Phytoplankton distribution in the river Thames, England

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Dedicated to Hilary Belcher

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Author's Declaration

This thesis and the data presented are entirely the results of my own endeavours except where due acknowledgment and reference have been given. The views expressed are those of the author and not necessarily those of the University or Environment Agency.

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1.1 Introductory remarks

The effects of environmental perturbations on food webs are poorly understood in rivers, including the River Thames. Planktonic species are certainly more than bits of carbon and chlorophyll that may be freely substituted one for another without affecting planktonic food web dynamics and productivity (Sandgren, 1988). Understanding the ecology of phytoplankton species and responses to environmental factors is key to successful river management schemes. This thesis presents phytoplankton species composition data collected from four sites on the Thames over two years. Environmental data was also collected with the aim of relating phytoplankton dynamics to environmental perturbations which could then be extrapolated to effects of river regulation.

The River Thames is situated in the south of England in a temperate oceanic climate where daily daylight hours range seasonally from eight hours in December to seventeen hours in June and rainfall ranges between 52 mm mean total in June and 68 mm mean total in December (30 year means at Mortimer Berkshire, from Burt, 1995).

The Thames rises 110 m above sea level near Cirencester in the West, and meanders eastward through Oxford, to London before discharging to the North Sea. The Thames is the longest river in Britain with a freshwater length of 243 km with a catchment area of 15 x 10^3 km^2. River bed gradient varies between 1.4 m km^{-1} and 0.13 m km^{-1}, The Thames is small compared to other european river such as the Seine (length 780 km, catchment area 79 x 10^3 km^2), Danube (length 2850 km, catchment area 817 x 10^3 km^2) and Volga (length 3530 km, catchment area 1360 x 10^3 km^2), (Stanners & Bourdeau, 1995).

The Thames runs over limestone, clay and chalk, rendering base rich water chemistry. It is highly eutrophic for much of its length, (1993-1995 Lower Thames median values, orthophosphate 920 μg P l^{-1} and total oxidised nitrogen 7.1 mg N l^{-1}) with phosphorus and nitrogen levels ranking in the top 25% of river stations on European rivers during 1989-91 (Stanners & Bourdeau, 1995). Of the phosphorus in the lower Thames, 93% comes from sewage discharge received from the 11.5 million people living in the catchment area. Only 7% originates from non-point sources such as agriculture (Tinsley & Bennett, 1995).

The catchment area of the Thames is intensively farmed and has a high proportion of urban areas including the highest concentration of motorways in Britain, which leads to rapid run off and spatey river discharge. The Thames is a highly-changed, channelised, over deepened, intensively managed river with flows regulated by 44 lock/weir systems. Discharge varies seasonally from a maximum of 1059 m^3 s^{-1} to minimum of 0.01 m^3 s^{-1} over a 112 year period at Teddington, the tidal limit of the Thames (Environment Agency Internal Report, 1996). This leads to a seasonal imbalance in water availability for public water supply.

The Thames supplies approximately 50 % of London's water (Jordan, 1996 *pers comm.*). Thames Water Utilities Ltd. (TWUL) is the major water supply company in Thames Region. In 1991 there was an average of 9% surplus in public water supply in the Thames catchment area compared to demand, the lowest surplus in England and Wales (Environment Agency, 1994). Of the water entering the Thames catchment as rainfall, 50% is currently used for public water supply.

A water resources development strategy has been developed for England and Wales to establish whether major water resources developments are required over the next 30 years, and if so which schemes are likely to be acceptable (Environment

Agency, 1994). This predicts that there will be a shortfall in supply, compared to demand in Thames Region in 2021 (Environment Agency, 1994).

To meet the forth coming increase in demand for public water supply various schemes have been proposed. One such scheme is the construction of a reservoir in South West Oxfordshire, with a surface area of 10 km^2 and a capacity of 10^{12} L, the third largest reservoir in Britain (Thames Water Utilities Ltd., 1993). The reservoir would be an off-line pumped surface storage reservoir filled with water from the Thames in high flow conditions. The water would then be stored until high water demand conditions when it would be pumped back into the Thames. The Thames would be used as an open pipeline for transport of water to the highest demand area, London, where it would be abstracted and treated for public water supply.

A further proposal is an inter-basin water transfer from the lower River Severn to a nearby reservoir, and then transferred to the upper Thames when demand was high. The water would then travel downstream in the Thames to London, where demand was highest.

The Thames is currently a highly altered, managed and complicated river system under great anthropomorphogenic pressure. The impacts to the ecology of the Thames from schemes such as a reservoir or inter-basin transfer, are being assessed by the Environment Agency through a series of environmental impact assessments (EIA). The information from the EIA will be used to assess the advantages and disadvantages of each scheme. Abstraction and discharge consent licences for the scheme will be set by the Environment Agency in order to protect the river environment from detrimental effects of proposed schemes.

This thesis represents two years' data (1993, 1994) from an on-going study of the Thames phytoplankton and is part of the multidisciplinary environmental impact

assessment.

Phytoplankton in the Thames is the major primary producer (Kowalczewski & Lack, 1971) and is an important component of the food web (Berrie, 1972). The responses of phytoplankton abundance and species composition to discharge augmented changes in the Thames are poorly understood (Oppenheim, 1992). The aim of this thesis was to establish a phytoplankton baseline prior to augmentation schemes, and to investigate the relationship between phytoplankton and environmental factors to help make informed decisions about augmentation schemes.

1.2 Phytoplankton succession in rivers

The source of phytoplankton rivers has been a contentious issue for many years (reviewed in Hynes, 1970; Whitton, 1975; Round, 1981; Reynolds, 1988). Potential sources of suspended algae are species washed in from the benthos; stones (epilithic), mud or sand (epipelic), plants (epiphytic) and animals (epizoic) (Bold & Wynne, 1985). Planktonic algae are washed in from bays (Lauterborn, 1893), ditches (Brehm, 1911), side-arms (Fritsch, 1902, 1903), cuts, on-line lakes (Cushing, 1964). Phytoplankton in rivers are imported by downstream water transport and from areas of higher phytoplankton density growing in hydraulic in-channel aggregated dead-zones (Young & Wallis, 1987) or otherwise known as in-stream storage zones (Reynolds *et al.*, 1991). Each of these algal sources may contribute to the algae in suspension in the Thames depending on the spatial, seasonal, physical, chemical and biological status of the river. Hynes (1970) points out that physically different types of river or stream contain varying contributions of algae in the water column from these different sources.

Large lowland river phytoplankton abundance, species composition and succession

is of interest in the current study, so discussion will be restricted to this 'type' of environment.

The environmental conditions in large lowland rivers are highly selective. In order for phytoplankton species to survive and reproduce in the downstream transport, turbid, turbulent conditions of a river they have to meet certain criteria; reproduce quickly, remain in suspension and be efficient at light-harvesting. Such specialized conditions lead to the relatively few dominant algae in river systems compared to lake systems (Reynolds, 1994). Commoner river phytoplankton genera are seen in numerous river studies (reviewed in Reynolds, 1994). The common river phytoplankton are centric diatoms, including *Cyclotella* and *Stephanodiscus*; pennate diatoms, including *Navicula*, *Nitzschia* and *Synedra*; green algae of the order Chlorococcales (e.g. *Ankistrodesmus*, *Chlorella*, *Crucigenia*, *Dactylococcus*, *Golenkinia*, *Pediastrum*, *Scenedesmus* and *Tetraedron*); Cryptomonads; occasionally filamentous Cyanophyta (*Oscillatoria*, *Pseudanabaena*) (Reynolds, 1994). In fact one lowland river phytoplankton species composition is very much like another.

There is a tendency for green chlorococcalean algae to be more numerous in the upper or middle reaches of the river, and centric diatoms often dominate further downstream. The division between these tendencies moves up and down the river depending on discharge. During declining flows the chlorococcalean dominated flora moves downstream, whereas during elevated, but not peak, discharge it move upstream (Reynolds & Glaister, 1993).

In the River Danube however, most of the Chlorococcalean green species were recruited from the channel bed into the plankton (Stoyneva, 1994). Reynolds & Descy (1996) conclude that most species of 'true' phytoplankton or potamoplankton, are meroplanktonic. This means they have part of their life cycle as a resting spore

in the bottom sediments (e.g. *Aulacoseira/ Stephanodiscus*) or grow on benthic macrophytes before being recruited into the phytoplankton (chlorococcalean species).

Billen *et al.*, (1994) suggest a slightly different source. They suggest that a large element of the phytoplankton in rivers (they worked on the Seine) are tychoplanktonic, and normally grow on the benthos, such as sediments or macrophytes, and are temporarily recruited into the plankton. These are both mechanisms to prevent total "wash-out" of a species during high discharge and to enable fast colonisation of the water column when the conditions are favourable.

The Thames has a documented history of a well developed phytoplankton. Centric diatoms are recorded as the dominant species in the Thames with a spring maximum during April or May of 72,000 cells ml^{-1}, of which 96% were diatoms, and a secondary, smaller peak, of 28,500 cells ml^{-1}, 88% diatoms, in autumn (Lack, 1971). Lack (1971) reviewed the qualitative phytoplankton species succession and abundance data from earlier workers on the Thames (Fritsch, 1902, 1903; Rice 1938 I & II) and compared it with his weekly studies for 1966 to 1968 at a site above the confluence with the River Kennet (very near to the Reading (152 km) sampling site in the current study!). Lack (1971) found there had been change in the dominant centric diatom species through time; Fritsch (1902, 1903) recorded *Melosira* as the dominant form, with *Stephanodiscus hantzschii* present, however Rice (1938 I & II) found an alternation in dominance between the two species. Lack (1971) and subsequent workers, Bowles & Quennell (1971), Lack *et al.*, (1978) all found *Stephanodiscus hantzschii* to be the dominant centric diatom species.

Peak abundances of pennate diatoms coincided with centric diatom peaks occurring in spring and autumn (Lack, 1969, 1971). *Nitzschia acicularis* dominated the pennate diatoms in spring, and *Synedra* ulna dominated the pennate diatoms in

autumn (Lack, 1971).

Phytoplankton abundance and centric diatom dominance decreases during summer (Fritsch, 1902, 1903; Rice I & II; Lack, 1969; Lack, 1971; Bowles & Quennell, 1971; Lack *et al*, 1978). Chlorophyta became more important during summer accounting for 30-40% and 43-51% of phytoplankton (Lack, 1969, 1971, respectively). Fritsch found the Chlorophyta genera *Closterium*, *Pediastrum* and *Scenedesmus* became common in June, whereas Rice observed their importance in May. Later workers (Lack, 1969; Lack, 1971; Bowles & Quennell, 1971) identified these genera, but only *Scenedesmus* was common. Lack (1971) also recorded *Ankistrodesmus falcatus* as a dominant Chlorophyta with *Chlamydomonas*, *Gonium*, *Pandorina*, *Pediastrum boryanum*, *Pediastrum duplex*, *Ankistrodesmus acicularis*, *Actinastrum hantzschii*, *Dictyosphaerum* sp., *Scenedesmus quadricauda* were present.

Minimum phytoplankton abundance occurs during winter, when pennate diatoms accounted for a greater proportion of the phytoplankton. Dominant species included *Cocconeis placentula*, (Rice, 1938 I & II; Lack, 1971) and *Asterionella gracillima* (Fritsch, 1902, 1903; Rice, 1938 I & II). Lack (1971) and later workers (Bowles & Quennel, 1971) did not find the characteristic appearance of *Asterionella* in winter found by previous workers Fritsch and Rice.

Lack (1971) observed that *Cryptomonas* spp. and *Rhodomonas minuta* periodically became common, reaching a maximum of 870 cells ml-1 (45% of total) in September 1967.

Other phytoplankton taxonomic groups, (Cryptophyta, Chrysophyta, Cyanophyta), were present in the Thames in small numbers periodically throughout the year (Lack, 1971).

Macro and micro benthic algal populations in the Thames vary spatially and

seasonally (John & Moore, 1985 I & II). The Thames upstream of the limit of navigation, by motorised boats, has a more developed submerged and floating leaved flora, with distinct seasonal succession, whereas the navigable river has a suppressed macrophyte flora due to mechanical damage to the plants by propellers and boat wash (John & Moore, 1985 I). Benthic micro algae are dominated by diatoms (*Cocconeis placentula*) and green algae (*Stigeoclonium* and *Protoderma* assemblage) (John & Moore, 1985 II). Most species of benthic micro algae grew regardless of the time of year, but were most abundant during May and June, and again during autumn and early winter (John & Moore, 1985 II). Certain common species were more numerous in early autumn to early winter which suggest that conditions were more suitable for growth of the benthos and settlement of phytoplankton from the water column. Reproductive cells (flagellated swarmers, resting spores, vegetative propagules) were especially numerous during this period. These temporary benthic micro-algae may act as overwintering stores of resting phytoplankton species and an inocula for the water column in favourable conditions in spring.

1.3 Factors affecting phytoplankton periodicity in rivers

The characteristics of the River Thames and its catchment area are fully described in Chapter two. It is, however, useful to consider that the Thames has been altered from its natural condition by man, to meet the needs of the human population through history.

Anthropomorphogenic and environmental effects will be discussed in the following sections in terms of their physical and seasonal, chemical and biological effects on phytoplankton abundance and species composition in the Thames and other lowland

rivers.

1.3.1 Physical factors and phytoplankton seasonality

The geology of the Thames catchment is limestone, clay and chalk making the Thames base rich. The Thames is a lowland river which falls 110 m over its meandering 243 km freshwater length. The slope of the river bed varies between 1.4 m km^{-1} in the upper reaches to 0.13 m km^{-1} in the lower Thames (Outhwaite, 1996 *pers. comm.*) which is relatively flat when compared to the gradient of the upper R. Severn 50 m km^{-1} and lower Severn 0.27 m km^{-1} (Reynolds & Glaister, 1993).

The Thames runs from west to east and experiences similar seasonal weather changes along its length. June (summer) experiences long days (17 h d^{-1} daylight), long periods of sunlight (June 30 year mean total sunshine 203 h, Mortimer), high air temperature (30 year mean 14.6 °C) and low rainfall (June 30 year mean total rainfall 52 mm). December (winter) experiences short days (8 h d^{-1} daylight), short periods of sunlight (December 30 year mean total daylight 44 h), lower air temperatures (December 30 year mean 4.4 °C) and higher rainfall (December 30 year mean total rainfall 68 mm)(Burt, 1995). In response to these seasonal weather changes the water temperature changes, as does the discharge of the Thames which ranged from a winter maximum of 1059 $m^3 s^{-1}$ to summer minimum of 0.01 $m^3 s^{-1}$ over a 112 year period at the tidal limit of the Thames (Environment Agency Internal Report, 1996). Time of travel for water passage down the Thames varies with discharge from 0.16 km h^{-1} at low discharge (discharge at Teddington Weir 14.2 $m^3 s^{-1}$) to 0.98 km h^{-1} when discharge is high (discharge at Teddington Weir is 142 $m^3 s^{-1}$), (Thames Water Authority, 1973).

Seasonal changes coincide with changing phytoplankton abundance and species composition (Fritsch 1902, 1903; Rice 1938 I, II; Lack, 1969, 1971; Lack, Youngman, Collingwood, 1978; Kowalczewski & Lack, 1971; Evans, 1971; Bowles & Quennell, 1971). During spring this occurs simultaneously and similarly, but with increasing abundance at sites down the Thames (Lack *et al.*, 1978). Phytoplankton abundance maxima in the Thames occurs during spring (April/May) and is dominated by the centric diatom *Stephanodiscus hantzschii* (Lack, 1969, 1971; Lack *et al.*, 1978). Phytoplankton abundance decreases throughout the summer, when Chlorophyta are most abundant, to minimum levels during winter (Lack, 1969, 1971). A secondary peak in *S. hantzschii* in autumn has been noted by Lack, 1969, 1971; Lack *et al.*, 1978; Kowalczewski & Lack, 1971; Evans, 1971; Bowles & Quennell, 1971.

A similar pattern of changing phytoplankton abundance with season and distance downstream has been noted in other lowland rivers: River Severn (Swale, 1969; Reynolds & Glaister, 1993), Rivers Stour and Lee (Swale, 1962, 1964 respectively), Sacramento River (Greenberg, 1964), many of the 18 British rivers surveyed in 1990/1 (Reynolds & Glaister, 1992), the Rhine (Ruyter van Steveninck *et al.*, 1992; Tubbing *et al.*, 1994).

An inverse relationship between phytoplankton density and discharge has been observed in the Thames (Lack 1969, 1971; Lack *et al.*, 1978; Kowalczewski & Lack, 1971; Bowles & Quennell, 1971) and other lowland rivers (Swale, 1964). High discharge causes "wash-out" of phytoplankton when downstream transport is greater than replication rate of the phytoplankton, thus diluting the phytoplankton. In the Thames a discharge of 40 $m^3 s^{-1}$ coincides with a decrease in phytoplankton (Lack, 1971), while discharges of 20 $m^3 s^{-1}$ and 22.9 $m^3 s^{-1}$ coincide with the spring

phytoplankton maximum (Bowles & Quennell, 1971; Lack *et al.*, 1978, respectively). Lack *et al.*, (1978) showed that the decline in phytoplankton associated with increased discharge occurred simultaneously at six sites over 21 km of the Thames and therefore the critical discharge value to cause a decline in phytoplankton must increase downstream.

This relationship was not true on all occasions in the Thames. Lack (1969) occasionally found that increased discharge was associated with increased algal abundance. He proposed that this was due benthic algae being washed into the over lying water column (Lack, 1969, 1971). This effect was also noted in the River Kennet (Lack, 1971).

Discharge is the rate of a quantity of water moving downstream past a specific point. Phytoplankton abundance and species composition is also affected by water velocity or time of travel of a parcel of water downstream between two points. This is a function of discharge, the angle of the river bed, bed roughness, channel cross-section, water viscosity, obstructions, near-bank eddies and retentive storage areas (Reynolds, 1992).

Phytoplankton abundance in lowland rivers usually increases downstream, however the number of cell replications needed to account for the increase in abundance during downstream transport is too great to have occurred in the time of travel of the water parcel. This paradox was highlighted by Reynolds (1988) and has also been noted in the Thames (Bowles & Quennell, 1971; Lack *et al.*, 1978). Young and Wallis (1987) promoted the aggregated dead-zone model which shows that rivers do not discharge water efficiently or uniformly. They showed that water is delayed or stored by a variety of in-stream structures, friction boundary layers, bed roughness, obstructions and near-bank eddies. Reynolds (1994) found that 6-18% of the area of

a reach of the River Severn was an in channel storage zone or deadzone. Within the storage zone abundances of phytoplankton were elevated. Fluid exchange between the river and the storage zone would have the effect of lengthening the river and increasing the amount of time available for cell replication. This helps to explain the paradox of elevated phytoplankton abundance downstream.

The discharge of the Thames is regulated, within the constraints of the seasonal weather changes, by 44 locks/weir systems which allow navigation by motorised boats between Cricklade and Teddington. The water level in each stretch of water between locks is manually regulated to a constant depth by opening and closing weir gates to maintain sufficient water depth for navigation, while preventing flooding and maintaining high levels of the valuable water resource for abstraction and public water supply. This creates an artificial river system where there are stretches of relatively smooth moving water in between locks punctuated by water falls over the weirs and zones of mixing below the weirs. This pattern becomes more un-natural in low flows during summer when the water in between the locks becomes almost static and lake-like but is periodically interrupted by weirs during downstream transport. It is not known whether the water held back by the locks act as a storage zone where phytoplankton abundance is elevated, though this does seem likely, especially during low flows when few gates of the weirs are open. The effects on phytoplankton of travelling over a weir unknown in the Thames.

Discharge patterns in the Thames are further complicated by heavy water abstraction in certain reaches for public, agricultural and industrial consumption. The majority of the abstraction occurs in the lower Thames for supply to London. This, and abstraction from ground water unevenly reduces discharge in the Thames.

Increased discharge in lowland rivers causes an increase in turbidity and thus

decreases the light transmittance through the water column which has a confounding effect on the "wash-out" of phytoplankton (Reynolds, 1988). The effect of increased discharge varies depending on the river bed angle, substrate and river cross-section. Increased discharge in a river with a steep sloping bed will cause an increase in water velocity, whereas a similar increase in discharge on a shallow angle of river bed tends tolead to an increase in water depth with a slight increase in velocity (Reynolds & Glaister, 1993). The Thames falls into the second category, as the gradient of the bed of the Thames is small and does not vary dramatically between headwaters and lower reaches (1.4 m km^{-1} and 0.13 m km^{-1}, respectively) (Outhwaite, 1996). High discharge raises the water level of the Thames by almost 1 m from its mean level. Fritsch (1903) observed an increase in water depth and velocity after rainfall caused a change in phytoplankton species composition.

Rivers are turbulent environments, and phytoplankton in suspension within the turbulent flow are moved up and down erratically through different light climates. Phytoplankton must be able to harvest light efficiently while periodically in the photic zone. To do this the alga must position its photosynthetic pigment to maximise the amount of light absorbed in a number of ways. Theoretically the best cell shapes for light absorbency and harvesting are small cells, flat discs, plates, needles and threads when correctly oriented (Reynolds, 1994). A further advantage is more photosynthetic pigment per cell and accessory pigments such as anthophylls in diatoms which absorb light from other parts of the spectrum (Reynolds, 1994). Fast cell replication is essential in moving water and a high surface area to volume ratio is beneficial. Synechococcoid picoplankton, nanoplanktonic flagellates, unicells and certain diatoms have optimal division rates in excess of one division per day, which gives them the advantage in rivers over the slower growing, larger species

(Reynolds, 1994).

Turbulent flow mixes the water column keeping phytoplankton in suspension. The turbulence of the water column changes at different discharges, water depths, bed roughness, channel form, channel sinuosity and obstacles in the river (Reynolds, 1994). The greater the turbulence the greater the size of particle that can be suspended in the water column. The Thames has been shown to be well mixed (Kowalczewski & Lack, 1971) which imply it is a turbulent system. To survive, phytoplankton need to remain in suspension to have access to the photic zone, thus the degree or strength of the turbulence will select phytoplankton species, and other particulate material, of a certain suspendibility. Different species have different settling rates, for example a diatom has a settling rate of about 3 $\mu m\ s^{-1}$ which requires more turbulent energy to remain in suspension than *Chlorella* which settles at about 0.3 $\mu m\ s^{-1}$ (Reynolds, 1994). Turbulence level selects species composition and abundance.

In lakes the rapid decrease in spring of diatom populations is, in part, due to the abrupt decline of turbulence and the simultaneous increase in the sinking velocities of the diatoms due to photoinhibition (Reynolds *et al.*, 1982; Reynolds, 1993; Neale *et al.*, 1991). A similar mechanism may be partially responsible for the rapid decline of the spring centric diatom maxima in lowland rivers which occurs during declining discharge and turbulence. Reynolds (1994) showed that there is a critical water depth between 1 and 3 m when turbulence declines and the heavier algae, especially diatoms with their high settling rate and non-motile status, experience accelerated sinking rates. This can be compounded by the physiological condition of the alga and the water temperature (Reynolds, 1994). When this occurs the loss rate through sinking cannot be balanced by cell division (Reynolds & Wiseman, 1982). The

Thames is dredged to a minimum of 2 m deep, for boat traffic, and has an average depth of 3 - 4.5 m with a maximum of 10.5 m (Waters, 1996 *pers. comm.*). Water depth varies by plus or minus 0.5 m under different discharge conditions (Waters, 1996 *pers. comm.*). Reduced discharge and turbulence enhances sinking of centric diatoms to a critical depth below which photosynthesis cannot keep pace with respiration. Garnier *et al.*, (1995) showed that the fate of most of the spring diatom productivity was sedimentation not downstream export, and sedimentation was less important phytoplanktonic loss factor in summer than spring. In less turbulent, low discharge conditions species with slower sinking rates, such as *Chlorella*, are favoured because they can remain in suspension in the photic zone. This may be a factor contributing to Chlorophyta being the dominant phytoplankton during summer low discharge conditions. Motile phytoplankton species are also favoured in these conditions because they can regulate their position in the water column to some extent and remain in the photic zone. Motile cryptophyceans, *Cryptomonas* and *Rhodomonas* were sometimes numerous in the Thames in summer, when discharge was low (Lack, 1971).

Availability of light for photosynthesis by phytoplankton is a product of day length. The Thames is exposed to seasonally varied day length from 18 hours daylight in June to eight hours in December. Phytoplankton abundance and species composition in the Thames seems to respond to the varying day length and light availability. In the Thames the lowest light intensities and shortest day lengths were associated with minimum phytoplankton abundance and the converse was true for high light intensities and long day length. It is difficult to separate the effects of day length from temperature (Rice, 1938; Lack, 1971; Kowalczewski & Lack, 1971). Phytoplankton models for the Thames used solar radiation as an important variable in

predicting phytoplankton growth (Whitehead & Williams, 1984; Whitehead & Hornberger, 1984). Lack (1971), Kowalczewski & Lack (1971), Whitehead & Williams (1984) and Whitehead & Hornberger (1984) believed that self-shading by the phytoplankton may be a limiting factor. Kowalczewski & Lack (1971) showed in the Thames that the highest percentage of light reaching the river bed compared to the water surface was 12 %, and generally 60 % of surface light was absorbed in the first 1 m depth of water and positive net production was restricted to the top 50 cm of the water column due to light being limiting caused by dense phytoplankton. Summer benthic algal growth is restricted to a 50 cm zone from the waters surface, by light limitation (John & Moore, 1985 II). Whether the increased turbidity and reduced light available to phytoplankton are due to suspended inert material, tripton, washed into the water column by high discharge, or dense phytoplankton, the algal species that can survive and reproduce in these conditions will have to be specialised. Turbid, turbulent conditions favour diatoms which have a high surface/volume ratio and are adaptable to low light conditions (Reynolds, 1994). Harvesting the available light efficiently means they can out compete species that need more light. Swale (1963) showed that light intensity during spring was more than enough for *S. hantzschii* to increase, even at low temperatures. Billen *et al.*, (1994) believe that water temperature is the primary control of algal growth and photosynthesis, and not light intensity. An optimum temperature for growth of diatoms (21°C) and green algae (37°C) has been incorporated into a phytoplankton model, RIVERSTRAHLER, for the River Seine network (Garnier *et al.*, 1995).

The physical environment is impacted by the 31,000 motorised boats registered on the Thames. Between 893,940 and 757,470 boats per year passed through locks between 1989 and 1995; this caused the locks to be filled and unfilled between

394,905 and 356,403 times per year between 1989 and 1995 (Environment Agency, 1996). The boat traffic is allowed to travel at a maximum of 8 km h^{-1}. This, and lock use, stirs up sediment mixing it in the water column increasing turbidity and decreasing light penetration through the water column. Macrophytes are physically damaged by boat wash and propellers (George, 1976), which reduce the stability of the river bed, reduce zones of refuge for plankton and compound the high turbidity conditions.

The navigable Thames, which includes phytoplankton sampling sites at Windsor (203 km), Reading (152 km) and Abingdon (101 km), has few macrophytes especially floating leaved species (John & Moore, 1985 I). The fourth phytoplankton sampling site, Inglesham (35 km), is located upstream of the river naviable by motorised boats, but is used by rowing boats and canoes. It has a well developed submerged and floating leaved macrophyte flora, which show seasonal variation (John & Moore, 1985 I).

The bed of the Thames is periodically dredged to remove sediment build ups which interfere with navigation and slow water passage in high flow conditions contributing to burst banks and flooding. This process also removes rooted plants, introduces sediment into the water column and alters the natural flow patterns.

1.3.2 Chemical factors and phytoplankton seasonality

The catchment area for the River Thames supports agriculture, industry and is highly urbanised, supporting 11.5 million people, most of which are concentrated in London around the lower Thames. Effluent from sewage treatment works, industrial and agricultural processes, and urban run-off either discharge directly to the Thames, or indirectly via tributaries. This affects water quality in many ways including

causing high concentrations of nitrogen and phosphorus, important algal nutrients, and increased particulate material. Concentrations of phosphorus and nitrogen vary seasonally in response to river discharge. Phosphorus concentrations increase as dilution from river discharge decreases. Maximum phosphate concentrations during this study (maximum 2.6 mg l^{-1}) and minimum nitrate concentrations (5.7 mg l^{-1}) occurred during July, August and September. Phosphate concentrations were lowest (0.35 mg L^{-1}) and nitrate concentrations highest (11 mg L^{-1}) during high flows (December, January, February).

Phosphate and nitrate concentrations in the Thames were always in excess of phytoplankton requirements, and thus not algal limiting (Lack, 1971; Bowles & Quennell, 1971; Lack *et al.*, 1978). Orthophosphate concentrations in the Thames at Farmoor 1968 varied between 1.68 - 0.26 mg l^{-1} and nitrate concentrations varied between 9.8 - 3.4 mg l^{-1} (Lack, 1971).

A similar situation exists, where nitrogen and phosphorus did not reach limiting concentrations, in the River Rhine (Ruyter van Steveinck *et al.*, 1992). There was no correlation between phosphate concentrations and chlorophyll *a* in the River Rhine (Tubbing *et al.*, 1994). In the River Seine however, there was good agreement between algal growth and nutrient concentrations in spring, a period of maximal phytoplankton abundance, but not summer, a period of decreasing phytoplankton abundance (Billen *et al.*, 1994).

Nutrient concentrations (phosphorus and nitrogen) in the Thames are higher than many other european large rivers, for example maximum phosphate and nitrate concentrations at the mouth of the Seine were less half and one third the maximum concentrations recorded in the lower Thames, respectively (Garnier *et al.*, 1995).

Silica concentrations are related to phytoplankton abundance in the Thames.

There is an inverse relationship between phytoplankton abundance and silica concentration (Lack, 1969, 1971; Lack *et al.*, 1978; Bowles & Quennell, 1971). Peak abundance of centric diatoms coincides with minimum concentrations of silica (Lack, 1971; Lack *et al.*,1978; Bowles & Quennell, 1971). When the centric diatom abundance decreased, the concentrations of silica increased (Bowles & Quennell, 1971). Minimum silica concentrations in the Thames were not limiting for diatom growth, and did not cause the characteristic decrease in centric diatom abundance that marks the end of the spring phytoplankton bloom (Lack *et al.*, 1978). Swale (1963) calculated that 1 X 10^6 cells of the dominant centric diatom in the Thames, *Stephanodiscus hantzschii* required approximately 40 μg Si to survive.

Bowles & Quennell (1971) measured silica concentrations and phytoplankton abundance in the Thames and tributaries Colne and Wey. They showed that the tributaries were loading the Thames with silica during spring which, they suggested, may lengthen the centric diatom bloom in the Thames.

The inverse relationship between centric diatom abundance and silica has been shown in other lowland rivers such as the Lee and Essex Stour (Swale, 1964), Severn (Swale, 1969) and Rhine (Ruyter van Steveninck *et al.*, 1992).

1.3.3 Biological factors and phytoplankton periodicity

Periodic dredging, boat propeller and wash damage all contribute to the reduced macrophyte cover, instability of the bed of the Thames and turbid environment of the water column causing domination of phytoplankton over rooted macrophytes.

The importance of zooplankton in controlling phytoplankton abundance and species composition in the Thames has not been assessed. The Thames is a cyprinid fishery and some species and age groups of fish graze on zooplankton, controlling their

abundance and decreasing the zooplankton control over phytoplankton numbers through grazing.

Zooplankton peak abundances in the Rhine coincide with the decline in phytoplankton abundance in May, indicating that zooplankton grazing decreases phytoplankton abundance. The abundance of zooplankton in the Rhine is possibly affected by other biological mechanisms such as seasonal hatchings of predatory juvenile fish and benthic invertebrates (Ruyter van Steveninck *et al.*, 1992) and filter feeding benthic Zebra mussels (Swale, 1969).

Zooplankton with fast generation times, such as rotifers and ciliated protozoans, are effective grazers as they can react quickly to increases in phytoplankton in a predator prey manner. The zooplankton in the Seine and tributaries Oise and Marne are dominated by short generation time species which increase in density with increasing stream order, peak abundances occur in May and June (Billen *et al.*, 1994). Garner *et al.*, (1995) found the zooplankton grazing rate was similar for Chlorophyta and diatoms, the zooplankton were not selective in there choice of phytoplankton.

A further biological control of phytoplankton abundance is lysis by fungal, bacterial or viral parasitism. Billen *et al.*, (1994) showed that this type of control mechanism may be more important at high phytoplankton abundances and they quote a critical point of greater than 175 $\mu g\ l^{-1}$ chlorophyll *a* where a tenfold increase in phytoplankton mortality occurs. Garnier *et al.*, (1995) place the critical point at 65 $\mu g\ l^{-1}$ chlorophyll *a* where a twenty-fold increase in mortality, compared to the pre-critical chlorophyll *a* concentrations, occurs. The same critical point was assumed for diatoms and Chlorophyta.

Garnier *et al.*, (1995) tested the effect of zooplankton grazing and lysis of

phytoplankton by excluding the effects of these factors from the RIVERSTRAHLER phytoplankton model for the Seine network. The simulation showed that phytoplankton abundance would increase further after the spring bloom, showing that grazing and lysis reduce phytoplankton abundance.

1.4 Effects of river management

The Thames is a highly managed river system. Its physical structure has been modified for navigation by straightening, channelisation, dredging, bank modifications, locks and weirs. The Thames flood plains have been extensively urbanised, flood relief schemes control flood water, allowing flooding to occur in the least damaging locations.

Surface run-off from agriculture and urban areas, plus effluent from sewage treatment works and other industrial effluent, discharge to the Thames loading the river with chemicals, including the plant nutrients phosphorus and nitrogen.

The river is a major source of water for public and industrial supply. Abstraction is highest in the lower Thames, due to the large demand from London. The abstraction causes a decrease in discharge. Abstraction in the Thames is controlled by a consent that a minimum discharge must remain at the limit of the freshwater river (Teddington Weir). This was set to safeguard the health of the freshwater Thames and prevent a saline intrusion from moving further upstream in the estuarine Thames. This limits abstraction from the Thames during low flow periods, which are usually the periods of greatest demand.

A water supply shortfall of between five and 629 ML/d has been forecast for the Thames catchment for the year 2021 (National Rivers Authority, 1994). The discharge in the Thames will not be sufficient to meet the increased demand.

Schemes have been proposed to meet the forthcoming demand which involve augmenting discharge in the Thames during low flow periods so that abstraction in the lower Thames can continue all year.

Discharge in the Thames may be augmented by an inter-basin water transfer from the lower River Severn to the upper Thames or a proposed off-line surface storage reservoir in South West Oxfordshire filled from abstractions from the Thames during high flows. The schemes may be used singly or in conjunction.

It is important to understand the ecological, physical and chemical implications to the Thames from these proposed schemes and different management scenarios. The Environment Agency needs to know the implications of different schemes to set abstraction and discharge consents for their operation to be most beneficial, or least detrimental, to the river ecology, while still delivering the increased discharge to the lower Thames to meet the increased water demand forecasted for the London area. Demands of the water systems for supply are frequently in direct contrast to the requirements of the environment in terms of both volumes and timings of flows (McMahon & Finlayson, 1995).

The major factors in the Thames that would be altered by discharge augmentation from a reservoir or inter-basin transfer need to be assessed and the likely ecological implications determined. The effects can be split into physical, chemical and biological, however the complexity of river systems is such that it is difficult to clearly chart the impacts of future river regulation.

River regulation could alter the 'natural' seasonal hydrological variability of discharge by removing the extremes of discharge by decreasing the peaks through abstractions, and the troughs by augmentation. This can alter the river channel cross-section by evening out formerly complex cross-section with in-channel benches

representing different modes of flow regime as occurred in the River Murray following discharge regulation (Maheshwari *et al.*, 1995). River regulation, abstraction and augmentation, can alter the river channel substrate by removing fine gravels under augmented discharge (Mawdsley, 1995). Abstraction to fill a reservoir will reduce discharge during peak flows and so prevent large bed material from being disturbed, therefore clogging up the bed leading to problems with spawning, salmonoid egg development and benthic fauna (Mawdsley, 1995). This effect would be undesirable in the Thames, especially in view that the Environment Agency are rehabilitating the Thames to support a Salmonoid fishery.

In the upper Mississippi River during a year of low rainfall and discharge, discharge was augmented resulting in stable water conditions and resulted in the sediment load being reduced and water clarity increasing. This led to an increase in submerged rooted plants at the channel edges and backwaters (Theilling *et al.*, 1996). When rainfall and discharge returned to being moderately high the suspended sediment increased, water clarity decreased and rooted macrophytes were again limited.

Increased discharge causes increased water velocity. An experimental water release from the Seine reservoir (30 $m^3 s^{-1}$) to the Seine (4 $m^3 s^{-1}$ pre-reservoir discharge) increased the transport speed of the water (Barillier *et al.*, 1993). The effects of the release were monitored 64 km downstream. Augmentation can cause an increase in river depth. The experimental release from the Seine Reservoir caused the water level in the River Seine to rise by 125-190 cm which washed plankton from backwaters and sidearms into the main river and resuspended sediment (Barillier *et al.*, 1993).

The thermal behaviour of a large water mass such as a reservoir will be quite

different to that of a river (Ridley & Steel, 1975). The temperature of the augmentation water depends on the depth at which water is drawn off the reservoir, and the depth of the reservoir. In temperate regions in the autumn the reservoir water is likely to be warmer than the river, and augmentation will therefore prolong the warm temperature of the river water (Ridley & Steel, 1975). River discharge augmentation by a reservoir will therefore cause the river water temperature regime to be more even. In deep reservoirs the water becomes thermally stratified, and discharges from deep draw offs may greatly alter the thermal nature of a receiving river (Ridley & Steel, 1975; Mawdsley, 1995). A release of reservoir water 3 °C warmer than the Murray was monitored 30 km downstream of the discharge (raised temperature by 1 - 1.5 °C), but was not noticeable by 100 km downstream (Maheshwari *et al.*, 1995).

In theory, reservoir discharges to a river in low discharge conditions should be advantageous due to dilution of pollutants in the river. In practice, effects are sometimes positive (decreased total organic carbon, decreased conductivity by dilution of pollutants) and sometimes negative (increased turbidity, increased biological oxygen demand)(Dupin *et al.*, 1987).

An experimental rapid reservoir release six times greater than the discharge in the river was made from the Seine Reservoir to the River Seine. The wave front of water forced down the river in front of the reservoir water caused a decrease in water quality by reducing dissolved oxygen from 80 % to 40 %, and resuspended sediments which increased nutrients, dissolved organic material and particulate organic material. When the reservoir water arrived, the water quality improved, the dissolved oxygen rose to 62 % saturation and nutrient concentrations decreased (Barillier *et al.*, 1993). This shows the importance of gradually changing the augmentation discharge to

retain good water quality.

The biological effects attributed to regulating discharge through discharge augmentation are largely a function of the changes in physical and chemical environment caused by the augmentation. The effect of augmented discharge on phytoplankton is not clear cut. High, rapidly added augmentation discharge from the Seine reservoir to the River Seine caused an increase in algae, predominantly periphyton, in the wave front of the water pushed ahead of the discharge water (Barillier *et al.*, 1993). Ács & Kiss (1993) found that numbers of periphytic algae increased with low discharge, and decreased with high discharge.

