Gully morphology in a semi-arid environment: application of laser scanning techniques

Hurst, Catherine Elizabeth

How to cite:

Hurst, Catherine Elizabeth (2006) *Gully morphology in a semi-arid environment: application of laser scanning techniques*, Durham theses, Durham University. Available at Durham E-Theses Online: http://etheses.dur.ac.uk/2329/

Academic Support Office, The Palatine Centre, Durham University, Stockton Road, Durham, DH1 3LE
e-mail: e-theses.admin@durham.ac.uk Tel: +44 0191 334 6107
http://etheses.dur.ac.uk

Gully Morphology in a Semi-Arid Environment: Application of Laser Scanning Techniques

Catherine Elizabeth Hurst

MSc

University of Durham
Department of Geography

January 2006

Declaration.

The author confirms that this work is her own and appropriate credit has been given where reference has been made to the work of others.

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

Acknowledgements.

Firstly, I would like to thank my parents for all their support, encouragement and patience with me, both throughout my first degree and during the whole of this year.

I would like to thank Dr. Ian Evans and Dr. Louise Bracken for all their guidance and help during the course of this work; particular thanks to Dr. Evans for his help with the statistics, and to Dr. Bracken for all her assistance in the field.

Thanks also goes to Dr. Nick Rosser who has been of great assistance, providing access to the laser scanner and Demon software, helping with the fieldwork and pointing me in the right direction with the initial DEM analysis. I would also like to thank Professor Mike Kirkby at Leeds University for his assistance in the field and for providing the rainfall data for this study.

Other people who have assisted me include the lab technicians, in particular Neil Tunstall and Amada Hayton, and thanks for Mike Lim for his initial help with the laser scanner. Thanks also goes to Katherine Arrell at Leeds University and Karl Pederson, formerly of the Durham University IT Service for their assistance with various ArcGIS issues.

Many people have also provided personal support during the past year, which has been very much appreciated. Thanks in particular goes to Hannah Myers, Trevona Hettarachchi, Owen Tucker, Angel Ng, Rebecca Sweet, Riba White, Alice Keen, and Jo Rae.

Abstract.

Recent studies carried out in semi-arid Mediterranean regions have shown gully erosion to have an increasingly significant contribution to soil loss in hillslopes. There is therefore a great need for further monitoring, experimental and modelling studies of gully erosion as a basis for predicting the effects of environmental, climatic and land use changes on erosion rates.

Fieldwork was carried out at two sites in the Rambla de Nogalte catchment, south east Spain in order to identify factors which influenced gully morphology at different spatial scales.

Laser scanning techniques were also applied in order to obtain topographic data that could be related to gully morphology and provide a new level of precision in monitoring gully erosion. The field results showed that there were many components to the erosional response of the hillslopes and gully morphological development, some of which proved to be more significant for gully morphological development than others. At the hillslope scale, the role of topography and land use characteristics were highlighted, and at the smaller scale, the soil surface roughness was the main factor affecting runoff generation and erosional processes.

Table of Contents.

List of Figures.

List of Tables.

1. Introduction.

1.1. Introduction: The Importance of Soil Erosion and Gullying.

The changing form of the landscape with time has long been a principal concern in geomorphology and its importance has been further highlighted in recent years, in part due to the current phenomenon of environmental change. More specifically, the observed trends of environmental change combined with extensive soil degradation and erosion in semi-arid areas has prompted much research into this topic (e.g. Bryan and Campbell, 1986; Cerda, 1997; Kirkby et al., 1998; Lasanta, 2000; Coppus and Imeson, 2002; Martinez-Casasnovas et al., 2003), all of which has highlighted the need for further work to be carried out on this subject. In particular, Poesen et al., (2003) note that there is a great need for further monitoring, experimental and modelling studies of gully erosion as a basis for predicting the effects of environmental, climatic and land use changes on erosion rates.

An understanding of slope processes at a range of scales is also of great importance when studying erosional processes. Indeed, it has been noted by Cammeraat (2002) that scale issues are one of the major challenges in the fields of contemporary physical geography and hydrology: in particular, the establishment of which processes are important at what spatio-temporal scale is problematic. It is tempting to think that there exists an underlying thread or feature at the catchment scale which connects the responses of individual hillslopes and parts of each hillslope to the whole, and that this thread will begin to express itself strongly as the catchment scale is approached (Sivapalan, 2003). However, all research which has been carried out has shown that this is not the case, due to the great heterogeneity of properties across a catchment – and indeed across a hillslope – which cannot be captured and investigated by a study at a single scale, and whose role therefore cannot be generalised. These properties include rainfall variability, topography, soils, vegetation and land use; the non-linear, scale-dependent interactions of each must be taken into account. In particular, there is currently a need for more work to be carried out in order to understand the response of semi-arid hillslopes to specific individual rainfall events: this is due to the fact that if examined systematically or on either a spatial or temporal basis, a lack of systematic patterns becomes apparent (Hooke and Mant, 2002: 200). Consequently, this spatial heterogeneity and need for event-based data presents a major challenge when studying soil erosion on hillslopes.

Soil erosion by gullying has been identified by many authors as a major source of sediment production in semi-arid environments and has been increasingly studied over the past decade, both by field experimentation (e.g. Martínez-Mena et al., 2002; Cantón et al., 2004) and by empirical and process-based modelling (e.g. Desmet et al., 1999; Kirkby and Bull, 2000; Jetten et al., 2003.) In addition, the increasing use of modern spatial information techniques, such as geographical information systems (GIS), digital elevation modelling (DEM) and terrestrial laser scanning (TLS) have created new possibilities for research into this field (Martinez-Casasnovas, 2003). In particular, these techniques allow the amount of eroded materials, the sediment production by gully erosion, the rate of concentrated-flow erosion in agricultural land, as well as topographic effects on the initiation and location of gullies to be determined with increasing accuracy.

Terrestrial laser scanning (TLS) is a relatively new emerging technology, which offers great potential and versatility for rapid collection of detailed data at a range of spatial scales. Despite some studies already carried out using laser scanning technology (e.g. Flanaghan et al., 1995; Darboux and Huang, 2003; Vosselman et al., 2004; Nagihara et al., 2004; Lichti, 2005), it is still in its relative infancy, and all possible avenues for its use have not yet been fully explored. In particular, TLS has not yet been implemented in a large field-based study of gully morphology and hillslope erosion, but its advantageous non-contact method of rapidly collecting accurate soil surface data means that this is an ideal technique for such research.

Gully erosion is defined as the erosion process whereby runoff water accumulates and often recurs in narrow channels and, over short periods, removes soil from this narrow area to considerable depths (Poesen et al., 2003). This phenomenon is particularly prevalent in many areas of south-east Spain due to the intense nature of rainfall events in this region. It is being further exacerbated by the expansion of agricultural practices onto land previously covered by natural mattoral vegetation, which is mostly composed of shrubs and perennial grasses (López-Bermúdez et al., 1998). In addition, soils can exhibit many forms of degradation other than physical loss, including salinisation, acidification, structural decline, water repellence and declining fertility (Conacher and Sala, 1998).

Expansion of agriculture and erosion by gullying are therefore major factors causing land degradation problems across much of the Mediterranean basin, due to the interactions of climate, lithology, soils, relief, and land use characteristics (Martinez-Casasnovas, 2003). It is necessary to develop our understanding of gully erosion in semi-arid regions in order to be able to control and potentially mitigate this increasing problem. Therefore, this is an important area in which more research is required, and the additional use of laser scanning techniques will help to provide much-needed data on gully morphology at the hillslope-scale and smaller.

1.2. Research Aim and Objectives.

Considering the current challenges and research needs discussed above, the main aim of this study was to understand and account for the formation of small gullies on semi-arid hillslopes in south-east Spain, in relation to the topographic settings, soil properties and rainfall characteristics.

In light of this aim, there were four main objectives to this study:

1. Explore the geomorphology of gullies at two sites formed under a rainfall event of known characteristics.
2. Determine a relationship between gully catchment area and gully cross-sectional development along each channel, using data obtained from the laser scanner.
3. Demonstrate the effects of physical soil properties on overland flow pathways and gully morphological development.
4. Evaluate the potential of the laser scanner as a tool for studying gully morphology.

1.3. Scale-Dependent Process Interactions and Gully Morphology.

Gully erosion represents an important sediment source in semi-arid environments such as south east Spain, and the evolution of gullies and channel forms within an individual catchment system is highly reliant upon scale-dependent interactions and feedback-dominated processes (Cammeraat, 2002). Properties affecting erosion processes and gully development on a hillslope include topography, the variability of soil properties, vegetation parameters and land use characteristics. The nature of each can be very heterogeneous across a range of spatial and temporal scales, and this must be taken into account when carrying out research. In south east Spain, where research for this study was carried out, the role of each of these factors was therefore investigated at both the large and small scales. The significance of each will now be briefly considered in turn, in relation to both this study and other research that has been carried out.

1.3.1. The Role of Processes Active at the Large Scale.

Due to the nature of rainfall events in south east Spain – namely that they are both infrequent and intense – the majority of gully erosion is inherently difficult to measure properly due to problems of establishing monitoring networks over large areas where rainfall and runoff are highly variable (Bull and Kirkby, 2002: 11). Consequently, there are numerous studies of generalised hydrological response at the catchment scale and at the experimental plot scale, but relatively few detailed studies at the hillslope scale (Martinez-Mena et al., 1998). Research into processes active at this scale in semi-arid areas is therefore lacking, and the study results to be presented and discussed in this thesis will add to the limited literature on this subject. A deeper knowledge and understanding of the hydrological and erosional response of hillslopes is also very useful for future mitigation against flood events and large-scale erosion. Further development of detailed hillslope models, validated using observations collected in hillslope-scale field experiments can therefore be extremely useful in this context (Sivapalan, 2003).

At the hillslope scale, topography plays an important role in determining gully development. For example, it has been demonstrated in previous research that for given conditions, gullying can preferentially occur or be facilitated on hillslopes where a certain topographic gradient is exceeded (e.g. Poesen, 1984; Martinez-Mena et al., 1998;). This is due to the fact that in semi-arid zones, runoff occurs in the form of Hortonian overland flow because rainfall intensities often exceed the infiltration capacity of the soil surface (Esteves and Lapetite, 2003). This means that the erosive potential of runoff will be mainly governed by hillslope gradient, and runoff direction will be determined by the degree of hillslope concavity. Topography is therefore considered a critical catchment characteristic which will have a major control over pathways for surface and near-surface flow processes (Quinn et al., 1991). This is because the topography affects the distribution of water on and within the soil, the rate at which water moves during and after rainfall, and the processes and rates of sediment movement down the slope (Gabbard et al., 1998).

In addition, slope curvature is a fundamental surface property whose application in geomorphology and hydrology has long been recognised, despite receiving less attention than slope gradient (Schmidt et al., 2003). Plan curvature is defined as the rate of change of a contour line, and it has been widely assumed that this large scale topographic attribute particularly affects hillslope processes and runoff in semi-arid environments. For example, a typical hillslope in this region of south-east Spain is shown in Figure 1.1, and it can be clearly seen that gullies have indeed developed in topographic concavities on steep areas of the slope. This is because overland flow direction is influenced by the relationship between slope gradient and slope curvature during rainfall events. Development of a better understanding of the influence of

Figure 1.1. A typical semi-arid hillslope in south-east Spain.

large-scale slope topography on overland flow is therefore important in erosion studies. In addition, comparative previous research has only been carried out on a limited range of slope angles and plot sizes (e.g. Poesen, 1984; Bryan and Campbell, 1986; Casali et al., 1999; Stomph et al., 2001; Cantón et al., 2004b) using relatively limited approaches. The research undertaken in this study at a variety of scales (> 100 m, ~ 50 m, < 5 m) using new laser scanning techniques to compliment more traditional methods will therefore provide much-needed data on erosion by gullying in semi-arid regions.

An additional effect of large-scale overland flow concentration in topographic concavities is increased vegetative growth due to localised increase in soil water content. This can also be seen in Figure 1.1. There is an important feedback between infiltration, vegetation and land use parameters at the hillslope scale in semi-arid areas, where water stress is an key control on vegetation growth and competition (Beven, 2002: 67). Vegetation is heavily dependent upon water supply from hillslopes, and in semi-arid areas, this is in very limited supply. In semi-arid areas, vegetation therefore develops in locations where the soil water content is highest (Gómez-Plaza et al., 2001). Hillslopes in semi-arid climates generally show poor hydrological connectivity; spatial patterns of soil water are unpredictable, soil water does not always increase towards the base of the slope, and pockets of moist soil may remain isolated in uphill positions (Puigdefabregas et al., 1998). A study carried out on a large area of 12.65 ha by Cantón et al., (2004b) investigated topographic controls on the spatial distribution of natural vegetation in south-east Spain. Results demonstrated that the distribution of ground-cover was related to nearly every terrain attribute (including elevation, slope gradient, plan curvature, profile curvature, contributing area, and slope length factor) due to their influence on soil water, and the majority of relationships were indeed statistically significant.

Many parts of south-east Spain have experienced a recent expansion in agriculture, involving removal of native vegetation in order to flatten sites for intensive farming. This has resulted in relatively widespread soil degradation in both this area and many parts of the Mediterranean region. In particular, the critical factor in this degradation process is ploughing, since it removes the protective cover of vegetation beneath tree crops, leaving the soil bare and open to the influence of erosion by wind and overland flow (Bull and Kirkby, 2002: 10). Extensive Mediterranean areas cultivated with rain fed crops such as cereals, olives, and almonds are therefore very sensitive to erosion due to the hilly topography and bare, shallow soils on which they are situated (Kosmas et al., 1997). The practice of ploughing between tree crops in order to reduce competition for soil water further exacerbates this degradation process.

In addition to the problems caused by land being used for agricultural purposes, subsequent abandonment of such land also affects runoff and sediment yield. In Spain, many large areas once used for agriculture have been recently set-aside in line with European Union agrarian policies, or simply abandoned. The surface affected by this is very large, and little information exists about the environmental consequences of extensive farmland abandonment in semi-arid areas, especially from a geomorphological and hydrological point of view (Lasanta et al., 2000). However, it is inevitable that a land-use change of such a scale must have implications on runoff, infiltration, erosion, and gully development. For example, a study carried out by Cerda (1997) on the nature of soil erosion after land abandonment in south-east Spain showed that it led to the degradation of the ecosystem at least during the first 3 years of abandonment. In addition, a rise in the spatial variability of erosional processes was observed, as well as an increase of runoff and erosion.

It is a well-known fact that variables affecting vegetation cover will also impact infiltration rates and consequently erosion processes (e.g. López-Bermúdez et al., 1998; Beven, 2002: 67; Kirkby et al., 2002). Therefore a study of changes to natural vegetation caused by agricultural practices is an important factor to include in any research into erosion by gullying. Indeed, it has been noted by several authors (e.g. Cerdà 1997; Kosmas et al., 1997; Slattery et al., 2002; Dunjó et al., 2003) that there is a need to develop our current understanding of landscape sensitivity to erosion caused by agricultural expansion and land degradation. In particular, there is a need for this research to be carried out at the hillslope to catchment scale.

While individual factors that influence erosion can be identified, it is clear that actual geomorphological and hydrological processes observed at the hillslope scale are rich complexity and heterogeneity (Sivapalan, 2003). This is because the hydrology of dryland hillslopes can be unpredictable due to the relative lack of rainfall and soil moisture in semi-arid areas, in addition to complex interactions between hillslope topography, vegetation and land use factors. Resulting hydrological isolation of areas on hillslopes can lead to spatial patterning of erosion and gully morphological development when observed at the hillslope scale. For that reason, studies that do not also account for these small-scale heterogeneities will be clearly inadequate for predictive purposes (Sivapalan, 2003). It was with this in mind that the research presented in this thesis was not only carried out at the hillslope-scale. The role of small-scale properties and process interactions was also studied in order to more accurately account for the formation of the small gullies at the two field sites in south-east Spain.

1.3.2. The Role of Small Scale Properties and Interactions.

Originally, erodibility was thought to be a constant characteristic (Nachtergaele and Poesen, 2002) but much research carried out over the past few years has demonstrated that this is by no means the case. Soil erodibility in fact varies over very short distances due to localised differences in microtopography, soil properties, infiltration rates, and vegetation. Consequently, on actual hillslopes, erosional conditions exhibit highly complex response patterns, reflecting the complex interplay of factors (Bryan, 2000). Information on the spatial distribution of soil properties is therefore crucial when predicting volumes and patterns of gully erosion (Nachtergaele and Poesen, 2002). Gully channels can only develop if concentrated (overland) flow occurs during a rain event (Poesen et al., 2003) and even then, the extent of erosion will depend upon the response of the soil surface to overland flow. Therefore another aspect related to the study of gully erosion is the incorporation of spatial variations in soil properties at the small-scale (Nachtergaele and Poesen, 2002). This need to include data on soil properties in any study of gully morphology has also been noted by Bryan (2000) and was used as the basis for his investigation into soil erodibility and processes of water erosion on hillslopes. It was demonstrated that geomorphic and hydrologic processes involved in hillslope sediment transport are indeed strongly influenced by soil properties. However, he also notes that the dynamic complexity of soil surface properties and their effect on hillslope sediment delivery processes has been largely ignored by geomorphologists, and there is still a need for more research into the role of soil properties in order to improve our understanding of this important factor.

Due to the nature of rainfall events in south-east Spain, the emphasis of erosion studies is mainly on overland flow and surface processes. Therefore, soil properties which can have a primary or secondary influence on erosion and gully morphological development include microtopography, particle size, soil organic matter content, infiltration rate, pH and electrical conductivity. Each of these will be briefly discussed.

During a rainfall event, runoff may be reduced by the provision of water storage in depressions at the soil surface (Cremers et al., 1996). Knowledge of the soil surface roughness, or microtopography, is therefore important when studying soil erosion: it is a main factor which both mitigates overland flow by producing discontinuous ponding and determines the initial runoff direction once overland flow begins. Microtopography is itself independent of hillslope gradient, although it is recognised that the presence of a slope may affect the role of this factor during rainfall (Kamphorst et al., 2000). However, the lack of a suitable measurement technique to accurately record soil microtopography at small grid spacings has confined potential description of roughness effects (Huang and Bradford, 1992). The development of GIS and TLS approaches offer the possibility to overcome parts of these problems, combining both process response modelling, spatial heterogeneity and landscape characteristics.

Once overland flow has been initiated, the resistance of the individual soil particles to the runoff will determine the extent of erosion taking place. Particle-size distribution plays the key role in soil susceptibility for material disintegration and erosion: the larger the range of particle sizes, the higher the degree of packing, and hence the greater resistance to breakdown processes (Gallart et al., 2002: 303). Therefore, the higher the concentration of a single particle size in a given small-scale area, the more likely it is that erosion will occur. In particular, silt is the soil particle most easily transported by overland flow (Farenhorst and Bryan, 1995) and areas with a high soil silt content will be predominantly vulnerable. The positive effects of vegetation on soil aggregate stability have also been noted by several authors, both in the form of surface vegetation and soil organic matter content (e.g. Solé-Benet et al., 1997; Lavee et al., 1998; Kirkby, 2001; Beven, 2002: 67). This is due to the important relationship between infiltration and vegetation in semi-arid areas: the density of vegetation increases with available water, and this will tend to offset the possibility of increased runoff generation with increased rainfall (Beven, 2002: 67). Low vegetation

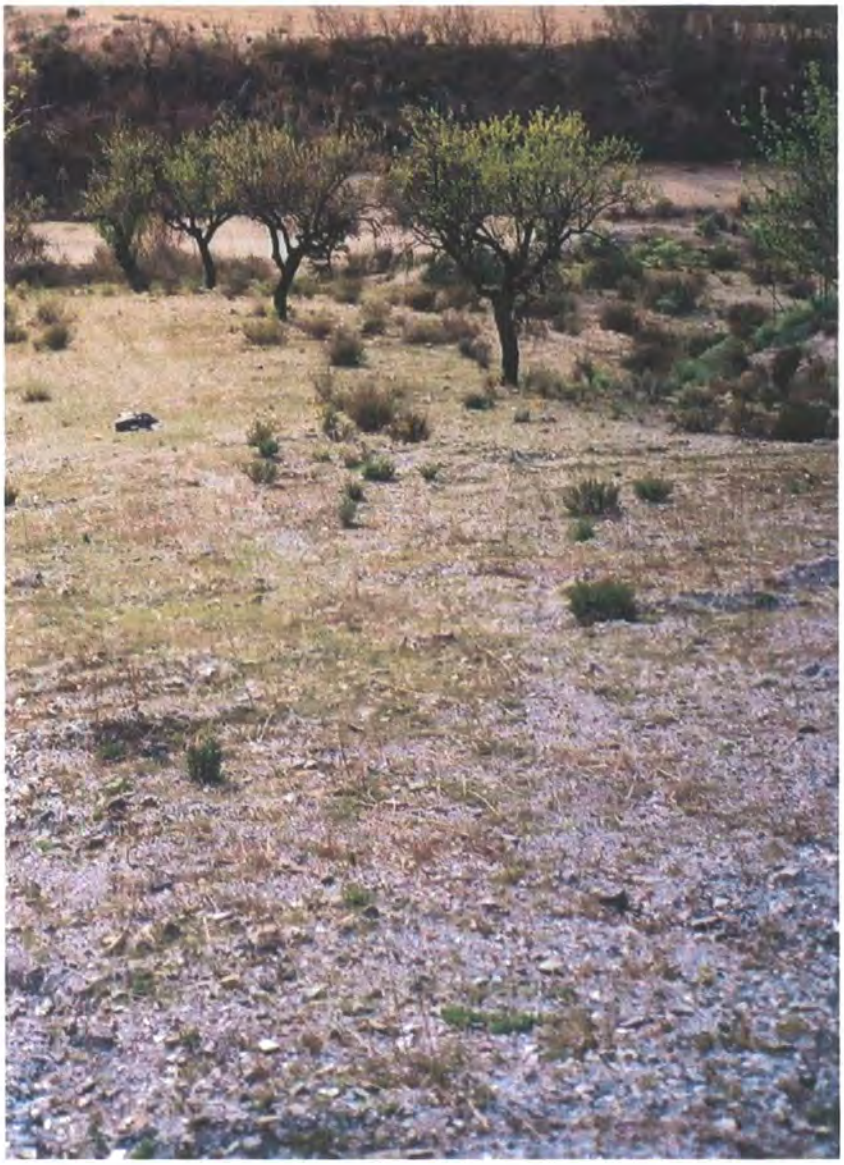


Figure 1.2. Abandoned site in south-east Spain: limited vegetation and ground cover make this site prone to erosion and result in degraded soil which is inhibits further re-growth.

cover means that the ground surface is unprotected against rainsplash and overland flow, and low soil organic matter content means that the intrinsic stability of the soil itself will be reduced, and will become gradually degraded (as can also be seen in Figure 1.2). Therefore, patterns in vegetation and soil can be important indicators of ecosystem health and hillslope hydrology (Imeson and Prinsen, 2004). This is because vegetated patches have higher rates of infiltration, and the organic matter content of the upper-most soil horizons – the top 6 cm – is largely dependent upon vegetation type and cover (Nicolau et al., 1996). Stable soil aggregates resist entrainment by flow or splash more effectively, which ultimately provides greater strength and resistance against the shear stresses generated in channel flow (Bryan, 2000). A further consequence of this is that areas on a hillslope with a high soil omc therefore have a higher water retention capacity which encourages infiltration: the colonisation and growth of additional vegetation is thereby encouraged in a small-scale positive feedback relationship. For example, in a study carried out by Kosmas et al., (2000), the effects of vegetation on the degree of erosion in semi-arid Mediterranean environment were investigated. Results demonstrated that soils on the landscape studied would improve in time under good vegetation cover conditions by accumulating organic material, enhancing soil aggregate stability, increasing infiltration capacity and decreasing erosion potential. The role of vegetation in creating spatial heterogeneity, and its implications for water and sediment redistribution in semi-arid regions is therefore a significant factor to consider in any study of erosion in the field.

Secondary variables which can impact vegetation growth, infiltration rate and ultimately gully morphological development at the small-scale include soil pH and electrical conductivity (ec). These soil properties are particularly significant in semi-arid environments where high evaporation rates and frequent lack of soil water can cause local accumulation of salts in the upper soil layers in this climate. A very alkaline soil or high ec can actively prevent re-growth of plant cover due to its inability to support vegetation, resulting in further land degradation. In addition, the abandonment of agriculture and cessation of ploughing can exacerbate this problem.

An investigation carried out by Dunjó et al., (2003) into soil erosion after land abandonment in north-east Spain demonstrated that continued land abandonment reduced soil infiltration and increased runoff and erosion during following years. This, in turn, slowed the establishment and growth of new vegetation, reducing the recovery rate of the land. Indeed, many sites in south-east Spain are currently experiencing this difficulty caused by agricultural abandonment. In addition, it is obvious that land-use change of such magnitude must have large effects on infiltration, runoff and sediment yield in the region. Although the area which could be affected by these processes is very large, little information actually exists about the environmental consequences of extensive farmland abandonment in semi-arid areas, especially from a geomorphological and hydrological point of view (Lasanta et al., 2000). Therefore, further research comparing naturally-vegetated hillslopes with both abandoned sites and sites used for agricultural purposes is necessary.

Considering all the above-mentioned factors, their spatial arrangement is critical in determining the extent of overland flow and its effectiveness as an eroding agent. Their connectivity and interaction is responsible for the evolution of a gully network structure on a hillslope. In addition, reconciliation between the simplicity observed at the hillslope scale and the complexity inferred by small-scale interactions must be reached. One way to achieve this is to focus on common concepts or patterns that have physical meanings, then determine linkages or connections between areas on a hillslope with similar hydrological response. This connectivity of runoff-generating and runoff-absorbing areas is important on all scale levels (Cammeraat, 2002), and will be considered further in the following section.

1.4. Hillslope Connectivity and Gully Development.

In south east Spain, water limitation is very much a driving factor in geo-ecosystem pattern development: the hydrologic connectivity of hillslopes is often poor due to the relative lack of water in this environment. Therefore, overland flow resulting from low-frequency, high-magnitude (or 'intense') rainfall events exceeding the infiltration capacity of the soil is an important runoff-generating mechanism. The region of south east Spain is no exception to this, and a frequent result of these intense rainfall events is the development of gullies, whose morphology is dependent upon the interactions of large- and small-scale factors discussed in sections 1.3.1 and 1.3.2 respectively.

Gully erosion results from a hydrological connection between a runoff contributing area and a runoff collecting network (Souchère et al., 2003). Once formed, however, gullies may further increase connectivity on a hillslope, facilitating the movement of both water and sediment across parts of the landscape. As scale increases, the connectivity between smaller areas becomes more important for the movement of water and sediment. Therefore, the role of gullies in connecting parts of a hillslope is very important and further research on this subject is needed. The development of GIS approaches offers the possibility to overcome parts of these problems, allowing integrated studying of small-scale spatial heterogeneity and large-scale hillslope characteristics. On actual hillslopes, however, conditions vary greatly over short distances reflecting the complex interplay of factors (Bryan, 2000). Therefore it is still necessary to include a translation of these finer-scale properties of landscape parts into a broader-scale framework (Cammeraat, 2002) in order to fully understand gully geomorphological development.

One method of accomplishing this is the procedure of identifying small-scale hillslope areas – or 'response units' – which have comparable internal characteristics and a similar response to rainfall, then considering their interaction at a larger scale. The spatial variation of these small-scale 'source' and 'sink' response units is caused by differences in hydrological behaviour between soil patches. This process also acknowledges that soil erodibility is not a single, simply identified property, but is the summation of a highly complex response pattern, strongly influenced by intrinsic soil characteristics and extrinsic, macroenvironmental variables (Bryan, 2000).

For example, this approach was used in a study by Kirkby et al., (2002) in which the generation of runoff at a field site in south-east Spain was determined independently for each potential source point, and the role of the landscape was in determining connectivity between these sources and the chosen outlet was investigated. Subcatchment areas were divided into 'hydrologically similar surfaces' (HYSS), as distinguished by using a combination of geology, land use, and topography. These were then employed in a model to show spatial patterns of runoff-response, and connectivity of areas to the larger channel network. Following the same line of research, other studies have been carried out in which 'source' and 'sink' areas called hydrological response units (HRUs) and hydrologically similar units (HSUs) have also been determined and identified over a variety of plot scales ranging from 10 m x 2 m (Bergkamp et al., 1996) to hillslopes (e.g. Cerda, 1995; Fitzjohn et al., 1998; Becker and Braun, 1999) and catchments (e.g. Karnoven et al., 1999; Kirkby et al., 2002).

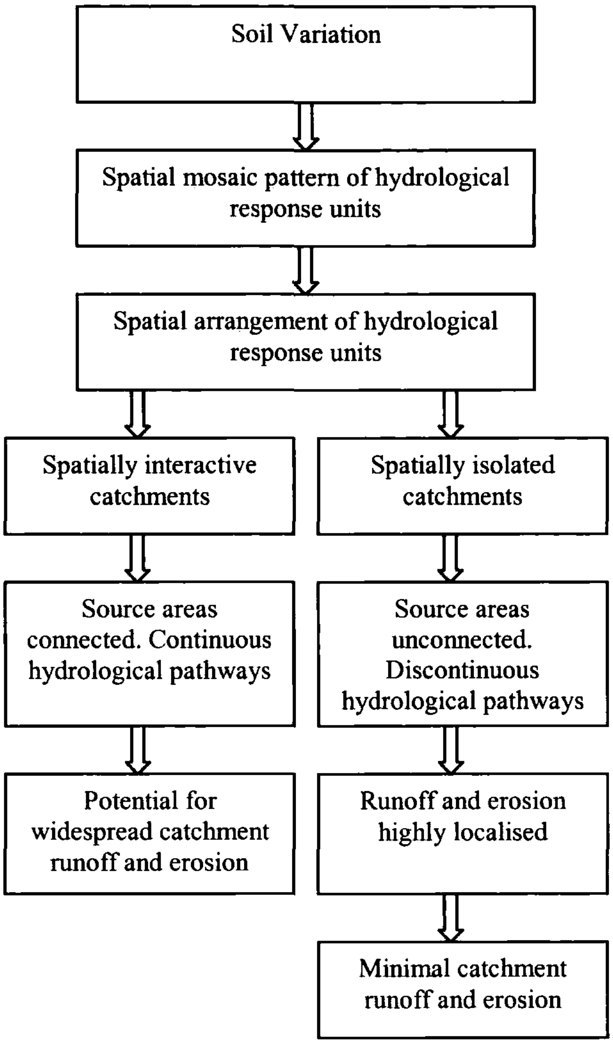


Figure 1.3. Conceptual model of the relationships between soil variation, the spatial arrangement of hydrological response units and the occurrence of widespread runoff and erosion (after Fitzjohn et al., 1998: 66).

At the small-scale, the spatial configuration of these units and their connection to the gully channel system determines the geomorphic and hydrologic response of the hillslope, as shown in the conceptual model in Figure 1.3. Surface runoff from source areas which are spatially isolated and upslope of the channel will be re-absorbed by the surrounding drier areas which act as sinks for overland flow, and will not contribute to hillslope outflow (Fitzjohn et al., 1998). In a semi-arid environment in particular, the connectivity of these runoff-generating and runoff-absorbing areas is important on all scale levels (Cammeraat, 2002). This is because rainfall and soil water are more limited in this environment, and runoff production is therefore more patchy. In addition, there is also a great need for better understanding of how different areas in a hillslope or catchment fit together and how these mosaics and the factors causing runoff and erosion change both spatially and temporally (Kirkby et al., 2002).

1.5. Summary.

Gully erosion is a significant sediment source in Mediterranean areas, and gullies act as effective links on a hillslope, transferring both overland flow and sediment relatively rapidly (Poesen et al., 2003). Runoff generation and gully erosion at the hillslope scale are shown to be an end result of spatially and temporally complex processes. As discussed in the sections above, these processes operate at different scales, but it is impossible to describe the end result at the hillslope scale by a simple aggregation of small-scale processes (Beven, 2002: 75). Therefore in order to properly understand the nature of gully morphological development on a hillslope in a semi-arid environment, a study must be undertaken at both scales.

There is a need for much more research to be undertaken in order to elucidate how various factors including precipitation, topography, land use, vegetation, and soil properties affect gully erosion (Poesen et al., 2002: 256). Previous work has also highlighted the need for a better understanding of how different areas within a hillslope system fit together, and how these mosaics and the factors causing runoff vary (Kirkby et al., 2002). In particular, at the small-scale, gully erosion on hillslopes has not received as much attention as erosion processes active at the large-scale (Valcárcel et al., 2003), which provides another challenge for future research.

The field research presented in this thesis has been conducted at two field sites with differing land uses, at both large and small scales in the context of a single, known rainfall event. It is hoped that by taking into account several variables including topography, land use, vegetation, and soil properties, that the work undertaken will provide much-needed data on gully erosion in semi-arid environments. In addition, the use of laser scanning technology will provide unprecedented data and allow gully morphology and process interactions to be more readily accounted for at both scales. In the next chapter, details of the study methodology will be given, followed by presentation and discussion of the research results.

2. Fieldwork Sites and Methodology.

2.1. Introduction.

The fieldwork for this study was carried out in south-east Spain in the Guadalentín basin. The climate in this area is semi-arid with long, hot and dry summers. Average annual rainfall in this region is between 235 mm y^{-1} and 350 mm y^{-1} (Castillo et al., 2003; Cantón et al., 2004) and the average annual temperature ranges from 14.7 °C to 17.8 °C (Kosmas et al., 1997; Vandekerckhove et al., 2003). This chapter will firstly describe the characteristics of the wider catchment and channel area, then discuss the individual field sites where the fieldwork was conducted. Secondly, the field methods used to carry out the research, including an outline of the laboratory work will be explained, followed by a description of the laser scanning techniques used.

2.2. Catchment and Channel Characteristics.

The fieldwork was conducted in the Rambla de Nogalte catchment, which is located within the Guadalentín basin in south-east Spain on the border between the Spanish provinces of Murcia and Almería. (Figure 2.1). The Rambla de Nogalte catchment is 171 km^2 and has a channel length of approximately 33 km, as measured from its upper reaches to the town of Puerto Lumbreras. The Nogalte is typical of many semi-arid basins in the Mediterranean: it is a dynamic catchment and the main channel is a broad gravel-bed river, varying greatly in width from just a few metres to over 300 m in places, surrounded by gently sloping convex hillslopes (Shannon et al., 2002). The main channel is dissected by a series of braided channels that carry the lower flow events that rework the channel bed in between larger flood events. The geology of the

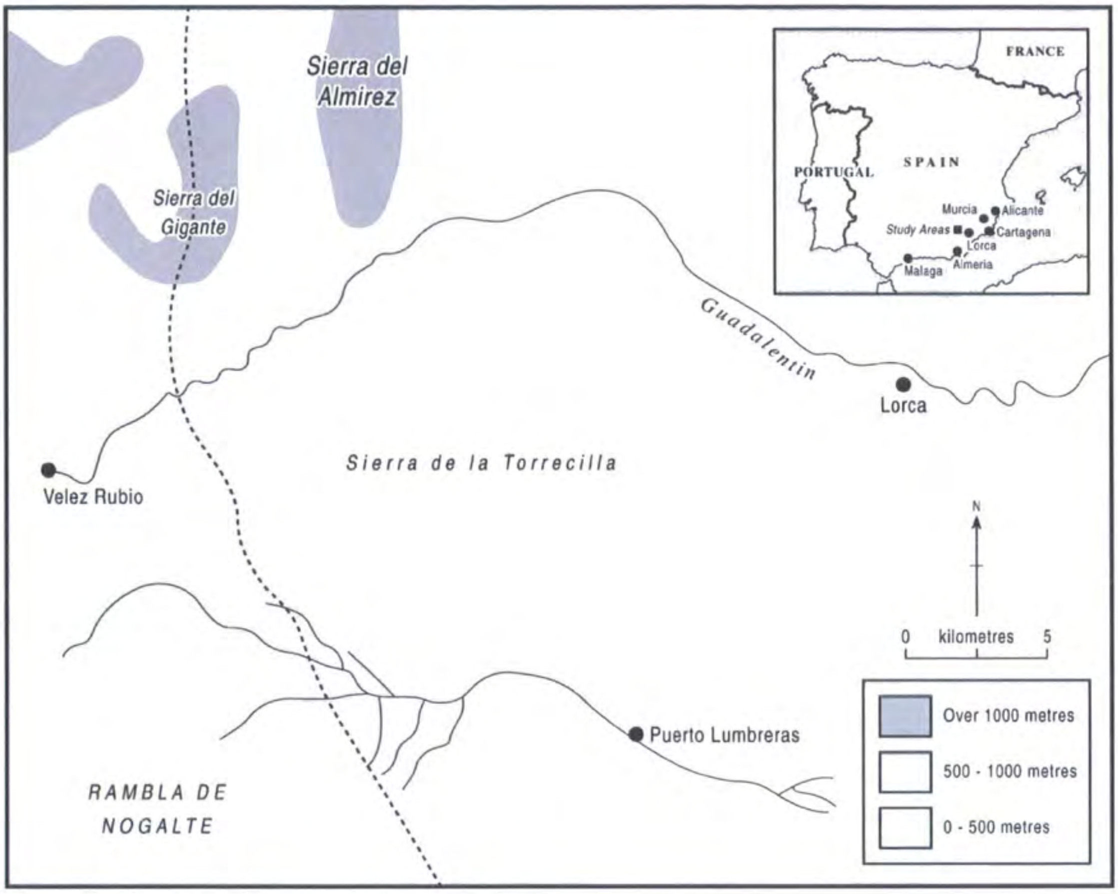


Figure 2.1. Map indicating the location of the Rambla de Nogalte. Dotted line indicates boundary between provinces of Murcia (to the east) and Almería (to the west).

Figure 2.2. The upper section of the Rambla de Nogalte catchment. The varying colours in the foreground reflect the underlying red and blue varieties of mica schist.

Rambla de Nogalte consists mainly of metamorphic rocks and conglomerates, dominated by red mica schist with localised outcrops of blue mica schist (Bull et al., 1999) (Figure 2.2). The red mica schist has a greater iron content than the blue, which causes this apparent difference in colour. The soils on the red mica schist are thick, whereas those developed on the blue mica schist are comparatively shallow with thin vegetation cover.

Land use in the Nogalte consists of a combination of almond and olive cultivation on suitable slopes, whereas shrubs and natural mattoral are prevalent elsewhere. Mattoral is a natural scrub mainly composed of grasses, rosemary, thyme, and anthyllis; it provides a more continuous ground cover compared to tree crops (Cantón et al., 2004). The zonation of vegetation along ephemeral ramblas is highly variable, both in terms of coverage and species, and this can be caused both by localised changes in the underlying bedrock and environmental factors (Cerdà, 1998; López-Bermúdez et al., 1998). The vegetation and land use of the Nogalte must be considered as key components of the channel system due to their influence on the processes and impacts of a flood event.

The Guadalentín basin, in which the Rambla de Nogalte is situated, was one of the most energetic water courses in the western Mediterranean during the nineteenth century, and has also suffered many large floods in the twentieth century in terms of morphological and socio-economic effects (López-Bermúdez et al., 2002). Consequently, the Rambla de Nogalte itself has also experienced catastrophic flood events in the past, the most recent of which occurred in October 1973. Due to the unanticipated nature of this flood, a market was being held within the Nogalte channel, which resulted in the death of many people from the town of Puerto Lumbreras. This event was the result of a severe storm related to an intense cold low-pressure cell, in which flood water discharges of over 2100 m^3s^{-1} were recorded and major re-working of the main channel occurred (López-Bermúdez et al., 2002).

2.3. Rainfall Characteristics.

The occurrence of flash flooding in semi-arid environments is related to the spatial and temporal patterns of rain storms in the catchment. Monthly rainfall totals ranging from 0 mm to over 200 mm have been recorded in the Rambla de Nogalte area, and yearly totals are in the region of 300 – 350 mm (Cantón et al., 2001). The wettest months tend to be in the latter part of the year, in particular September, October and

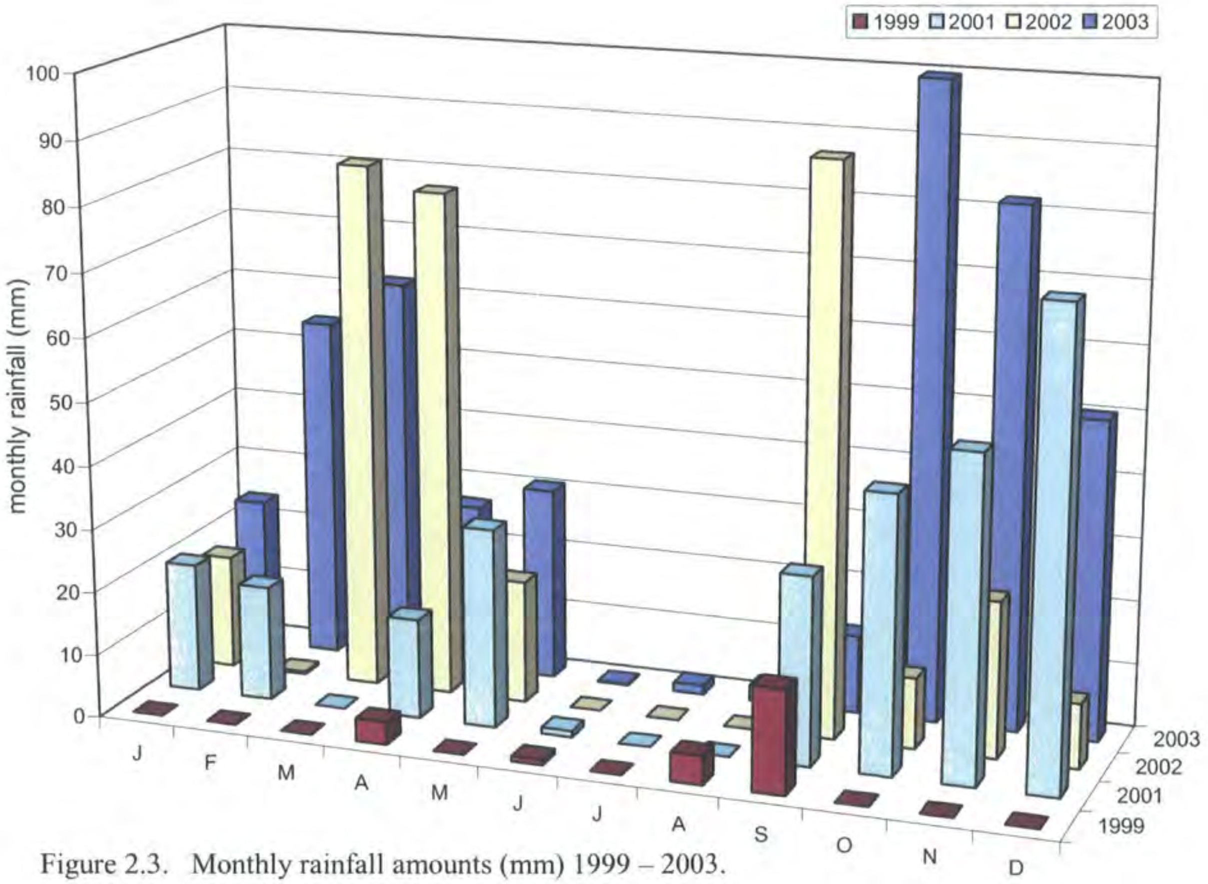


Figure 2.3. Monthly rainfall amounts (mm) 1999 – 2003.
Data taken from rain gauge 'South 1' situated within the Ramble de Nogalte catchment at 41° 58' N, 59° 01' W.

November. There is little or no rainfall in June, July and August. The nearest meteorological station to the Rambla de Nogalte is located 16 km from the catchment in the town of Lorca. Tipping bucket rain gauges have also previously been installed at several locations across the Nogalte catchment, providing a more local rainfall record, as shown in Figure 2.3. The specific location of these rain gauges is shown in Figure 2.4.

2.4. Field Site Characteristics.

A reconnaissance of the Rambla de Nogalte channel and catchment area was carried out before selecting individual sites in which to carry out the field research. The sites were chosen on the basis of several attributes, the first of which being how comparable they were to one another: this meant taking into consideration the sites' topography, land use, geology, and the presence of ephemeral gullies on the land. The number and location of the field sites was also taken into consideration in order to reduce the travelling time, thereby maximising the efficiency of the research period. The topography and agricultural land use at both sites were comparable factors: both Site 1 and Site 2 had gently sloping convex hillslopes and were planted with almond trees. However, the geology at each site was different: the former consisted of a red mica schist, whereas the latter was predominantly a blue mica schist. By basing the site selection on certain similar characteristics, the number of variables that required investigation was reduced. Taking too many variables into consideration would not have been feasible given the timescale in which the research was conducted. The location of Site 1 and Site 2 within the Rambla de Nogalte is indicated in Figure 2.4.

