3. THE EFFECTS OF PHOSPHORUS ON AQUATIC MACROPHYTES

There are two main ways in which P can detrimentally affect macrophytes: (a) through direct action; and (b) through the secondary effects of competition with vigorous macrophyte species or epiphytic, filamentous and planktonic algae. Evidence to support both can be found in the literature, which is described below; however, the mechanism that would appear to dominate in the real environment is competition.

3.1 Tolerances of individual species

High concentrations of SRP (ie above 2.5 mg P l^{-1}) have been found to bring about retardation of growth of *Elodea nutallii* (Basiouny and Gerard 1984); however, such concentrations are rare under natural conditions. Maximum growth was obtained at a concentration of 0.016 mg P l^{-1}. Forsberg (1965) suggested that phosphorus could have toxic effects on charophytes at SRP concentrations as low as 0.020 mg l^{-1}, but this was not substantiated by studies of Blindow (1988, 1992), who found in laboratory and field studies that charophytes tolerated SRP concentrations well in excess of this (up to 0.370 mg l^{-1}). However, there may be considerable variation in tolerance between individual species, which would account for the discrepancy.

The growth of *Ceratophyllum demersum* was found to be significantly reduced at a concentration of 30 % domestic waste (Sahai and Singh 1977), although the limiting factors were not specifically identified. Phosphate (the exact form is not defined), ammonia and total nitrogen concentrations at this level of dilution were >1.8 mg l^{-1}, >2.7 mg l^{-1} and >3.3 mg l^{-1} respectively.

Jeffries (1989) described the ranges of observed water quality (including phosphorus, nitrate, ammonia, suspended solids and BOD concentrations) under which macrophyte species have been observed (Table 3.1). This work was based on a review of published literature on the effects of water quality on a wide range of biological groups. Jeffries commented that macrophytes and bryophytes were the most poorly represented of all groups in the scientific literature when considering studies relating distribution to water quality. For this reason, the ranges indicated in Table 3.1 may not reflect the full actual ranges of tolerance exhibited by species in natural conditions. There are certainly some discrepancies when compared with data presented by Haslam (1978) of concentrations with which species were best correlated for a range of water quality determinands, using data obtained from water authority monitoring (Table 3.2). In some cases, the upper concentration of the observed range of Jeffries is lower than the apparently preferred concentration listed by Haslam, eg for *Sagittaria sagittifolia*, *Sparganium erectum*, *Sparganium emersum*, and *Schoenoplectus lacustris*.

Table 3.1 Observed tolerances of macrophyte and bryophyte species to nutrients and suspended solids (by observation of occurrence) (after Jeffries 1989).

Species	SRP[1]	Nitrate	Ammonia	Suspended solids	BOD
	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
Chara	0.01-0.36	0.03-2.0			
Nitella		0-2.3		-30	
Apium nodiflorum	0-0.26	5.0-8.0		0-28	
Alismo plantago-aquatica	0-0.42	0.01-2.0	0.01-0.95		
Berula erecta	0-0.26	5.0-8.0		0-28	
Callitriche stagnalis	0-0.42	0.005-8.0	0.01-0.95	0-28	1.5-60
Ceratophyllum demersum	0.1-1.73	0.12-15	0-0.27		
Elodea canadensis	0-1.73	0-60	0-0.95	1.0-80	1.5-6.0
Glyceria maxima	0-0.26	5.0-8.0		0-28	
Groenlandia densa	0-0.26	5.0-8.0		0-28	
Hippuris vulgaris	0-0.2		0.1-1.2		
Isoetes lacustris	0-0.17	0-0.72			
Juncus bulbosus	0-0.2	0-0.05	0.1-1.2		
Lemna minor/gibba agg	0-0.42	0-2.0	0.01-1.2		2.1-15
Littorella uniflora		0-0.05			
Lobelia dortmanna	0-0.17	0.003-0.72		0-1.1	
Mentha aquatica	0-0.26	5.0-8.0		0-27	
Myosotis spp	0-0.26	5.0-8.0		0-28	
Myriophyllum spicatum	0-1.73	0.005-8.0	0.01-1.2	0-80	
M. alterniflorum	0.01-0.36	0-0.4			
Nuphar lutea	0-1.73		0.1-1.2		1.5-15
Nymphaea alba	0-0.2		0.1-1.2		
Oenanthe spp	0-0.42	0.01-7.0	0.01-0.95	0-28	
Phragmites communis	0-0.39	0.05-7.2	0.01-0.95		
Potamogeton crispus	0-1.73	0.005-60	0-0.95	1.0-80	1.5-15
P. natans	0-0.03	0.005-4.8		-30	
P. pectinatus	0-1.73	0.005-4.8	0-0.95		1.5-15
Ranunculus peltatus		0-0.6		0-0.1	
Sagittaria sagittifolia	0.06-0.15	0.64-1.6	0-0.27		
Schoenoplectus lacustris	0-0.26	5.0-8.0		0-27	
Sparganium erectum/ emersum	0-0.04	0.8-12.6		4.0-45	1.5-15
Stratiotes aloides	0.1-0.46	1.4-15			
Utricularia spp	0-0.46	0.09-2.5			
Zannichellia palustris	0.06-0.15	0.04-1.6	0-0.27		

Table 3.1 cont.

Species	SRP[1] mg l^{-1}	nitrate mg l^{-1}	ammonia mg l^{-1}	suspended solids mg l^{-1}	BOD mg l^{-1}
Bryophytes:					
Drepanocladius	<0.01	0.05			
Fontinalis	0-0.98	0.02-12	0.001-0.005	4.0-30	1.0-8.0
Leptodictyon				10-200	1.0-12
Rhynchostegium	0-1.04	0.1-32			-2.9
Scapania	0-0.01	0.02-0.96	0.001-0.005		-2.9

[1] Most "phosphorus" measurements in the literature cited by Jeffries were of "PO_4" and "Soluble Reactive Phosphorus". Jeffries presented data as PO_4 mg l^{-1}, which have been converted to SRP (ie PO_4-P) mg l^{-1}.

Table 3.2 **Concentrations of phosphorus with which species are best correlated** (after Haslam 1978).