The removal of extreme discharge conditions through abstraction and augmentation in the River Murray system had the effect of reducing discharge variability and flora and fauna populations declined. Maheshwari *et al.*, (1995) believed this may cause the capacity for aquatic species to respond to, and recover from, extreme floods to be lost. The loss of species diversity through river regulation also occurred in the Murray-Darling river system where regulation may be responsible for the relative abundance of native and alien fish. Desynchronizing of environmental cycles and reproductive cycles of native fish is possibly due to river regulated quality and quantity changes (Gehrke *et al.*, 1995). Changes in species abundance and composition due to augmentation discharge or abstraction may affect the synchronised of interactions between different trophic levels. This could have a detrimental effect on the ecology of a river with knock on effects through the food web if the correct food is not available at the correct time.

Phytoplankton is the major primary producer in the Thames (Berrie, 1972) and its abundance and species composition changes seasonally (Lack, 1969, 1971) in response to environmental and biological controls. Phytoplankton forms an

fundamental component in the productivity of the Thames and as such must be synchronised with other members of the food web. River regulation by discharge augmentation from the proposed South West Oxfordshire Reservoir or Severn-Thames transfer must be developed and managed in such a way that the phytoplankton abundance and species composition is not altered to the extent that it endangers the integrity of the ecosystem.

This thesis aimed to collect information about phytoplankton dynamics in relation to environmental factors to improve the understanding of the Thames ecosystem so the biological integrity can be maintained.

1.5 Aims

The aims of the project are to :

1. Describe physical and biological features of the River Thames and its catchment area.
2. To provide baseline data on the spatial and seasonal distribution of phytoplankton density and species composition at four sites on the Thames during 1993 and 1994.
3. Statistically investigate relationships between environmental factors and phytoplankton density and species composition.
4. Highlight the significant correlations between phytoplankton periodicity and environmental factors.
5. Discuss the potential effects of river management on phytoplankton periodicity and species composition in view of correlations highlighted in this study.

Chapter 2. Description of study area and sampling sites

2.1 Location of the Thames catchment

The Thames is situated in the south of England (Fig. 2.1). It rises in the west, near to Cirencester, and meanders eastwards through Oxford, Reading and onto London and its tidal limit at Teddingdon Weir. The Thames catchment is highly urbanised, supporting 11.5 million people many of which are concentrated in the London area (Fig. 2.1).

2.2 Geology of the Thames catchment

The Thames rises on Lias clays and Cotswold Limestones, it then flows across the clays of the Oxford Vale and on to chalk of the Downs and Chiltern Hills. Next it travels across the clays and gravels of the London Basin to the estuary (Fig. 2.2).

2.3 Hydrological characteristics of the Thames

Discharge in the Thames at the sampling sites varies seasonally as shown in Figures 2.3, 2.4, 2.5 and 2.6. Discharge is highest during December, January, February and March with mean monthly discharge at Teddington Weir, the tidal limit, over the past 119 years of 101, 127, 123, 103 $m^3 s^{-1}$, respectively. The lowest mean monthly discharge occurs during June, July, August, September and October with 36.6, 23.0, 21.4, 23.1 and 38.8 $m^3 s^{-1}$, respectively, based on 119 years data at Teddington Weir.

Historically, (119 years at Teddington Weir) the gauged maximum daily mean discharge was 1059 $m^3 s^{-1}$, whereas the minimum daily mean discharge was only 0.01 $m^3 s^{-1}$ (Environment Agency Internal Report, 1996).

The Thames is punctuated by 44 lock/weir systems that regulate discharge to some

extent. The distance between the sampling sites and the upstream lock/weir is never far, except at Inglesham which is upstream of all locks. The distances of lock/weirs upstream of the sampling sites are:

Inglesham - source 35 Km upstream of sampling site

Abingdon - 4.72 Km downstream of Sandford Lock

Reading - 7.11 Km downstream of Mapledurham Lock

Windsor - 4.30 Km downstream of Bovney Lock.

The Thames is unusual because of these short stretches of ponded water interspersed with water falls over the weirs which will mix the water column.

The input discharge from tributaries of the Thames can be seen in Fig. 2.7. This also shows the consented input from sewage treatment works and abstraction consents for reservoirs and industry. When the lowest discharge in the Thames (August 1990) is viewed against the possible consent to discharge from the proposed South West Oxfordshire Reservoir (new reservoir) it can be seen that the reservoir could substantially augment discharge in the Thames and account for a larger proportion of discharge than the Thames itself (Fig. 2.7).

2.4 Water quality in the Thames

Water quality in the Thames is measured chemically and biologically by the Environment Agency. Both techniques indicate that the Thames is good to fair quality, despite the man-made impacts from sewage treatment works, industries, abstractions for water supply, dredging and navigation (Fig. 2.8 & Fig. 2.9).

Chemical quality is measured using the parameters percentage dissolved oxygen, biochemical oxygen demand and ammonia.

Biological quantification of water quality uses a macro-invertebrate scoring system

called Biological Monitoring Working Party (BMWP).

2.5 Site descriptions

2.5.1 Inglesham

Inglesham is 35 Km downstream of the source of the Thames (Fig. 2.10). It is above the limit of navigation by motor boats and as such is dredged less than the sites in the navigable stretch of the river. This site is upstream of the locks. It is approximately 6 m wide and up to 2 m deep, although more usually 1.5 m deep in the central channel. The river bed substrate is gravel and silt. During the summer and autumn there is a dense crop of rooted macrophytes.

2.5.2 Abingdon

Abingdon is 101 Km downstream of the source Thames (Fig. 2.11). It is a navigable stretch of the Thames and is periodically dredged to remove sediment build-ups which would hinder boat traffic and could slow discharge in high flows and cause flooding.

The river is approximately 10 m wide and a maximum of 3.5 m deep, with the main channel being approximately 3.2 m in depth. The river bed substrate is clean stones. There are very few rooted macrophytes, possibly due to the mechanical damage from boat traffic and dredging.

2.5.3 Reading

Reading is 152 Km downstream of the source Thames (Fig. 2.12) and is very similar to Abingdon. It is a navigable stretch of the Thames and is periodically dredged to remove sediment build-ups which would hinder boat traffic and could slow discharge in high flows and cause flooding.

The river is approximately 15 m wide and a maximum of 3.5 m deep, with the main channel being approximately 3.2 m in depth. The river bed substrate is hard with traces of chalk. There are very few rooted macrophytes, possibly due to the mechanical damage from boat traffic and dredging.

2.5.4 Windsor

Windsor is 203 Km downstream of the source Thames (Fig. 2.13) and is similar to Abingdon and Reading. It is a navigable stretch of the Thames and is periodically dredged to remove sediment build-ups which would hinder boat traffic and could slow discharge in high flows and cause flooding.

The river is approximately 20 m wide and a maximum of 3.8 m deep, with the main channel being approximately 3.2 m in depth. The river bed substrate is clean stones. There are very few rooted macrophytes, possibly due to the mechanical damage from boat traffic and dredging.

Fig. 2.1 Map of the Thames catchment in relation to England and Wales showing the River Thames and major tributaries, urban areas, sampling sites and proposed augmentation sites

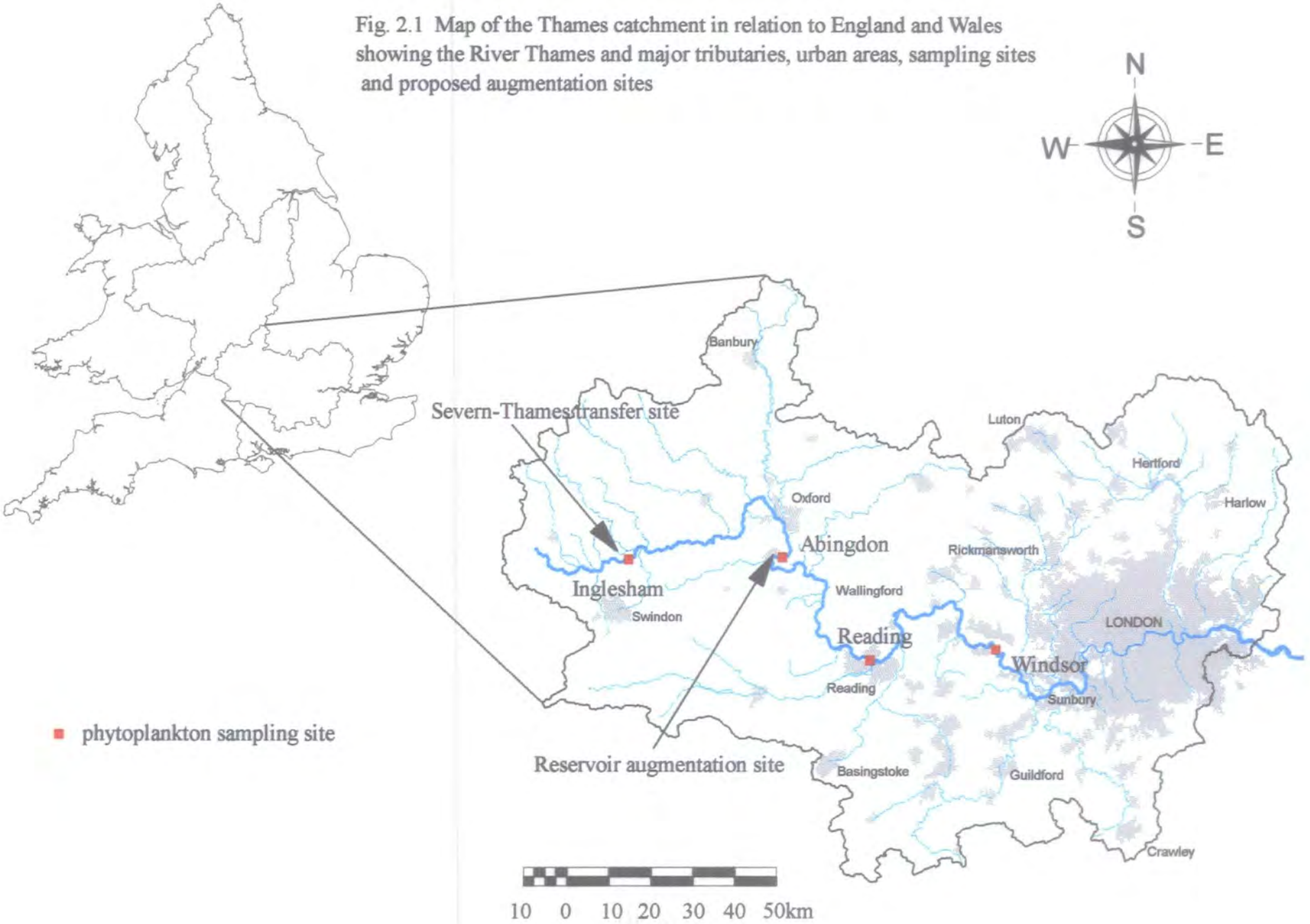


Fig. 2.2 Map of the Thames catchment showing the geology

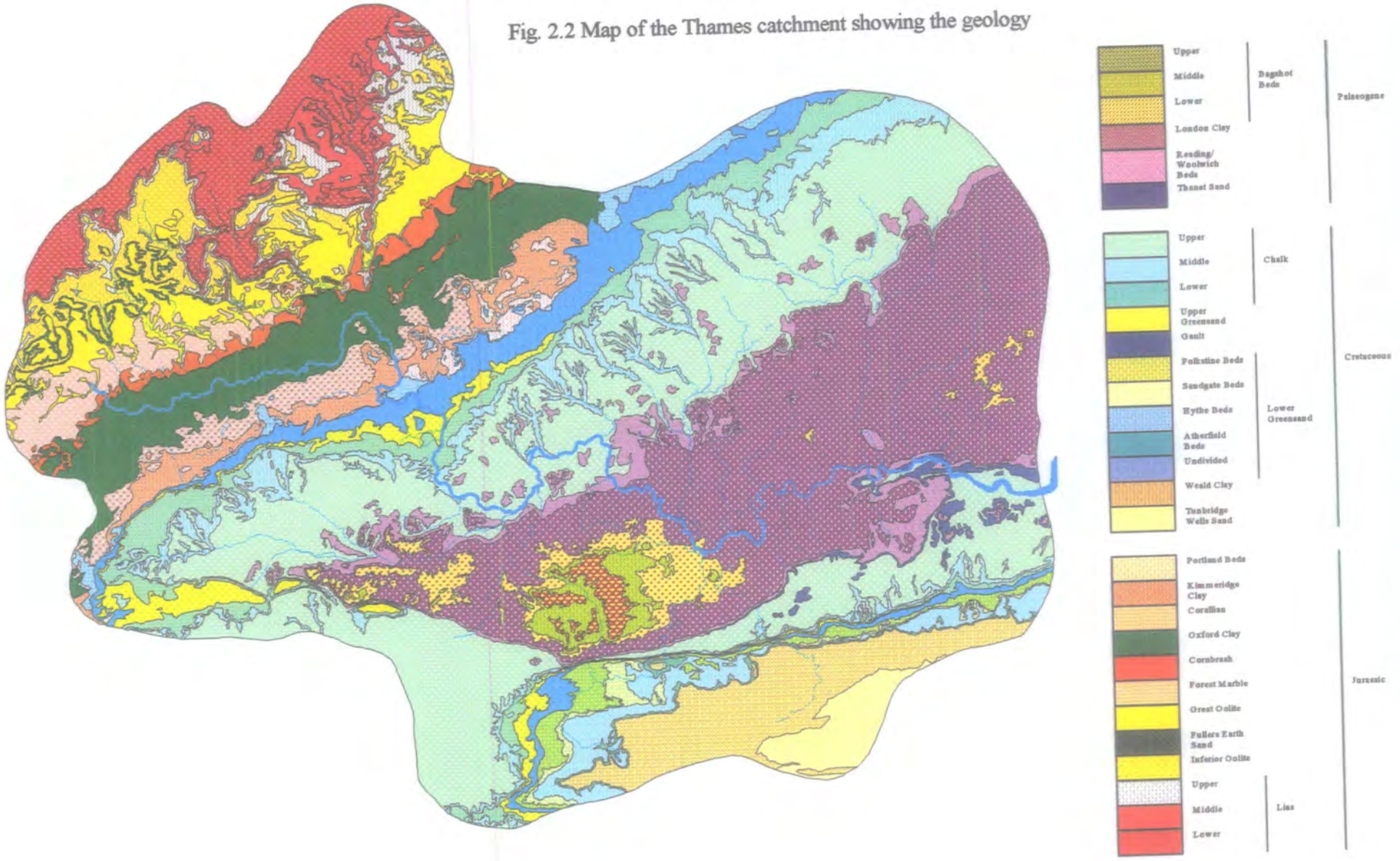


Fig. 2.3 Hydrograph of the River Thames at Cricklade, near Inglesham

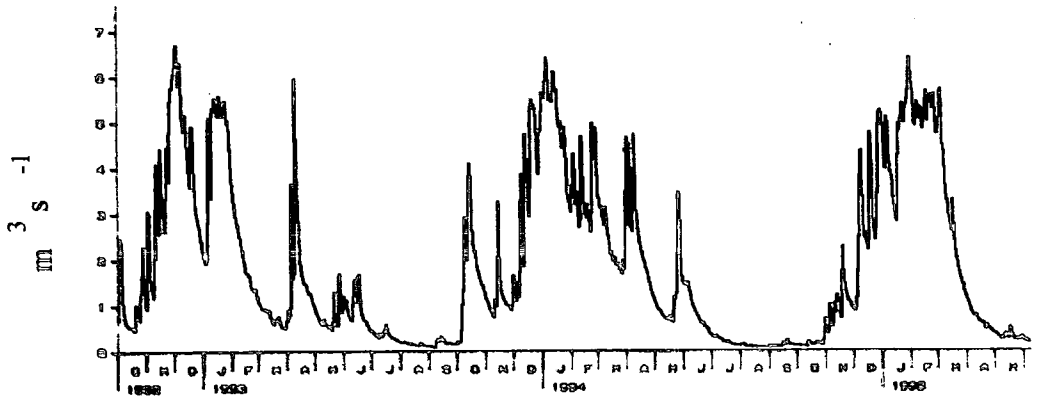


Fig. 2.4 Hydrograph of the River Thames at Day's Lock, near Abingdon

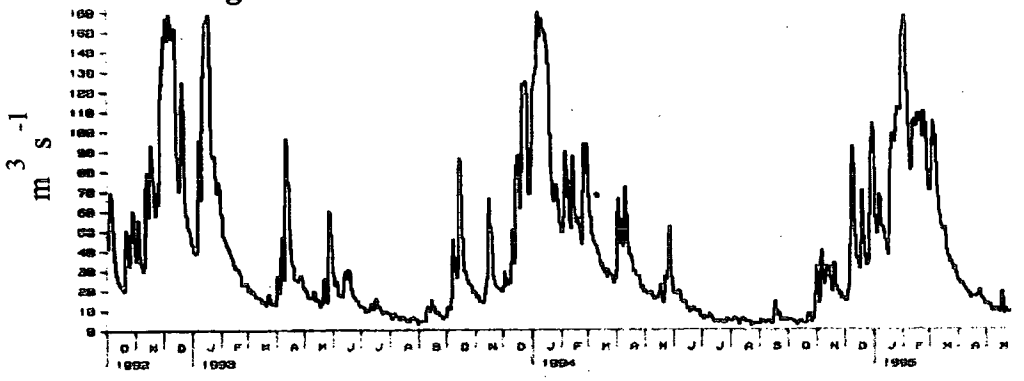


Fig. 2.5 Hydrograph of the River Thames at Reading

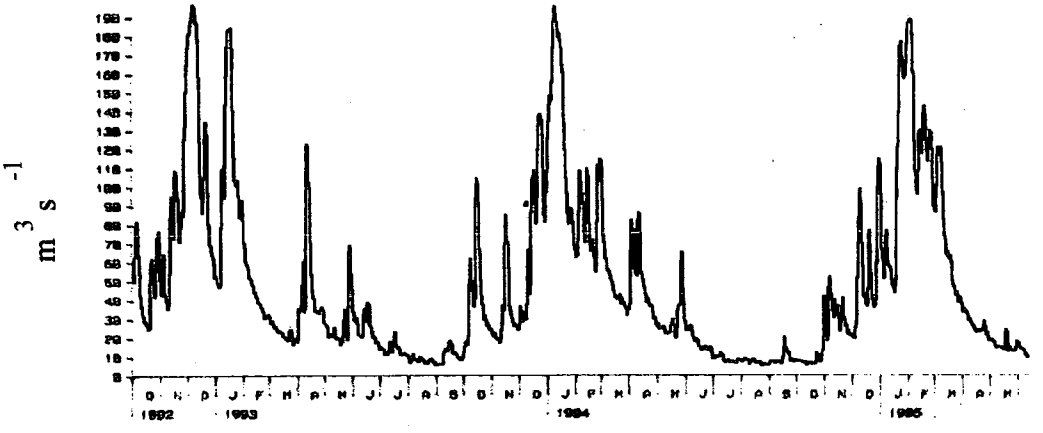


Fig. 2.6 Hydrograph of the River Thames at Windsor

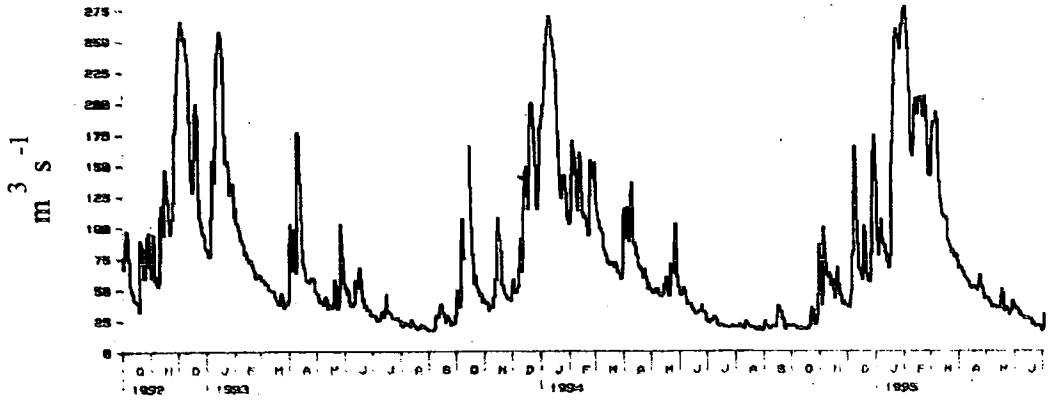


Fig. 2.7 River Thames from source to Teddington Weir showing discharge from tributaries, effluent and abstraction consent in relation to the lowest mean monthly discharge.

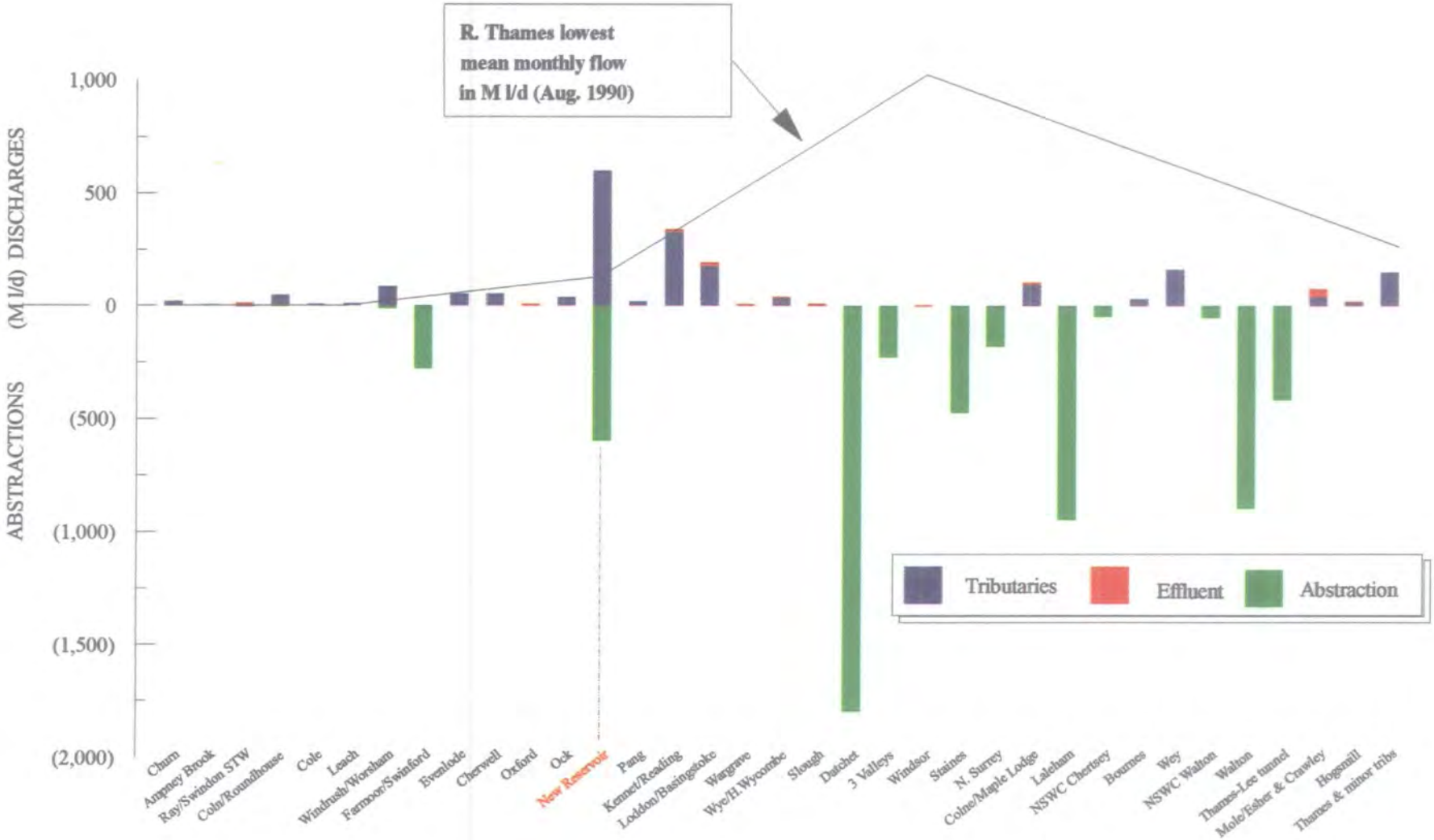
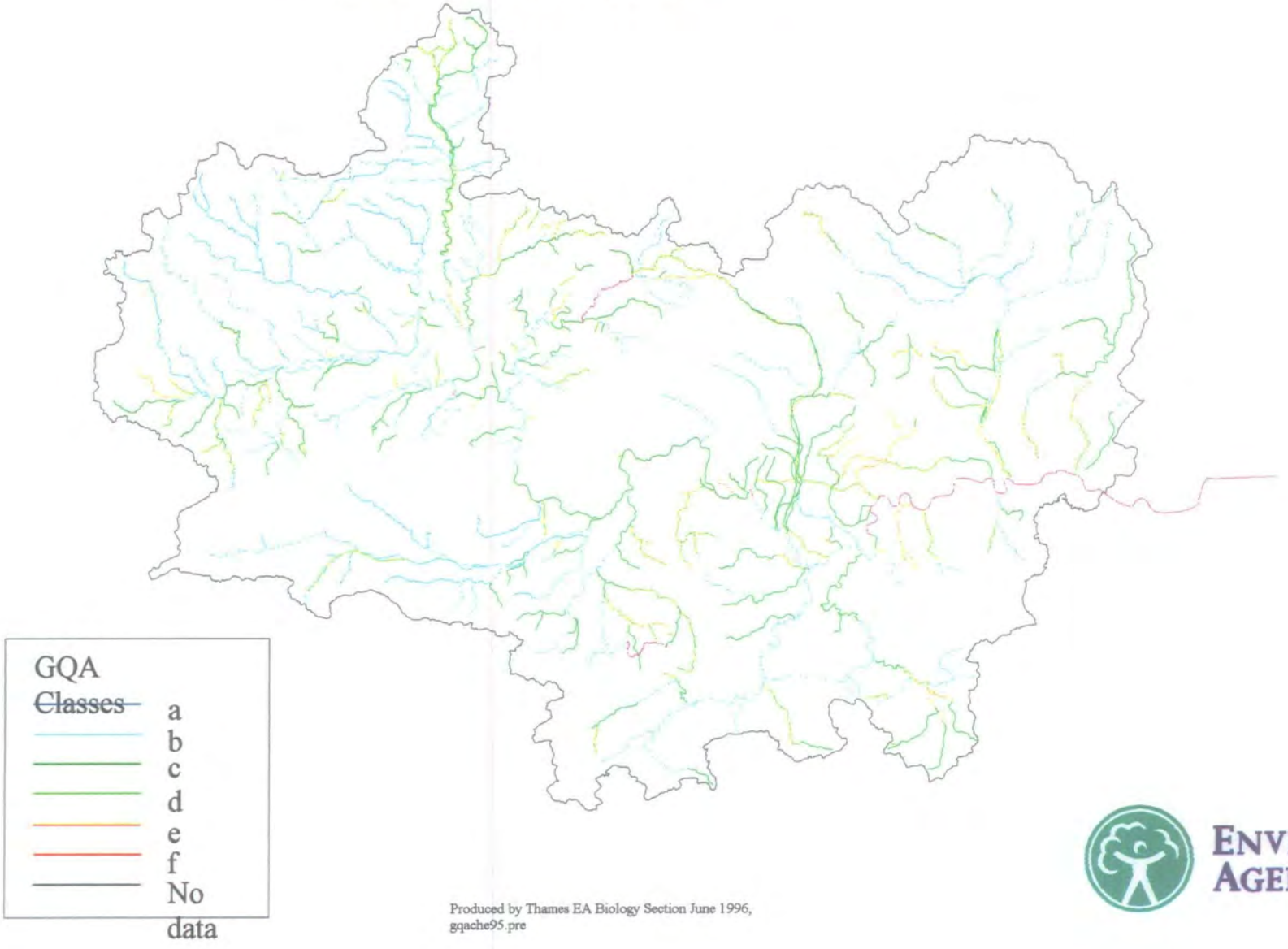


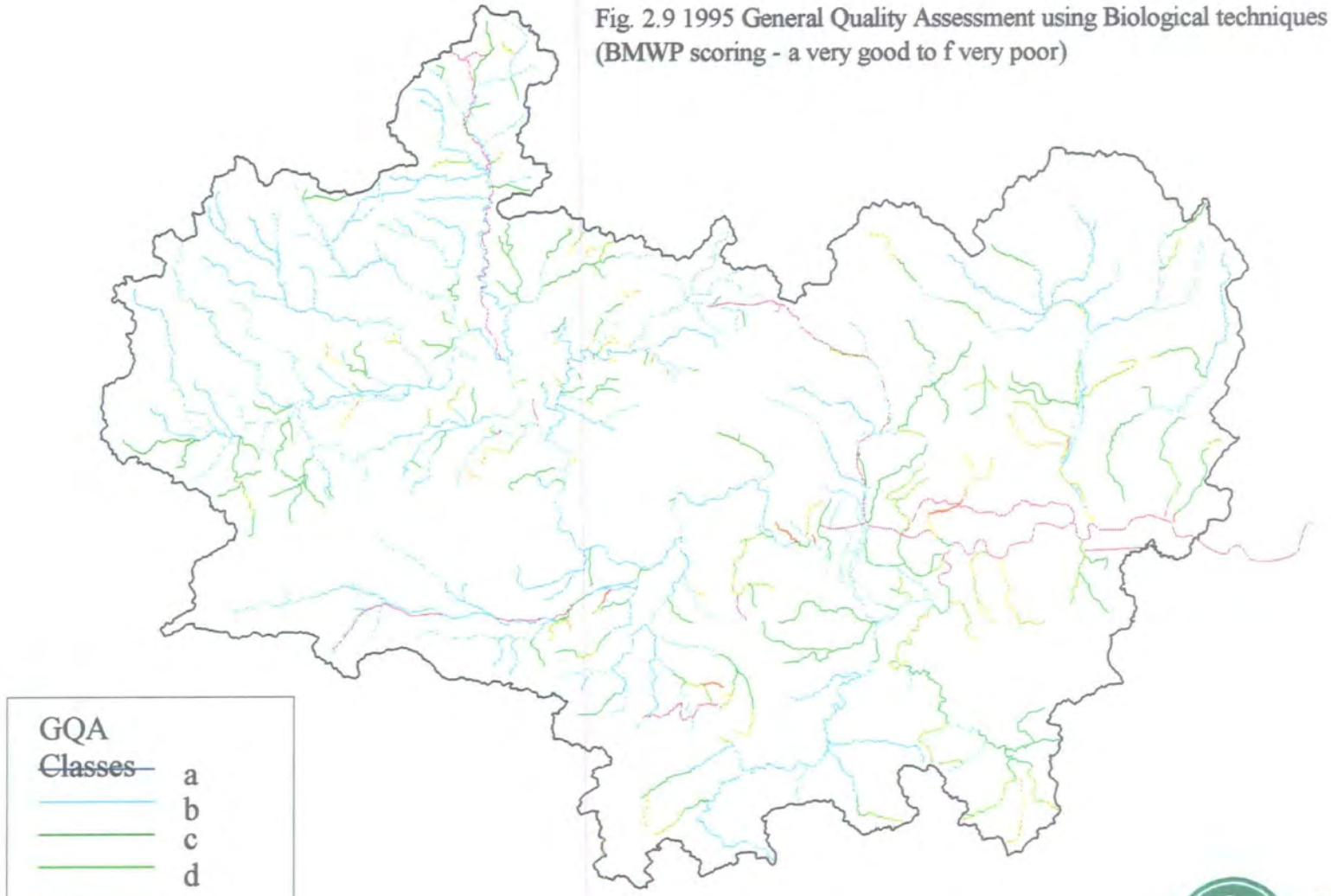
Fig. 2.8 1995 General Water Quality Assessment based on chemical quality (a: very good to f: very poor)



Produced by Thames EA Biology Section June 1996,
gqache95.pre

ENVIRONMENT AGENCY

Fig. 2.9 1995 General Quality Assessment using Biological techniques
(BMWP scoring - a very good to f very poor)



Produced by Thames EA Biology Section June 1996,
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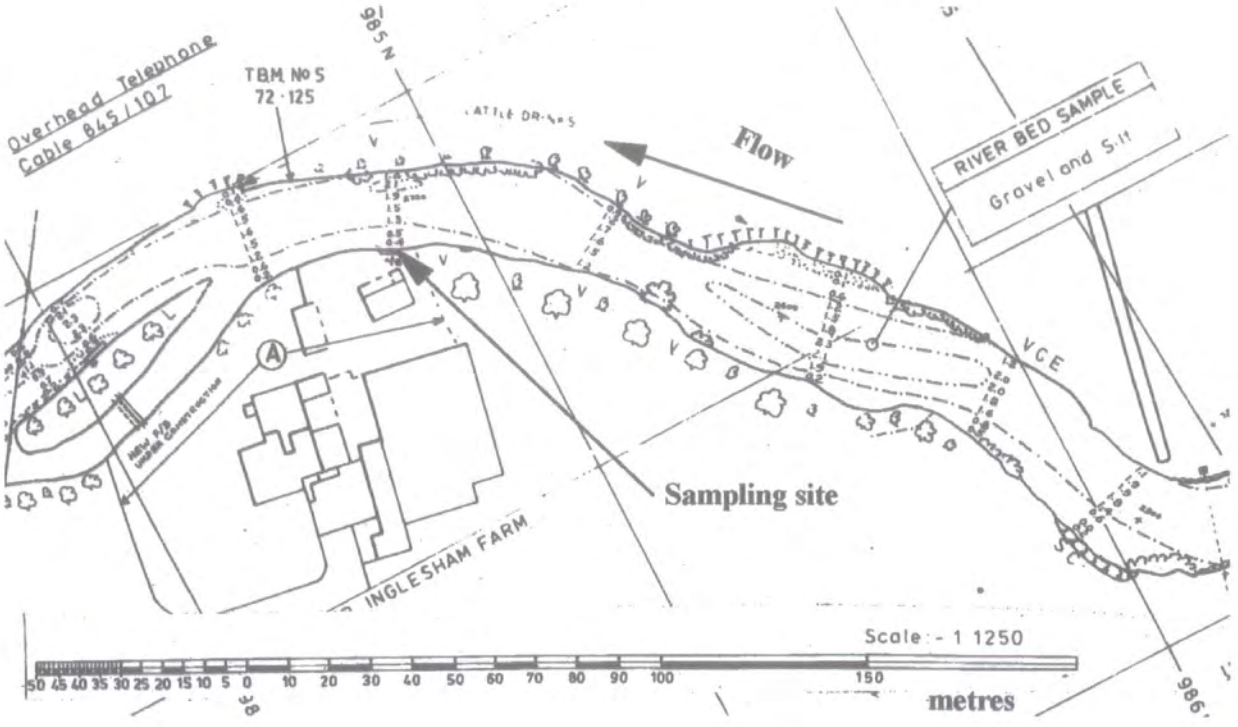
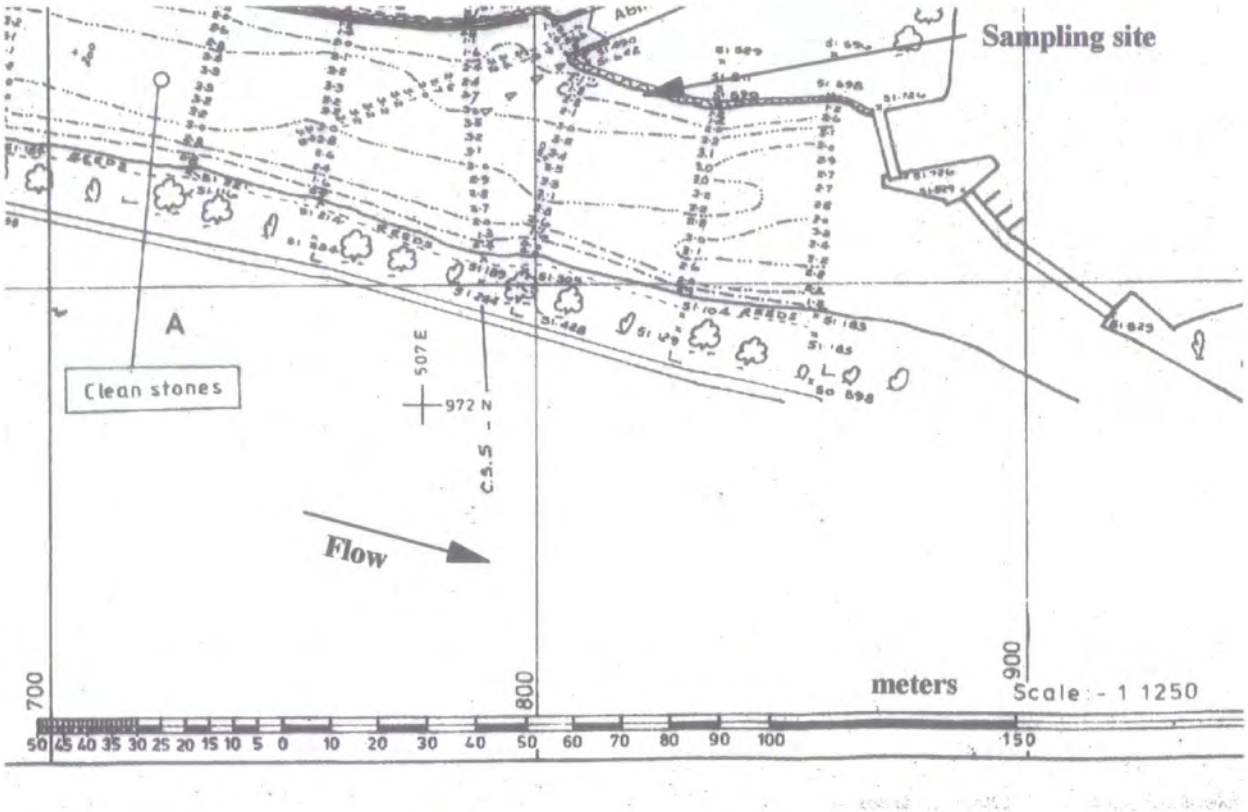
ENVIRONMENT AGENCY

Fig. 2.10 Map and photograph of the sampling site at Inglesham showing water depths and river bed substrate