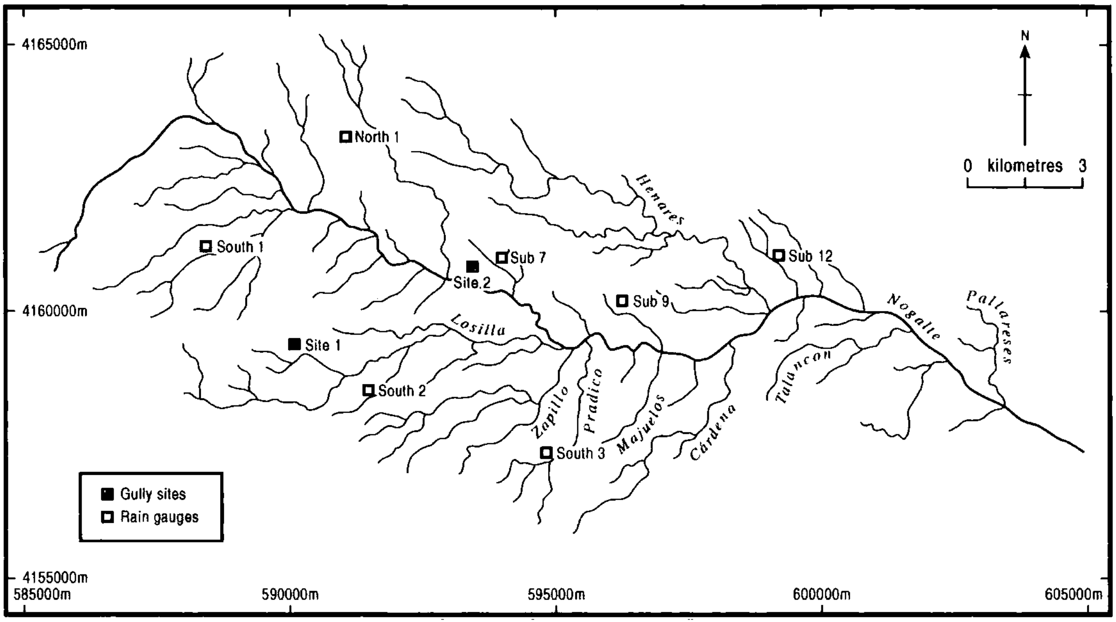


Figure 2.4. Map indicating the fieldwork sites within the Nogalte catchment.

2.4.1. Site 1.

The first site, located at 1°58'43" W, 37°35'15" N, is a maintained almond plantation which is also used for the grazing of sheep and goats. In between the crop of almond trees there is relatively little vegetation: this is because the field is ploughed in order to leave the soil bare to prevent the almond trees having to compete for water with grasses that establish in between plough events. However, The almond trees themselves provide little ground cover, and grasses and small shrubs eventually establish in some areas, providing some soil surface protection until the field is next ploughed. This field was last ploughed in June 2003 and will be next ploughed again at the end of March 2004. This site was selected primarily because of the presence of three relatively large ephemeral gullies on the hillslope (Figure 2.5). It can be seen that the gullies are situated within topographic hollows, and the fans at the base of each indicate how much sediment has been eroded and mobilised as a result of their

Figure 2.5. Photograph of Site 1.

formation. The gully features are removed when the field is ploughed between large storms, but the sediment eroded will have increased the prominence of the topographic hollow in each case, thereby adding to the likelihood that ephemeral gullies will preferentially form in the same locations in future. The current size of each sediment fan suggests that this is indeed the case, since it would have taken more than one rainfall event for such volumes of sediment to be mobilised. According to the farmer, the three gullies currently present at Site 1 were formed in October 2003 during a single intense rainfall event. This event was recorded by several tipping bucket raingauges in the Rambla de Nogalte catchment, and will allow the morphology of each gully to be associated with a given rainfall amount and intensity.

2.4.2. Site 2.

The second site is located at 1°57'50" W, 37°35'37" N and is an abandoned almond plantation, which now forms part of privately-owned land. It is hoped by the land-owners that natural mattoral vegetation will regenerate if the area beneath the almond trees is no longer ploughed and maintained. However, it is taking a considerable amount of time for natural vegetation to re-establish, and much of the soil surface remains relatively bare (Figure 2.6). This site was selected because the existence of ephemeral gullies on the land, as well as the presence of almond trees, made it comparable to Site 1. However, the geology at Site 2 was different because blue mica schist is predominant in this area of the Nogalte: the topsoil is much more slaty than at the first site and is of a more grey-blue appearance.

Figure 2.6. Photograph of site 2

2.5. Field and Laboratory Methodology.

As previously discussed in Chapter 1.2.1, the aim of this study was to understand the formation of small gullies on semi-arid hillslopes in south-east Spain in relation to the topographic settings, soil properties and rainfall characteristics (Chapter 1.2). In order to carry out this aim and complete the research objectives, a number of techniques have been used to obtain data for this study. The methodologies employed can be broadly divided into the following three sections: the more traditional field methods used, the laboratory work carried out, and the use of laser scanning techniques. Each of these which will be discussed individually in the following sections.

2.5.1. Field Methods.

The field methods were employed in order to obtain data which could explain the presence of the gullies in terms of topography, rainfall, and soil surface characteristics. The interaction of these factors will affect the behaviour of overland flow and therefore erosion and gully morphological development.

At each site, the gully morphology was first measured by hand. Gully cross profiles were taken by measuring widths and depths across each channel at five metre intervals from the base to the top of the slope (Figure 2.7). This permitted gully morphology to be recorded, and also allowed the total gully volume – and therefore sediment loss – to be calculated. These gully cross profiles measured by hand will also be compared with similar data obtained from the laser scanner in order to evaluate its potential as a tool for studying gully morphology.

Rainfall data was obtained from several tipping bucket rain gauges that have been installed across the Rambla de Nogalte catchment. The data stored by the rain gauges was downloaded onto a laptop computer in the field, and was saved for later analysis. This system of rainfall observations will provide an insight into processes operating within an ephemeral channel catchment, and it will be possible to link erosion and flood events to specific rain storms. However, rainfall intensity alone will not account

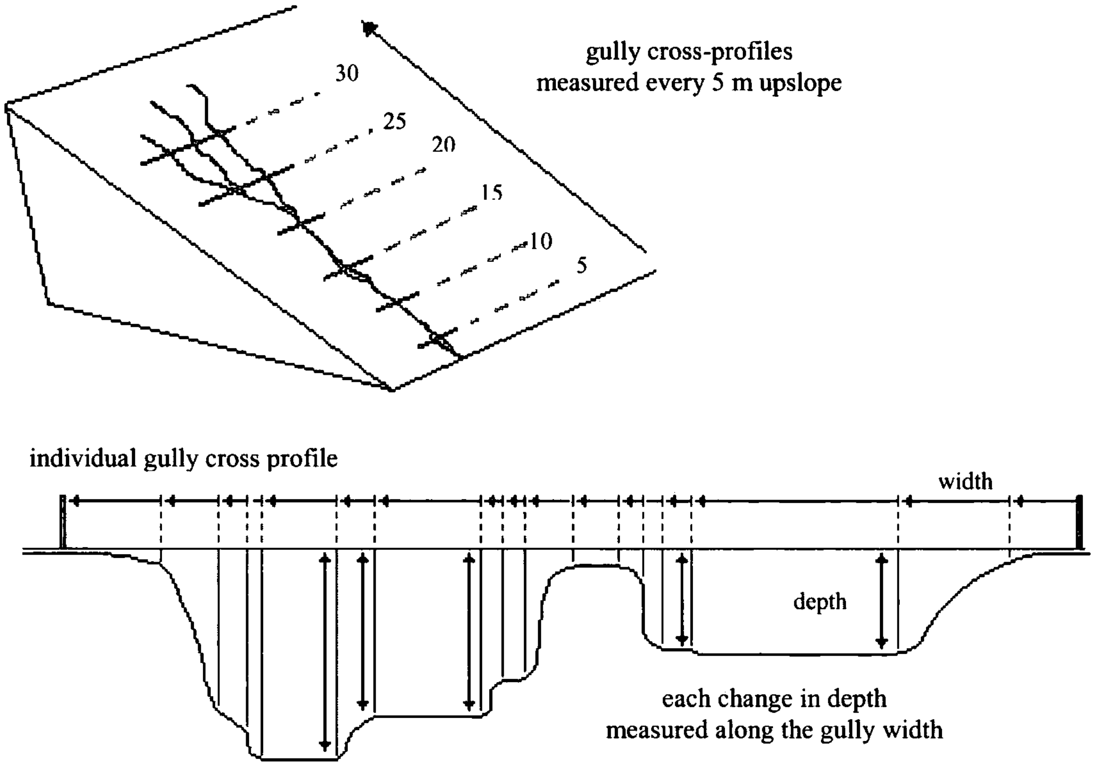


Figure 2.7. Method of gully cross profile measurement.

for areas of the catchment that produce higher runoff discharges; in order to adequately explain the catchment's response to a rainfall event, it is necessary to take topographic settings, soil properties and land use factors into consideration.

Agricultural practices and soil structural development both exert a major influence on infiltration parameters in the field. Therefore it is advantageous to make in situ measurements of infiltration with minimum disturbance of the soil surface. Point infiltration measurements were conducted in the field using a double-ring infiltrometer, and each measurement was taken no further than 5 metres from the sides of the gullies at each site. This was in order to obtain data which would give a general overview of surface infiltration trends across each hillslope in areas immediately associated with the gullies. Had these measurements been made within the gully channels themselves, the results would have been influenced by the fact that they were conducted on a previously-eroded surface.

Fifteen measurements of infiltration were made at Site 1, and three were made at Site 2; the locations of these point infiltration measurements on each hillslope are indicated in Figures 2.8 and 2.9. The infiltrometer inner ring used measured 6 cm in diameter, and the outer ring was 11 cm in diameter (Figure 2.10). Each ring was 15 cm tall, and the inner ring had a 100 mm scale measured on the inside with a tape measure. At each location the rings were inserted into the soil to a depth of 5 cm, taking care to disturb the surface as little as possible. For each experiment, a 500 ml measuring cylinder was used – approximately 400 ml water was poured first into the inner ring until full, and then the remaining 100 ml was poured into the outer ring. This use of an outer buffer ring ensured that flow was one-dimensional for the most part of the infiltration experiment. A stopwatch was then used to measure the time

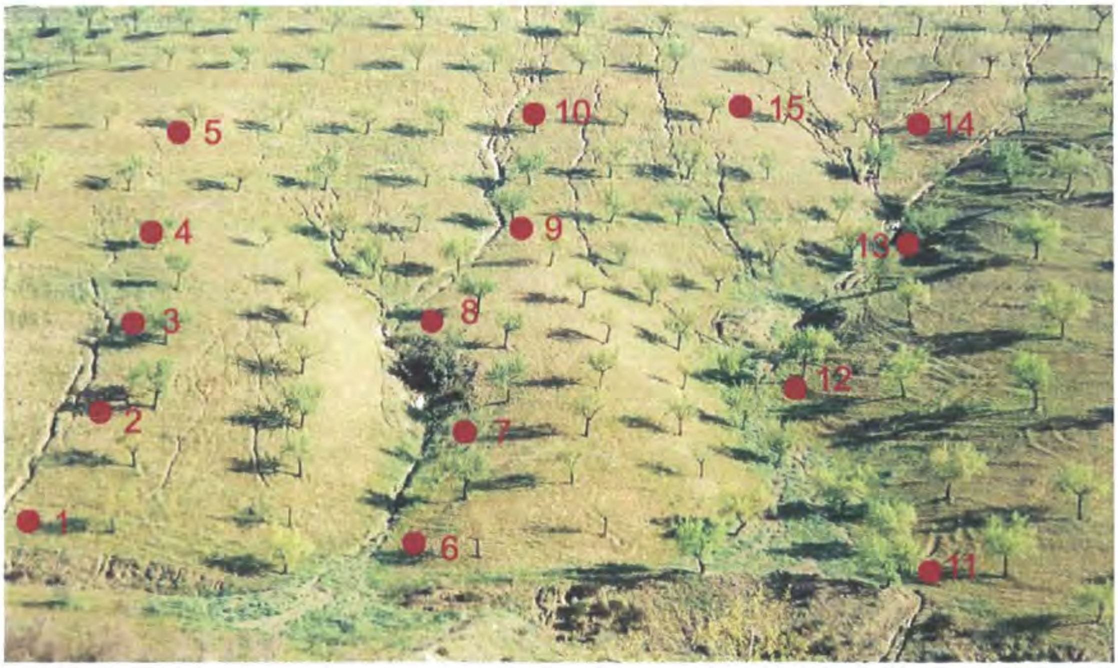


Figure 2.8. Site 1: location of infiltration measurements.

Figure 2.9. Site 2: location of infiltration measurements.

Figure 2.10. The double ring infiltrometer used to conduct point infiltration measurements in the field.

taken for each 10 mm drop in water level in the inner ring until all the water had infiltrated. This procedure was repeated twice at each location without moving either of the infiltrometer rings. This was primarily to observe and measure how the response of the soil to the second run of the experiment was affected by its behaviour in the previous run, providing further insight into the properties having an influence on the infiltration at each location.

Soil samples were taken from both Site 1 and Site 2 at the same location as each infiltration measurement site. The samples were taken from the top 6 cm of the soil profiles using a metal spatula. In semi-arid environments, the upper-most soil horizon (the top 6 cm) contains the soil organic matter and particle size fractions which directly determine the response of the soil surface to rainfall and runoff (Nicolau et al., 1996) These were then used for further analysis in the laboratory. By taking these soil samples at locations corresponding exactly to the infiltration experiments, it will be possible to account for observed differences in the infiltration results in terms of soil characteristics. Soil samples were only taken in areas which corresponded with infiltration experiments because the objective of this fieldwork was to obtain a general overview of surface trends across each hillslope, rather than conduct a detailed analysis of soil surface properties.

2.5.2. Laboratory Work.

The aim of this work was to obtain information on soil properties which could be related to parameters such as the hillslope topography, vegetation, land use, and the infiltration data, in order to account for the gully morphology observed in the field. The soil samples taken at each site were analysed in the laboratory and the soil pH, electrical conductivity, organic matter content, and the particle size distribution were determined. The methodologies will now be discussed, along with the significance of measuring each soil factor.

Soil Particle Size Distribution

Grain size is a fundamental soil property, affecting the entrainment, transport and deposition of sediment (Blott and Pye, 2001), and selective erosion by a range of processes can strongly influence hillslope evolution and gully erosion. Selective erosion may also have important chemical implications, including the selective movement of nutrients and pesticides attached to particles and microaggregates (Farenhorst and Bryan, 1995). Consequently, determining the particle size distribution of a range of soil samples taken from across a hillslope is necessary when considering the erosion processes taking place.

Particle size distribution was determined for each soil sample using a Coulter® LS 230 Particle Size Analyser. Small stones and pebbles measuring over 5 mm were removed beforehand, and a representative sample of between 1 and 2 g from each soil sample was weighed out for further preparation. Each sample was then treated with hydrogen peroxide and heated overnight in order to burn off any organic matter that was present. The samples were then cooled and centrifuged, allowing excess liquid to be drained away, leaving the soil samples for use in the particle size analyser. Each sample was then added to the Coulter® LS 230 Particle Size Analyser in order to determine the grain size distribution. This involves the division of the sediment sample into a number of size fractions, enabling a grain size distribution to be constructed from the weight or percentage volume of sediment in each size fraction.

The Coulter® LS 230 uses laser-based technology to provide accurate results for particle sizes from 0.04 μm to 2000 μm in a single scan (Coulter Corporation, 1998). The particle size data obtained for each sample was then imported into the GRADISTAT computer program for statistical analysis.

Soil Organic Matter

The soil organic matter content is a very important soil property, affecting the physical, chemical and biological characteristics of the soil. Organic matter promotes infiltration by increasing the water-holding capacity of soils, a factor which is of particular importance in semi-arid environments where soil water is by definition in limited supply. Additionally, it promotes the development of stable soil structures by increasing granulation. Furthermore, organic matter is a source of plant nutrients, which will affect soil fertility and therefore agricultural productivity.

In this study, the organic matter content of each soil sample was determined by the loss on ignition method. All the soil samples were passed through a 2 mm sieve, and a representative sample of between 5 g and 7 g soil from each was weighed out into a crucible. These were first dried at 105 °C, re-weighed, and then placed in a furnace at 550 °C for four hours. Following removal from the furnace, the samples were cooled in dessicators before being weighed one final time. Any weight loss constituted the organic matter burnt off, and could be used to calculate the percentage organic matter content of the soil sample.

Soil pH and Electrical Conductivity

Many soil properties and processes are affected by the soil pH, including microbial activity, clay mineral formation, and the ability of a soil to adequately support the growth of crops or vegetation. pH is therefore considered an important soil chemical property. The degree of a soil's acidity or alkalinity is determined by the hydrogen ion (H^+) concentration in the soil solution: the lower the H^+ ion concentrations, the higher the pH value. Crops yield best in soils with pH levels between 6.0 and 7.0, but many soils from semi arid environments tend to have more alkaline pH values due to precipitation of salts in the upper soil horizons.

The pH of each soil sample was measured by taking a representative sample weighing 20 g and initially adding 8 ml distilled water in order to make a thin paste, in which the soil : water ratio was accordingly less than 1:1. This paste was then left to stand for one hour before measuring the pH using a glass electrode. The quantity of distilled water in each sample was then increased to 50 ml, and again to 100 ml and the pH was measured each time. When more water is used, the concentration of H+ ions becomes diluted and the measurements may yield higher pH values (Tan, 1996: 106). As a result it is advantageous to take soil pH measurements at different soil : water ratios.

The electrical conductivity (ec) was also determined in turn for each soil sample collected in the Rambla de Nogalte. Samples were prepared as for the pH measurements, then this procedure was carried out using a solution consisting of 20 g air-dried soil mixed with 50 ml distilled water. Each sample solution was then transferred to a measuring cell, and the ec reading was taken. Soil ec is a component that integrates many soil properties affecting crop productivity: these include soil texture, soil organic matter content, salinity, cation exchange capacity, and exchangeable calcium (Ca) and magnesium (Mg). In particular, the level of soluble salts in a soil solution can be classified by determining the ec. As the level of soluble salts increases, the usual effect is decreased plant growth, therefore this soil chemical property has considerable significance (Benton-Jones, 2001: 150). The relationship between a soil's ec and its degree of a salinity is shown in Table 2.1. Salinity currently affects approximately 25 % of the croplands in the world and is becoming an increasing problem, particularly in semi arid environments due to agricultural irrigation practices combined with high evaporation rates.

Degree of salinity	Electrical Conductivity (μS cm^{-1})
Non saline	0 – 200
Slightly saline	210 – 4000
Moderately saline	4100 – 8000
Strongly saline	8100 – 16.000
Very strongly saline	> 16.100

Table 2.1. The relationship between a soil's salinity and its electrical conductivity. Adapted from Benton-Jones (2001).

2.6. Use of the Laser Scanner.

As discussed in Chapter 1, terrestrial laser scanning offers an advantageous method of collecting accurate soil surface data, which creates new possibilities for research into erosion by gullying. Therefore, a laser scanner (as shown in Figure 2.11) was used in order to produce large-scale detailed digital elevation models of the hillslopes at Site 1 and Site 2. In addition to this, small-scale high-resolution plot scans were made at various locations across each hillslope. The practical use of this tool will now be explained, including a description of the machine itself, the methods of its usage in the field, followed by an explanation of the software used to analyse the data collected.

2.6.1. Laser Scanner Specifications and Field Usage.

The terrestrial laser scanner used in this study, the MDL LaserAce® scanner (Figure 2.11), is one of a new, emerging generation of portable laser scanners currently available, offering great potential for rapid collection of three-dimensional (3D) spatial datasets of entire surfaces (Lichti et al., 2002). The MDL LaserAce® operates following being mounted on a tripod, as depicted in Figure 2.12. According to the manufacturer's product specification (Measurement Devices Limited), this instrument is capable of measuring at a range of up to 700 m, with scanning accuracy of 5 cm. Its maximum spatial resolution is 1 cm, and it can scan up to 250 points per second (MDL, 2003). This scanner operates using a pulse method in which a brief pulse of laser light is emitted, and after reflection by the object being measured, is sensed by a photodetector (Lichti et al., 2002). Once the scan area has been designated, the scanner then sweeps with it the laser; reflected points are stored with individual *xyz* coordinates and recorded on the scanner's memory card, which can hold up to 32 Mb of data, which constitutes 3 million points (MDL, 2001).

The MDL LaserAce® scanner is an extremely robust piece of equipment, weighing just 8.1 kg and requiring relatively simple transportation and field set-up. This makes its on-site use and field potential greatly versatile. In particular, it is comparatively easy to use when compared to the likes of earlier scanners: many required the construction of two-dimensional frames with a track to allow the scanner to alter

Figure 2.11. The MDL LaserAce® scanner (front view).

position. Furthermore, this meant that the area which could be scanned was very limited and use in the field was often impossible (e.g. Huang and Bradford, 1990; Huang and Bradford, 1992; Darboux and Huang, 2003). Currently, a new generation of terrestrial laser scanners (TLS) is becoming increasingly available, offering rapid collection of detailed 3-dimensional data which can be used in a very wide variety of contexts, or as a complementary procedure to more traditional field methods. The ability to monitor the temporal evolution of three-dimensional forms at high resolutions has led to successful applications that have improved the understanding of a variety of fluvial and terrestrial environments (e.g. Latulippe et al., 2001; Genovois et al., 2001; Lim et al., 2005). Other geographically-focused applications of this technique include 3D mapping and change detection in urban environments: TLS techniques have been used in this context to add 3 dimensional data to existing 2 dimensional datasets of towns and cities (Vosselman et al., 2005). Laser scanning has also been used in a sedimentological context for the evaluation of gravel sphericity and roundness (Hayakawa and Oguchi, 2005), for the monitoring and classification of

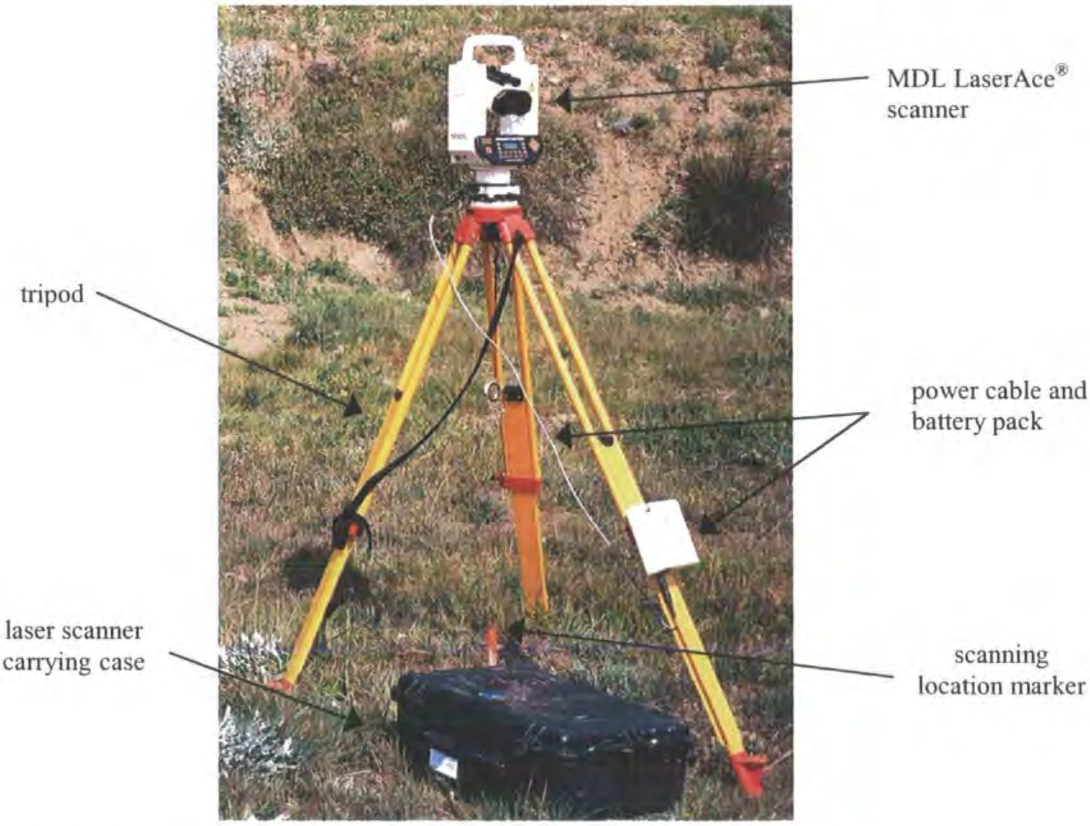


Figure 2.12. The MDL LaserAce® scanner and equipment used in the field.

landslide bodies (Bitelli et al., 2005), for the study of sand dune topography in high spatial resolution (Nagihara et al., 2003), and also in the identification of tree canopy characteristics and foliage density measurement for ecological purposes (Wei and Salyani, 2005). Terrestrial laser scanning has also been used for monitoring the process of hard rock coastal cliff erosion (Rosser et al., 2005), in which the rate and mechanisms governing the retreat of these cliffs are directly measured and monitored in detail. A review of systems and applications of ground-based laser scanners similar to the MDL LaserAce® used in this study was carried out by Lichti et al., (2002). They describe some of the fundamentals of laser scanner operation, followed by a detailed review of five commercially-available scanners (RIEGL LMS-Z210; RIEGL I-SITE, Cyrax 2500, Callidus, and Optech ILRIS-3D). However, even in the few years since Lichti et al., (2002) carried out their system comparisons, significant improvements in TLS have been made: for example, these are highlighted by Bitelli et al., (2005) in their study of landslide bodies over several years in Bologna, Italy. Two studies were carried out: one in May 2002, using a RIEGL LMS-Z210 laser scanner, and one in April 2004 using a RIEGL LMS-Z420i laser scanner. They note that the latter had a much better field performance: in particular, the measurement range, scanning speed, and point cloud intensity of the instrument showed improvement. The RIEGL LMS-Z210 had a data acquisition distance of 2 to 350 m, with a nominal accuracy of about 2.5 cm in the distance, at a rate of 6000 points per second; whereas the RIEGL LMS-Z420i had a data acquisition distance of 2 to 800 m, with a nominal accuracy of about 1 cm in the distance, at a rate of 12.000 points per second (Bitelli et al., 2005). The authors also state that should these technological improvements continue, TLS could represent an effective and rapid solution to produce economical and accurate terrain models in the field.

In addition, a terrestrial laser scanner system comparable to the MDL LaserAce® used in this study was employed by Nagihara et al., (2004) for the study of sand dune topography. They used a Cyrax 2500 laser scanner, manufactured by Cyra Technologies, a subsidiary of Leica Geosystems. The Cyrax 2500 was capable of capturing distances of over 100 m and measuring positions within 6 mm accuracy (Nagihara et al., 2004). It was found that the 3-dimensional surface model of the sand dune created using the point data, could describe its morphology in unprecedented detail, with a level of accuracy far superior to traditional surveying techniques. It is hoped that the use of a comparable laser scanner for the study of gully morphology and erosion in the field will provide unique results, and some much-needed detailed data at scales larger than laboratory or plot scale.

The scans made in the field using the MDL LaserAce® scanner were of two types, and each will now be explained in turn. Firstly, large-scale scans were made of each hillslope at both Site 1 and Site 2 in order to capture hillslope surface topographic detail which included the gullies. These initial scans were made at 20 cm resolution. However, one problem encountered in the field was caused by the almond trees. Their presence meant that it was not possible to scan the whole hillslope from one tripod position. This was due to a 'shadow effect' which was created by the trees: the area immediately behind the almond trees would not be scanned, but rather, the trees themselves would (as shown in Figure 2.16). This problem associated with TLS was also noted by Bitelli et al., (2005): they state that zones characterised by vegetation cover, shadows or other obstacles are not always feasible areas in which to carry out laser scanning. In these cases, only manual work on the datasets carried out by an operator after scanning can produce high quality data.

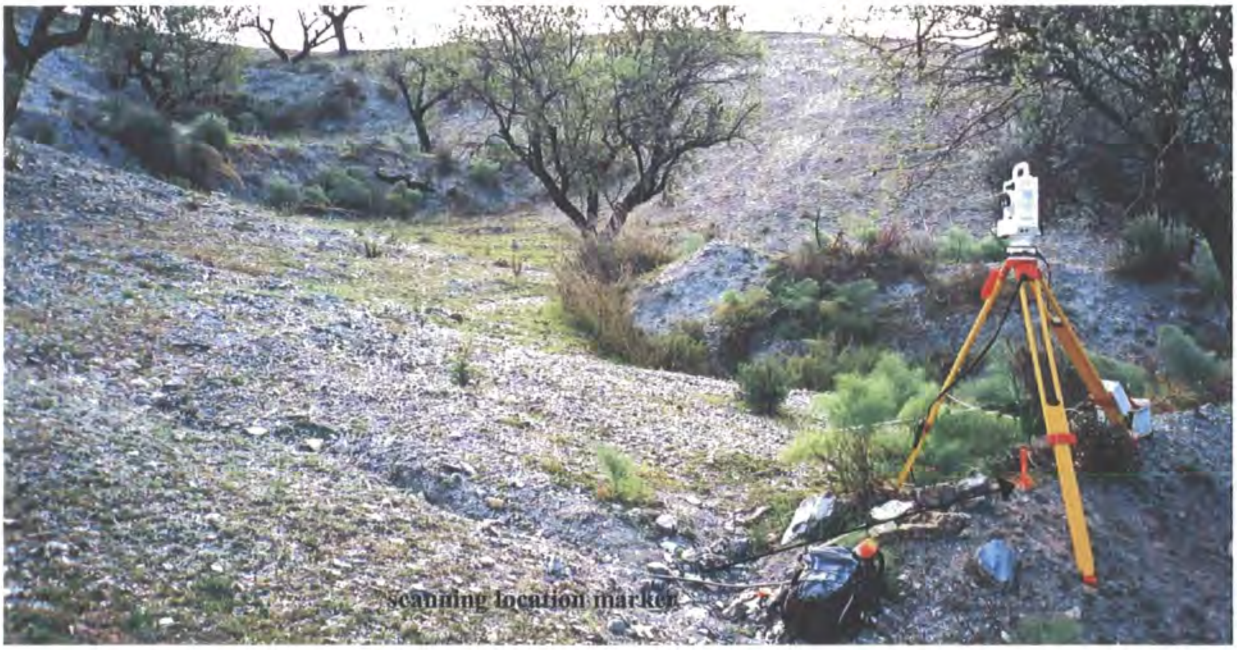


Figure 2.13. The MDL LaserAce® scanner in use at Site 2. The orange marker indicates the location of the initial scanning position (base point).

In order to overcome the problem posed by the almond trees at Site 1 and Site 2, locations were selected on each hillslope to which the scanner and tripod could be moved in order to scan around and behind the trees, obtaining the best possible 3-dimensional representation of the area. The scanning locations were identified by orange markers (Figure 2.13) and their *xyz* coordinates were taken relative to all other orange markers on the hillslope before each movement of the laser scanner. This permitted the scans to be linked together and overlapped during subsequent data processing, generating a more detailed 3-dimensional coverage of the hillslope. The location of these orange scanning location markers at both sites is shown in Figures 2.14 and 2.15. At each field site, small-scale plot scans of the individual gullies were also carried out. These were made at several locations along each gully, either where topography experienced a significant change which appeared to influence the channel, or where it was decided the morphology of the gully justified a

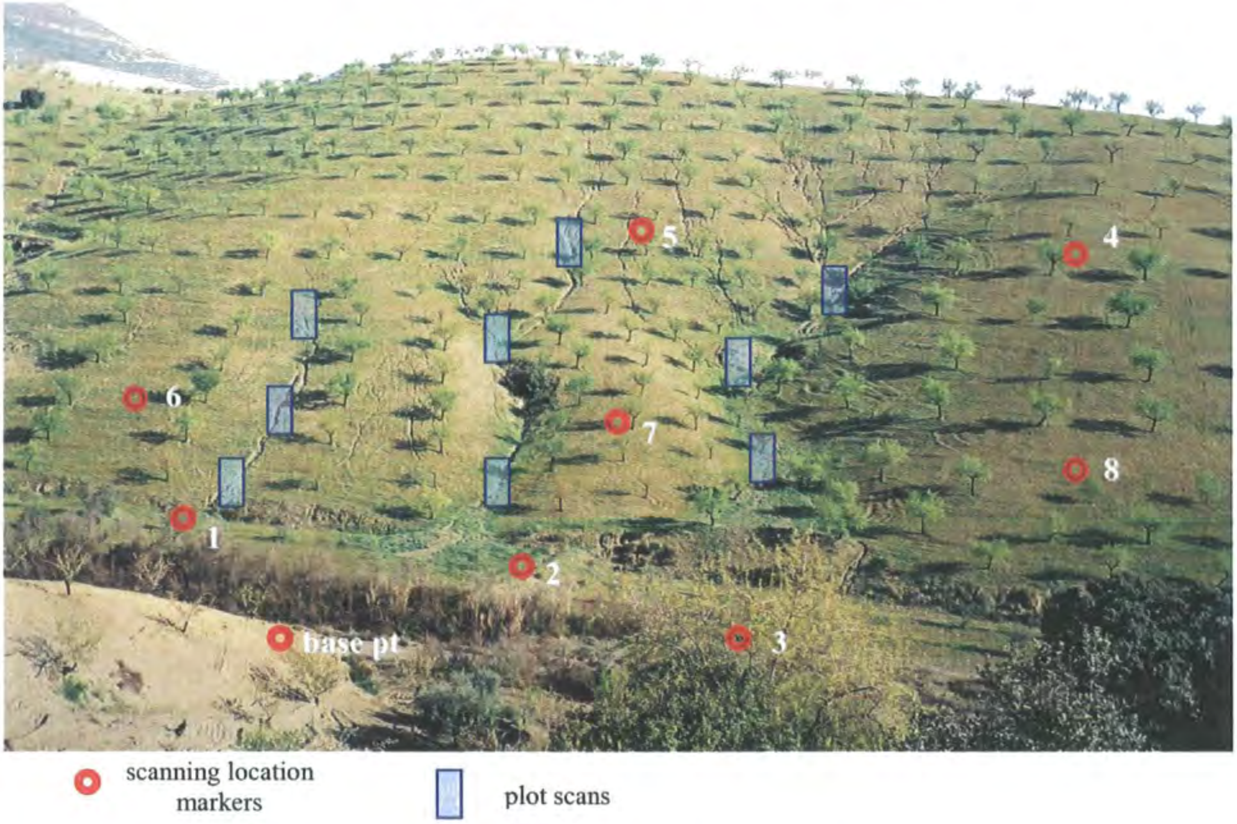


Figure 2.14. Site 1: plots scans and scanning location markers.

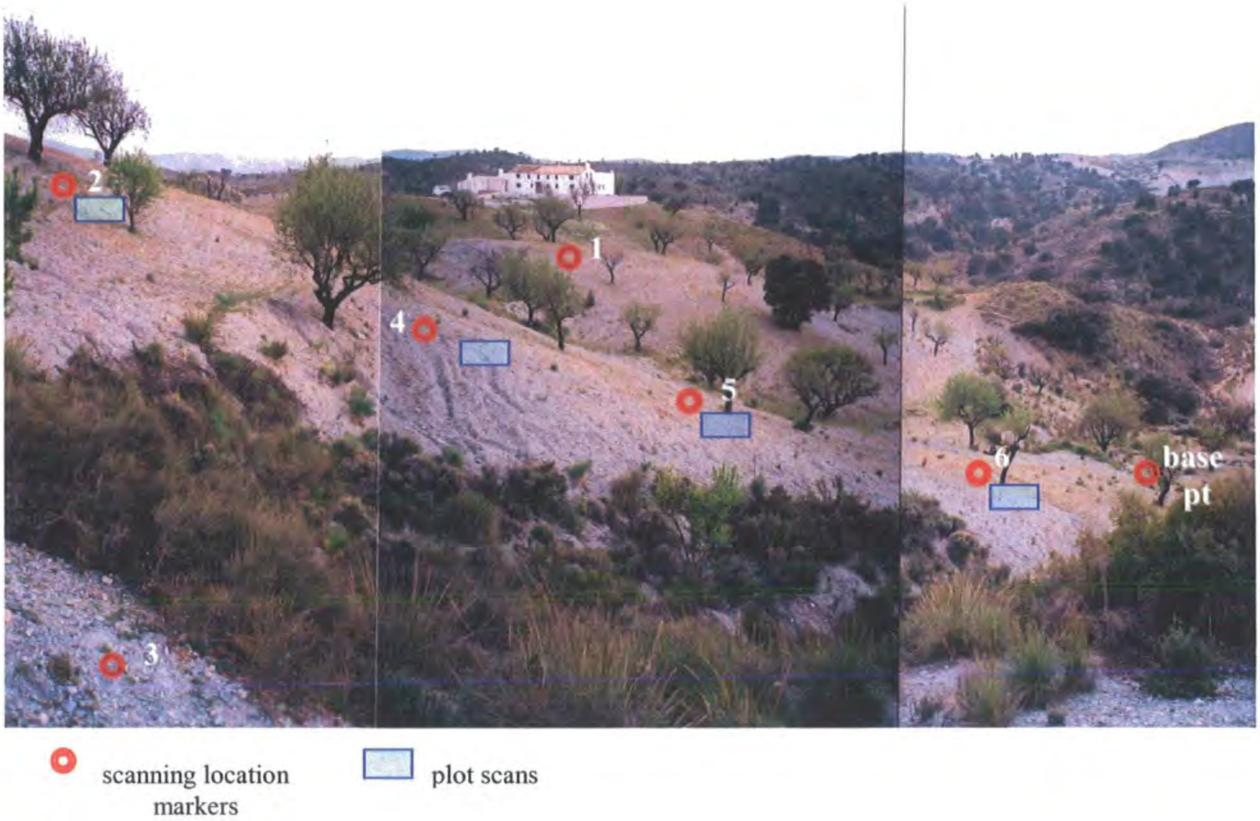


Figure 2.15. Site 2: plots scans and scanning location markers.

more detailed investigation than the large scale scans would provide. The plot scans measured a few m² and were scanned at 1 cm resolution in order to obtain very detailed soil surface data which could be used for further investigation and analysis. The location of each is shown in Figures 2.14 and 2.15.

2.6.2. Laser Scanner Data Analysis

The laser scanner generates 3-dimensional data consisting of many thousands of points, each with *xyz* coordinate attributes. These are displayed in the form of a 'point cloud' (Figure 2.16) which can then be triangulated into a continuous surface for more useful analysis. The analysis takes place in several stages, and each will be explained in turn. The initial work is carried out in Archaeoptics Demon software, in which the point clouds are first identified and then prepared for triangulation. The point clouds

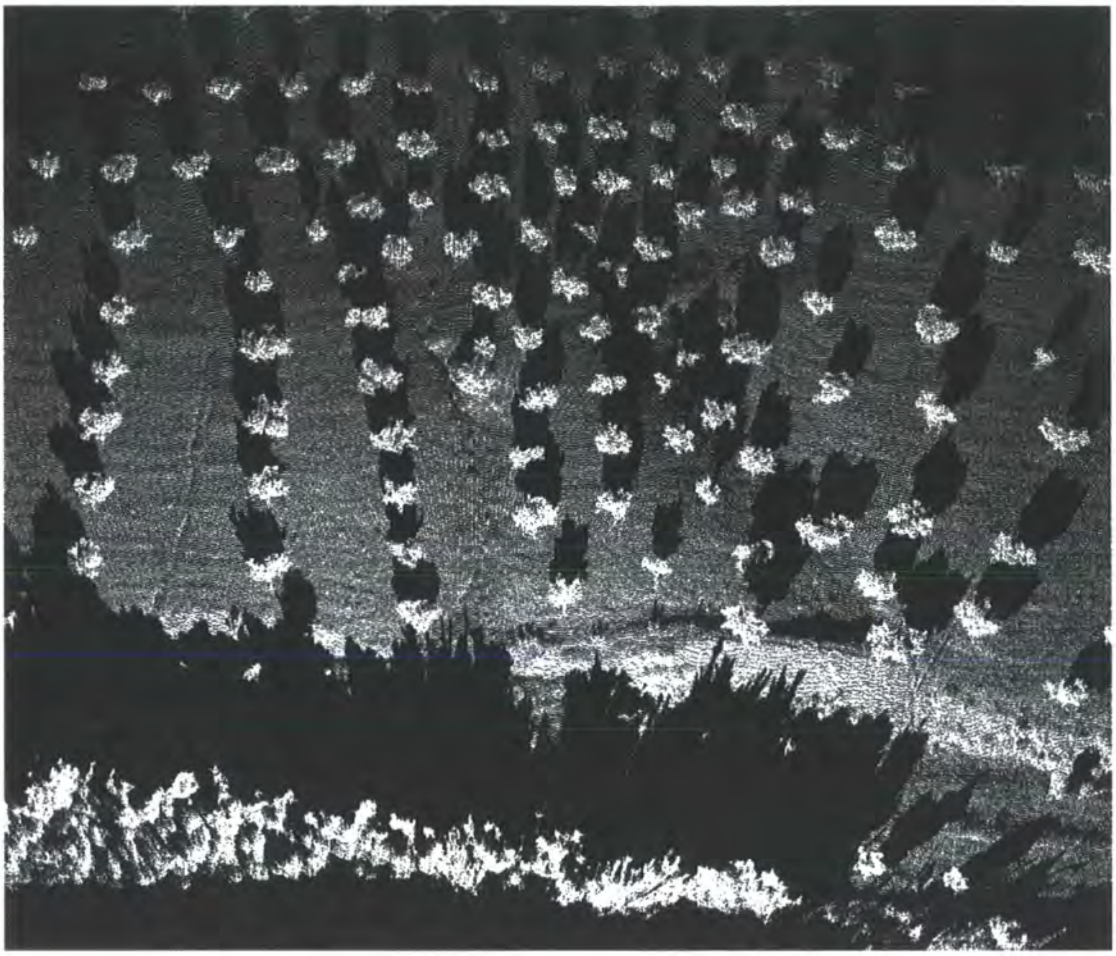


Figure 2.16. Point cloud of the hillslope at Site 1 including almond trees & shadows.

from both sites included almond trees whose presence hindered the generation of a flat surface when 2-dimensional triangulation was carried out: the software would not distinguish between points constituting trees and those representing the soil surface. Therefore it was necessary to first remove the points constituting almond trees: this was done by manually selecting all the relevant points and individually removing them from the point cloud in order to produce a smooth surface. However, this process was very time-consuming and labour intensive, as shown by the step-by-step breakdown in Figure 2.17. Once this process was completed and all the trees were removed from an entire hillslope scan (Figure 2.18), relatively large areas were left 'bare' in which surface detail was not available due to the shadow effect caused by the presence of almond trees.

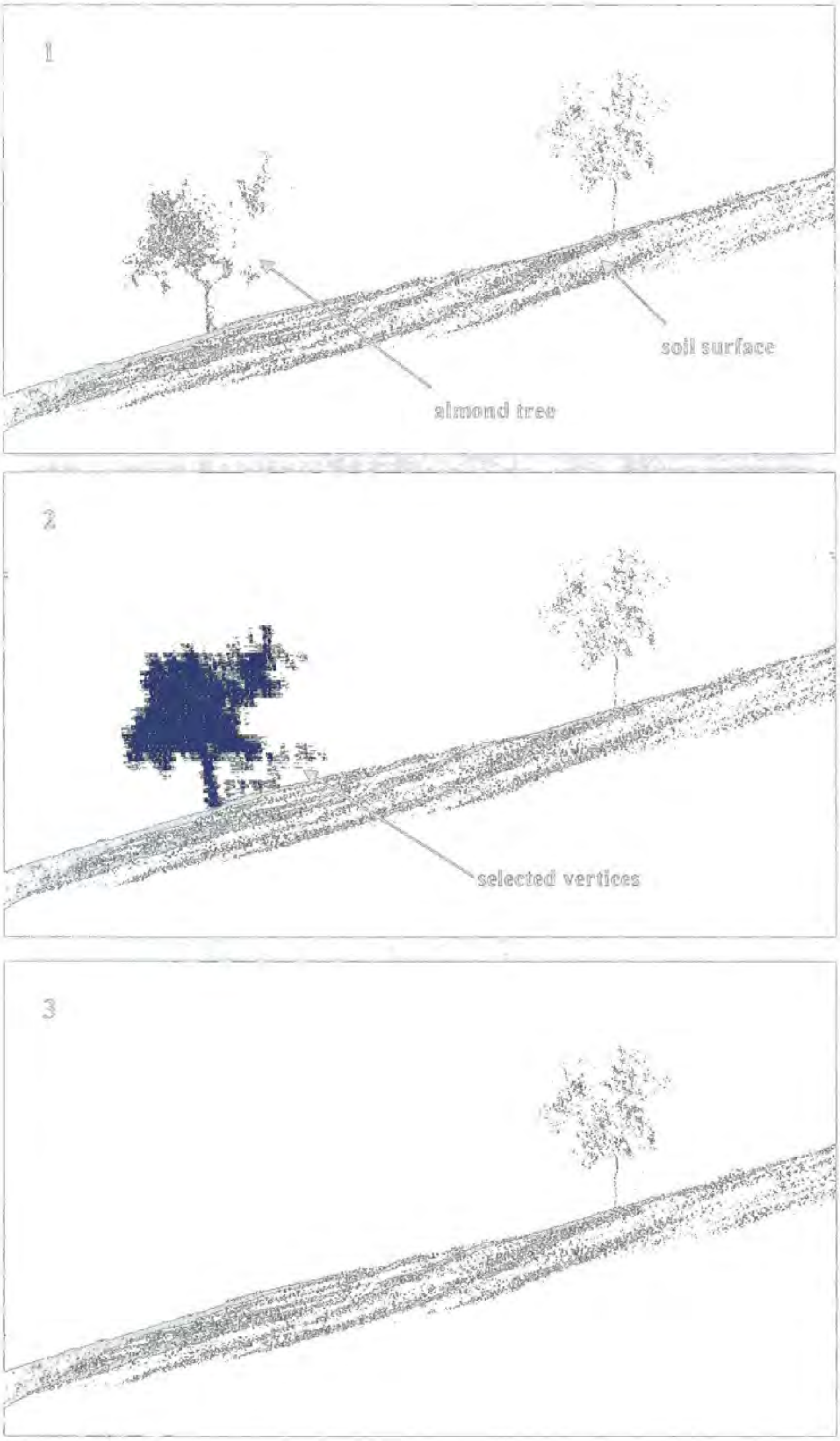


Figure 2.17. The removal of almond trees from the point cloud scans.