SRP ($mg\ l^{-1}$)	**Plant Species**
<0.3	*Apium nodiflorum, Berula erecta, Callitriche* spp, *Elodea canadensis, Potamogeton natans, Ranunculus* spp, mosses
0.3-1.2	*Lemna minor* agg, *Potamogeton pectinatus*
1.2-3.0	*Nuphar lutea, Sagittaria sagittifolia, Schoenoplectus lacustris, Sparganium erectum, Sparganium emersum*
>3.0	*Myriophyllum spicatum*

Jeffries (1989) also presented general tables for macrophytes and bryophytes indicating the range of water quality reported in the literature to be associated with natural, degraded and severe loss conditions (Table 3.3). The extremely large overlap in the ranges of SRP concentrations associated with the three conditions serves to indicate the wide differences in upper and lower tolerance thresholds between different plant species/communities. Plant species of oligotrophic waters can be lost before nutrient levels are high enough to allow eutrophic species to survive. In this sense, the information presented is over-summarised, but it does indicate that severe damage to certain macrophyte communities has been reported in the scientific literature at SRP concentrations as low as 20 $ug\ l^{-1}$.

Palmer (1989, 1992) observed that some floating and submerged macrophyte species were restricted to nutrient-poor (standing) waters, some are typical of nutrient-rich sites (Table 3.4), but many species were more catholic in their requirements. However, threshold phosphorus concentrations for individual species or communities were not reported.

Table 3.3 **Concentrations of selected water quality determinands associated with natural, degraded and severe loss conditions** (after Jeffries 1989).

Condition	SRP mg l^{-1}	nitrate mg l^{-1}	ammonia mg l^{-1}	suspended solids mg l^{-1}	BOD mg l^{-1}
Macrophytes					
Natural[1]	0.02-0.15 (0-5.4)	1.4-4.0 (0-60)	0.03-0.8 (0-2.3)	4.3-27 (0-390)	1.7-6.9 (0.6-15)
Degraded[2]	0-0.1-7.8	0-2.0-99	0-0.2-3.5	30-1210	1.0-20
Severe or[2] total loss	0.02-0.2-2.9	0-2.0-11	8.0-45	10-60-25,000	1.0-6-270
Bryophytes					
Natural[3]	0-0.02	0.1-2.0	0.001-0.05	4.0-200	1.0-12
Degraded[2]				100	
Severe or total loss[2]				100-5,000	

1 Upper range is mean minima to mean maxima where more than five ranges were recorded. Lower range (in parentheses) is extreme minimum to extreme maximum.

2 Where one value is given, degradation is thought to occur above this value. Where two values are given, degradation is thought to occur throughout the range. Where three values are given (eg 10-60-25,000) degradation is thought to occur throughout the range but particularly above the middle value.
Where "less than" (ie <) values are indicated, degradation is thought to occur below a certain concentration as well as in the range listed above that concentration.

3 Observed range where few ranges recorded in the literature.

Table 3.4 **Species restricted to nutrient-poor, or typical of nutrient-rich, standing waters** (after Palmer 1989).

Species restricted to nutrient-poor waters:	**Species typical of nutrient-rich waters:**
Juncus bulbosus var *fluitans*	*Lemna* spp
Potamogeton polygonifolius	*Myriophyllum spicatum*
Lobelia dortmanna	*Potamogeton pectinatus*
Sparganium angustifolium	
Myriophyllum alterniflorum	

Newbold (1992) has concluded, from field observations over an extended period of time, that whilst certain species are capable of thriving in a wide range of nutrient concentrations, other species seem to be obligate to particular trophic levels. However, the trophic bands that species were related to were defined in terms of Total Phosphorus in standing waters, and a number of the species noted are not found in rivers. Table 3.5 gives the trophic bands used and Table 3.6 identifies species apparently obligate to these bands.

Table 3.5 **Trophic bands for standing waters** (after Newbold 1992).

Trophic Level	**Total Phosphorus** ($mg\ l^{-1}$)
Ultra-oligotrophic	<0.005
Oligotrophic	0.005-0.01
Mesotrophic	0.01-0.03
Eutrophic	0.03-0.10
Hypertrophic	>0.10

Haslam (1978) regarded the following river plants as the most eutrophic species when occurring as a group: *Nuphar lutea*, *Rorippa amphibia*, *Sagittaria sagittifolia*, *Schoenoplectus lacustris* and *Sparganium emersum*. In the development of a system using macrophytes as indicators of organic pollution in Ireland, Caffrey (1987) regarded *Rananculus pseudofluitans* and *Callitriche intermedia* as "sensitive species" and, at the other extreme, *Potamogeton pectinatus* as pollution-tolerant and an obligate eutrophic species. Haslam (1978) also regarded *Potamogeton pectinatus* as very tolerant of both sewage and industrial pollution. However, phosphorus data to support these assertions were lacking in all cases.

Generally, when phosphorus data are presented in the literature in relation to macrophytes, tolerance values are quoted as water column concentrations. Although reference to the trophic status infers sediment as well as water column nutrient levels, information on sediment chemistry is seldom published in the literature. Haslam (1978) presented information on the sediment pore water concentrations of various determinands at which species are best related, using SRP data from water authority monitoring; the information relating to SRP is given in Table 3.7.

Table 3.6 Species thought to be obligate to specific trophic bands (after Newbold 1992).

Trophic Requirements	**Species**
Obligate oligotrophs	*Potamogeton polygonifolius, Sparganium angustifolium, Subularia aquatica*(R)
Obligate oligo/ mesotrophs	*Juncus bulbosus, Scirpus fluitans, Utricularia minor*(BW), *Lobelia dortmanna, Isoetes lacustris*(R), *Nitella* sp, *Utricularia vulgaris*(agg)(BW), *Sparganium mininium, Potomageton alpinus, Nuphar pumila, Elatine hexandra*(A?), *Carex aquatilis*(BS), *Carex nigra*(BS), *Apium inundatum*(BW,BS)
Obligate eutrophs	*Potamogeton trichoides*(BW), *Potamogeton friesii*(BW)
Obligate meso/eu/ hypertrophic	*Potamogeton pectinatus, Myriophyllum spicatum, Zannichellia palustris, Oenanthe aquatica*

A Generally absent from rivers, backwaters or banksides
BS Rare on banksides
BW Rare in backwaters
R Rare in rivers

3.2 Assignment of trophic rankings

Attempts have been made to relate the distribution of macrophyte species to nutrient status and to allocate trophic rankings to riverine species (Newbold and Palmer 1979, Holmes and Newbold 1984, Newbold and Holmes 1987). However, this work has generally suffered (at least until now) from a lack of supporting information on observed nutrient levels, being based largely on the field knowledge of experienced workers. The inferred trophic status as indicated by trophic ranks or indices does not differentiate between the influences of water and sediment chemistry and therefore can only be used as an indicator of the effects of changed nutrient levels in general.