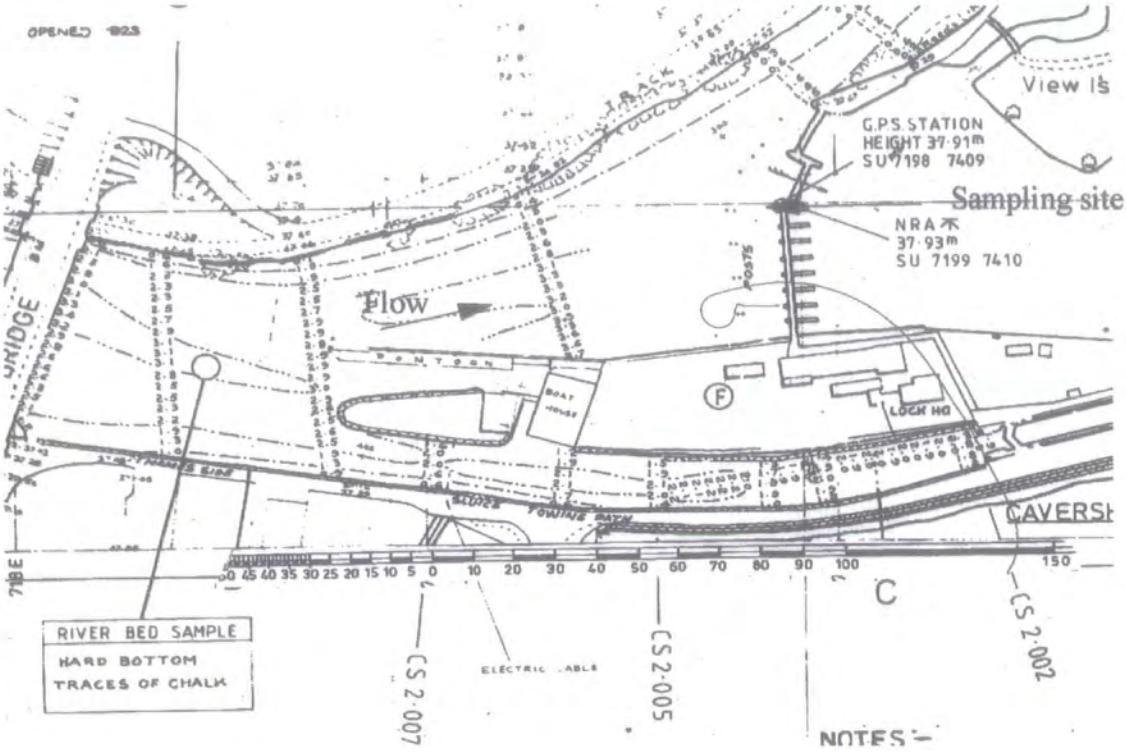
View from sampling site looking upstream

Fig. 2.11 Map and photograph of the sampling site at Abingdon, showing water depths and river bed substrate



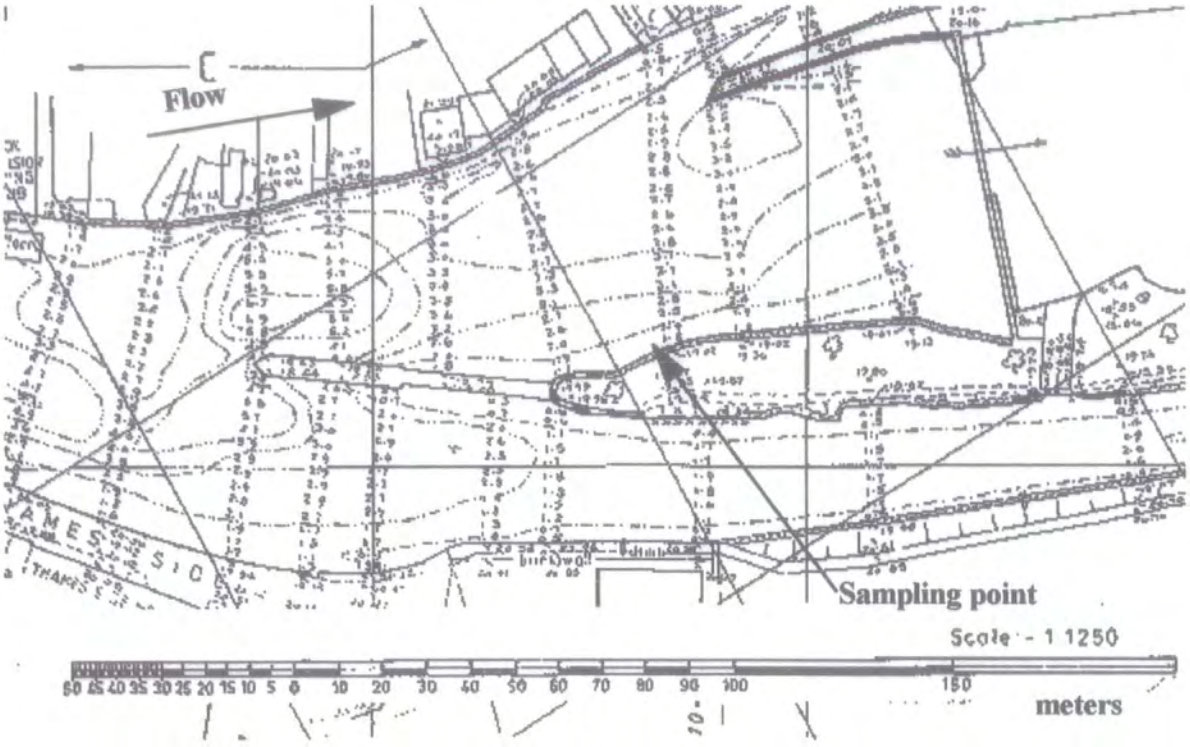
View from sampling site looking upstream

Fig. 2.12 Map and photograph of the sampling site at Reading showing water depths and river bed substrate material

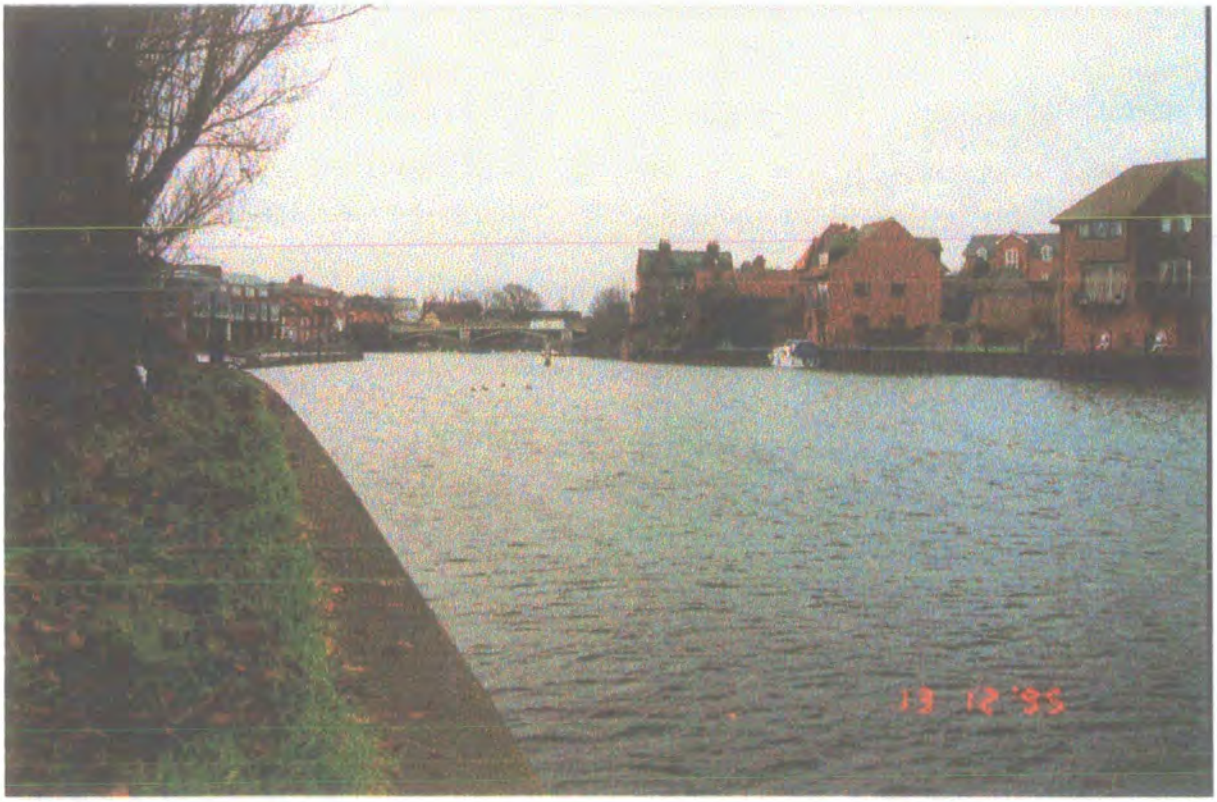


View from sampling site looking upstream

Fig. 2.13 Map and photograph of the sampling site at Windsor showing water depths and river bed substrate material



View from sampling site looking upstream



3.1 Sampling programme

3.1.1 Collection

Water samples were collected using a 3-L bucket and rope. The bucket was rinsed with water from the sampling site. A further sample was taken from mid-stream just below the surface. This sample was then transferred to four plastic bottles, two 1-L for chemical analysis, a 1-L bottle containing 25 mL Lugol's Iodine for quantitative phytoplanktonl count and half filling a 100-mL bottle for observation of the live phytoplankton.

3.1.2 Treatment prior to analysis

The two 1-L samples for chemical analysis and 100-mL bottle for live phytoplankton were placed in a cold box after collection. The sample contained Lugol's iodine was now preserved and was kept in a bottle carrier. In the laboratory the chemical samples were stored in a 4 °C cold room and analyzed within 48 h of collection. The 100 mL sample, for live phytoplankton observation, was kept in a fridge for a maximum of 24 h prior to microscopic examination.

3.2 Physical factors

3.2.1 Discharge

The discharge data were supplied from archived Environment Agency data. The discharge data used was the mean discharge value for each sampling site on the day the sample was taken (Discharge 1), and the mean discharge over ten days prior to sampling, including the sampling day (Discharge 10).

The mean discharge values for discharge 1, were from gauging stations at the sampling sites for Reading (152 km) and Windsor (203 km). Modelled values were calculated for Abingdon (101 km) and Inglesham (35 km) by the Environment Agency Hydrology Section using gauged values on the Thames and tributaries. Mean discharge values for Discharge 10 were from gauging stations at the sampling sites for Reading (152 km) and Windsor (203 km). Due to the difficulty of modelling discharge over ten days for the sampling sites at Abingdon (101 km) and Inglesham (35 km), the nearest gauging station to each site was used. Values from the gauging station at Days Lock, 15 km downstream, were used to represent the discharge at the Abingdon (101 km) sampling site. Values from the gauging station at Cricklade were used to represent the discharge at Inglesham (35 km), 15 km upstream.

3.2.2 Water temperature

Water temperature was measured at approximately 5 cm below the surface of the water at each sampling site with a WTW Oximeter (OXI 196).

3.2.3 Light availability

3.2.3.1 Sunlight hours

Sunlight hours data were recorded at Bracknell and supplied by the Meteorological Office. The Meterological Office advised that the sunlight hours measured at Bracknell would be similar to those experienced at all of the sampling sites, thus data from just one site, Bracknell, were used. The total sunlight hours for the week and fortnight preceding sampling were used.

3.2.3.2 Water clarity (Secchi depth)

A 30 cm diameter Secchi Disc was used to measure the clarity of the water at each sampling site. The Secchi Disc was lowered into the river until the definition between the black and white quarters was just lost. The Secchi Disc was then raised and lowered about the point of definition to more accurately assess the point at which definition is lost. While the Secchi Disc was being used, care was taken not to disturb benthic algae or mud which would decrease the water clarity. On some occasions the Secchi Disc hit the bottom before reaching the point of loss of definition between the black and white quarters. Observations from previous Secchi depth values showed that the Secchi depth measured at each of the four sites on the same day were very similar. Thus, when the Secchi Disc hit the bottom of the river before reaching the point of definition the mean Secchi depth of other sites where a real Secchi depth could be measured on that day were used as a substitute measurement. This is a problem with using this method to measure water clarity. A light meter is now being used to measure the amount of light reaching different depths within the water column. This will avoid the problems of the Secchi Disc, however this data collection started too late for this thesis.

3.2.4 pH

Samples from 3.1.2 were analyzed by National Laboratory Service (NLS) using a WTW meter for pH. The data were accessed via an archive system.

3.3 Chemical analysis

NLS analyzed the samples for phosphorus; total and soluble reactive: nitrogen; total oxidised, nitrate, nitrite, ammoniaca nitrogen, silica, chlorophyll *a*, pH. Samples

were stored and analyzed within 48 h of collection (see 3.1.2). The results from the analyses were added to an archive, where they could be accessed by the Environment Agency.

Samples were not pre-filtered. Continuous flow injection techniques were used to analyze soluble reactive phosphorus, nitrate, nitrite and silica. This method injects the sample into a moving stream of reagent. The reagent and sample mix, and react as they move towards the detector.

3.3.1 Dissolved oxygen

The percentage saturation dissolved oxygen was measured on site with a calibrated WTW Oximeter (OXI 196). A reading was taken with the probe about 5 cm below the surface of the water and held away from the side of the river. The probe was moved through the water until the reading stabilised. This reading and the time of day was noted. The dissolved oxygen meter was calibrated, following the manuals instructions, at the beginning of each sampling run.

3.3.2 Phosphorus components

3.3.2.1 Total

The method followed was described in 'Total phosphorus in sewage sludge' (HMSO, 1985).

Limit of detection is 0.5 mg L^{-1}.

3.3.2.2 Soluble reactive

A flow injection method was used, as described in 'Flow injection analysis - An

Essay Review and Analytical Methods, Method D - For the determination of reactive phosphorus' (HMSO, 1990a).

The limit of detection is 0.03 mg L^{-1}.

3.3.3 Nitrogen components

3.3.3.1 Total oxidised

A flow injection method following the method described in 'Flow injection analysis - An Essay Review and Analytical Methods, Method B - For the determination of oxidised nitrogen' (HMSO, 1990b).

The limit of detection is 0.1 mg L^{-1}.

3.3.3.2 Nitrate

Nitrate is calculated by the subtraction of nitrate from total oxidised nitrogen.

3.3.3.3 Nitrite

A flow injection method following the method described in 'Flow injection analysis - An Essay Review and Analytical Methods, Method C - For the determination of nitrite' (HMSO, 1990c).

The limit of detection is 0.004 mg L^{-1}.

3.3.3.4 Ammoniacal

A flow injection method following the method described in 'Flow injection analysis - An Essay Review and Analytical Methods, Method A - For the determination of ammonia' (HMSO, 1990d).

The limit of detection is 0.03 mg L^{-1}.

3.3.4 Silicate (reactive silica)

A flow injection method following the method described in 'Flow injection analysis - An Essay Review and Analytical Methods, Method F - For the determination of silicate' (HMSO, 1990e).

The limit of detection is 0.2 mg L^{-1}.

3.4 Chlorophyll *a*

The following method was used: 'The determination of chlorophyll *a* in plant material (phytoplankton) in suspension in water (solvent extraction method - methanol). (HMSO, 1980).

The limit of detection is 1 μg L^{-1}.

3.5 Phytoplankton concentration, identification and enumeration

3.5.1 Concentration of Lugol's iodine preserved sample by sedimentation

The sedimentation method followed Ütermohl in Lund *et al.*, (1958) with the following modifications. The phytoplankton was sedimented in three 100 mL tubes per sample for 48 hours. The supernatant was syphoned off leaving the sedimented phytoplankton. A sub-sample of the concentrated phytoplankton sample was then transferred to a Lund slide for enumeration rather than counting the phytoplankton through the base of a specially modified sedimentation tube (as in Lund *et al.*, 1958). Usually the phytoplankton was still very sparse and the three phytoplankton concentrates were combined and sedimented for 48 hours. The supernatant was again syphoned off leaving a known volume of water. The concentration of the

phytoplankton could then be calculated.

3.5.2 Concentration of live phytoplankton by centrifugation

The phytoplankton was often sparse at river concentrations, and thus was concentrated by centrifugation for quicker microscopic observation of the species present. The 50 mL samples were centrifuged at 5000 g for 15 min. The supernatant was carefully syphoned off and the concentrated live phytoplankton could be observed.

3.5.3 Phytoplankton identification

The live phytoplankton samples were examined at a range of magnifications between 100 and 1000. Qualitative lists of the phytoplankton species present were made and the dominant ones noted. This information helps the identification of the Lugol's iodine preserved samples where certain species are disrupted by the preservation technique (see 4.3.2 and 4.3.3).

Live and Lugol's iodine preserved phytoplankton were identified using information collected from a range of sources and collated in a card index (see Chapter 4.1.1).

3.5.4 Phytoplankton enumeration

A Lund Slide was used for the enumeration of the phytoplankton. The use and calibration of the Lund slide follows Lund (1959).

Only cells of 3μm and greater in their longest dimension containing cell contents showing they were alive at the time of preservation, were counted. Discrete organisms, which have been called 'algal units', were counted. This was not always equivalent to number of cells. Filamentous algae were counted as one algal unit per

filament, colonial algae were counted as one algal unit per colony. The problem of disintegrating colonies is discussed in section 4.3.3. This counting method will decrease the importance of filamentous or colonial algae. The alternative would be that all of the tens or hundreds of cells making up a single filamentous or colonial alga were counted causing the count to appear to be dominated by that single species, when in fact the alga only occured once in a diverse phytoplankton sample.

3.6 Database

A purpose built database using DBASE III was developed by the Environment Agency to store the environmental and phytoplankton data. Codings followed Whitton *et al.*, (1978). Extra taxa were added at their appropriate point.

3.7 Statistical analysis

3.7.1 Strategy for missing data

Missing data were replaced by routine measurements taken within ten days of the sample at the same site, or nearby, by other Environment Agency staff. Missing Secchi depth values were filled in as discussed in section 3.2.3.2.

3.7.2 Spearman's Rank Correlation Coefficient (r_s)

The data were not normally distributed (see Appendix 1a-1d) so the non-parametric test Spearman's Rank Correlation Coefficient was used to statistically investigate associations between phytoplankton density, species composition and environmental factors.

The null hypothesis was that the two variables under study were not associated, and that the observed value r_s differed from zero only by chance.

The analysis was carried out using MINITAB statistical software Release 10 for windows. Data were ranked and then two variables were correlated using Spearman's Rank Correlation Coefficient. This tested whether the relationship between the variables was significantly positive or significantly negative. An r_s of +1 indicating perfect positive correlation between two variables, and an r_s of -1 indicating perfect negative correlation (two-tailed test). An r_s value of zero indicates that there is no association between the two variables.

The sample size was always greater than 10, so two degrees of freedom were used (n-2, where n is the total number of paired values) (Siegel, 1956).

The critical value for r_s, with a certain number of paired values was looked up in a Table of two-tailed critical values for Spearman's Rank Correlation Coefficient with two degrees of freedom at significance levels P=0.05 or 5%, P=0.01 or 1% and P=0.01 or 0.1%. These degrees of significance were designated the following terms:-

P=0.05 or 5%	significant
P=0.01 or 1%	highly significant
P=0.001 or 0.1%	extremely significant

Spearman's Rank Correlation Coefficient was then used to investigate the relationship between phytoplankton density and environmental factors for each site in each 'season'. The relationship between the taxa categories described in Section 4.4 were next investigated using the same site/season pattern. Finally, the relationship between dominant species and environmental factors was analyzed for each site and each season.

3.8 Sampling programme

Each site was sampled at fortnightly intervals during 1993 and 1994, except during December 1993, January and February 1994 when samples were taken at monthly intervals. The sampling interval was reduced during the winter months because very little phytoplankton was present. The samples were taken in an upstream direction following an *a priori* decision.

Chapter 4

Taxonomic aspects

4.1 Taxonomic card index

4.1.1 Construction of the index

A phytoplankton species card index was constructed using photomicroscopy, line drawings and measurements of phytoplankton taxa. Information on each taxon was stored on a separate card. Cards were organised in alphabetical order, then further divided into taxonomic groups for ease of use of the index.

The card index was used to ensure consistent identification and naming of taxa.

4.1.2 Illustrations of species found in the Thames

Fig. 4.1 and 4.2 illustrate taxa found in the Thames.

4.2 Floras

The naming of diatoms followed Krammer and Lange-Bertalot (1986, 1988, 1991a,b). Naming of Chlorococcales followed Komárek & Fott (1983) Phytoplankton des Süsswassers Volume 16 part 7. West & Fritsch (1904), Fritsch (1949) and Belcher & Swale (1979) were used to aid identification of all taxonomic groups. Where the name of the taxa had been changed since Whitton *et al.*, (1978) the new name was used.

4.3 Taxonomic problems and solutions

4.3.1 Centric diatoms

Many species of centric diatoms were combined or 'lumped' because they could

not be differentiated during the counting procedure due to chloroplasts obscuring the diagnostic features and the low magnification (times 320). Without acid digestion of the frustule contents, mounting and examination using an oil immersion lens at high magnifications (times 1000) many of the diagnostic features which differentiate between species of centric diatom could not be resolved.

Different size classes of centric diatoms were considered as a classification method. This idea was rejected after looking in the literature concerning size ranges for different species. The size ranges overlapped a great deal and this classification method would not seem to give any useful information.

Finally, three groups of centric diatoms were used based on the taxa observed in the Thames using differences resolvable while counting the Lugol's iodine preserved sample using the Lund Slide. The three groups were: *Melosira varians*, *Skeletonema potamos* and all other centric diatoms: excluding the previous categories. The last group is probably comparable to phytoplankton identified as *Stephanodiscus hantzschii* in earlier work on the Thames (Chapter 1.2).

4.3.2 *Chlorella* and *Chlamydomonas*-type

The Thames samples contained large numbers of small green unicells which became apparent when counting cells of 3 μm and greater. Closer examination of these using an oil immersion lens and fluorescence microscopy (by Judith Taylor, Institute of Freshwater Ecology) showed that the majority of these cells were Chlorophyta and only a few belonged to the Cyanophyta. The small unicells were then classified as *Chlorella*-type and *Chlamydomonas*-type (with flagella). These categories were then sub-divided into round or oval and then further sub-divided into size categories according to their longest dimension. The size categories were small

(3-5 μm), medium (6-9 μm) and large (>10 μm). These categories are not expected to be mutually exclusive and it is highly probable that a *Chlorella*-type oval small will grow into a *Chlorella*-type oval medium. Also a proportion of these cells are probably Cyanophyta; this may change seasonally and spatially. This method of categorisation was an effort to split a very large group, that is predominantly green unicells, into categories that may yield more information. More detailed taxonomic determination would require study of life cycles. This was not practical in this study.

4.3.3 Loss of flagellum and algal disruption

Preservation with Lugol's Iodine can cause algae with flagella to drop them and delicate colonial species can disintegrate into their constituent parts. This makes phytoplankton identification and enumeration of these species problematic.

Identification of live phytoplankton (Chapter 3.5.3) can help with the problems caused by the preservation technique. If a live algal sample is dominated by *Chlamydomonas*-type oval small, then it can be expected that the preserved sample will also be dominated by this taxon. When identifying the preserved sample extra care needs to be taken looking for this taxon and cells of the correct size and shape with features that indicate lost flagella.

The number of cells making-up delicate colonial species were counted in the live material. The mean number of cells per colony for ten colonies was calculated and noted. When single cells from a colonial species were encountered in the Lugol's Iodine count a single cell was counted as one algal unit. If another single cell of the colonial species was encountered the algal unit count remained at one. This continued until the number of single cells of the colonial species was one greater

than the average number of cells calculated for the colonial from the live material. Then the colonial species was counted as two algal units, and so on as more single cells of a colonial species were encountered.

This method will bias the count, however the alternative of counting each cell of a colony as an algal unit would bias the count even more.

4.3.4 Species diagnosis - aggregation or division

In the early stage of the project, algae were split into different groups if differences could be seen. If the species could not be fully identified it was given its genus name and called Sp. 1, for example *Ankistrodesmus* sp. 1. This alga was measured, photographed, drawn and added to the card catalogue (Chapter 4.1.1). The Fritsch collection and Dr. H Belcher were next consulted to improve the identification using the card index and preserved material. Many of the taxa that were split were in fact the same species showing phenotypic variation. Other taxa could be given a species name.

The database of algal species was updated to give the taxa their correct species names for the complete data set.

4.4 Taxonomic categories used for data analysis

Seven taxonomic categories of interest were made by adding together species counts. These groups were:-

Chlorococcales - non-motile, coccoid, unicelllar, green algae

Volvocales and Tetrasporales combined green algae which are motile or have characteristics of motile cells and are grouped together in Whitton *et al.*, (1978)

Cyanophyta - due to special interest in rivers

Euglenophyta and Cryptophyta combined - motile and not of the Volvocales/Tetrasporales group

Bacillariophyta - centric diatoms- dominantly planktonic in origin

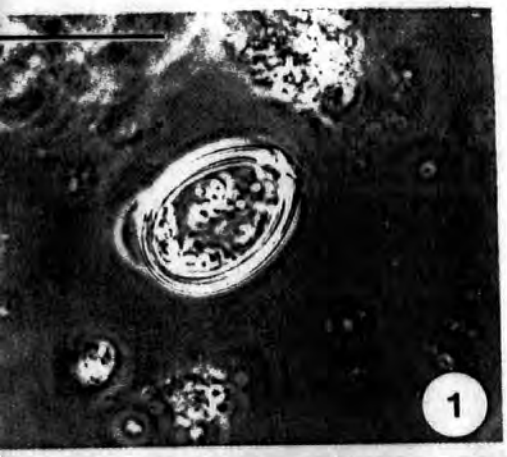
Bacillariophyta - pennate diatoms - dominantly benthic in origin

Other - any taxa not yet categorised

A full listing of the taxa found in the Thames during the two year study is detailed in Table 5.2.

The rationel behind these categories was to split the total phytoplankton count into groups of taxonomically or functionally similar organisms and see how the density of these groups related to environmental factors.

Dominant phytoplankton species were also used for data analysis to study the relationship of dominance with environmental factors.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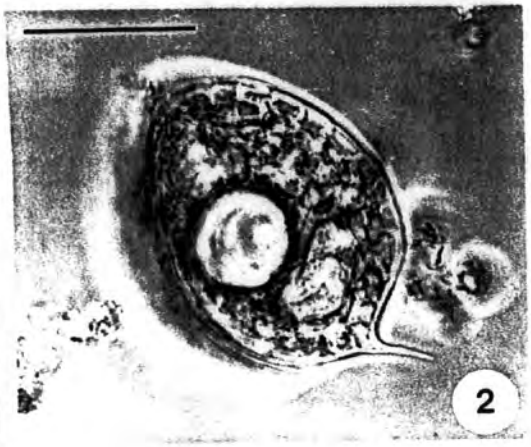
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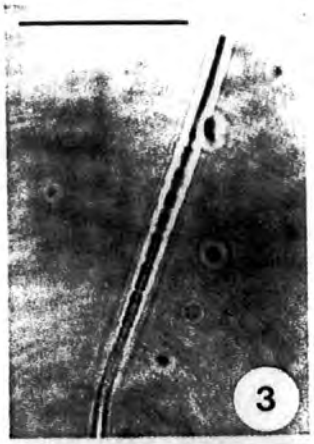
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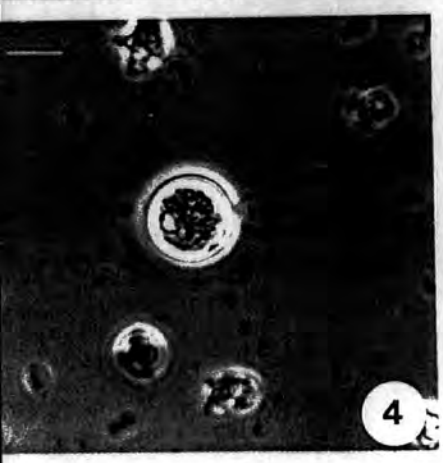
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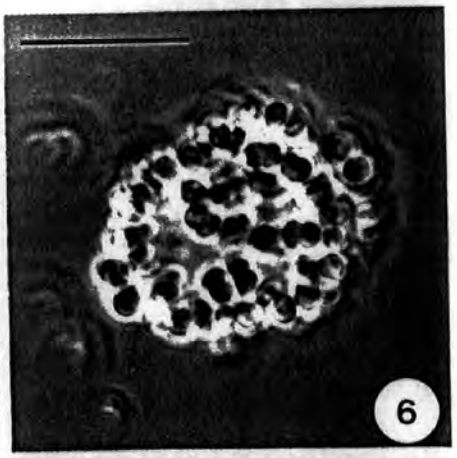
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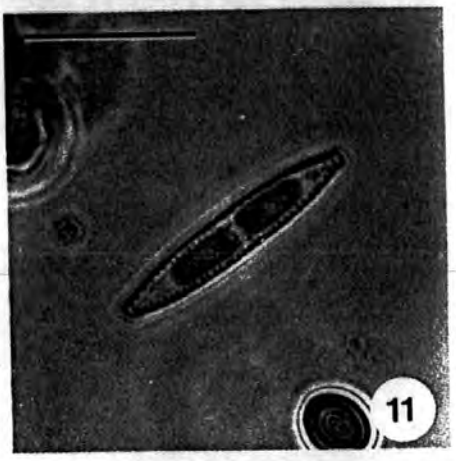
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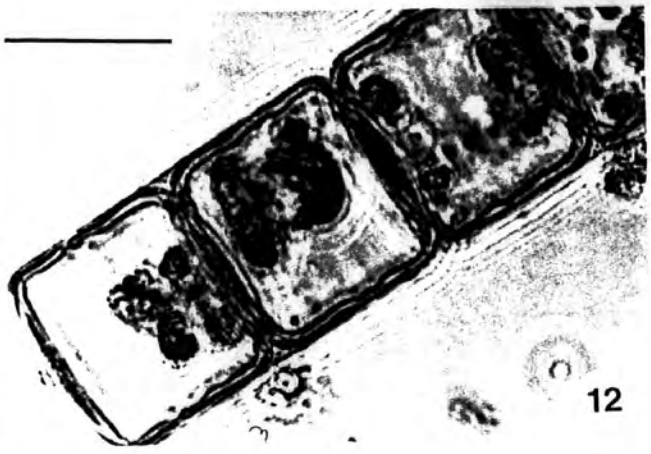
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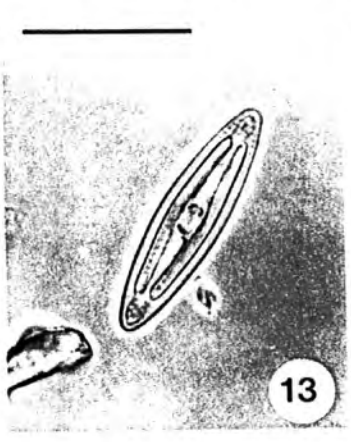
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Legend for Fig. 4.1

1-3, 5, 6, 11, 12-14 taken at 1000x magnification. Fig. 4, 7-10 taken at 320x magnification. Scale bar = 20 μm.

1) Euglenophyta: *Trachelomonas* sp

2) Euglenophyta: *Phacus pleuronectes*

3) Cyanophyta: *Aphanizomenon* sp

4) Chlorophyta: *Chlamydomonas* round large sp

5) Chlorophyta: *Chlamydomonas* oval large sp

6) Chlorophyta: *Dictyosphaerium pulchellum*

7) Chlorophyta: *Lagerheimia ciliata*

8) Chlorophyta: *Scenedesmus obliquus*

9) Chlorophyta: *Ankistrodesmus angustus*

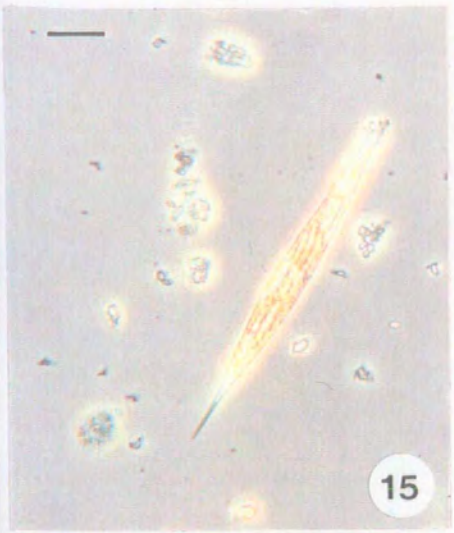
10) Chlorophyta: *Scenedesmus quadricauda*

11) Pennate diatom: *Nitzschia* sp 10

12) Centric diatom: *Melosira varians*

13) Pennate diatom: *Navicula tripunctata*

14) Centric diatom: Centric diatoms: excluding *Skeletonema* and *Melosira*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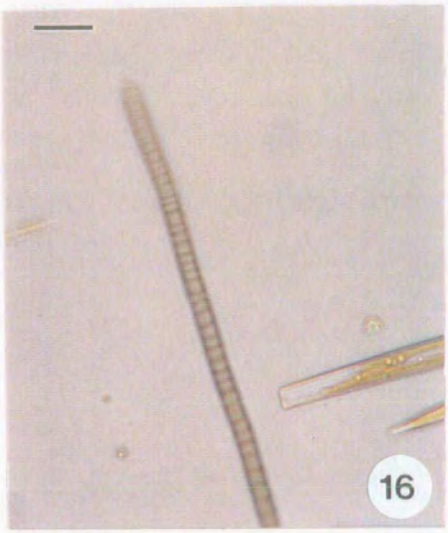
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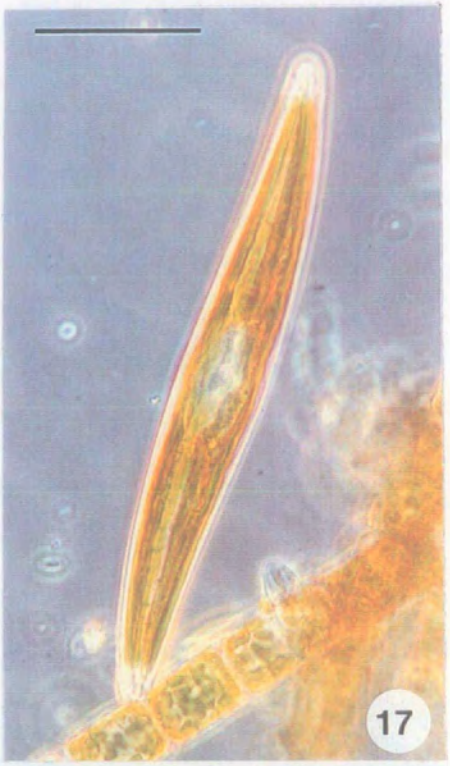
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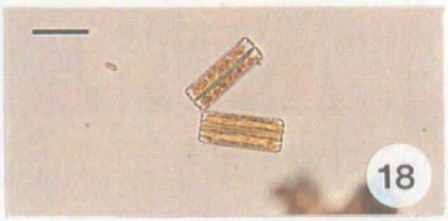
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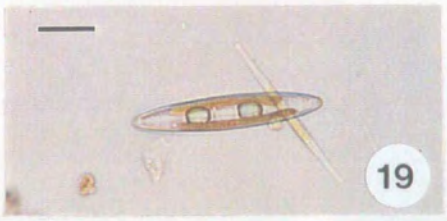
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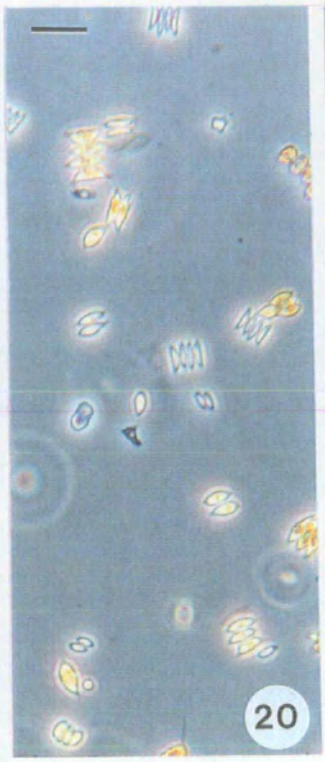
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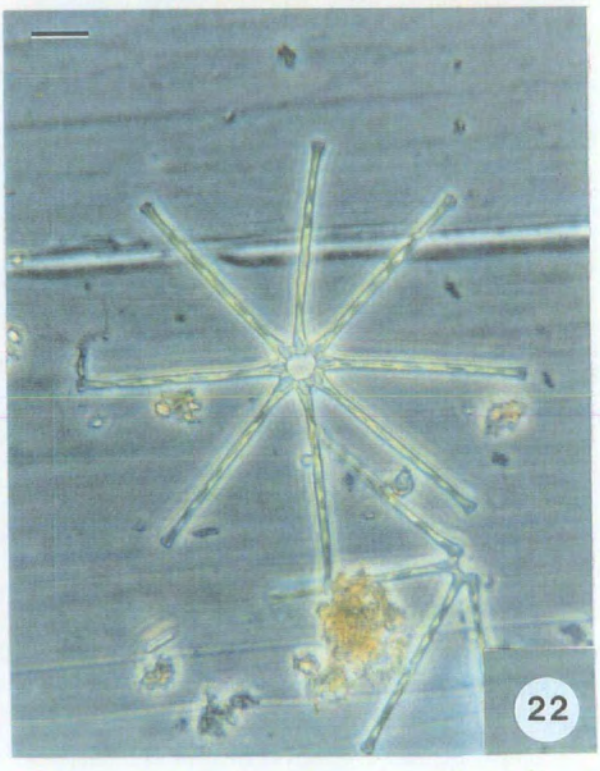
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Legend for Fig. 4.2

17 taken at 1000x magnification. 15-16, 18-22 taken at 320x magnification. Scales bar = 20 μm.

15) Euglenophyta: *Euglena acus*

16) Cyanophyta: *Oscillatoria* sp 1

17) Pennate diatom: *Gyrosigma* sp

18) Pennate diatom: *Diatoma* sp

19) Pennate diatom: *Navicula tripunctata*

20) An example of a preserved sample full of Chlorophyta *Scenedesmus* sp

21) Chrysophyta: *Dinobryon* colony

22) Pennate diatom: *Asterionella formosa*

Chapter 5

Spatial and temporal patterns in phytoplankton

5.1 Phytoplankton density

One aim was to examine seasonal patterns in phytoplankton density at each site, and also compare patterns at different sites along the river. This was achieved by graphing total phytoplankton density over two years for each site (Fig. 5.1). Phytoplankton density varied seasonally at all sites. The trend was an increase during spring, then a decline in summer and autumn, to lowest levels in winter. This pattern became more marked with increasing distance from source. Marked peaks in phytoplankton density in spring occurred simultaneously at Abingdon (101 km), Reading (152 km) and Windsor (203 km), but not Inglesham (35 km).

To quantify further phytoplankton density at different sites and different years, the maximum, minimum and mean for phytoplankton density were calculated (Table 5.1). This showed that mean phytoplankton density increased with increasing distance from source in 1993 and 1994. The maximum or peak densities did not follow such a clear pattern, the site furthest from source did not have the highest peak in phytoplankton density. Inglesham (35 km) had the smallest peak in density in both years and Abingdon (101 km) had the highest density in 1993, and Reading (152 km) in 1994. Minimum phytoplankton densities occurred during the winter and were similar at all sites.