1: The scan is moved to an angle where individual trees can be clearly distinguished

2: The vertices for removal are manually selected from the scan & highlighted in blue

3: The selection is removed

Figure 2.18. Point cloud of the hillslope at Site 1 with almond trees removed.

This problem of 'bare' areas was mainly dealt with by combining and overlapping multiple scans, as demonstrated in Figure 2.19. The integration of these multiple scans gives more surface detail as well as reducing the shadow effect caused by the trees. The overlapped point clouds could then be triangulated into a smooth surface to allow for further analysis in ArcGIS (as shown in Figure 2.20).

The small-scale plot scans did not include any almond trees, which meant that their triangulation into surfaces was much more straightforward. However, due to the density of the point cloud generated by the 1 cm scanning resolution used, and therefore the sheer volume of data involved, the plot scans could not be exported directly to ArcGIS software for further topographical analysis without overloading the software. In order to overcome this problem, multiple cross sections of each plot scan at 2 % intervals were made in the Demon software, and the cross sections themselves

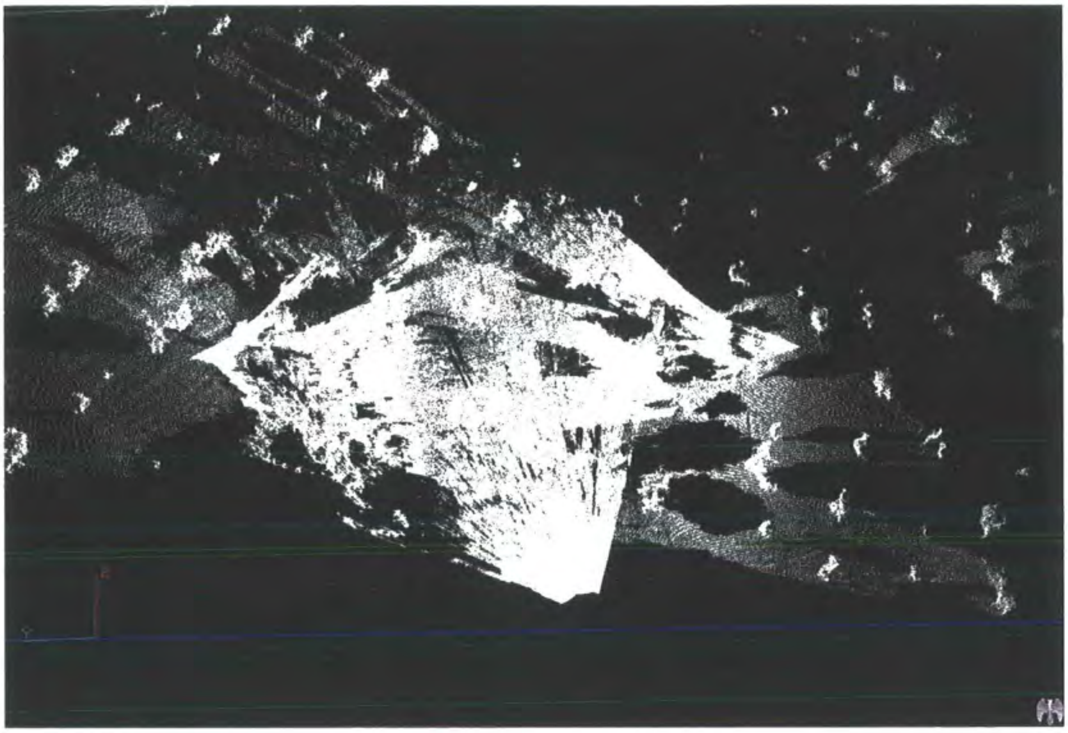


Figure 2.19. The integration of 3 individual scans of the hillslope at Site 2.

Figure 2.20. Triangulated surface of the hillslope at Site 1.

were exported instead. An example of this process is shown in Figure 2.21. While this process was fairly time consuming and resulted in slight detail from the plot scans being lost, it was still the most feasible and most effective alternative to using the point clouds themselves. Once the cross sections had been made and exported into ArcGIS, contours were created (Figure 2.22), the cross sections were convered to raster format. Topographic attributes including elevation and slope gradient (Figure 2.23) were determined using SpatialAnalyst and 3D Analyst extensions. In addition, the ArcGIS Spatial Analyst Hydrology Tools extension was used to identify sinks, determine flow direction, flow accumulation, and ultimately to produce detailed small-scale flow network data (Figure 2.24). The importance of this data presented in the images below will be discussed in Chapters 3 and 4.

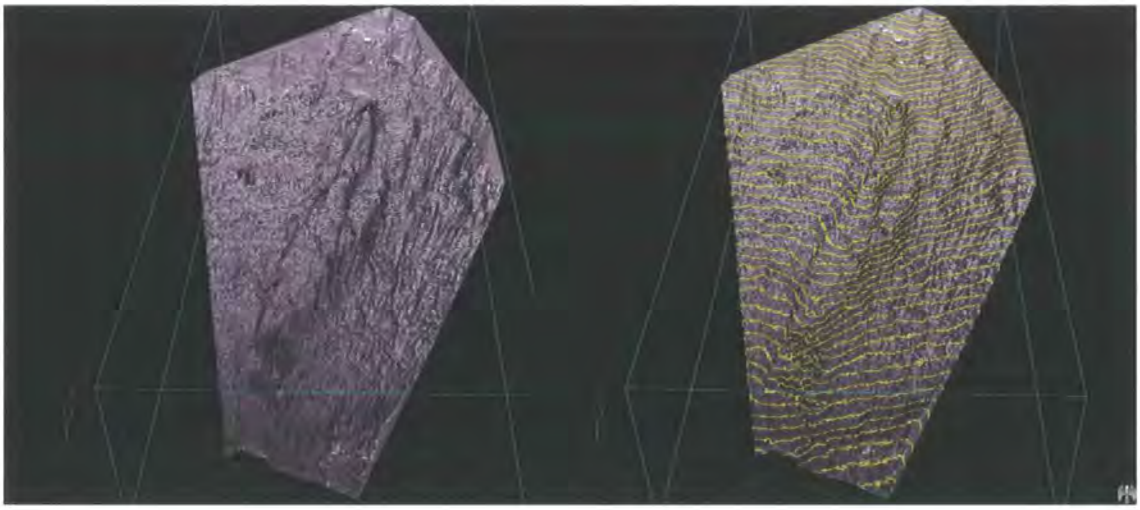


Figure 2.21. Plot scan (left), and the same scan with cross sections taken at 2 % intervals.

This small-scale plot scan data obtained using the laser scanner will allow gully erosion and morphology to be better understood in the context of the larger hillslope. Furthermore, the examples of plot scan data shown in Figures 2.22 – 2.24 demonstrate that despite being based on cross-sections taken from the original plot scans, the

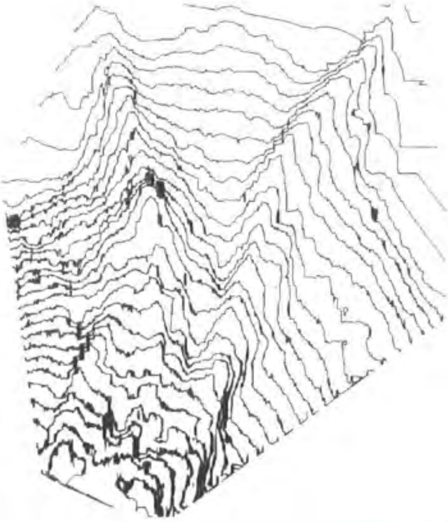


Figure 2.22. (above left). Contour image generated from cross-sections imported into ArcGIS.

Figure 2.23. (above). Slope gradient image created from contour data and *xyz* topographic attributes.

Figure 2.24. (left). Flow network data generated using small-scale topographic attributes and large-scale slope gradient.

results are still highly detailed. In particular, this data will aid in understanding the relationship between physical soil properties and overland flow generation. Gully morphological dimensions derived from the plot scans could also be used to calculate local channel volume, thereby giving the amount of sediment eroded from the hillslope during a specific rainfall event.

2.7. Summary.

Gully erosion is an important sediment source in semi-arid environments, and the evolution of gullies within hillslope systems is highly dependent upon the interaction of several variables at both the large- and small-scale. The research methods presented in this chapter have demonstrated how fieldwork has been carried out in order to fulfil the research aim of understanding the formation of small gullies on semi-arid hillslopes in south east Spain. In particular, this research will provide some much-needed data on hillslope erosion and gully morphological development at different scales in a semi-arid context. Furthermore, the use of a combination of methods at different scales, including traditional field techniques, laboratory analysis, and terrestrial laser scanning, will provide a more comprehensive research project which will further the current understanding of erosion by gullying. The field results will be presented and discussed in Chapter 3 from a hillslope scale perspective, and in Chapter 4 in the context of small-scale process interactions. The data from these two scales will be reconciled and discussed further in Chapter 5.

3. Hillslope Morphology.

3.1. Introduction.

Recent studies in semi-arid Mediterranean areas have shown gully erosion to have an increasingly significant contribution to soil loss on hillslopes (Martinez-Casasnovas et al., 2003). However, much research has been carried out at the plot scale and only a few investigations have been executed at larger scales. The interaction between erosional processes on slopes and channel morphology is consequently one area where current understanding needs to be developed (Bull and Kirkby 2002 p12). There is therefore a clear need for more detailed monitoring and investigation of erosion processes active in this environment in order to better understand gully geomorphology at the hillslope scale.

Field research for this study was carried out at two sites in the Rambla de Nogalte, south-east Spain. Both a laser scanner and traditional fieldwork methods were used and the relationship between rainfall, runoff and sediment transport was investigated. The laser scanner was used to obtain detailed topographic data which could give information on related attributes such as hillslope gradient, slope length, catchment area and slope curvature. These are properties which have been shown to have a clear effect on drainage networks and gully channel development at the hillslope scale (Poesen et al., 2003). Fieldwork data includes gully cross-profile measurements, infiltration rates measured at points across each hillslope, and laboratory analysis carried out on soil samples taken from both Site 1 and Site 2. Rainfall data was also obtained from several tipping bucket raingauges across the catchment, and will be used to relate the amount of soil eroded to a specific rain event in which the gullies were formed.

The field results will be analysed at two different scales: the hillslope to individual gully scale (> 100 m – ~ 50 m) and the individual gully to small scale (~ 50 m – < 5 m). While it is useful to divide the discussion of results in this way, the data at different scales nevertheless remain non-linearly linked. However, in order to understand the effects of processes active at the small and intermediate scales, patterns and processes must first be taken into account at the broader scale (Bergkamp, 1998). In this chapter, results and relevant discussion will therefore focus on the hillslope scale. The gullies at Site 1 will be referred to as A, B and C as shown in Figure 3.1. The single gully at Site 2 will be referred to as gully D. A table of definitions explaining terms and abbreviations used throughout the chapter is given in Table 3.1

Figure 3.1. Gullies A, B and C at Site 1.

Term Used	Definition
Gradient	Hillslope gradient, as measured at a specific point in the field (°)
Upslope	Position on hillslope as measured from base of slope (m)
omc	Soil organic matter content (%)
ec	Soil electrical conductivity, measured in
Catchment Area	Size of the surface area on hillslope which contributes to the supply of overland flow for a particular gully (m^2)
Gully Point Volume ("Pt vol")	Volume of a 5 metre section of gully channel (e.g. from 0m to 5m upslope, or 5m to 10m upslope), calculated from measurements made in the field (m^3)
Cumulative Volume	Cumulative volume of several consecutive 5 metre sections of gully channel (m^3)
Infiltration Rate	For a given, single location, the rate at which 800 ml water infiltrated into the soil (mm min^{-1})
Overall Infiltration	Average of infiltration rates along the length of a gully or for a particular area

Table 3.1. List of definitions of terms used to describe gully morphology and site characteristics.

3.2. Hillslope Morphology and Large Scale Topography.

In order to study the effects of large scale topography on the observed geomorphology of a nested system of gullies at Site 1 and a single gully at Site 2, large scale scans were taken in both locations at 20 cm resolution. The topographic data obtained from the laser scanner was initially imported into Archaeoptics Demon software, where points constituting almond trees were removed and the hillslope scans were linked together and overlapped. This process, described in full in Chapter 2, was carried out in order to maximise detail in the scans and to account for any areas where data had been lost due to shadow effects from the almond trees. When using digital surface representations, care must be taken due to the potential sources of error – in particular, disparities between the digital and 'real' surface may exist. This would result in the digital surface not being representative, reducing the accuracy of results. Therefore, care was taken in this study to ensure that as much detail as possible from the laser scans was retained. After initial analysis in Demon, the data was exported to ArcGIS and topographic attributes including hillslope gradient, slope length and catchment area were derived for Site 1 and Site 2.

At each field site, gully morphology was also measured by hand: cross-sectional width and depth measurements were made for each gully at 5 m intervals from the base of the slope to the top of the gully. This process was also described fully in Chapter 2. The data collected allowed variables including channel width and depth relationships, gully volume, and soil loss to be calculated. It is clear from other studies carried out that factors such as these affect the density of a drainage network and hence the probability of gully channel development (Poesen et al., 2003). The inclusion of topographic data, whether obtained by traditional methods or by a laser scanner, is therefore important when studying the dynamics of gully morphology and runoff-producing areas, and when accounting for sediment mobilised on a hillslope.

3.2.1. Channel Morphological Development and Slope Form.

Slope profiles reflect the operation of processes over long time spans, and observations made in the Nogalte area in south east Spain show a presence of mainly convex rolling hills (Kirkby et al., 2003). Topographic data obtained from the laser scanner shows the hillslope at Site 1 to also exhibit this broad convex quality (Figure 3.2). However, the presence of several concavities on the hillslope interrupts the convexity, and also suggests that the equilibrium of processes that has been active in maintaining the convexity is gradually changing. This is consequently causing the hillslope form to change. In particular, the presence of a system of three gullies appears to play a large role in this hillslope's evolution.

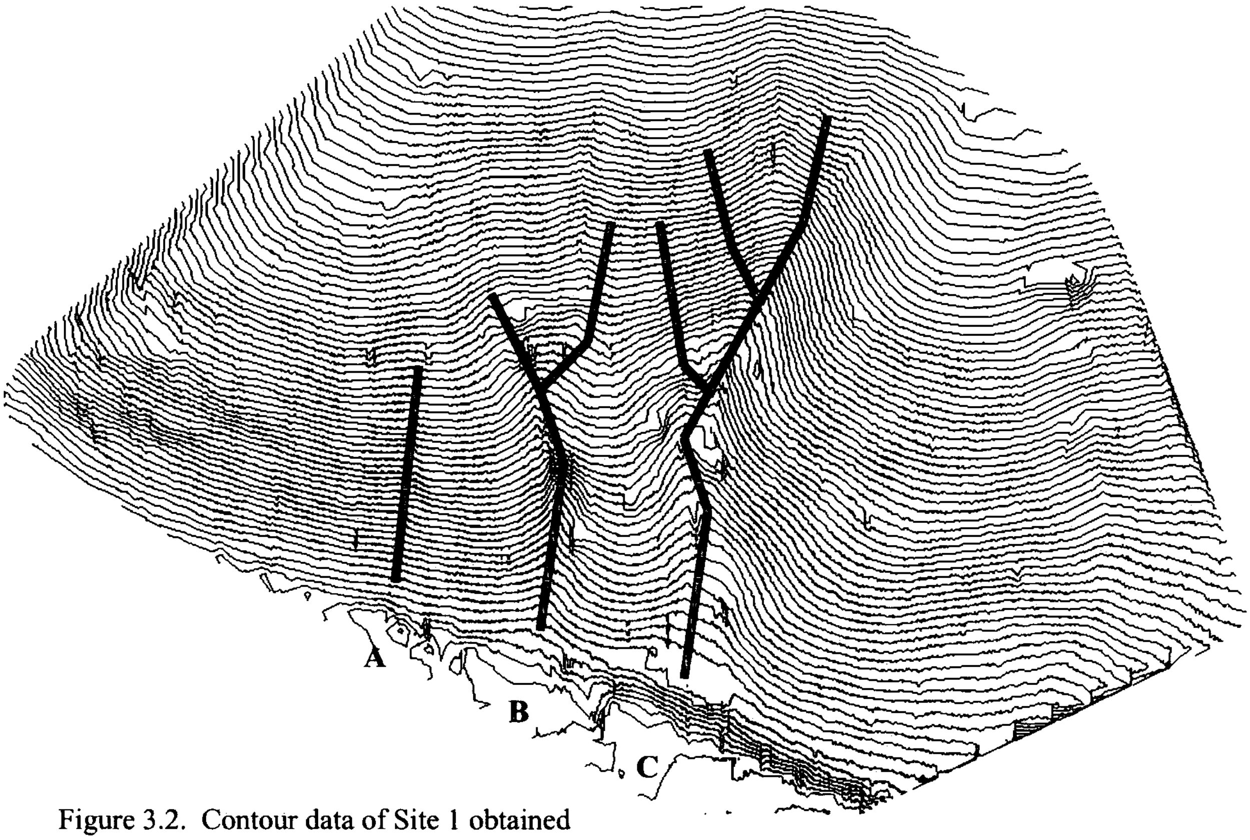


Figure 3.2. Contour data of Site 1 obtained from the laser scanner data. The location of gullies A, B and C is indicated. Contour interval of 1 metre.

From both observation and field data, the morphology of these gullies at the large scale appears to be governed to a certain extent by the plan curvature of the hillslope. The presence of the gullies within obvious topographic concavities at this site certainly points to this. Plan curvature is defined as the rate of change of direction of a contour line, and curvature is a fundamental surface property. Its application in geomorphology and hydrology has long been recognised, despite receiving less attention than slope gradient (Schmidt et al., 2003). It has been widely assumed that plan curvature particularly affects hillslope processes in semi-arid environments where overland flow often occurs (eg. Carson and Kirkby 1972, p390-397; Parsons 1988, p101-106). In this case it appears that the plan curvature of the convex slopes influences the overland flow direction during rainfall events, more so than the independent variable slope gradient. This topographic attribute therefore plays a role in determining the location and morphology of hillslope features such as gullies, but its interaction with the slope gradient renders its influence more important. As previously mentioned, this is most clearly seen in the fact that the three gullies at Site 1 – referred to as A, B and C – lie within topographic hollows where the slope gradient is steeper than elsewhere on the hillslope.

Gully	Catchment area (m^2)	Average width (m)	Average depth (m)	Average slope (°)	Gully length
A	57.3	1.54	0.24	22.64	55.59
B	225.2	2.06	0.29	21.96	140.64
C	381	2.2	0.28	23.25	145.3
D	92.3	2.36	0.22	23.64	62.1

Table 3.2. Topographic and morphological data for gullies A – D.

The slope gradient data for Site 1, presented in Table 3.2 and Figure 3.3, shows that while the mean hillslope gradient is 12.6 °, the mean gradients for the topography surrounding each individual gully are much higher. This highlights the fact that the gullies are preferentially situated in areas on the hillslope with a high gradient. Gully A has an average gradient of 22.64 °, gully B 21.96 °, and gully C 23.25 °. Every time the gullies are ploughed back into the soil, they preferentially form in the same locations following each rainfall event. This means that during rainfall events more sediment is lost from the same areas on the hillslope, which increases both the prominence of the hollows and the local slope gradient in a positive feedback system. For gullies B and C in particular, it appears that this feedback process has been in operation for some time, due to the relative size of the concavities and the presence of large sediment fans at the base of each gully. This factor of recurring gully formation, combined with the steeper topography in these locations suggests that the slope gradient does have a control over the morphology of the gullies at this site.

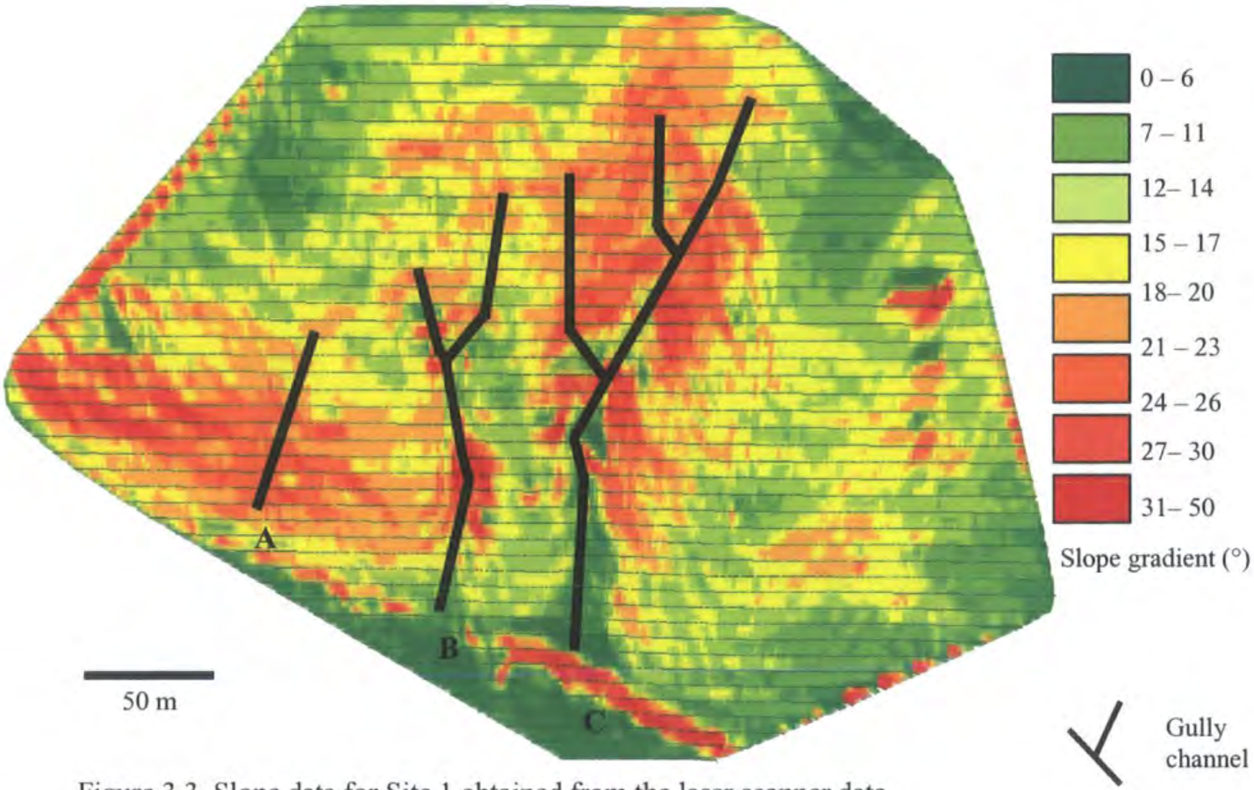


Figure 3.3. Slope data for Site 1 obtained from the laser scanner data.

When the slope gradient data obtained from both measurements taken in the field and laser scanner data is considered in more detail, a relationship can be observed between the variables hillslope gradient and gully width. If these two variables are correlated, an R^2 value of 0.51 is obtained ($r = 0.72$; Table 3.3). While this is not indicative of an especially strong relationship, it nevertheless indicates that an important relationship is present: the higher the slope gradient, the wider the gullies at Site 1 tend to be. This can be accounted for by the fact that the gully width is determined by the amount of runoff carried by the channel, which is, in turn, determined by slope steepness. The strong continuity of gullies A, B and C down the hillslope is also indicative of a constant runoff contribution from sideslopes during rainfall events. If the overland flow direction was not governed by the slope gradient which directs it towards the gullies, they would either remain a uniform width and depth along their length downslope, or they would be discontinuous due to the occurrence of infiltration within the gully channel. Therefore the higher the amount of runoff, the wider the gully channel will become in order to accommodate the flow of water and evacuate it from the hillslope. This also points to the spatial differentiation of areas on the hillslope at Site 1: some areas preferentially produce overland flow, while others act as connective links for runoff and eroded sediment between areas on the hillslope. This concept of hillslope connectivity will be discussed in the context of this study in section 3.3 and in the following chapter.

	width	depth	volume	cumulative volume	gradient	catchment area	upslope
width	1.0						
depth	0.27	1.0					
volume	0.63	0.76	1.0				
cumul vol	-0.26	0.25	-0.04	1.0			
gradient	0.72	0.41	0.66	-0.58	1.0		
catchmt area	-0.05	-0.08	0.01	0.41	-0.24	1.0	
upslope	-0.26	0.20	-0.04	0.96	-0.58	0.63	1.0

Table 3.3. Correlation (r values) of gully morphological and hillslope variables for gullies A , B and C. (For definitions of these variables, see Table 3.1).

The relationship between width and hillslope gradient is $R^2 = 0.51$, but this value is affected by the presence of several outliers in the dataset, as can be seen in Figure 3.4. These outliers correspond to areas of reduced slope gradient where the channel remains nevertheless relatively large. These were either locations where deposition had occurred within the channel, or towards the base of each gully just upslope of where large sediment fans were present. This was particularly the case for gully C: despite having the largest catchment area (381 m^2) and the highest average width and depth (2.2 m and 0.29 m respectively), the large sediment fan at the base of the hillslope reduces the slope gradient and the apparent effect of topography on the erosion process. While the gully remains wide, the local slope gradient is much reduced. Following a field study, this phenomenon was also noted by Gabbard et al.,

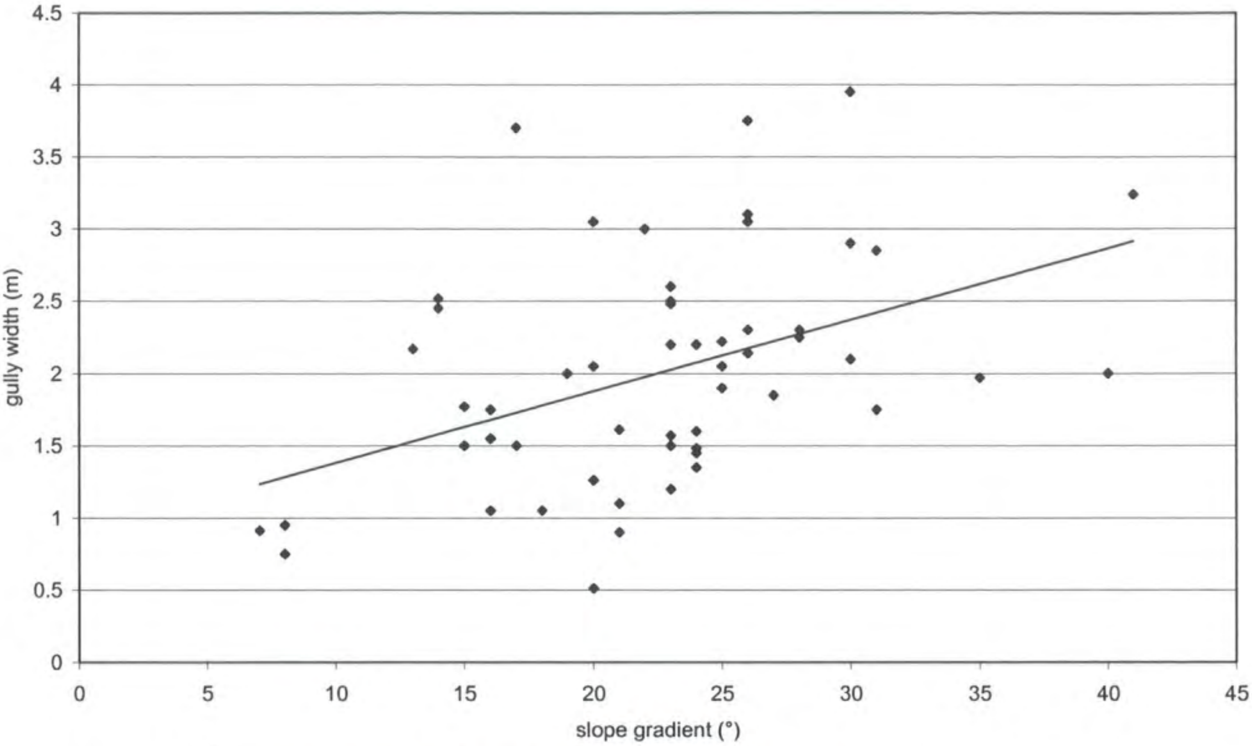


Figure 3.4. Relationship between slope gradient & gully width at Site 1. $R^2 = 0.51$.

Figure 3.5. Site 1: gully B situated within a topographic concavity. The wide channel is visible, and the sediment fan is present in the foreground.

(1998): sediment deposition was shown to be a significant process at this slope position, reducing the local influence of gradient and affecting morphology at both the local and large scales. A relatively large sediment fan was also present at the base of gully B (Figure 3.5) and the data corresponding with this location also exhibits a similar reduction in slope gradient. Slope values are between just 7 ° and 14 °, compared to an average of 21.96 ° for the whole of gully B.

The gully at Site 1 which shows the strongest correlation between channel width and slope gradient is gully A. The R^2 value for this single gully is 0.52, which is slightly higher than $R^2 = 0.51$ for all three gullies (Table 3.3). This indicates that for this gully, slightly more so than for the others, the steepness of the slope influences its width. The fact that gully A has a stronger correlation with its topographic surroundings can be attributed to two main factors. First, gully A is much smaller than gullies B and C: it measures only 55.59 m in length compared to 140.64 m and 145.3 m for the other two respectively. There is therefore less potential for localised areas of shallow gradient where deposition can occur, and no branches or tributaries joining a main channel. Secondly, gully A appears to be relatively less mature than gullies B and C. For example, it has the smallest sediment fan of the three gullies on the hillslope, measuring approximately 7.5 m^3. This suggests that its formation is more recent than gullies B and C, whose sediment fans measured 10.75 m^3 and 22.1 m^3. respectively. Its catchment area is also significantly smaller at 57.3 m^2. The topographic concavity in which gully A is situated is also much less pronounced, which indicates less positive-feedback compared with gullies B and C. These properties all point to the likelihood that topography will exert a more direct influence on gully A's morphology due to the interplay of comparatively fewer factors, as is reflected in the results.

Whereas the relationship between gradient and gully width at Site 1 has an R^2 value of 0.51, the relationship between the gully depth and hillslope gradient is much less strong, having an R^2 value of just 0.17. This indicates that the role of hillslope gradient in determining gully depth is relatively less important than determining width at this site. The gully depth is therefore more likely to be governed both by the amount of runoff carried by the gully and the physical environment in which it is situated: for example, the erosivity of the soil surface, and the infiltration rate of the soil. These factors will be discussed subsequently in section 3.2.2.

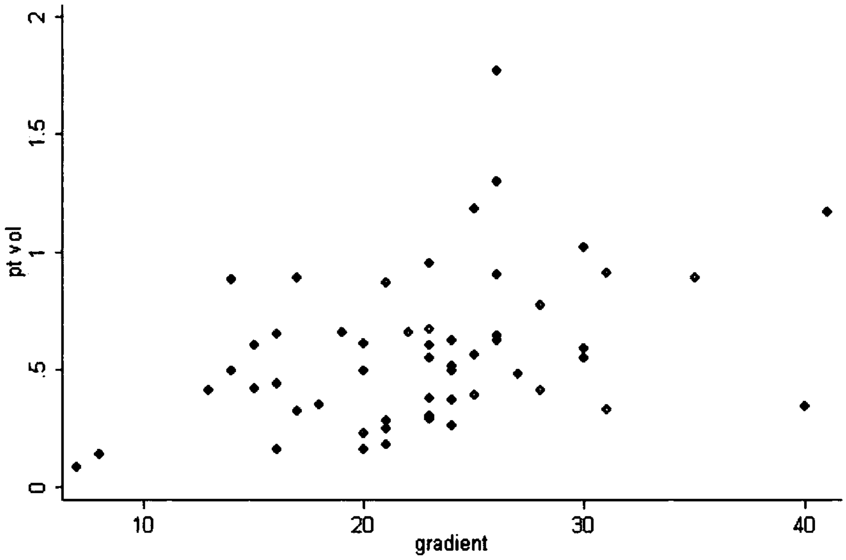


Figure 3.6. Local gully volume compared with slope gradient. $R^2 = 0.43$.

The fact that hillslope gradient influences gully width, and to a lesser extent gully depth, inevitably implies that other morphological characteristics including gully volume and soil loss will also be affected by slope gradient. As can be seen from the results, the relationship between local gully volume (defined as the volume of a 5 m length of the gully) and hillslope gradient is has an R^2 value of 0.43 (Figure 3.6), indicating that the slope gradient does indeed affect the gully morphology at Site 1. While this is a significant relationship, it is affected by the presence of several outlying points, upon whose removal the relationship does improve. The fact that the gully volume is increasing downslope shows that the amount of gully flow is also increasing, and therefore runoff contribution from the sideslopes to the gully channels is significant. This is also manifested in the strong relationship between upslope location and gully cumulative volume ($R^2 = 0.91$). The relationships between cumulative volume and gully width and depth at Site 1 are also relatively strong, having R^2 values of 0.50 and 0.58 respectively (Figure 3.7, top two graphs). This relationship is to be expected, since the width and depth determine the gully volume, and therefore the amount of soil eroded at a given point. The relationships between width, depth and upslope position are slightly less significant (Figure 3.7, bottom two graphs), indicating that it is the the local slope gradient rather than the specific hillslope location which determines gully morphology.

Multiple regression analysis was carried out using the data obtained from Site 1 in order to give further insight into the relationships between several large scale topographic attributes and gully morphology. In particular, the regression of the three variables local gully volume, local gradient and distance upslope (Equation 1) gives an R^2 value of 0.62, indicating that this relationship is highly significant.

$$\text{Local gully volume} = -0.98 + (0.062\,x\ \text{Local gradient}) + (0.0060\,x\ \text{Distance upslope})$$

$$p = 0.01, \quad R^2 = 0.62$$

Equation 1

As shown in Figure 3.6, when just the two variables of local gully volume and local gradient are regressed, the R^2 value is weaker at 0.43, which shows that the inclusion of upslope position is very important. This data therefore demonstrates that gully width is strongly influenced by a combination of both the local gradient and the upslope position, with larger sections of the gullies being preferentially located on steeper topography and towards the base of the slope. If the variable of infiltration rate is included in the regression along with local gully volume, local gradient and position upslope, the R^2 value is again significant at 0.62. This demonstrates that the gully morphology is also dependent on infiltration rate, therefore this factor does have an influence on erosion processes and channel form.

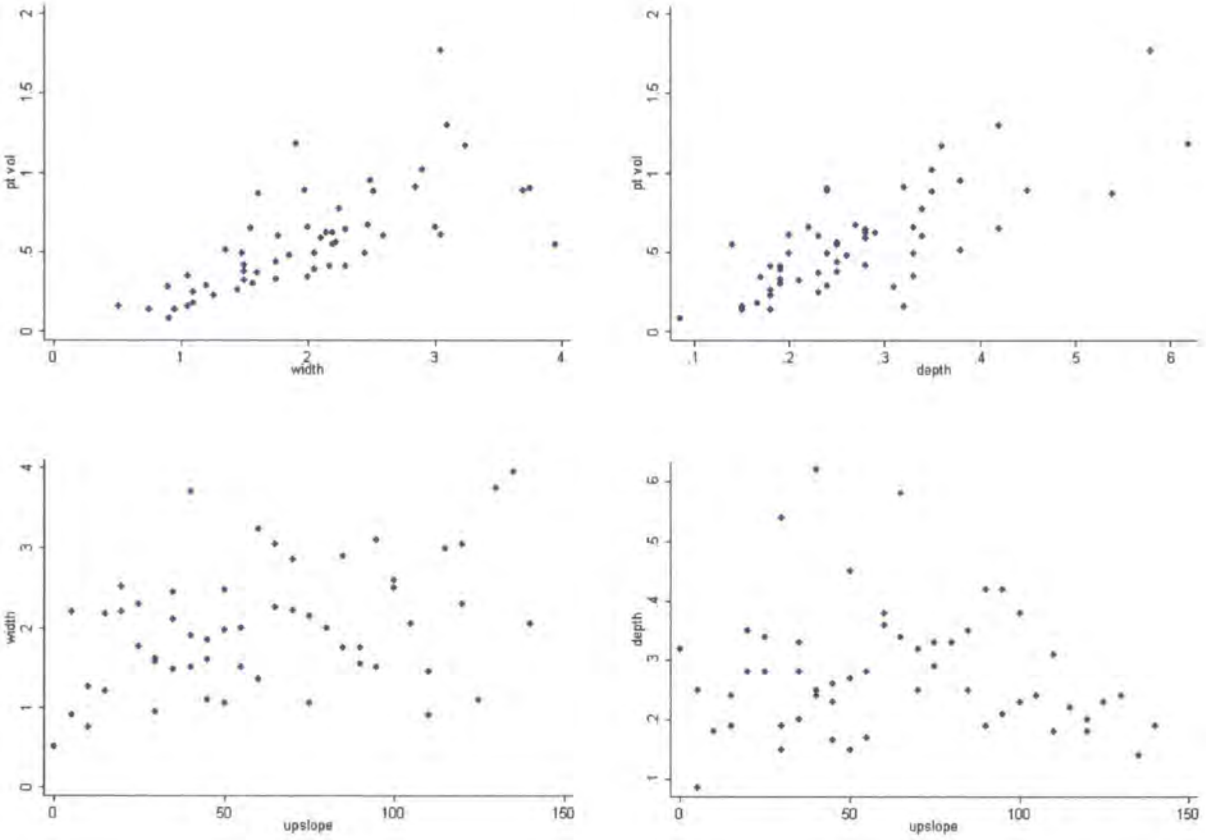


Figure 3.7. Width and depth compared to gully volume (top two graphs). Width and depth compared to upslope location (bottom two graphs). For definition of variables, see Table 3.1.

In contrast with Site 1, just a single channel was present at Site 2: gully D (Figure 3.8). Large scale scans were taken at this site and channel width and depth were also measured by hand as for Site 1. As previously discussed in Chapter 2, Site 2 is also located within the Nogalte catchment but differs from Site 1 because it is no longer maintained as an almond plantation – it has been abandoned to let natural vegetation re-establish. Topographic data for Site 2 was obtained both in the field and from laser scanner results; from this data, gully D is shown to have the lowest volume (0.57 m^3) and the lowest soil loss of all four gullies (5.3 m^3 ha^{-1}); gully D is also the second shortest in length, measuring only 62.1m. This is due to the fact that the hillslope is much smaller than Site 1 (435 m^2 compared to 1735 m^2), and has a hillslope length of just 93 m.

Figure 3.8. Picture of gully D at Site 2.

The effects of slope length on gully morphology have also been demonstrated in other studies, including that of Kuhn and Yair (2004) carried out on badlands in Israel. Their results highlighted the critical role of the interaction between rainfall-runoff conditions, slope angle, and soil surface characteristics for geomorphology in an arid environment. In particular, it was found that the form and morphology of rill systems were crucial for the transmission of runoff on hillslopes, and integrated rill networks were more likely to produce continuous flow than single parallel channels due to the downslope increase in runoff volume. Parallels can be drawn between the work carried out by Kuhn and Yair (2004) and the research presented in this thesis. The morphology of the gullies at sites 1 and 2 – in particular gully volume – has been shown to be specifically determined by interactions between the slope gradient, position on the hillslope, and infiltration rates. Their combined influence on overland flow and runoff direction at the large scale causes a downslope increase in runoff volume, and improves connectivity between areas of the hillslope.

Gully D also differs from gullies A – C at Site 1 because it is not seasonally ploughed back into the soil due to the abandonment of the site, providing a permanent connection down the hillslope. Its morphology will be more static between rainfall events when relatively little erosion or sediment mobility occurs, because in semi-arid areas, the redistribution of sediment is largely driven by overland flow and surface wash processes (Puigdefabregas et al., 1999). Therefore, in order to fully appreciate gully morphological development at the large scale, the role of other variables including land use, rainfall characteristics, and hillslope connectivity must be taken into consideration. The influences of these factors on large-scale gully morphology will now be discussed in the following sections.

3.2.2. Slope Gradient and Hillslope Variability in Infiltration.

With respect to a particular erosion process acting on a hillslope, the erodibility of a soil surface varies greatly both in space and time (Parsons, 1988: 108). This spatial variation across a hillslope can be caused by a combination of factors including differences in infiltration rates, the diversity of soil properties including soil type and surface roughness at different scales, vegetation and soil organic matter content, and large scale topography, as previously discussed. While these variables operate at the local scale, they will inevitabley have an impact upon large scale gully morphological development and hillslope hydrologic response. In addition, the dynamic interaction of these factors can cause positive feedbacks between water and sediment redistribution and spatial patterning, which strongly influences the heterogeneity of hillslope characteristics (Cammeraat, 2002). However, it is also important to note that any model at the hillslope or catchment scale will be very much an approximation of the full physical controls on the infiltration and runoff process (Beven, 2002: 57-107) and only general trends will be captured by a study of these processes.

As described in Chapter 2, infiltration rates were measured at several locations across the hillslope at Site 1 and Site 2. This data provides an insight into the general trends of infiltration across each hillslope in areas immediately associated with the gullies. Infiltration is an important factor to consider with respect to the nature of rainfall events in semi-arid areas: the fact that they are both infrequent and intense means that the large-scale infiltration response of the hillslope will determine the extent of gully morphological development. This is due to the fact that in such environments, erosion is transport limited, and mainly occurs as a result of infiltration-excess overland flow during rainfall events. All studies of infiltration rates in semi-arid environments have revealed great spatial heterogeneity and temporal variability in results (Beven, 2002). Therefore it is important to note that any large-scale study involving infiltration rates in semi-arid environments can only give a very partial picture of the nature of overland flow at the hillslope scale. The original infiltration data from Site 1 and Site 2 are given in Appendix 1, and are presented in Figures 3.9 and 3.10.

From this data it is clear that infiltration rates in this area exhibit considerable spatial variation both within and between sites, which will affect large-scale gully morphological development. The results exhibit an initially high infiltration rate at each location, which then drops to a more steady and sustainable figure as the local soil profile gradually wets up. At Site 1, infiltration rates are shown to increase with

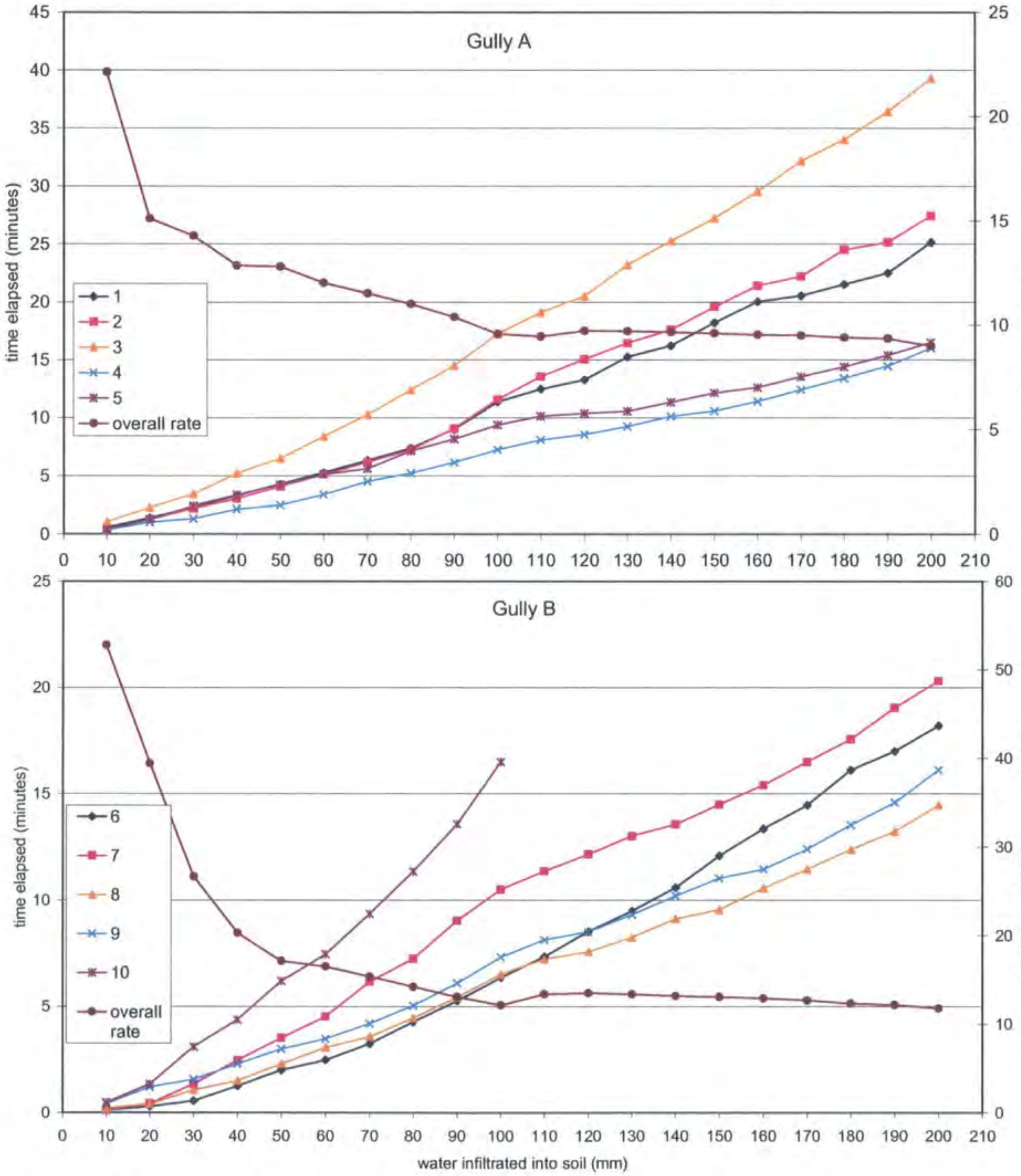


Figure 3.9. Infiltration times and rates from gully A (top) and gully B (above) at Site 1. Numbers 1-5 and 6-10 correspond to infiltration experiment locations, as shown in Figure 2.8.

