (1977-88).

All these wells are in recharge areas close to the foothills where the effects of recharge and withdrawal are marked. Notice the continuous decline in groundwater levels in Al Hamraniyyah and Al Madam coincidental with the dry period 1984-1986. Well GWR-3 in Al Hamraniyyah did not recover after this period of drought and had run dry by 1986.
Groundwater level hydrographs for the three Dubai public supply wellfields in the desert foreland: (A) Al Hibab (1976-88); (B) Al Wuhoosh (1972-88); and, (C) Al Aweer (1961-88).

In all the public supply wellfields of Dubai in the desert foreland, despite the careful monitoring and the fact that the bulk of the domestic water demand is being provided by desalinated water, groundwater levels still show the consistent decline. The noticeable groundwater level fluctuations in the Al Hibab hydrograph are because of the closer location of this wellfield to the foothills than the Al Aweer wellfield which shows milder groundwater level fluctuation. There has been a general drop of levels of 12-15m. in the Al Aweer wellfield despite the large storage capacity of this desert foreland aquifer. However, the pump levels of most of the wells in Al Wuhoosh and Al Aweer wellfields are below MSL.
Figure: 5.51. (A to C)

Groundwater level hydrographs for: (A) Mohayyer East; and, (B) and (C) Suwaihan Road public supply wells of the northern dune area of Al Ain (1978-88).
Source: WED Al Ain.

(Commentary for the hydrographs Figs. 5.51 to 5.54 is given below Fig. 5.54)
Groundwater level hydrographs for: (A) and (B) Bida' Bint Ahmad; and, (C) and (D) Al Kara' public supply wells of the northern dune area of Al Ain (1977-88).

(Commentary for the hydrographs Figs. 5.51 to 5.54 is given below Fig. 5.54)
Groundwater level hydrographs for: (A) and (B) Al Kara' North; (C) Al Hayer North; and, (D) Jubaita (Bida' Bint Saud) public supply wells of the northern dune area of Al Ain (1981-88).

(Commentary for the hydrographs Figs. 5.51 to 5.54 is given below Fig. 5.54)
Groundwater level hydrographs for: Bida' Bint Saud (A) West, (B) East, (C and D) Al Hamam public supply wells of the northern dune area of Al Ain (1979-88).

(Commentary for the hydrographs Figs. 5.51 to 5.54.)

In the wellfields of the northern dune area of Al Ain, careful monitoring of the wellfields, made possible by the large number of wells in each wellfield, and alternating abstraction with wells not in operation being allowed to rest for long periods to recover the levels in their vicinities. The result has been the not so sharp fluctuation of groundwater levels, although the general systematic decline in groundwater levels is maintained in all the wells. Al Kara' wellfield, which is the oldest among this group of wellfields north of Al Ain, illustrates clearly this decline (Fig. 5.52 C and D; Fig. 5.53 A and B). The most acute continuous drop in groundwater levels has been in Mohayyer East and Al Hayer North wellfields where many wells have run dry (Fig. 5.51 A; Fig. 5.53 C). The rate of redrilling or deepening of wells in Mohayyer East wellfield is the highest among all the Al Ain wellfields.
Figure: 5.55. (A to E)

Groundwater level hydrographs of MEW wellfields in the desert foreland and piedmont plains of the Northern Emirates: (A) Wadi Fareekh; (B) Tawis Shunuf and Rashed; (C) Tawi Sirrah 1; (D) Al Dhaid; and, (E) Idhn (1984-88).

Despite the short period of groundwater level records (1984-88), the usual dramatic fluctuation in water levels in foothill and piedmont plain locations (D and E), and the less so dramatic fluctuation in desert foreland locations (B and C), are clearly demonstrated. The sharp fluctuation in Tawis Shunuf and Sirrah are also partly as a result of inaccurate groundwater level readings or the malfunctioning of the much-troubled groundwater level recorders of the MEW.
Figure: 5.56.

Average groundwater level fluctuation in the MEW Sahwat wellfield in Wadi Ghaleelah in Ras Al Khaimah, 3km. from the coast at Mina Saqr in Khawr Khuwair (1980-87).