5.2 Phytoplankton composition

To investigate further which type of phytoplankton was dominant at different times of the year the phytoplankton were placed into seven taxonomic groupings according

to cell organisation (see Chapter 4.4). The density of each of these groups were graphed in Fig. 5.2. To look more closely at changing patterns of phytoplankton composition, the densities of the seven Taxon Groups were converted into percentage abundance values (Fig. 5.3). To see which species were dominant within a taxon group the percentage contributions of each species as part of the total phytoplankton density at each site has been calculated (Table 5.2).

From an initial inspection of Fig. 5.2 phytoplankton density and composition can be split into three arbitrary sections which are associated with seasons. Each season can then be focused on in turn and the phytoplankton composition can be examined in detail and later tested for correlations with environmental factors.

The seasons will be classified as follows:

Spring - March to May 1993, and April to June 1994, when peaks in phytoplankton density, dominated by centric diatoms, occurred at Abingdon (101 km), Reading (152 km) and Windsor (203 km).

Summer and Autumn - June to September 1993 and July to October 1994, where phytoplankton densities were falling and several Taxon Groups were abundant.

Winter - January and February 1993, October 1993 to March 1994, then November and December 1994. The lowest phytoplankton densities occurred during this period, and were dominated by Chlorococcales.

The dominant Taxon Groups were considered the most important components of the phytoplankton and thus were the focus of the investigation.

5.2.1 Spring

This period is associated with the highest densities in phytoplankton. Centric

diatoms and Chlorococcales were dominant at Abingdon (101 km), Reading (152 km) and Windsor (203 km). At Inglesham, (35 km) however, Chlorococcales and pennate diatoms were dominant.

Peaks in phytoplankton density at Abingdon (101 km), Reading (152 km) and Windsor (203 km) were largely due to centric diatoms which formed two successive peaks in density and occurred simultaneously at the different sites. During peaks in phytoplankton density the centric diatoms accounted for over 60% abundance at Abingdon (101 km), Reading (152 km) and Windsor (203 km), and up to 90% abundance at Reading (152 km) in May 1993 (Fig.5.2 & Fig.5.3). The centric diatoms were taxa other than *Skeletonema/Melosira* (Table 5.2).

Chlorococcales were dominant at Inglesham (35 km) throughout the spring period, accounting for between 25 and 90% of the total phytoplankton density (Fig. 5.2 & Fig. 5.3). The dominant taxon in the Chlorococcales order was *Chlorella* oval/round, small and medium (Table 5.2). This was the same at all sites.

At Abingdon (101 km), Reading (152 km) and Windsor (203 km) Chlorococcales increased in density at the same time as centric diatoms reached peak densities, however the very high density of centric diatoms resulted in the proportion of Chlorococcales appearing low (Fig. 5.2 & Fig. 5.3). Chlorococcales became the dominant taxonomic group when the centric diatom blooms declined (Fig. 5.2 and 5.3).

Centric diatoms were not dominant at Inglesham (35 km), however there was an increase in the percentage abundance of this group in this season in comparison with the other seasons (Fig. 5.2 & Fig. 5.3). The dominant centric diatom taxa was the same as at the other sites, that is, centric diatoms:excluding *Skeletonema/Melosira*.

Pennate diatoms periodically reached 40% abundance at Inglesham (35 km) (Fig.

5.3). The dominant taxon was *Cocconeis placentula*, a benthic diatom, and other pennate diatom spp. (Table 5.2). Pennate diatoms were less abundant at Abingdon (101 km), Reading (152 km) and Windsor (203 km) accounting for a maximum of 10% of the phytoplankton density (Fig. 5.3).

5.2.2 Summer and Autumn

Chlorococcales were dominant at all sites for most of the summer period (Fig. 5.2 & Fig. 5.3). The dominant taxon in the Chlorococcales group were *Chlorella* oval/round, small and medium (Table 5.2). This was the same at all sites.

At Abingdon (101 km), Reading (152 km) and Windsor (203 km) the abundance of the Euglenophyta/Cryptophyta group increased . This group accounted for a maximum of 70% of the total phytoplankton density at Abingdon (101 km) in July 1994 (Fig. 5.3). This group was dominated by a Cryptophyta species *Rhodomonas minuta* (Table 5.2). The Euglenophyta/Crytophyta group were less abundant at Inglesham (35 km) accounting for less than 5% of the total phytoplankton density.

The 'other group', dominated by *Spermatopsis exsultans*, increased to 30% dominance at Reading (152 km) in October 1994, 10% at Windsor (203 km) in August 1993 and 30% at Windsor (203 km) in October 1994 (Fig. 5.3). This group were present in very low abundances of less than 5% at Reading (152 km) in summer 1993 and Inglesham (35 km) and Reading (152 km) in 1993 and 1994 (Fig. 5.3).

In 1993 there were periodic increases in centric diatom abundance at Abingdon (101 km), Reading (152 km) and Windsor (203 km), there were not repeated in 1994 (Fig. 5.2 & Fig. 5.3). At Inglesham (35 km) in July 1994 there was a peak in the abundance centric diatoms (Fig. 5.2 and 5.3). The dominant centric diatom taxa at

all sites was centric diatoms: excluding *Skeletonema/Melosira* (Table 5.2).

Pennate diatoms were more abundant at Inglesham (35 km) than the other sites, principally due to *Cocconeis placentula* (Fig. 5.2 & Fig. 5.3).

5.2.3 Winter

This period was associated with the lowest density of phytoplankton. Chlorococcales were dominant at all sites accounting for up to 95% of the total phytoplankton density (Fig. 5.2 & Fig. 5.3).

Fig. 5.3 shows the build up in January and February of centric diatoms prior to the centric diatom bloom in spring at Abingdon (101 km), Reading (152 km) and Windsor (203 km).

Pennate diatoms were more abundant at Inglesham (35 km) than the other sites (Fig. 5.2 & Fig. 5.3).

5.3 Dominant phytoplankton taxa

It was considered important to study the dominant phytoplankton species in more detail due to their large contribution to the total phytoplankton population. Species with the highest percentage dominance are collated in Table 5.3. Combined, the phytoplankton density of the seven top ranking phytoplankton taxa accounted for approximately 85% of total phytoplankton density (Table 5.3).

Chlorococcales were the most common group, with four representatives, out of the seven top ranking taxa (Table 5.3). These were *Chlorella*-type oval small which ranked first at Inglesham (35 km) (57% of total) and Abingdon (101 km) (29%), and second at Reading (152 km) (26%) and Windsor (203 km) (29%). *Chlorella*-type round small, oval medium and round medium ranked between second and seventh at

the four sites.

As discussed in Chapter 4.3.2 each of the *Chlorella*-type taxa is probably an amalgamation of several different species. Another consideration is if, for example, *Chlorella*-type oval small increased in size it would be classified as *Chlorella* oval medium. This is not an ideal situation, however this type of classification will give worth while data about the spatial and seasonal patterns of unicellular small phytoplankton, predominantly of the Chlorococcales group.

Two taxa from the Centric diatom group ranked in the top seven taxa. These were centric diatoms: excluding *Skeletonema/Melosira* and *Skeletonema potamos.* Centric diatoms: excluding *Skeletonema/Melosira* is an amalgamation of different species that could not be separated into different species groups using the preservation and counting techniques employed in this study. It was, however, thought useful to collect this data as the different species making up this taxa are similar in cell organisation (see Chapter 4.3.1). Centric diatoms:excluding *Skeletonema/Melosira* was the most dominant grouping of centric diatoms, ranking first at Reading (152 km) (34% total) and Windsor (203 km) (31% total) and second at Abingdon (101 km) (26% total) and third at Inglesham (35 km) (29% total), (Table 5.3).

The distribution and density of *Skeletonema potamos* differed from the other centric diatoms:excluding *Skeletonema/Melosira. Skeletonema potamos* was not present at Inglesham (35 km), and only ranked nineteenth (0.27% total) at Abingdon (101 km). The sites further from source had a higher density of this species, that is, at Reading (152 km) (3.4% total, ranking sixth) and Windsor (203 km) (2.9% total, ranking seventh).

The remaining top ranking species was *Rhodomonas minuta* , a member of the

Cryptophyta. This species was present at all of the sites, ranking fourth at Abingdon (101 km) (7% total), Reading (152 km) (4.5% total) and Windsor (203 km) (4.7% total), and seventh at Inglesham (35 km) (1.1% total).

5.4 Periodicity of three common phytoplankton taxa

Examination of the phytoplankton density of different taxonomic groups showed changes in dominance between sites and seasons. To further examine changes in phytoplankton density at different sites and seasons three individual taxa from three different taxon groups were chosen from the seven top ranking species (Table 5.3). Focusing on these taxa will demonstrate patterns in density of three abundant taxa, each from a different taxonomic group. The three taxa are:

Chlorella-type oval small - Chlorococcales Group

Centric diatom: excluding *Skeletonema/Melosira* - Centric Diatom Group

Rhodomonas minuta - Euglenophyta/Cryptophyta Group

The phytoplankton density from each of these taxa are graphed (Fig. 5.4).

There was a rough seasonal sequence to these three taxa at Abingdon (101 km), Reading (152 km) and Windsor (203 km) in 1993, which was repeated in 1994. In winter there were low levels of *Chlorella*-type oval small and little else. Progressing to spring where the density of centric diatoms:excluding *Skeletonema/Melosira* peaked, while *Chlorella*-type oval small and *Rhodomonas minuta* were present in lower levels. In summer and autumn *Chlorella*-type oval small dominated and an increase in *Rhodomonas minuta* was noted. Centric diatom groups: excluding *Skeletonema/Melosira* was present in low density (Fig. 5.4).

Fig. 5.4 shows that at Inglesham (35 km) there was no clear pattern to the density of the three taxa repeating in 1993 and 1994. At Inglesham (35 km) *Chlorella*-type

oval small was the dominant taxa, of the three, for most of the study period, however the density of this taxa did increase from lowest levels in winter to higher densities in spring, summer and autumn (Fig. 5.4) The density of centric diatom:excluding *Skeletonema/Melosira* was low for the whole of the study, except for early July 1994 when it peaked at about 8,000 units mL^{-1} . *Rhodomonas minuta* was present at low levels for most of the study period.

5.5 Summary of findings

Phytoplankton density at all sites followed a similar pattern, with an increase in density during spring, then a decline in summer and autumn, to lowest levels in winter.

This pattern became more marked with increasing distance from source with the mean phytoplankton density increased with increasing distance from source in 1993 and 1994.

Phytoplankton composition was examined by separating the phytoplankton into seven Taxon Groups based on taxonomy and cell organisation.

To further investigate these groups the data was split into three arbitrary seasons, Spring, Summer/Autumn and Winter based on similarities in phytoplankton density and composition (Chapter 5.2 and Fig. 5.2).

All of the 'seasons' started approximately one month later in 1994 than 1993.

Spring - Chlorococcales and centric diatoms were dominant at Abingdon (101 km), Reading (152 km) and Windsor (203 km).

Spring - Chlorococcales, and to a lesser degree pennate diatoms, were dominant at Inglesham (35 km).

Peaks in phytoplankton density in spring at Abingdon (101 km), Reading (152 km)

and Windsor (203 km) were due to high numbers of centric diatoms dominated by centric diatom:excluding *Skeletonema/Melosira.*

Summer/autumn - Chlorococcales were usually dominant at all sites.

Summer/autumn - the Eugenophyta/Cryptophyta group, dominated by *Rhodomonas minuta*, increased in abundance at Abingdon (101 km), Reading (152 km) and Windsor (203 km), but not Inglesham (35 km).

Winter - Chlorococcales were dominant at all sites.

The phytoplankton density of seven taxa accounted for approximately 85% of the total at each site (Table 5.3).

Chlorella-type oval small, Centric diatoms:excluding *Skeletonema/Melosira* and *Rhodomonas minuta*, were chosen to further examine changes in density at different site and seasons on an individual taxa basis.

At Abingdon (101 km), Reading (152 km) and Windsor (203 km) there was a seasonal sequence in 1993 and 1994 of the three selected taxa:

Winter	Spring	Summer/Autumn	Winter
Chlorella-type oval small	Centric diatoms:excluding *Skeletonema* and *Melosira*	*Chlorella*-type oval small and *Rhodomonas minuta*	*Chlorella*-type oval small

At Inglesham (35 km) there was no repeated pattern to the three taxa, except that *Chlorella*-type oval small was the most dominant taxa and the density of all taxa was low in winter and increased periodically in spring and summer/autumn seasons.

Table 5.1 Maximum, minimum, mean and standard error of the mean for phytoplankton density (algal units mL^{-1}) at four sites in 1993 and 1994

Site	Year	n	Maximum	Minimum	Mean
Inglesham	1993	23	20527	1846	10739
	1994	22	21448	1818	6534
Abingdon	1993	23	64739	1169	16447
	1994	22	57634	1723	12372
Reading	1993	23	51646	1401	16163
	1994	22	73029	1806	15709
Windsor	1993	23	63698	1600	19476
	1994	22	67897	2178	20076

Table 5.2 Phytoplankton taxa identified at different sites as a percentage of the total cell number at each site during the study period

SPECIES	INGLE	ABING	READ	WIND
Taxon group 1 - Cyanophyta				
filament number 1	0.02	<0.01	<0.01	-.--
filament number 2	0.01	-.--	-.--	-.--
Anabaena spp.	0.02	0.01	-.--	<0.01
Aphanocapsa spp.	<0.01	-.--	-.--	-.--
Gloeocapsa magma (Bréb.) Kütz.	-.--	-.--	<0.01	-.--
Lyngbya spp.	0.01	-.--	-.--	-.--
Merismopedia spp.	-.--	-.--	-.--	<0.01
Merismopedia glauca (Ehr.) Näg.	-.--	-.--	<0.01	0.01
Merismopedia sp.1	-.--	-.--	-.--	0.04
Merismopedia sp.2	0.03	0.13	0.02	0.20
Oscillatoria spp.	0.02	0.02	0.01	-.--
Oscillatoria <2μm diameter	-.--	<0.01	-.--	-.--
Phormidium tenue (Menegh)Gomont	-.--	<0.01	<0.01	0.02
Phormidium spp.	0.02	0.01	0.01	0.01
Pseudanabaena spp.	<0.01	0.21	-.--	0.08
b/g unid sp.1	-.--	0.01	-.--	-.--
b/g unid sp.2	0.03	0.38	0.07	0.21
b/g unid sp.3	<0.01	-.--	-.--	0.01
Raphidiopsis sp.1	-.--	-.--	<0.01	-.--
Taxon group 2 - Euglenophyta and Cryptophyta				
Euglenophyta				
Euglena acus Ehr.	<0.01	-.--	-.--	-.--
Euglena viridis Ehr.	0.03	-.--	-.--	0.01
Euglena sp.1	-.--	0.01	0.01	0.01
Euglena spp.	0.01	<0.01	0.02	-.--
Phacus longicauda (Ehr.) Duj.	-.--	0.01	-.--	-.--
Phacus pleuronectes (Müll.) Duj.	-.--	<0.01	-.--	-.--
Phacus sp.1	<0.01	-.--	-.--	0.01
Phacus sp.2	<0.01	-.--	-.--	-.--
Phacus sp.3	0.04	0.05	-.--	<0.01
Phacus spp.	0.03	<0.01	0.01	0.01
Phacus agilis Carter	<0.01	-.--	-.--	-.--
Trachelomonas sp.1	0.01	-.--	-.--	-.--
Trachelomonas sp.4	-.--	0.03	0.01	-.--
Trachelomonas sp.5	-.--	<0.01	-.--	-.--
Trachelomonas spp.	<0.01	0.02	-.--	-.--
Cryptophyta				
Chroomonas spp.	0.27	0.11	0.07	0.13
Cryptomonas sp.1	0.04	0.27	0.05	0.21
Cryptomonas sp.2	0.08	0.26	0.25	0.13
Cryptomonas sp.3	0.03	0.04	-.--	-.--
Cryptomonas sp.4	0.01	0.03	0.04	<0.01
Cryptomonas sp.5	-.--	-.--	<0.01	-.--
Cryptomonas spp.	0.07	-.--	<0.01	<0.01
Rhodomonas minuta Skuja	1.13	6.99	4.52	4.66
Taxon group 3 - other taxa				
Dinophyta				
Glenodinium spp.	0.02	-.--	-.--	-.--
Gymnodinium sp.1	-.--	0.04	0.01	0.03
Gymnodinium sp.2	-.--	-.--	0.02	-.--

	INGLE	ABING	READ	WIND
Gymnodinium spp.	-.--	0.02	<0.01	-.--
Peridinium sp.1	-.--	0.01	<0.01	-.--
Peridinium spp.	-.--	-.--	0.01	-.--
Chrysophyta				
Dinobryon spp.	0.04	0.02	-.--	-.--
Syncrypta sp.1	0.01	<0.01	0.03	<0.01
Syncrypta spp.	0.03	-.--	-.--	-.--
Xanthophyta				
Goniochloris mutica (A.Br.) Fott.	0.02	0.01	0.05	<0.01
Goniochloris spp.	-.--	0.10	-.--	-.--
Prasinophyta				
Spermatozopsis exsultans Korsch.	0.02	0.08	0.52	1.18
Conjugatophyta				
Closterium gracile Bréb.	-.--	-.--	-.--	0.01
Closterium sp.1	-.--	0.01	-.--	-.--
Closterium sp.2	0.03	-.--	-.--	-.--
Cosmarium sp.3	-.--	<0.01	-.--	-.--
Staurastrum sp.1	-.--	<0.01	-.--	-.--
Staurastrum chaetoceras (Schroed.) G.M.Smith	-.--	<0.01	-.--	-.--
Group 4 - Centric Diatoms				
Melosira granulata (Ehr.)Ralfs.	-.--	0.01	0.01	<0.01
Melosira varians Ag.	0.09	0.39	0.22	0.60
Centric: not *Skeletonema/Melosira*	5.48	8.12	34.78	31.03
Skeletonema potamos (Weber) Hasle	-.--	0.27	3.41	2.95
Group 5 - Pennate Diatoms				
Achnanthes lanceolata (Bréb.) Grün.	0.06	0.05	0.01	0.04
Achnanthes minutissima Kütz.	0.05	-.--	-.--	<0.01
Achnanthes spp.	0.01	0.01	-.--	-.--
Amphora ovalis (Kütz.) Kütz.	0.01	0.01	0.03	<0.01
Amphora sp.1	-.--	<0.01	-.--	-.--
Amphora spp.	-.--	<0.01	-.--	-.--
Asterionella formosa Hass.	-.--	0.03	0.01	<0.01
Asterionella spp.	0.01	-.--	-.--	-.--
Cocconeis pediculus Ehr.	<0.01	-.--	-.--	<0.01
Cocconeis placentula Ehr.	0.80	0.13	0.05	0.02
Cocconeis sp.1	-.--	-.--	<0.01	0.01
Cocconeis sp.2	-.--	<0.01	-.--	-.--
Cocconeis spp.	-.--	-.--	-.--	<0.01
Cymatopleura solea (Bréb.) Sm.	-.--	<0.01	0.01	-.--
Cymbella cistula (Ehr.) Krch.	0.01	-.--	-.--	-.--
Cymbella sp.2	<0.01	-.--	-.--	<0.01
Cymbella sp.3	<0.01	-.--	-.--	-.--
Cymbella sp.4	<0.01	-.--	-.--	-.--
Cymbella sp.5	-.--	-.--	-.--	<0.01
Cymbella spp.	-.--	-.--	<0.01	0.01
Diatoma vulgare (Bory)	0.34	0.02	<0.01	0.04
Diatoma spp.	0.04	<0.01	-.--	0.01
Encyonema minutum (Hilse) Mann	0.09	0.01	-.--	0.04
Fragilaria brevistriata Grun.	-.--	-.--	<0.01	-.--
Fragilaria construens (Ehr.) Grün.	-.--	<0.01	-.--	-.--
Fragilaria pinnata Ehr.	0.02	-.--	-.--	-.--

	INGLE	ABING	READ	WIND
Fragilaria sp.3	0.01	-.--	-.--	0.01
Fragilaria sp.4	0.16	0.01	-.--	<0.01
Fragilaria sp.5	-.--	-.--	-.--	<0.01
Fragilaria sp.7	-.--	-.--	-.--	<0.01
Gomphonema spp.	-.--	-.--	-.--	0.01
Gomphonema parvulum Kütz.	0.01	0.02	0.01	<0.01
Gomphonema sp.1	-.--	<0.01	-.--	-.--
Gomphonema sp.2	<0.01	-.--	<0.01	-.--
Gomphonema spp.	0.18	0.06	<0.01	0.01
Gyrosigma spenceri Quekett	<0.01	-.--	-.--	-.--
Meridion spp.	0.03	-.--	-.--	-.--
Navicula cryptocephela Kütz.	-.--	0.04	-.--	-.--
Navicula menisculus Schum.	0.14	0.08	0.01	0.02
Navicula radiosa Kütz.	0.05	<0.01	-.--	-.--
Navicula sp.1	<0.01	-.--	-.--	-.--
Navicula sp.3	<0.01	<0.01	-.--	-.--
Navicula sp.5	-.--	-.--	<0.01	-.--
Navicula sp.6	-.--	0.01	0.01	-.--
Navicula sp.8	<0.01	-.--	-.--	-.--
Navicula sp.9	-.--	<0.01	-.--	-.--
Navicula spp.	0.03	-.--	0.02	<0.01
Navicula sp.10	-.--	-.--	<0.01	-.--
Navicula sp.14	-.--	0.01	-.--	-.--
Navicula capitoradiata Germain	0.06	-.--	0.01	0.04
Navicula mutica Kütz.	0.28	0.04	0.05	0.17
Navicula similis Krasske	-.--	<0.01	-.--	-.--
Navicula tripunctata (Müller) Bory.	0.13	<0.01	0.01	<0.01
Nitzschia acicularis (Kütz.) Sm.	0.27	0.16	0.58	0.28
Nitzschia amphibia Grun.	-.--	-.--	0.01	-.--
Nitzschia dissipata (Kütz.) Grun.	<0.01	-.--	0.02	0.02
Nitzschia linearis (Ag.)Sm.	0.02	0.08	0.02	0.01
Nitzschia palea (Kütz.) Sm.	0.03	<0.01	-.--	<0.01
Nitzschia sigmoidea (Nitzsch.) Sm.	0.05	-.--	-.--	0.01
Nitzschia sp.2	<0.01	-.--	-.--	-.--
Nitzschia sp.3	0.47	0.17	0.10	0.12
Nitzschia sp.4	-.--	-.--	-.--	<0.01
Nitzschia sp.5	0.01	-.--	-.--	<0.01
Nitzschia sp.6	0.04	-.--	-.--	<0.01
Nitzschia sp.7	0.22	0.03	0.01	0.01
Nitzschia sp.8	0.18	0.03	<0.01	<0.01
Nitzschia sp.9	0.03	0.02	<0.01	0.04
Nitzschia spp.	0.16	0.06	0.10	0.05
Nitzschia sp.10	0.06	<0.01	0.01	0.01
Nitzschia sp.11	0.05	<0.01	<0.01	0.01
Nitzschia sp.12	0.01	<0.01	<0.01	-.--
Nitzschia sp.13	<0.01	<0.01	-.--	-.--
Nitzschia sp.14	0.06	0.05	0.02	0.01
Nitzschia sp.15	0.02	0.01	<0.01	0.01
Nitzschia sp.16	<0.01	-.--	-.--	-.--
Nitzschia sp.17	0.01	<0.01	0.04	<0.01
Nitzschia sp.18	0.03	0.01	0.01	0.01
Nitzschia sp.20	0.04	<0.01	-.--	<0.01
Nitzschia sp.21	-.--	-.--	<0.01	-.--
Nitzschia sp.22	-.--	<0.01	-.--	-.--
Nitzschia sp.23	-.--	<0.01	-.--	-.--
Nitzschia sp.24	0.02	-.--	<0.01	-.--
Nitzschia sp.26	0.01	-.--	-.--	0.01
Nitzschia sp.27	0.01	0.03	-.--	<0.01
Nitzschia sp.28	0.02	-.--	-.--	-.--
Nitzschia capitellata Hustedt	-.--	0.01	<0.01	-.--
Nitzschia constricta (Kütz.) Ralfs	-.--	-.--	0.01	-.--
Nitzschia dubiae sp.1	<0.01	-.--	-.--	<0.01
Nitzschia hungarica Grun.	-.--	-.--	-.--	<0.01
Nitzschia levidensis (Sm.) Grun.	-.--	-.--	0.01	-.--

	INGLE	ABING	READ	WIND
Nitzschia sigmoid type 1	-.--	0.01	-.--	-.--
Nitzschia sublinearis Hustedt	-.--	-.--	-.--	0.19
Rhoicosphenia abbreviata (Ag.) Lange-Bertalot	0.05	0.03	0.01	<0.01
Surirella ovata Kütz.	0.04	0.04	0.01	0.02
Surirella robusta Ehr.	-.--	<0.01	-.--	-.--
Surirella spp.	0.02	-.--	-.--	-.--
Surirella brebissoniiKrammer & Lange-Bertalot	<0.01	-.--	-.--	0.01
Surirella minuta Bréb.	0.03	-.--	-.--	-.--
Synedra acus Kütz.	0.11	0.35	0.19	0.12
Synedra ulna (Nitzsch.) Ehr.	0.12	0.19	0.13	0.04
Synedra sp.2	<0.01	-.--	-.--	-.--
Synedra sp.3	-.--	-.--	0.01	-.--
Synedra sp.4	0.02	-.--	-.--	-.--
Synedra spp.	-.--	-.--	<0.01	-.--
Tabellaria spp.	0.02	-.--	-.--	-.--
pennate diatom sp.4	-.--	-.--	<0.01	-.--
pennate diatom sp.6	0.01	-.--	-.--	<0.01
pennate diatom spp.	0.82	0.15	0.09	0.12
pennate small sp.1	0.07	<0.01	-.--	-.--
Taxon group 6 - Volvocales & Tetrasporales				
Chlamydomonas monadina Stein	0.05	0.17	0.13	0.05
Chlamydomonas round large	0.04	0.10	0.15	0.04
Chlamydomonas round medium	0.50	0.70	0.60	0.29
Chlamydomonas round small	0.66	1.02	0.86	0.76
Chlamydomonas oval large	0.26	0.11	0.32	0.19
Chlamydomonas oval medium	0.89	1.03	1.22	0.64
Chlamydomonas oval small	1.03	1.34	0.96	0.90
Gonium spp.	-.--	<0.01	-.--	<0.01
Pascherina tetras (Korsh.) Silva	-.--	-.--	-.--	0.04
Taxon group 7 - Chlorococcales				
Ankistrodesmus gracilis (Reinsch) Korš.	0.08	0.23	0.16	0.19
Actinastrum hantzschii Lagerh.	-.--	-.--	<0.01	-.--
Actinastrum sp.1	-.--	0.11	-.--	0.04
Actinastrum sp.2	-.--	0.01	-.--	0.01
Chlorella round large	0.11	0.21	0.22	0.03
Chlorella round medium	2.21	1.81	1.64	2.12
Chlorella round small	16.06	14.74	13.93	14.41
Chlorella oval large	0.37	0.34	0.33	0.14
Chlorella oval medium	5.05	3.67	3.11	2.96
Chlorella oval small	57.31	29.20	26.19	29.01
Coelastrum microporum Näg.	-.--	0.10	0.16	0.14
Coelastrum pseudomicroporum Korš.	-.--	-.--	-.--	0.04
Coelastrum sp.1	0.02	0.05	0.04	0.32
Coelastrum sp.2	0.01	0.01	-.--	-.--
Coelastrum spp.	-.--	-.--	<0.01	-.--
Crucigenia tetrapedia (Kirchn.) W. & G. West	0.07	0.04	0.01	<0.01
Crucigenia apiculata (Lem.) Schmidle	0.07	0.19	-.--	-.--
Crucigenia sp.1	0.01	-.--	-.--	-.--
Dictyosphaerium pulchellum Wood	-.--	-.--	0.08	-.--
Dictyosphaerium sp.1	-.--	-.--	0.03	-.--
Dictyosphaerium spp.	-.--	-.--	0.08	-.--
Dictyosphaerium botrytella Kom. & Perm.	-.--	-.--	0.01	-.--
Didymogenes spp.	0.05	0.10	0.10	0.06
Golenkinia radiata Chodat.	-.--	0.01	-.--	-.--
Golenkinia sp.1	-.--	-.--	-.--	<0.01
Kirchneriella intermedia Korš.	0.01	-.--	-.--	-.--
Kirchneriells subcapitata Korš.	0.17	0.07	0.05	0.15
Koliella longiseta (Vischer) Hindàk	0.15	0.12	0.16	0.07

	INGLE	ABING	READ	WIND
Micractinium spp.	-.--	-.--	0.08	-.--
Monoraphidium arcuatum (Korš.) Hind.	0.09	0.29	0.34	0.45
Monoraphidium contortum (Thur.) Kom.-Legn.	0.25	0.56	0.92	0.44
Monoraphidium minutum (Näg.) Kom.-Lehn.	0.33	0.16	0.24	0.32
Oocystis sp.1	0.11	0.03	0.03	<0.01
Oocystis sp.2	-.--	<0.01	-.--	0.01
Oocystis sp.3	0.01	<0.01	-.--	-.--
Oocystis spp.	<0.01	<0.01	-.--	-.--
Pediastrum boryanum (Turp.) Menegh.	<0.01	0.04	0.01	0.02
Pediastrum duplex Mey.	-.--	0.01	-.--	-.--
Scenedesmus acuminatus (Lagerh.) Chod.	0.05	0.04	0.09	0.29
Scenedesmus obliquus (Turp.) Kütz.	<0.01	0.11	0.01	0.01
Scenedesmus quadricauda (Turp.) Bréb.	0.47	0.21	0.26	0.23
Scenedesmus spp.	-.--	-.--	-.--	<0.01
Tetraedron caudatum (Corda) Hansg.	<0.01	<0.01	<0.01	0.01
Tetraedron minimum (A. Br.) Hansg.	0.03	0.04	0.01	0.03
Tetraedron regulare (Kütz.) sensu Skuja	-.--	0.01	-.--	-.--
Tetrastrum staurogeniaeforme (Schrod.) Lemm.	0.07	0.05	0.03	0.05
Tetrastrum glabrum (Roll) Ahlstr. & Tiff.	0.09	0.02	0.15	0.15
Tetrastrum hastiferum (Arnoldi) Kors.	-.--	-.--	0.04	0.01
Tetrastrum triangulare (Chod.) Kom.	-.--	0.02	-.--	-.--
Westella botryoides (W.West) De-Wild.	0.03	1.16	0.01	0.01
Lagerheimia sp.1	-.--	-.--	<0.01	-.--
Lagerheimia genevensis (Chod.) Chod.	-.--	0.05	0.05	0.09
Golenkiniopsis sp.1	-.--	-.--	<0.01	-.--
colonial sp.1	-.--	<0.01	-.--	-.--
Klebsormidiophyceae				
Stichococcus sp.2	-.--	<0.01	<0.01	-.--
species X unknown	1.83	1.71	0.89	1.36

Taxa in bold accounted for 0.5% or greater of the total phytoplankton count at that site

Table 5.3 Dominant phytoplankton taxa expressed as rank and percentage of the total

Taxa	Inglesham (35 km)	Abingdon (101 km)	Reading (152 km)	Windsor (203 km)
Chlorella-type oval small (Chlorococcales group)	**1** (57.31%)	**1** (29.20%)	**2** (26.19%)	**2** (29.01%)
Centric diatom; excluding *Skeletonema/Melosira* (Centric diatom group)	**3** (5.48%)	**2** (28.12%)	**1** (34.78%)	**1** (31.03%)
Chlorella-type round small (Chlorococcales group)	**2** (14.06%)	**3** (14.74%)	**3** (13.93%)	**3** (14.41%)
Rhodomonas minuta Skuja. (Euglenophyta/Cryptophyta group)	**7** (1.13%)	**4** (6.99%)	**4** (4.52%)	**4** (4.66%)
Chlorella-type oval medium (Chlorococcales group)	**4** (5.05%)	**5** (3.67%)	**6** (3.11%)	**5** (2.96%)
Skeletonema potamos (Weber) Hasle (Centric diatom group)	none	**19** (0.27%)	**5** (3.41%)	**6** (2.95%)
Chlorella-type round medium (Chlorococcales group)	**5** (2.21%)	**6** (1.81%)	**7** (1.64%)	**7** (2.12%)
Percentage of phytoplankton counts attributed to dominant taxa	85.24%	84.80%	84.17 %	84.19%

In **bold** is the rank, in terms of algal units mL^{-1}, of that taxa at each site. In brackets is the percentage of the total phytoplankton density that the taxa makes up.

Fig. 5.1 Total phytoplankton density at four sites

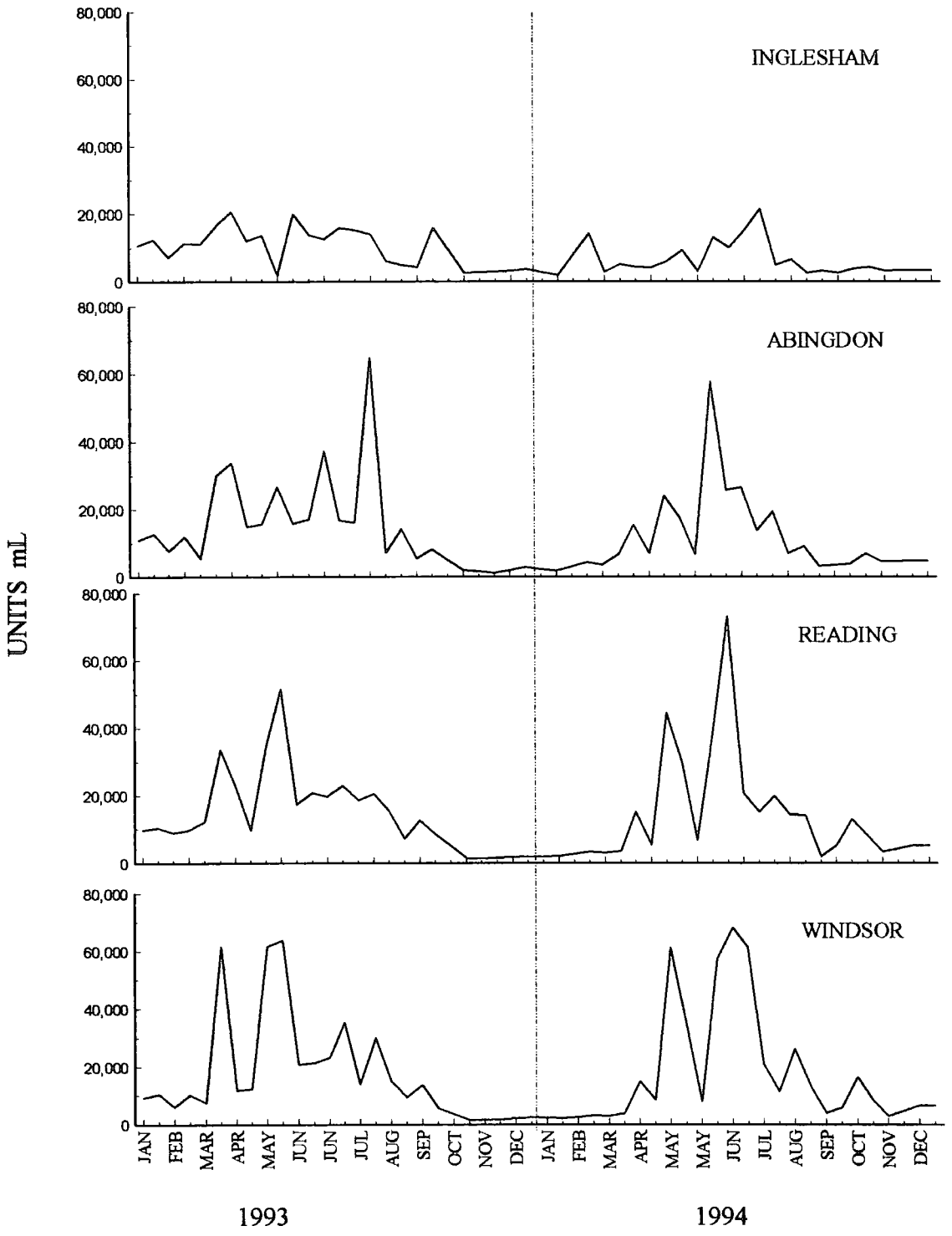
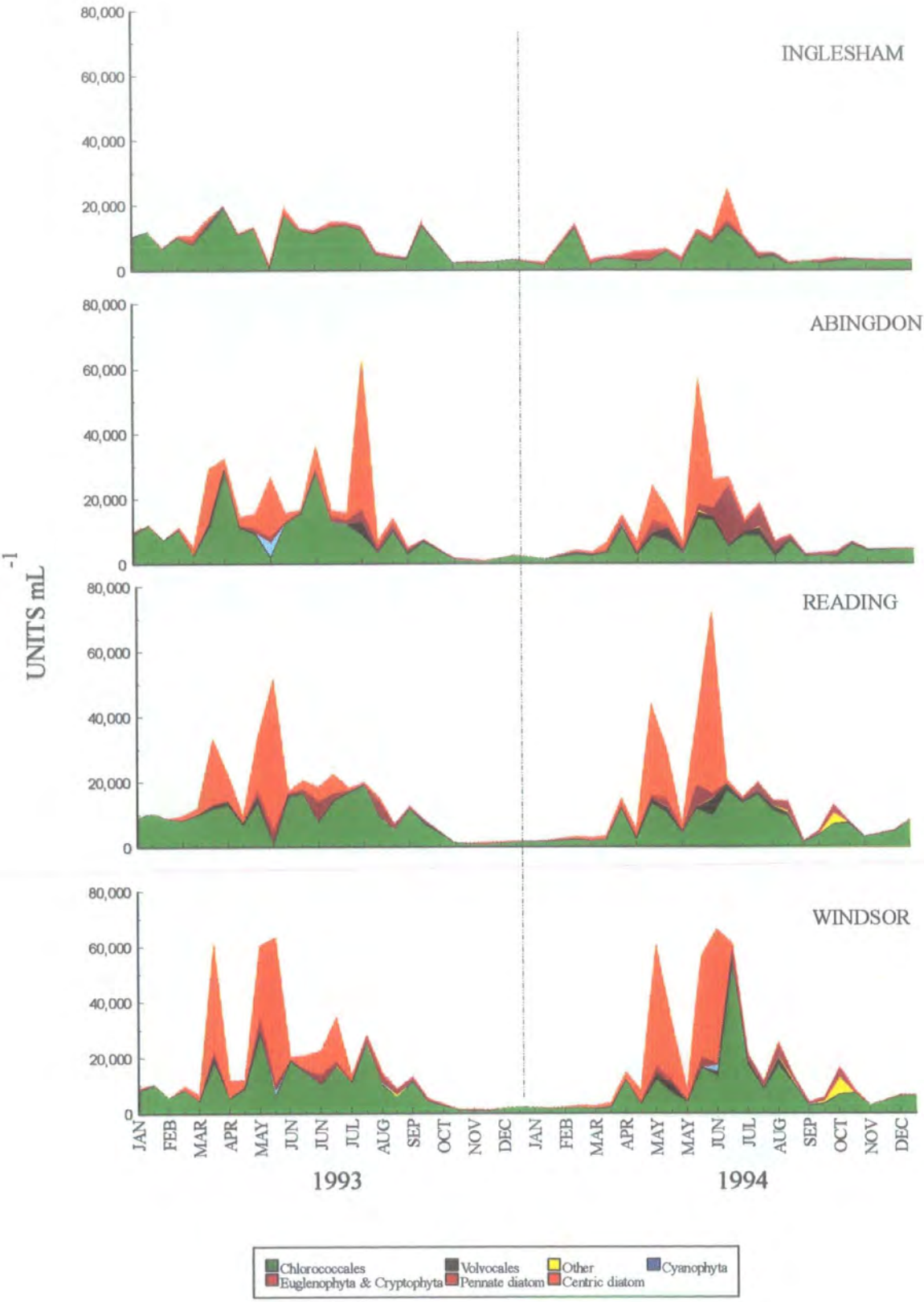
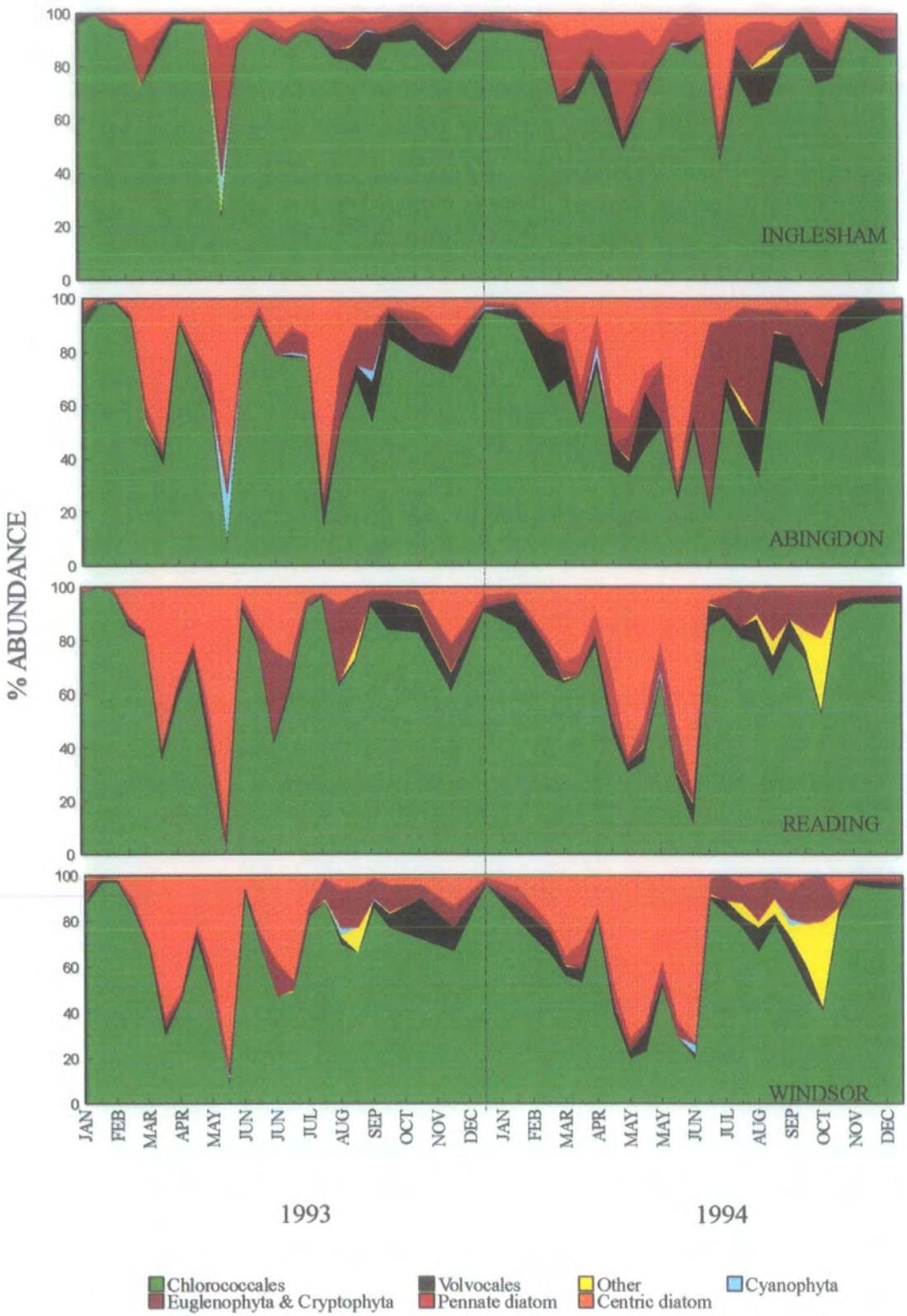