Newbold and Palmer (1979) ranked 150 aquatic plant species according to their perceived nutrient status. It is not clear from the original paper how much environmental data was used; however, Holmes and Newbold (1984) commented that the assignment of these ranks was based primarily on information on pH, conductivity and alkalinity in combination with field experience and information produced by Clapham *et al.* (1962). It was considered desirable to obtain more water quality data to confirm or regrade the rankings, and

Table 3.7 Concentrations of pore water Soluble Reactive Phosphorus with which species are best correlated (after Haslam 1978).

SRP ($mg\ l^{-1}$)	**Plant Species**
<1	*Alismo plantago-aquatica, Ceratophyllum demersum, Elodea canadensis, Glyceria maxima, Nuphar lutea, Polygonum amphibium, Sagittaria sagittifolia*
1-2	*Mentha aquatica, Myriophyllum spicatum, Nuphar lutea, Polygonum amphibium, Phragmites communis, Sagittaria sagittifolia*
2-3	*Callitriche* spp, *Myriophyllum spicatum, Potamogeton pectinatus, Sparganium erectum, Veronica beccabunga,* mosses
>3	*Myosotis scorpioides, Sparganium erectum*
Poorly correlated or related to widely ranging bands	*Apium nodiflorum, Carex acutiformis, Lemna minor* agg, *Phalaris arundinacea, Potamogeton crispus, P. perfoliatus, Ranunculus* spp, *Nasturtium officinale, Schoenoplectus lacustris, Sparganium emersum*

therefore the actual optimal nutrient concentrations of both water column and sediment required by each species may not necessarily be reflected by the rankings. Furthermore, the rankings themselves do not describe the wide tolerances of some species.

Newbold and Holmes (1984) applied Trophic Ranks to the communities characteristic of British river types as identified by Holmes (1983). The mean Trophic Score for each community closely reflected the general nutrient status described by Holmes; however, the latter was not based upon environmental data so it is not possible to define threshold concentrations for phosphorus. The nature of the substrate was thought to be a major determining factor in the differences between Trophic Scores, with pollution as a modifying factor. Newbold and Holmes (1987) also applied Trophic Ranks to communities of truly aquatic species to produce a Trophic Index. The authors used the score to demonstrate enrichment of the River Hull (see Section 3.3).

Palmer (1989) devised a Trophic Ranking Score for macrophytes in standing waters based on their observed range of tolerance. The average TRS for a site was considered to be a more subtle assessment of the trophic status of a site than would have been obtained by keying out a plant assemblage to site type. The author considered that it was best to use only floating and submerged species to obtain the TRS for a site as the open water plants were thought to be more reliable indicators of water chemistry than emergent species. The TRS was obtained for each of 23 Scottish lochs from historical data from 1904/5 and 1983/4 in order to identify changes in trophic status attributed to acidification or eutrophication.

3.3 The effects of changes in phosphorus levels on communities and species

Evidence of detailed effects on communities due to small changes in phosphorus concentrations is generally scant, largely due to a lack of focused survey work including collection of relevant environmental data. Comparisons of macrophyte survey data are weakened by the semi-quantitative or qualitative (presence-absence) nature of data collection and natural variations in communities due to environmental factors and natural community cycles.

The process of eutrophication may typically involve three phases of degradation of the plant community (Newbold 1992):

o an increase in higher plant density and productivity
o an increase in pollution-tolerant higher plants
o an increase in algae coupled with periodic [abnormal] algal blooms

Eutrophication produces changes in the levels of phosphorus in all compartments of the phosphorus cycle, but the scientific literature documenting the effects of eutrophication rarely specifies the changes occurring to each form of phosphate. In addition, most of the literature describing changes in macrophyte communities is based upon still rather than flowing water. In still waters, phytoplankton blooms are more likely to occur than in river systems due to longer retention times. In addition, the role of sedimentary phosphorus in contributing to water column nutrient concentrations may be more marked in lentic waters, owing particularly to the increased likelihood of anoxic conditions in sediments and stratification of the water column. Slow flowing lowland rivers do, however, approach the characteristics of still waters and can be subject to both algal blooms and sediment anoxia.

3.3.1 Rivers

Owens and Edwards (1961) recorded changes in macrophyte communities between three reaches of the River Ivel, from an upstream *Berula-Callitriche* community through an intermediary *Berula-*, *Callitriche-* and *Ranunculus*-dominated community, to a *Ranunculus*-dominated community downstream. A sewage works downstream of the uppermost reach resulted in an increase in SRP concentrations from 0.02 to 0.54 mg l^{-1} (and ammonia from 0.15 to 0.24 mg l^{-1}). However, the authors concluded that pollution was not responsible for these changes, as nutrients were not considered to be limiting. The amount of available solar radiation was considered more important.

Haslam (1978) considered that fertilised effluent from a watercress bed into a small chalk brook had encouraged the growth of *Groenlandia densa* and *Zannichellia palustris*, but phosphorus levels were not measured.

Chalk (1982, 1986) and Robbins (1982) described the effects of fish farms in the upper River Hull or West Beck, a Yorkshire chalk stream, a stretch of which is an SSSI. The beck is generally "clean" with mild organic pollution, principally from fish farms. Effluents were found to increase the amount of Total Phosphorus in the sediment by 60-150%, concentrations ranging from a minimum of 0.5 mg g^{-1} dry weight at upstream sites to a maximum of 5.3 mg g^{-1} downstream. Unfortunately, there were few contemporaneous water column data for nutrients. Nitrate concentrations (c 6.5 mg l^{-1}) were little changed downstream of one farm. Ammoniacal nitrogen did increase from 0.02 mg l^{-1} above the same farm to 0.14 mg l^{-1} below. SRP levels were only measured downstream of the farm and concentrations of 0.02 to 0.15 mg l^{-1} were recorded.