A classic example of seawater intrusion. Wells of the Sahwat wellfield have most of their pump levels at 14m. below mean sea-level.
Groundwater level hydrographs for: (A and B) Wells GG-8, 9 and 10 in upstream (1977-88); and Wells GG-1 and 3 in downstream, Wadi Al Baseerah; and, (C) Kalba, on the coastal end of the Wadi Ham outwash fan, on the east coast (1977-88).

Apart from hydrograph (A), which shows groundwater levels of wells in the mid- and upstream locations in Wadi Al Baseerah in which such levels are above MSL, hydrograph (B) shows groundwater levels in wells in the Dibba coastal aquifer to be standing at 2.0-14.0m. below MSL. Similarly, the hydrograph for Kalba (C) shows the average groundwater level to fluctuate between 2.0m. and 4.0m. below MSL.
Groundwater level hydrographs showing monthly groundwater fluctuation in Dhuhuriyyeen (Wadi Sha'am) and Kidnah (Wadi Al Farfar, west of Fujairah) HEW wellfields for the two consecutive years 1987-1988.

Both hydrographs show the sharp seasonal fluctuation in groundwater levels due to recharge and subsequent discharge in mountain wadis. The difference between the two wellfields is in their respective location in limestone and ophiolite mountains. Dhuhuriyyeen is in Wadi Sha'am in Ru’us Al Jibal, where the groundwater levels are deep (below 60m. from ground surface) and where their positive and negative responses are milder because of the absorption of water by the surrounding limestone. Kidnah, on the other hand, is situated in Wadi Al Farfar, which is covered by a thin alluvial mantle underlain by an impervious ophiolite base-rock; hence the more dramatic positive and negative responses in its groundwater levels.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>52.0</td>
<td>140.6</td>
<td>7.2</td>
<td>7.4</td>
</tr>
<tr>
<td>Feb</td>
<td>122.6</td>
<td>23.4</td>
<td>4.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Mar</td>
<td>4.8</td>
<td>2.8</td>
<td>8.3</td>
<td>8.0</td>
</tr>
<tr>
<td>Apr</td>
<td></td>
<td></td>
<td>14.5</td>
<td>10.7</td>
</tr>
<tr>
<td>May</td>
<td></td>
<td></td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Jun</td>
<td></td>
<td></td>
<td>23.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Jul</td>
<td></td>
<td></td>
<td>18.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Aug</td>
<td></td>
<td></td>
<td>17.0</td>
<td>17.0</td>
</tr>
<tr>
<td>Sep</td>
<td></td>
<td></td>
<td>16.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Oct</td>
<td></td>
<td></td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Nov</td>
<td></td>
<td></td>
<td>14.0</td>
<td>14.0</td>
</tr>
<tr>
<td>Dec</td>
<td></td>
<td></td>
<td>13.0</td>
<td>13.0</td>
</tr>
</tbody>
</table>

Source of groundwater level data: NAF.
Groundwater level hydrographs for: (A) Habhab in the northern carbonate mountains (1988); (B) Siji in the ophiolite central mountains (1988); and, (C) Tawi Jaheeli in the western edge of the northern part of the piedmont plains (1987).

All these hydrographs show the relationship between recharge and groundwater levels in mountain and foothill locations. Notice the sudden rise of water levels following the winter rains. The levels remain stable up to September, helped by summer rains before starting to fall for both Habhab and Siji. In Tawi Jaheeli the fall in the groundwater level is continuous despite doses of recharge from the winter rains (until April) because of its location on a discrete gravel wadi channel and also the heavy groundwater abstraction in the vicinity.
Groundwater level hydrographs for: (A) Al Burairat; and, (B) Idhn in the northern carbonate mountains (1988).

Whereas Al Burairat is situated within the limestone mountains, Idhn is situated at the edge of the mountain zone where Wadi Idhn opens on the plains. The hydrographs for both wells show the usual sharp responses to recharge, although such responses are relatively milder for Al Burairat due to the larger storage and absorption capacity of Wadi Al Baseerah.
Groundwater level hydrographs for: (A) Well GP-15 and (C) Well GWR-4 in Al Dhaid in upstream locations in wadis in the piedmont plains; and, (B) Well GWR-2 in Falaj Al Mualla on the sandy western fringe of the piedmont plains (1987).