Fig. 5.2 Phytoplankton density of seven taxon groups at four sites



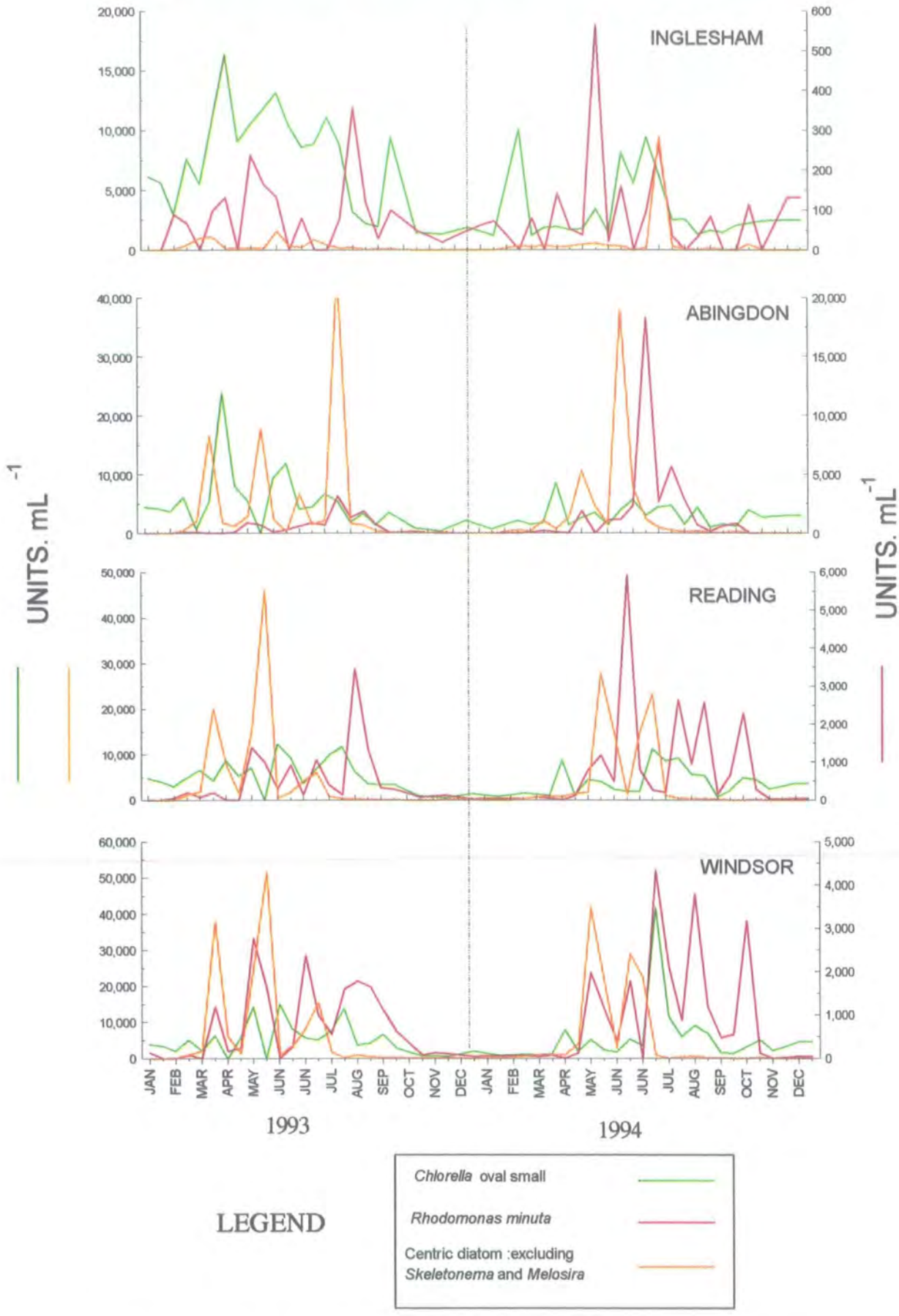
2Y4TAX.PRE

Fig. 5.3 Percentage abundance of seven phytoplankton Taxon Groups at four sites



2Y%TAX.PRE

Fig. 5.4 Density of three common taxa: *Chlorellla*-type oval small, *Rhodomonas minuta* and Centric diatoms :excluding *Skeletonema* and *Melosira*



Left Y-axis scale corresponds to *Chlorella* type oval small and Centric diatom:excluding *Skeletonema/Melosira*

Right Y-axis scales corresponds to *Rhodomonas minuta* Skuja.

2YDOMTAX.PRE

Chapter 6

Phytoplankton dynamics in relation to environmental factors

6.1 Background to Chapter 6

Phytoplankton density and composition have been shown to follow a crude seasonal pattern: density was greatest in spring, then decreased throughout summer and autumn, to lowest levels during the winter.

In this chapter the relationship between observed phytoplankton patterns and environmental variables will be statistically investigated, and significant relationships highlighted as possible causes or effects of observed patterns in phytoplankton.

The data were split into sites and seasons to investigate the inter-relationships between phytoplankton and environmental variables. Spearman's Rank Correlation Co-efficient technique was used to test correlations.

Only spring and summer/autumn seasons were examined due to the importance of understanding the relationships between phytoplankton density, species composition and environmental variables during this period. These are the seasons when phytoplankton are abundant, problematic for water treatment for supply and discharge augmentation by potential regulation schemes would occur. It is particularly important to understand the effects of environmental variables on phytoplankton dynamics of which river regulation schemes could alter, such as discharge, water clarity and temperature.

Improved understanding of the effects river management have on phytoplankton density, species composition and related water quality parameters will hopefully lead to more effective, environmentally-sensitive river management.

6.2 Co-variable and weather/discharge related environmental variables

6.2.1 Co-variable environmental variables

A number of the original fifteen environmental variables were expected to be correlated with each other over the two year study. This was confirmed by a Spearman's Rank Correlation Co-efficient of all the environmental data over the period of the study (Appendices 2a-2d).

Table 6.1 summarises the pairs of variables that were positively correlated at the 0.1 percent level, approaching perfect correlations, at all four sites during the whole study period. These were; mean discharge on the sampling day (Discharge 1) and ten days prior to sampling (Discharge 10), total sunlight hours over the seven days prior to sampling (Sun 7) and fourteen days prior to sampling (Sun 14), soluble reactive - P and total oxidised - P, NO_3 - N and total oxidised - N.

The co-variable environmental factors were recognised, however they were still included in the Spearman's Rank Correlation Co-efficient analysis to test whether one of the co-variables was better correlated to phytoplankton density and composition than the other. It is especially interesting to compare the relationship between phytoplankton and the same environmental variable measured over different time spans, for example sunlight hours over the seven and fourteen days prior to sampling (Sun 7 and Sun 14), or discharge on the sampling day and ten days prior to sampling (Discharge 1 and Discharge 10).

6.2.2 Weather and discharge related environmental variables

Seasonal waether patterns affect many of the environmental variables measured in the current study, either directly or indirectly. For example, rainfall has a great impact on the river environment because it affects river discharge which in turn directly affects water chemistry by dilution and run off.

It is important to establish which environmental variables are significantly correlated with weather factors such as sunlight hours, water temperature and river discharge (via rainfall). Only then can relationships between phytoplankton density, composition and environmental factors be understood more fully in later analysis.

River regulation schemes will chiefly alter river discharge regimes, therefore it is important to investigate the effects of discharge on other environmental factors. The relationship between Discharge 10 and other environmental variables over the two year period was investigated by calculating Spearman's Rank Correlation Co-efficient. The results are summarised in Table 6.2 and are available in full in Appendix 2a-2d.

Table 6.2 shows that low Discharge 10 is associated (P=0.1%) with high water temperature, high sunlight hours (seven and fourteen days prior to sampling), high water clarity, high total oxidised - P and high soluble reactive - P at all sites. At Abingdon, Reading and Windsor high chlorophyll *a* was associated, to a lesser degree (P=5%) with low discharge.

High discharge 10 is associated (P=0.1%) with high Discharge 1, high total oxidised - N and high NO_3 - N at Abingdon (101 km), Reading (152 km) and Windsor (203 km). This relationship did not occur at Inglesham.

The relationship between NO_2 - N, NH_4 - N, SiO_2, dissolved oxygen and discharge 10 was less clear. There was no correlation between discharge 10 and pH at any site when the whole study period was analysed together.

6.3 Phytoplankton density in relation to environmental variables in different seasons

6.3.1 Spring

Significant correlations between phytoplankton density and environmental variables during spring are summarised in Table 6.3, and in full in Appendices 3a-3d.

Phytoplankton density was negatively correlated with water clarity, at a five percent level, at all

sites except Inglesham (35 km) (Table 6.3).

Out of the fifteen environmental variables, the same six were either positively or negatively significantly correlated (P=5%) with phytoplankton density at Reading (152 km) and Windsor (203 km) (Table 6.3). It is interesting that a significant negative correlation (P=5%) exists between phytoplankton density and mean discharge over the ten days prior to sampling (Discharge 10) at Reading and Windsor but not between phytoplankton density and discharge on the sampling day (Discharge 1) at the same sites (Table 6.3). A similar pattern occurred with sunlight hours. A significant positive correlation (P=5%) exists between sunlight hours over the fourteen days prior to sampling (Sun 14) and phytoplankton density at Reading (152 km) and Windsor (203 km), but the sunlight hours over the seven days prior to sampling (Sun 7) were not significantly (P=5%) correlated with phytoplankton density.

Phytoplankton density was correlated positively (P=5%) with pH and percentage dissolved oxygen, and negatively correlated with silica concentration at Reading (152 km) and Windsor (203 km) .

At Inglesham (35 km) phytoplankton density was not significantly correlated (P=5%) with any of the environmental variables (Table 6.3).

Chlorophyll *a* was not significantly correlated (P=5%) with phytoplankton density at any sites.

6.3.2 Summer and autumn

Significant correlations between phytoplankton density and environmental variables during summer and autumn are summarised in Table 6.4 and in full in Appendices 4a-4d.

Phytoplankton density was negatively correlated (P=5%) with water clarity, and positively correlated (P=1% or 5%) with chlorophyll *a* concentration at all sites.

The relationship between other environmental variables and phytoplankton density in the summer/autumn season was less clear than in spring.

Discharge on the day of sampling (Discharge 1) was not significantly correlated (P=5%) with phytoplankton density at any sites. At Reading (152 km), the mean discharge over the ten days prior to sampling (Discharge 10), was correlated negatively (P=5%) with phytoplankton density. During spring however, the opposite was true and Discharge 10 was negatively correlated (P=5%) with phytoplankton density at Reading (152 km).

At Windsor (203 km) alone were the sunlight hours for the seven and fourteen days prior to sampling (Sun 7 and 14) positively correlated (P=1%) with phytoplankton density.

6.4 Relationships between dominant taxon groups and environmental variables in the spring season

6.4.1 Chlorococcales group in relation to environmental variables during spring

Significant correlations between Chlorococcales density and environmental variables are summarised in Table 6.5.

Few environmental variables were significantly correlated with Chlorococcales density in the spring season.

At Windsor (203 km) there was a significant positive correlation (P=5%) between Chlorococcales density and pH, percentage dissolved oxygen and negative correlation (P=5%) with water clarity.

Density of Chlorococcales was negatively correlated (P=5%) with Chlorophyll *a* at Inglesham (35 km), but positively correlated (P=5%) with total phytoplankton density.

None of the environmental variables were significantly (P=5%) correlated with Chlorococcales density at Abingdon (101 km) or Reading (152 km).

6.4.2 Centric diatom group in relation to environmental variables during spring

Significant correlations between Centric diatom density and environmental variables are summarised in Table 6.6. Centric diatom density was negatively correlated (P=5%) or (P=1%) with discharge on the sampling day (Discharge 1) and mean discharge over the ten days preceding sampling (Discharge 10) at Abingdon (101 km), Reading (152 km) and Windsor (203 km), but not Inglesham (35 km).

The sunlight hours over the fourteen days prior to sampling (Sun 14) were highly significantly (P=1%) or significantly (P=5%) positively correlated with centric diatom density at Abingdon (101 km), Reading (152 km) and Windsor (203 km), but not Inglesham (35 km). The sunlight hours over the seven days preceding sampling were not significantly (P=5%) correlated to centric diatom density at any site.

A strong negative correlation (P=1%) exists between Silica concentration and density of centric diatoms at Abingdon (101 km), Reading (152 km) and Windsor (203 km), but not Inglesham (35 km).

Centric diatom density was positively correlated (P=5%) with both pH and percentage dissolved oxygen at Reading (152 km) and Windsor (203 km) only.

Water clarity was not significantly correlated with centric diatom density at any sites.

6.5 Relationships between dominant taxon groups and environmental variables in the summer and autumn season

6.5.1 Chlorococcales density in relation to environmental variables in summer and autumn

Significant correlations between Chlorococcales density and environmental variables during summer and autumn are summarised in Table 6.7.

As in spring, there were very few environmental variables significantly correlated with

Chlorococcales density in the summer/autumn season.

At Inglesham (35 km) and Abingdon (101 km), Chlorococcales density was positively correlated (P=5%) with discharge on the sampling day (Discharge 1) but not the mean discharge over the ten days prior to sampling (Discharge 10). At the same sites, water clarity was negatively correlated (P=1% and 5%) with Chlorococcales density.

Chlorococcales density was positively correlated (P=1% or 5%) with total phytoplankton density at all sites, however chlorophyll *a* was only positively correlated (P=5%) with Chlorococcales density at Abingdon (101 km).

6.5.2 Euglenophyta and Cryptophyta density in relation to environmental variables in summer and autumn

Significant correlations between Euglenophyta/Cryptophyta density and environmental variables during summer and autumn are summarised in Table 6.8.

At Abingdon (101 km) Eugenophyta/Crytophyta taxon group density was negatively correlated (P=5%) with discharge on the sampling day (Discharge 1) and the mean discharge over the ten days preceding sampling (Discharge 10).

At Abingdon (101 km) and Windsor (203 km) sunlight hours over the seven days prior to sampling (Sun 7) were positively correlated (P=1% or 5%) with the density of this group, but sunlight hours over the fourteen days prior to sampling were not significantly correlated (P=5%) with the Euglenophyta/Crytoptophyta density.

Water temperature was also positively correlated (P=5%) with the density of this group at Abingdon (101 km) and Windsor (203 km).

A negative correlation between NO_2-N and NH_4-N (P=1% and 5%) with density of this group was noted at Windsor (203 km).

6.6 Density of three common taxa in relation to environmental variables

The relationship between individual phytoplankton taxa and environmental variables was further investigated by focusing on three common taxa from three different taxon groups. The chosen taxa *Chlorella* -type oval small, centric diatoms:excluding *Melosira/Skeletonema* and *Rhodomonas minuta*. Correlations between these taxa and environmental variables were only tested during seasons when the taxon group the taxon was classified as were dominant.

6.6.1 *Chlorella*-type oval small in relation to environmental variables during spring and summer/autumn seasons

Significant correlations between *Chlorella*-type oval small density and environmental variables are summarised in Table 6.9.

The density of *Chlorella*-type oval small was significantly correlated with few environmental variables in spring or summer/autumn seasons and was not correlated with any variables at Reading (152 km) or Windsor (203 km).

At Inglesham (35 km) *Chlorella*-type oval small density was negatively correlated with chlorophyll *a* and water clarity, and positively correlated with total phytoplankton density and discharge on the sampling day (Discharge 1) and NO_2 - N.

At Inglesham (35 km) and Abingdon (101 km) certain environmental variables were significantly correlated with the density of this taxa, however there was no repeatable pattern of correlations from site to site or between seasons.

6.6.2 Centric diatoms:excluding *Skeletonema/ Melosira* in relation to environmental variables during spring

The relationship between centric diatoms:excluding *Skeletonema/Melosira* and environmental variables was only examined during spring as this was the period when these taxa are most

abundant.

Significant correlations between centric diatoms:excluding *Skeletonema/Melosira* density and environmental variables are summarised in Table 6.10.

At all sites, except Inglesham (35 km), increased density of this taxonomic group was negatively correlated (P=5%) with discharge on the day of sampling (Discharge 1) and more strongly negatively correlated (P=1%) with the mean discharge over the ten days preceding sampling (Discharge 10).

At Inglesham (35 km) the converse was true and a positive correlation exists between density of these taxa and Discharge 1 (P=5%) and Discharge 10 (P=1%).

There was a significant positive correlation (P=5%) between the density of these taxa and the total sunlight hours over the fourteen days preceding sampling (Sun 14) at all sites except Inglesham (35 km). The total sunlight hours over the seven days prior to sampling (Sun 7) was only significantly positively correlated (P=5%) with density of these taxa at Abingdon (101 km).

A negative correlation (P=5%) exists between Silica concentration and density of centric diatoms:excluding *Melosira/Skeletonema* at Abingdon (101 km), Reading (152 km) and Windsor (203 km). This relationship did not exist at Inglesham (35 km).

A significant positive correlation (P=5%) between pH and this taxa exists at Reading (152 km) and Windsor (203 km).

6.6.3 *Rhodomonas minuta* density in relation to environmental variables during the summer and autumn season

Significant correlations between *Rhodomonas minuta* density and environmental variables during summer and autumn are summarised in Table 6.11.

The relationship between *Rhodomonas minuta* and environmental variables was only examined during the summer and autumn season as this was the period when this taxon is most

abundant.

Density of *Rhodomonas minuta* was negatively correlated, at a five percent significance level, with the mean discharge over the ten days preceding sampling (Discharge 10) at Abingdon (101 km) and Windsor (203 km). The density of this taxon was also negatively correlated (P=5%) with discharge on the sampling day (Discharge 1) at Abingdon (101 km).

Water temperature and sunlight hours over the seven days prior to sampling (Sun 7) were both positively correlated with density of *Rhodomonas minuta* at a one percent significance level at Abingdon (101 km) and five percent significance level at Windsor (203 km).

None of the environmental variables were significantly correlated with density of *Rhodomonas minuta* at Inglesham (35 km) or Reading (152 km).

6.6 Comments on chapter 6

The statistically significant associations between phytoplankton density, species composition and environmental factors are summarised in Tables 6.12 and 6.13.

Table 6.1 Co-variable environmental variables positively correlated at the 0.1 percent level or P=0.001 at all sites during 1993 and 1994 using Spearman's Rank Correlation Co-efficient

Discharge 1	Discharge 10
Sun 7	Sun 14
Soluble reactive - P	Total oxidised - P
NO_3 - N	Total oxidised - N

Appendix 2a-2d contain all Spearman's Rank Correlation Co-efficient solutions.

Table 6.2 Summary of significant positive and negative correlations between Discharge 10 and other environmental variables during the whole study period using Spearman's Rank Correlation Co-efficient (Appendicies 2a-2d)

	Inglesham (35 km)	Abingdon (101 km)	Reading (152 km)	Windsor (203 km)
Discharge 1	○○○	○○○	○○○	○○○
Water temperature	●●●	●●●	●●●	●●●
Sun 7	●●●	●●●	●●●	●●●
Sun 14	●●●	●●●	●●●	●●●
Water clarity (Secchi depth)	●●●	●●●	●●●	●●●
pH				
Dissolved oxygen				
Total oxidised - P	●●●	●●●	●●●	●●●
Soluble reactive - P	●●●	●●●	●●●	●●●
Total oxidised - N		○○○	○○○	○○○
NO_3 - N		○⊙○	○⊙○	○⊙⊙
NO_2 - N		●	●	⊙⊙○
NH_4 - N			⊙○	○
SiO_2	●	○		
Chlorophyll-*a*		●●	●●	●

N = 45 - 2 d.f. = 43

Positive correlation		classification	Negative correlation	
⊙	P=0.05 or 5%	significant	●	P=0.05 or 5%
⊙○	P=0.01 or 1%	highly significant	●●	P=0.01 or 1%
⊙⊙⊙	P=0.001 or 0.1%	extremely significant	●●●	P=0.001 or 0.1%

Table 6.3 Significant positive and negative correlations between phytoplankton density and environmental variables in spring using Spearman's Rank Correlation Co-efficient. (Appendicies 3a-3d)

	Inglesham (35 km)	Abingdon (101 km)	Reading (152 km)	Windsor (203 km)
Discharge 1				
Discharge 10			OO	O
Water temperature				
Sun 7				
Sun 14			◉	◉
Water clarity (Secchi depth)		O	O	O
pH			◉	◉
% D.O.			◉	◉
Total - P				
Soluble reactive - P				
Total oxidised - N				
NO_3 - N				
NO_2 - N		◉		
NH_4 - N				
SiO_2			O	O
Chlorophyll-*a*				

N = 12 - 2 d.f = 10

	Positive correlation	classification	Negative correlation	
◉	P=0.05 or 5%	significant	O	P=0.05 or 5%
◉◉	P=0.01 or 1%	highly significant	OO	P=0.01 or 1%
◉◉◉	P=0.001 or 0.1%	extremely significant	OOO	P=0.001 or 0.1%

Table 6.4 Significant positive and negative correlations between phytoplankton density and environmental variables in summer and autumn using Spearman's Rank Correlation Co-efficient. (Appendicies 4a-4d)

	Inglesham (35 km)	Abingdon (101 km)	Reading (152 km)	Windsor (203 km)
Discharge 1				
Discharge 10			O	
Temperature		O		
Sun 7				OO
Sun 14				⊙⊙
Water clarity (Secchi depth)	O	O	O O	O
pH		OO		
% D.O.				
Total - P			O	
Soluble reactive - P			O O	
Total oxidised - N				
NO_3 - N				
NO_2 - N	⊙	⊙		
NH_4 - N				
SiO_2		O	O	
Chlorophyll-a	O	⊙O	⊙⊙	⊙⊙

N = 18 - 2 d.f = 16

	Positive correlation	classification		Negative correlation
⊛	P=0.05 or 5%	significant	O	P=0.05 or 5%
⊛⊛	P=0.01 or 1%	highly significant	OO	P=0.01 or 1%
⊛⊛⊛	P=0.001 or 0.1%	extremely significant	OOO	P=0.001 or 0.1%

Table 6.5 Significant positive and negative correlations between Chlorococcales density and environmental variables during spring using Spearman's Rank Correlation Co-efficient

	Inglesham (35 km)	Abingdon (101 km)	Reading (152 km)	Windsor (203 km)
Discharge 1				
Discharge 10				
Water temperature				
Sun 7				
Sun 14				
Water clarity (Secchi depth)				○
pH				●
Dissolved oxygen				●
Total oxidised - P				
Soluble reactive - P				
Total oxidised - N				
NO_3 - N				
NO_2 - N				
NH_4 - N				
SiO_2				
Chlorophyll-*a*	○			
Total phytoplankton density	●			

n=12-2 d.f =10

Positive correlation	classification	Negative correlation
●P=0.05 or 5%	significant	○P=0.05 or 5%
●●P=0.01 or 1%	highly significant	○○P=0.01 or 1%
●●●P=0.001 or 0.1%	extremely significant	○○○P=0.001 or 0.1%

Table 6.6 Significant negative and positive correlations between Centric diatom taxon group density and environmental variables during spring using Spearman's Rank Correlation Coefficient

	Inglesham (35 km)	Abingdon (101 km)	Reading (152 km)	Windsor (203 km)
Discharge 1		OO	O	O
Discharge 10		O	O	OO
Water temperature				O
Sun 7				
Sun 14		OO	O	O
Water clarity (Secchi depth)				
pH			O	O
Dissolved oxygen			O	O
Total oxidised - P				
Soluble reactive - P				
Total oxidised - N				
NO_3 - N				
NO_2 - N				
NH_4 - N	●		O	
SiO_2		OO	OO	OO
Chlorophyll-*a*				
Total phytoplankton density			●●	●●

n=12-2d.f=10

Positive correlation	classification	Negative correlation
●P=0.05 or 5%	significant	OP=0.05 or 5%
●●P=0.01 or 1%	highly significant	OOP=0.01 or 1%
●●●P=0.001 or 0.1%	extremely significant	OOOP=0.001 or 0.1%

Table 6.7 Significant negative and positive correlations between Chlorococcales density and environmental variables during summer and autumn using Spearman's Rank Correlation Coefficient.

	Inglesham (35 km)	Abingdon (101 km)	Reading (152 km)	Windsor (203 km)
Discharge 1	○	○		
Discharge 10				
Water temperature				
Sun 7				
Sun 14				
Water clarity (Secchi depth)	○○	○		
pH				
Dissolved oxygen				
Total oxidised - P				
Soluble reactive - P				
Total oxidised - N		◉		
NO_3 - N		◉		
NO_2 - N				
NH_4 - N				
SiO_2				
Chlorophyll-*a*		●		
Total phytoplankton density	●●	●●	●	●●

N = 18 - 2 d.f = 16

Positive correlation	classification	Negative correlation
●P=0.05 or 5%	significant	○P=0.05 or 5%
●●P=0.01 or 1%	highly significant	○○P=0.01 or 1%
◉◉◉P=0.001 or 0.1%	extremely significant	○○○P=0.001 or 0.1%

Table 6.8 Significant negative and positive correlations between Euglenophyta/Cryptophyta taxon group density and environmental variables during summer and autumn using Spearman's Rank Correlation Co-efficient

	Inglesham (35 km)	Abingdon (101 km)	Reading (152 km)	Windsor (203 km)
Discharge 1		O		
Discharge 10		O		
Water temperature		OO		O
Sun 7		OO		O
Sun 14				
Water clarity (Secchi depth)				
pH			O	
Dissolved oxygen				
Total oxidised - P				
Soluble reactive - P				
Total oxidised - N				
NO_3 - N				
NO_2 - N				O
NH_4 - N				OO
SiO_2				
Chlorophyll-*a*				
Total phytoplankton density	⊛			

N = 18 - 2 d.f = 16

Positive correlation	Classification	Negative correlation
⊛P=0.05 or 5%	significant	OP=0.05 or 5%
⊛⊛P=0.01 or 1%	highly significant	OOP=0.01 or 1%
⊛⊛⊛P=0.001 or 0.1%	extremely significant	OOOP=0.001 or 0.1%

Table 6.9 Significant positive and negative correlations between *Chlorella*-type oval small density and environmental variables during spring and summer/autumn seasons using Spearman's Rank Correlation Co-efficient

Site	Inglesham (35 km)		Abingdon (101 km)		Reading (152 km)		Windsor (203 km)	
Season	Spring	Summer Autumn	Spring	Summer Autumn	Spring	Summer Autumn	Spring	Summer Autumn
Discharge 1		●						
Discharge 10								
Water temperature								
Sun 7								
Sun 14								
Water clarity (Secchi depth)		OO						
pH								
Dissolved oxygen								
Total oxidised - P								
Soluble reactive - P								
Total oxidised - N								
NO_3 - N								
NO_2 - N		●●						
NH_4 - N								
SiO_2								
Chlorophyll-*a*	O							
Total phytoplankton density	●●			●				

N = 18 - 2 d.f = 16

Positive correlation	classification	Negative correlation
●P=0.05 or 5%	significant	OP=0.05 or 5%
●●P=0.01 or 1%	highly significant	OOP=0.01 or 1%
●●●P=0.001 or 0.1%	extremely significant	OOOP=0.001 or 0.1%

Table 6.10 Significant negative and positive correlations between Centric diatoms:excluding *Skeletonema* and *Melosira* density and environmental variables during spring using Spearman's Rank Correlation Co-efficient

	Inglesham (35 km)	Abingdon (101 km)	Reading (152 km)	Windsor (203 km)
Discharge 1	⊙	OO	O	O
Discharge 10	●●	OO	OO	OO
Water temperature				⊕
Sun 7		◔		
Sun 14		●●	●	●
Water clarity (Secchi depth)				
pH				
Dissolved oxygen				
Total oxidised - P				
Soluble reactive - P	O			
Total oxidised - N				
NO_3 - N				
NO_2 - N	●			
NH_4 - N	●		O	
SiO_2		OO	OO	O
Chlorophyll-*a*				
Total phytoplankton density			●●	●

n=12-2d.f=10

Positive correlation classification — Negative correlation

●P=0.05 or 5% significant — OP=0.05 or 5%

●●P=0.01 or 1% highly significant — OOP=0.01 or 1%

●●●P=0.001 or 0.1% extremely significant — OOOP=0.001 or 0.1%

Table 6.11 Significant negative and positive correlations between *Rhodomonas minuta* density and environmental variables during summer and autumn using Spearman's Rank Correlation Co-efficient

	Inglesham (35 km)	Abingdon (101 km)	Reading (152 km)	Windsor (203 km)
Discharge 1		O		O
Discharge 10		O		
Water temperature		OO		O
Sun 7		OO		O
Sun 14				
Water clarity (Secchi depth)				
pH				
Dissolved oxygen				
Total oxidised - P				
Soluble reactive - P				
Total oxidised - N		O		
NO_3 - N				
NO_2 - N				
NH_4 - N				O
SiO_2				
Chlorophyll-*a*				
Total phytoplankton density				

N = 18 - 2 d.f = 16

Positive correlation	classification	Negative correlation
⊙ P=0.05 or 5%	significant	O P=0.05 or 5%
⊙⊙ P=0.01 or 1%	highly significant	OO P=0.01 or 1%
⊙⊙⊙ P=0.001 or 0.1%	extremely significant	OOOP=0.001 or 0.1%

Table 6.12 Summary of environmental variables associated, at a five percent or greater probability level, with high densities of total phytoplankton, dominant taxon groups and dominant taxa during the spring season

			Inglesham (35 km)	Abingdon (101 km)	Reading (152 km)	Windsor (203 km)
SPRING		Environmental variables associated (P=5% or greater) with HIGH total phytoplankton density at different sites	None	high NO_3 - N low water clarity	high sun 14, high pH, high % D.O. low water clarity, low discharge 10 low SiO_2	high sun 14, high pH, high % D.O. low water clarity, low discharge 10 low SiO_2
		Environmental variables associated (P=5% or greater) with HIGH CHLOROCOCCALES DENSITY	high phytoplankton low Chlorophyll *a*	none	none	high pH, high % D.O. low water clarity
		Environmental variables associated (P=5% or greater) with HIGH CENTRIC DIATOM DENSITY	high NH_4 - N	high Sun 14 low discharge 1, low discharge 10 low SiO_2	high Sun 14,high pH, high % D.O. high phytoplankton low discharge 1, low discharge 10 low NH_4 - N, low SiO_2	high water temp high Sun 14, high pH' high % D.O. high phytoplankton low discharge 1, low discharge 10 low SiO_2
		Environmental variables associated (P=5% or greater) with HIGH *CHLORELLA*-TYPE OVAL SMALL DENSITY	high phytoplankton low Chlorophyll *a*	none	none	none
		Environmental variables associated (P=5% or greater) with HIGH CENTRIC DIATOM: EXCLUDING *SKELETONEMA & MELOSIRA* DENSITY	high discharge 1, high discharge 10 low soluble reactive P high NO_3 - N, high NH_4 - N	high sun7, high sun 14 low discharge 1, low discharge 10 low SiO_2	high sun 14, high phytoplankton low discharge 1, low discharge 10 low NH_4 - N low SiO_2	high water temp high sun 14, high phytoplankton low discharge 1, low discharge 10 low SiO_2

[1] Associations are calculated by Spearman's Rank Correlation Co-efficient, therefore low densities of phytoplankton, taxon group and dominant taxa have the converse association with environmental variables to the high phytoplankton densities

Table 6.13 Summary of environmental variables associated, at a five percent or greater probability level, with high densities of total phytoplankton, dominant taxon groups and dominant taxa during the summer and autumn season

			Inglesham (35 km)	Abingdon (101 km)	Reading (152 km)	Windsor (203 km)
SUMMER & AUTUMN		Environmental variables associated (P=5% or greater) with HIGH total phytoplankton density at different sites	high NO_3 - N high Chlorophyll *a* low water clarity	high water temp,high pH high NO_3 - N, high Chlorophyll *a* low water clarity low SiO_2	high discharge 10 high Chlorophyll *a* low water clarity low soluble reactive - P low total - P, low SiO_2	high sun 7, high sun 14 high Chlorophyll *a* low water clarity
		Environmental variables associated (P=5% or greater) with HIGH CHLOROCOCCALES DENSITY	high discharge 1 high total phytoplankton low water clarity	high discharge 1 high total oxidised - N, high NO_3 - N high Chlorophyll *a* high total phytoplankton low water clarity	high total phytoplankton	high total phytoplankton
		Environmental variables associated (P=5% or greater) with HIGH EUGLENOPHYTA & CRYPTOPHYTA DENSITY	high total phytoplankton	high water temp, high sun 7 low discharge 1, low discharge 10	high pH	high water temp, high sun 7 low NO_3 - N, low NH_4 - N
		Environmental variables associated (P=5% or greater) with HIGH *CHLORELLA*-TYPE OVAL SMALL DENSITY	high discharge 1, high NO_3 - N low water clarity	high total phytoplankton	none	none
		Environmental variables associated (P=5% or greater) with HIGH *RHODOMONAS MINUTA* SKUJA. DENSITY	none	high water temp, high sun 7 low discharge 1, low discharge 10 low total oxidised - N	none	high water temp, high sun 7 low discharge 10 low NH_4 - N

[2]Associations are calculated by Spearman's Rank Correlation Co-efficient, therefore low densities of phytoplankton, taxon group and dominant taxa have the converse association with environmental variables to the high phytoplankton densities

Chapter 7

General discussion

7.1 The Thames issue

The Thames is a lowland, eutrophic, highly regulated river under great anthropomorphogenic pressure from navigation, effluent discharges, abstraction for public water supply and periodic seasonal low flows. Surprisingly, the Thames has good chemical and biological quality, supporting a diverse, but highly modified,flora and fauna (Chapter 2.1.5).

Future water supply shortages have been predicted for the Thames catchment, and in particular the London area. The Thames is a major source of water for supply. During low flow periods the Thames has insufficient water to meet the forthcoming increased demand. Schemes are proposed to increase discharge in the Thames during low flow periods by discharge augmentation in the upper or middle Thames from a reservoir or inter-basin water transfer. The increased discharge would then be abstracted from the lower Thames in the area of highest demand, London. Often the demands of the water system for supply are in direct contrast to the requirements of the environment in terms of both volumes and timings of flows. It is important to understand the ecological, physical and chemical implications to the Thames of proposed schemes.

The inter-relationships between the ecology of the Thames and physical and chemical factors and are not well understood. Nor are the implications of river management to river ecology (Chapter 1). Phytoplankton is the main primary producer in the Thames (Kowalczewski & Lack, 1971) and play a key role in the river ecosystem (Berrie, 1972).