Organic enrichment from the fish farms on the West Beck was found to encourage the growth of filamentous algae, notably *Vaucheria* (Chalk 1986). This was accompanied by a decrease in the growth of the dominant *Ranunculus penicillatus* var *calcareus*, particularly at times of low flow when growth became stunted and epiphytic algae plus silt were deposited on its leaves and stems. However, at times of higher flow, *Ranunculus* growth seemed to be stimulated by enrichment, highlighting the complicated relationship between macrophyte growth and nutrient levels. A reduction of *Groenlandia densa* was observed, and historic records suggested that *Oenanthe* sp and *Batrachospermum* sp had disappeared from some sites. However, *Oenanthe* did occur further downstream and is considered to require high nutrient levels in chalk streams. In general, it was considered that communities below some farms were composed of species adapted to increasingly eutrophic, silty, lowland conditions. It was suspected that the discharges may have caused the succession of a *Callitriche* spp/*Ranunculus*-dominated community to encroaching emergent species (*Sparganium erectum*), filamentous algae and silt-tolerant macrophytes, although the relative importance of raised phosphorus concentrations compared to increased siltation and other water quality factors is not clear. The establishment of *Zannichellia palustris* was attributed to its tolerance of organic pollution and high phosphorus levels. *Potamogeton pectinatus* and *Cladophora*, species tolerant of organic pollution, were recorded at downstream sites.

A Trophic Index was used by Newbold and Holmes (1987) on the Hull to relate changes in macrophyte communities to available nutrient data collected by Yorkshire Water Authority. A small increase in the index, corresponding to an inferred increase in trophic status, was indicated between sites upstream and downstream of a fish farm. This change apparently corresponded to significant increases in phosphate-phosphorus, nitrate-nitrogen and ammonia levels, although data was not presented. The observed community change was lessened by impacts evident at the upstream site.

Later studies by Carr and Goulder (1990) on the River Hull demonstrated that SRP concentrations increased significantly downstream of a fish farm, along with Total Phosphorus, organic phosphorus and ammoniacal nitrogen. Again, there were no significant changes in nitrate or total inorganic nitrogen.

Mantle (1980) observed that the mosses *Brachythecium* sp and *Amblystegium riparium* disappeared downstream of a fish farm, although no other substantial changes were noted in the vegetation, dominated by *Nasturtium officinale* and *Ranunculus* sp.

Cranston and Ferguson (1991) reported the results of a macrophyte survey of the Rivers Test and Itchen and compared this with historic surveys and water quality information. The authors noted that there had been an expansion of certain species, notably *Z. palustris*, *Callitriche* spp, *P. crispus*, *P. lucens*, *Schoenoplectus lacustris* and *O. fluviatilis* and a decline in *G. densa*. Low flows and the increased deposition of silt were regarded as contributory factors for the expansion of *Z. palustris*. Siltation was also regarded as favouring *Callitriche* spp. In general, the species that had increased were those associated with relatively high Trophic Rank (of Newbold and Palmer 1979) and those associated with siltation. The changes in macrophytes were not directly attributed to water quality, which was not described in the report. A trend to increased phosphate levels has been indicated at one site on the Test by Garland (1991). Raised nutrient levels were listed by Cranston and Ferguson (1991) as a possible explanation of the increase of filamentous algae, particularly *Cladophora*, which is found throughout most of the two rivers surveyed. Weed cutting practices are a possible complicating factor in the interpretation of vegetation changes on these rivers.

Studies upstream and downstream of a sewage treatment works outfall on the River Teith in Central Scotland found extensive growths of *Cladophora* noticeable for 3 km downstream of the discharge (Fozzard and Halcrow 1991). This growth was associated with an increase (at 95 %ile flow) in Total Phosphorus concentrations of 0.02-0.03 mg l^{-1} above the typical baseline of 0.01 mg l^{-1}. Further downstream, where Total Phosphorus levels had declined to 0.026 mg l^{-1} but where organic material was still present in the river due to other discharges, no algal problems were observed. This suggests that phosphorus was the factor inducing the excessive growth, rather than the input of organic material. No observations were made of the macrophyte communities upstream and downstream of the discharge, but presumably the extensive *Cladophora* growth downstream would have had a damaging effect.

Carbiener *et al.* (1990) and Carbiener and Ortscheit (1987) described communities found in groundwater-fed streams in the upper Rhine valley that were considered to be part of a sequence of eutrophication (Table 3.8). The streams studied were deliberately homogeneous in hydrochemistry except for trophic status, in order to exclude a variety of confounding factors. They used Principal Components Analysis to classify macrophyte communities, followed by Factorial Discriminant Analysis to reclassify sites according to water quality data (400 water samples were taken over a period of 17 years). They obtained good agreement between the two methods of site grouping, and determined threshold SRP and ammonia concentrations associated with each identified community. They further considered that the community type was determined by ambient water concentrations of SRP and ammonium, and that physical parameters, such as current velocity, morphometry and temperature only induced minor changes in species composition or shifts in relative abundance. This work is the most comprehensive study found of the relationship between riverine plant communities and phosphorus concentrations, albeit relating to only a limited range of habitat.

Table 3.8 Plant communities characteristic of different trophic states (after Carbiener and Ortscheit 1987).

Trophic State	Community	Tolerance[1] SRP (mg l^{-1})	N-NH_4 (mg l^{-1})
Highly oligotrophic	*Potamogeton coloratus*, *Chara hispida*, *Juncus subnodulosus*	0.015 (0.030)[2]	0.015 (0.030)[2]
Oligo-mesotrophic	*Sium erectum* fo. *submersa* (dominant)[3], *Mentha aquatica* fo. *submersa*	0.003-0.010 (0-0.020)[2]	0.029 (0-0.070)[2]
Mesotrophic	*Callitriche obtusangula* (generally dominant)[3], eutrophic species absent	0.023 (0.050)[2]	0.030 (0.130)[2]
Eutrophic	*Zannichellia palustris*, *Potamogeton densus*, *Ranunculus trichophyllus*, *Callitriche obtusangula*, *Sium erectum*, *Nasturtium officinale*	0.010-0.060 (0.050)[2]	0.080 (0.130)[2]
Eutrophic	*Ranunculus fluitans*, *Oenanthe fluitans*, *Potamogeton perfoliatus*, *P. pectinatus*, *Ceratophyllum demersum*	0.024-0.042 (0.700)[2]	0.090 (0.475)[2]

1 Tolerance values given as a range or as the upper value of a range with an ill-defined lower value (ie "traces"). Values are based on mean of between 4 and 30 samples made over several years of study.