Wherever the permeable alluvium extends along wadi courses into the sandy desert foreland with its composition varying from coarse to medium sand and gravel, as in Wadi Al Dhaid and Wadi Khadhrah (A and C), the steepness of the recovery limbs in the hydrographs is maintained, a result of the funnelling of floods along the wadi channels. Further away in the fringes of the piedmont plains, as at Falaj Al Mualla (B) or in the desert foreland, the responses in the water levels are milder.

The mild graph in the series of hydrographs for Falaj Al Mualla is due to the fact that Well GWR-2 is located near the desert foreland where the aquifer has a large storage capacity; hence the slight variation in the limbs of the hydrographs in response to recharge in years of least, medium or heavy rainfall.

Source of groundwater level data: MAF.

Figure: 5.62. (A to F)
Figure 5.63.

Groundwater level hydrograph for the observation Well BHF-15 at Sha'arah, downstream of the Wadi Ham Dam, showing monthly groundwater level fluctuation for the two consecutive years 1987-1988.

The graph shows typical responses to recharge from the winter rains and the subsequent discharge that follows throughout the drier months in a mountain wadi in the ophiolite mountains. This hydrograph for Well BHF-15 at Sha'arah demonstrates the monthly response of the well to inputs during a moderate rainfall year (1987) and that of an exceptionally rainy year (1988). Rainfall was of a localized incidence in 1987 but was more widespread in 1988 with a substantial quantity feeding the wadi alluvium from the surrounding hills. In this particular example, the steep base-rock gradients and intensive groundwater abstraction by the farms in the vicinity of the well usually lead to the draining of the recharged water as fast as it is put in as is evident by the sharp rise and decline of the limbs of the graph for 1988.
Groundwater level hydrographs for: (A) Al Madam; and, (B to D) Muleiha in the Ghareef Plain in the south-central part of the western piedmont plains (1988).

The four hydrographs are for groundwater levels in a similar environment as that of Sha'am and Al Burairat, surrounded and underlain by carbonate rocks. They are located in the Ghareef geosyncline where the Quarternary alluvial mantle is thin. The recession and recovery limbs are identical in all the four hydrographs despite the variation in the groundwater level in each. The reservoir capacity could be large as can be conjectured from the moderate fluctuation in the plots. It is also possible that the wells represent levels in a confined aquifer showing slight changes in groundwater levels.
Groundwater level hydrographs for: (A) Masfut; (B) Gulfa; and, (C) Muzeirea' in the Hatta-Masfut-Muzeirea' intermontane basin (1988).

The location of both Masfut and Gulfa is in a mountain wadi, with the latter being in a narrower wadi than the former; hence, the sharp recession and recovery limbs in both hydrographs but with those for Gulfa being sharper (A and B). Muzeirea' is located on the lower section of the Muzeirea' outwash fan where groundwater collects from the higher parts of the outwash fan; hence the less acute rise and fall of the limbs in the hydrograph. The shallower groundwater level depths in the Masfut and Gulfa hydrographs than that for Muzeirea' are because of the comparatively thinner water-bearing alluvial mantle that overlies the baserock.
Figure 5.66. (A to E)

Groundwater level hydrographs for the observation wells GG-9, 2, 6, 4 and 1 in Wadi Al Baseerah (1988).

These wells were selected to illustrate the gradual softening of the recession and recovery limbs in the groundwater level hydrographs from upstream mountain wells to downstream coastal wells. In this series of hydrographs of monthly groundwater level fluctuation the extreme responses to recharge and discharge of Well GG-9 progressively flatten in the other wells downstream until the response is negligible in Well GG-1, in which the groundwater level is about 4.0m. below MSL (refer to Fig. 5.57 A and B).
Figure: 5.67.

Configuration of the water-table along Wadi Al Baseerah between the observation well GG-9 (upstream) and the observation well GG-1 on the Dibba coastal strip (1988).