The Environment Agency has the task of maintaining and improving the Thames through the correct use of these schemes based on the best possible understanding of the Thames ecosystem. This thesis is part of a multidisciplinary baseline study of the Thames to supply additional information for river management.

7.2 Spatial and seasonal distribution of phytoplankton

Phytoplankton density varied seasonally and spatially along the Thames (Fig. 5.1). Seasonal changes occurred similarly and simultaneously throughout the year at sites spread over 167 km. The similarity was strongest between the downstream sampling sites, Abingdon (101 km), Reading (152 km) and Windsor (203 km), and to a lesser degree at Inglesham (35 km) (Fig. 5.1). Lack *et al.*, (1978) also observed simultaneous chlorophyll *a* maxima at six sites over 21 km in the middle reaches of the Thames during the spring algal bloom.

Phytoplankton density followed a seasonal pattern: lowest during winter, rapidly increased to a spring maximum, followed by a decline during summer and autumn (Fig. 5.1). This is a similar pattern to other large, lowland, temperate region rivers (Chapter 1.2). Seasonal patterns in phytoplankton density in 1993 were repeated in 1994, however the spring maxima in 1994 occurred one month later than in 1993 (Fig. 5.1).

The magnitude of seasonal variation in phytoplankton density changed spatially. Seasonal variation was greater at sites further from source. This could be seen by the difference in the standard error of the mean for phytoplankton density in 1993 and 1994 (Table 5.1). At Abingdon (101 km), Reading (152 km) and Windsor (203 km) the standard error of the mean were surprisingly similar, but twice the value for Inglesham (35 km), the most upstream site.

Phytoplankton populations are constantly being washed downstream. The speed of washing out varies with discharge velocity. At high discharge (283 m^3 s^{-1} at Teddington Weir) modelled discharge takes approximately 7 days to travel from source to Windsor (203 km). This can be broken down into time of travel between sites as follows: source to Inglesham <1 day, Inglesham to Abingdon 1 day, Abingdon to Reading 2 days, Reading to Windsor 2½ days. During low discharge periods (25.5 m^3 s^{-1} at Teddington Weir) modelled discharge takes approximately 32 days to travel from source to Windsor (203 km). This can be broken down into time of travel between sites: source to Inglesham 2 days, Inglesham to Abingdon 12 days, Abingdon to Reading 10 days, Reading to Windsor 8 days.

Phytoplankton population near the source of the Thames has less time to replicate than a site 100 km downstream. If time of travel, and thus time for replication by phytoplankton, were the only control over phytoplankton density a continued increase

in phytoplankton density downstream, in proportion to time of travel between sites, would be expected. Mean phytoplankton density did increase with increased distance from source, but not in proportion to the time of travel. Maximum phytoplankton densities were similar at Abingdon, Reading and Windsor, and approximately three time greater than Inglesham (Table 5.1).

Inglesham (35 km) is a second order stream, whereas Abingdon (101 km) and Reading (152 km) are fourth order, and Windsor (203 km) is a fifth order stream. Barrillier *et al.*, (1994) found that stream order was related to phytoplankton density. Low stream order, as at Inglesham (35 km), was associated with low phytoplankton density, whereas higher stream orders, such as at Abingdon (101 km), Reading (152 km) and Windsor (203 km), were associated with higher phytoplankton densities. The current study concurs with this finding.

Abundance and density of phytoplankton species composition changed seasonally and spatially. The four sites can be classified into two groups based on density, species periodicity and dominance (Fig. 5.2 & Fig. 5.3). The first group is Inglesham (35 km) which was dominated by Chlorococcales (small unicellular green algae) throughout each season and for the whole of the study period. During increases in total phytoplankton density there was an increase in the density of other taxon groups, including centric diatoms which were co-dominant during spring at the other sites. This group will be called the 'upstream site'.

The second group is Abingdon (101 km), Reading (152 km) and Windsor (203 km). At these sites seasonal patterns in species dominance and density were similar, and occurred simultaneously throughout the seasons. This group is characterised by a spring maximum in density co-dominated by centric diatoms (dominated by an aggregation called centric diatoms:excluding *Skeletonema* and *Melosira*) and Chlorococcales (small unicellular green algae). During summer and autumn centric diatom density declined and Chlorococcales became dominant. Density of motile Euglenophytes and Cryptophytes, in particular *Rhodomonas minuta*, increased during the summer/autumn period. Chlorococcales dominated during winter. This group are called the 'downstream sites'.

Patterns of phytoplankton species composition and density in 1993 were repeated, with minor differences in density, in 1994 (Fig. 5.2 & Fig. 5.3).

There are similarities and differences between the seasonal pattern of

phytoplankton density and species succession in the current study when compared to previous studies on the Thames (detailed in Chapter 1.2). The seasonal pattern of density observed by Lack (1969, 1971) was similar to the findings at the 'downstream sites' of the current study, as were the high densities of centric diatoms during spring. Increased dominance of green algae during summer was noted by Lack (1969, 1971), the dominant species were *Pediastrum*, *Scenedesmus* and *Ankistrodesmus* . These species are large compared to the *Chlorella*-type Chlorococcales species that dominated the green algae in the current study during summer, autumn and winter seasons. The phytoplankton dynamics at Inglesham (35 km) were different to those noted by previous workers on the Thames (Chapter 1.2), however this is the first study of the Thames at a site so close to the source.

The dominance of Chlorococcales, in particular *Chlorella*-type oval small and *Chlorella*-type round small, had not been noted in the Thames by previous workers (Chapter 1.2). In fact previous workers cited centric diatoms or diatoms as the dominant component of the Thames phytoplankton (see Chapter 1.2). There are a number of possible reasons why this change in species dominance has occurred. Firstly, phytoplankton species composition may have changed over the 18 years since the previous study. Secondly, phytoplankton sampling, concentration and enumeration techniques used in the current study are different from those used by early workers. This will bias the phytoplankton picture. Fritsch (1902, 1903) and Rice (1938 I & II) collected phytoplankton samples using nets which would have allowed the smaller taxa to pass through and bias towards larger species. Later workers (Lack, 1969, 1971, 1978; Bowles and Quennel, 1971) used quantitative collection, concentration and counting techniques, but did not specify the minimum size of algae cell that was included in the phytoplankton enumeration technique. The Chlorococcales species that dominated the Thames for much of the year in the current study are very small and inconspicuous, in particular *Chlorella*-type oval small (3-5 μm diameter) and *Chlorella*-type round small (3-5 μm diameter), and could have been missed from the count by earlier workers. The taxonomic limitations of identifying very small unicellular cells (*Chlorella*-type) should be born in mind, as discussed in Chapter 4.3.2. and 4.3.3. The proportion of small unicellular algal cells in a river was surprising and cells smaller than the 3μm cut off point of the current study were observed during counting. A further quantitative,

long term study to investigate the density and periodicity of phytoplankton smaller than 3 μm, the pico-sized algae, in the Thames was initiated in 1996.

Inglesham was the only site where benthic algae (*Cocconeis placentula*) accounted for greater than 0.5% of the total phytoplankton (Table 5.2). This site was physically different from the others, being more shallow (thus photic zone reached the river bed more often), having more macrophytes and a silty substrate (Chapter 2). These conditions are conducive for benthic micro-algal growth.

7.3 Relationships between phytoplankton and environmental factors

The current statistical analysis of the field data can only point to associations between environmental factors and phytoplankton dynamics, it cannot state cause and effect relationships. Discharge related environmental factors are detailed in Table 6.2 and should be closely considered in reaching conclusions about the relationships between phytoplankton and environmental factors.

7.3.1 Phytoplankton density and environmental factors

Associations between phytoplankton density, species composition, succession and environmental factors were only investigated during spring and summer/autumn seasons, as these periods were deemed the most important to the aims of the project (see Chapter 1.1, 1.5 and 6.1).

Associations between phytoplankton density and environmental factors are complicated, varying seasonally and spatially.

During spring no environmental factor was significantly correlated with phytoplankton density at all four sites (Table 6.12).

During the summer/autumn period the significant relationships between environmental factors and phytoplankton density at different sites was even more inconsistent than during spring (Table 6.13). There was no clear pattern of association where a number of environmental variable were significantly correlated with phytoplankton density at all sites and all seasons using current analysis techniques.

Decrease in river discharge has often been cited as a contributing factor to the rapid increase in phytoplankton density during spring in the Thames and other rivers (Chapter 1.3.1). In the current study discharge was not a panacea dictating phytoplankton density at all sites and in all seasons. However, low discharge, over

the ten days preceding phytoplankton sampling (Discharge 10), was significantly correlated with high phytoplankton density at the two downstream sites, Reading (152 km) and Windsor (203 km) during spring (Table 6.12). Interestingly the discharge on the same day as the phytoplankton was collected (Discharge 1) was not significantly correlated with phytoplankton density at any sites during the spring period. Thus phytoplankton density seems to be more influenced by discharge conditions over the ten days prior to sampling than those on the same day as the sample was taken.

Discharge did not affect phytoplankton density at the upstream sites, Inglesham, and Abingdon during spring or summer/autumn seasons (Table 6.12 & Table 6.13).

Previous workers on the Thames, who cited discharge as an important determining factor for phytoplankton density, studied the mid to lower Thames, where, in the current study, discharge was an important factor. Thus there is some agreement about the effect of discharge on phytoplankton density between previous studies and the current one.

It is difficult to separate the effects of increased day length and water temperature which have been regarded as trigger factors for increased phytoplankton growth (Chapter 1.3.1), and are also associated with decreased discharge (Table 6.2). Increased phytoplankton density was associated with increased sunlight hours over the 14 days prior to sampling (Sun 14) at Reading and Windsor during spring and Windsor during summer and autumn (Table 6.12 & Table 6.13). The sunlight hours over the seven days prior to sampling (Sun 7) were less influential over phytoplankton density, only being significantly correlated with phytoplankton density at Windsor during summer/autumn. Sunlight hours did not appear to influence phytoplankton density at the upstream site Inglesham and Abingdon.

High phytoplankton density was associated with low water clarity (Table 6.12 & Table 6.13). It is likely that the high density of phytoplankton actually causes the low water clarity. Phytoplankton may reach densities which cause self-shading and prevented increased phytoplankton growth, an opinion also given by Lack (1971), Kowalczewski & Lack (1971), Whitehead & Williams (1984) and Whitehead & Hornberger (1984). This is a possible reason for the similar phytoplankton maxima at Abingdon, Reading and Windsor (Fig. 5.1).

7.3.2 Phytoplankton species composition and environmental factors

Investigation of associations between phytoplankton species composition and environmental factors was restricted to dominant phytoplankton taxonomic groups, dominant taxa and environmental factors in spring and summer/autumn seasons.

Different taxon groups were associated with different environmental factors. The relationships also varied seasonally and spatially.

Centric diatom density was associated with more environmental factors than Chlorococcales (small green unicells) thus the response of centric diatom density to environmental factors is more predictable than Chlorococcales. High centric diatom density, in particular centric diatoms: excluding *Skeletonema/Melosira*, was associated with low discharge on the sampling day (Discharge 1) and ten days preceding sampling (Discharge 10), high sunlight hours over 14 days prior to sampling (Sun 14) during spring at Abingdon (101 km), Reading (152 km) and Windsor (203 km).

Centric diatom density increased in response to longer term high sunlight hours (Sun 14 compared to Sun 7) Table 6.12. The dense centric diatom growth at Abingdon, Reading and Windsor almost certainly depleted the reactive silica (Table 6.12) but, did not reach limiting levels for *Stephanodiscus hantzschii*, according to Swale (1963).

At Inglesham (35 km), the relationship between centric diatoms: excluding *Melosira/Skeletonema* and discharge was opposite to that at all other sites. Increased discharge on the sampling day (Discharge 1) and over ten days preceding sampling (Discharge 10) was associated with an increase in the density of centric diatoms: excluding *Melosira/Skeletonema* (Table 6.12). This phenomena may be due to centric diatoms: excluding *Melosira/Skeletonema* being washed into the main river from side-arms or storage zones. The river bed at Inglesham (35 km) is of a slightly steeper angle than the downstream sites. Reynolds & Glaister (1993) showed that an increase in discharge in a river with a steep angled bed caused an increase in water velocity and this increased power for scouring, whereas a similar increase in discharge in a less steep bedded river resulted in an increase in water depth, with little increase in water velocity, thus less scouring. This is another possible reason for the increase in phytoplankton density with increased discharge at Inglesham (35 km) and not other sites.

High Chlorococcales density at Inglesham (35 km) was also associated with high discharge on the sampling day (Discharge 1) in summer/autumn. *Chlorella* -type oval small had a similar relationship with discharge in summer/autumn. This increased density of centric diatoms and Chlorococcales associated with increased discharge at Inglesham may be related to the difference in the habitat at this site compared to the other sites. The environment at Inglesham is more conducive for macrophyte growth, with associated attached epiphytes and benthic algal growth than the other sites. Inglesham is more shallow than other sites, is above the limit of navigation where weed cutting and dredging is less influential, and the river bed is a silty substrate rather than solid chalk which dominates the river at the other sites (see Chapter 2). Centric diatoms and Chlorococcales may be benthic or epiphytic in origin, being washed off their attachment sites when discharge increases on the sampling day (Discharge 1). Increased discharge over the ten days prior to sampling (Discharge 10) was not associated with increased centric diatoms: excluding *Melosira/Skeletonema* or Chlorococcales density, perhaps because after ten days of high discharge the loose benthic diatoms had already been scoured. This demonstrates that different time spans of high discharge events affect taxonomic groups differently.

During the summer/autumn season the Euglenophyta/Cryptophyta taxonomic group, and especially *Rhodomonas minuta*, increased in density when total phytoplankton density was declining. Cryptomonads have frequently been recorded to increase when other populations decline as if a temporary "niche" had opened in an "opportunistic" life strategy (Klaveness, 1988). This was true during the current study. *Chlorella*-type small green unicells have a similar sinking rate than centric diatoms (Reynolds, 1994), and Cryptophyta/Euglenophyta are motile and able to regulate their position in the water column (Klaveness, 1988) (see Chapter 1.2.2), thus these taxa are more suited to the summer/autumn low discharge, low temperature conditions. Cryptomonads are found in almost any body of natural water in the world (Klaveness, 1985a), and are present throughout the year. Peaks in density usually follow disruptions such as wind mixing or periods of precipitation (Klaveness, 1988). This did not seem to be true for the current study where associations between the density of this group and environmental factors at Inglesham (35 km) and Reading (152 km) were sparse. At Abingdon (101 km) and Windsor

(203 km) high densities were sometimes associated with the stable conditions of low discharge on the sampling day (Discharge 1) and/or discharge over the previous ten days (Discharge 10), high water temperature and high sunlight hours over the seven days prior to sampling (Sun7) (Table 6.13). The literature on Cryptomonads (reviewed by Klaveness, 1988) was limited with regard to this group in the river environment, most literature was based on lake environments. It is possible that a mixed environment in a lake, conditions shown to favour Cryptomonads, are similar to a river under low discharge conditions, and that higher discharge conditions are unsuitable for dense cryptomonad populations.

Nitrogen and phosphorus compounds showed no clear pattern of significant correlations with density of taxon groups. Levels of these plant nutrients were high, and probably not limiting and thus did not affect phytoplankton species composition. The decline in the density of centric diatoms was probably not due to limitation by silica, phosphate or nitrate levels.

Phytoplankton density during summer and autumn was low, which was surprising because the environmental conditions are suitable for high phytoplankton densities. It is possible that biological factors were controlling phytoplankton density at this time. The effects of biological factors, such as zooplankton grazing and parasitism, were not included in the current study. Fungal chytrid parasites were observed on centric diatoms and large *Chlamydomonas* -type cells during late summer and early autumn. Zooplankton, chiefly small ciliated protozoa, have been noted in the phytoplankton samples. Future studies should include quantification of these factors to assess their role in phytoplankton dynamics.

7.4 Possible implications of river management to phytoplankton dynamics

The complexity of river systems is such that it is difficult to chart clearly the impact of river regulation (McMahon & Finlayson, 1995). The effects of discharge augmentation from reservoirs and inter-basin transfers to rivers are detailed in Chapter 1.4.

The current study investigated the associations between phytoplankton density, species composition and environmental factors in the Thames over a two year period. The probable physical and chemical effects of discharge augmentation to the Thames from the South West Oxfordshire reservoir or Severn to Thames inter-basin water transfer are interpreted in relation to the findings of this study.

An inter-basin transfer from the lower Severn would enter the Thames near Inglesham. Phytoplankton density and species composition are significantly correlated with very few environmental factors at this site (Table 6.12 and Table 6.13) making it difficult to predict effects of the transfer. The dense bloom of centric diatoms which occurs at Abingdon, Reading, Windsor (Fig. 5.2) and the lower Severn (Reynolds & Glaister, 1993) does not occur at Inglesham. It may be problematic to transfer water heavily laden with centric diatoms from the lower Severn to a location on the Thames (Inglesham) where they are less dense. The effect of this transfer would depend on the reasons why centric diatoms do not occur in high densities at Inglesham. If this is due to lack of time for cell replication and the conditions at Inglesham are suitable for centric diatom growth, then the transferred algae would probably survive. If however, the conditions at Inglesham were unsuitable for dense centric diatoms development then the transferred algae may die causing a deterioration in water quality and may have unknown effects on the biology of the river. It is possible that Inglesham is unsuitable for dense centric diatom growths as according to Reynolds (1994) centric diatoms require a minimum water depth of 1 m to remain in suspension. Conversely water depth may be increased at Inglesham to give the capacity of water needed and therefore be greater than the critical 1 m depth leading to the centric diatom bloom occurring at Inglesham to a similar level as at the other sites.

The most direct effect of augmentation will be increased discharge. Discharge has a number of effects on other environmental factors. Discharge effects turbulence of the water, which in turn dictates how much material, including phytoplankton,

remains in suspension. At lower discharge and turbulence levels centric diatoms are too heavy to remain in suspension and drop out of the photic zone. In the current study centric diatoms were abundant during periods of decreasing discharge during spring, but not low discharges in summer/autumn. Augmented discharge in summer/autumn will increase turbulence keeping centric diatoms in suspension which may prolong the centric diatom bloom. This may have knock-on effects to the Thames ecosystem which has developed complex inter relationships between its members through selection by a sequence of environmental factors which would be altered by discharge augmentation.

The occurrence of the Crytophyta/Euglenophyta taxon group, and in particular the dominant species *Rhodomonas minuta*, is associated with high water temperatures and low discharge during the summer and autumn season. Discharge augmentation will alter the discharge conditions in the river, and may change the water temperature (Ridley & Steel, 1975). The altered conditions may be unsuitable for this taxon group, which are a good food source for zooplankton (Klaveness,1988) and this could have implications for the rest of the food web. Gosselain *et al.*, (1994) and Reynolds (1994) found that grazing of phytoplankton by zooplankton was greatest during low flow periods. The removal of these low flow periods by discharge augmentation may create conditions unsuitable for zooplankton, which is a valuable food source for fish fry and macro-invertebrates.

Low water clarity was associated high phytoplankton density in spring and summer/ autumn seasons (Table 6.12 & Table 6.13) which possibly caused self-shading of the phytoplankton resulting in a similar maximum phytoplankton density at Abingdon, Reading and Windsor. If augmented water had a higher water clarity than the river, the result would be a temporary increase in the depth of the photic zone at the point of discharge. This may lead to increased benthic micro and macro-algal growth, until the phytoplankton again increased in density to its maximum relating to self-shading.

Chlorococcales were the dominant taxon group for much of each year at all sites. The density of this group were not significantly correlated with many environmental variables and so it is difficult to predict the effects of discharge augmentation on this group.

Silica concentration was the only nutrient measured that was clearly correlated

with phytoplankton density and species dominance. Centric diatom density was negatively correlated with silica concentration, however the silica concentration did not reach limiting concentrations (Swale, 1963). Augmented discharge with high levels of silica would therefore probably not affect phytoplankton density and species composition.

Experience from discharge augmentation of other rivers shows that gradual changes in discharge can be favourable to the water quality (Dupin *et al.*, 1987) and that abrupt changes can decrease water quality by decreasing dissolved oxygen, increased biological oxygen demand, increased turbidity and sudden temperature changes (Maheshwain *et al.*, 1995; Dupin *et al.*, 1987).

A final consideration are Cyanophyta. Farmoor reservoir is filled from the Thames which is eutrophic. This reservoir experiences blooms of potentially toxic Cyanophyta for much of each year (Environment Agency, 1996). The proposed South West Oxfordshire reservoir would also be filled from the Thames, and is highly likely to develop blooms of Cyanophyta. Discharge augmentation of the Thames with water containing potentially toxic Cyanophyta should be not be allowed as the prime reason for the augmentation is to abstract water in the London area for public water supply.

Summary

The Thames is a lowland river situated in the south of England in a temperate oceanic climate where temperature, daylength and rainfall vary seasonally. It is under great anthropomorphogenic pressure from navigation, effluent discharges, abstraction for public water supply and periodic seasonal low flows. The Thames catchment supports 11.5 million people with the highest concentration in the London area. The Thames supplies London with 50% of its public water supply (Jordan, 1996). Water supply shortages have been forecasted for the Thames catchment, and in particular the London area. During seasonal low flows the discharge in the Thames is insufficient to meet the forecasted increase in demand for abstraction.

Various water management schemes have been proposed to meet the forth coming water supply shortage. Two proposed schemes involve discharge augmentation of the upper or middle Thames during low flow periods so that water is available for abstraction in the lower Thames. The environmental implications of such schemes need to be assessed, and the best possible practice for managing the schemes adopted.

This thesis is part a multi-disciplinary study of the Thames to improve the understanding of how the ecosystem works and interacts with environmental factors, especially the ones that will be altered by the augmentation schemes.

Phytoplankton density and species composition were studied at four sites on the freshwater Thames over a two year period (January, 1993-December, 1994). The sites were Inglesham (35 km from source), Abingdon (101 km from source), Reading (152 km from source) and Windsor (203 km from source).

Samples were taken at fortnightly intervals throughout the spring, summer and autumn, and four weekly intervals during the winter period. Samples were collected in an upstream direction.

Fifteen environmental factors were measured at each site to test for correlations with the phytoplankton density and species composition. The environmental factors are: mean discharge over the ten days prior to sampling, mean discharge on the sampling day, water temperature, sunlight hours over the 14 and seven days prior to sampling, water clarity (Secchi Depth), pH, percentage dissolved oxygen, total phosphorus, soluble reactive phosphorus, total oxidised nitrogen, nitrate, nitrite,

ammonia and soluble reactive silica.

Phytoplankton taxa of 3 μm and greater in length were identified to species level, where possible, and counted.

Each year was split into seasons based on changes in phytoplankton density and species composition. The associations between the phytoplankton density, species composition and environmental factors could then be examined in greater detail, spatially and seasonally.

Phytoplankton density at all sites followed a similar pattern, with an increase in density during spring, then a decline in summer and autumn, to lowest levels in winter. This seasonal pattern was similar in 1993 and 1994.

Mean phytoplankton density increased with increased distance from source, although the variability in phytoplankton density, from maximum to minimum densities, was similar at Abingdon, Reading and Windsor, but twice the value for Inglesham.

Phytoplankton was split into six taxonomic-morphological groups, and one mixed group, so that broad changes in phytoplankton species composition could be examined.

Phytoplankton species composition varied seasonally and spatially. The four sites can be classified into two groups based on density, species periodicity and dominance. The first group is Inglesham (35 km from source) which was dominated by Chlorococcales (small unicellular green algae) throughout each season and for the whole of the study period. During increases in total phytoplankton density there was an increase in the density of other taxon groups, including centric diatoms which were co-dominant during spring at the other sites. The second group is Abingdon (101 km from source), Reading (152 km from source) and Windsor (203 km from source). At these sites seasonal patterns in species dominance and density were similar, and occurred simultaneously throughout the seasons. This group is characterised by a spring maximum in density co-dominated by centric diatoms (dominated by a aggregation called centric diatoms:excluding *Skeletonema* and *Melosira*) and Chlorococcales. During summer and autumn centric diatom density declined and Chlorococcales became dominant. Density of motile Euglenophytes and Cryptophytes, in particular *Rhodomonas minuta*, increased during the summer/autumn period. Chlorococcales dominated during winter.

Associations between phytoplankton density, species composition and environmental factors are complicated, varying seasonally and spatially. There were no environmental factors that were significantly correlated with either phytoplankton density or species composition at all sites and during all seasons.

Phytoplankton density was more influenced by environmental factors over a period of time prior to sampling. Sunlight hours over the 14 days prior to sample collection were significantly correlated with phytoplankton density at more sites and seasons than over the seven days prior to sampling. Further, phytoplankton density was significantly correlated with discharge over the ten days prior to sampling on more occasions than the discharge on the sampling day.

High phytoplankton density was significantly correlated with low water clarity. This is probably due to dense phytoplankton causing the low water clarity. The maximum phytoplankton density observed at Abingdon, Reading and Windsor was similar and possibly regulated by light limitation through self-shading.

The response of centric diatoms to environmental factors is more predictable than that of Chlorococcales. Centric diatom density was significantly correlated with environmental factors more commonly than Chlorococcales.

Centric diatom density was negatively correlated with silica concentration, but did not reach limiting levels.

Phosphorus and nitrogen were present in high concentrations, and were probably not limiting. These nutrients were rarely significantly correlated with phytoplankton density or species composition.

The relationships between phytoplankton density, species composition and environmental factors are complicated, and vary seasonally and spatially. This means it is difficult to predict the effects of discharge augmentation to the Thames phytoplankton. The downstream sites Reading and Windsor are correlated with more environmental factors than the upstream sites, Abingdon and Inglesham, thus the effects of discharge augmentation of the lower Thames could be predicted with more confidence than the upper Thames.

Only a small number of environmental factors were measured in the current study. There may be other factors that affect phytoplankton density and species composition, by direct and indirect routes that were not measured in this study, such as microbial loops and zooplankton grazing. Further investigations will help to

unravel the patterns of phytoplankton density and species composition in the Thames.

It seems very likely that discharge augmentation from a reservoir or inter-basin water transfer from another river will alter the phytoplankton in the Thames as both of the augmentation sources have different water chemistry and ecology.

The current phytoplankton study is on-going, and as more years of data are compiled and more environmental factors are measured, the understanding of the Thames phytoplankton will improve.

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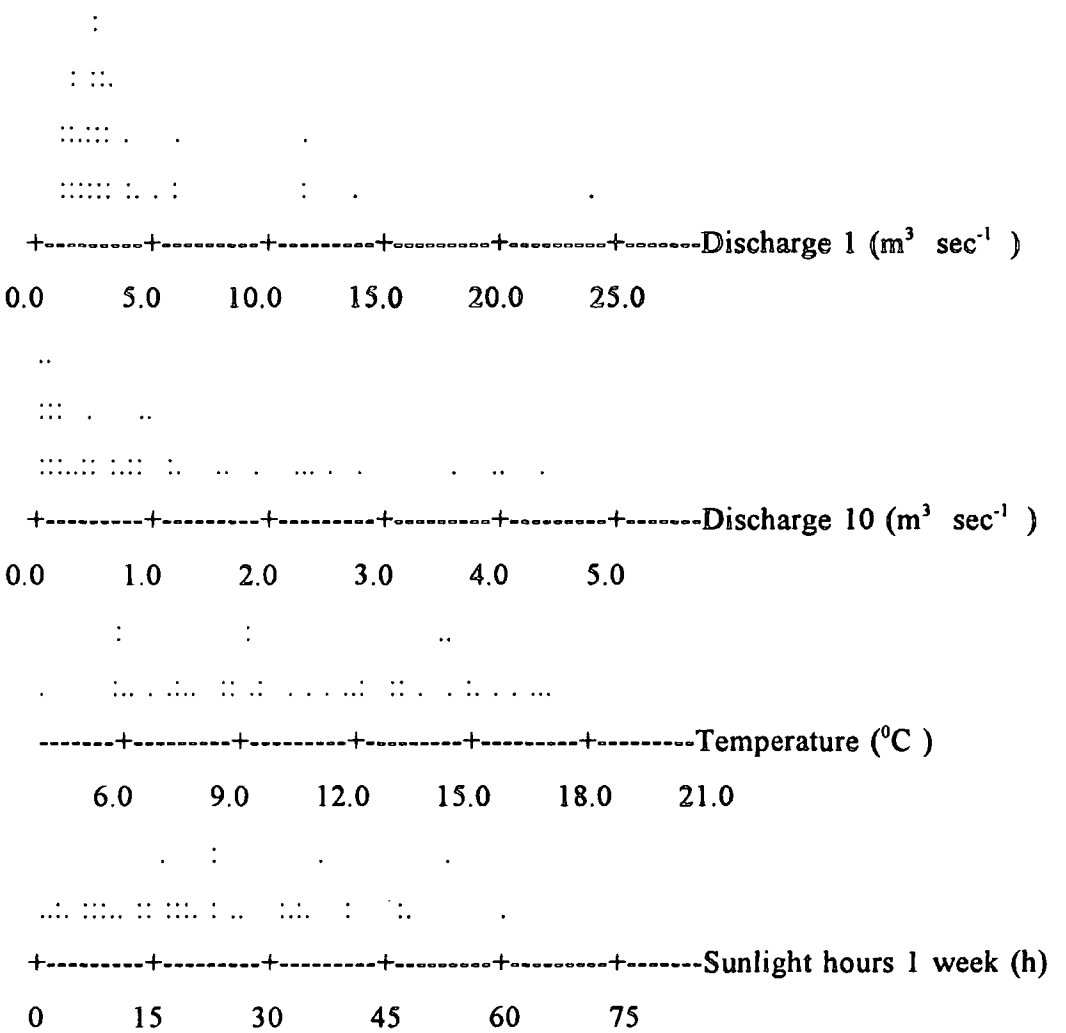
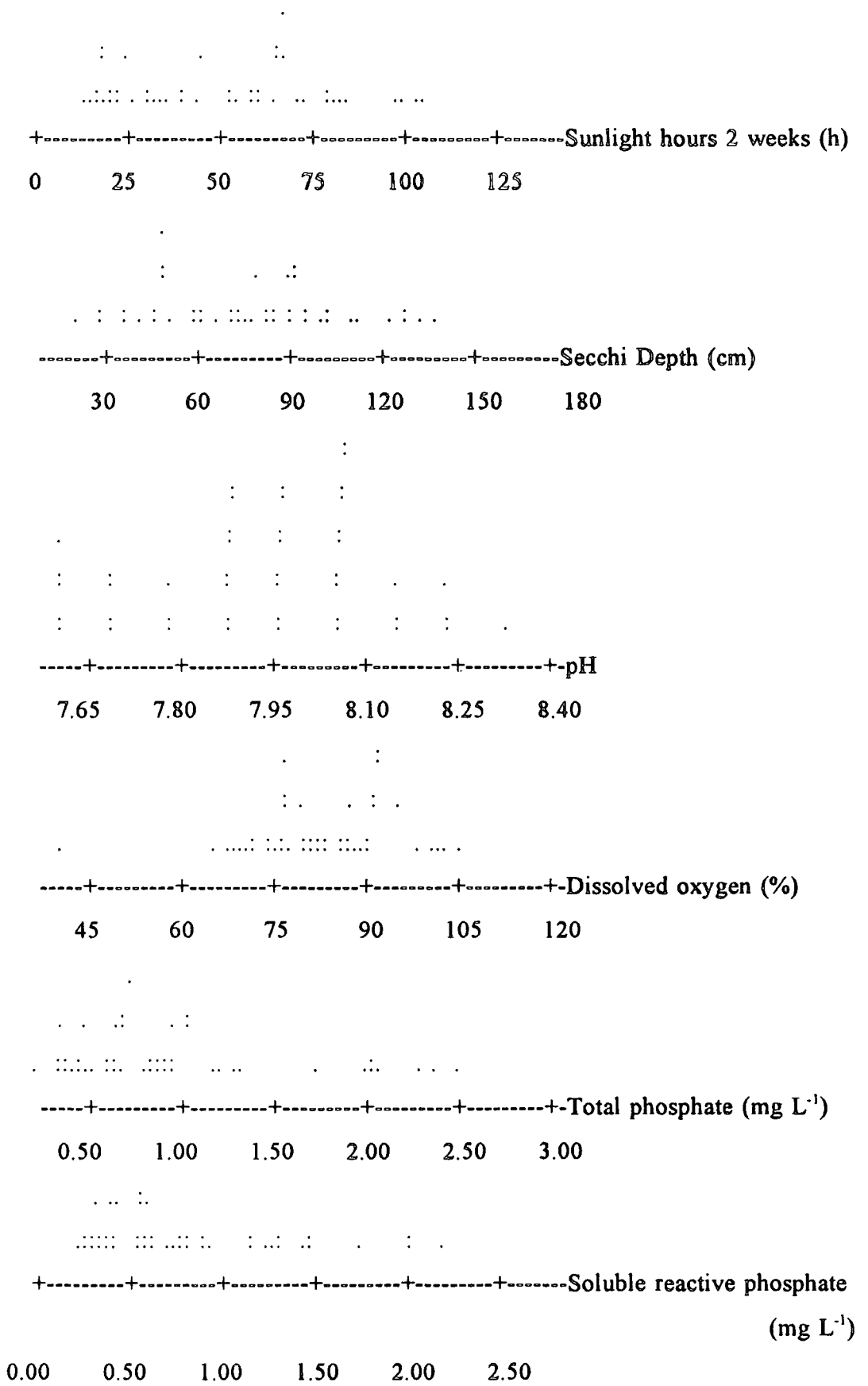
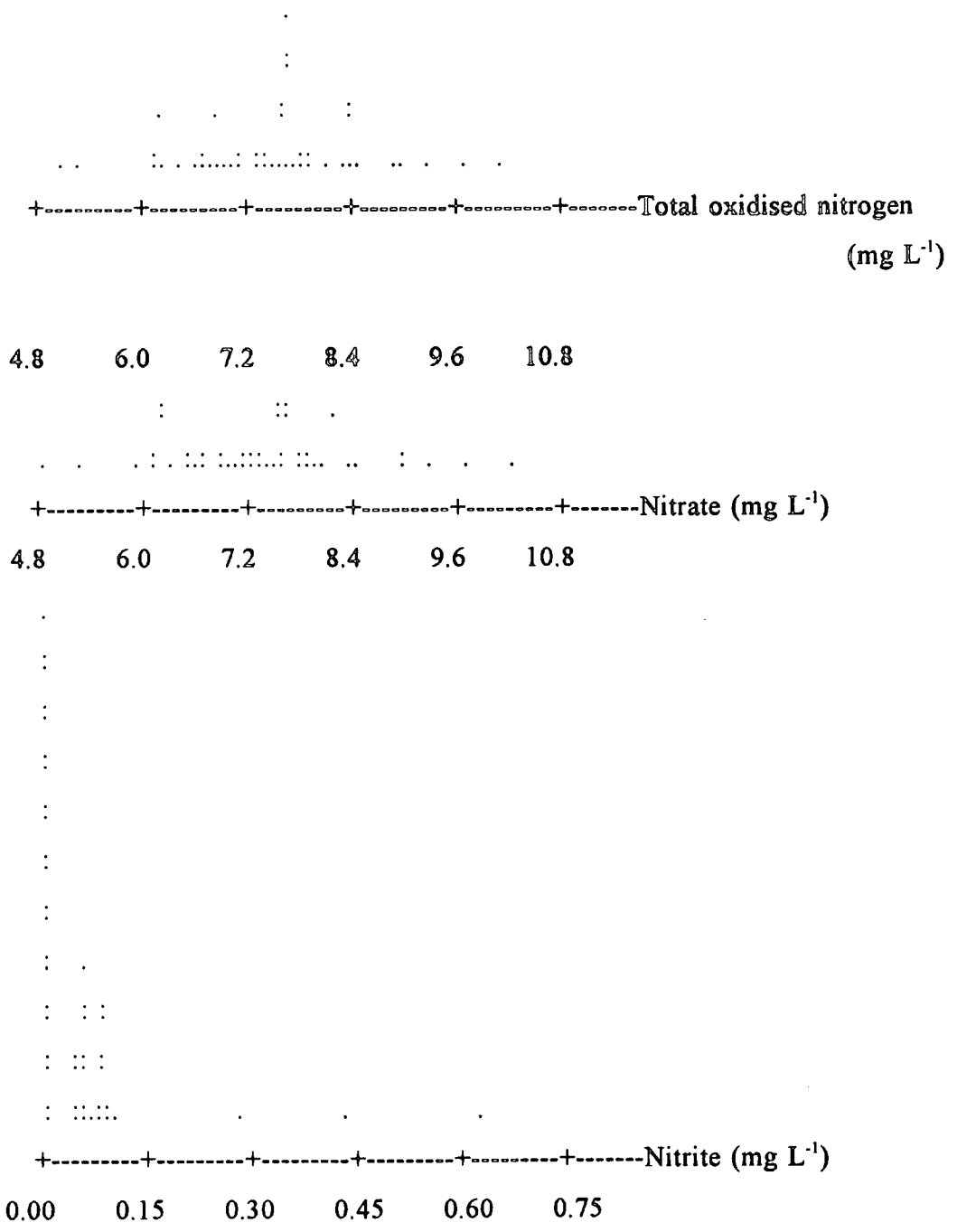
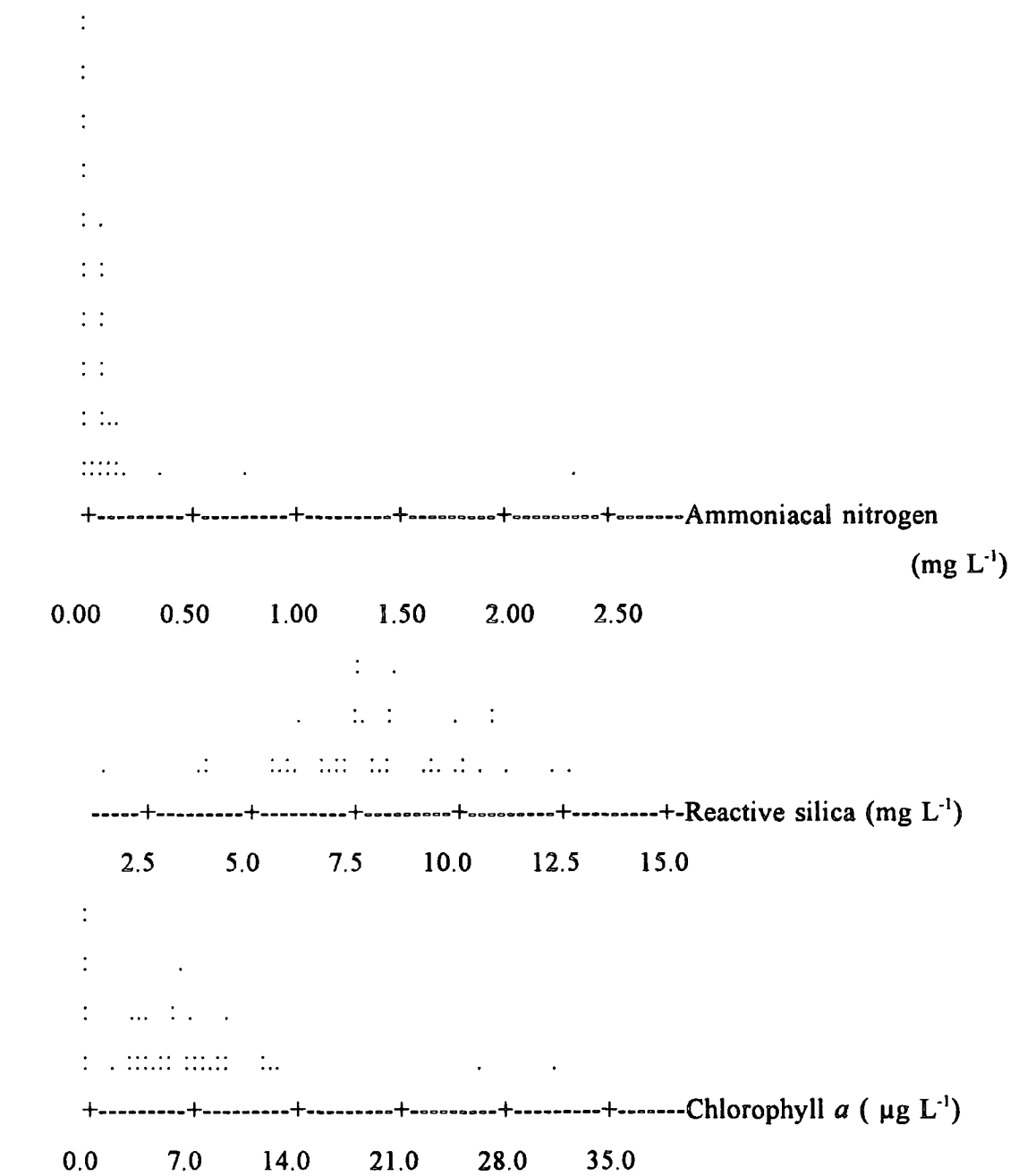
Appendices