2 The authors cited other studies in the same geographical area giving alternative threshold concentrations.

3 These species are not characteristic of a single trophic state and it is the absence of more characteristic species and resulting dominance of these species that is indicative of the trophic state.

3.3.2 Still waters

A great deal of work has been conducted in the Norfolk Broads (eg Mason and Bryant 1975, Osborne and Moss 1977, Moss 1980, Balls *et al.* 1989, Stansfield *et al.* 1989) where, in general, diverse macrophyte communities have been rather rapidly replaced by phytoplankton communities concurrent with hypereutrophication. The mechanism of the decline of macrophytes was considered to be light attenuation due to the raised turbidity caused by phytoplankton blooms. Phillips *et al.* (1978) considered blanket growths of epiphytes to be an important factor, reducing photosynthesis of macrophytes. However, the changes in the Broads have been compounded by the effects of increased boat traffic (ie bank erosion, raised concentrations of suspended solids, diesel contamination and direct physical destruction of plants).

Mason and Bryant (1975) described some of the observed changes in macrophyte communities in the Broads of different river systems, though the riverine flora was not discussed. In general, the macrophyte losses were severe throughout most of the Broads, with *Nymphaea alba* and *Nuphar lutea* frequently being the only macrophytes remaining from once diverse floras. The Broads of the River Ant were dominated by *Stratiotes aloides* at the start of this century, but by 1968 only floating-leaved macrophytes with some *Ceratophyllum demersum* were present (these species were not found in 1972). *Ceratophyllum demersum* was choking the nearby Alderfen Broad in 1963 but the plant had almost disappeared in 1968. Irvine *et al.* (1989) noted a general sequence of change from low-growing plants (Charophytes, *Najas marina*) to taller, ranker plants (*Potamogeton*, *Ceratophyllum*, *Myriophyllum* and *Hippuris*) to phytoplankton; however, these changes were not compared with phosphorus data.

Balls *et al.* (1989) demonstrated that fertilisation of experimental ponds did not necessarily result in the loss of plant populations, as nutrient levels remained low in the presence of submerged plants, whereas increases in nutrient concentrations were recorded in ponds without macrophytes. Stansfield *et al.* (1989) suggested a contributory factor to changes from macrophyte-to-algal dominated systems may have been the historic use of organochlorine pesticides, which may have reduced populations of algal-grazing Cladocera and allowed algae to increase.

Reductions in phosphorus loadings to the Broads system have alleviated some of the problems in the area, but the internal release of phosphorus from sediments and the inability of plant communities to return have affected attempts to rehabilitate waters. Moss *et al.* (1986) described experiments to restore Alderfen and Cockshoot Broads. Both lakes were isolated to some extent from external nutrient sources. Prior to isolation, Total Phosphorus concentrations in the two Broads were 0.07-0.10 mg l^{-1} in the winter and up to 0.5 mg l^{-1} in June. Sediment was also removed from Cockshoot Broad. Within three years, concentrations were generally below 0.1 mg l^{-1}. The abundance of algae in Alderfen Broad declined greatly for several years and the Broad became dominated by *Ceratophyllum demersum*. However, the mechanism for the release of phosphate from the sediment was reactivated due to the reduction in turbulence in the water column brought about by the plants and the organic matter supplied to the sediment surface during their decay. Total phosphorus concentrations of over 0.8 mg l^{-1} were again recorded in the Broad and macrophyte growth again declined. In Cockshoot Broad, a reduction in Total Phosphorus concentration from 0.148 mg l^{-1} in 1979 to 0.067 mg l^{-1} in 1987 was measured and a reduction in algae was sustained. In addition, recolonisation by a diverse community of plants had begun within several years.

Osborne and Moss (1977) presented water quality data from nineteen stations on the River Ant and Barton Broad. In the summer, the river shows high nutrient levels (0.2-0.5 mg l^{-1} SRP; 1-5 mg l^{-1} NO3-N) upstream of Barton Broad, but low levels below (<0.1 mg l^{-1} SRP; <0.2 mg l^{-1} NO3-N) due to algal uptake and growth in the Broad. In the winter, nutrient levels are more similar upstream and downstream of the Broad (>0.1 mg l^{-1} SRP; >1 mg l^{-1} NO3-N). From palaeolimnological evidence, Moss (1980) calculated that the mean Total Phosphorus levels in the Broad had risen from 0.01 mg l^{-1} in 1800, to 0.05 mg l^{-1} in 1900, 0.07 mg l^{-1} in 1920, 0.12 mg l^{-1} in 1940, and 0.36 in 1975. Associated with the 1940 level of 0.12 mg l^{-1} there had been an abundance of macrophytes including *Stratiotes aloides*, a floating species obtaining nutrients from the water and indicative of fertile conditions. The Broad is now dominated by algal blooms. Newbold (1992) considered that a guide level of 0.100 mg l^{-1} TP is appropriate for the naturally eutrophic R. Ant and Barton Broad.

Bristow *et al.* (1977) studied the distribution of aquatic macrophytes along a nutrient gradient in a Lake Ontario bay. Fewer species and a lower density of cover were recorded in the nutrient-rich upper bay and this was attributed to algal blooms and the resulting high turbidity. The four year mean "total phosphate" concentrations (precise form undefined) were 0.082 mg l^{-1} in the upper bay and 0.022 mg l^{-1} in the lower bay. The predominant species in the upper bay was *Myriophyllum spicatum*, with *Ceratophyllum demersum*, *Elodea canadensis*, *Heteranthera dubia* and *Potamogeton pusillus* also being found. Other *Potamogeton* species (*P. zosteriformis*, *P. pectinatus*, *P. richardsonii* and *P. crispus*), *Chara globularis* and *Ranunculus aquatilis* were more prevalent in the lower bay. However, water level fluctuations, substrate and exposure conditions may have also influenced the observed macrophyte distribution. The authors considered *M. spicatum* and *P. crispus* to have growth forms that permitted the plants to survive highly turbid conditions, having trailing stems at the surface.

Newbold (1992) noted that enrichment had caused increased growths of the rush, *Juncus bulbosus* var *fluitans*, in the oligotrophic Loch Lubnaig and increased growths of Canadian Pondweed *Elodea canadensis* in the mesotrophic Loch Harray, although phosphorus data were not reported.