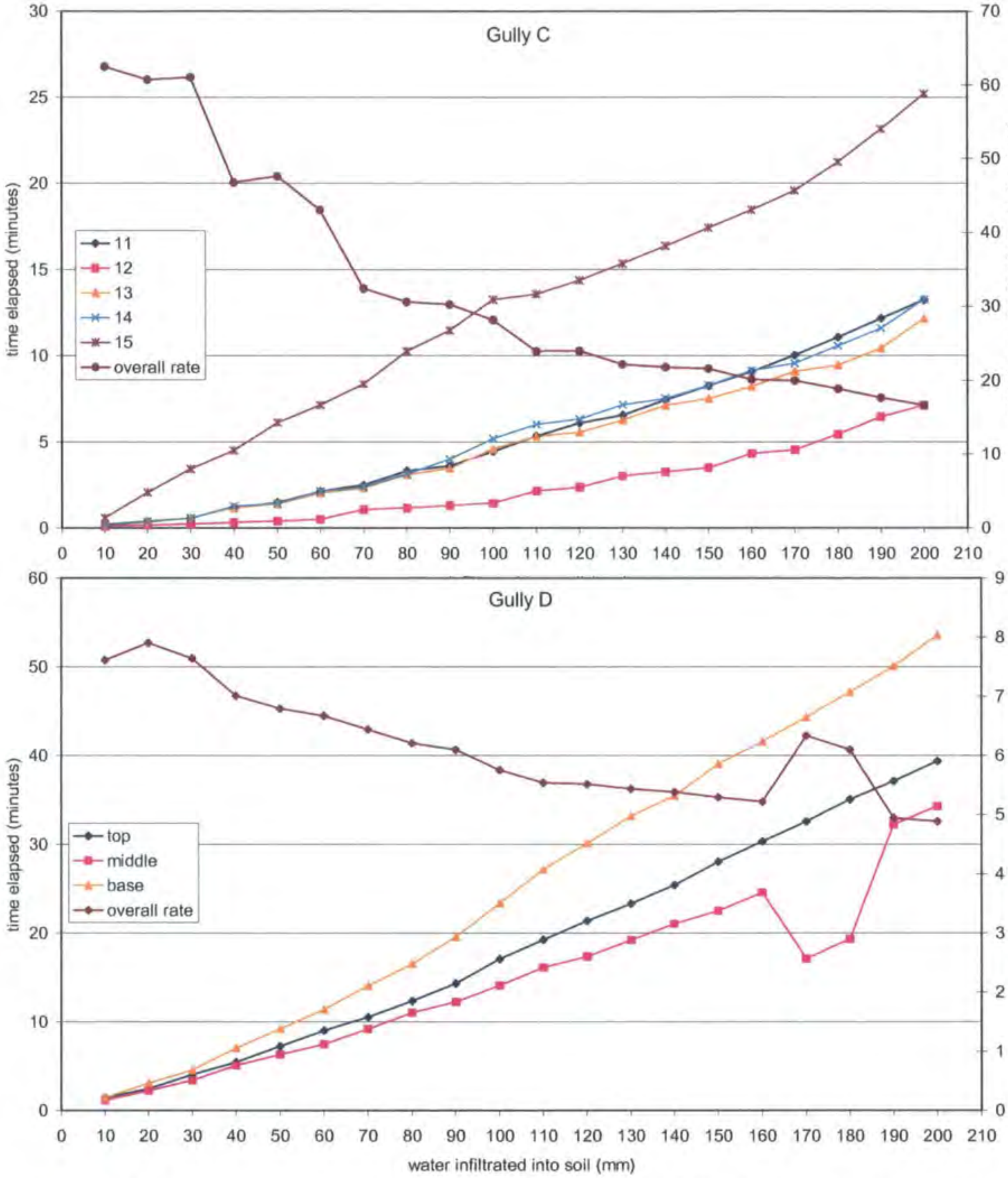


Figure 3.10. Infiltration times and rates from gully C at Site 1 (top), and gully D at Site 2 (above). Numbers 11-15 and 'top, middle, base' refer to infiltration experiment locations, as shown in Figures 2.8 and 2.9.

increasing gully size: gully A has an overall infiltration rate of 1.13 mm min^{-1}; gully B, 1.75 mm min^{-1}, and gully C, 3.25 mm min^{-1}. The gully at Site 2 (gully D) shows much slower overall infiltration rates than those at Site 1, having an average infiltration rate of just 0.61 mm min^{-1}. Observed differences between the two sites can be attributed mainly to variations in soil type and land use. These factors will be discussed in more detail in the context of small-scale variations in the following chapter.

Due to the fact that the infiltration rate of the soil determines a hillslope's response during a rainfall event, the different infiltration rates measured across the hillslope at Site 1 can give an insight into how the gullies A, B and C were formed. When the infiltration results are correlated with the large scale gully morphological data obtained from both the laser scanner data and measurements made in the field, relationships can be observed. In particular, the relationship between infiltration rate and upslope position is of importance (Figure 3.11). When these two variables are correlated, they give an r value of 0.51, indicating that there is a trend for higher infiltration rates to occur towards the top of the hillslope at Site 1.

This spatial differentiation of infiltration at the large scale can be partially attributed to the influence of hillslope topography: in particular, it has been noted by

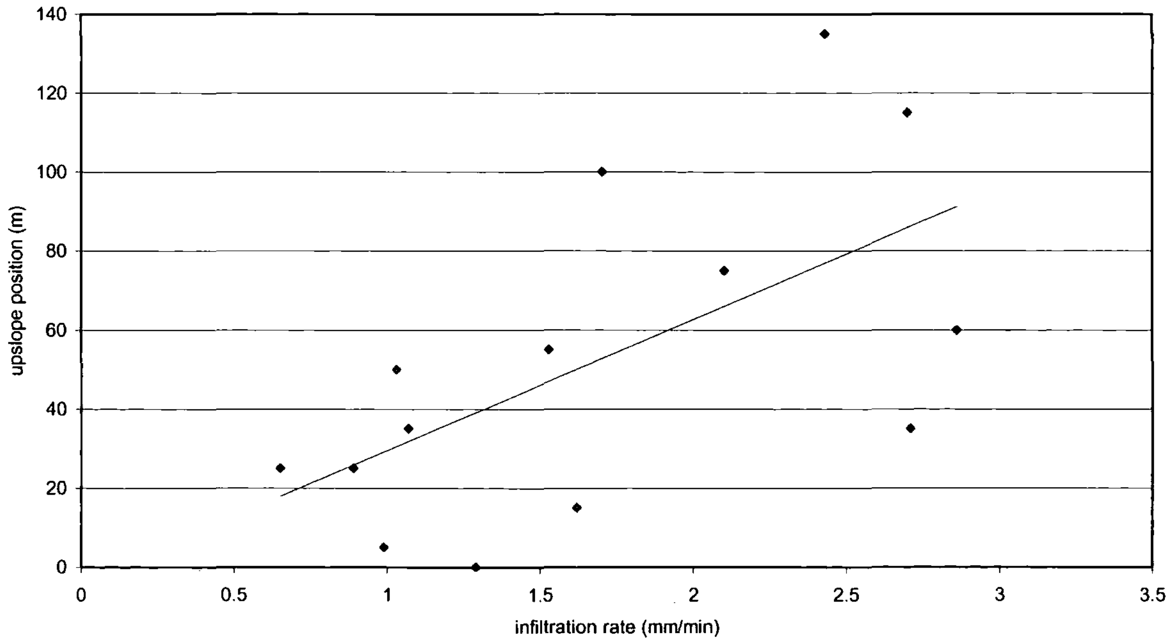


Figure 3.11. Infiltration rates correlated with upslope position at Site 1. n = 15.

Truman et al., (2001) that soil detachment and sediment transport processes associated with rainfall and runoff vary spatially, especially as slope length increases. This was highlighted by the results presented in the previous section: the interactions between infiltration, the local gradient and upslope location had an imprortant influence on gully volume: the regression of these variables had a highly significant ($p = 0.01$) R^2 value of 0.62.

Slope gradient is also an important topographic control on infiltration: at the top of the hillslope at Site 1, the gradient is less steep, which means that rather than promoting runoff, the soil surface will be able to provide more storage for water during a rainfall event. The increased storage capacity means there will be a higher potential for infiltration to occur, thereby reducing runoff. From observations made in the field, it could be seen that as a result of this process, gullying was initiated in areas at Site 1 where the hillslope topography began to increase in steepness.

This same process was noted by Poesen (1984) during an experiment investigating the relationship between specific slope angles and infiltration rates during simulated rainfall events. Runoff volume was found to increase on the steeper slopes because of the corresponding decrease in surface storage capacity and reduced infiltration rates. In a field study carried out by Esteves and Lapetite (2003), the high spatial variability in infiltration rates and surface storage capacities was also shown to play an important role in determining gully morphology at several scales. Runoff generation and gully initiation in their study was highly localised, and the entire soil surface by no means contributed to overland flow; rather, some areas with higher infiltration rates acted as 'runoff sinks' and others with lower infiltration rates acted as 'runoff sources' for the hillslope. Therefore, in order to fully interpret the infiltration results in the context of individual gully morphology at each site, land use must also be taken into account. Indeed, Bull et al., (2000) found that a combination of variables including slope gradient, land use and soil type all had an effect on runoff generation in the Nogalte basin.

Kirkby and Bull (2000) noted that gully channel growth is primarily governed by hillslope form and processes that occur upslope of the channel head. If Figure 3.12 is considered, it can be seen that for gullies B and C, the infiltration rate is lowest just upslope of the gully heads. In the case of Gully B, the infiltration rate near the gully head was just 0.99 mm/min, compared to 2.43 mm/min at the base of the slope. Similar results highlighting the roles played by slope gradient and vegetation were demonstrated by Solé-Benet et al., (1997) following research carried out in south-east Spain. In their study, runoff was positively correlated with slope gradient and negatively correlated with the presence of vegetation and organic matter. Following a study carried out in dryland environments, spatial variation in vegetation and soil organic matter on the hillslope was shown to give rise to differences in hydrological behaviour between areas during a rainfall event: those areas with more vegetation experienced higher infiltration rates, whereas bare patches were runoff-producing areas. The organic matter content of the soil samples from Site 1 also indicates spatial organisation at the local rather than hillslope scale. Samples with the highest organic matter content were found at the base of gullies A, B and C.

This comparatively higher organic matter content in these specific locations can potentially be attributed to two main factors. First, the catchment area obviously

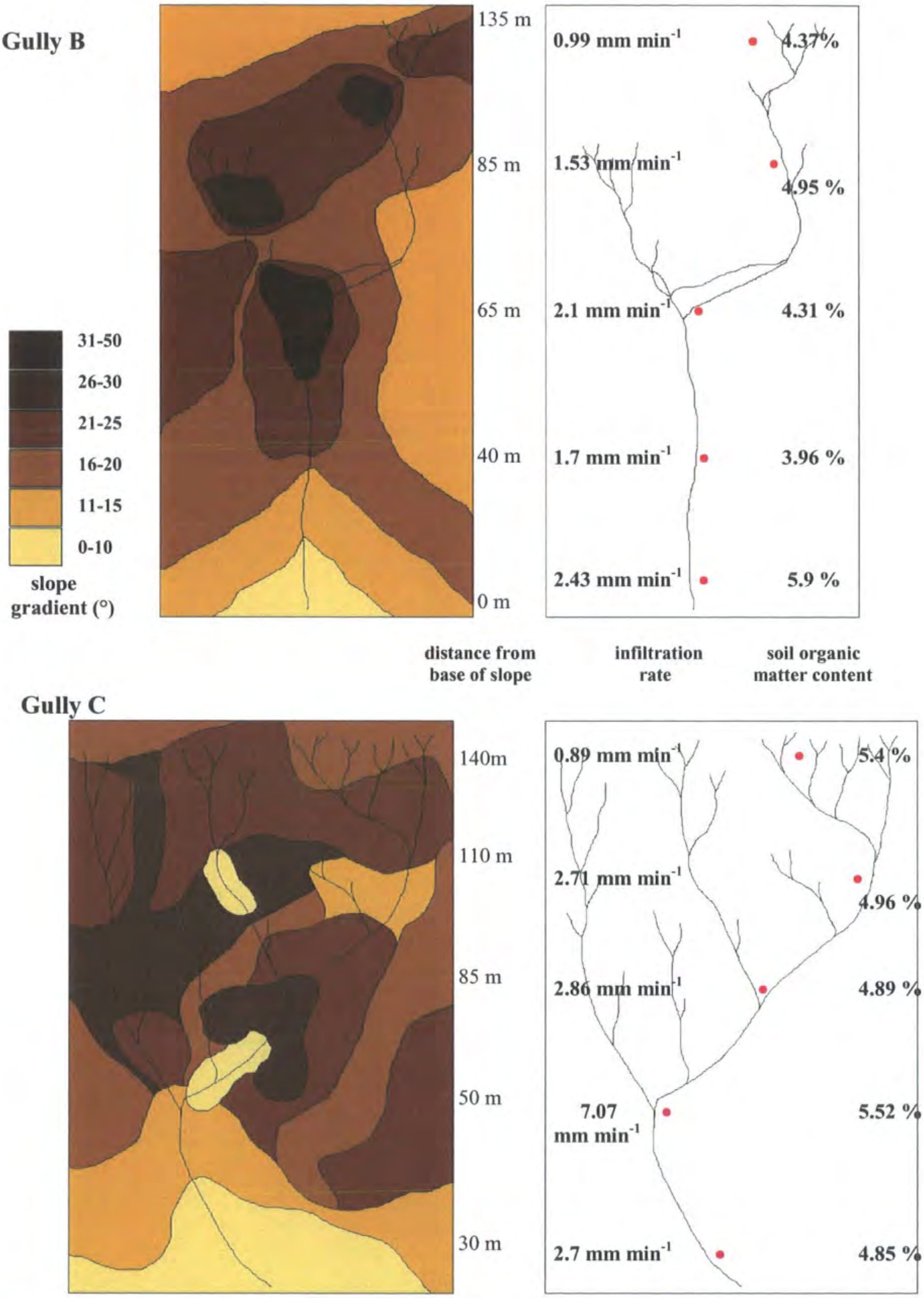


Figure 3.12. Map contrasting soil type, slope gradient, and infiltration rates for gullies B & C. Variables shown in each diagram: slope gradient (°), distance from base of slope (m), infiltration rate (mm min^{-1}) and soil organic matter content (%).

increases towards the base of the gullies, which means that the amount of runoff carried by the gully at this location will be higher than elsewhere on the hillslope. Following a rainfall event, levels of soil moisture at the base of the gullies will therefore be expected to be higher, which – particularly in a semi-arid environment – will encourage the localised presence of organic matter and the growth of vegetation. This is shown both by the data and from observations made in the field: what little vegetation was present on the hillslopes had preferentially grown within or in close proximity to the gully channels, increasing the amount of organic matter present in the soil at the base of the hillslope. Secondly, the transportation of sediment and organic matter through the gully channel occurs by overland flow processes. Towards the base of the hillslope at Site 1, the slope gradient decreases, which will slow any runoff and promote localised deposition. This was observed in the form of the sediment fans located at the base of each gully. Therefore any organic matter that has been transported along with sediment during a rainfall event may be preferentially relocated to the base of the gully, increasing the amount of organic matter present at this location.

From these results, it is clear that factors affecting vegetation have an impact on infiltration rates at Site 1 and Site 2. This is because the presence and growth of vegetation will tend to protect the soil surface from rainsplash and crust formation, as well as improving the soil structure (Beven, 2002). Closely related to vegetation at a particular site is the factor of land use. The management and cultivation practices being used on a semi-arid hillslope will affect soil texture, structure, and grain size distribution – factors whose influence on gully morphology has been demonstrated in the previous sections. Therefore it is necessary to take land use into account.

3.2.3. Gully Morphology and Land Use Change.

In Chapter 1, the influence of land use change on soil degradation both across the Mediterranean region, and more specifically in the Rambla de Nogalte, was discussed. Differences in gully morphology between Site 1 and Site 2 can be mainly attributed to the contrasting land use practices in each case. While the soil surface at both sites is disturbed by intense rainfall events, Site 1 is additionally disturbed by seasonal ploughing. As previously mentioned, Site 1 is currently being used for agricultural purposes, whereas agriculture at Site 2 has been abandoned in order to let natural vegetation re-establish. As a result of this, the gullies at Site 1 (A, B and C) are ephemeral, whereas gully D at Site 2 is permanent. At Site 2 there is therefore a permanent established connection between the top and base of the hillslope, facilitating the movement of both water and sediment during rainfall events. This was also noted by Poesen et al., (2002: 237) who stated that "land use has a particularly strong control on the life span of a gully: ephemeral gullies typically develop in cultivated areas, whereas permanent gullies develop on abandoned fields or rangelands."

In contrast to gully D's stability, it has long been recognised that ephemeral gullies tend to be in a non-equilibrium state and are therefore inherently unstable (Hook and Mant, 2002: 173). This instability is clearly visible at Site 1 where the feedback processes between gullies A – C and the hillslope are exacerbating the topographic hollows in which they are situated. The morphological data for this site (presented in the previous section) showed how, during a single intense rainfall event in which 40mm water fell, three gullies were eroded on the hillslope at Site 1, whereas just a single gully was eroded from Site 2. The amount of soil lost from Site 1 is therefore higher compared with that from Site 2, when one considers that both hillslopes were affected by the same rainfall event.

Land use alters erosion rates by directly affecting the soil surface response to rainfall in several ways. At Site 1, the soil surface in between the almond trees is kept as bare as possible by regular ploughing in order to minimise the trees' competition for moisture. There is therefore a large area of unprotected soil at Site 1 which is freely exposed to any rain which may fall. As previously mentioned, the soil at this site has a high silt content (44.2 %) and the abundance of fines actively encourages the formation of crusts, thereby preventing infiltration and promoting runoff. Therefore the high amount of exposed soil will encourage crusting and runoff. Silt particles are also very easily mobilised by overland flow, which will further facilitate erosion and gullying at this site. Cultivation practices also alter the natural soil surface roughness, which will have an impact on both infiltration and runoff direction during rainfall events. This same effect was noted by Kirkby et al., (2002) following fieldwork carried out in south-east Spain; the land use was shown to define surface depression storage and influence runoff thresholds. Microtopography and small-scale soil physical properties will be discussed in Chapter 4 in the context of gully morphology and small-scale variables.

Although Site 2 has been abandoned, the regrowth of natural vegetation is still relatively slow due to both the presence of these surface crusts and the inherent lack of water available in a semi-arid environment. Previous research has shown similar results: while the disruption of cultivation will eventually increase the infiltration capacity of a soil as vegetative cover progressively spreads (Greenland et al., 1977), immediately following abandonment, before vegetation has had a chance to re-establish, infiltration rates have been shown to temporarily decrease due to the formation of surface crusts (eg. Nicolau et al., 1996; Lopez-Bermudez et al., 1998).

Differences between Site 1 and Site 2 can be further appreciated by comparing gully A and gully D. These two gullies have similar morphology: both measure approximately 50 metres in length, and comprise a single channel with a small sediment fan towards the base of the hillslope, with no large tributaries joining the channel at any point. The catchment area of gully D the larger of the two at 92.3 m^2, compared with 57 m^2 for gully A. Despite having the smaller catchment area, gully A has a higher volume than gully D (6.01 m^3 compared with 5.3 m^3) and consequently a higher total soil loss (0.95 m^3 ha^{-1} compared with 0.57 m^3 ha^{-1}). While the catchment area and potential runoff contribution to gully D may be higher, the presence of relatively more vegetation and therefore an improved soil structure encourages infiltration, whereas at Site 1 the bare soil and lack of surface vegetation promotes runoff and gully erosion. In a similar study carried out by Lopez-Bermudez et al., (1998) in south-east Spain, the progressive recovery of natural vegetation after land abandonment was recorded. This recovery was characterized by a improved relationship between the vegetation and soil moisture factors; this gradually increased infiltration rates and reduced runoff.

3.3. Hillslope Connectivity: Rainfall and Gully Morphology.

As demonstrated by results from this study, soils cannot be analysed in isolation from the geomorphological systems on hillslopes of which they are an integral part (Gerrard, 1992: 50). However, within the large-scale settings at Sites 1 and 2, spatial patterns can develop on hillslopes as a result of localised differences in topography and soil properties. This patterning can cause a mosaic of areas with contrasting hydrological response to develop, which will affect the hillslope response to surface runoff and infiltration during a rainfall event. The infiltration and soil property data in this study can therefore be used to delineate such patches on the hillslope as 'source' and 'sink' areas: those which will contribute to runoff generation during a rainfall event, and those areas which will preferentially infiltrate more water.

At the large scale, the relationship or connectivity between these patches plays an important role in determining a hillslope's response during a rainfall event. This is due to the fact that the potential for overland flow on hillslopes in semi-arid areas is highly dependent upon the location and arrangement of runoff producing areas. Consequently the spatial arrangement of these patches will affect gully morphological development at the hillslope scale. As previously discussed, in semi-arid environments the redistribution of sediment is largely driven by overland flow and surface wash processes (Puigdefabregas et al., 1999) which are themselves affected by both the hillslope gradient and rainfall variables. As a consequence, the development of 'source' and 'sink' areas in semi-arid regions, in addition to most of the geomorphic work transferring sediment and water between hillslope elements, occurs during extreme rainfall events.

3.3.1. Rainfall Variability in a Semi-Arid Environment.

Rainfall data for Site 1 and Site 2 was obtained from several tipping bucket raingauges located across the Rambla de Nogalte catchment. The location of each raingauge was shown in Figure 2.4 (Chapter 2). These raingauges have been present for several years and from their rainfall records, it can be observed that the wettest months in this region tend to be in the latter part of the year, particularly September, October and November, as was discussed in full in Chapter 2. It is known that the ephemeral gullies A, B and C at Site 1 formed specifically during an intense rainfall event which occurred in early October 2003. The two rain gauges situated nearest this hillslope – 'South 1' and 'South 2' – captured this rainfall event, and it can be seen from their records that the rainfall endured several hours overnight from the 6th to the 7th October 2003. The data from these raingauges is shown in Figures 3.14 and 3.15, and many similarities between the datasets can be observed. This indicates that this rainfall event affected a large part of the catchment, and was not merely a small or localised phenomenon.

The cumulative amount of rain which fell during this event reached almost 40 mm, the majority of which fell in 4 hours (6th October, 4.57 pm – 9.08 pm), as indicated by the red line in Figures 3.14 and 3.15. The intensity of this rainfall event can be further appreciated when one considers that the total annual rainfall in this region of Spain is only between 235 mm and 350 mm (Castillo et al., 2003; Canton et al., 2004a). The fact that gullies A, B and C at Site 1 were formed solely in this rainfall event also means that the amount of rain which fell can be directly related to the morphology of the gullies present in the field.

One of the most distinct morphological features caused by the intense rainfall at Site 1 is the presence of multiple channels towards the top of gully C. If the rainfall is unable to infiltrate and a single channel gully is not sufficient to facilitate the evacuation of overland flow, the drainage network on a hillslope will effectively be enlarged.

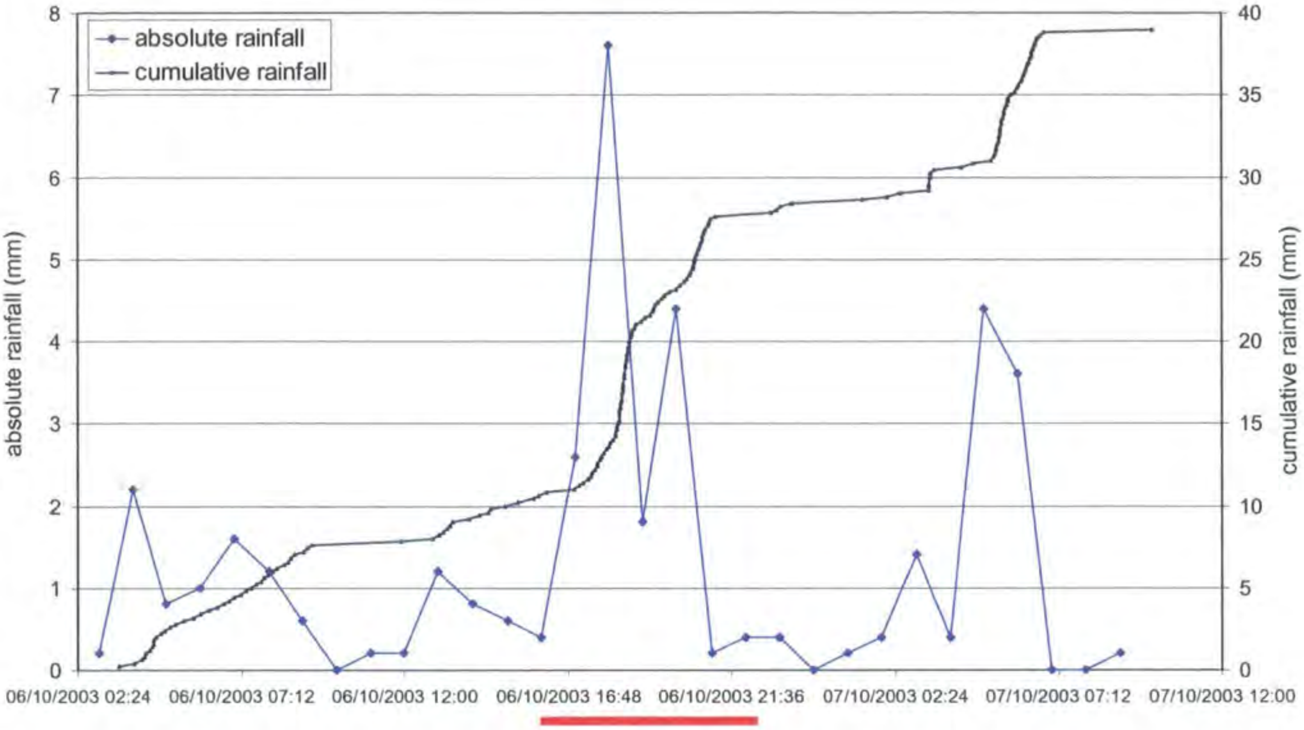


Figure 3.14. Rainfall data from raingauge South 1. The red line indicates the period of more intense rainfall (duration of approximately 4 hours. 4.57pm – 9.08pm).

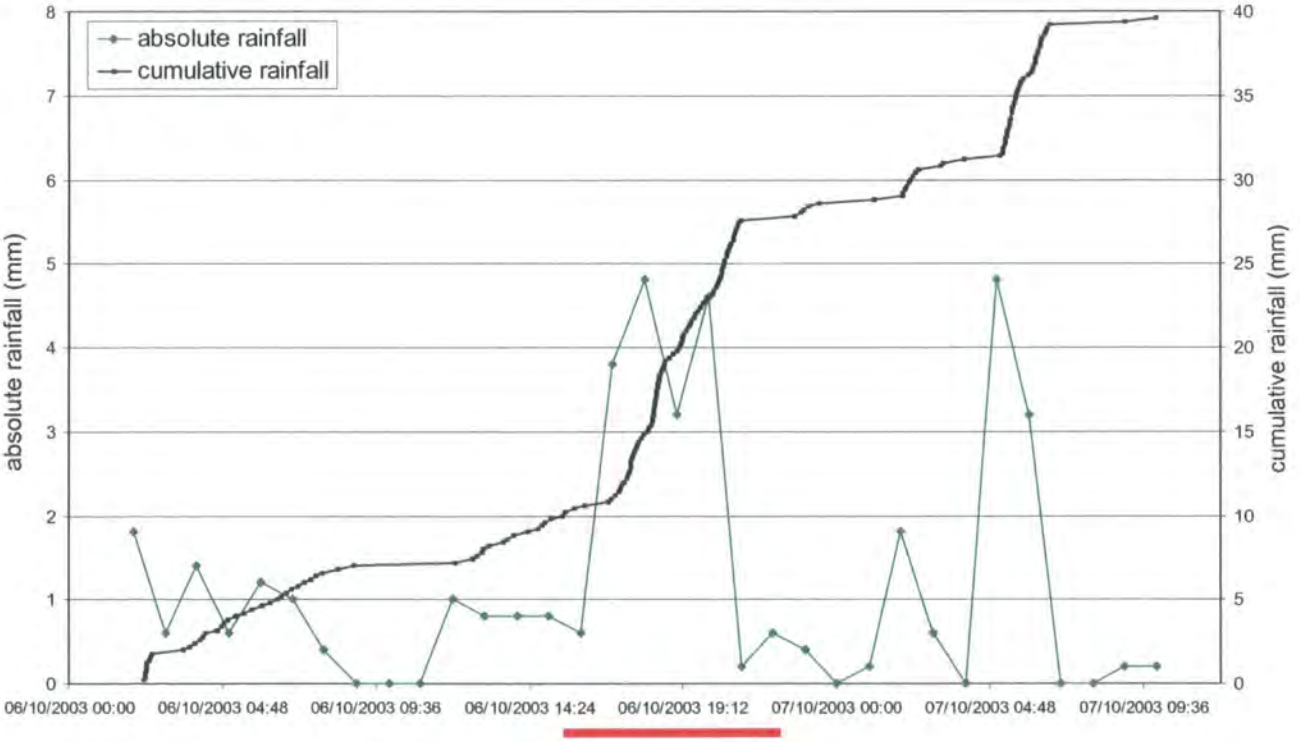


Figure 3.15. Rainfall data from raingauge South 2. The red line indicates the period of more intense rainfall (duration of approximately 4 hours. 4.57pm – 9.08pm).

This was the case for gully C, where multiple channels were been eroded towards the top of the slope during the rainfall event. These channels eventually merged together before joining with the main gully channel further down slope (Figure 3.16). The fact that these multiple channels are continuous and tend to increase in volume downslope indicates that, for gully C, runoff contribution from the sideslopes during the rainfall event was significant. The location of these tributaries also corresponds to areas of slope gradient steeper than the surrounding area, which shows the importance of gradient in determining runoff direction and gully initiation during a rainfall event at Site 1.

In a similar study carried out by Kuhn and Yair (2004), the formation of parallel rills on steep badland hillslopes during an intense rainfall event was examined. Results showed that the form and morphology of rill networks, in particular the degree of integration along slopes, was critical for the catchment hydrologic response. As for Site 1, the different infiltration capacities on slopes in their study were determined by changing soil properties. The spatial arrangement of runoff source and sink areas also had a major effect on channel morphology.

Figure 3.16. Multiple channels towards the top of the hillslope at gully C.

The results presented by Kuhn and Yair (2004) are comparable to those obtained in this study, particularly observations made concerning the influence of infiltration rates. At Site 1, infiltration rates exhibit spatial variability across the hillslope, (as discussed in section 3.2.2) and have a significant effect on hillslope connectivity and gully morphological development. Results show that there is a general trend for lower infiltration rates to be located on steeper areas of the hillslope at Site 1, whereas the flatter topography towards the top of the hillslope exhibits higher infiltration rates. Therefore, as the whole hillslope is affected by the intense rainfall, areas with steeper gradient will be those preferentially producing more runoff, and can therefore be distinguished as 'source' areas.

Evidence of this was seen at Site 1, where the volume of gullies A, B and C was higher in areas of increased gradient ("local volume" or "point volume" defined as the volume in m^3 of a 5 metre section of gully channel: see Table 3.1 for full definitions). When regressed, these two variables had an R^2 value of 0.43. When plotted together on the same set of axes, this relationship between local slope gradient and cross sectional gully volume can be clearly seen (Figure 3.17). At most points along each gully, the volume increases or decreases virtually in line with the local gradient. However, there are a few points where the gully volume experiences a sudden increase which cannot be attributed to the gradient (for example, gully B at 20 m and 65 m, gully C at 40 m and 90 m). Instead, these correspond to locations where tributaries joined the main channel and therefore experienced a higher localised volume of runoff, which enlarged the gully. Smaller discrepancies are attributed to localised variations in infiltration rates and soil properties.

The field data shows infiltration rates at Site 1 are relatively high, yet the presence of gullies A, B and C on this hillslope indicate that there must still have been high amounts of overland flow during the rainfall event. It is therefore necessary to ask the question, why have these gullies still formed when the potential for infiltration is apparently so high? There are, however, several reasons for the presence of the gullies at this site. Firstly, the infiltration data is composed of information from specific points which can be directly related to the gullies. This data only gives a partial picture of the hillslope infiltration rates, so even if high rates are measured in these locations, it is not to say that the entire hillslope will have a similar hydrological response. Many other studies have also revealed great spatial heterogeneity and hydrological discontinuity across semi-arid hillslopes (eg. Fitzjohn et al., 1998; Lopez-Bermudez et al., 1998; Parsons et al., 1999), highlighting the fact that this is a widespread and natural occurrence in such environments.

Secondly, the gullies were formed as a response to the topographical convergence of runoff pathways, which means that these areas experience not only direct rainfall, but additional run-on from areas upslope. This increased amount of overland flow means that the infiltration rate of the soil will quickly reduce as the soil profile wets up. Thirdly, the spatial arrangement and interaction between other factors including local slope gradient, soil particle size, vegetation, and soil organic matter content, will affect the infiltration rates at any given location on the hillslope.

The different variables for each study point at Site 1 are presented in Table 3.5, and in order to further understand their interaction and relative influences on one another, multiple regression analysis was carried out. The results from this show the effects of

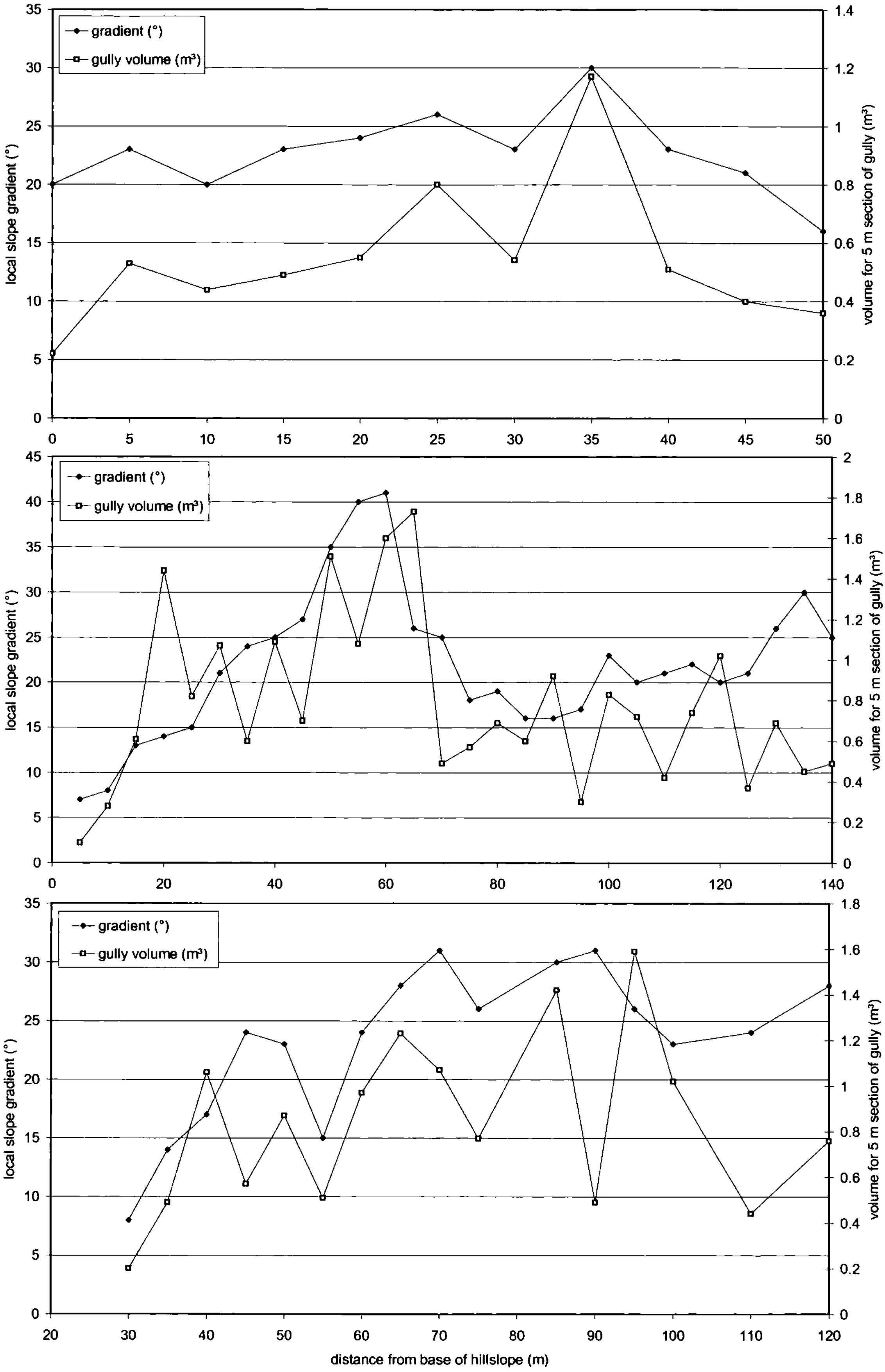


Figure 3.17. Gully volume plotted with local slope gradient for Site 1: gully A (top graph), gully B (middle) and gully C (bottom).

the interaction of several variables on the erosion process and gully morphology. In particular, the regression of local gully volume with local slope gradient and distance upslope gave a highly significant R^2 value of 0.62 ($p = 0.001$; see Equation 1). The regression of local gully volume with local infiltration rate and local slope gradient gave a slightly lower R^2 value of 0.48, but was nevertheless significant ($p = 0.006$; Equation 2).

$$\text{Local gully volume} = -0.39 + (0.044 \, x \text{ Local gradient}) + (0.067 \, x \text{ Distance upslope})$$

$$p = 0.006; \quad R2 = 0.48$$

Equation 2

These results indicate that when considering gully morphology, it is useful to take both the local slope gradient and the position on the hillslope into account. A similar conclusion was reached by Gabbard et al., (1998) following a study of simulated hillslope processes, in which it was found that processes active at different positions on a hillslope had distinct effects on the dominant erosion processes at a given location. This was due to variations of key controlling factors, including soil hydrological conditions and the connectivity between areas on the hillslope.

3.3.2. Hillslope Connectivity in a Semi-Arid Environment.

The potential overland flow contribution from areas on a hillslope to the catchment outflow is dependent upon their spatial arrangement, or connectivity. However, connectivity on hillslopes in semi-arid regions is a subject area where relatively little is known (Bull and Kirkby, 2002: 11). It is therefore important for further research on this subject to be carried out. As mentioned in the previous section, the research presented in this chapter allows distinction to be made between areas on the hillslopes at Site 1 and Site 2, identifying some as 'runoff source' and others as 'runoff sink' areas. These are areas which will have specifically different responses during a rainfall event, and therefore influence gully morphological development at each site. The distinction between these areas is based on the spatial arrangement of large-scale factors which have been shown to have a major influence on gully morphology at each site. In particular, these include hillslope topographic variables (including slope gradient, slope length), variations in infiltration rates and soil properties, and rainfall characteristics. The use of detailed hillslope models, validated using data collected in large-scale field studies, is therefore extremely useful in this context (Sivapalan, 2003).

Due to the lack of available water in semi-arid environments, hillslopes often show poor hydrologic connectivity (Puigdefabragas et al., 1998). It is therefore during major rainfall events when the majority of sediment mobilisation occurs on hillslopes. Where there is connectivity between particular source areas, a constant stream of overland flow will be facilitated during a rainfall event, maximising hillslope runoff and erosion. However, if any of these patches are spatially isolated, runoff from 'source' areas will be absorbed by the surrounding drier areas which act as 'sinks' for overland flow (Fitzjohn et al., 1998). As demonstrated in the previous sections, particular areas on the hillslopes with steeper topography will promote runoff, as will areas with lower infiltration rates. The interaction between these areas – particularly locations in which they coincide – will further encourage runoff, and if a connection is established between such source areas, outflow at the base of the hillslope will be facilitated. If gully A is considered, there are several areas on this section of the hillslope in which these variables coincide. These are indicated in Figure 3.18.

The section of the gully channel at 25 m upslope in Figure 3.18 is worth drawing particular attention to: here, the gully is both at its widest (2.3 m) and deepest (0.28 m). This coincides with the lowest measured infiltration rate for the entire gully (0.65 mm min^{-1}) and a relatively steep slope gradient of 26 °. It can therefore be inferred that the low infiltration rate at this location combined with a 26 ° slope gradient improves connectivity, which increases the amount of runoff, and in turn enlarges the gully channel at this location. The influence of several variables on gully morphological development was also demonstrated by Bryan (2000). He stated that soil erodibility is not a single, simply-identified property, but is more appropriately regarded as the summation of a highly complex pattern, strongly influenced by intrinsic soil characteristics and extrinsic macroenvironmental variables.

If data obtained from gully D at Site 2 is considered (Figure 3.18), it can be seen that there are areas on the hillslope at which the relatively steep topography interacts with the infiltration rates and soil organic matter content. However, although relationships promoting connectivity are active on this hillslope, the relationships do not appear to be as obvious as for gully A. In particular, at 20 m upslope, the channel of gully D is at its deepest, which corresponds to the area of steepest gradient, but the slowest measured infiltration rate is located towards the base of the hillslope. The same is true for the gully width results – while the gully channel is nevertheless relatively wide in areas of steep gradient and slow infiltration rate, the widest parts do not appear to be directly related to the interaction between these factors. Rather, results suggest they come from independent variability. At a length of 25 m upslope, the catchment area of gully A measures 35.7 m^2, and the cumulative gully volume is 5.68 m^3. This indicates that for both these gullies, the slight majority of erosion preferentially occurs in the

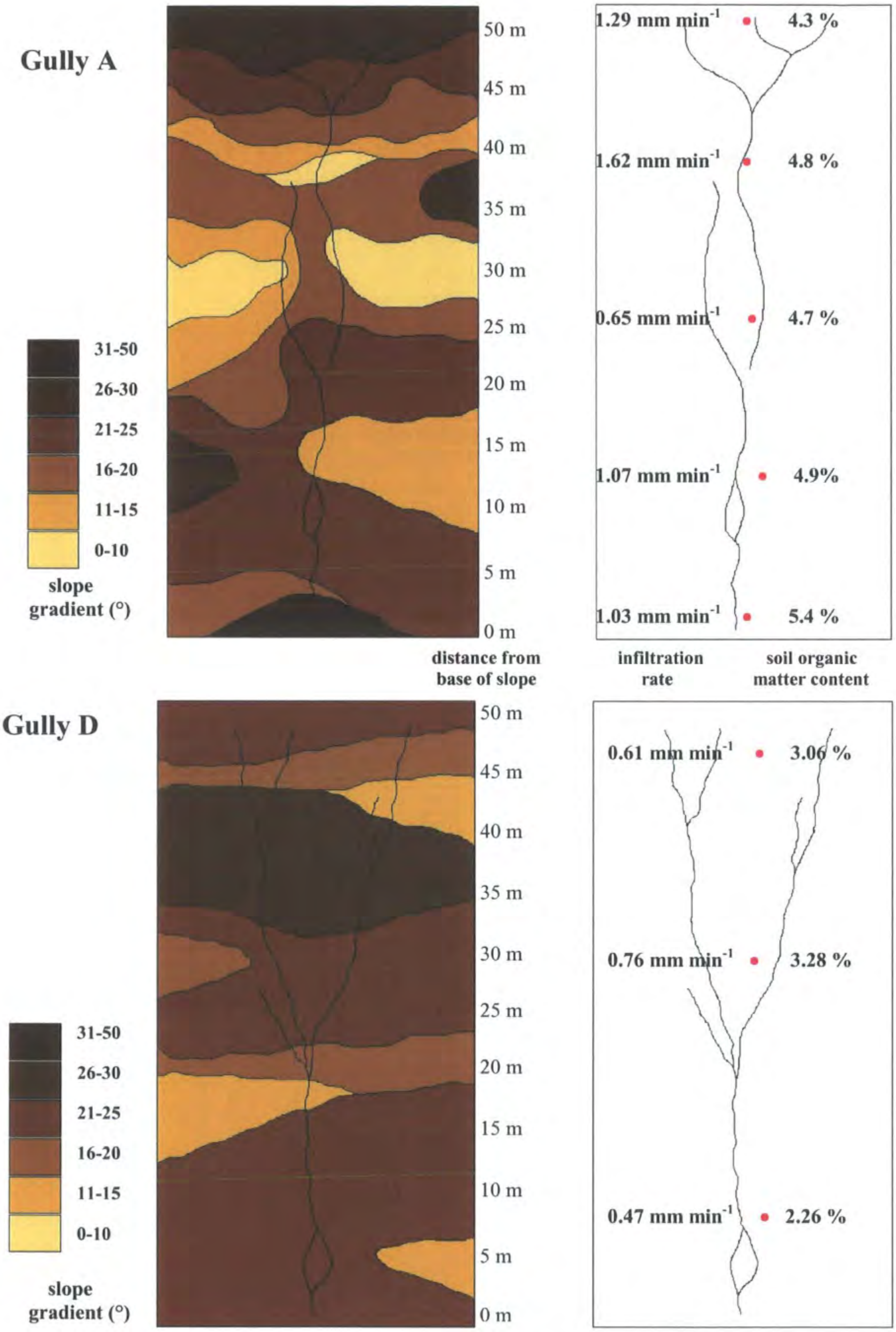


Figure 3.18. Sketch map of gully A (top) and of gully D (bottom). Variables shown in each figure: slope gradient (°), distance from base of slope (m), infiltration rate (mm min^{-1}, defined as the overall rate for that point) and soil organic matter content (%).

upper half of the gully. These areas further upslope are also where the gradient is relatively steeper, therefore any runoff is both promoted and will have more erosive potential.