Appendix 1a Dotplots of data collected at Inglesham during 1993 and 1994

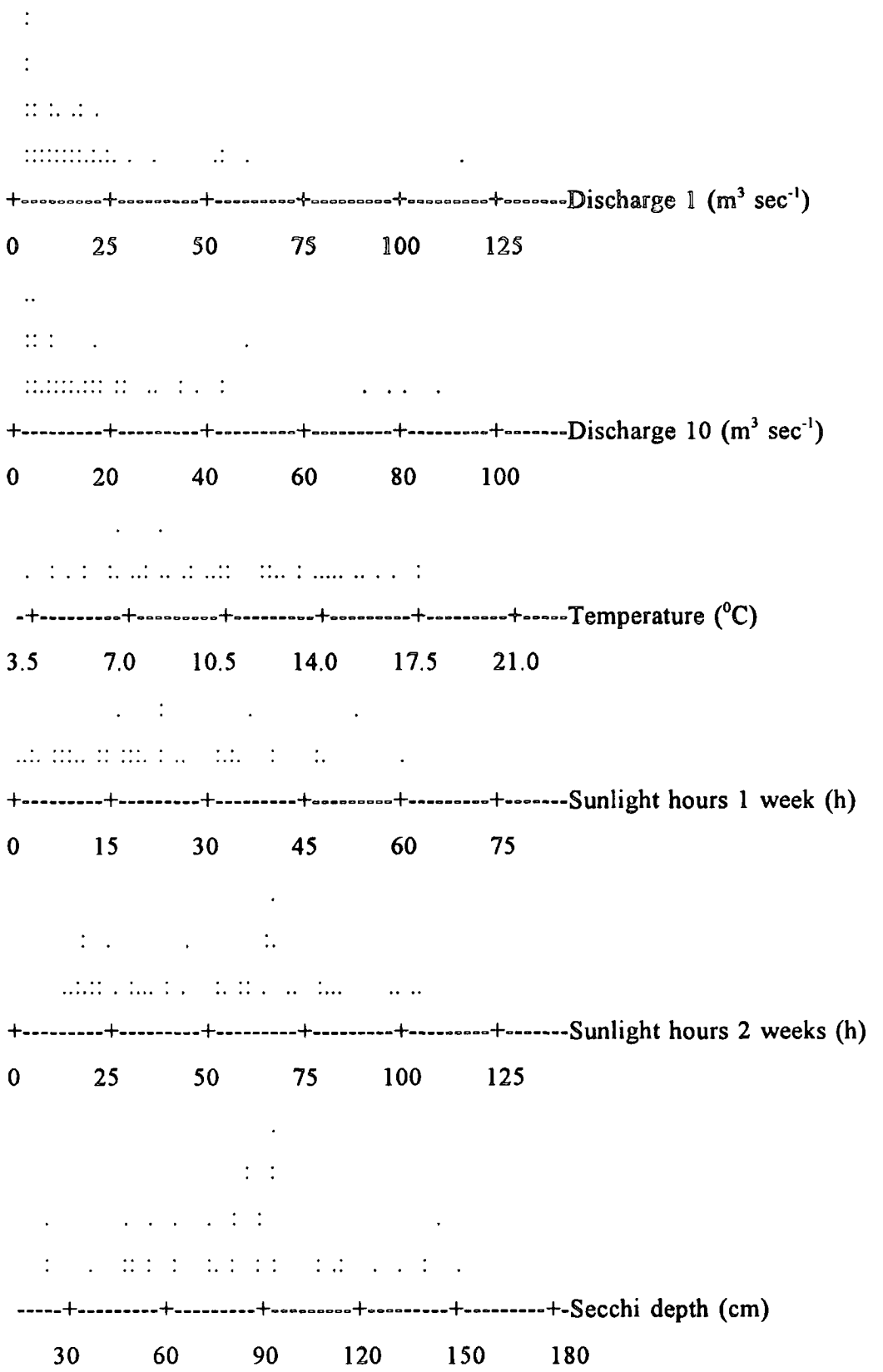



Sunlight hours 2 weeks (h)
0
25
50
75
100
125
Secchi Depth (cm)
30
60
90
120
150
180
pH
7.65
7.80
7.95
8.10
8.25
8.40
Dissolved oxygen (%)
45
60
75
90
105
120
Total phosphate (mg L-1)
0.50
1.00
1.50
2.00
2.50
3.00
Soluble reactive phosphate (mg L-1)
0.00
0.50
1.00
1.50
2.00
2.50


+----------+----------+----------+----------+----------+-------Total oxidised nitrogen
(mg L-1)
4.8 6.0 7.2 8.4 9.6 10.8
+---------+---------+---------+---------+---------+-------Nitrate (mg L-1)
4.8 6.0 7.2 8.4 9.6 10.8
+---------+---------+---------+---------+---------+-------Nitrite (mg L-1)
0.00 0.15 0.30 0.45 0.60 0.75

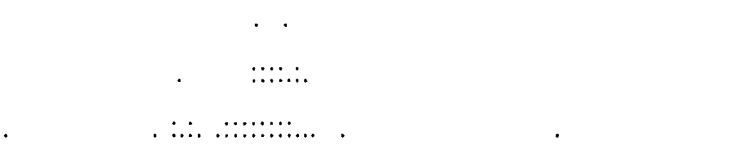

+---------+---------+---------+---------+---------+-------Ammoniacal nitrogen
(mg L-1)
0.00 0.50 1.00 1.50 2.00 2.50
-----+---------+---------+---------+---------+---------+-Reactive silica (mg L-1)
2.5 5.0 7.5 10.0 12.5 15.0
+---------+---------+---------+---------+---------+-------Chlorophyll a (µg L-1)
0.0 7.0 14.0 21.0 28.0 35.0

Appendix 1b Dotplots of data collected at Abingdon during 1993 and 1994



---+---------+---------+---------+---------+---------+---pH

7.60 7.80 8.00 8.20 8.40 8.60



-------+---------+---------+---------+---------+---------Dissolved oxygen (%)

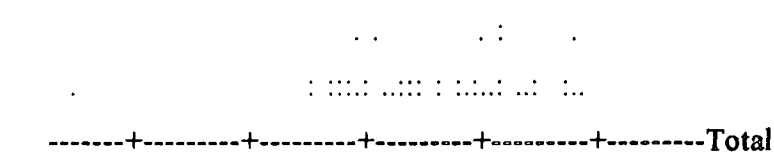
60 80 100 120 140 160

+---------+---------+---------+---------+---------+-------Total phosphate (mg L^{-1})

0.00 0.50 1.00 1.50 2.00 2.50

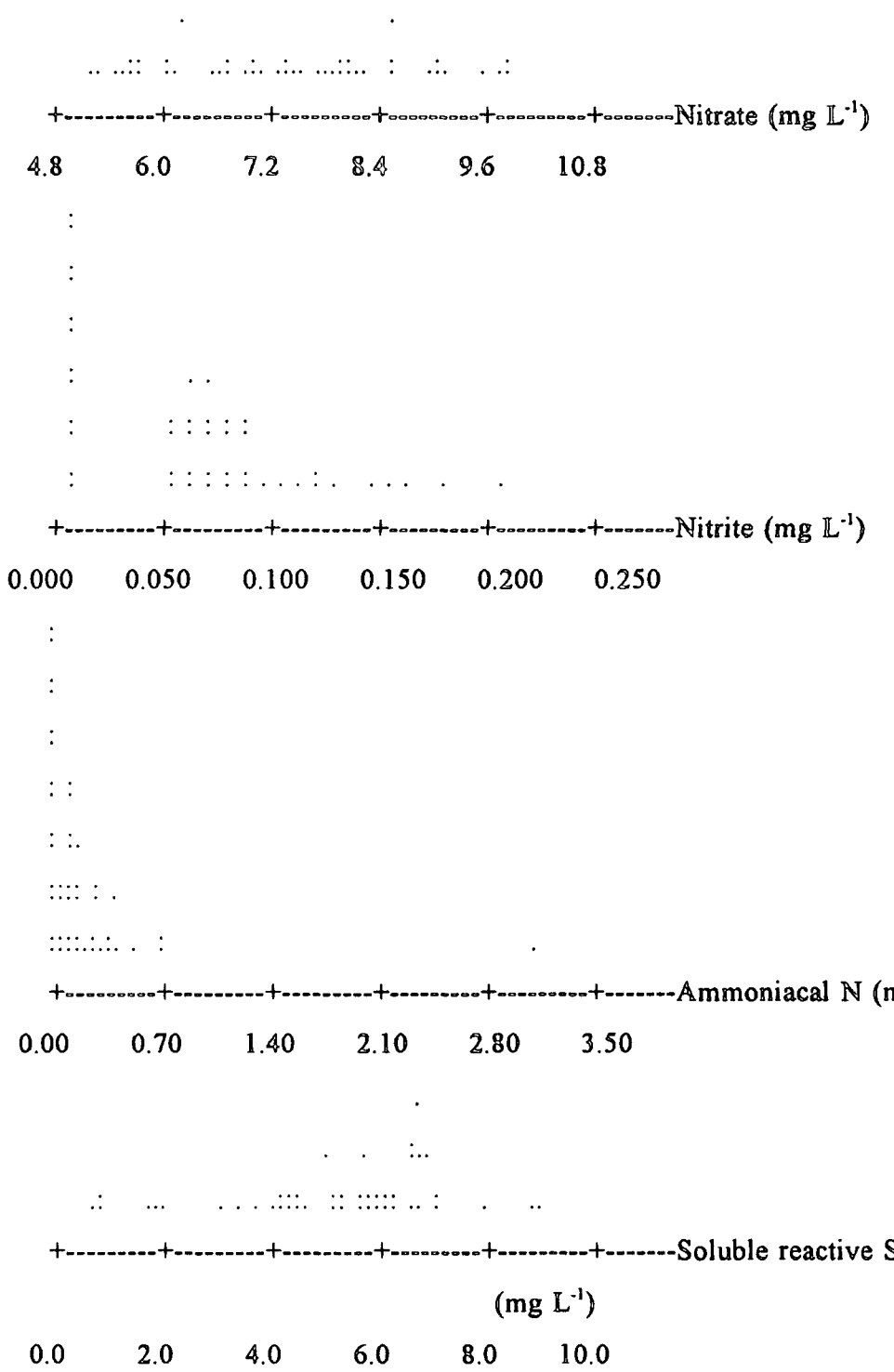
+---------+---------+---------+---------+---------+-------Soluble reactive phosphate (mg L^{-1})

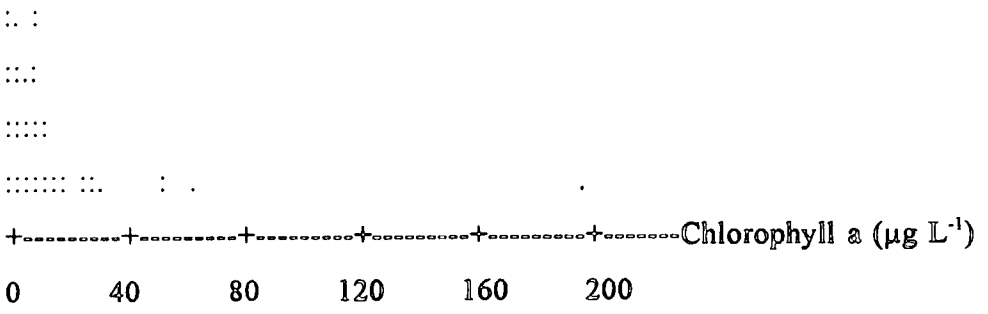
0.00 0.50 1.00 1.50 2.00 2.50



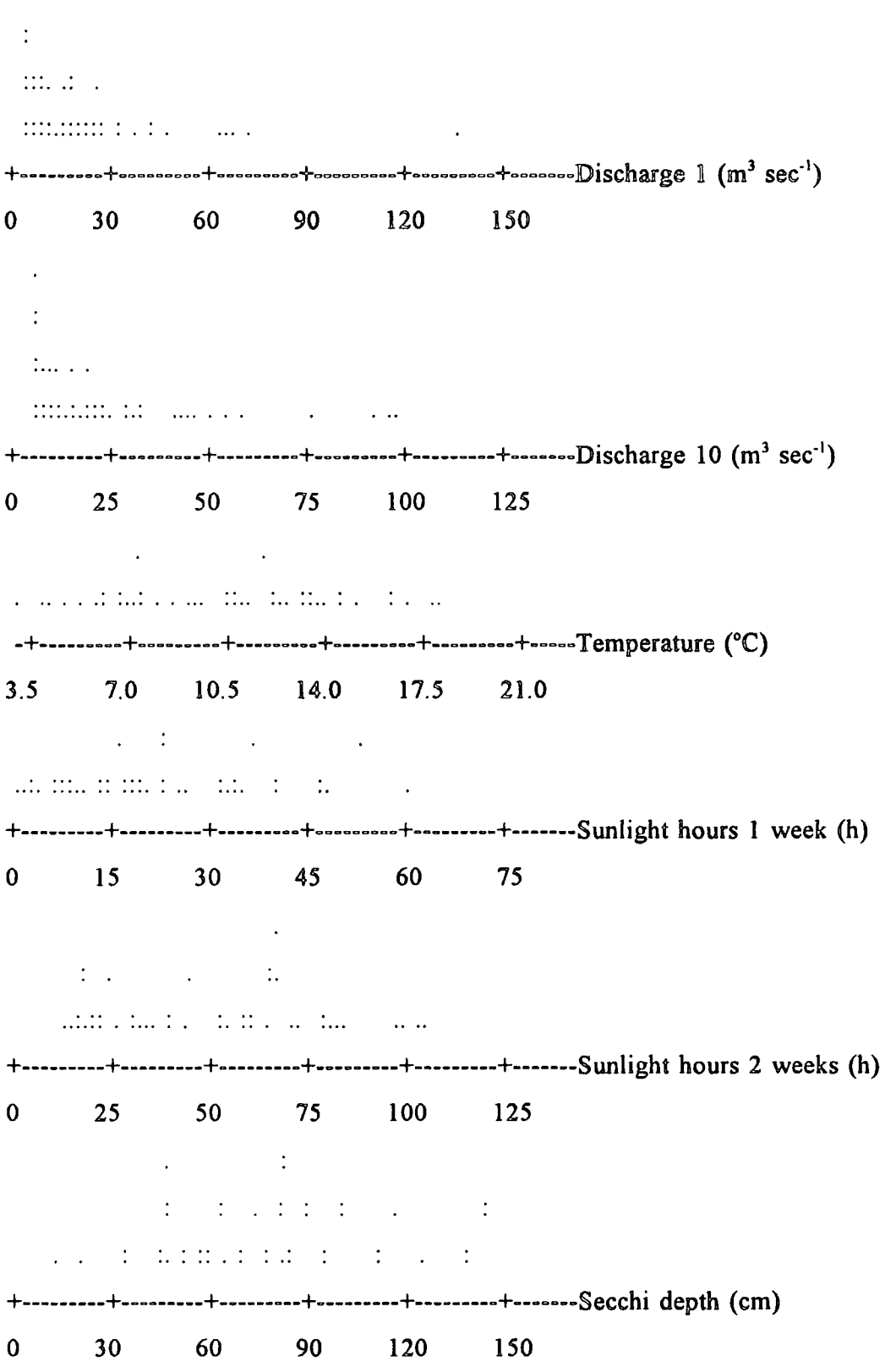
-------+---------+---------+---------+---------+---------Total oxidised nitrogen (mg L^{-1})

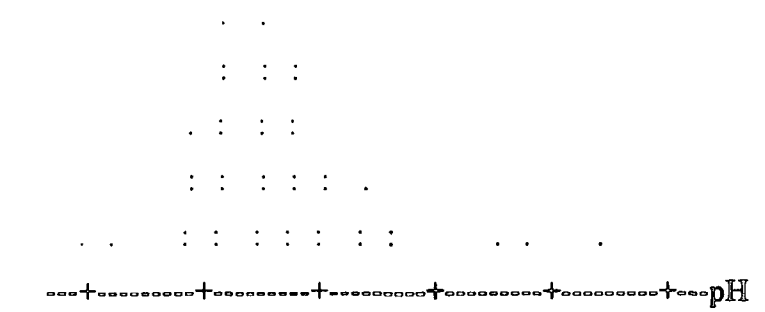
2.0 4.0 6.0 8.0 10.0 12.0


+---------+---------+---------+---------+---------+-------Nitrate (mg L-1)
4.8 6.0 7.2 8.4 9.6 10.8
+---------+---------+---------+---------+---------+-------Nitrite (mg L-1)
0.000 0.050 0.100 0.150 0.200 0.250
+---------+---------+---------+---------+---------+-------Ammoniacal N (mg L-1)
0.00 0.70 1.40 2.10 2.80 3.50
+---------+---------+---------+---------+---------+-------Soluble reactive SiO2
(mg L-1)
0.0 2.0 4.0 6.0 8.0 10.0

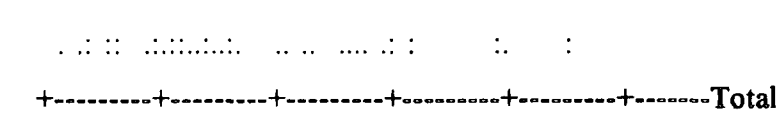

+---------+---------+---------+---------+---------+-------Chlorophyll a (µg L-1)
0 40 80 120 160 200

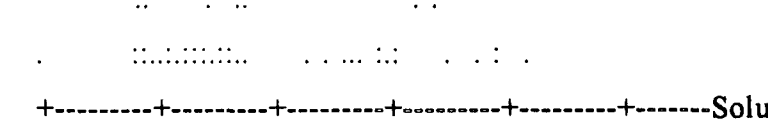
Appendix 1c Dotplots of data collected at Reading during 1993 and 1994

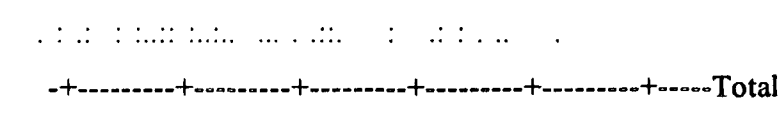


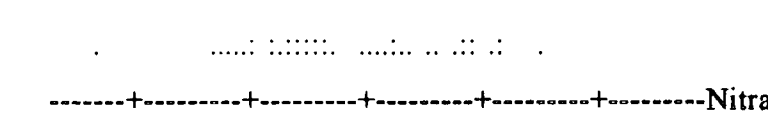

pH
7.50
7.80
8.10
8.40
8.70
9.00

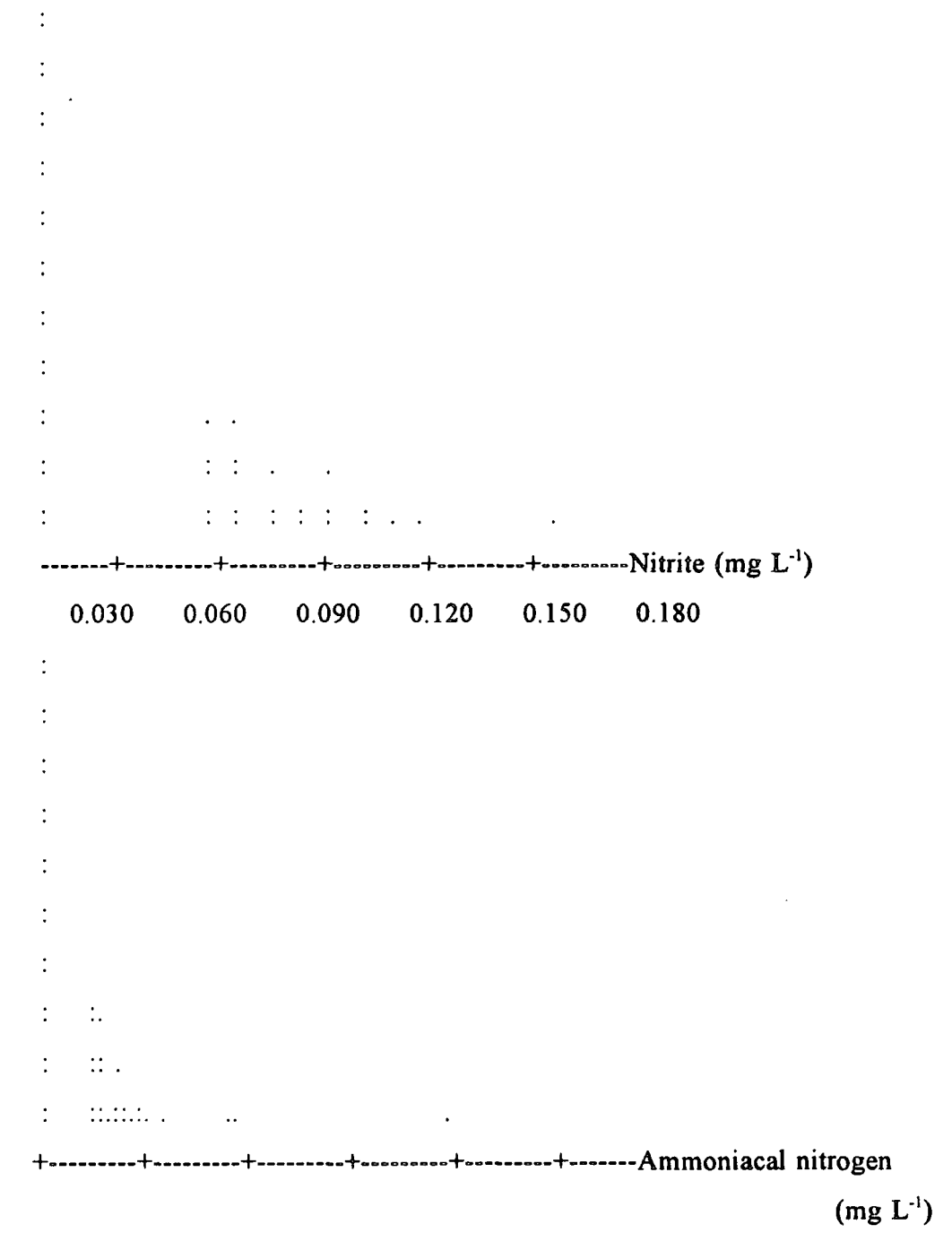

Dissolved oxygen (%)
80
96
112
128
144
160

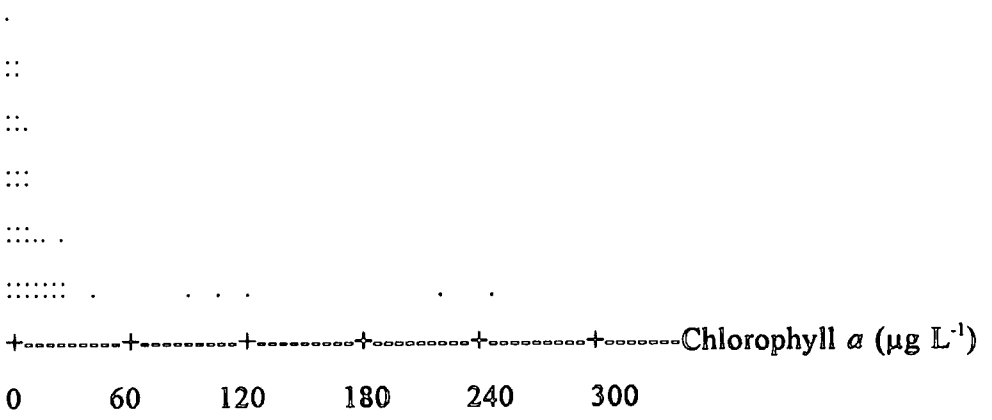

Total phosphate (mg L-1)
0.20
0.40
0.60
0.80
1.00
1.20


Soluble reactive phosphate
(mg L-1)
0.00
0.25
0.50
0.75
1.00
1.25

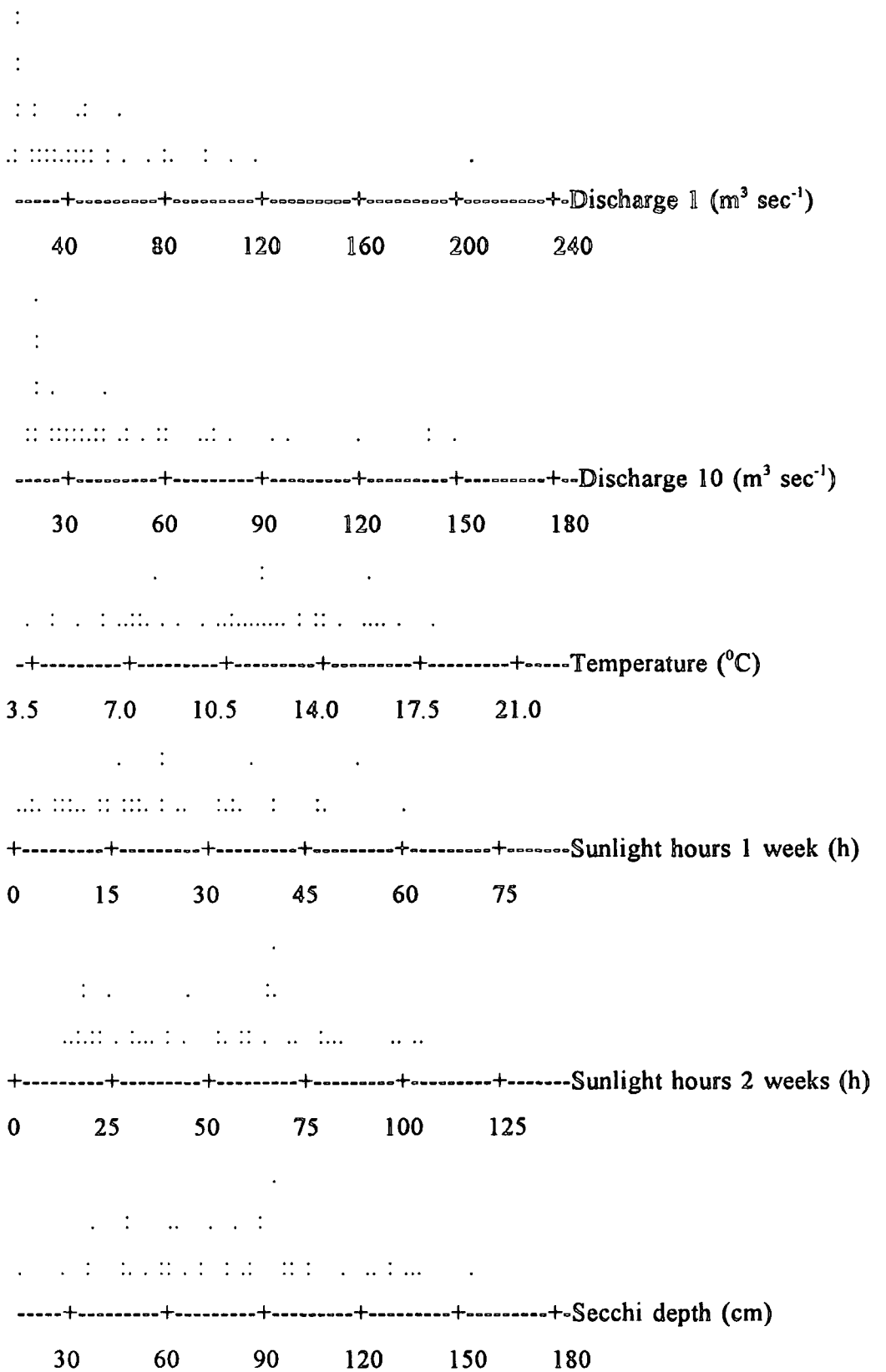

Total oxidised nitrogen
(mg L-1)
6.0
7.0
8.0
9.0
10.0
11.0

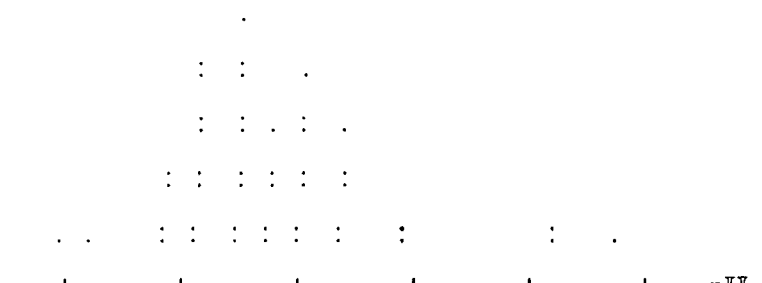

Nitrate (mg L-1)
4.5
6.0
7.5
9.0
10.5
12.0


Nitrite (mg L-1)
0.030
0.060
0.090
0.120
0.150
0.180
Ammoniacal nitrogen
(mg L-1)
0.00
0.10
0.20
0.30
0.40
0.50
Soluble reactive silica
(mg L-1)
0.0
2.5
5.0
7.5
10.0
12.5


+---------+---------+---------+---------+---------+-------Chlorophyll a (µg L-1)
0 60 120 180 240 300

Appendix 1d Dotplots of data collected at Windsor during 1993 and 1994



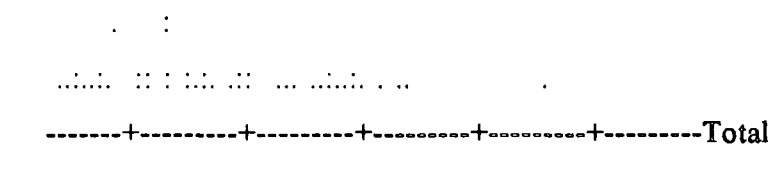


pH

7.50 7.80 8.10 8.40 8.70 9.00

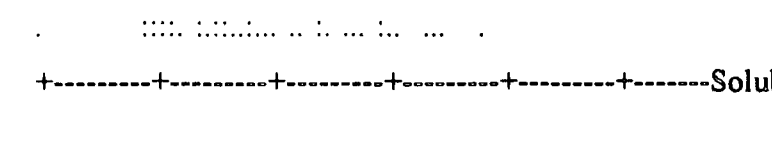
Dissolved oxygen (%)

84 96 108 120 132 144



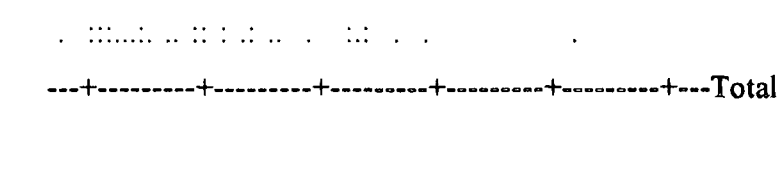
Total phosphorus (mg L^{-1})

0.50 0.75 1.00 1.25 1.50 1.75



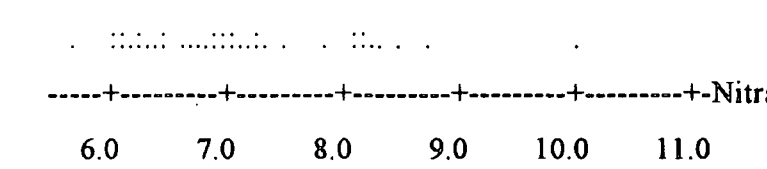
Soluble reactive phosphorus (mg L^{-1})

0.00 0.30 0.60 0.90 1.20 1.50



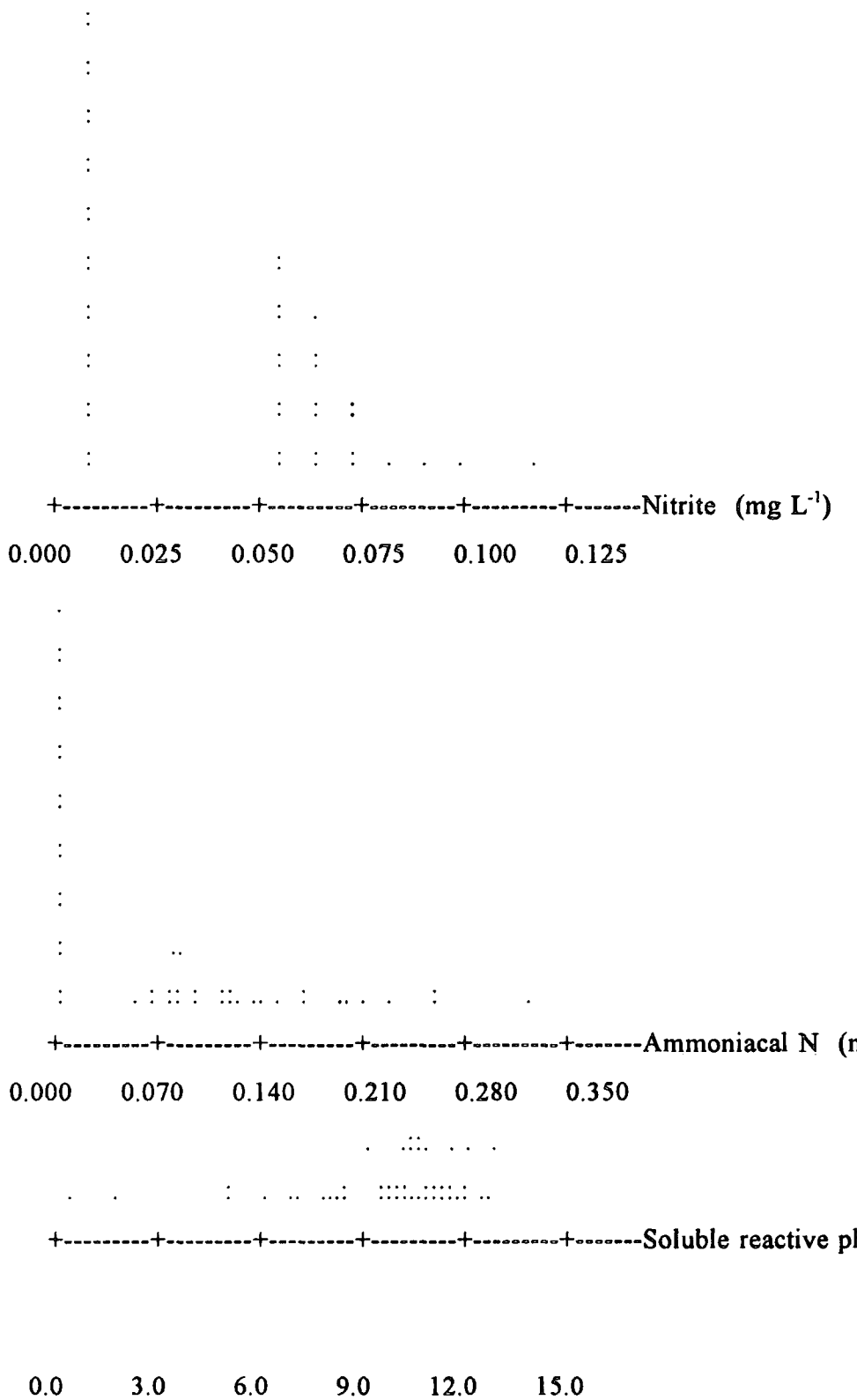
Total oxidised nitrogen (mg L^{-1})

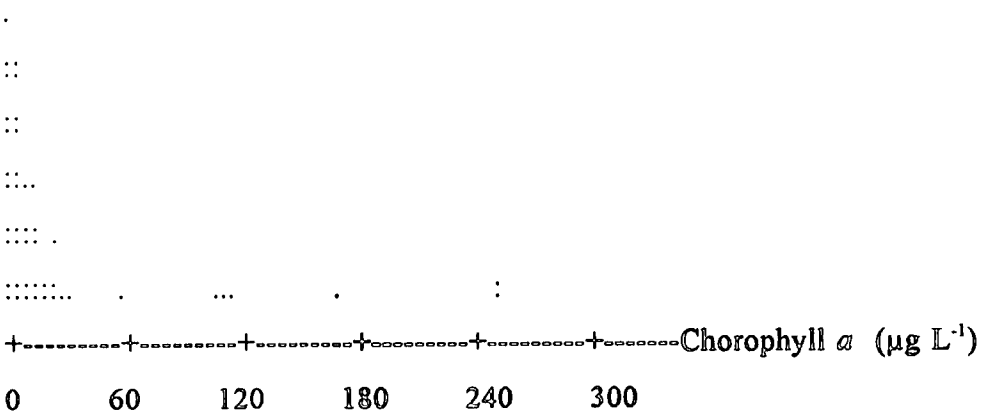
6.0 7.0 8.0 9.0 10.0 11.0



Nitrate (mg L^{-1})

6.0 7.0 8.0 9.0 10.0 11.0


+---------+---------+---------+---------+---------+-------Nitrite (mg L-1)
0.000 0.025 0.050 0.075 0.100 0.125
+---------+---------+---------+---------+---------+-------Ammoniacal N (mg L-1)
0.000 0.070 0.140 0.210 0.280 0.350
+---------+---------+---------+---------+---------+-------Soluble reactive phosphorus (mg L-1)
0.0 3.0 6.0 9.0 12.0 15.0


Chorophyll a (µg L-1)
0
60
120
180
240
300

Appendix 2a Spearman's Correlation Co-efficients for Inglesham during the whole study period (1993/4)