(Refer also to Fig. 5.44 for the location of the wells, and Fig. 5.66 A-E for the groundwater level hydrographs for the same wells)
Rainfall

<table>
<thead>
<tr>
<th>Month</th>
<th>January</th>
<th>February</th>
<th>March</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area average</td>
<td>37.0</td>
<td>33.7</td>
<td>12.0</td>
</tr>
<tr>
<td>Monthly total for Fujairah</td>
<td>258.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Groundwater level hydrographs for: (A) Well BHF-15 at Sha'arah downstream of Wadi Ham Dam; (B) Well BHF-12 at Fujairah airport; and, (C) Well GWR-5 at Al Saff in Kalba (1988).

This is another example of the varied response of groundwater levels to recharge and discharge. Well BHF-15 (A) is located at the apex of the Wadi Ham outwash fan at the point where the waters of Wadi Ham disgorge on the outwash fan, Well BHF-12 (B) in the lower half of the outwash fan at Fujairah airport and Well GWR-5 (C) at the coastal lowest end of the outwash fan at Kalba. Notice the dramatic rise of the recovery limb in upstream Well BHF-15 following the January rains, the milder response of the limb in midstream Well BHF-12 and the slight response in downstream Well GWR-5. The fact that the groundwater level in the last well is below MSL is an added factor to the weak response of the level to the input from the January rains.
Cross-section along the three observation wells BHF-15 at Sha'arah, BHF-12 at Fujairah airport and GWR-5 at Al Saff in Kalba showing the configuration of the water-table in the Wadi Ham outwash fan. Notice the level of the water-table in relation to the MSL at the Wells BHF-12 and GWR-5 (also refer to Fig. 5.68 A to C).

(Refer also to Fig. 5.43 for the location of the wells, and Fig. 5.68 A-C for the groundwater level hydrographs for the same wells)
Groundwater level hydrographs of MEW wellfields in the northern limestone mountains (A and B), in the central ophiolite mountains (E), in the piedmont plains (C) and in the desert foreland (D) (1987-88).

Notice the sharp trends in the limbs of the graph for Kidnah (E) in a wadi in the ophiolite mountains, the milder responses of the limbs for Dhuhuriyyeen and Al Beeh (A and B) in wadis in the limestone mountains and the nearly flat limbs in the hydrographs for Wadi Fareekh and Sirrah in the piedmont plains and desert foreland reflecting the larger storage capacity and distance from the recharge zone.
Figure: 5.71.

Chart from the groundwater level recorder of Well GP-15, southeast of Al Dhaid, showing the daily groundwater level fluctuation for February-March 1987.

The chart illustrates the daily fluctuation of groundwater levels directly affected by pumping from two private wells in a nearby garden. The higher limbs in the hydrograph after the 22nd. of February reflects recharge from the rains of late February and March of that year after the continuous fall in the groundwater level.
Figure: 5.72.

Chart from the groundwater level recorder of Well GP-15, southeast of Al Dhaid, showing the daily groundwater level fluctuation for July 1987.

The chart illustrates the daily fluctuation in water levels caused by pumping from nearby agricultural wells but within the progressive recession of the groundwater levels due to the lack of any noticeable recharge during the summer months. Notice the broadening of the hydrograph limbs at regular intervals representing the stoppage of the pumps during the weekend (Friday).
GP-15
South-east of Al Dhaid
November 1988

Average water level on 26/11/88
was 27.27 m

Figure: 5.73.
Chart from the groundwater level recorder of Well GP-15, souteast of Al Dhaid, showing the daily groundwater level fluctuation for November 1988.

The response in groundwater level to the daily pumping from nearby wells is more acute than has been shown in the previous charts (Figs. 5.71 and 5.72) due to the long summer period of drought since the February 1988 rains which were the heaviest since 1982. Notice the flattening of the hydrograph limb between November 15th. and 26th. when the nearby wells were rested during that period.
In Al Ain where groundwater levels have sunk deeply in the past two decades, the short-lived fluctuation in groundwater levels due to pumping from nearby wells is even more extreme than in the central parts of the piedmont plains in Al Dhaid (Figs. 5.71 to 5.73). The fluctuation in groundwater levels in GWR-7, between the start and the peak of pumping in nearby wells was 5.0m., almost twice as much as the difference in levels in the Dhaid region further north.