Arts *et al.* (1990) attributed recorded but qualitative changes in vegetation in soft water bodies in the Netherlands to changes in nutrient status (nitrogen, phosphorus, and carbon) and the accumulation of organic material. Unfortunately, data on nutrient concentrations were not included to support these conclusions. Plant communities consisted of few species in very soft waters, a diverse community in soft waters and a reduced species diversity in the more enriched waters. The changes were often part of natural successional processes in a transition to land. However, the authors pointed to eutrophication-related changes. Soft-water species most resistant to changes were *Hypericum elodes*, *Schoenoplectus fluitans*, *Lythrum portula* and *Ranunculus flammula*. *Lemna minor* and *Riccia fluitans* were considered to be indicative of eutrophicated water. Floating-leaved nymphaeids were often the last survivors of more diverse vegetation.

Makarewicz and Dilcher (1988) examined the distribution of macrophytes in the inshore waters of Lake Ontario. The plant community, dominated by *Potamogeton pectinatus*, was considered to be existing at the extremes of the tolerance of component species, on the basis of the relatively low biomass recorded (5.0 g ash-free dry weight m^{-2}) in the generally productive waters from which they had previously been absent for some years. Anecdotal evidence suggested that macrophytes had been present at the location from 1930 to the early 1940s, but had been absent from 1950 to the late 1970s. The re-establishment of macrophytes was suggested as being the result of a phosphorus abatement programme and reduced turbidity. The other species of rooted macrophytes recorded were *P. crispus* and *Myriophyllum* sp. Other environmental stresses considered to be possibly affecting the distribution and abundance of macrophytes were wave action, currents, fluctuating water levels, water pollution, and grazing by waterfowl.

Fraser *et al.* (1986) studied the distribution of macrophytes in relation to the physical and chemical characteristics of 24 lakes in Canada. The lakes were all of relatively high alkalinity (30-139 mg l^{-1} $CaCO_3$) and were dominated by species considered typical of hard waters, (eg *Potamogeton filiformis*, *P. foliosus*, *P. praelongus*, *P. strictiformis*, *P. strictifolius*, *P. zosteriformis*) and species tolerant of a wide range of alkalinities (eg *Potamogeton berchtoldii*, *Nuphar variegatum* and *Sparganium angustifolium*). Where lakes were of lower alkalinity (14-33 mg l^{-1} $CaCO_3$), plant species more typical of soft waters were recorded, eg *Potamogeton spirillus*, *P. epihydrus* and *Sparganium fluctuans*. Plant distributions were not considered to be closely related to concentrations of phosphorus and other nutrients (nitrogen, potassium and sodium) in the water column. However, the range of phosphorus concentrations encountered was not very different between the two types of community compared. Sediment and shore type did seem to influence the occurrence of several species, but sediment nutrient concentrations were not measured. Significant differences between the chemistry of soft- and hardwater lakes were observed for conductivity, total alkalinity and pH, but not for total phosphorus, total Kjeldahl nitrogen, potassium, sodium, sulphate and colour.

Blindow (1992) found that the maximum SRP concentrations associated with a number of charophyte species varied from 0.013 to 0.370 mg l^{-1} (for those species found at more than one site). It is assumed that these are mean concentrations; if so, most are well in excess of 0.020 mg l^{-1}, a concentration at which Forsberg (1965) had suggested could have toxic effects on charophytes. Blindow (1992) suggested that light, rather than phosphorus was the more direct limiting factor in eutrophic waters. The absence of charophytes from lakes with high phosphorus concentrations was thus considered to be explained by the close relationship between phosphorus and light availability. Angiosperms were able to grow at greater depths than charophytes in turbid lakes, due to adaptations to poor light availability, such as shoot elongation, canopy formation and rapid growth during spring. However, in clear, more oligotrophic waters charophytes may be found at greater depths and were superior competitors for space.

John *et al.* (1982) described changes in four charophyte-dominated marl-rich lakes in Ireland, two of which (Lough Ennell and Lough Sheelin) had demonstrated a notable increase in nutrient status due to inadequately treated sewage and pig slurry. In these two lakes, contraction of area and changes in the composition of charophyte beds were attributed to high phosphorus levels, inhibiting charophyte growth and increasing competitive interactions by stimulating the development of algae (with resulting turbidity) and other aquatic plants. The maximum depth at which charophytes were observed decreased following enrichment and both *Chara hispida* and *C. desmacantha* were displaced by *C. contraria*. Jupp *et al.* (1974) recorded that a decline in *C. aspersa* was correlated with an increase in two species of *Potamogeton* rather than its replacement by other charophytes. No phosphorus data were presented by the authors.

Extensive studies have been carried out on Bosherton Lakes, a marl system in Pembrokeshire. Hinton (1989) reported that eutrophication of the once clear-water lakes followed the commissioning of a sewage works discharging into the system in 1967. This led to a reduction in charophytes (largely *C. hispida* and some *C. globularis*) and an invasion by *Myriophyllum spicatum* and

Potamogeton pectinatus in the late 1970's. Phytoplankton blooms were prevalent when measures to reduce nutrient inputs were taken, involving the diversion of sewage in 1984. The system has since shown some recovery. Levels of phosphorus varied between the individual lakes and were influenced by their highly calcareous nature (which tends to reduce soluble phosphorus concentrations). Phases of community succession were associated with phosphorus levels as in Table 3.9. Newbold (1992) considered that a guide level of 0.025-0.050 mg l^{-1} TP was appropriate for the system.

Table 3.9 Phases of macrophyte succession and threshold concentrations of phosphorus in the Bosherton Lakes (after Hinton 1989).

Means are annual means except where indicated.

Phase & Community	**SRP**		**Total P**		**Chlorophyll**	
	max.	**mean**	**max.**	**mean**	**max.**	**mean**
	(mg P l^{-1})		(mg P l^{-1})		$\mu g\ l^{-1}$	$\mu g\ l^{-1}$
Phase 1						
Chara hispida/ Nymphaea alba	<0.01	<0.005	<0.1	<0.05	<10	<5
Phase 2						
Potamogeton/ Myriophyllum	>0.3	0.01-0.15	>0.6	0.1-0.25	100	2-50[1]
Phase 3						
Phytoplankton dominance	>0.5	0.03-0.15	>0.8	0.1-0.25	>100	>50[2]

[1] summer mean

Jupp and Spence (1977) reported on the effects of raised nutrient levels and phytoplankton concentrations on macrophyte communities in Loch Leven. The loch had demonstrated a reduction of macrophyte diversity from twenty-three species in 1910 to twelve species in 1974 and a reduction of colonised depth zone from 5 m to less than 1 m. The common species recorded were *Chara aspersa*, *Nitella opaca*, *Potamogeton filiformis* and *Zannichellia palustris*. The latter two species, along with *Cladophora* and *Enteromorpha*, were regarded as indicative of cultural enrichment. High phytoplankton densities (mainly *Anabaena* spp) developed as a result of SRP concentrations greater than 0.05 mg l^{-1}. These blooms were correlated with reduced biomass of the dominant macrophyte *Potamogeton filiformis*. This macrophyte grew better when recorded levels of phosphorus were below this value and levels of chlorophyll *a* were correspondingly low (ie below 40 $\mu g\ l^{-1}$). The authors concluded that cultural eutrophication is a causative factor in macrophyte decline in Loch Leven, the principal mechanism being the secondary effect of light attenuation (shading) occurring during dense algal blooms.