	Disc1	Disc10	Temp	Sun7	Sun14	SECCHI	pH	DO	TotP	SRP	TON	NO3	NO2	AmmN	SiO2	CHLA
Disc1																
Disc10	**0.836**															
Temp	**-0.617**	**-0.666**														
Sun7	**-0.497**	**-0.478**	**0.727**													
Sun14	**-0.523**	**-0.548**	**0.732**	**0.903**												
SECCHI	**-0.594**	**-0.470**	0.282	0.185	0.180											
pH	-0.169	-0.117	0.227	**0.404**	**0.343**	0.265										
DO	-0.021	0.112	0.083	0.243	0.212	0.056	**0.375**									
TotP	**-0.761**	**-0.904**	**0.547**	**0.412**	**0.513**	**0.499**	-0.023	-0.048								
SRP	**-0.718**	**-0.872**	**0.495**	**0.324**	**0.397**	**0.459**	-0.083	-0.199	**0.883**							
TON	0.071	0.182	-0.276	**-0.387**	**-0.398**	-0.082	-0.022	-0.082	-0.197	-0.092						
NO3	-0.029	0.091	-0.244	**-0.311**	**-0.301**	0.022	-0.027	-0.022	-0.113	-0.013	**0.898**					
NO2	0.092	-0.034	0.135	0.066	0.136	**-0.394**	-0.235	-0.088	0.077	0.022	-0.199	**-0.347**				
AmmN	0.196	0.182	-0.254	-0.018	-0.082	-0.174	-0.139	**-0.376**	-0.131	-0.128	-0.012	-0.015	**0.398**			
SiO2	**-0.335**	**-0.513**	0.146	-0.179	-0.154	0.213	-0.261	**-0.657**	**0.433**	**-0.508**	0.050	0.045	0.037	0.134		
CHLA	-0.290	**-0.348**	**0.555**	**0.536**	**0.509**	0.116	0.093	0.077	0.293	0.247	-0.225	-0.236	0.106	-0.015	0.089	
TotCel	0.064	-0.044	0.242	**0.328**	**0.322**	-0.296	-0.113	0.120	0.156	0.071	-0.181	-0.171	**0.533**	0.237	-0.216	0.184

n=45

n-2 d.f. = 43

P=5% =0.301

P=1% = 0.391

P=0.1% = 0.462

Appendix 2b Spearman's Correlation Co-efficients for Abingdon during the whole study period (1993/4)

	Disc1	Disc10	Temp	Sun7	Sun14	SECCHI	pH	DO	TotP	SRP	TON	NO3	NO2	AmmN	SiO2	CHLA	TotCel
Disc1																	
Disc10	0.934																
Temp	-0.775	-0.715															
Sun7	-0.592	-0.568	0.740														
Sun14	-0.632	-0.626	0.747	0.903													
SECCHI	-0.610	-0.558	0.234	0.190	0.209												
pH	-0.193	-0.140	0.252	0.383	0.317	0.007											
DO	0.275	0.356	-0.117	-0.009	0.003	-0.381	0.247										
TotP	-0.802	-0.896	0.663	0.411	0.477	0.477	0.017	-0.466									
SRP	-0.799	-0.895	0.597	0.347	0.424	0.504	-0.037	-0.482	0.970								
TON	0.759	0.802	-0.701	-0.427	-0.467	-0.432	-0.084	0.448	-0.801	-0.784							
NO3	0.731	0.767	-0.717	-0.446	-0.454	-0.318	-0.223	0.389	-0.807	-0.772	0.902						
NO2	-0.306	-0.392	0.399	0.247	0.321	0.024	-0.071	-0.329	0.520	0.446	-0.451	-0.490					
AmmN	0.002	-0.142	0.082	0.191	0.169	0.127	-0.010	-0.347	0.225	0.234	-0.283	-0.187	0.332				
SiO2	0.306	0.253	-0.329	-0.635	-0.608	-0.135	-0.469	-0.257	-0.055	-0.012	0.107	0.104	0.190	0.023			
CHLA	-0.395	-0.319	0.603	0.702	0.678	0.094	0.327	0.214	0.191	0.105	-0.263	-0.344	0.106	-0.004	-0.450		
TotCel	-0.311	-0.265	0.557	0.651	0.626	-0.276	0.369	0.349	0.105	0.028	-0.142	-0.200	0.185	-0.205	-0.609	0.533	

n=45

n-2 d.f. = 43

P=5% =0.301

P=1% = 0.391

P=0.1% = 0.462

Appendix 2c Spearman's Correlation Co-efficients for Reading during the whole study period (1993/4)

	Disc1	Disc10	Temp	Sun7	Sun14	SECCHI	pH	DO	TotP	SRP	TON	NO3	NO2	AmmN	SiO2	CHL.A
Disc1																
Disc10	**0.928**															
Temp	**-0.803**	**-0.750**														
Sun7	**-0.535**	**-0.550**	**0.727**													
Sun14	**-0.592**	**-0.612**	**0.746**	**0.903**												
SECCHI	**-0.493**	-0.474	0.071	-0.075	-0.035											
pH	-0.239	-0.168	0.298	0.586	**0.594**	-0.029										
DO	0.217	0.298	-0.045	0.096	0.204	**-0.304**	**0.479**									
TotP	**-0.750**	**-0.851**	**0.491**	0.163	0.271	**0.495**	-0.134	**-0.423**								
SRP	**-0.766**	**-0.891**	**0.533**	0.272	**0.348**	**0.536**	-0.123	**-0.457**	**0.936**							
TON	**0.757**	**0.807**	**-0.758**	**-0.528**	**-0.537**	**-0.331**	-0.067	0.295	**-0.751**	**-0.757**						
NO3	**0.688**	**0.701**	**-0.671**	**-0.439**	**-0.423**	-0.286	-0.069	**0.348**	**-0.698**	**-0.649**	**0.916**					
NO2	**0.322**	0.279	-0.193	-0.129	-0.195	**-0.428**	-0.184	0.114	-0.174	-0.225	0.211	0.072				
AmmN	**0.438**	**0.314**	**-0.542**	**-0.371**	**-0.530**	0.061	**-0.380**	**-0.369**	-0.106	-0.045	0.151	0.149	0.191			
SiO2	-0.142	-0.116	-0.082	**-0.389**	**-0.414**	**0.329**	**-0.603**	**-0.535**	**0.375**	**0.358**	-0.187	-0.261	-0.054	**0.383**		
CHLA	**-0.422**	**-0.389**	**0.686**	**0.753**	**0.778**	-0.174	**0.577**	**0.327**	0.100	0.152	**-0.429**	**-0.351**	0.010	**-0.417**	**-0.370**	
TotCel	**-0.373**	**-0.414**	**0.632**	**0.706**	**0.692**	**-0.339**	**0.484**	**0.309**	0.119	0.149	**-0.333**	-0.233	0.094	**-0.529**	**-0.499**	**0.655**

n=45

n-2 d.f. = 43

P=5% =0.301

P=1% = 0.391

P=0.1% = 0.462

Appendix 2d Spearman's Correlation Co-efficients for Windsor during the whole study period (1993/4)

	Disc1	Disc10	Temp	Sun7	Sun14	SECCHI	pH	DO	TotP	SRP	TON	NO3	NO2	AmmN	SiO2	CHLA
Disc1																
Disc10	0.961															
Temp	-0.778	-0.745														
Sun7	-0.524	-0.515	0.745													
Sun14	-0.587	-0.599	0.770	0.903												
SECCHI	-0.590	-0.568	0.225	0.011	0.017											
pH	-0.273	-0.209	0.379	0.618	0.599	-0.030										
DO	0.211	0.264	0.011	0.197	0.204	-0.376	0.285									
TotP	-0.833	-0.877	0.657	0.347	0.408	0.574	0.053	-0.361								
SRP	-0.842	-0.898	0.626	0.347	0.425	0.610	-0.018	-0.267	0.924							
TON	0.577	0.621	-0.775	-0.583	-0.578	-0.209	-0.220	0.065	-0.602	-0.555						
NO3	0.558	0.598	-0.767	-0.601	-0.599	-0.187	-0.264	0.056	-0.586	-0.537	0.979					
NO2	0.484	0.453	-0.494	-0.393	-0.476	-0.319	-0.377	-0.114	-0.317	-0.346	0.353	0.297				
AmmN	0.386	0.321	-0.485	-0.593	-0.550	-0.094	-0.594	-0.087	-0.149	-0.058	0.355	0.352	0.466			
SiO2	-0.261	-0.240	0.069	-0.275	-0.269	0.406	-0.468	-0.493	0.362	0.382	-0.138	-0.116	0.099	0.186		
CHLA	-0.321	-0.303	0.648	0.715	0.728	-0.112	0.524	0.415	0.195	0.209	-0.625	-0.648	-0.421	-0.445	-0.258	
TotCol	-0.426	-0.400	0.681	0.780	0.773	-0.223	0.598	0.405	0.260	0.254	-0.456	-0.460	-0.344	-0.444	-0.423	0.684

n=45

n-2 d.f. = 43

P=5% =0.301

P=1% = 0.391

P=0.1% = 0.462

Appendix 3a Spearman's Rank Correlation Co-efficients for Inglesham during spring (March to May 1993, April to June 1994)

	Disc1	Disc10	Temp	Sun7	Sun14	SECCHI	pH	DO	TotP	SRP	TON	NO3	NO2	AmmN	SiO2	CHLA	TotCel	CYN	CRP	OTH	CEN	PEN	V0
Disc1																							
Disc10	0.804																						
Temp	-0.552	-0.315																					
Sun7	-0.559	-0.448	0.566																				
Sun14	-0.692	-0.650	0.650	0.909																			
SECCHI	0.049	0.140	0.063	-0.070	-0.063																		
pH	0.173	0.307	-0.162	0.000	-0.014	0.303																	
DO	-0.456	-0.572	0.470	0.267	0.526	0.312	0.303																
TotP	-0.715	-0.928	0.245	0.231	0.420	-0.119	-0.477	0.466															
SRP	-0.271	-0.622	0.137	-0.063	0.165	-0.042	-0.523	0.374	0.623														
TON	0.028	0.232	0.261	-0.521	-0.296	0.239	0.092	0.124	-0.190	0.131													
NO3	0.063	0.261	0.240	-0.536	-0.314	0.219	0.105	0.112	-0.223	0.131	0.998												
NO2	-0.465	-0.663	-0.262	-0.274	-0.052	-0.176	-0.397	0.141	0.751	0.601	0.057	0.040											
AmmN	0.030	-0.079	-0.576	-0.060	-0.213	0.000	0.217	-0.251	0.150	-0.248	-0.433	-0.441	0.275										
SiO2	0.250	0.254	-0.547	-0.377	-0.564	-0.247	-0.162	-0.673	-0.095	-0.344	-0.146	-0.153	0.219	0.641									
CHLA	-0.173	0.109	0.663	0.550	0.511	0.473	0.244	0.273	-0.191	-0.381	0.110	0.091	-0.618	-0.221	-0.354								
TotCel	-0.329	-0.336	-0.231	0.070	0.007	-0.168	-0.356	-0.232	0.319	0.285	-0.317	-0.328	0.442	0.045	0.039	-0.564							
CYANO	-0.038	-0.177	0.355	-0.043	0.285	-0.097	-0.008	0.475	0.178	0.178	0.384	0.385	0.035	-0.414	-0.415	0.285	-0.591						
CRYPTO	-0.466	-0.571	0.123	0.637	0.599	-0.560	-0.035	0.065	0.409	-0.037	-0.564	-0.580	0.160	0.350	0.173	-0.021	0.165	-0.032					
OTHER	-0.254	-0.458	0.042	-0.008	0.096	0.308	-0.306	0.372	0.636	0.320	-0.151	-0.174	0.461	0.303	0.122	0.107	-0.237	0.233	-0.019				
CENTRIE	-0.147	-0.154	-0.329	-0.035	-0.021	0.636	0.452	0.211	0.144	-0.060	-0.042	-0.060	0.247	0.658	0.074	0.116	-0.014	-0.215	-0.077	0.370			
PENNATE	-0.406	-0.308	0.161	0.301	0.343	0.636	0.328	0.456	0.256	-0.028	0.000	-0.025	0.120	0.396	-0.067	0.515	-0.322	0.016	0.039	0.599	0.783		
VOLVO	0.011	0.235	-0.196	0.084	0.098	-0.081	0.131	-0.436	0.339	-0.361	0.088	0.092	-0.086	0.039	-0.005	0.127	0.112	0.081	0.026	-0.431	0.147	-0.056	
CHLORC	-0.203	-0.266	-0.357	-0.014	-0.105	-0.308	-0.377	-0.337	0.291	0.236	-0.401	-0.406	0.442	0.142	0.152	-0.677	0.972	-0.591	0.193	-0.237	-0.070	-0.434	

n=12 n-2 d.f.=10 Critical values : P=5%=0.648 P=1%=0.794 P=0.1%=0.879

Appendix 3b Spearman's Rank Correlation Co-efficients for Abingdon during spring (March to May 1993, April to June 1994)

	Disc1	Disc10	Temp	Sun7	Sun14	SECCHI	pH	DO	TotP	SRP	TON	NO3	NO2	AmmN	SiO2	CHLA	TotCol	CY	CR	OT	CE	PE	VO
Disc1																							
Disc10	0.839																						
Temp	-0.361	-0.133																					
Sun7	-0.329	-0.448	0.578																				
Sun14	-0.587	-0.643	0.648	0.909																			
SECCHI	-0.036	-0.029	0.020	0.022	-0.011																		
pH	0.050	-0.103	-0.071	-0.018	0.085	-0.020																	
DO	-0.515	-0.294	0.081	-0.091	0.200	0.221	0.315																
TotP	-0.678	-0.678	0.193	0.189	0.259	0.167	-0.281	-0.011															
SRP	-0.690	-0.655	0.025	0.134	0.197	0.114	-0.361	0.127	0.916														
TON	0.035	0.356	-0.307	-0.737	-0.649	0.174	-0.136	0.164	-0.095	0.014													
NO3	0.053	0.361	-0.328	-0.722	-0.641	0.206	-0.146	0.140	-0.137	-0.032	0.993												
NO2	-0.335	-0.554	0.240	0.389	0.443	-0.451	-0.024	-0.097	0.497	0.457	-0.708	-0.750											
AmmN	0.785	0.465	-0.321	-0.016	-0.274	0.114	0.127	-0.425	-0.547	-0.637	-0.286	-0.251	-0.225										
SiO2	0.710	0.664	-0.720	-0.787	-0.956	-0.088	-0.066	-0.299	-0.351	-0.251	0.457	0.452	-0.335	0.434									
CHLA	-0.280	-0.259	0.693	0.658	0.725	0.279	0.130	0.309	0.018	-0.152	-0.633	-0.609	0.224	0.043	-0.720								
TotCol	-0.510	-0.601	0.329	0.510	0.629	-0.659	-0.018	-0.095	0.371	0.373	-0.480	-0.508	0.763	-0.473	-0.566	0.102							
CYN	-0.165	-0.211	-0.211	-0.184	-0.055	-0.158	0.093	0.506	-0.064	0.037	-0.250	-0.248	0.354	0.031	0.115	0.211	-0.009						
CRP	-0.401	-0.289	0.317	0.563	0.563	0.088	0.018	0.459	-0.099	0.092	-0.288	-0.261	0.083	-0.212	-0.474	0.483	0.155	0.351					
OTHER	-0.338	0.013	0.389	0.188	0.175	0.287	0.013	0.263	0.238	0.277	0.139	0.138	-0.122	-0.559	-0.258	0.238	-0.063	-0.148	0.428				
CENTRIE	-0.846	-0.790	0.518	0.559	0.811	-0.011	0.231	0.410	0.399	0.289	-0.286	-0.277	0.291	-0.531	-0.900	0.553	0.566	0.037	0.394	0.213			
PENNATE	0.364	0.046	0.028	0.469	0.291	-0.259	0.415	-0.463	-0.172	-0.257	-0.629	-0.625	0.337	0.329	-0.106	0.125	0.350	-0.313	-0.085	-0.025	-0.039		
VOLVO	0.011	-0.161	0.279	0.483	0.406	-0.270	0.616	-0.221	0.021	-0.169	-0.468	-0.496	0.243	0.172	-0.324	0.219	0.375	-0.340	-0.074	0.000	0.326	0.719	
CHLORC	0.035	-0.021	-0.228	0.154	0.000	-0.619	-0.110	-0.483	0.126	0.225	-0.116	-0.126	0.291	-0.188	0.123	-0.459	0.538	-0.275	-0.077	0.138	-0.091	0.518	0.319

n=12 12-2 d.f.=10 Critical values : P=5%=0.648 P=1%=0.794 P=0.1%=0.879

Appendix 3c Spearman's Rank Correlation Co-efficients for Reading during spring (March to May 1993, April to June 1994)

	Disc1	Disc10	Temp	Sun7	Sun14	SECCHI	pH	DO	TotP	SRP	TON	NO3	NO2	AmmN	SiO2	CHLA	TotCel	Cyn	Crp	Oth	Cen	Pen	Vol
Disc1																							
Disc10	0.736																						
Temp	-0.558	-0.407																					
Sun7	-0.352	-0.489	0.641																				
Sun14	-0.473	-0.615	0.635	0.885																			
SECCHI	0.152	0.354	-0.432	-0.479	-0.429																		
pH	-0.569	-0.502	0.382	0.505	0.713	-0.249																	
DO	-0.641	-0.440	0.434	0.270	0.556	-0.307	0.740																
TotP	-0.580	-0.624	0.198	-0.107	0.022	-0.187	-0.060	0.289															
SRP	-0.072	-0.427	-0.057	-0.006	-0.044	-0.072	-0.499	-0.295	0.593														
TON	-0.044	0.149	-0.455	-0.609	-0.501	0.288	-0.246	-0.101	0.298	0.062													
NO3	-0.058	0.129	-0.446	-0.613	-0.498	0.271	-0.229	-0.087	0.317	0.069	0.999												
NO2	-0.090	-0.303	0.118	-0.034	-0.017	-0.628	-0.111	0.107	0.279	0.420	-0.180	-0.158											
AmmN	0.595	0.532	-0.350	-0.123	-0.434	0.114	-0.409	-0.717	-0.678	-0.168	-0.226	-0.244	0.095										
SiO2	0.510	0.612	-0.640	-0.694	-0.909	0.334	-0.695	-0.574	-0.197	0.039	0.236	0.226	0.149	0.661									
CHLA	-0.409	-0.287	0.603	0.624	0.663	-0.389	0.614	0.669	-0.216	-0.363	-0.540	-0.548	0.153	-0.141	-0.468								
TotCel	-0.610	-0.797	0.624	0.632	0.775	-0.681	0.671	0.718	0.435	0.096	-0.333	-0.311	0.320	-0.628	-0.766	0.591							
CYN	0.419	-0.314	0.464	0.070	0.096	-0.334	0.018	0.157	0.289	0.096	-0.175	-0.175	0.581	0.086	-0.022	0.316	0.210						
CRP	-0.635	-0.569	0.700	0.608	0.635	-0.400	0.700	0.467	-0.006	-0.182	-0.539	-0.522	0.279	-0.100	-0.524	0.711	0.644	0.472					
OTHER	0.210	0.070	0.044	-0.017	-0.131	0.277	-0.106	0.468	-0.332	0.018	-0.013	-0.013	-0.205	0.328	0.035	-0.079	-0.192	-0.181	0.171				
CENTRIC	-0.648	-0.775	0.635	0.538	0.786	-0.492	0.682	0.779	0.470	0.118	-0.245	-0.220	0.225	-0.784	-0.848	0.525	0.945	0.157	0.586	-0.192			
PENNATE	-0.118	-0.380	0.338	0.650	0.727	-0.653	0.579	0.400	-0.251	-0.124	-0.580	-0.575	0.386	-0.007	-0.539	0.701	0.634	0.210	0.640	-0.048	0.523		
VOLVO	-0.151	-0.393	0.402	0.536	0.586	-0.458	0.417	0.423	0.107	0.141	-0.498	-0.475	0.121	-0.442	-0.566	0.407	0.710	-0.332	0.405	0.074	0.685	0.541	
CHLORC	-0.093	-0.275	0.190	0.412	0.341	-0.404	0.225	0.278	0.256	0.160	-0.353	-0.333	-0.017	-0.395	-0.309	0.105	0.538	-0.472	0.906	-0.201	0.456	0.204	0.828

n=12 n-2 d.f.=10 Critical values : P=5%=0.648 P=1%=0.794 P=0.1%=0.879

Appendix 3d Spearman's Rank Correlation Co-efficients for Windsor during spring (March to May 1993, April to June 1994)

	Disc1	Disc10	Temp	Sun7	Sun14	SECCHI	pH	DO	TotP	SRP	TON	NO3	NO2	AmmN	Sio2	CHLA	TotCol	CYN	Crypto	Other	Centric	Pennate	Volvo	Chlrc
Disc1																								
Disc10	0.731																							
Temp	-0.676	-0.401																						
Sun7	-0.407	-0.615	0.577																					
Sun14	-0.555	-0.720	0.610	0.885																				
SECCHI	0.146	0.430	-0.207	-0.408	-0.433																			
pH	-0.569	-0.619	0.505	0.558	0.666	-0.408																		
DO	-0.787	-0.539	0.536	0.333	0.498	-0.335	0.625																	
TotP	-0.212	-0.195	0.105	-0.179	-0.171	0.248	-0.025	0.006																
SRP	-0.261	-0.459	-0.102	0.127	0.138	-0.001	-0.056	0.332	0.391															
TON	0.253	0.198	-0.738	-0.598	-0.543	0.090	-0.537	-0.313	0.017	0.051														
NO3	0.223	0.179	-0.715	-0.583	-0.525	0.102	-0.536	-0.302	0.039	0.070	0.999													
NO2	0.540	0.305	-0.334	-0.174	-0.412	-0.297	-0.369	-0.590	-0.012	-0.297	0.194	0.166												
AmmN	0.530	0.553	-0.264	-0.326	-0.465	-0.264	-0.615	-0.264	0.004	0.024	0.263	0.250	0.569											
SiO2	0.451	0.698	-0.423	-0.544	-0.791	0.485	-0.516	-0.388	-0.118	-0.138	0.182	0.162	0.383	0.326										
CHLA	-0.481	-0.359	0.669	0.591	0.630	-0.277	0.736	0.722	-0.077	0.174	-0.834	-0.830	-0.450	-0.274	-0.298									
TotCol	-0.622	-0.762	0.545	0.633	0.787	-0.749	0.747	0.709	-0.127	0.163	-0.338	-0.328	-0.328	-0.285	-0.787	0.609								
CYN	-0.463	-0.463	0.386	0.154	0.386	-0.387	0.390	0.464	0.386	0.193	-0.309	-0.309	0.041	-0.040	-0.463	0.388	0.464							
CRP	-0.759	-0.699	0.850	0.715	0.784	-0.414	0.529	0.573	0.066	0.121	-0.454	-0.421	-0.420	0.324	-0.713	0.520	0.777	0.309						
OTHER	0.332	0.559	-0.105	-0.446	-0.314	0.464	-0.137	-0.499	0.070	-0.621	0.035	0.035	0.023	-0.090	0.157	-0.264	-0.437	-0.123	-0.332					
CENTRIC	-0.681	-0.802	0.687	0.632	0.835	-0.570	0.680	0.583	-0.074	0.121	-0.433	-0.415	-0.398	-0.445	-0.813	0.541	0.894	0.463	0.872	-0.314				
PENNATE	-0.484	-0.516	0.467	0.703	0.769	-0.449	0.508	0.322	-0.501	-0.118	-0.333	-0.319	-0.200	-0.394	-0.484	0.414	0.671	0.154	0.638	-0.131	0.687			
VOLVO	-0.481	-0.459	0.525	0.630	0.710	-0.274	0.731	0.591	-0.165	-0.132	-0.396	-0.384	-0.578	-0.497	-0.655	0.589	0.712	0.077	0.642	-0.157	0.602	0.487		
CHLORC	-0.478	-0.571	0.313	0.544	0.566	-0.678	0.596	0.655	-0.338	0.179	-0.099	-0.091	-0.345	-0.170	-0.500	0.475	0.845	0.000	0.619	-0.559	0.648	0.588	0.674	

n=12 n-2 d.f.=10 Critical values : P=5%=0.648 P=1%=0.794 P=0.1%=0.879

Appendix 4a Spearman's Rank Correlation Co-efficients for Inglesham during summer and autumn (June to Sept '93, July to Oct '94)

	Disc1	Disc10	Temp	Sun7	Sun14	SECCHI	pH	DO	TotP	SRP	TON	NO3	NO2	AmmN	SiO2	CHLA	TotCel	Cyano	Crypto	Other	Centric	Pennate	Volvo	Chlore
Disc1																								
Disc10	0.877																							
Temp	-0.010	0.056																						
Sun7	-0.037	0.028	0.867																					
Sun14	0.130	0.036	0.688	0.851																				
SECCHI	0.635	-0.547	-0.064	-0.100	-0.239																			
pH	0.070	0.009	0.402	0.485	0.504	-0.030																		
DO	0.252	0.226	0.185	0.178	0.133	-0.266	0.462																	
TotP	-0.738	-0.790	0.044	0.032	0.051	0.669	0.000	-0.254																
SRP	-0.738	-0.807	-0.051	0.035	-0.031	0.542	-0.243	-0.363	0.816															
TON	-0.064	-0.150	-0.067	-0.134	-0.241	-0.232	0.097	0.009	0.037	0.147														
NO3	-0.075	-0.154	-0.074	-0.180	-0.281	-0.193	0.055	0.033	0.062	0.162	0.985													
NO2	0.458	0.544	0.195	0.216	0.287	-0.513	-0.184	-0.195	-0.515	-0.489	-0.155	-0.215												
AmmN	0.163	0.342	-0.086	-0.031	-0.068	-0.107	-0.304	-0.538	-0.252	-0.229	0.050	-0.013	0.724											
SiO2	-0.667	-0.669	-0.186	-0.279	-0.287	0.698	-0.463	-0.604	0.784	0.749	-0.048	-0.023	-0.259	0.062										
CHLA	-0.058	-0.005	0.325	0.379	0.243	-0.154	-0.134	0.182	0.103	0.113	-0.006	-0.045	0.118	-0.103	-0.103									
TotCel	0.475	0.451	0.405	0.388	0.441	-0.630	-0.188	-0.051	-0.335	-0.254	-0.122	-0.193	0.661	0.307	-0.285	0.529								
Cyano	0.060	0.037	-0.266	-0.329	-0.237	0.345	0.128	-0.084	0.151	0.056	-0.209	-0.180	-0.450	-0.154	0.049	-0.291	-0.278							
Crypto	0.088	0.009	0.140	0.272	0.284	-0.127	-0.260	-0.109	0.041	0.102	-0.378	-0.414	0.224	0.194	-0.036	0.443	0.505	-0.037						
Other	-0.362	-0.411	0.137	0.243	0.197	0.561	-0.184	-0.113	0.555	0.563	-0.057	-0.039	-0.176	-0.068	0.513	0.349	-0.108	-0.236	0.143					
Centric	0.548	0.618	0.103	0.016	-0.032	-0.295	-0.219	-0.082	-0.440	-0.587	-0.191	-0.261	0.605	0.546	-0.219	0.298	0.615	-0.145	0.355	-0.118				
Pennate	0.205	0.181	0.726	0.709	0.644	-0.431	0.325	0.488	-0.209	-0.123	0.015	-0.016	0.214	-0.269	-0.479	0.557	0.607	-0.259	0.131	0.053	0.053			
Volvo	-0.740	-0.611	0.254	0.309	0.145	0.618	0.042	-0.147	0.729	0.721	-0.007	0.019	-0.432	-0.271	0.608	0.065	-0.368	-0.088	-0.257	0.551	-0.512	-0.006		
Chlore	0.531	0.433	0.287	0.213	0.315	-0.511	-0.117	0.109	-0.450	-0.357	0.079	0.019	0.624	0.219	-0.429	0.399	0.912	-0.262	0.388	-0.349	0.498	0.600	-0.562	

n =18 - 2 d.f. =16 Critical values: P =5% =0.503 P =1% =0.635 P=0.1%=0.724

Appendix 4b Spearman's Rank Correlation Co-efficients for Abingdon during summer and autumn (June to Sept '93, July to Oct '94)

	Disc1	Disc10	Temp	Sun7	Sun14	SECCHI	pH	DO	TotP	SRP	TON	NO3	NO2	AmmN	SiO2	CHLA	TotCel	Cymo	Crypto	Other	Centric	Pennate	Volvo	Chlorc
Disc1																								
Disc10	0.868																							
Temp	-0.483	-0.386																						
Sun7	-0.322	-0.308	0.855																					
Sun14	-0.174	-0.232	0.720	0.851																				
SECCHI	-0.499	-0.588	0.053	0.104	-0.022																			
pH	-0.211	-0.051	0.473	0.469	0.402	-0.189																		
DO	0.417	0.616	-0.117	-0.095	-0.139	-0.516	0.348																	
TotP	-0.608	-0.834	0.166	0.237	0.249	0.546	-0.051	-0.572																
SRP	-0.555	-0.775	0.064	0.132	0.182	0.516	-0.017	-0.545	0.972															
TON	0.867	0.888	-0.236	-0.104	0.060	-0.605	-0.143	0.442	-0.633	-0.583														
NO3	0.783	0.717	-0.031	0.079	0.203	-0.385	-0.293	0.256	-0.537	-0.570	0.860													
NO2	0.082	0.026	0.065	0.222	0.340	-0.110	-0.140	-0.392	0.090	0.082	0.221	0.151												
AmmN	0.057	-0.163	0.118	0.375	0.425	0.089	-0.117	-0.512	0.295	0.237	0.081	0.191	0.789											
SiO2	0.374	0.299	-0.642	-0.686	-0.633	0.118	-0.637	-0.183	-0.164	-0.089	0.225	0.168	0.072	-0.183										
CHLA	0.176	0.263	0.386	0.379	0.311	-0.563	0.613	0.408	-0.369	-0.411	0.210	0.072	0.082	-0.007	-0.454									
TotCel	0.032	0.195	0.600	0.445	0.484	-0.543	0.667	0.422	-0.305	-0.366	0.182	0.142	-0.013	-0.101	-0.576	0.829								
Cymo	0.097	0.218	-0.237	-0.208	-0.246	0.041	-0.248	0.089	0.135	0.164	0.173	0.072	0.220	0.022	0.291	-0.345	-0.183							
Crypto	-0.582	-0.511	0.748	0.716	0.469	0.203	0.473	-0.261	0.306	0.191	-0.475	-0.363	0.213	0.217	-0.429	0.463	0.414	-0.262						
Other	0.013	0.058	0.004	-0.232	-0.103	0.119	0.009	0.134	-0.155	-0.184	0.001	-0.028	-0.278	-0.291	-0.047	0.164	0.231	-0.236	-0.051					
Centric	0.084	0.323	0.453	0.426	0.317	-0.545	0.469	0.460	-0.407	-0.461	0.285	0.195	0.136	0.074	-0.626	0.756	0.717	-0.065	0.322	0.120				
Pennate	0.311	0.199	-0.220	-0.096	-0.032	-0.019	-0.187	-0.134	0.051	0.097	0.316	0.280	0.326	0.363	0.291	-0.182	-0.140	0.332	-0.150	-0.330	-0.237			
Volvo	-0.538	-0.497	0.342	0.213	0.071	0.495	0.319	-0.023	0.194	0.097	-0.688	-0.533	-0.170	-0.135	-0.277	0.190	0.199	-0.287	0.569	0.389	0.030	-0.394		
Chlorc	0.517	0.486	0.233	0.211	0.387	-0.623	0.227	0.498	-0.384	-0.417	0.591	0.568	0.054	0.054	-0.341	0.593	0.736				0.184			

n =18 - 2 d.f. =16 Critical values: P =5% =0.503 P =1% =0.635 P=0.1%=0.724

Appendix 4c Spearman's Rank Correlation Co-efficients for Reading during summer and autumn (June to Sept '93, July to Oct '94)

	Disc1	Disc10	Temp	Sun7	Sun14	SECCHI	pH	DO	TotP	SRP	TON	NO3	NO2	AmmN	SiO2	CHLA	TotCel	Cyano	Crypto	Other	Centric	Pennate	Volvo	C
Disc1																								
Disc10	0.920																							
Temp	-0.332	-0.196																						
Sun7	-0.212	-0.194	0.858																					
Sun14	0.004	-0.059	0.651	0.884																				
SECCHI	-0.701	-0.724	-0.098	-0.159	-0.308																			
pH	0.029	-0.041	0.533	0.786	0.836	-0.067																		
DO	0.406	0.414	0.183	0.109	0.203	-0.277	0.313																	
TotP	-0.672	-0.721	-0.275	-0.325	-0.375	0.861	-0.240	-0.409																
SRP	-0.729	-0.792	-0.263	-0.249	-0.335	0.915	-0.154	-0.433	0.954															
TON	0.661	0.640	-0.309	-0.191	0.054	-0.671	-0.140	0.164	-0.614	-0.613														
NO3	0.611	0.582	-0.307	-0.205	-0.027	-0.683	-0.253	0.139	-0.564	-0.591	0.909													
NO2	0.536	0.587	-0.189	-0.272	-0.328	-0.339	-0.249	0.175	-0.482	-0.417	0.423	0.308												
AmmN	-0.026	-0.128	-0.202	-0.225	-0.346	0.327	-0.232	-0.510	0.291	0.272	-0.319	-0.368	0.180											
SiO2	-0.735	-0.611	-0.139	-0.067	-0.320	0.550	-0.409	-0.371	0.390	0.481	-0.281	-0.320	-0.083	0.132										
CHLA	0.272	0.323	0.594	0.733	0.754	-0.507	0.753	0.485	-0.639	-0.611	0.162	0.184	-0.106	-0.506	-0.472									
TotCel	0.441	0.542	0.452	0.435	0.495	-0.677	0.366	0.344	-0.645	-0.723	0.343	0.419	0.170	-0.454	-0.581	0.760								
Crypto	-0.054	-0.025	0.160	0.289	0.337	-0.069	0.545	0.143	-0.086	-0.059	0.054	-0.072	-0.092	-0.204	-0.213	0.415	0.242							
Other	-0.267	-0.347	0.158	0.300	0.361	0.122	0.458	0.152	0.066	0.240	-0.062	-0.175	-0.011	-0.454	0.039	0.194	0.009	0.253						
Centric	0.567	0.571	0.419	0.536	0.637	-0.776	0.524	0.303	-0.779	-0.816	0.436	0.418	0.209	-0.291	-0.645	0.793	0.893	0.383	0.014					
Pennate	0.748	0.645	-0.147	0.017	0.182	-0.550	0.295	0.479	-0.560	-0.583	0.280	0.213	0.350	0.104	-0.676	0.433	0.293	0.142	-0.131	0.475				
Volvo	-0.112	0.004	0.394	0.381	0.397	0.093	0.467	0.326	-0.107	-0.030	-0.221	-0.331	0.030	-0.461	-0.043	0.387	0.278	0.004	0.526	0.127	-0.003			
Chlore	0.034	0.235	0.289	0.011	-0.096	-0.336	-0.402	-0.162	-0.333	-0.416	0.177	0.349	0.184	-0.103	0.117	0.110	0.510	-0.375	-0.370	0.252	-0.180	0.049		

n =18 - 2 d.f. =16 Critical values: P =5% =0.503 P =1% =0.635 P=0.1%=0.724

Appendix 4d Spearman's Rank Correlation Co-efficients for Windsor during summer and autumn (June to Sept '93, July to Oct '94)

	Disc1	Disc10	Temp	Sun7	Sun14	SECCHI	pH	DO	TotP	SRP	TON	NO3	NO2	AmmN	SiO2	CHLA	TotCel	Cyano	Crypto	Other	Centric	Pennate	Volvo	C
Disc1																								
Disc10	0.917																							
Temp	-0.514	-0.334																						
Sun7	-0.319	-0.217	0.858																					
Sun14	-0.096	-0.096	0.676	0.884																				
SECCHI	-0.708	-0.687	0.128	-0.082	-0.302																			
pH	-0.192	-0.121	0.571	0.753	0.736	-0.090																		
DO	0.497	0.574	0.063	0.131	0.210	-0.510	0.214																	
TotP	-0.796	-0.787	0.206	0.037	-0.047	0.643	-0.049	-0.550																
SRP	-0.828	-0.820	0.175	-0.026	-0.196	0.809	-0.126	-0.586	0.910															
TON	0.322	0.302	-0.453	-0.424	-0.151	-0.427	-0.419	-0.041	-0.008	-0.132														
NO3	0.309	0.272	-0.420	-0.435	-0.237	-0.464	-0.545	0.072	-0.011	-0.128	0.824													
NO2	0.250	0.381	-0.058	-0.091	-0.210	-0.054	-0.223	-0.011	-0.320	-0.233	-0.025	-0.136												
AmmN	0.471	0.400	-0.666	-0.712	-0.597	0.001	-0.708	-0.181	-0.321	-0.144	0.364	0.259	0.445											
SiO2	-0.609	-0.492	0.177	-0.163	-0.306	0.562	-0.326	-0.480	0.705	0.752	0.219	0.152	-0.199	0.024										
CHLA	0.437	0.374	0.289	0.622	0.754	-0.685	0.555	0.527	-0.541	-0.682	-0.127	-0.047	-0.143	-0.413	-0.699									
TotCel	0.252	0.341	0.470	0.692	0.659	-0.544	0.458	0.463	-0.359	-0.500	-0.130	-0.026	-0.008	-0.449	-0.331	0.836								
Cyano	0.392	0.204	-0.299	-0.172	-0.046	-0.185	0.107	-0.090	-0.249	-0.302	-0.269	-0.350	0.144	0.216	-0.442	0.175	-0.026							
Crypto	-0.441	-0.402	0.521	0.613	0.476	0.085	0.411	-0.244	0.283	0.229	-0.082	-0.031	-0.516	-0.659	0.260	0.290	0.405	-0.445						
Other	-0.700	-0.776	0.130	0.007	0.039	0.434	-0.030	-0.214	0.805	0.723	0.084	0.138	-0.620	-0.392	0.576	-0.328	-0.263	-0.362	0.296					
Centric	0.529	0.615	0.083	0.271	0.384	-0.778	0.435	0.700	-0.619	-0.782	0.121	0.048	0.015	-0.254	-0.554	0.691	0.623	0.141	-0.058	-0.396				
Pennate	0.271	0.120	-0.287	-0.098	-0.059	-0.113	0.257	-0.044	-0.369	-0.274	-0.085	-0.209	-0.361	-0.012	-0.225	0.213	0.005	0.376	0.256	-0.222	0.148			
Volvo	-0.319	-0.240	0.282	0.150	0.067	0.404	0.141	-0.214	0.163	0.258	-0.323	-0.535	0.373	0.128	0.262	-0.239	-0.030	0.210	-0.197	0.055	-0.280	-0.131		
Chlcc	0.123	0.250	0.313	0.392	0.301	-0.307	-0.078	0.153	-0.210	-0.275	0.099	0.254	0.243	-0.071	0.017	0.414	0.738	-0.300	0.336	-0.211	0.161	-0.234	0.103	

n =18 - 2 d.f. =16 Critical values: P =5% =0.503 P =1% =0.635 P=0.1%=0.724