3.4. Summary.

The large scale data obtained from the hillslopes at Site 1 and Site 2 demonstrates the importance of relationships between specific factors, which specifically influence the morphological development of the gullies present. From these results, it can therefore be concluded that – at the large scale – the potential overland flow contribution and the extent and severity of runoff and erosion on these particular hillslopes is dependent on the distribution and interaction of runoff-producing areas. These are determined by the following: slope gradient, infiltration rates, and physical soil properties. More specifically, the results indicate that slope gradient has relatively the most independent influence on gully morphological development at these sites, but its interaction with the other factors – particularly infiltration rate – is also important.

The data have demonstrated the spatial heterogeneity of factors which influence gullying and erosion on a hillslope. It is therefore necessary to consider these small-scale variations in more detail in order to fully account for the morphology of gullies A – D. The factors active at the small-scale will be discussed in the next chapter.

4. Small Scale Gully Morphology.

4.1. Introduction.

Processes affecting runoff generation and gully morphological development are important at all scale levels. In the previous chapter, results highlighting the roles of large-scale processes were presented, and factors including hillslope topography, land use and the distribution of infiltration rates were shown to have a specific influence on gully morphology. However, while it is important to consider such large-scale processes, conditions on hillslopes also vary greatly over very short distances, reflecting a complex interplay of factors (Bryan, 2000). The inclusion of small-scale data is therefore necessary in any study of soil erosion. In fact, models which do not account for these small-scale heterogeneities will be clearly inadequate in accounting for gully morphology (Sivapalan, 2003).

A change in the scale at which processes are being observed does not merely involve changes in the spatial and temporal dimensions and in the number of components of a system, but instead results in new variables, new relationships, and as a rule leads to the identification of new problems (Haggett et al., 1965). Therefore, due to the importance of small-scale processes, fieldwork was carried out at Site 1 and Site 2 to gather data on gully morphology at the < 5 m scale. In order to obtain very detailed morphological and topographic data for further analysis, the laser scanner was used to take several high resolution scans of areas on the hillslope measuring a few m^2. These "plot scans" corresponded to several locations along each gully, either where the local topography experienced a significant change which appeared to influence the channel, or where the gully's morphology justified a more detailed investigation than the hillslope scans could provide. Plot scans were taken at Site 1 and Site 2 in the locations indicated in Figure 2.14 and Figure 2.15 (Chapter 2). Nine scans from Site 1 and three from Site 2 will be considered in this chapter. As described in detail in Chapter 2, the plot scans were first analysed using Archaeoptics Demon software and were then imported into ArcGIS software where attributes including local slope gradient, runoff direction, elevation and flow networking were derived. Unlike the hillslope scans, these smaller-scale plot scans did not contain any almond trees, therefore their triangulation into surfaces was relatively more straightforward.

In addition to the small-scale plot scans made at each site, fieldwork was carried out by hand in order to obtain further data. This included local infiltration measurements, soil sample analysis, and small-scale measurements of gully morphology made by hand. This data was employed in the previous chapter in the context of large scale morphology, but will also be used in this chapter to demonstrate the significance of local relationships and to account for small-scale variations in gully form. Flanaghan et al., (1995) noted that the detailed measurement of variables such as these on the small scale is essential when attempting to characterise gully morphology and soil erosion by gullying.

4.2. Gully Morphology and the Role of Microtopography.

At the small scale, gully morphology and erosion on hillslopes have received little attention (Valcarcel et al., 2003) and it has also been noted by Canton et al., (2001) that the spatial distribution of soil properties at the small scale have an important role that should be evaluated in further work. Therefore, due to the presence of this research gap, the work carried out for this study will provide some much-needed data on soil properties and erosional processes active at the small scale. The presentation of this data has been divided into local runoff processes causing gully initiation, and local surface properties affecting gully morphological development at the small scale. Each of these will be discussed in turn in the following sections.

4.2.1. Local Runoff Processes and Gullying.

Gully initiation occurs as a result of localised runoff, caused by the interactions between rainfall characteristics and properties of the soil surface. While this is an accurate generalisation, it is well known that the nature of these interactions is in fact very complex and must be studied in detail. The soil surface is the first point of contact for rainfall, and therefore it is of great importance in determining gully initiation. In particular, the soil surface roughness, or microtopography, affects runoff by altering the overland flow direction at the local scale. According to Cremers et al., (1996), surface roughness can be divided into four main categories: these are micro-relief variations due to individual grains and micro-aggregates (0 – 2 mm); random surface variations due to soil clodiness (~ 100 mm); systematic differences in elevation caused by farm implements, such as furrows (100 – 200 mm); and higher orders of soil surface roughness (> 200 mm), representing variations at field or small catchment level.

The soil surface roughness is subject to spatial and temporal changes at all scales. For example, in an agricultural environment, tillage operations often produce abrupt changes in roughness, whereas rainfall impacts upon the soil microtopography by decreasing surface roughness (Kamphorst et al., 2000). In addition, the soil surface roughness affects the amount of depressional storage, the fraction of the soil which can be covered by ponded water, the amount of rainfall excess needed to start runoff and the overland flow rate (Cremers et al., 1996; Bryan, 2000). The provision of water storage in surface depressions can significantly alter the nature of overland flow: for example, a smooth inclined surface will generate runoff initially much quicker than a randomly rough inclined surface (assuming the nature of rainfall & infiltration is the same for each). Therefore knowledge of soil surface roughness is important for all runoff and soil erosion modelling.

The plot scans taken at Site 1 and Site 2 were used to obtain surface roughness data for each location. These images from gullies A, B and C are presented in Figures 4.1 (a–c) alongside corresponding contour data (aerial view). From these representations of the surface, the variations in soil roughness can be seen. Despite several attempts, it was not possible to accurately calculate the surface depressional storage from the plot scans due to the nature of the scans and the fact that they were taken on a large scale inclined plane. This limitation and potential ways of improving future data collection with a laser scanner will be discussed further in Chapter 5. Therefore, small scale changes in slope gradient are presented in Figures 4.1 (a–c) in order to demonstrate the variability of the local soil surface. The plot scan data from Site 1 and Site 2 demonstrate, however, that localised zones of high surface roughness do correspond with areas coinciding with gully channel initiation. In addition, isolated areas of high slope steepness correspond to the gully sidewalls and steps in surface gradient within the gully channels formed by the runoff. During the intense event in which gullies A, B and C were formed at Site 1, almost 40 mm rain fell, and the implications of this rainfall event were discussed in the previous chapter in the context

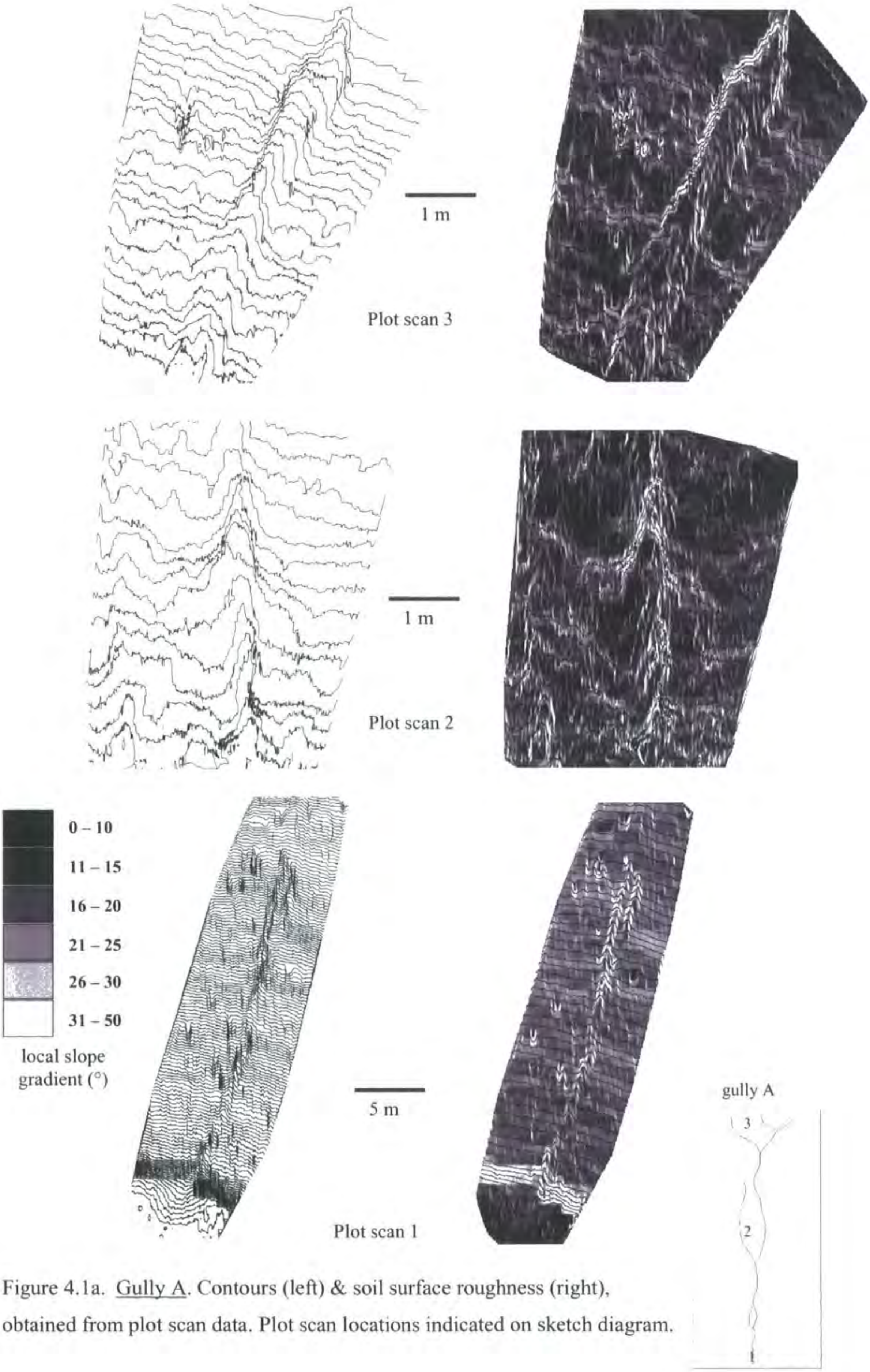


Figure 4.1a. Gully A. Contours (left) & soil surface roughness (right), obtained from plot scan data. Plot scan locations indicated on sketch diagram.

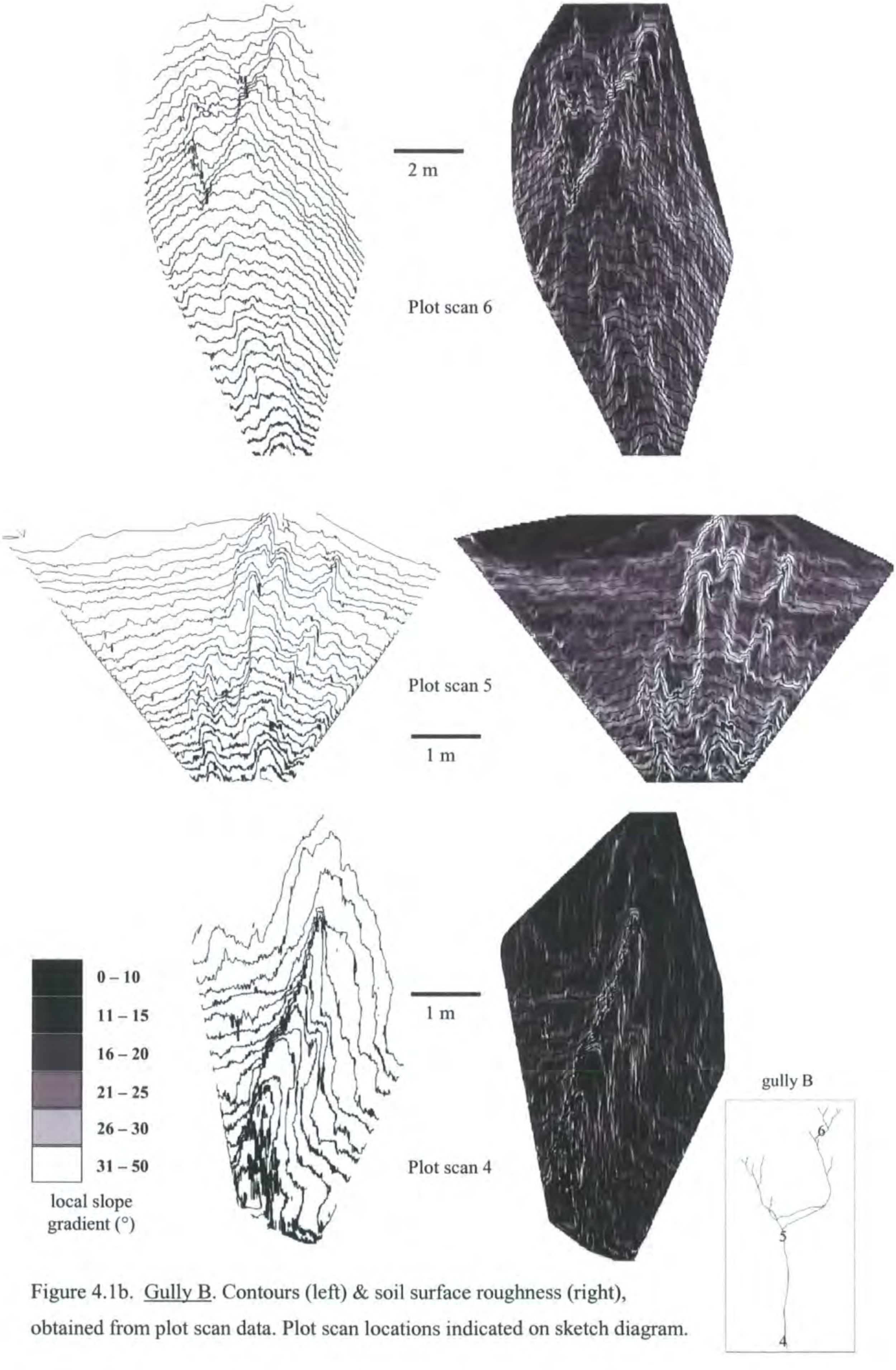


Figure 4.1b. Gully B. Contours (left) & soil surface roughness (right), obtained from plot scan data. Plot scan locations indicated on sketch diagram.

of the whole hillslope (Chapter 3.3.1). How a particular hillslope or watershed responds to rainfall depends upon on the nature of the surface heterogeneities (Sivapalan, 2003), and it is clear from the plot scan data that the influences of the rainfall appear much more varied than at the large scale, and interact to a great extent with the local soil surface roughness.

The point infiltration data from Site 1 and Site 2 shows variation between the plot scans, which can be related to location along the gullies. More specifically, gully C at Site 1 exhibits a very high infiltration rate at the base of the hillslope, being 7.07 mm min^{-1} (plot scan 7). At this location, the soil has the highest organic matter content of the whole gully, at 5.52 %. These factors suggest that at this point along the gully, the nature of the soil surface properties are such that this location acts as a sink area for runoff. This is supported by the gully with and depth measurements made in the field at this point. The depth of the gully at this location is only 0.27 m compared to 0.35 m for plot scan 8 (taken 35 m further upslope). This reduction in gully size suggests that more overland flow is being infiltrated here, which is reducing the amount of runoff actively available to widen the gully. The surface roughness data in Figure 4.1 also showed that plot scan 7 covers a relatively complex section of the gully C channel. There is a reduction in slope gradient to 23 ° at this point and three tributaries are joining together. The overland flow contribution from all three will provide more turbulent flow, which will slightly increase the soil surface roughness and therefore provide more depressional storage for the runoff. This combined with the reduced slope gradient and high soil organic matter content will further encourage infiltration at this point on the gully, reducing its overall local size.

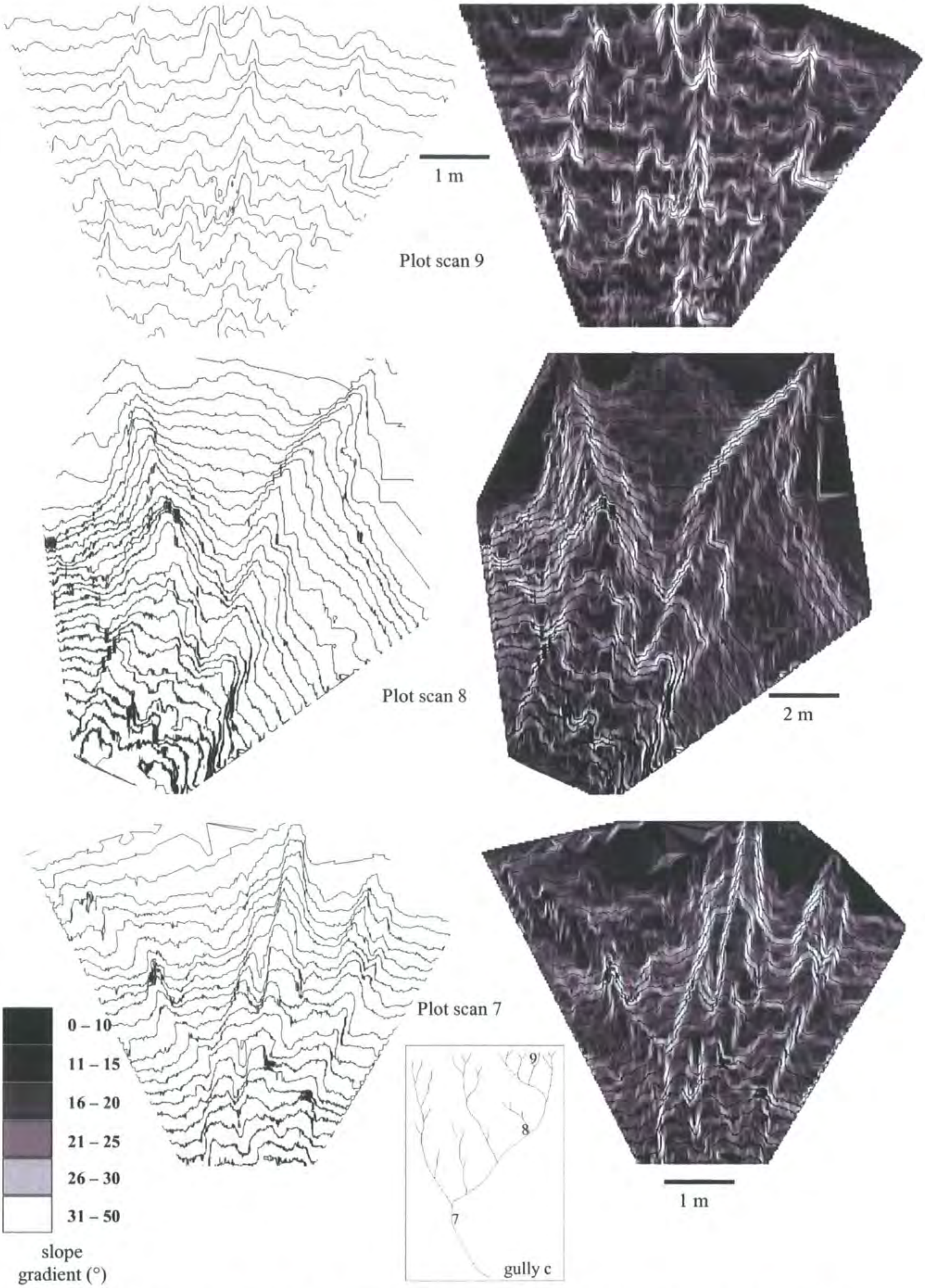


Figure 4.1c. Gully C. Contours (left) & soil surface roughness (right), obtained from plot scan data. Plot scan locations indicated on sketch diagram (just above).

During a rainfall event, a rough surface will initially reduce the energy available for erosion from the runoff (Martinez-Mena et al., 1999). However, small-scale surface roughness will inevitably become modified during rainfall events, and the initial randomness of the surface roughness will gradually develop into a certain amount of organisation. For instance, this can mean that the runoff direction will be altered and overland flow in the immediately-surrounding area may be preferentially directed towards the main gully channel instead. Evidence of this was seen at Site 1 and Site 2 in both the scale and complexity of the gully channel networks, both in the field and as represented in the laser scanner data. Rainfall and the hydraulic conditions of overland flow provide the major erosive potential to alter the surface morphology in a positive feedback system, mainly through their influence on the soil surface roughness. This causes the initiation and development of gullies, and in the early stages, the surface is subject to the runoff.

Once the gully has developed sufficiently and a flow network has been established, the runoff becomes subject to the gullies and will be actively directed towards the channels. For example, gully B at Site 1 exhibits a relatively complex gully network at the top of the hillslope, which gradually develops into a large single channel towards the base. Such links between areas on the hillslope and the gully channels at the small scale are essential for the eventual establishment of hillslope connectivity at all scales.

This positive feedback process which causes alteration of the soil surface microtopography during rainfall events has also been noted by many authors (e.g. de Boer, 1992; Cremers et al., 1996; Diskin and Nasimov, 1996; Kamphorst et al., 2000;

Coppus and Imeson, 2002), and has been shown to be a natural part of the erosion process. While the role of microtopography is important for gully initiation, once this has taken place, further morphological development will rely to a great extent on the connectivity between different areas of the hillslope and the spatial arrangement of source and sink areas.

4.2.2. Local Surface Properties and Gully Morphological Development.

The soil surface response to rainfall plays a very important role in gully initiation, and the spatial variation of surface properties across a hillslope will further determine the morphological response of the soil following gully initiation. Small-scale changes in soil properties and infiltration rates across a hillslope, and the localised effects of land use all contribute to the morphological development of gullies and hillslope connectivity. Therefore, in order to investigate the role of physical soil properties in shaping gully morphology, soil samples were taken at both Site 1 and Site 2 from locations that corresponded to the infiltration measurements. Using these soil samples, the pH, electrical conductivity, soil organic matter content and particle size distributions were determined. The methods used to carry out these analyses were described in detail in Chapter 2. Physical properties such as these will give an insight into local variations in soil surface properties, and will aid the relation of a gully's morphological features to its physical settings at the local scale.

Grain size is one of the most fundamental properties of sediment particles, affecting their entrainment, transport and deposition. This data therefore provides information concerning sediment provenance, potential for transportation and depositional conditions (Blott and Pye, 2001). The program Gradistat was used to classify the grain size data, as described in Chapter 2. The results for each sample are categorised according to the British Standards Institution classification system (Table 4.1) and the full dataset is given in Appendix 2. Overall results are presented in ternary plots in Figure 4.2. This data shows that there is relatively little differentiation in soil type across the hillslopes: the majority of samples are classified as Sandy Silt, with a few

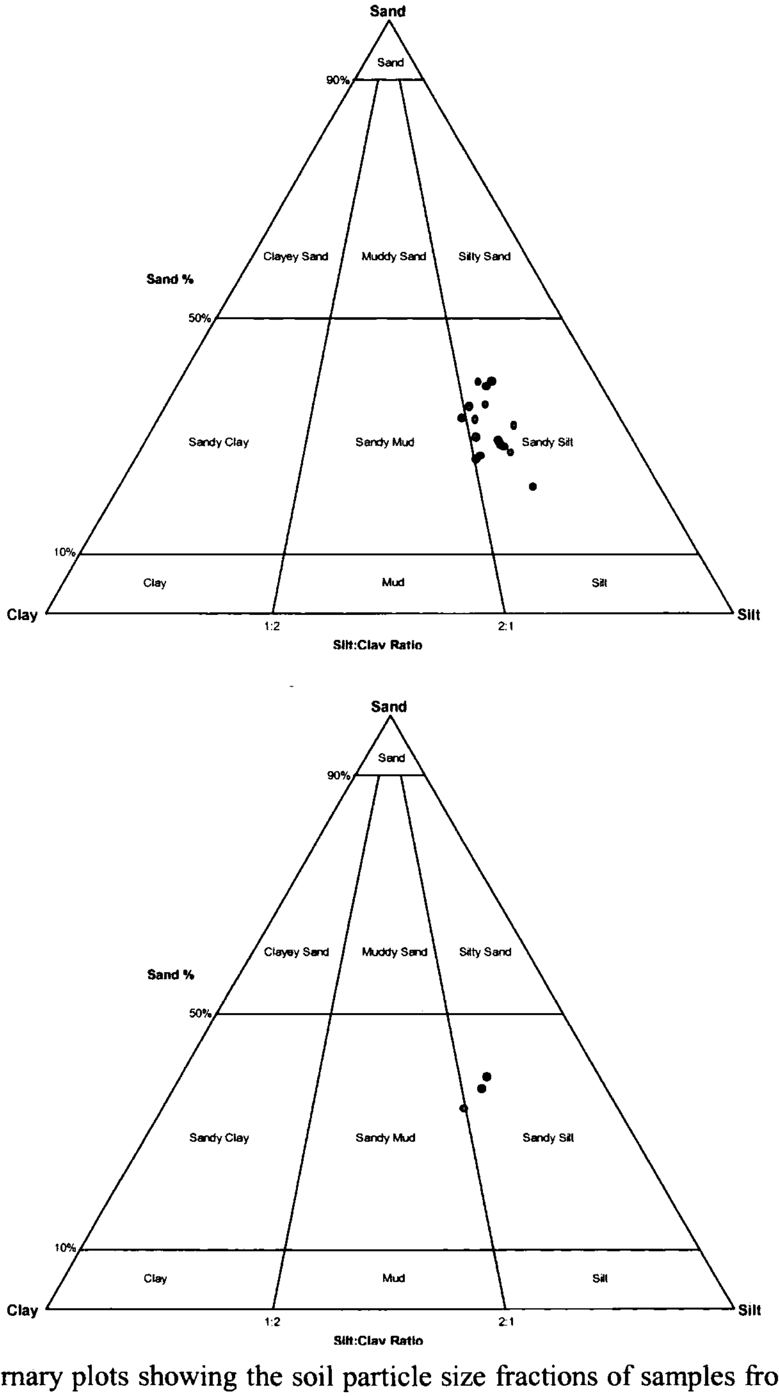


Figure 4.2. Ternary plots showing the soil particle size fractions of samples from Site 1 (top) and Site 2 (bottom).

Description	Grain Size
Gravel	64 mm – 4 mm
Sand	< 4 mm – 64 μm
Silt	< 64 μm – 4μm
Clay	< 4 μm

Table 4.1. Grain size classifications and descriptive terminology.

tending towards Sandy Mud. The fact that the soil types across the hillslopes are relatively homogeneous demonstrates that gully morphology will not be significantly affected by strong variation in soil properties. Rather, the fact that the soil at both sites has a consistently high silt content will play a greater role in erosion processes: this is due to the fact that silt is the most easily erodible particle size.

If the grain size results for the gullies are considered more specifically alongside data from the same locations at Site 1 (Table 4.2, and later in Figure 4.4), it can be seen that areas which have a higher silt content correspond to locations just upslope of the gully heads. In the case of gullies B and C in particular, samples originating from alongside plot scans 6 and 9, taken towards the top of the hillslope, have high silt contents – 60.3% and 54% respectively – and these locations correspond to the slowest infiltration rates at gullies B and C. The high silt content of the soil in these locations means that during a rainfall event, the formation of a surface crust will be facilitated by the high proportion of fines. The presence of a surface crust will then reduce infiltration rate – as shown in the results – thus encouraging surface ponding and overland flow, eventually causing gully initiation. Silt is also the most easily eroded soil particle, and any such sediment which does not form a crust will therefore be easily mobilised during overland flow, potentially causing gully initiation.

		A			B			C		
	plot scan	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	dist from base of slope (m)	5	30	50	35	85	140	50	85	110
	upslope catchment area (m^2)	57	35.7	7.4	138.5	51.2	15.7	349.5	295.2	248.8
	cross sectional area (m^2)	0.22	0.8	0.36	1.09	0.6	0.45	0.87	1.42	0.44
	local slope gradient (°)	22	23	16	24	16	25	23	30	24
	gully width (m)	0.51	2.3	1.05	1.9	1.75	3.95	2.48	2.9	1.45
	gully depth (m)	0.32	0.25	0.15	0.62	0.25	0.14	0.27	0.35	0.18
	infiltration rate (mm min^{-1})	1.03	0.65	1.29	2.43	1.53	0.99	7.07	2.86	2.71
soil properties	sand (%)	32.8	38.5	28.2	35.3	39.3	21.4	26.2	35.2	29
	silt (%)	46.1	44.8	42.6	46.3	43.3	60.3	49.6	44	51.5
	clay (%)	21.1	16.6	19.2	18.3	17.4	3.95	2.48	2.9	1.45

Table 4.2. Small scale data for gullies A-C at Site 1.

From these results it can therefore be inferred that particle size at this site does affect gully morphological development at the local scale. This was also the case for gully A: while the sample with the highest silt content did not correspond to the slowest infiltration rate, it was, however, located at the top of the gully. The correlation of all the soil property data is presented in Table 4.3 and from this, several important relationships can be seen. In particular, the infiltration rates at Site 1 have a relatively strong correlation with the clay particle size fractions in the soil ($R^2 = 0.59$). To a certain extent, this relationship is surprising, since the presence of clay causes swelling in the soil once it becomes wet, which prevents further infiltration from occurring. In order to properly interpret this result, the relationship of these two variables with the organic matter content of the soil must again be taken into consideration.

The correlation between soil organic matter and percentage clay content is relatively high, with an R^2 value of 0.47 (Figure 4.3). This relationship can be explained by the fact that clay particles are more effective at holding onto moisture than other soil fractions, therefore in a semi-arid environment where the presence of vegetation is mainly limited by water availability, its growth will tend to be concentrated in locations with a higher soil moisture content. Consequently, a local increase in vegetation and organic matter in these clay-rich areas may actively encourage infiltration during a rainfall event. The fact that the presence of clay across the hillslope at this site is not uniform will also encourage the spatial differentiation of runoff-producing areas. The role of vegetation as a source of spatial heterogeneity was also noted by Puigdefabregas et al., (1999) in a study of hillslope and channel responses to rainfall in a semi-arid environment.

As discussed in section 4.1, gully width and depth data was also collected by hand in locations which corresponded with the plot scans. Therefore this data can be related to the more detailed morphological features captured by these scans. Gully width and depth measurements made in the field were taken at 5 metre intervals in an upslope direction starting from the base of the gully. Although this data gives good detail at

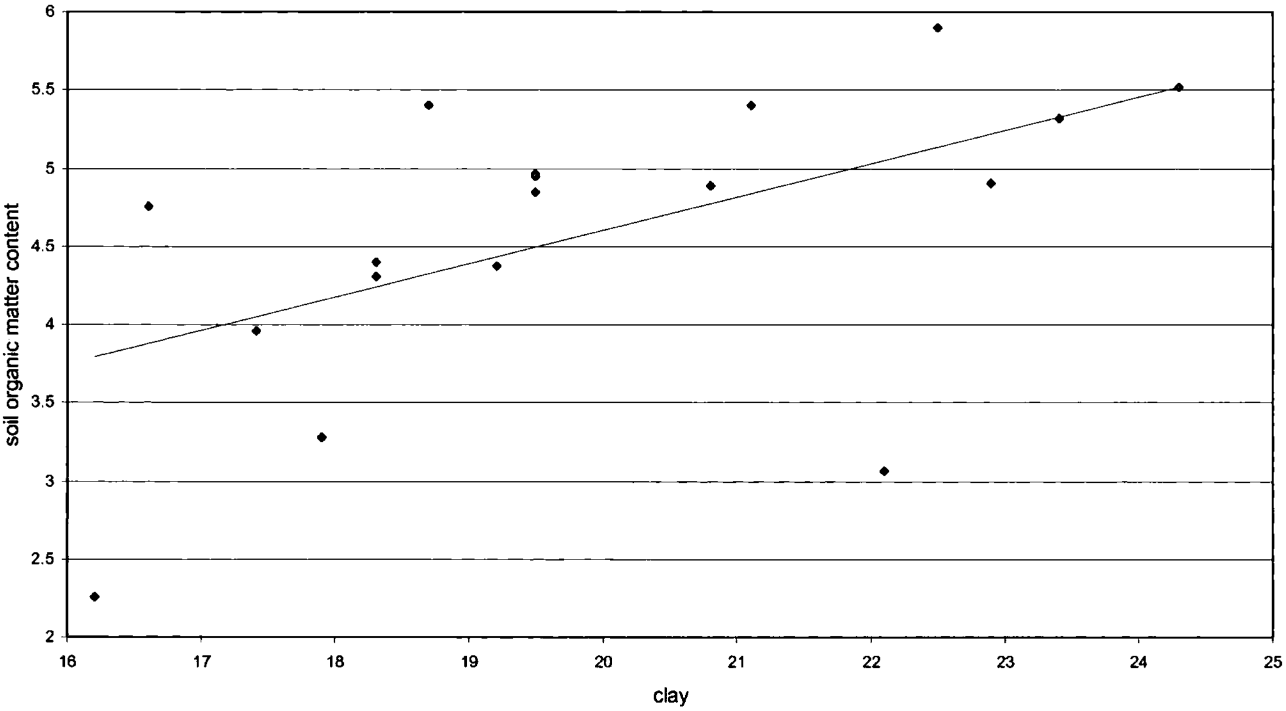


Figure 4.3. Relationship between soil organic matter and percentage clay fraction. $R^2 = 0.48$

	sand	silt	clay	infiltratn	pH	ec	omc	width	depth	ptvol	cumulvol	slope	upslope
sand	1.00												
silt	-0.89	1.00											
clay	-0.34	-0.12	1.00										
infiltratn	-0.25	-0.08	0.59	1.00									
pH	0.25	-0.47	0.44	-0.02	1.00								
ec	0.26	-0.27	-0.01	-0.34	0.49	1.00							
omc	-0.29	-0.02	0.69	0.36	0.27	-0.12	1.00						
width	-0.22	0.31	-0.14	0.09	-0.39	-0.53	-0.02	1.00					
depth	0.39	-0.44	0.04	0.02	0.13	-0.26	0.18	-0.26	1.00				
ptvol	0.22	-0.25	0.04	0.14	-0.08	-0.30	0.23	0.63	0.76	1.00			
cumulvol	0.07	-0.29	0.43	0.37	0.09	-0.06	0.24	-0.25	0.24	-0.03	1.00		
slope	-0.05	0.10	-0.19	-0.11	0.01	-0.14	0.02	0.72	0.41	0.66	-0.57	1.00	
upslope	0.59	-0.29	0.47	0.50	0.02	-0.14	0.34	-0.26	0.20	-0.03	0.96	-0.58	1.00

Table 4.3. Correlation table for all variables. n = 15. infiltratn = infiltration rate (mm/min); ec = electrical conductivity (µS cm^{-1}); omc = % organic matter content; ptvol = gully volume at a point (m^3); cumulvol = cumulative gully volume (m^3); slope = gradient (°); upslope = position on hillslope as measured from base (m)

the large scale, it is too far apart to realistically capture the very small-scale intricacies of the gully morphology. Therefore, very detailed width measurements were derived from the plot scan data instead. These are much more accurate than any measurements that could have been collected by hand in the same amount of time.

If this data for Site 1 is considered, the presence of several trends in gully morphology across the hillslope are demonstrated (as shown in Table 4.2). One of the initially most obvious morphological differences between gullies A, B and C is the number of tributary channels which join each main gully channel at several locations downslope. At the large scale, gully A has a relatively simple morphology, and this is reflected in its physical properties at the small scale. Since there are no areas along gully A where tributary channels join, there are no areas where the gully experiences localised widening due to channel convergence and increased runoff volume.

The form and morphology of rill and gully networks is critical for catchment hydrologic response (Kuhn and Yair, 2004). While the morphology of the three gullies at this site appear very different, several important similarities do exist between A, B and C (Figure 4.4). The three gullies all have the highest soil silt content at the top of the gully; all have the highest soil organic matter content (omc) at the base of the gully; all are widest at their middle point; and all but one (gully C) are deepest towards the base of the gully channel. The morphological implications of each of these variables will be discussed in turn.

Flow concentration alone does not necessarily cause rill incision (Bryan, 2000). Instead, as previously discussed, rill and gully development is linked to the interaction of overland flow with small-scale surface properties; in particular, to the susceptibility of soil particles to entrainment and transportation. Over the range of grain sizes, the sediment travel distance increases as size decreases, so that erosion is effectively transport-limited for coarse debris, and supply-limited for fine material (Kirkby and Bull, 2000). This is particularly important in a semi-arid environment, where erosion is often transport-limited due to infrequent rainfall events: this is the case in the Rambla Nogalte, where there are also large amounts of gravel throughout the catchment.

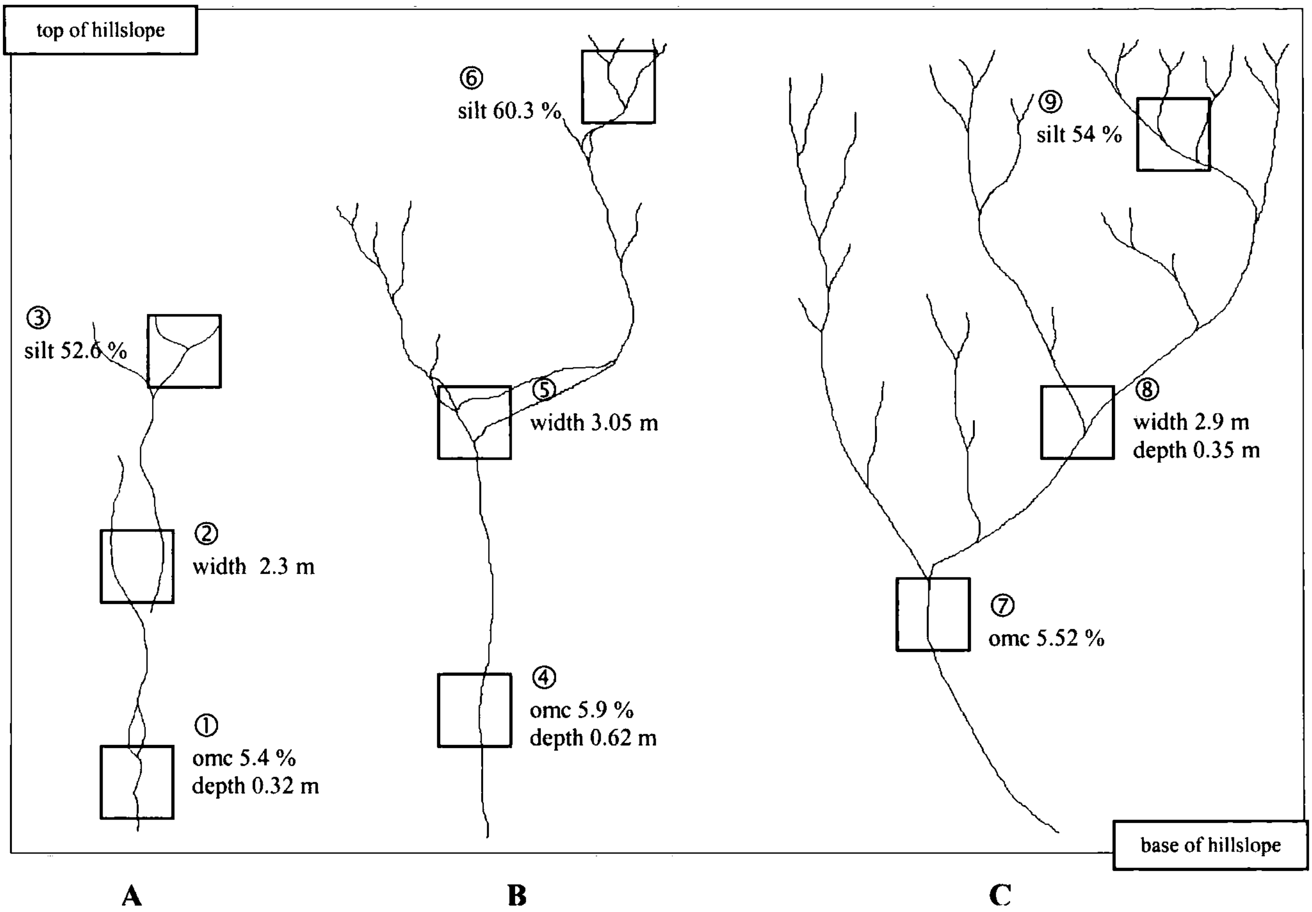


Figure 4.4. Sketch diagram of gullies A, B and C at Site 1. Location of plot scans ① – ⑨ are shown by squares. <u>Highest</u> data values for each gully are given alongside the corresponding plot scan: width (m), depth (m), soil omc (%) and soil silt content (%).

As demonstrated by the data, at Site 1 high localised silt concentrations are present where the gullies are least well-developed. This combined with the fact that silt is one of the most easily transportable soil fractions, implies that the majority of the silt has already been eroded from other, more mature parts of the gullies which experience higher runoff amounts. In addition, areas still having a high silt content – namely, the gully heads towards the top of the hillslope – may also potentially experience the majority of morphological development during future rainfall events. Indeed, channel growth is governed by the processes that occur upslope of the channel head (Kirkby and Bull., 2000) and it is the instability of gully heads which is responsible for channel expansion and erosion, eventually leading to the degradation of agricultural land which is an increasing concern in semi-arid areas. Gully heads are therefore important links between upper hillslope areas and gully channels; they can function as sediment sources depending on environmental conditions and vegetation elements (Poesen et al., 2002: 241).

The presence of organic matter in the soil has a positive effect on soil aggregate stability, thus reducing erosion during rainfall and runoff events (e.g. Martinez-Mena et al., 1999; Albaladejo et al., 1998; Lavee et al., 1998) and preventing gully extension at channel heads. The highest soil organic matter content for gullies A – C were found towards the base of the slope in each case (Figure 4.2). Compared to other studies carried out in semi-arid regions, the soil taken from Site 1 and Site 2 is relatively rich in organic matter. For example, in soil samples taken from former farmland in north-east Spain Lasanta et al., (2000) only measured between 0.7 % and 1.3 % organic litter and a low nutrient content. This low omc was shown to inhibit plant colonisation, lower infiltration, and eventually reduce the water content of the soil.

At Site 1 the reverse is true: the presence of high soil omc towards the base of the gully channels indicates that these will be areas where the infiltration rate – and therefore soil moisture – will be expected to be higher. Although the field data does not show the infiltration rates here for gully A to be particularly high (plot scan 1 – 1.03 mm min^{-1}), at these locations the infiltration rates for gullies B and C are indeed the quickest times measured along the whole of each gully. These are 2.43 mm min^{-1} (plot scan 4) and 7.07 mm min^{-1} (plot scan 7) respectively. The high infiltration rate at these locations allows them to be distinguished as 'sinks' where runoff is preferentially infiltrated. At the small scale, the interaction of the soil omc and infiltration rates with the soil surface during rainfall – runoff events inevitably has an impact on local gully form and morphology, which are critical for catchment hydrological response.

The agricultural practices employed at Site 1 – seasonal ploughing in between almond trees and the grazing of sheep and goats – have an effect on the small scale soil omc and the particle size distribution. The presence of organic matter increases the structural stability of a soil, and the removal of natural vegetation by ploughing the soil in semi-arid environments has been shown in many studies to significantly reduce the omc of the soil, consequently increasing erosion and rates of gullying (e.g. Cerda, 1997; Kosmas et al., 1997; Valcarcel et al., 2003).

Agricultural practices also have a strong influence on overland flow. For example, during a rainfall event, tillage lines on the soil surface which are left as a result of ploughing can change the natural overland flow direction, causing flow concentration and gullying in what would otherwise be stable areas. Following a field study in northwestern Spain, similar effects of agricultural operations were noted by Valcarcel et al., (2003), who stated that lineal features left on the landscape often acted as initial "axes of erosion." These lineal features were observed on the soil surface at both Site 1 and Site 2, and have been captured in the plot scans. In Figure 4.3 (Site 2), the soil surface exhibits relict surface roughness effects as a direct result of ploughing. Small, flat terracettes are visible on the hillslope, which act as areas of surface ponding. At Site 1 (Figure 4.5), ridges crossing gully channels at a right angle are visible in the scan, as indicated by the arrows. Results indicate that these local patches of raised topography will affect the morphological development of the gully at this site by initially preventing runoff, and eventually altering overland flow direction. The spatial variability of gully erosion in these locations is therefore notably affected by agricultural operations.

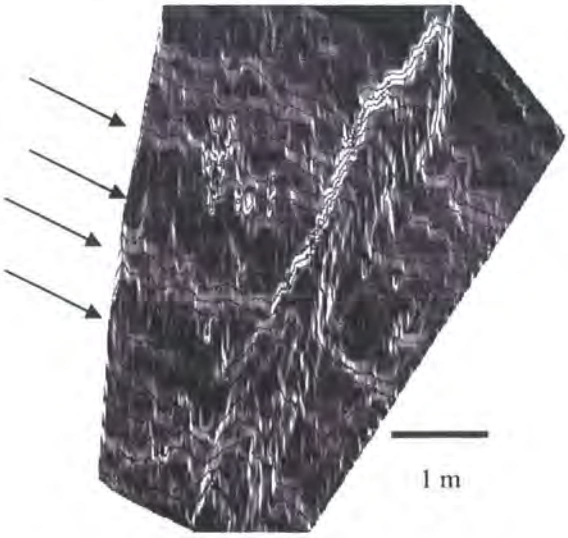


Figure 4.5. Plot scans from Site 1 with arrows indicating surface roughness elements (terracettes and relict plough lines).

In addition to showing distributions of soil particle size and soil omc and demonstrating the influence of land use practices, the data also shows the nature of the physical gully channel development. As mentioned before, gullies A – C are widest midway along their length where slope gradient is also steepest, and gullies A and B are both deepest towards the base. If this data is used in conjunction with the upslope catchment area for each plot scan, the nature of the relationship between cross-sectional area, erosion volume and catchment area can be determined. These can then be used to further account for the gully morphology.