3.4 Factors affecting macrophyte status and its relationship with phosphorus

There are a number of factors other than phosphorus levels influencing macrophyte communities in rivers, many of which are inter-related. These factors complicate the interpretation of macrophyte survey data and hence the identification of relationships between ambient phosphorus levels and macrophytes. As a consequence, these factors would also interfere with the effectiveness of water column phosphorus standards in protecting macrophyte interest.

3.4.1 Seasonal succession

Aquatic macrophyte communities exhibit seasonal cycles of composition and relative abundance, determined largely by growth cycles and competitive interactions. For instance, the growth and recession of *Ranunculus*-dominated plant stands in the R. Lambourn, a southern chalk stream, was described by Ham *et al.* (1981). Seasonal patterns of change were mainly influenced by those of *Ranunculus*. Percentage cover was normally lowest in March, with a peak in the summer which could be influenced by cutting. Natural recession occurred from the summer onwards, with the greatest loss of plants occurring during August and September. Loss continued throughout the winter. A second period of growth occurred in the autumn (October), although this increase was small in comparison to the summer growth. Growth was considered to be restricted by the shading effects of an accumulation of epiphytic algae and associated detritus on the surface of the plants. *Berula* and *Callitriche* were thought to be able to compete when *Ranunculus* growth was poor.

Understanding of the relationship between macrophyte communities and phosphorus levels can be confounded by natural community succession. Comparison of macrophyte survey results undertaken at different times of the year, especially if the data are quantitative or semi-quantitative, can lead to spurious conclusions concerning species declines or disappearances. This has to be borne in mind when: a) undertaking monitoring work; and b) interpreting data.

3.4.2 Current velocity

Current velocity influences plant distribution through both its direct physical effect and also a variety of indirect effects, altering nutrient uptake rate, nutrient availability, substrate composition. Nutrient uptake rate is increased at higher velocities owing to an increased rate of phosphorus replacement at the leaf surface. The scouring effect of high water velocities produces coarse substrates with lower phosphorus adsorption capacity than the silt and mud substrates of lower energy environments.

Wiegleb (1984) studied the habitat conditions of macrophyte communities at 43 locations in Lower Saxony, Germany. The author considered that physical parameters such as current velocity were responsible for the basic zonation, whilst chemical parameters modified the zones to a large extent.

Haslam (1978) discussed the correlation of current velocity with individual species, distinguishing between species tolerant of high but uniform velocities and those resistant to spate conditions. Species that are submerged without roots (eg *Ceratophyllum demersum*) or floating (eg *Lemna minor* agg) are unlikely to be found in streams with appreciable current. Other species most closely associated with negligible or low velocities (although this does not mean that they cannot occur at high uniform velocities or even spate conditions) are: *Elodea canadensis*, *Nuphar lutea*, *Potamogeton pectinatus*, *Sagittaria sagittifolia*, *Schoenoplectus lacustris*, *Sparganium emersum* and *Sparganium erectum*. The emergents *Carex acutiformis*, *Glyceria maxima* and *Phragmites australis* would only be found above the water level of streams with appreciable current. The nuisance alga *Enteromorpha* is also considered to be associated with low current velocities. Examples of species considered to tolerate high uniform velocities better than spates are: *Apium nodiflorum*, *Berula erecta*, *Nuphar lutea*, *Oenanthe fluviatilis*, *Ranunculus aquatilis*, *R. calcareus* (usually) *Nasturtium officinale*, *Schoenoplectus lacustris* (possibly) and *Zannichellia palustris*. Species considered to tolerate spates better than high uniform velocities are: *Elodea canadensis*, *Myriophyllum spicatum*, *Polygonum amphibium*, *Potamogeton crispus*, *P. perfoliatus* (perhaps), *Ranunculs fluitans* and *Sparganium erectum*. The reasons for the preference of the latter species vary: they may be difficult to uproot, regrow rapidly from fragments or require fine substrates for rooting.

Madsen and Sondergaard (1983) found in physiological studies that photosynthetic rates are positively correlated with current speeds over the range likely to occur in weed beds (0.0-0.2 m s^{-1}). Ham *et al.* (1981) stated that higher discharge in the chalk stream environment was thought to benefit *Ranunculus*, although the converse was thought to be true for rivers with a greater range of discharge, eg the River Wye, presumably due to direct physical effects increasing wash-out.

Nilsson (1987) reported that up to current speeds of 0.3 m s^{-1}, instream macrophyte cover increased, but cover decreased at higher speeds. Current speeds of above 0.3 m s^{-1} prevented accumulation of organic material. Riparian vegetation was found to increase with increasing current velocity. Chambers *et al.* (1991) investigated in some detail the effects of current velocity on aquatic macrophytes in rivers in Alberta. Biomass decreased with increasing current velocity within weed beds over the range 0.01-1 m s^{-1}, and at current speeds of over 1 m s^{-1} macrophytes were rare. Substrate types and their nutrient content differed over the range of current speeds. Detailed transplant experiments were carried out in which *Potamogeton pectinatus* plants grown in pails containing differing substrate types were positioned at different current speeds. These demonstrated that biomass and shoot density were affected by both the direct effects of current velocity and its indirect effect on sediment nutrient concentrations. Current velocity was negatively correlated with biomass.

Boeger (1992) investigated the influence of three different current velocities (high, 22.6 cm s^{-1}; medium, 11 cm s^{-1}; and low, below 2 cm s^{-1}) and substrata on the growth of *Ranunculus aquatilis*. The results indicated that current velocity and substrate were inextricably linked, the effects being combined. However, the least plant growth was recorded at the lower velocity.