Although the connection between gully width and upslope catchment area does not appear to be particularly straightforward at Site 1, the gully depth does demonstrate a slightly stronger relationship, as was discussed in a larger-scale context in Section 3.2.1 and shown in Figure 3.7. If just gullies A and B are considered, there is a downslope increase in gully depth as catchment area increases. As a result, these two gullies both appear to become progressively deeper towards the base of the hillslope. This phenomenon of increasing gully depth towards the base of the hillslope was also noted in a field study carried out by Bryan (2000). He also observed that once overland flow concentrates into rill channels, many surface roughness elements are submerged and depth increases downchannel, producing hydraulically smooth flow. Gully or channel depth at any location therefore reflects the balance between rainfall rate, flow delivery from upslope and infiltration rate (Bryan, 2000). The gully depth therefore reflects the dynamic interaction and feedback of several variables and is closely linked to the soil properties at the small The interaction between factors including catchment area, gully volume, local slope gradient and erosion is also complex, but essential to consider when accounting for gully form and morphology.

	width	depth	x-section area	cumul-ve volume	local slope	length upslope
width	1.00					
depth	0.27	1.00				
x-section area	0.63	0.76	1.00			
cumulative vol	-0.26	0.25	-0.04	1.00		
local slope	0.72	0.41	0.66	-0.58	1.00	
length upslope	-0.26	0.20	-0.04	0.96	-0.58	1.00

Table 4.4. (n = 15) Site 1: correlation between variables gully width (m), gully depth (m), cross-sectional area (m^2), cumulative gully volume (m^3), local slope gradient (°), and length up from the base of slope (m).

The correlation between these and other variables from Site 1 is presented in Table 4.4. Several important relationships are highlighted by this dataset: in particular, that between the gully width and the local slope has a highly significant R^2 value of 0.52, demonstrating that the gully channels tend to be wider on steeper slopes.

The relationship between the three variables of local slope gradient, local gully volume and distance upslope is also relatively strong, having an R^2 value of 0.62 and a high significance when these are regressed together ($p = 0.001$; see Equation 1). This indicates that the interaction of these variables is key to the morphology of the gullies, and zones in the landscape where the gullies start will be more controlled by gradient, while the presence of concavities controls the trajectory of the gullies until the slope gradient is too low and sediment deposition dominates (Poesen et al., 2003). The data presented in Figure 4.6 also demonstrates that the catchment area influences the gully morphology.

The relationship between the cumulative volumes and the catchment areas for gullies A, B and C is very strong: the R^2 values are all close to 0.9 (gully A: $R^2 = 0.98$, gully B: $R^2 = 0.88$, gully C: $R^2 = 0.92$). Naturally, the cumulative volume will be an increasing value, but it can be argued that gully A has the strongest relationship because it has the simplest morphology, therefore its channel growth and development is not interrupted or affected by the presence of large tributaries joining the main channel, or abrupt topographic changes, as in the cases of gullies B and C. In a study carried out by Esteves and Lapetite (2003) into runoff generation in a dryland gully catchment, similar results were obtained. Field observations demonstrated that the entire catchment area of a morphologically-complex gully did not contribute to runoff. This strengthens the relevance of mapping the soil surface features in the evaluation of the runoff capability of the catchments.

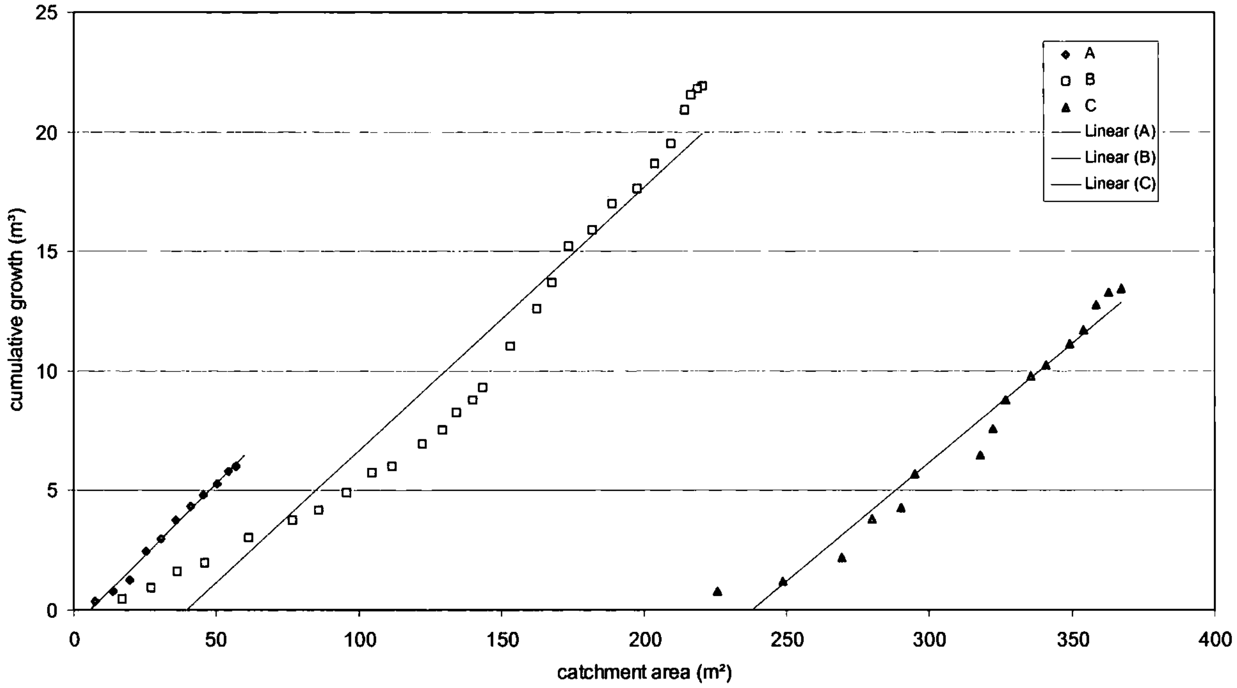


Figure 4.6. Gullies A – C cumulative gully channel growth (m^3) vs catchment area (m^2).

Despite the strength of the relationships between factors discussed above, the presence of some scatter and outlying points in the results shows that there are small-scale areas which behave differently and cannot be accounted for in a generalised statement about the hillslope. These areas, where the effects of rainfall and runoff differ, lead to the selective establishment of flow networks and gullying. This will be discussed further in the next section.

4.3. Small Scale Erosion Processes and Establishment of Connectivity.

4.3.1. Flow Network Establishment.

The large scale data presented and discussed in Chapter 3 demonstrated that the morphology of the gullies at both Site 1 and Site 2 is the result of the complex interplay of several variables. This is also true for the small scale morphology of the gullies. The data presented in this chapter has also shown that local factors including rainfall, slope gradient, soil properties and infiltration rates vary greatly over short distances. Their variation and interaction across the hillslopes causes the establishment of small-scale areas with differing hydrological response. This has also been observed by many authors, including Fitzjohn et al., (1998). Following the study of a gully catchment in central Spain, they stated that the extent and severity of runoff and erosion across the catchment was dependent upon soil variation, which could create a spatial mosaic pattern of hydrological response. Such areas may be manifested as local 'source' and 'sink' patches, which causes the hillslopes in semi-arid areas to operate in isolated cells rather than in catenal sequences (Van Wesemael et al., 2000). Therefore the behaviour of the runoff in these patches will determine the initial flow networks and eventual gully morphology and hillslope connectivity.

The hydrological connection between a runoff contributing area and a runoff collecting network results in gully erosion (Souchère et al., 2003) and the presence of the three gullies at Site 1 and gully D at Site 2 demonstrates that connection on both hillslopes was established at some point during the rainfall event on the 6th October. Therefore, using the plot scan data from Site 1 and Site 2, the small scale flow networks were derived. Surface properties including local slope gradient and the presence of surface depressions were used to account for the runoff patterns at each plot scan location. ArcGIS software was first used to derive the network flow routing for each scan. The flow network parameter is determined by applying the slope gradient and runoff direction data derived from each plot scan. This data is presented in Figure 4.7 (a – d) and demonstrates the complexity of the runoff network at the small scale for each of the plot scans in unprecedented detail.

The flow networks at each plot scan location are dendritic, but even at this small scale, they show a general trend in which the flow converges towards one or several main gully channels or tributaries. A particularly good example of this can be clearly seen in plot scan 8 (Figure 4.7c): the data at this point indicate the convergence of two major tributaries, located mid-slope on gully C. The runoff data for this plot scan shows how the overland flow network is organised in such a way that almost all the runoff is directed towards these two main tributaries. It is at this point that the slope gradient is steepest along the length of gully C, and the gully channel is at its widest (2.9 m) and deepest (0.35 m). The strong definition of the gully channel at this location suggests that this is a runoff-producing "source" area and connectivity with neighbouring parts of the hillslope will be high.

In contrast, the flow network data for plot scan 2 (Figure 4.7a; taken at the middle of gully A) shows that in detail there is no continuous flow network. Instead, there are several discontinuous directions of overland flow, some of which lead into the main gully channel before stopping, and others which run parallel with it. The relatively high number of discontinuous channels present around the main gully in this plot scan shows that the connectivity of this point on the hillslope with other areas is low. The high number of channels demonstrates that – given sufficient rainfall – this location is also a potential source area.

In a comparable study of the relationship between soil surface roughness and connectivity carried out by (Darboux et al., 2001), it was suggested that flow network structures evolve into "self-organised" configurations, where the overall sinuosity and gradient of the flow paths undergo a decrease, as observed in more-developed river networks. The nature of the flow network data obtained from the laser scanner in this study does appear to support this theory: it demonstrates morphological differences between upslope areas and those closer to the base of the hillslope. In particular, as the channels approach the base of the slope they become less dendritic and significantly more defined, as flow concentration is highest and slope gradient begins to decrease, as shown by the field data and laser scanner results. Therefore, this suggests that while the overall morphology of the gullies at the large scale can be more "self-organised", there is inevitable high spatial variability in gully channel development at the small scale.

The fact that in each plot scan, the nature of each overland flow pattern is very different demonstrates the complex nature of runoff at this small scale. It also highlights the fact that while generalisations about local-scale runoff patterns are often made, they can never be completely accurate. As demonstrated in the plot scan flow network data, the establishment of hillslope connectivity begins with the linking of small-scale areas, and the strong relationship between gully morphology and landform at both sites demonstrates that there is an important topographic control on soil properties. In particular, the flow network data and its relationship with the soil properties highlights the need for further understanding of the continuity and hydrological connectivity between different areas of the hillslope.

4.3.2. Small-Scale to Hillslope-Scale Connectivity.

The data presented in the previous section has demonstrated that the form and morphology of rill and gully flow networks are critical for hillslope hydrologic response. The connectivity between runoff-generating and runoff-absorbing areas on a hillslope is important at all scale levels (Cammeraat, 2002), especially in dryland environments such as the Rambla de Nogalte. This is because connections in semi-arid regions are only established during rainfall events due to the lack of soil moisture during most of the year, and areas quite close to one another can exhibit a contrasting response. Runoff at the hillslope scale is therefore determined by the response of partial areas to rainfall events, and it is during such events that the linkages within and between hillslopes and channels are very important (Coppus and Imeson, 2002).

As demonstrated by the results presented in this and the previous chapter, one difficulty in accounting for hillslope connectivity and gully morphology is achieving a proper reconciliation between the complexity inferred by processes active at the small-scale and the relative simplicity inferred by those at the hillslope-scale

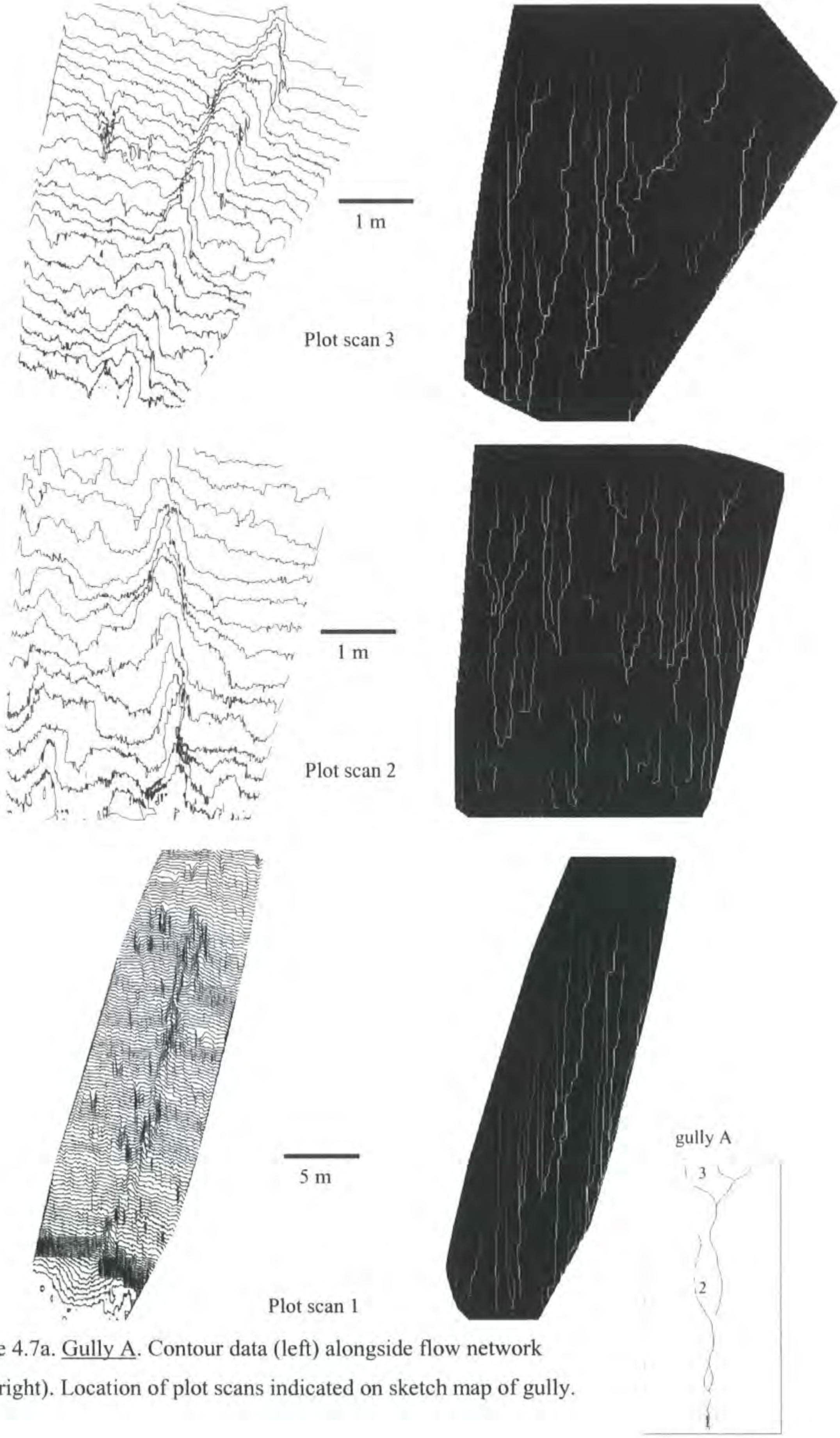


Figure 4.7a. Gully A. Contour data (left) alongside flow network data (right). Location of plot scans indicated on sketch map of gully.

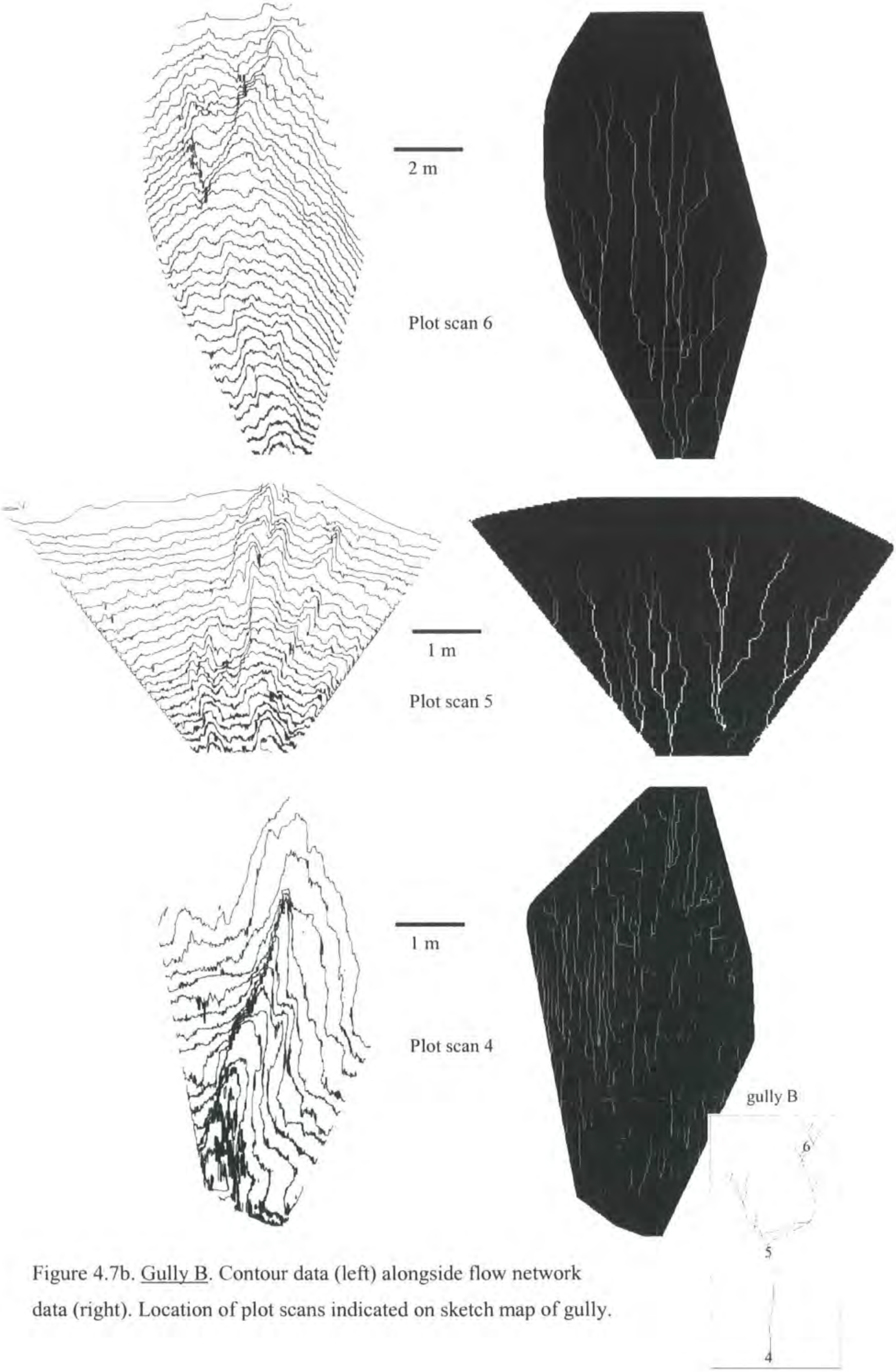
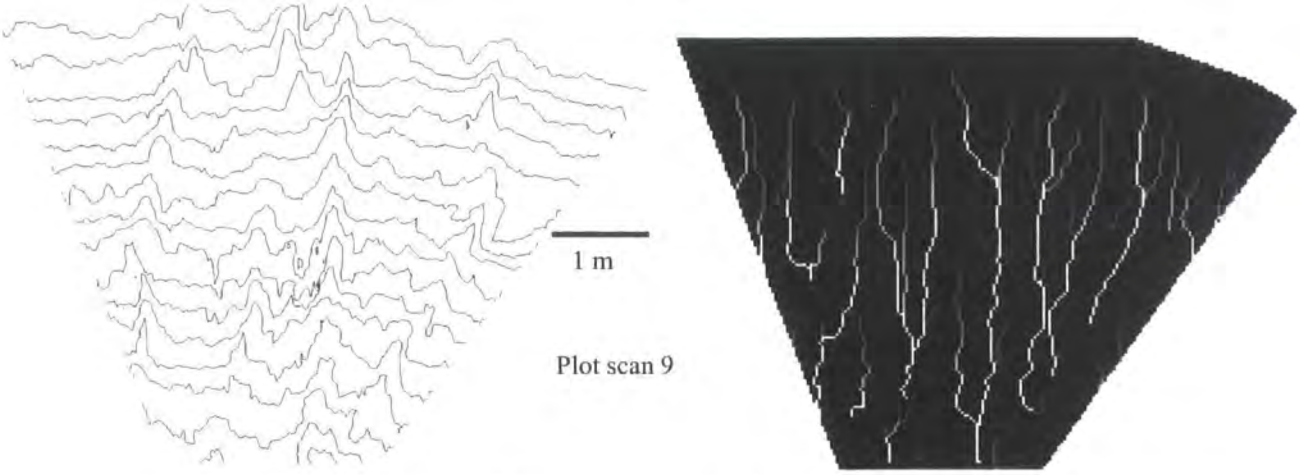


Figure 4.7b. Gully B. Contour data (left) alongside flow network data (right). Location of plot scans indicated on sketch map of gully.

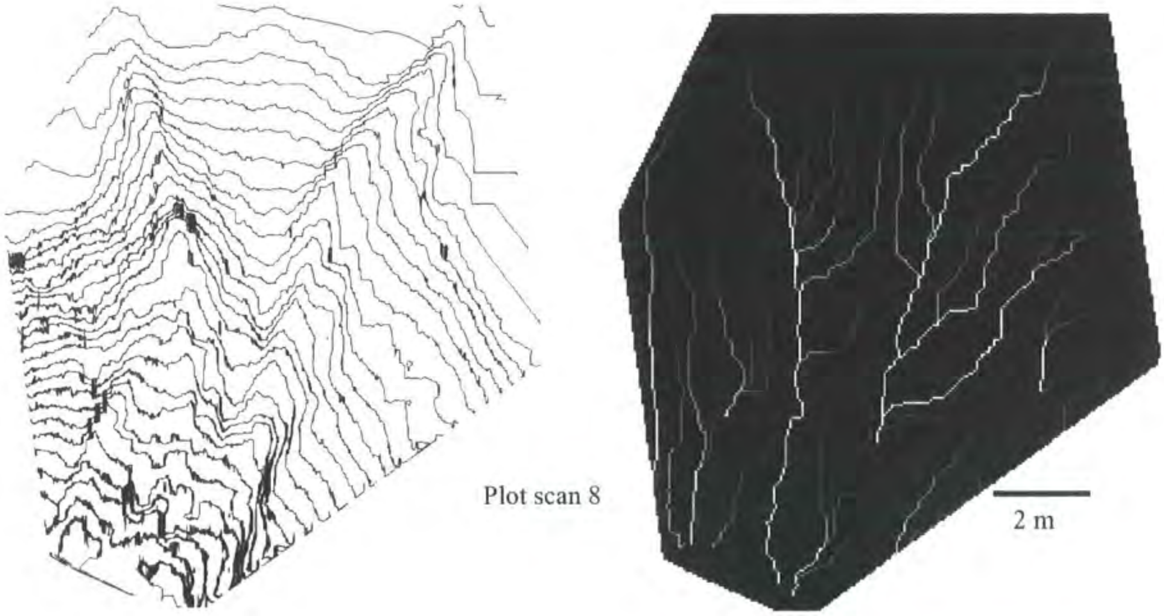
(Sivapalan, 2003). This difficulty is best overcome by the study of common concepts which are able to transcend the range of scales in question. In particular, the combination of the flow network data with the local slope gradient, soil properties and infiltration results allows connectivity between source and sink areas to be effectively identified for each gully.

This data for gullies A – D can be seen in Figures 4.7 (a-d). This data demonstrates that the more mature gullies – B and C – have more distinct, well-established flow networks. While plot scans 1, 2 and 3 from gully A demonstrate connectivity is indeed occurring (Figure 4.7a), no obvious tributary network is visible, as in the other plot scans (Figures 4.7b-c). This relative youth of gully A also results in its highest width and depth values (2.3 m and 0.32 m respectively) being smaller than the same values for gullies B and C (3.95 m, 0.62 m; and 2.9 m, 0.35 m respectively). These results suggest that the connectivity of a gully increases as the gully becomes more mature. Hillslopes with well-established gullies will therefore experience greater runoff and erosion during a rainfall event. Areas such as these, which respond quickly to rainfall will produce high runoff discharges, allowing for flow continuity along the drainage network (Yair and Kossovsky, 2002).

For two of the gullies at Site 1, the widest sections of the channels are in the mid-slope area: gully A, plot scan 2; and gully C, plot scan 8. This demonstrates that the erosivity of the runoff at the mid-point of these gullies has reached its maximum potential; upslope from here, the channels are still growing and being eroded, whereas downslope from here, the channels are experiencing slower incision and deposition as the reduced slope gradients (< 22 ° and < 24 ° respectively) are causing runoff to slow

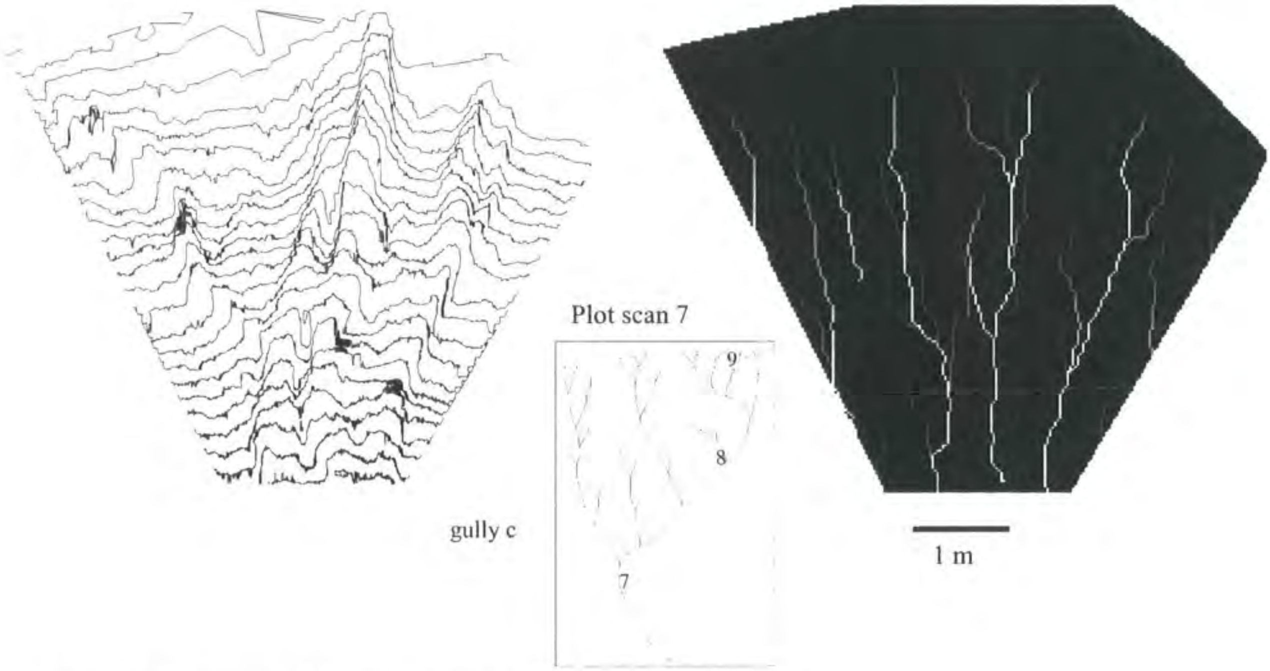


Plot scan 9



Plot scan 8

Plot scan 7



gully c

Figure 4.7c. Gully C. Contour data (left) alongside flow network data (right). Location of plot scans indicated on sketch map of gully.

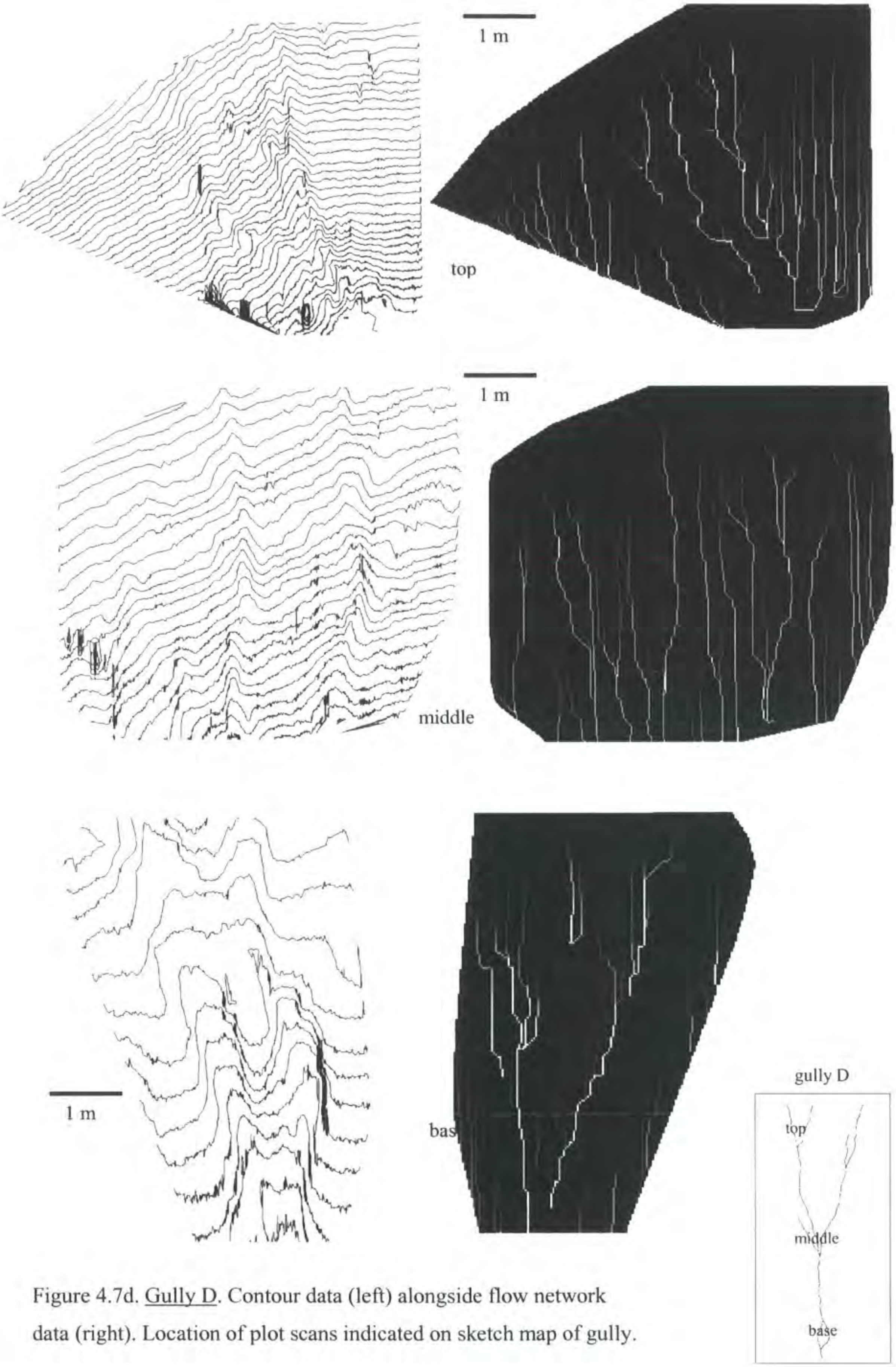


Figure 4.7d. Gully D. Contour data (left) alongside flow network data (right). Location of plot scans indicated on sketch map of gully.

down. For gully B, however, whilst the widest section of gully is towards the upper part of the hillslope (140 m upslope), at its mid-point the flow network is most well-developed (Figure 4.7b, plot scan 5). This data demonstrates that the steeper parts of the hillslope at Site 1 are areas where the topography will therefore have a greater influence on overland flow and gully morphological development during a rainfall event when the hillslope is in the wet state. Topographical data from the laser scanner allowed such areas of steeper gradient to be distinguished. The data presented in Table 4.1 shows that the gullies in Figures 4.7a-c which have more distinct flow networks also tend to have steeper slope gradients.

Although connectivity of the flow networks at Site 1 appears to be governed largely by the hillslope topography, accurately describing runoff generation is complicated by differences in soil surface conditions and by the numerous processes active across the hillslope. One method of anticipating the connectivity of an area on the hillslope is by identifying local 'source' and 'sink' areas which will have different local hydrological behaviour during a rainfall event. It has been shown that areas with a lack of vegetation, low soil omc and low infiltration rate are prone to runoff generation, therefore where these are found in combination with a steep gradient, they become 'source' patches. Steep slopes at Site 1 have higher runoff rates and lower runoff thresholds, as shown by the high density of tributary channels for gullies B and C.

The distribution of these 'source' areas (as determined by the data collected in the field) is shown in more detail in Figure 4.8 and Figure 4.9. The spatial configuration of these small-scale units and their connection to the gully channels determines the hillslope geomorphologic and hydrologic response, as they are linked though parts of the channel systems (Cammeraat, 2002). Similar results were found by Canton et al., (2001) following a study carried out in south east Spain. Erosional processes were monitored in a badlands environment and it was found that most of the runoff-generating surfaces were spatially distributed in such a way that they were almost always connected, allowing the transfer of sediments from hillslopes to channels.

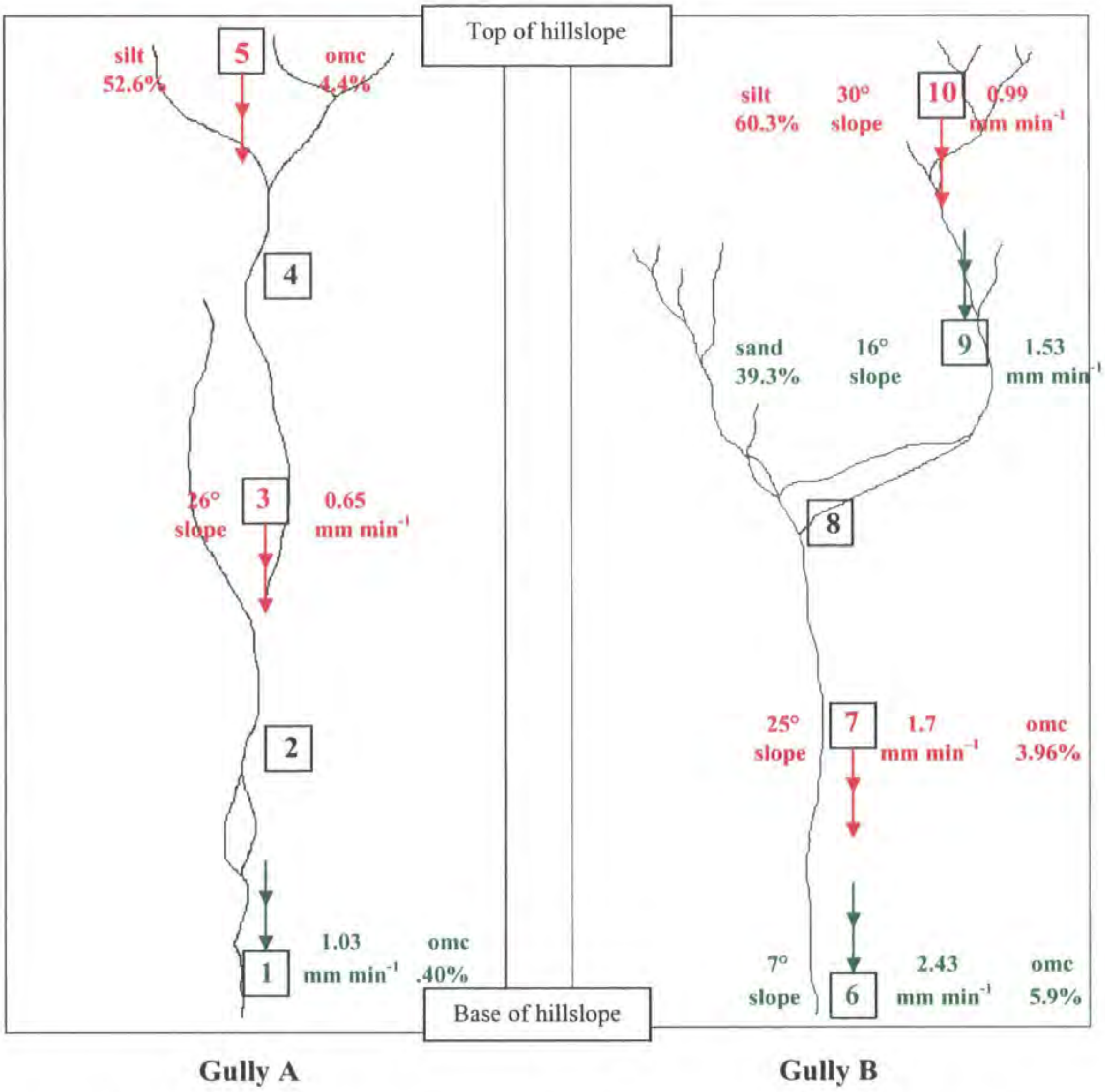


Figure 4.8. Sketch diagrams showing source & sink areas for gullies A and B: Red arrows & corresponding data indicate source areas. Green arrows & corresponding data indicate sink areas. Delineation based on soil properties (omc, soil particle size, infiltration rate) and topographic attributes for 5 study areas along each gully (labelled 1 – 5 for gully A and 6 – 10 for gully B).

In contrast to the 'source' areas of runoff generation, there exist several areas on the hillslope where connectivity is low and rainfall is preferentially infiltrated. These 'sink' locations tend to be areas with a reduced slope gradient, a relatively high soil omc, and a higher proportion of large particle size fractions in the soil. A higher soil surface roughness and comparatively faster infiltration rate are also characteristic of these locations. The distribution of the 'sink' areas at Site 1 is shown in Figures 4.8 and 4.9. There also exist some areas on the hillslope at Site 1 where the hydrological behaviour cannot be determined (e.g. locations 2, 8, 11 and 13), showing that the response of semi-arid hillslopes to rainfall is often unpredictable (Puigdefabregas et al., 1998). However, small-scale data obtained from the laser scanner and fieldwork results indicate that the three gullies at Site 1 do exhibit the potential for very localised 'source' areas at the top of the hillslope and 'sink' areas towards the base. The presence of source areas at the top of each gully will promote runoff near the gully heads, furthering the morphological development of these areas during rainfall events. As discussed in section 4.2.2, the instability of gully heads is responsible for channel expansion and erosion, eventually leading to land degradation.

The presence of 'sink' areas at the base of the gullies was initially implied by the presence of large sediment fans, and has been further demonstrated by the data. As the gullies mature, the sediment fans will increase in size as overland flow ceases in these areas, and sediment is deposited. Despite the presence of some well-defined 'source' and 'sink' areas, the hydrological behaviour of much of the hillslope remains difficult to determine. The overland flow yield at these sites is significantly non-uniform due to the high spatial variability of infiltration rates and soil properties across the hillslopes. Perhaps if observations were carried out in the field during or just after a rainfall event, the hydrological behaviour of the hillslopes would become clearer. The spatial arrangement of these 'source' and 'sink' areas across the hillslopes at Site 1 and Site 2 shows the importance of considering the interaction of small-scale processes in a larger context in order to fully appreciate the morphology of the gullies observed.

If the distribution of the distinct source and sink areas are considered alongside the morphology of each gully, links between the two can be established. For gully A – the youngest gully – the presence of source areas at the gully head and mid-way downslope coincide with more developed sections of the gully channel: at these locations, the gully is at its widest due to the higher amounts of overland flow. In contrast, the shallow slope gradient and low soil omc at the base of the slope correspond with the 'sink' area. At this location, the gully is narrowest and the volume for this 5 m section of the gully is the lowest at 0.22 m^3. To summarise, in line with its simple morphology, gully A exhibits a relatively clear-cut tendency for 'source' areas to be on the upper parts of the slope, whereas 'sink' areas are located towards the base (Figure 4.8).

As previously discussed, gully B has a more complex morphology than gully A, and this is reflected in the distribution of 'source' and 'sink' attributes in the data (Figure 4.8). There is a clear 'source' area at the gully head, where the infiltration rate is lowest at 0.99 mm min^{-1}, soil silt content is highest (60.3 %) and slope gradient is steepest (30 °). There is also a clear sink area at the base of the slope, where the infiltration rate is highest (2.43 mm min^{-1}), soil omc is highest (5.9 %) and slope gradient is shallowest (7 °), but the mid-slope section in between is more complex.

The large topographic concavity at 70 m downslope acts as a large 'sink' area where sediment has been locally deposited and vegetation is present. 30 m further downslope, the area exhibits properties suggesting it is a 'source' area: it has the lowest soil omc, and a high slope gradient (25 °). This spatial patternation of the 'source' and 'sink' areas for gully B suggest that in order for it to become hydrologically connected, a high rainfall amount is necessary. Comparable conclusions were reached in a similar study on landscape position and erosion

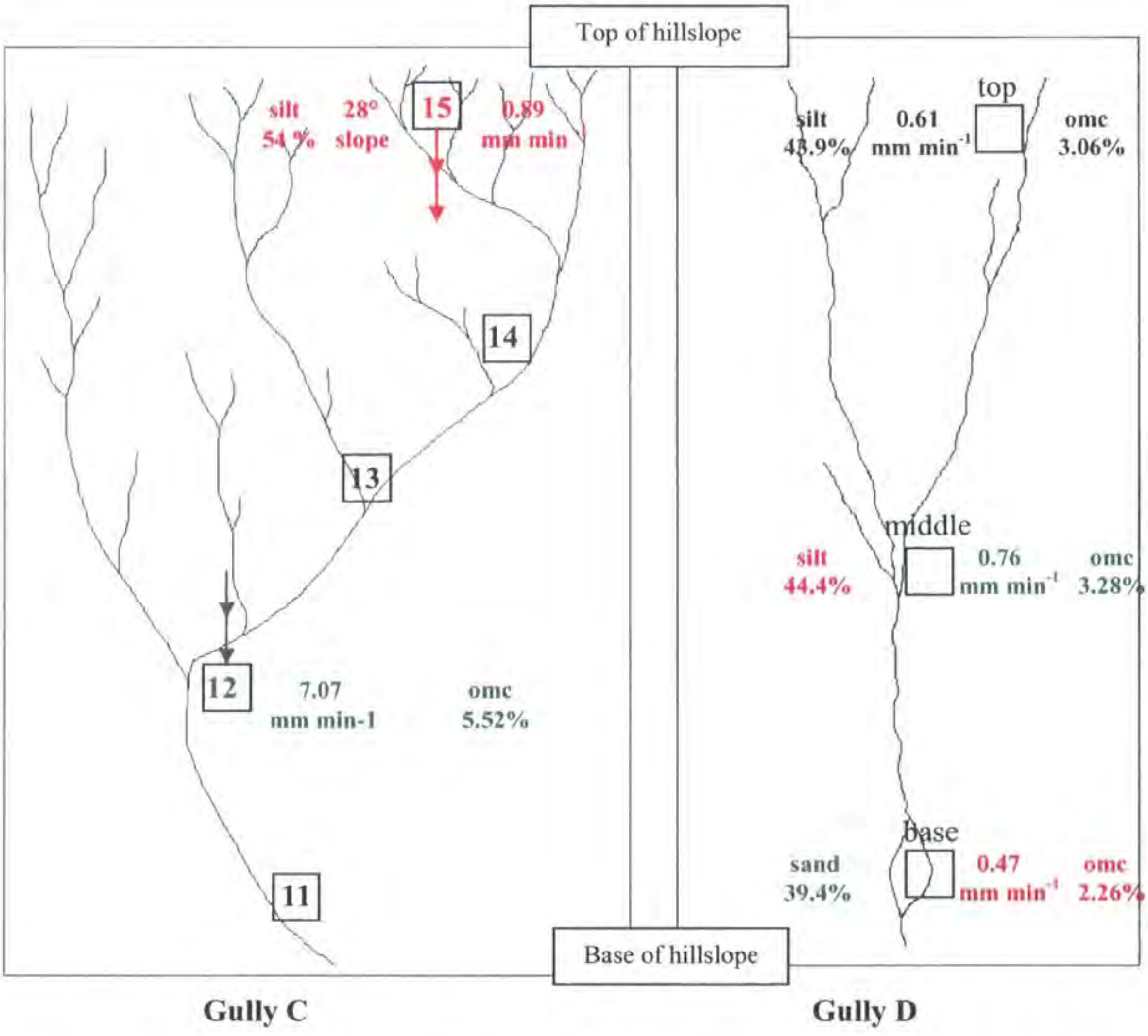


Figure 4.9. Sketch diagrams showing source & sink areas for gullies C and D: Red arrows & corresponding data indicate source areas. Green arrows & corresponding data indicate sink areas. (Black text indicates area source/sink cannot be adequately distinguished) Delineation based on soil properties (omc, soil particle size, infiltration rate) and topographic attributes for 5 study areas along each gully (labelled 11 – 15 for gully C and top, middle, base for gully D).

processes carried out by Gabbard et al., (1998). It was shown that different positions on the hillslopes would have different hydrological conditions, and that these would affect erosion processes (as shown in Figure 4.10). More specifically, runoff conditions were present near the hillslope summit and shoulder areas, the middle slope experienced a concentration in erosion processes, and the toe of the slope was characterised by sediment deposition and excessive soil moisture. Therefore, the surface runoff which was reabsorbed by surrounding drier areas acting as sinks did not contribute to catchment outflow.