Another important aspect of current velocity is that it determines the retention time of water in the river and thus the likelihood of significant phytoplankton growth. In the Thames, the critical mean discharge for algal bloom formation appears to be 0.48 m s^{-1} (Reynolds 1988), a value very similar to the maximum velocity at which Gessner (1955) concluded that true potamoplankton could be supported. However, Bowles and Quennell (1971) found that the spring diatom bloom in the lower Thames occurred only when the mean velocity was <0.3 m s^{-1}, with peak algal levels occurring at velocities of <0.1 m s^{-1}.

Strong relationships have been found between river nutrient concentrations and current velocity. Oborne *et al.* (1980) studied the relationships with catchment features and current velocity of a number of water quality parameters along much of the length of the River Wye. Spatial variations in nutrient concentrations were principally related to population and land use patterns. Nutrient concentrations increased downstream, with phosphorus typically ranging from <0.01 to >0.10 mg l^{-1} SRP. SRP loads were significantly related to (human) population density in both wet and dry periods, whereas nitrate loads was only related in dry periods, presumably due to high N leaching from land in wet weather. SRP concentrations were generally inversely related to river flow, whereas nitrate and suspended solids concentrations increased with flow. Seasonally, there were substantial summer increases in SRP concentrations in the lower catchment, but there was no seasonal trend in upland sites. Summer increases in phosphate levels were attributed to the proportional increase in sewage effluent contributions during low summer flow. Although the authors only measured SRP, they cited a study (Smith 1976) that concluded that in the River Main, Northern Ireland, 75% of the sewage loading of total phosphorus was in the form of SRP after treatment. Similar relationships of phosphorus and nitrate with current velocity have been reported by Edwards (1973) for the Rivers Yare and Wensum. Other rivers studied by Edwards (1973), the Tas and Tud, were not so influenced by sewage contamination and hence did not show a significant negative correlation between phosphorus and current velocity.

3.4.3 Substrate

Particle size influences both the nutrient capacity of the substrate and the potential for anchorage by rooted plants. It is inevitably closely linked to current velocity, although plants may themselves obscure this relationship by trapping fine sediments. Haslam (1978) listed species associated with particular substrate types and these match associations with current velocity quite closely. Plants themselves may influence sediment composition through sediment nutrient uptake, contributions of their own remains and by trapping external material.

Chambers *et al.* (1991) found that in transplant experiments with *P. pectinatus* plants, sediment type influenced the growth of the plants, with both biomass and shoot density being greatest in a sand/silt sediment mixture with the highest phosphorus content, compared to a sand/silt mixture with the highest nitrogen and organic content and a sand substrate with the lowest nutrient content. Plant tissue concentrations were strongly correlated with the sediment type.

Barko and Smart (1986) found the growth of aquatic macrophytes in North American lakes to be relatively poor on highly organic sediments, and that both sediment organic matter content and texture were important in affecting the growth potential of plants on different sediments. Large declines in growth of *Myriophyllum spicatum* and *Elodea nutallii* were associated with increases in sediment organic matter up to a concentration of 20% dry sediment mass. In addition, poor growth was obtained on inorganic sediments with a low organic (<10%) and high sand fraction (>75% dry sediment mass). Low growth in highly organic sediments has been suggested as being related to growth inhibition by phytotoxins under anaerobic conditions, an inadequacy of oxygen supply to the roots and nutrient limitation due to complexation with organic matter. Growth experiments following differential centrifugation of organic sediments suggested that sediment density rather than organic matter was most influential in regulating growth. Sediment density increased with increasing sand content and decreased with increasing organic matter. Although concentrations of P in the sediment were positively correlated with organic matter, there was no relationship between interstitial water and sediment concentrations of P. Combined additions of solutions containing phosphorus (as $CaHPO4$) and iron (as Fe_2O_3) resulted in significant increases in growth of *Elodea* plants. The authors considered that as sediment organic matter accumulates in lakes, submerged macrophytes appear to be replaced by floating-leaved and emergent forms with greater root to shoot biomass.

In the study by Boeger (1992) of the influence of three different flow velocities and substrata (mud, sand and gravel) on the growth of *Ranunculus aquatilis*, growth in mud was highest at all velocities but more complicated for other substrates. In sand and gravel growth was highest at medium velocity.

3.4.4 Sedimentation

Brookes (1986) discussed the effects of excess suspended solids generated by land drainage works on plant communities downstream. The response of plant species to severe sedimentation was related to their ability to vary their rooting level. For example, *Ranunculus penicillatus* var *calcareus* was unable to adjust its rooting level and underwent severe decline due to smothering. *Nasturtium officinale*, however, was less affected, the species being able to adjust rooting level. Haslam (1978) presented a classification of plant species according to whether the potential of each to vary its rooting level. Sediment deposition in the Norfolk Broads has been considered to be a factor in the elimination of macrophyte stands.

Robbins (1982) considered that increased sedimentation downstream of a trout farm on the West Beck had led to an increased plant and algal biomass. However, the effect of sedimentation was confounded by the high phosphorus concentrations in the sediment.

3.4.5 Light

Light is an essential requirement for photosynthesis and plant growth and is a major determinant of plant distributions in rivers. Factors affecting the availability of light to plants include water depth, turbidity (which can be increased by algal blooms), and the shading effects of other plants (including instream macrophytes, epiphytes, filamentous algae and riparian trees). Some of these factors can be affected by changes in phosphorus levels, but clearly light levels can vary irrespective of the effects of phosphorus. Dawson and Kern-Hansen (1979) concluded from studies in Denmark that the reduction in biomass of three main problem species of submerged aquatic macrophytes was proportional to the intensity of light at the stream surface. They recommended that light levels should be reduced to around half that available in the open, which would be expected to increase the diversity of plant species. Although little work on changes in macrophyte communities seems to have been undertaken in Denmark since this time, the Danish National Environmental Research Institute (DNERI) believes that SRP is of minor importance to riverine macrophyte communities in general, compared to light levels and current velocity (pers comm Torben Lauridsen, DNERI).

3.4.6 Other possible chemical limiting factors

A variety of water quality parameters may influence the composition and health of aquatic macrophyte communities, including pH, herbicides and heavy metals. Again, Jeffries (1989) gives some data on levels for natural, degraded and severe/total loss conditions from a review of the published literature.