Gully C has the most complex morphology of all the gullies at Site 1. However, despite its complex form, it is the most mature gully and therefore has a clearer and more well-defined 'source' are and 'sink' area than A and B. The upper part of the gully has more properties demonstrating the presence of a 'source' area, whereas the

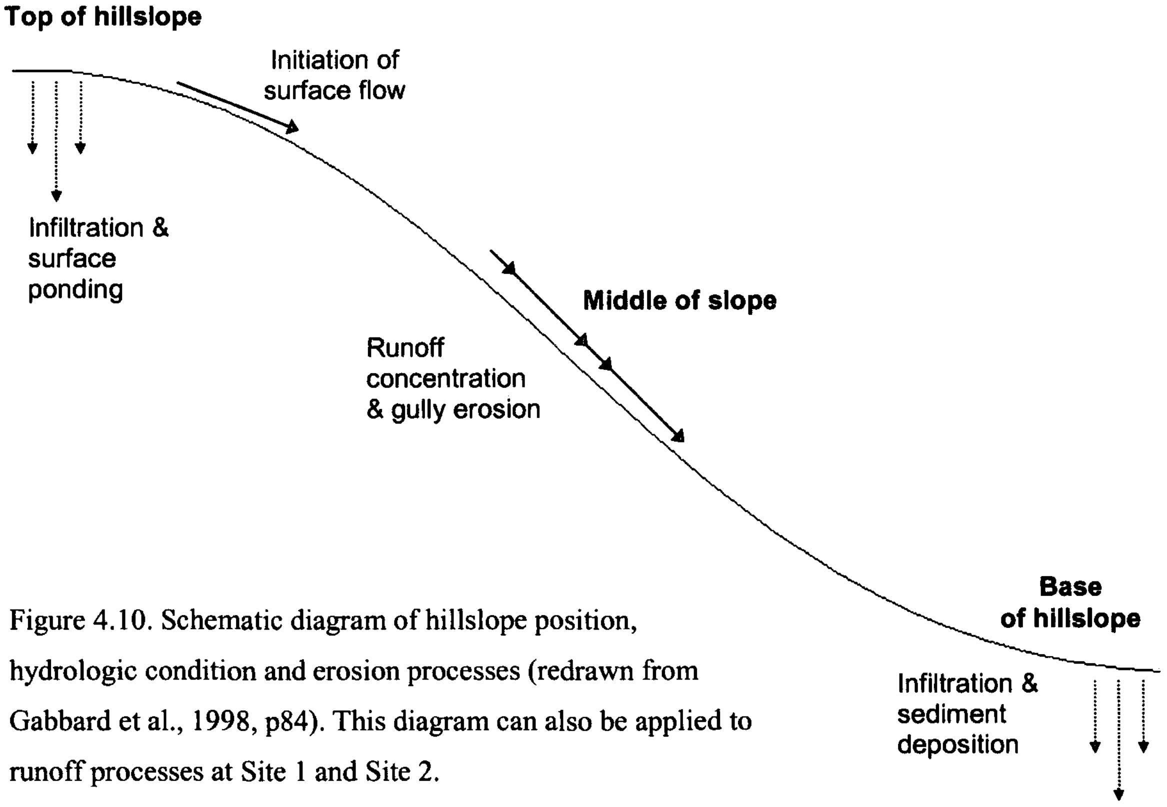


Figure 4.10. Schematic diagram of hillslope position, hydrologic condition and erosion processes (redrawn from Gabbard et al., 1998, p84). This diagram can also be applied to runoff processes at Site 1 and Site 2.

lower part has more physical characteristics associated with a 'sink' area (Figure 4.9). This hydrological behaviour is reflected in the gully's morphology: it is extremely dendritic in its upper parts, due to the source area causing gully initiation. However, these multiple channels eventually join together towards the lower half of the hillslope, forming a more defined gully. This corresponds to the increase in sink areas. At Site 2, gully D has a simple form, which is comparable to the morphology of gully A. However, it is comparatively larger than gullies A – C relative to the size of the hillslope.

The form of gully D has been caused by the abandonment of agriculture at this site: the slow regrowth of natural vegetation has meant that much of the soil at this site is permanently exposed, and therefore more vulnerable to rainfall events. The gully is therefore larger because it is never ploughed back into the soil, and increases in size with each rainfall event. The high soil pH (8.7) measured at Site 2 is characteristic of abandoned land in semi-arid environments, and is caused by the formation of salts at the soil surface. This alkalinity in itself will inhibit plant regrowth and development, affecting the regulation of major trace nutrient elements in the soil to vegetation. Kirkby et al., (2002) found similar results following a study in south east Spain: land use was shown to have a significant effect on gully morphology, defining both the surface depression storage, and the proportion of the soil surface that was bare of vegetation. Due to the contrasting nature of results obtained from the data collected at Site 2, no clear source or sink areas can be distinguished, which suggests connectivity between areas on the hillslope is highly complex (Figure 4.9).

These results have demonstrated the extent to which gully development on the hillslopes at both Site 1 and Site 2 is very reliant upon small-scale variation in soil properties and the nature of large-scale hillslope topography.

4.4. Summary and Conclusion.

Following the presentation of the results, it was demonstrated that the interaction of many factors – at both large and small scales – caused the formation of gullies A - D. More specifically, however, the large scale topography and the local variation in soil properties (particularly the particle size distribution and infiltration rate) have been shown to be the main morphological agents during a rainfall event. Results have indeed shown that runoff generation is a spatially distributed process where surface morphology, in both macro and micro scales, controls the surface flow routing (Darboux et al., 2001). Results also indicated that the application of data obtained from investigation carried out at one scale cannot be 'scaled-up' and applied to another. In order to generate useful data, appropriate fieldwork must therefore be carried out at more than one scale. Comparable results have also been presented by other authors following field investigations in semi-arid environments (e.g. Valcarcel et al., 2001; Esteves and Lapetite, 2003).

Connectivity between areas on hillslopes is essential for gully morphological development: it is only by the transfer of runoff from one area to another that erosion occurs. The small-scale results have demonstrated the particular presence of localised 'source' and 'sink' areas along the length of each gully govern the connectivity of the hillslopes at Site 1 and Site 2. While the results from this study have shown the hydrological behaviour of specific sections on the hillslope, it was not possible, however, to distinguish the hydrologic response of some small-scale areas studied, and further investigation at both sites is necessary in order to establish a more highly detailed picture of hydrological connectivity and to anticipate the nature of future gully form.

In summary, therefore, areas where it is anticipated that the most runoff will occur are found on the steepest slopes with low vegetation cover and a low infiltration rate (which is itself determined by the soil particle size and soil omc). It is the connectivity of these areas with their surroundings that will govern hillslope hydrological response and gully morphological development. Results from fieldwork carried out at both large and small scales will be considered in the next chapter in the context of the field sites, and the the success of the research aims and objectives will be evaluated.

5. Research Synthesis and Conclusions.

5.1. Introduction.

Fieldwork was carried out at two field sites in the Rambla de Nogalte catchment in south-east Spain in order to understand the formation of small gullies on semi-arid hillslopes in relation to their topographic settings, soil properties and rainfall characteristics. Results demonstrated that several processes have an influence on the gully morphology at the hillslope scale, and their relative influences determine the nature of gully morphological development at each site. The results from the study of four gullies, A – D, have been discussed in chapters 3 and 4 in the context of large- and small-scale data respectively. The reconciliation of the data obtained at both scales allows the gully morphology to be analysed in a wider context than other studies that have been carried out, and the use of the laser scanner has also provided topographical data in unprecedented detail.

In this final chapter, the conclusions of all the research will be presented and the success of the study will be evaluated in the context of the research aims and objectives that were laid out in Chapter 1.

5.2. Gully Morphology: Cause and Effect Development Processes.

In order to account for the morphology of the gullies at Site 1 and Site 2 several components of hillslope response were studied, some of which transpired to be more significant than others. The combined use of small-scale and large-scale data allowed the gully morphology and hillslope connectivity to be better accounted for, which is particularly important considering that there is a need for an improved understanding of how different areas within a catchment fit together and how these affect runoff and erosion (Kirkby et al., 2002). This study has shown that the inter-scalar relationships between gully form, hillslope topography and local soil properties (including infiltration) were of particular importance in altering erosion processes. This demonstrated that understanding and interpreting relationships at both scales is essential to the explanation of gully morphology.

5.2.1. Gully Form: Large Scale Topographical Determination?

At Site 1, a maintained almond plantation, three gullies of increasing size (A, B and C) were present on the hillslope. Gully A had the simplest morphology, comprising a single channel with few morphological changes down its 50 m length and no large tributaries. It also had the smallest sediment fan, which measured 7.5 m^3, and the catchment area for gully A measured 57 m^2, which was also the smallest of the three (Figure 5.1). Despite being the smallest gully, results presented in Chapter 3 demonstrated that the hillslope topography had the strongest influence on this gully: the correlation between channel width and slope gradient was $R^2 = 0.52$, compared to just 0.43 for gullies B and C. This relationship was attributed to its comparative immaturity and smaller size. There are fewer areas of localised shallow gradient where deposition can occur, unlike B and C, whose more varied form presents several locations for topographic independence of the gullies. There are also no branches or tributary channels joining gully A, and its relatively recent formation also means that its sediment fan has not begun to encroach onto the base of the gully channel, reducing the local slope gradient. Therefore, the topography at this location does play the main role in determining the nature of gully A's morphology.

Gully B was the second-largest gully and had a more complex form than gully A. Its upper half consisted of two main channels with tributaries, which converged mid-slope to form a single channel that continued to the base of the hillslope. The catchment area for this gully was larger at 220.5 m² (Figure 5.1), which affected the gully widths and depths measured: the larger catchment area means that during the rainfall event in which this gully formed, there was more runoff captured by this gully and more erosion took place. This is also the reason that it has a larger sediment fan (10.75 m³, as measured in the field) whose presence reduces the local slope gradient.

The largest gully at Site 1, gully C, had the most complex morphological form: it had a large network of tributary channels, all of which eventually joined together very close to the base of the hillslope to form a single, main gully. It had the largest catchment area (381 m²) and correspondingly, the highest average width and depth of

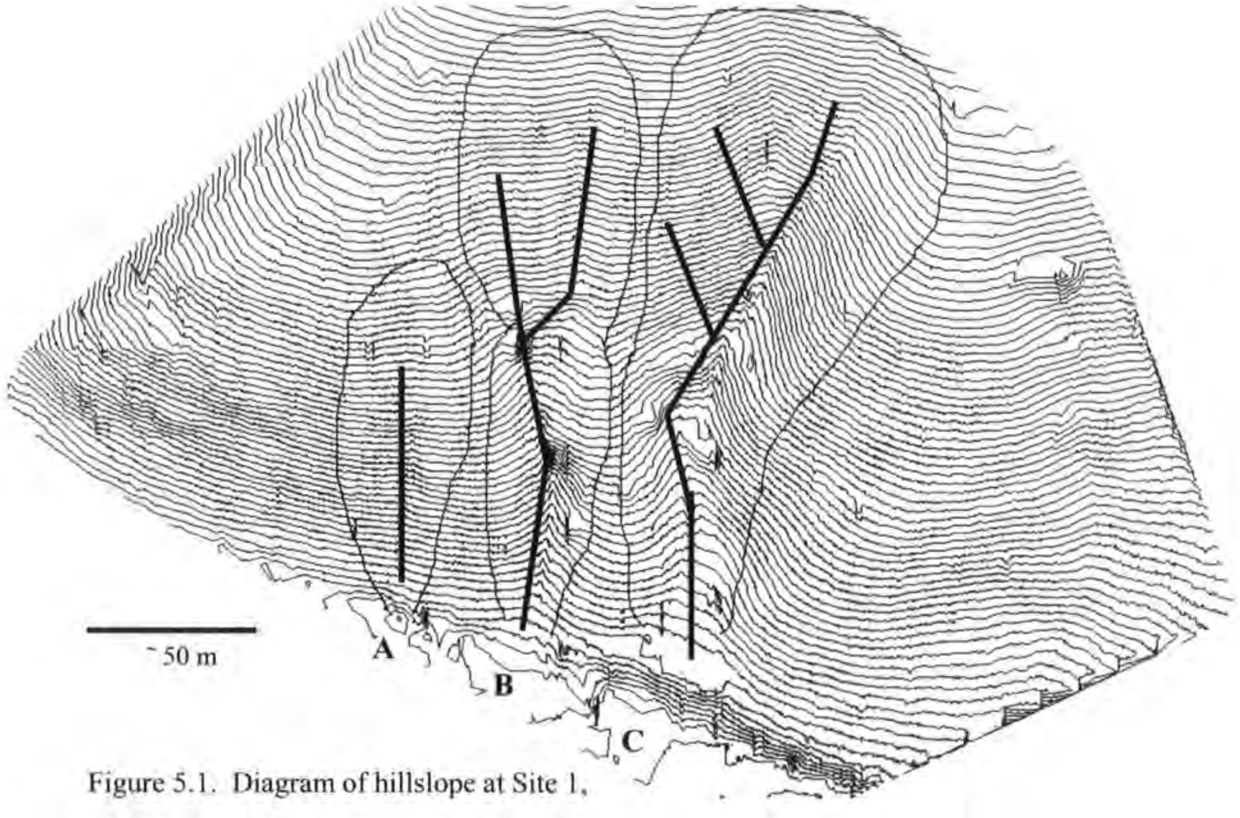


Figure 5.1. Diagram of hillslope at Site 1, showing sketch of gullies A, B and C and their catchment areas.

all three gullies at this site (2.2 m and 0.29 m respectively). From initial observations, the relative sizes and morphology of gullies B and C appeared to be more dependent on the large scale topography than gully A: the gullies were located within topographic hollows (Figure 5.1) where the local slope gradient was steeper than elsewhere on the hillslope. The average slope gradient at Site 1 was 12.6 ° but in areas surrounding gullies B and C, the slope measured 21.96 ° and 23.25 ° respectively (as measured over their respective lengths of 140 m and 145 m). This data was used in multiple regression analysis together with the position upslope parameter (measured in metres from the hillslope base), as discussed in Chapter 3. The resulting R^2 value was a highly significant 0.62, compared with $R^2 = 0.41$ when upslope position was not included. Results therefore show that the gullies are indeed preferentially forming in areas with a steeper slope gradient, and that the larger sections of the channel are located on steeper topography and on the lower part of the slope.

The fact that these large-scale topographical variables play such an important role in the morphological development of the gullies inevitably means that they not only have an influence over the gully channel volumes, but over the amount of sediment eroded. Results presented in chapter 3 showed that the larger the catchment area was, the more complex the morphology of the gully became. Therefore, determination of the sediment eroded also became more difficult. Calculated from the field data and laser scanner results, the weight of the soil lost at Site 1 measured 89.3 kg in total: 11.3 kg, 48.5 kg and 29.5 kg for gully A, B and C respectively. These results reflected the complexity of the gullies' form and the inherent non-linear relationships between variables. While gully C has the largest catchment area (381 m^2), highest average slope gradient (23.25 °), and is the longest gully at this site (145.3 m), its volume of sediment eroded is not the highest. This can be accounted for when the following are considered: the complex form of gully C, comprising a wide network of tributaries and a large sediment fan which is increasingly retreating up the gully channel, means that because it is the largest gully the erosion amount is difficult to exactly calculate. In addition, many localised areas of deposition within the gully further complicate the matter: their presence shows that while much sediment is being eroded to form this gully, a large amount never makes it to the hillslope base, but remains on the hillslope until a further rainfall event can again mobilise it.

Gully	Sediment eroded (kg)	Gully length (m)	Mean slope gradient (°)
A	11.3	55.59	22.64
B	48.5	140.64	21.96
C	29.5	145.3	23.25
D	12.7	62.1	23.64

Table 5.1. Morphological attributes of the gullies at Site 1 (A-C) and Site 2 (D).

At Site 1, the topography is also being further exaggerated by repetitive gullying in the same locations: despite being ploughed back into the soil by agricultural practices, during the next rainfall event, the gullies merely re-form in the same places. However, results demonstrated that gullies B and C experienced more positive-feedback with the topography in which they were situated than did gully A. The gullies formed as a result of runoff flow concentration in topographic concavities, taking advantage of the high soil silt in these areas. This was also noted by Nachtergaele and Poesen (2002) following a study carried out in Belgium: they showed that with water erosion, concavities concentrate runoff, often resulting in intense gully erosion. In addition, a study of runoff generation in a small, semi-arid gully catchment was carried out by Esteves and Lapetite (2003): they also demonstrated that bare, sloping zones in the vicinity of the gullies were the main contributing areas, and this was intensified in particularly concave areas. However, it is also important to note that flow concentration alone does not necessarily cause gully incision, but that small-scale properties of the soil surface are essential components of hillslope response.

5.2.2. Gully Form: The Role of Small-Scale Soil Physical Properties.

At the small scale, results from analysis of the soil surface data demonstrated the great spatial heterogeneity of surface properties and the variability of the hillslope response to rainfall. Results showed that the interaction of small-scale areas with their neighbouring counterparts therefore played a major role in gully morphological development. Such areas at Site 1 and Site 2 were identified by the plot scan data, which was presented and discussed in Chapter 4. Of particular importance were the infiltration results, which gave an insight into the hillslope's surface response during a rainfall event. In Chapter 3, a positive relationship between infiltration rate and upslope position was determined ($R^2 = 0.5$), indicating that infiltration was higher towards the top of the hillslope. This can be attributed to the local gradient, which was relatively shallow at the top of the slope and encouraged infiltration and ponding, rather than runoff. Indeed, the recurring formation of the gullies and tributary channels in areas of steep slope positively showed that these locations have less potential for surface water storage and are therefore more prone to runoff. This has also been identified by other authors including Poesen et al., (2003): following a study of gully erosion in several regions, their results showed that clear that zones in the landscape where gullies start were more controlled by slope gradient. In particular, topographic attributes such as slope gradient and drainage area affected the density of the drainage network and hence the probability of gully channel development. Kirkby et al., (2000) also carried out a study of gully growth in south-east Spain and they noted that gully channel growth was non-linearly dependent upon the contributing area, runoff rate, and local hillslope gradient.

The nature of the infiltration at the small-scale was further demonstrated by the plot scan results (Chapter 4). At the small-scale, infiltration rates displayed a significant relationship with the organic matter content (omc) of the soil, as shown in Figure 5.2. For gullies B and C at Site 1, and gully D at Site 2, the highest infiltration rates measured (2.43 mm min^{-1}; 7.07 mm min^{-1}; and 0.76 mm min^{-1} respectively) coincided with the highest soil omc values (5.9 %; 5.52 %; and 3.28 % respectively). This can be explained by the fact that areas with a larger amount of organic matter have a higher soil aggregate stability, which reduces erosion and promotes infiltration. A higher soil omc also encourages the further colonisation and growth of vegetation in the same areas, which will promote more infiltration and vegetative growth in a small-scale positive feedback relationship. Therefore, as discussed in Chapter 4, these areas where organic matter is prevalent can be distinguished as 'sink' areas.

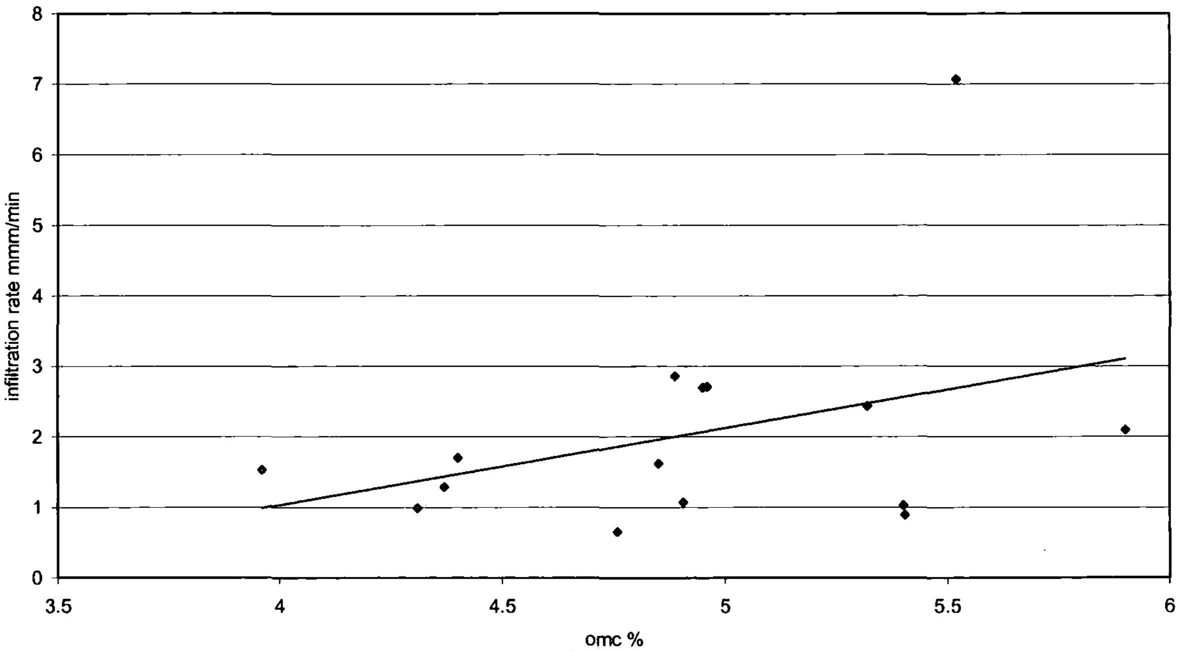


Figure 5.2. Site 1: infiltration rate (mm min^{-1}) vs soil organic matter content (%).

Data showed that in areas towards the top of the hillslope at Site 1 where the gullies initiated, the soil had a high silt content, which actively encouraged erosion and headwall retreat. The formation and development of rills and gullies is linked to the susceptibility of soil particles to entrainment and transportation. Silt is the most easily erodible soil fraction, and the high proportion of silt at the top of the hillslope (gully A: 52.6 %, gully B: 60.3 %, gully C: 54 %) means that this is where the majority of future morphological development and gully extension will take place.

Further downslope towards the mid-sections of the hillslopes at Site 1, data showed that the gullies began to increase in size, reaching their maximum widths (A: 2.3 m, B: 3.05 m, C: 2.9 m) and in the case of gully C, its maximum depth as well (0.35 m) (as shown in Figure 4.4, Chapter 4). The results demonstrated that in these locations the erosive power of the runoff was greatest, due to a combination of steep slope gradient with high intensity rainfall and highly erodible soil particles. Related to this subject area – and of particular significance – were the results presented in Chapter 3 which demonstrated the relationship between local hillslope gradient and the local gully volume (for a 5 metre length of gully). The morphologically larger parts of the gullies were located towards the middle of the slope, where gradient was steeper (A: 26 °, B: 26 °, C: 30 °). As demonstrated in Chapter 3, the apparent influence of the slope gradient on local gully volume at the small scale was very strong: when these two variables were plotted against one another in Figure 3.17, they virtually followed the same pattern with the exception of some small discrepancies which were attributed to small-scale variation in infiltration rates and soil properties, in addition to the localised presence of tributaries joining the main gully channel.

Comparable results to these were also noted by Gabbard et al., (1998) following a study of hillslope position and its influence on erosion processes. They successfully demonstrated from their data that different positions on a hillslope experience different erosion processes in accordance with local slope gradient and soil surface properties (as shown by Figure 4.10 in Chapter 4). In particular, they noted that differences in the hydrological conditions of particular areas of the hillslope actively caused preferential rill and gully erosion, and the movement of water was the dominant mechanism in shaping the landform.

The movement of water across the hillslopes at Site 1 and Site 2 was also shown by the results to be greatly affected by the land use and agricultural practices active at each site. Vegetation and land use are clearly important factors which control the intensity and frequency of overland flow and erosion (Kosmas et al., 1997), and these results will be discussed in the next section.

5.2.3. Gully Form: The Site Specific Influences of Land Use.

As discussed in chapter 1, one of the main differences between Site 1 and Site 2 was land use: Site 1 is a maintained almond plantation which is also used for the grazing of sheep and goats, whereas agriculture at Site 2 has been completely abandoned in order to let natural vegetation re-establish. This fundamental difference can account for several variations observed between the two field sites. The soil samples taken from Site 1 and Site 2 were also used to obtain pH and electrical conductivity (ec) data, which supported the measured geomorphological trends of the gullies at each site. The results demonstrated that pH was over ten times higher at Site 2 where agriculture had been abandoned: values measured 8.7 (top of hillslope), 8.3 (middle of hillslope) and 8.5 (base of hillslope). The electrical conductivity measurements were shown to be significant, also being an order of magnitude higher at Site 2 than at Site 1 (140 µS cm^{-1}, 112 µS cm^{-1}, 135 µS cm^{-1} respectively). The higher pH and ec values are a logical result of agricultural abandonment in a semi-arid area: the accumulation of salts at the soil surface is directly due to cessation of ploughing, and higher pH and ec levels. Comparable results were obtained in a study carried out by Boix-Fayos et al., (1998) into variations in runoff and soil properties in south-east Spain. Chemical and physical analyses were performed on soil samples taken from forty-two points on six hillslopes in order to characterise the distribution of soil surface properties. It was found that higher pH and ec values were higher for the most humid and most arid sites, which was attributed to soil water evaporation and precipitation of salts in the upper soil layers.

Another impact of soil salinity is a reduced ability of the site to support recolonisation of vegetation, having an important effect on gully morphology. At Sites 1 and 2 in particular, without the presence of vegetation runoff will be further promoted and therefore gully erosion will be facilitated. Whilst collecting data in the field, it was noted that the vegetation at Site 2 was indeed more sparse than at Site 1, and the soil omc measured at this site was also lower, with values of only 3.06 %, 3.28 % and 2.26 % measured at each plot scan location compared to values nearer 5 % at Site 1. This relationship is shown more clearly in Figure 5.3. This indicates that at Site 2, not only is the soil omc reduced by agricultural abandonment, but that regrowth of the natural mattoral vegetation is being further inhibited by high pH and salinity at the soil surface, which are a direct result of abandonment. These results demonstrate that some of the most important soil properties vary according to the current land use.

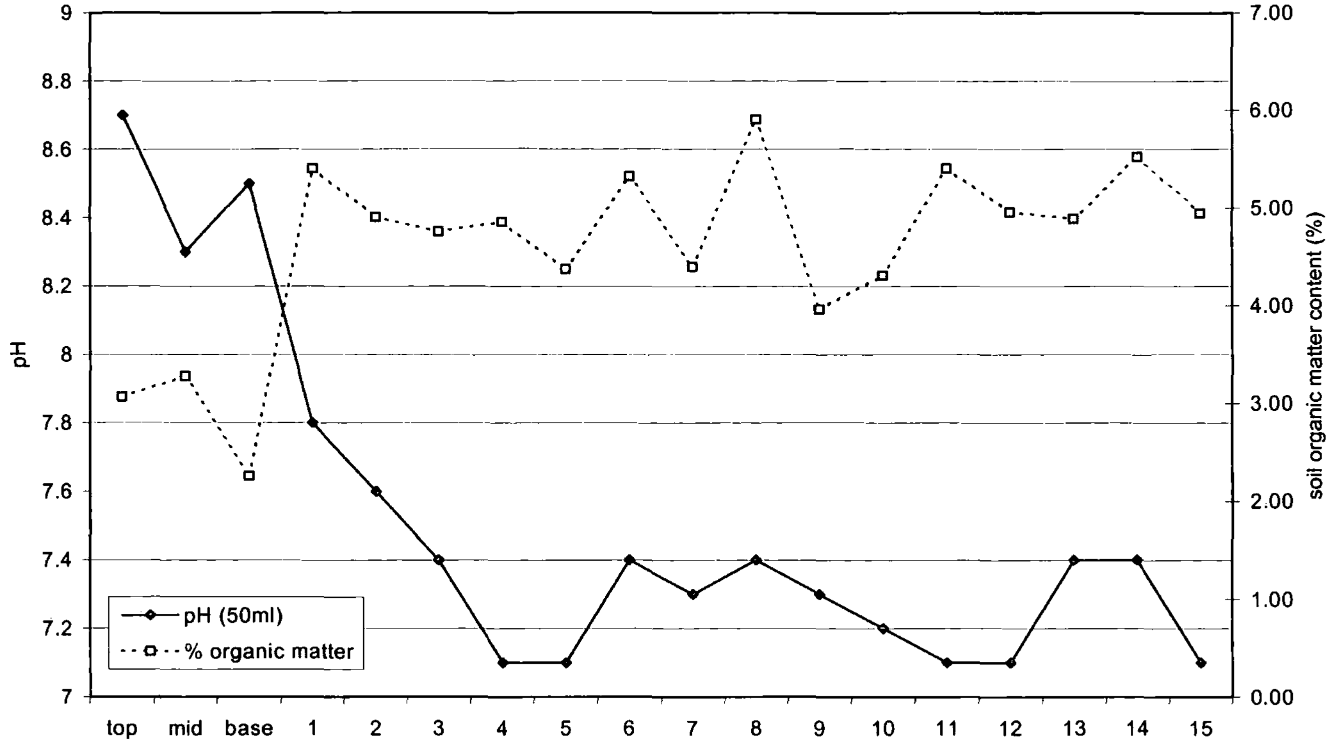


Figure 5.3. Soil organic matter content compared with soil pH levels for Site 1 (1-15) and Site 2 (top-mid-base).

Despite the field data and geomorphological evidence supporting the low amount of organic matter in the soil at Site 2, these results are initially a bit surprising. This is because the omc at Site 2 is lower than for Site 1 where ploughing is still taking place: this usually incorporates omc into the soil, reducing the amount of organic matter present at the surface. However, this comparatively higher omc at Site 1 can be explained by the fact that ploughing only takes place at least twice a year, which does in fact give vegetation a chance to grow to a certain extent in between plough-events. At the time this study was carried out, the site was due for ploughing in 2 months: therefore, this factor will have affected the soil organic matter data and results.

This study demonstrated that both erosion processes and gully morphological development are affected by agricultural practices and land use: in short, the strong relationship demonstrated between hillslope form and soil properties is further affected by cultivation. The agricultural use of a hillslope therefore alters the innate balance between rainfall, vegetation, and soil properties, causing gully erosion where otherwise it might not have occurred. Results from Site 1 and Site 2 showed that agricultural operations apparently increased the topographic control on soil properties, causing runoff to have more erosive power. The same was noted in a study carried out by Van Wesemael et al., (2000): they investigated spatial patterning of soil physical properties on semi-arid hillslopes. It was found that spatial variation in soil properties could be attributed to agricultural practices and cultivation of hillslopes. In particular – just as for Site 1 and Site 2 – they found that frequent ploughing of the hillslopes resulted in erosion and denudation of the soil which would otherwise not have taken place. The effects of the agricultural practices employed at each site therefore actively demonstrates the great importance of land use for runoff generation and sediment loss in this semi-arid environment.

The individual consideration of all these factors which have been discussed above is useful when accounting for gully morphology, but only if they are then taken to form part of a larger overall picture in which they are connected together, having interactive relationships. Their association and connectivity creates distinct rainfall-runoff relationships between areas on the hillslopes, and causes the erosion of morphological forms such as the gullies observed at each site.

5.3. Flow Network Development and Hydrological Connectivity.

It has been suggested by several authors that the flow network structure of a hillslope evolves into a "self-organised" configuration (Darboux et al., 2001), where connectivity between flow paths is determined by the hydrological response of individual 'patches', and gully erosion and morphological development is a direct result of this. As further research is carried out, the role of connectivity is being increasingly recognised as significant in accounting for gully erosion in semi-arid areas. The large-scale data, discussed in Chapter 3, successfully demonstrated the presence of distinct areas on the hillslopes at Site 1 and Site 2 where hydrological response to rainfall appeared to vary. The main factors involved in causing this varied response included hillslope gradient and soil physical properties. In particular, the relationship between gully channel volume and slope gradient was shown to have a highly significant R^2 value of 0.43, indicating that larger sections of the gully were present on areas of the hillslope where runoff was more energised by the gradient.

When this relationship was further investigated and the position on the hillslope was also taken into consideration along with the two factors of gully channel volume and slope gradient, the R^2 value rose to 0.62. This demonstrated that not only were areas of steep gradient involved in controlling gully morphology, but that they appeared to be occurring at the same position on the hillslopes. This indicates that as the flow network of the gullies themselves began to develop and hillslope connectivity was strengthened, the topography in which the gullies are situated was also affected in a positive-feedback relationship, and large-scale hillslope evolution began to take place. When this factor was considered, the flow network development of the gullies could be better accounted for. As mentioned previously, field results showed that towards the top of the hillslopes, the gullies were much more dendritic and less-well developed. This can be explained by the fact that the slope gradient at this location was not yet steep enough to cause immediate runoff and erosion, but rather localised infiltration and surface ponding were promoted until infiltration-excess runoff occured. However, as discussed in Chapter 4.2.2, this is also where the majority of future gully extension and development is most likely to take place: results show that the gully heads are situated in silt-rich soils (gully A: 52.6 % silt, gully B: 60.3 %, gully C: 54 %), which are easily erodible soil fractions. The instability of gully heads is responsible for much channel expansion and erosion in semi-arid areas, which is becoming an increasing concern due to the degradation of much agricultural land. This phenomenon has also been noted by Bull and Kirkby (2002: 263): they state that gully erosion caused by the instability of gully heads is a serious problem in dryland environments and is responsible for the destruction of agricultural land, as well as structures such as roads, bridges and pipelines. Any environmental changes that have an impact on the gully head therefore have a large potential impact upon the landscape. Bull and Kirkby (2002: 292) also note that further research into understanding the problem of gully head development is therefore important in predicting future landscape evolution, morphology and response to climate change.

Having been initiated in the upper part of the slope, the gullies at Site 1 and Site 2 experienced improvement of connectivity and the majority of morphological development in their middle sections. Results showed that at this position on the hillslope the gullies were at their widest (Figure 4.4) due to concentration of run-on from upslope and the large size of the catchment areas at this point. In addition, the intensity of overland flow into the topographic hollows had further exacerbated this. Results also clarified the role played by the size of the catchment areas: their independent impact on the gully morphology was not shown to be particularly strong, although the relationship between gully depth and catchment area did have some slight correlation (Figure 3.7). This relatively surprising conclusion that catchment area did not directly affect gully form can be accounted for by taking two factors into consideration. Firstly, it is not the independent factor of catchment area which has the most powerful morphological impact, but the *interaction* of the catchment area with the hillslope gradient. For example, if the catchment area was very large but on flat terrain, little erosion would occur. In the case of Site 1, this is demonstrated when the slope gradient factor is included in the regression analysis: the relationship does improve (albeit only slightly, rising to $R^2 = 0.31$). As mentioned before, perhaps most indicative of this relationship is the fact that gullies A – D are all widest mid-way down the slope (A: 2.3 m, B: 3.05 m, C: 2.9 m) where gradient is also steepest: the catchment area is dependent upon this to provide runoff with erosive potential (Figure 5.4). Secondly, the interaction between catchment area and gully form is further complicated by the interaction of other variables including soil properties, vegetation and land use – all of which have been discussed above and shown to play

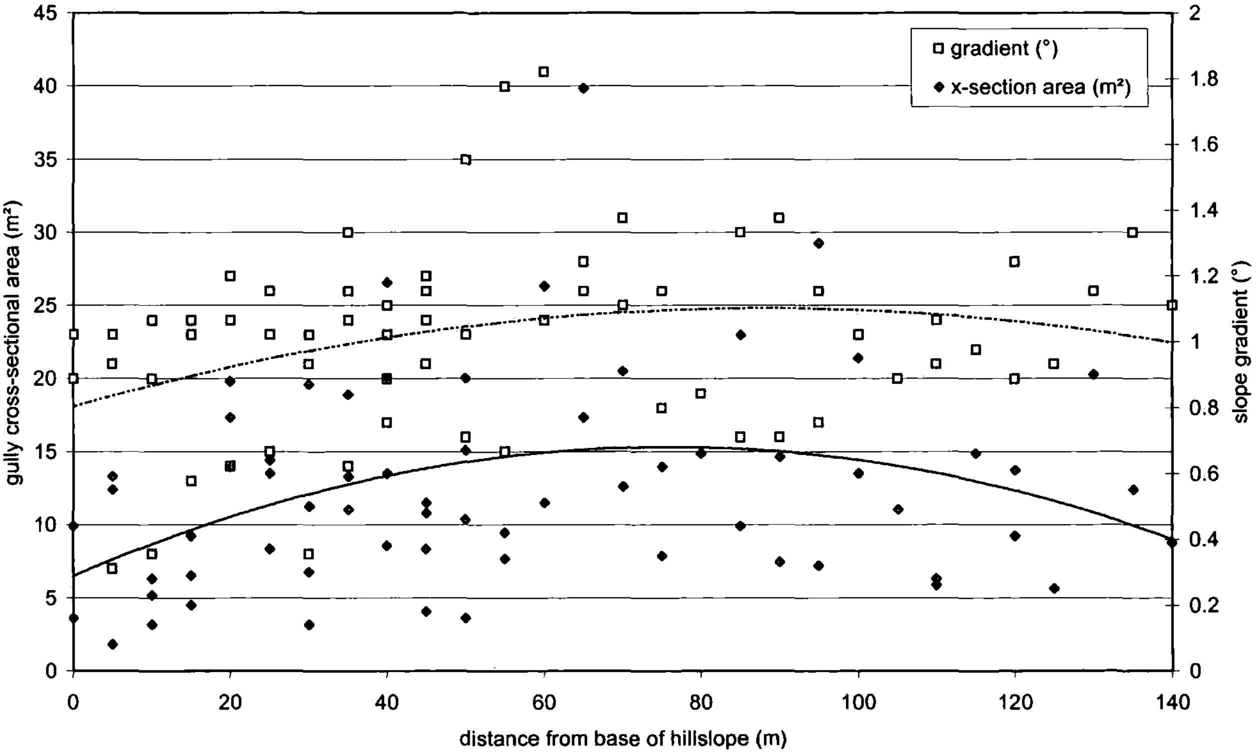


Figure 5.4. Progressional change of gully cross-sectional area (m^2) and slope gradient down the hillslope at Site 1: the two reach their maximum values mid-slope.

an important role at Site 1 and Site 2. Results from this study therefore demonstrate that while the size of the catchment area does determine the amount of water captured and carried by the gullies, it is not the main driving force behind their morphology.

Downslope from their mid-point, the flow network of the gullies developed into a single incised channel, until slope gradient and the erosivity of the runoff became reduced and deposition and infiltration took place. As discussed in section 5.2, results also indicated that at the base of the hillslope, soil omc was at its highest for each gully at Site 1 (gully A: 5.4 %, gully B: 5.9 %, gully C: 5.5 %) due to the increased water content of the local soil profile. The fact that gullies A – D increase in size downslope demonstrates that connectivity was successfully established across the whole hillslope during the rainfall event on October 6th, and runoff contribution from sideslopes was significant. The eventual concentration of runoff in the gully channels from the middle section of the slope had a positive effect on flow continuity and runoff contribution. Indeed, this successfully demonstrates that the form and morphology of the gullies is critical for the hydrological response and hillslope connectivity at these sites. In a similar study carried out by Fitzjohn et al., (1998) into gully erosion in a semi-arid catchment, it was shown that the spatial arrangement and hence the spatial connectivity of runoff producing areas were critical in determining the extent of overland flow and its effectiveness as an eroding agent. The form of gully channels at this site determined the connectivity of runoff-generating and runoff-absorbing areas, and ultimately the evolution of the catchment.

In Chapter 4, small-scale topographical data (microtopography) obtained from the laser scans was considered in order to further explain the nature of these complex relationships observed at the larger scale. Canton et al., (2001) made the point that the spatial distribution of soil surfaces in microcatchments have an important role in erosion processes that should be evaluated in further work. Results from this study supported this, as the gully morphology and connectivity at Site 1 and Site 2 could be better accounted for when considered as a result of the interaction of smaller 'source' and 'sink' areas on the hillslope. The data collected at this small scale allowed the identification of such areas and demonstrated their importance. In addition, establishment of connectivity is more important for semi-arid areas where runoff production is more patchy than for humid areas with continued rainfall onto expanding saturated areas (Kirkby et al., 2002). In semi-arid climates, most rainfall is lost to evapotranspiration and little is available for subsurface flow, therefore independent determination of runoff for each small-scale area is of great importance.

The hydrological nature of each plot scan was presented and discussed in Chapter 4.3.2, where distinctions between 'source' and 'sink' areas were made. At Site 1, source areas were located at the top of for each gully for A, B and C, as well as towards the lower part of the hillslope for gullies A and B (Figure 5.5). In contrast, distinct sink areas were located towards the base of the slope for each gully before their respective sediment fans began (which occurred further up the channel for gully C, due to the presence of a larger sediment fan). The same data for Site 2 (gully D) was presented in Figure 4.9 (Chapter 4), but no distinct source or sink areas could be determined due to the complex connectivity at this site. It is suggested that the abandonment of agriculture at this site has had an effect on the hydrological balance of the hillslope: while the site tends to re-adjust to its natural state following abandonment, interactions between soil physical properties and the distribution of

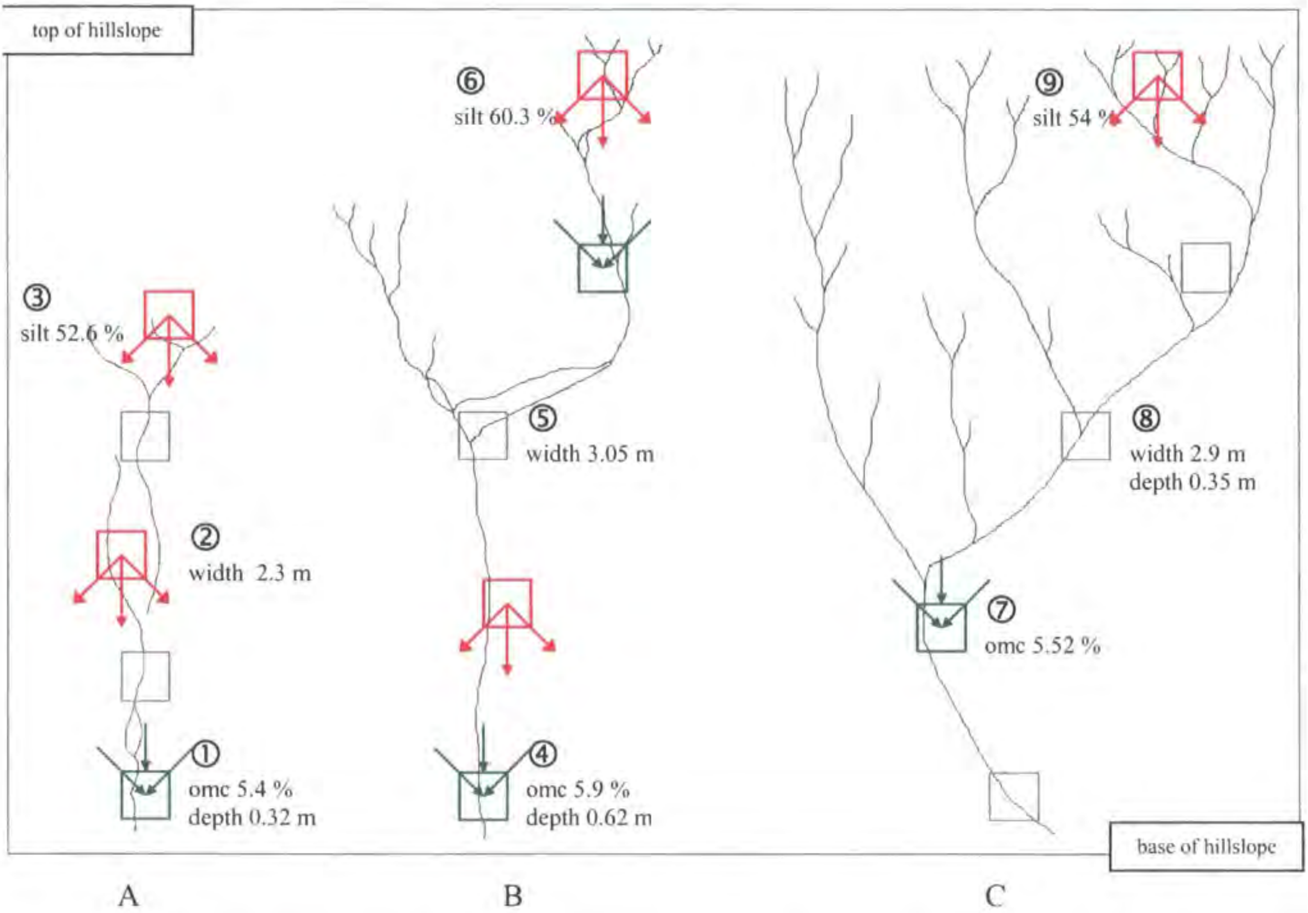


Figure 5.5. Sketch diagram of Site 1 showing source and sink areas for gullies A, B and C. Squares indicate small-scale study areas (origin of soil samples and location of infiltration experiments). Circled numbers indicate plot scan locations. Red colour indicates source areas, green colour indicates sink areas. Grey indicates source/sink could not be adequately determined. Delineation based on soil properties (omc, particle size, infiltration rate) and topographic attributes for each study area.

vegetation are extremely complex. This small-scale data demonstrates the effect that soil physical properties have on overland flow pathways and hydrological connectivity: for example, as shown by the annotations in Figure 5.5, a high soil silt content is favourable to the development of source areas, whereas a high soil omc promotes infiltration and therefore sink areas. In addition, the inclusion of the small-scale data with the larger-scale results from Site 1 and Site 2 has shown that the collection and analysis of data from both scales is indispensable.

The results from this study demonstrate that the flow network development and hydrological connectivity at Site 1 are the result of interaction between the large-scale topography, soil properties and land use. The most potent variable in this relationship was shown to be the hillslope gradient, which gives overland flow its erosive potential during intense rainfall events. Soil properties including particle size and organic matter content and vegetation then determine the extent to which erosion may take place: in the case of Site 1, for a rainfall event measuring just over 40 mm, this figure reached approximately 89.3 kg in total. Results successfully demonstrated that the relationship between gully morphology and catchment area was complex, and that this was not the main variable influencing gully form. Instead, the combination of slope gradient and position on the hillslope proved to be the most significant interaction of factors when accounting for local gully volume (the regression of these variables gave a highly significant R^2 value of 0.62).

In conclusion, the reconciliation of the data obtained at both scales, combined with data obtained from the laser scanner, gave a unique insight into the formation of small gullies on a semi-arid hillslope. Gully morphology has been accounted for and shown to be mainly a result of the interactions between large-scale topography and small-scale soil properties. The relationship is nevertheless complex, and this study has also highlighted the need for further research into this subject area to be carried out. Finally, in order to fully evaluate the overall success of this study, attention must be given to the research aim and objectives first set out in Chapter 1.

5.4. Research Evaluation, Limitations and Future Research Potential.

5.4.1. Research Summary and Evaluation.

The aim of this research was to understand the formation of small gullies on semi-arid hillslopes in south-east Spain, in relation to their topographic settings, soil properties and rainfall characteristics. Research was successfully carried out on two field sites, and the data obtained has been presented and discussed in the latter chapters of this thesis. Results demonstrated that the nature of the gully morphological development at each field site was caused by the response of scale-dependent interactions between specific variables to an intense rainfall event: these were hillslope topography, small-scale soil properties, vegetation and land use. These interactions were then investigated further following the four research objectives set out in Chapter 1.2.

The first of the four research objectives was to explore the geomorphology of gullies at two sites formed under a rainfall event of known characteristics. This was accomplished by obtaining detailed rainfall data and carrying out field studies at Site 1 and Site 2. Gully form was first measured by hand, infiltration experiments were then carried out, and soil samples were taken for later laboratory analysis. In addition, a terrestrial laser scanner was used to obtain representations of the large-scale hillslope topography and the small-scale variations in soil surface in unprecedented detail.

The data obtained in the field was successfully analysed, and the second objective was carried out: this was to determine a relationship between gully catchment area and gully cross-sectional development along each channel, using data obtained from the laser scanner. The nature of the role played by catchment area was shown to be complex and greatly reliant upon interaction with other variables. In particular it was shown that while the size of the upslope catchment area will affect the overall amount of water captured and carried by the gullies, their morphology was not determined solely by this variable. Instead, the morphologically largest section of each gully was located mid-way down its length where slope gradient was also to be steepest. This relationship was investigated further using multiple regression: the three variables of local gully volume, local slope gradient, and length upslope (for definitions, see Table 3.1) gave the most significant results: the R^2 value was 0.62, demonstrating that it is these two factors which have the most influence on gully morphology (with local gully volume as the dependent variable). This also showed that it was important to allow for position on the hillslope, as well as slope gradient when accounting for gully form.

The data obtained was also used to demonstrate the effects of physical soil properties on overland flow pathways and gully morphological development, which constituted the third research objective. The inclusion of the laser scanner data proved essential at this point when exploring the geomorphology of gullies A – D: this was due to its unique ability to capture detail at both the large and small scales. These results, therefore, were particularly important considering that scale issues are one of the current major challenges in the field of physical geography (Cammeraat, 2002).

The main physical soil properties identified in the research as having an important influence on erosion and gully morphology were particle size, soil organic matter content, and infiltration rate. Results demonstrated that gully initiation could be attributed to the specific reaction of small-scale areas to intense rainfall: at this scale, infiltration rate and the susceptibility of the soil particles to erosion were the most potent variables. Significant patterns detected in the data from Site 1 included silt being the most abundant soil fraction at each of the gully heads (gully A: 52.6 %, gully B: 60.3 %, gully C: 54 %), and soil organic matter having the highest concentration at the base of each gully channel (gully A: 5.4 %, gully B: 5.9 %, gully C: 5.5 %). Once gullying had initiated, the form and morphology of the gullies themselves could be attributed to a complex feedback mechanism with local slope gradient and with vegetation. Data also demonstrated that the hillslope must be considered as a summary of interactions between 'source' and 'sink' areas: the spatial configuration of these surface units and their connectivity with their surroundings at both scales determines the hydrological response of the hillslope.

The final research objective was to evaluate the potential of the laser scanner as a tool for studying gully morphology. The results from the study demonstrated that the laser scans were essential to evaluation and interpretation of much of the gully morphology. The use of a laser scanner in this study also provided this piece of work with a unique quality: this is the first time laser scanning techniques have been successfully implemented in the study of gully geomorphology on such a large scale in the field, and results have shown that the data generated provided a new level of precision in terms of understanding and monitoring erosion processes. As an emerging technology, terrestrial laser scanning (TLS) is still in its infancy, which is evident in the limited amount of published work (Lichti et al., 2002), therefore the research carried out in this study provides important data into the use of laser scanning in a geomorphological context. The data obtained using the laser scanner also demonstrated the potential this piece of equipment has for carrying out investigations into erosion by gullying. Its ability to collect both large and highly detailed representations of the soil surface in relatively little time is remarkable, and can be applied to any medium both within and beyond physical geography. Despite some drawbacks including initial difficulties in processing the point cloud scans, and the somewhat tedious time-consuming process of extracting useful information from the scan data, the overall evaluation of its use in this context is very positive.

5.4.2. Limitations and Future Research Potential.

While this study was successful in that the research aim and objectives were completed, there were nevertheless limitations which inhibited both collection of information in the field and analysis of resulting data. Firstly, although the laser scanner proved to be an extremely useful piece of equipment for gathering data in the field, it also had some limitations which must be considered. One limitation was the size of the datasets generated by the laser scanner: their sheer size (in some cases, larger than 5 Gb) meant that the computers could not cope with the analyses to be carried out. As a consequence, the point clouds had to be simplified then rendered as surfaces; in order to import into ArcGIS software, additional cross-sections of the surface had to be taken every 2 % across each scan. This was a long, tedious process in which some of the surface details were inevitably lost. However, it is hoped that with the advancement of technology, future processing and analysis of such large datasets will become easier. A further practical consideration is the high cost of the laser scanner itself, which means that its use in other studies may not be financially viable until cheaper products are provided on the market.

The potential for future research into gully morphological development itself is vast, and this is also an area where more research is required, as has also been recognised and discussed by several authors (e.g. Canton et al., 2001; Bull and Kirkby, 2002: 12; Cammeraat, 2002; Poesen et al., 2003; and Valcarcel et al., 2003). Whilst intelligent interpolation of the laser scan data was carried out in this study, it is an area where future research into this subject could most definitely be carried out: for example, one future option for research may be to carry out a similar field study in which many more plot scans were taken and linked together, creating a more detailed dataset in which gully erosion could be effectively monitored over a given timescale. Indeed, the expansion of agriculture in semi-arid areas and increases in soil degradation – particularly in this region of Spain – means that the continued monitoring and assessment of gully erosion in this area is of great importance.

5.5. Final Research Conclusions.

In this thesis, the survey of two sites in south-east Spain was carried out in order to characterise the formation of gullies on semi-arid hillslopes in relation to topographic settings, soil properties and rainfall characteristics. The use of a laser scanner complemented data obtained by more traditional methods, providing a unique opportunity to take detailed measurements of gully form and hillslope erosion and then relate them to ancilliary measurements of rainfall, soil texture, soil omc, and infiltration in order to give new insights into the nature of gully form and development on semi-arid hillslopes. These results were then presented and interpreted in Chapters 3 – 5.

Hillslope topography at the large-scale and soil properties at the small-scale were both of particular significance in determining the morphology of gullies A-D. The land use practices at each site also played a major role in gully morphological development. In conclusion, rather than a single dominant process, it was the positive feedbacks and interactions *between* processes which affected gully morphological development at the field sites studied, and led to the formation of the small gullies on the hillslopes studied in south-east Spain. This study has demonstrated that there is a need to develop our current understanding of interactions on semi-arid hillslopes, and more research must be carried out into the spatial configuration and connectivity of hydrologically different areas. Understanding and mitigating erosion in semi-arid environments is therefore both an exciting challenge for the future as well as an important subject area in geomorphology itself.

References.

Abrahams, A.D., Parsons, A.J. and Hirsch, P.J. 1992. *Field and Laboratory Studies of Resistance to Interrill Overland Flow on Semi-Arid Hillslopes, Southern Arizona.* UCL Press, London

Baize, D. 1993. Soil Science Analysis: A Guide to Current Use. Wiley, England

Becker, A., and Braun, P. 1999. Disaggregation, aggregation and spatial scaling in hydrological modelling. *Journal of Hydrology*, 217, 239-252

Benton-Jones, J. 2001. *Laboratory Guide for Conducting Soil Tests and Plant Analysis.* CRC Press LLC, Florida

Bergkamp, G., Cammeraat, L.H., Martinez-Fernandez, J. 1996. Water movement and vegetation patterns on shrubland and an abandoned field in two desertification-threatened areas in Spain. *Earth Surface Processes and Landforms*, 21, 1073-1090

Bergkamp, G. 1998. A hierarchical view of the interactions of runoff and infiltration with vegetation and microtopography in semiarid shrublands. *Catena*, 33, 201-220

Berntsson, R. and Larson, M. 1987. Spatial variability of infiltration in a semiarid environment. *Journal of Hydrology,* 90, 117-133

Beven, K. 2002. Runoff generation in semi-arid areas. In: Bull, L.J., and Kirkby, M.J. (eds) Dryland Rivers, hydrology and geomorphology of semi-arid channels. Wiley, England.

Beven, K.J. and Kirkby, M.J. 1979. A physically-based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin,* 24 (1), 43-69

Bitelli, G., Dubbini, M., and Zanutta, A. 2005. Terrestrial laser scanning and digital photogrammetry techniques to measure landslide bodies. Annual congress of the *International Society for Photogrammetry and Remote Sensing*, Istanbul 2004.

Blöschl.G. and Grayson., R. 2000. Spatial Observations and Interpolation. In: Grayson,R. and Blöschl, G. (eds) *Spatial Patterns in Catchment Hydrology: Observations and Modelling.* Cambridge University Press, UK. p17-51

Blott, S.J., and Pye, K. 2001. Technical Communication: Gradistat: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms*, 26, 1237-1248.

Boix-Fayos, C., Calvo-Cases, A., Imeson, A.C., Soriano-Soto, M.D. and Tiemessen, I.R. 1998 Spatial and short-term temporal variations in runoff, soil properties along a Mediterranean climatological gradient. *Catena,* 33, 123-138

Bonnell and Williams. 1986. The generation and redistribution of overland flow on a massive oxic soil in a eucalyptus woodland within the semi-arid tropics of northern Australia. *Hydrological Processes,* 1, 31-46

Bryan, R.B. 2000. Soil erodibility and processes of water erosion on hillslopes. *Geomorphology,* 32, 385-415

Bryan, R.B. and Campbell, I.A. 1986. Runoff and sediment discharge in a semi-arid ephemeral drainage basin. *Zeitschrift für Geomorphologie N.F. Suppl. Bd.* 58, 121-143

Bull, L.J. and Kirkby, M.J. 2002. Channel heads and channel extension. In: Bull, L.J., and Kirkby, M.J. (eds) Dryland Rivers, Hydrology and Geomorphology of Semi-Arid Channels. Wiley, England.

Bull, L.J., Kirkby, M.J., Shannon, J., and Hooke, J.M. 1999. The impact of rainstorms on floods in ephemeral channels in southeast Spain. *Catena,* 38, 191-209

Cammeraat, L.H. 2002. A review of two strongly-contrasting geomorphological systems within the context of scale. *Earth Surface Processes and Landforms,* 27, 1201-1222

Cammeraat, L.H. 2004. Scale dependent thresholds in hydrological and erosional response of a semi-arid catchment in south east Spain. *Agriculture, Ecosystems and Environmen*t, 104, 317-332.

Cantón, Y., Domingo, F., Solé-Benet, A., and Puigdefábregas, J. 2001. Hydrological and erosion response of a badlands system in semiarid SE Spain. *Journal of Hydrology,* 252, 65-84

Cantón, Y., Solé-Benet, A., and Domingo, F. 2004a. Temporal and spatial patterns of soil moisture in semiarid badlands of SE Spain. *Journal of Hydrology*, 285, 199-214

Cantón, Y., Del Barrio, G., Solé-Benet, A., and Lázaro, R. 2004b. Topographic controls on the spatial distribution of ground cover in the Tabernas badlands of SE Spain. *Catena*, 55, 341-365

Castillo, V.M., Gómez-Plaza, A., and Martínez-Mena, M. 2003. The role of antecedent soil water content in the runoff respose of semiarid catchments: a simulation approach. *Journal of Hydrology*, 284, 114-130

Cerdà, A. 1997. Soil erosion after land abandonment in a semiarid environment of southeastern Spain. *Arid Soil Research and Rehabilitation,* 11, 163-176

Cerdà, A. 1998. The influence of geomorphological position and vegetation cover on the erosional and *Hydrological Processes* on a Mediterranean hillslope. *Hydrological Processes*, 12, 661-671

Cerdà, A. 2002. The effect of season and parent material on water erosion on highly eroded soils in eastern Spain. *Journal of Arid Environments,* 52, 319-337

Clarke, M.L. and Rendell, H.M. 2000. The impact of the farming practice of remodelling hillslope topography on badland morphology and soil erosion processes. *Catena,* 40, 229-250

Conacher, A.J. and Sala, M. 1998. *Land degradateion in Mediterranean environments of the world: nature and extent, causes and solutions.* Wiley, Chichester.

Coppus, R. and Imeson, A.C. 2002. Extreme events controlling erosion and sediment transport in a semi-arid sub-andean valley. *Earth Surface Processes and Landforms*, 27, 1365-1375

Corradini, C., Morbidelli, R., and Melone, F. 1998. On the interaction between infiltration and Hortonian runoff. *Journal of Hydrology* 204 p52-67

Coulter Corporation, 1998. www.beckman.com/products/instrument/partChar/pc_ls13320.asp

Cremers, N.H.D.T., van Dijk, P.M., de Roo, A.J.P., and Verzandvoort, M.A. 1996. Spatial and temporal variability of soil surface roughness and the application in hydrological and soil erosion modelling. *Hydrological Processes*, 10 (3), 1035-1047

Cresser, M., Killham, K., Edwards, T. 1993. *Soil Chemistry and its Applications.* Cambridge Environmental Chemistry Series 5. Cambridge University Press.

Darboux, F. and Huang, C. 2003. An instantaneous profile laser scanner to quantify soil microtopography. *Soil Science Society of America Journal*, 67 (1), 92-99

Darboux, F., Davy, P., Gascuel-Odoux, C., and Huang, C. 2001. Evolution of soil surface roughness and flowpath connectivity in overland flow experiments. *Catena*, 46, 125-139

De Boer, D.H. 1992. Constraints on spatial transference of rainfall-runoff relationships in semiarid basins drained by ephemeral streams. *Hydrological Sciences Journal,* 37(5), 491-504

Desmet, P.J.J., Poesen, J., Govers, G. and Vandaele, K. 1999. Importance of slope gradient and contributing area for optimal prediction of the initiation and trajectory of ephemeral gullies. *Catena,* 37, 337-392

Diskin, M.H. and Nazimov, N. 1996. Ponding time and infiltration capacity variation during steady rainfall. *Journal of Hydrology*, 178, 369-380

Dunjó, G., Pardini, G., and Gispert, M. 2003. Land use change effects on abandoned terraced soils in a Mediterranean catchment in northeast Spain. *Catena*, 52, 23-37

Dunne, T., Zhang, W. and Aubry, B.F. 1991. Effect of rainfall, vegetation and microtopography on infiltration and runoff. *Water Resources Research,* 27(9), 2271-2285

Esteves, M., and Lapetite, J.M. 2003. A multi-scale approach of runoff generation in a Sahelian gully catchment: a case study in Niger. *Catena*, 50, 255-271

Farenhorst, A. and Bryan, R.B. 1995. Particle size distribution of sediment transported by shallow flow. *Catena*, 25, 47-62

Faulkner, H. 1995. Gully erosion associated with the expansion of unterraced almond cultivation in the coastal Sierra de Lujar, Southern Spain. Land Degradation and Rehabilitation, 9, p179-200. Referenced in: Poesen, J., Nachtergaele, J., Verstraeten, G., and Valentin, C. 2003. Gully erosion and environmental change: importance and research needs. *Catena*, 50, 91-133

Fitzjohn, C., Ternan, J.L., and Williams, A.G. 1998. Soil moisture variability in a semiarid gully catchment: implications for runoff and erosion control. *Catena*, 32, 55-70

Flanagan, D.C., Huang, C., Norton, L.D., and Parker, S.C. 1995. Laser scanner for erosion plot measurements. *Transactions of the American Society of Agricultural Engineers*, 38(3), 703-710

Fried, J.S., Brown, D.G., Zweifler, M.O., and Gold, M.A. 2000. Mapping contributing areas for stromwater discharge to streams using terrain analysis. In: Wilson, J.P. and Gallant, J.C. (eds) *Terrain Analysis: Principles and Applications.* Wiley, New York. p183-204

Friedman, G.M., and Sanders, J.E. 1978. *Principles of Sedimentology*. Wiley, New York.

Gabbard, D.S., Huang, C., Norton, L.D., and Steinhardt, G.C. 1998. Landscape position, surface hydraulic gradients and erosion processes. *Earth Surface Processes and Landforms*, 23, 83-93

Gallart, F., Solé, A., Puigdefabregas, J., and Lazaro, R. 2002. Badland systems in the Mediterranean. In: Bull, L.J., and Kirkby, M.J. (eds) *Dryland Rivers, hydrology and geomorphology of semi-arid channels*. Wiley, England.

Genovois, R., Galgaro, A. and Tecca, P.R. 2001. Image analysis for debris flow properties estimation. *Physics and Chemistry of the Earth Part C*, 26(9), 623-631

Gómez-Plaza, A., Martínez-Mena, M., Albaladejo, J., and Castillo, V.M. 2001. Factors regulating spatial distribution of soil water content in small semiarid catchments. *Journal of Hydrology*, 253, 211-226

Gordon, S., Lichti, D., Stewart, M., and Franke, J. 2003. *Structural deformation measurement using terrestrial laser scanners.* 11th International Symposium on Deformation Measurements.

Grayson, R. and Blöschl, G. 2000. Spatial Processes, Organisation and Patterns. In Grayson, R. and Blöschl, G. 2000 (eds) *Spatial Patterns in Catchment Hydrology: Observation and Modelling.* Cambridge University Press, UK, p3-17

Harvey, A.M. 1984. Geomorphic response to an extreme flood: a case from SE Spain. *Earth Surface Processes and Landforms,* 9, 267-279

Hayakawa, Y., and Oguchi, T. 2005. Evaluation of gravel sphericity and roundness based on surface area measurements with a laser scanner. *Computers and Geosciences*, 31, 735-741.

Hesse, P.R. 1971. *A Textbook of Soil Chemical Analysis.* Murray, London.

Hooke, J. and Mant, J. 2002. Morpho-dynamics of Ephemeral Streams. In: Bull, L.J., and Kirkby, M.J. (eds) *Dryland Rivers, Hydrology and Geomorphology of Semi-Arid Channels.* Wiley, England.

Horton, R.E. 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. *Bulletin of the Geological Society of America,* 56, ,275-370.

Huang, C. and Bradford, J.M. 1990. Portable laser scanner for measuring soil surface roughness. *Transactions of the American Society of Agricultural Engineers,* 54(5), 1402-1406

Huang, C. and Bradford, J.M. 1992. Applications of a lased scanned to quantify soil microtopography. *Transactions of the American Society of Agricultural Engineers*, 56(1), 14-21

Huang, C.H., and Bradford, J.M. 1993. Applications of a Laser Scanner to Quantify Properties of Soil Crusts. In: Poesen, J.W.A. and Nearing, M.A. (eds) *Soil Surface Sealing and Crusting.* Catena Supplement, 24, p129-139

Imeson, A.C. and Prinsen, H.A.M. 2004. Vegetation patterns as biological indicators for identifying runoff and sediment source and sink areas for semi-arid landscapes in Spain. *Agriculture, Ecosystems and Environment*, 104, 333-342

Jetten, V., Govers, G., and Hessel, R. 2003. Erosion models: quality of spatial predictions. *Hydrological Processes,* 17, 887-900

Kamphorst, E.C., Jetten, V., Guérif, J., Pitkänen, J., Iverson, B.V., Douglas, J.T., and Paz, A. 2000. Predicting depressional storage from soil surface roughness. *Transactions of the American Society of Agricultural Engineers*, 64, 1749-1758

Karnoven, T., Koivusala, H., Jauhianinen, M., Palko, J., and Weppling, K. 1999. A hydrological model for predicting runoff from different land use areas. *Journal of Hydrology*, 217, 253-265.

Kirkby, M.J. 2001. Modelling the interactions between soil surface properties and water erosion. *Catena*, 46, 89-102

Kirkby, M.J. and Bull, L.J. 2000. Some factors controlling gully growth in fine-grained sediments: a model applied in SE Spain. *Catena*, 40, 127-146

Kirkby, M., Bracken, L., and Reaney, S. 2002. The influence of land use, soils, and topography on the delivery of hillslope runoff to channels in SE Spain. *Earth Surface Processes and Landforms*, 27, 1457-1473

Kirkby, M.J., Bull, L.J., Nachtergaele, J., Vandekerckhove, L. 2003. Observed and modelled distributions of channel and gully heads – with examples from SE Spain and Belgium. *Catena*, 50, 415-434

Kosmas, C., Danalatos, N., Cammeraat, L.H., Chabart, M., Diamantopoulmos, J., Farand, R., Gutierrez, L., Jacob, A., Marques, H., Matrinez-Fernandez, J., Mizara, A., Moustakas, N., Nicolau, J.M., Oliveros, C., Pinna, G., Puddu, R., Puigdefabrigas, J., Roxo, M., Simao, A., Stamou, G., Tomasi, N., Usai, D., and Vacca, A. 1997. The effects of land use on runoff and soil erosion rates under Mediterranean conditions. *Catena*, 29, 45-59

Kosmas, C., Danalatos, N.G., and Gerontidis, St. 2000. The effect of land parameters on vegetation performance and degree of erosion under Mediterranean conditions. *Catena*, 40, 3-17

Kuhn, N.J., and Yair, A. 2004. Spatial distribution of surface conditions and runoff generation in small arid watersheds, Zin Valley Badlands, Israel. *Geomorphology*, 57, 183-200

Lane, S., Richards, K., and Chandler, J. 1998. Landform Monitoring, Modelling and Analysis: Land Form in Geomorphological Research. In: Lane, S.N., Chandler, J. H., and Richards, K.S. (eds) *Landform Monitoring, Modelling and Analysis*. John Wiley and Sons, England. p1-19.

Lasanta, T., García-Ruiz, J.M., Pérez-Rontomé, C., and Sancho-Marcén, C. 2000. Runoff and sediment yield in a semi-arid environment: the effect of land management after farmland abandonment. *Catena*, 38, 265-278

Latulippe, C., Lapointe, M.F., and Talbot, T. 2001. Visual characterisation technique for gravel-cobble river bed surface sediments; validation and environmental applications. Contribution to the programme of CIRSA (Centre Interuniversitaire de Recherche sur le Saumon Atlantique). *Earth Surface Processes and Landforms*, 26(3), 307-318

Lavee, H., Imeson, A.C., Sarah, P. 1998. The impcat of climate change on geomorphology and desertification along a Mediterranean-arid transect. *Land Degradation and Development* 9, 407-122. Quoted in Martínez-Mena, M., Alvarez-Rogel, J., Albaladejo, J., and Castillo, V.M. 1999. Influence of vegetal cover on sediment particle size distribution in natural rainfall conditions in a semiarid environment. *Catena*, 38, 175-190

Lichti, D.D. 2005. Spectral filtering and classification of terrestrial laser scan point clouds. *The Photogrammetric Record*, 20(111), 218-240

Lichti, D.D. Gordon, S.J., and Stewart, M.P. 2002. Ground-based laser scanners: operation, systems and applications. *Geomatica*, 56(1), 21-33

Lim, M., Petley, D.N., and Rosser, N.J., Allison, R.J., Long, A.J., and Pybus, D. 2005. Combined digital photogrammetry and time-of-flight laser scanning for monitoring cliff evolution. *Photogrammetric Record,* 20(110), 109

Liu, Q.Q., Chen, L., and Li, J.C. 2001. Influences of slope gradient on soil erosion. *Applied Mathematics and Mechanics*, 22 (5), 510-519

López-Bermúdez, F., Romero-Díaz, A., Martínez-Fernandez, J., and Martínez-Fernandez, J. 1998. Vegetation and soil erosion under a semiarid Mediterranean climate: a case study from Murcia (Spain). *Geomorphology*, 24, 51-58

López-Bermúdez, F., Conesa-García, C., and Alonso-Sarría, F. 2002. Floods: magnitude and frequency in ephermeral streams of the Spanish Mediterranean region. In: Bull, L.J. and Kirkby, M.J. 2002. *Dryland rivers: hydrology and geomorphology of semi-arid channels*. Wiley, England. p329-350

Martínez-Casanovas, J.A. 2003. A spatial information technology approach for the mapping and quantification of gully erosion. *Catena,* 50, 293-308

Martínez-Casanovas, J.A., Antón-Fernández, C., and Ramos, M.C. 2003. Sediment production in large gullies of the mediterranean area (NE Spain) from high-resolution digital elevtion models and GIS analysis. *Earth Surface Processes and Landforms*, 28, 443-456

Martínez-Mena, M., Alvarez-Rogel, J., Albaladejo, J., and Castillo, V.M. 1999. Influence of vegetal cover on sediment particle size distribution in natural rainfall conditions in a semiarid environment. *Catena*, 38, 175-190

Martínez-Mena, M., Castillo, V., and Albaladejo, J. 2002. Relations between interrill erosion processes and sediment size distribution in a semi-arid Mediterranean area of SE Spain. *Geomorphology,* 45, 261-275

MDL: "Measurement Devices Limited". 2001. www.mdl.co.uk/index.php

MDL: "Measurement Devices Limited". 2003. *LaserAce ® scanner: Combined reflectorless total station and scanner.* (pdf. file available to download at www.mdl.co.uk/products_scanner.php)

Nachtergaele, J., and Poesen, J. 1999. Assessment of soil losses by ephemeral gully erosion using high-altitude (stereo) arial photographs. *Earth Surface Processes and Landforms*, 24, 693-706

Nachtergaele, J., and Poesen, J. 2002. Spatial and temporal variations in resistance of loess-derived soils to ephemeral gully erosion. *European Journal of Soil Science*, 53, 449-463

Nagihara, S., Mulligan, K., and Xiong, W. 2004. Technical Communication: Use of a three-dimensional laser scanner to digitally capture the topography of sand dunes in high spatial resolution. *Earth Surface Processes and Landforms*, 29, 391-398

Nicolau, J.M., Solé-Benet, A., Puigdefábregas, J., and Gutiérrez, L. 1996. Effects of soil and vegetation of runoff along a *Catena* in semie-arid Spain. *Geomorphology,* 14, 297-309

Obando, J. 1993. Modelling vegetation-erosion competition on abandoned land under fluctuating rainfall regimes. In: Fantechi, R., Peter, D., Balabanis, P., and Rubio, J.L. (eds), *Desertification in a European Context: Physical and Socio-Economic Aspects.* Proceedings of the European School of Climatology and Natural Hazards Course, El Campello, Pueblo Acantilado, Alicante, Spain. European Commission, Luxembourg. p553-565

Pilgrim, D.H., Chapman, T.G., and Doran, D.G. *et al.* 1988. Problems of rainfall-runoff modelling in arid and semiarid regions. *Hydrological Sciences Journal,* 33(4), 379-400

Poesen, J. 1984. The influence of slope angle on infiltration rate and Hortonian overland flow volume. *Zeitschrift für Geomorphologie N.F. Supplement Band,* 49, 117-131

Poesen, J., Vanderkerckhove, L., Nachtergaele, J., Oostwoud-Wijdenes, D., Verstraeten, G., and van Wesemael, B. 2002. Gully erosion in dryland environments. In: Bull, L.J. and Kirkby, M.J. *Dryland rivers: hydrology and geomorphology of semi-arid channels.* Wiley, England. p229-262

Poesen, J., Nachtergaele, J., Verstraeten, G., and Valentin, C. 2003. Gully erosion and environmental change: importance and research needs. *Catena*, 50, 91-133

Puigdefabrigás, J., del Barrio, G., de Boer, M., Gutiérrez, L. and Solé, A. 1998. Differential responses of hillslope and channel elements to rainfall events in a semi-arid area. *Geomorphology*, 23, 337-351

Puigdefabrigás, J., Solé, A., Gutiérrez, L., del Barrio, G., and Boer, M. 1999. Scales and processes of water and sediment redistribution in drylands: results from the Rambla Honda field site in Southeast Spain. *Earth-Science Reviews,* 48, 39-70

Quinn, P., Beven, K., Chevallier, P., and Planchon, O. 1991. The prediction of hillslope flowpaths for distributed hydrological modelling using digital terrain models. In: Beven, K.J., and Moore, I.D. *Terrain Analysis and Distributed Modelling in Hydrology*. Wiley, England.

Renschler, C.S., Mannaerts, C., and Diekkrüger, B. 1999. Evaluating spatial and temporal variability in soil erosion risk – rainfall erosivity and soil loss ratios in Anadalusia, Spain. *Catena,* 34, 209-225

Ritchie, J.C., Grissinger, E.H., Murphey, J.B., and Garbrecht, J.D. 1994. Measuring channel and gully cross-sections with an airborne laser altimeter. *Hydrological Processes*, 8 (3), 237-243

Rosser, N.J., Petley, D.N., Lim, M., Dunning, S.A., and Allison, R.J. 2005. Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion. *Quarterly Journal of Engineering Geology and Hydrogeology*, 38(4), 363-375

Schmidt, J., Evans, I.S., and Brinkman, S. 2003. Comparison of polynomial models for land surface curvature calculation. *International Journal of Geographical Information Science*, 17(8), 797-814

Shannon, J., Richardson, R., and Thornes, J. 2002. Modelling event-based fluxes in ephemeral streams. In: Bull, L.J. and Kirkby, M.J. 2002. *Dryland rivers: hydrology and geomorphology of semi-arid channels*. Wiley, England. p129-172

Sivapalan, M. 2003. Process complexity at hillslope scale, process simplicity at the watershed scale: is there a connection? Invited Commentary. *Hydrological Processes*, 17, 1037-1041

Slattery, M.C., Gares, P.A., and Phillips, J.D. 2002. Slope-channel linkage and sediment delivery on North Carolina coastal plain cropland. *Earth Surface Processes and Landforms*, 27, 1377-1387

Smettem, K.R.J., Smith, R.E., and Broadbridge, P. 2002. Field measurement of infiltration parameters. In: Smith, R.E., Smettem, K.R.J., Broadbridge, P., and Woolhiser, D.A. (eds) *Infiltration Theory for Hydrologic Applications*. American Geophysical Union.

Sobieraj, J.A., Elseneer, H. and Cameron, G. 2004. Scale dependency in spatial patterns of saturated hydraulic conductivity. *Catena*, 55, 49-77

Solé-Benet, A., Calvo, A., Cerdà, A., Lázaro, R., Pini, R., and Barbero, J. 1997. Influences of micro-relief patterns and plant cover on runoff related processes in badlands from Tabernas (SE Spain). *Catena*, 31, 23-38

Souchère, V., Cerdan, O., Ludwig, B., Le Bissonais, Y., Couturier, A., and Papy, F. 2003. Modelling ephemeral gully erosion in small cultivated catchments. *Catena*, 50, 489-505

Stomph, T.J., de Ridder, N., and Van de Giesen, C. 2001. A flume design for the study of slope length effects on runoff. *Earth Surface Processes and Landforms*, 26, 647-655

Tan, K.H. 1996. *Soil Sampling, Preparation and Analysis*. Marcel Dekker Inc. New York.

Truman, C.C., Wauchorpe, R.D., Sumner, H.R., Davis, J.G., Gascho, G.J., Hook, J.E., Chandler, L.D., and Johnson, A.W. 2001. Slope length effects on runoff and sediment delivery. *Journal of Soil and Water Conservation*, 56(3), 249-256

Tucker, G.E., and Bras, R.L. 1998. Hillslope processes, drainage density, and landscape morphology. *Water Resources Research* 34(10), 2751-2764

Twigg, D.R. 2000. The Global Positioning System and its Use for Terrain Mapping and Monitoring. In Wilson, J.P., and Gallant, J.C (Eds) *Terrain Analysis: Principles and Applications*. John Wiley and Sons, USA, p37-62

Udden, J.A. 1914. Mechanical composition of clastic sediments. *Bulletin of the Geological Society of America*, 25, 655-744.

Valcárcel, M., Taboada, M.T., Paz, A., and Dafonte, J. 2003. Ephemeral gully erosion in northwestern Spain. *Catena,* 50, 199-216

Vandekerckhove, L., Poesen, J., and Govers, G. 2003. Medium-term gully headcut retreat rates in Southeast Spain determined from aerial photographs and ground measurements. *Catena*, 50, 329-352

Vosselman, G., Kessels, P., and Gorte, B. 2005. The utilisation of airborne laser scanning for mapping. *International Journal of Applied Earth Observations and Geoinformation*, 6, 177-186

Wei, J. and Salyani, M. 2005. Development of laser scanner for measuring tree canopy characteristics: Phase 2. Foliage density measurement. *Transactions of the American Society of Agricultural Engineers*, 48(4), 1595-1601

Wentworth, C.K. 1922. A scale of grade and class terms for clastic sediments. *Journal of Geology*, 30, 377-392.

Williams, A.G., Ternan, J.L., Fitzjohn, C., de Alba, S., and Perez-Gonzalez, A. 2003; Soil moisture variability and land use in a seasonally arid environment. *Hydrological Processes,* 17, 225-235

Wilson, J.P., and Gallant, J.C. 2000. Digital Terrain Analysis. In Wilson, J.P., and Gallant, J.C (Eds) *Terrain Analysis: Principles and Applications*. John Wiley and Sons, USA, p1-28

Yaalon, D.H. 1997. Soils in the Mediterranean region: what makes them different? *Catena*, 28, 157-169

Zhu, T.X., Cai, Q.G., and Zeng, B.Q. 1997. Runoff generation on a semiarid agricultural catchment: field and experimental studies. *Journal of Hydrology*, 196, 99-118

Appendix 1.

A.1. Infiltration Data: Site 1 and Site 2.

(All infiltration rates in mm min^{-1})

gully A

	infiltration point				
mm infiltrated	1	2	3	4	5
10	0.55	0.35	1.04	0.35	0.39
20	1.37	1.24	2.24	1	1.26
30	2.29	2.2	3.39	1.3	2.37
40	3.25	3	5.18	2.12	3.33
50	4.25	4.06	6.45	2.47	4.19
60	5.25	5.1	8.34	3.36	5.08
70	6.3	6.15	10.24	4.47	5.565
80	7.35	7.21	12.38	5.22	7.1
90	9	9.06	14.46	6.13	8.14
100	11.37	11.55	17.21	7.21	9.35
110	12.45	13.53	19.08	8.07	10.1
120	13.24	15.01	20.46	8.54	10.35
130	15.22	16.41	23.2	9.23	10.54
140	16.22	17.57	25.26	10.12	11.33
150	18.2	19.56	27.2	10.56	12.12
160	20.01	21.4	29.52	11.4	12.58
170	20.53	22.19	32.14	12.4	13.54
180	21.52	24.5	34.01	13.4	14.39
190	22.47	25.13	36.4	14.44	15.38
200	25.15	27.43	39.28	16	16.49

gully B

	infiltration point				
mm infiltrated	6	7	8	9	10
10	0.12	0.12	0.19	0.43	0.47
20	0.29	0.43	0.4	1.21	1.33
30	0.56	1.34	1.06	1.56	3.09
40	1.26	2.45	1.5	2.3	4.36
50	2.01	3.51	2.3	3	6.19
60	2.48	4.51	3.06	3.46	7.44
70	3.24	6.15	3.57	4.18	9.35
80	4.26	7.22	4.44	5.03	11.33
90	5.26	9.01	5.42	6.08	13.56
100	6.34	10.48	6.49	7.31	16.49
110	7.33	11.35	7.21	8.12	
120	8.52	12.15	7.56	8.49	
130	9.48	13	8.24	9.31	
140	10.58	13.55	9.11	10.19	
150	12.07	14.49	9.54	11.02	
160	13.35	15.39	10.54	11.45	
170	14.46	16.48	11.44	12.39	
180	16.11	17.56	12.37	13.52	
190	17	19.05	13.21	14.58	
200	18.2	20.3	14.46	16.12	

gully C

	infiltration point				
mm infiltrated	11	12	13	14	15
10	0.17	0.09	0.16	0.16	0.58
20	0.38	0.16	0.34	0.35	2.05
30	0.55	0.22	0.58	0.56	3.41
40	1.2	0.32	1.16	1.25	4.5
50	1.48	0.4	1.4	1.42	6.1
60	2.11	0.5	2.01	2.11	7.13
70	2.5	1.06	2.32	2.38	8.35
80	3.31	1.15	3.08	3.13	10.23
90	3.59	1.29	3.46	4	11.46
100	4.44	1.44	4.58	5.17	13.24
110	5.32	2.13	5.3	6	13.56
120	6.09	2.36	5.55	6.3	14.35
130	6.55	3.01	6.25	7.15	15.32
140	7.43	3.25	7.1	7.51	16.34
150	8.25	3.5	7.51	8.26	17.4
160	9.06	4.32	8.21	9.13	18.45
170	10.02	4.53	9.08	9.55	19.56
180	11.05	5.43	9.45	10.55	21.21
190	12.16	6.44	10.41	11.58	23.13
200	13.22	7.1	12.14	13.25	25.18

gully D

	infiltration point		
mm infiltrated	top	middle	base
10	1.42	1.13	1.44
20	2.45	2.21	3.08
30	4.05	3.37	4.54
40	5.43	5.04	7
50	7.19	6.27	9.18
60	9	7.45	11.37
70	10.52	9.13	14.03
80	12.31	11.01	16.5
90	14.31	12.19	19.55
100	17.07	14.08	23.34
110	19.22	16.09	27.14
120	21.37	17.32	30.06
130	23.28	19.17	33.15
140	25.4	21.01	35.44
150	28.03	22.48	39.03
160	30.3	24.55	41.56
170	32.55	17.11	44.29
180	35.03	19.31	47.12
190	37.1	32.2	50.04
200	39.35	34.28	53.52

Appendix 2.

A.2. Particle Size Distribution: Site 1 and Site 2.

gully A

sample number	1	2	3	4	5
SAMPLE TYPE:	Polymodal, Very Poorly Sorted	Polymodal, Very Poorly Sorted	Polymodal, Very Poorly Sorted	Bimodal, Very Poorly Sorted	Polymodal, Very Poorly Sorted
TEXTURAL GROUP:	Sandy Mud	Sandy Mud	Sandy Mud	Sandy Mud	Sandy Mud
SEDIMENT NAME:	Very Fine Sandy Fine Silt	Very Fine Sandy Mud	Very Fine Sandy Medium Silt	Very Fine Sandy Coarse Silt	Very Fine Sandy Medium Silt
% GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% SAND:	32.9%	33.1%	38.5%	21.5%	29.3%
% MUD:	67.1%	66.9%	61.5%	78.5%	70.7%
% V COARSE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%
% COARSE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% MEDIUM GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% FINE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% V FINE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% V COARSE SAND:	0.0%	0.0%	0.0%	0.0%	0.0%
% COARSE SAND:	0.0%	0.0%	0.0%	0.0%	0.0%
% MEDIUM SAND:	0.0%	0.0%	0.0%	0.0%	0.0%
% FINE SAND:	13.1%	15.6%	19.1%	7.0%	11.8%
% V FINE SAND:	19.7%	17.6%	19.4%	14.4%	17.5%
% V COARSE SILT:	9.1%	8.6%	9.0%	11.4%	10.1%
% COARSE SILT:	8.7%	8.6%	9.1%	15.2%	10.6%
% MEDIUM SILT:	9.3%	8.9%	9.7%	14.0%	10.9%
% FINE SILT:	9.7%	9.1%	9.2%	11.0%	10.5%
% V FINE SILT:	9.3%	8.8%	7.9%	8.7%	9.2%
% CLAY:	21.1%	22.9%	16.6%	18.3%	19.5%

gully B

sample number	6	7	8	9	10
SAMPLE TYPE:	Polymodal, Very Poorly Sorted	Trimodal, Very Poorly Sorted	Polymodal, Very Poorly Sorted	Polymodal, Very Poorly Sorted	Polymodal, Very Poorly Sorted
TEXTURAL GROUP:	Sandy Mud	Sandy Mud	Sandy Mud	Sandy Mud	Sandy Mud
SEDIMENT NAME:	Very Fine Sandy Medium Silt	Very Fine Sandy Medium Silt	Very Fine Sandy Fine Silt	Very Fine Sandy Medium Silt	Very Fine Sandy Medium Silt
% GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% SAND:	28.5%	28.2%	26.8%	35.3%	29.9%
% MUD:	71.5%	71.8%	73.2%	64.7%	70.1%
% V COARSE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% COARSE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% MEDIUM GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% FINE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% V FINE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% V COARSE SAND:	0.0%	0.0%	0.0%	0.0%	0.0%
% COARSE SAND:	0.0%	0.0%	0.0%	0.0%	0.0%
% MEDIUM SAND:	0.0%	0.0%	0.0%	0.0%	0.0%
% FINE SAND:	11.2%	12.0%	11.1%	17.3%	13.8%
% V FINE SAND:	17.3%	16.2%	15.7%	18.0%	16.1%
% V COARSE SILT:	10.5%	10.3%	9.0%	9.5%	8.4%
% COARSE SILT:	11.0%	11.8%	9.5%	9.3%	9.4%
% MEDIUM SILT:	11.5%	12.0%	10.7%	9.8%	10.1%
% FINE SILT:	10.4%	10.3%	10.8%	9.7%	10.1%
% V FINE SILT:	8.5%	8.2%	9.8%	8.0%	9.8%
% CLAY:	19.5%	19.2%	23.4%	18.3%	22.5%

gully C

sample number	**11**	**12**	**13**	**14**	**15**
SAMPLE TYPE:	Polymodal, Very Poorly Sorted	Polymodal, Very Poorly Sorted	Polymodal, Very Poorly Sorted	Polymodal, Very Poorly Sorted	Polymodal, Very Poorly Sorted
TEXTURAL GROUP:	Sandy Mud	Sandy Mud	Sandy Mud	Sandy Mud	Sandy Mud
SEDIMENT NAME:	Very Fine Sandy Medium Silt	Very Fine Sandy Coarse Silt	Very Fine Sandy Very Coarse Silt	Very Fine Sandy Very Fine Silt	Very Fine Sandy Very Coarse Silt
% GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% SAND:	27.3%	29.0%	35.3%	26.1%	39.3%
% MUD:	72.7%	71.0%	64.7%	73.9%	60.7%
% V COARSE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% COARSE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% MEDIUM GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% FINE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% V FINE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%
% V COARSE SAND:	0.0%	0.0%	0.0%	0.0%	0.0%
% COARSE SAND:	0.0%	0.0%	0.0%	0.0%	0.0%
% MEDIUM SAND:	0.0%	0.0%	0.0%	0.0%	0.0%
% FINE SAND:	11.5%	11.9%	14.1%	10.6%	18.7%
% V FINE SAND:	15.8%	17.1%	21.1%	15.6%	20.6%
% V COARSE SILT:	9.7%	10.6%	11.1%	9.9%	10.1%
% COARSE SILT:	11.9%	11.3%	9.0%	9.8%	8.5%
% MEDIUM SILT:	12.4%	10.9%	7.7%	9.6%	7.9%
% FINE SILT:	10.9%	9.9%	7.8%	10.1%	8.4%
% V FINE SILT:	9.1%	8.9%	8.4%	10.2%	8.5%
% CLAY:	18.7%	19.5%	20.8%	24.3%	17.4%

gully D

sample	**base**	**middle**	**top**
SAMPLE TYPE:	Polymodal, Very Poorly Sorted	Polymodal, Very Poorly Sorted	Polymodal, Very Poorly Sorted
TEXTURAL GROUP:	Sandy Mud	Sandy Mud	Sandy Mud
SEDIMENT NAME:	Fine Sandy Very Coarse Silt	Very Fine Sandy Very Coarse Silt	Fine Sandy Mud
% GRAVEL:	0.0%	0.0%	0.0%
% SAND:	39.4%	37.4%	34.1%
% MUD:	60.6%	62.6%	65.9%
% V COARSE GRAVEL	0.0%	0.0%	0.0%
% COARSE GRAVEL:	0.0%	0.0%	0.0%
% MEDIUM GRAVEL:	0.0%	0.0%	0.0%
% FINE GRAVEL:	0.0%	0.0%	0.0%
% V FINE GRAVEL:	0.0%	0.0%	0.0%
% V COARSE SAND:	0.0%	0.0%	0.0%
% COARSE SAND:	0.0%	0.0%	0.0%
% MEDIUM SAND:	0.0%	0.0%	0.0%
% FINE SAND:	20.2%	18.0%	18.5%
% V FINE SAND:	19.2%	19.4%	15.5%
% V COARSE SILT:	10.6%	10.0%	7.9%
% COARSE SILT:	10.2%	9.0%	8.2%
% MEDIUM SILT:	8.3%	8.4%	8.5%
% FINE SILT:	7.9%	8.9%	9.5%
% V FINE SILT:	7.5%	8.4%	9.8%
% CLAY:	16.2%	17.9%	22.1%