

Review Articles

Eutrophication of Freshwater and Coastal Marine Ecosystems A Global Problem

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DOI: <http://dx.doi.org/10.1065/espr2002.12.142>

Abstract

Goal, Scope and Background. Humans now strongly influence almost every major aquatic ecosystem, and their activities have dramatically altered the fluxes of growth-limiting nutrients from the landscape to receiving waters. Unfortunately, these nutrient inputs have had profound negative effects upon the quality of surface waters worldwide. This review examines how eutrophication influences the biomass and species composition of algae in both freshwater and coastal marine systems.

Main Features. An overview of recent advances in algae-related eutrophication research is presented. In freshwater systems, a summary is presented for lakes and reservoirs; streams and rivers; and wetlands. A brief summary is also presented for estuarine and coastal marine ecosystems.

Results. Eutrophication causes predictable increases in the biomass of algae in lakes and reservoirs; streams and rivers; wetlands; and coastal marine ecosystems. As in lakes, the response of suspended algae in large rivers to changes in nutrient loading may be hysteretic in some cases. The inhibitory effects of high concentrations of inorganic suspended solids on algal growth, which can be very evident in many reservoirs receiving high inputs of suspended soils, also potentially may occur in turbid rivers. Consistent and predictable eutrophication-caused increases in cyanobacterial dominance of phytoplankton have been reported worldwide for natural lakes, and similar trends are reported here both for phytoplankton in turbid reservoirs, and for suspended algae in a large river.

Conclusions. A remarkable unity is evident in the global response of algal biomass to nitrogen and phosphorus availability in lakes and reservoirs; wetlands; streams and rivers; and coastal marine waters. The species composition of algal communities inhabiting the water column appears to respond similarly to nutrient loading, whether in lakes, reservoirs, or rivers. As is true of freshwater ecosystems, the recent literature suggests that coastal marine ecosystems will respond positively to nutrient loading control efforts.

Recommendations and Outlook. Our understanding of freshwater eutrophication and its effects on algal-related water quality is strong and is advancing rapidly. However, our understanding of the effects of eutrophication on estuarine and coastal marine ecosystems is much more limited, and this gap represents an important future research need. Although coastal systems can be hydrologically complex, the biomass of marine phytoplankton nonetheless appears to respond sensitively and predictably to changes in the external supplies of nitrogen and phosphorus. These responses suggest that efforts to manage nutrient inputs to the seas will result in significant improvements in coastal zone water quality. Additional new efforts should be made to develop models that quantitatively link ecosystem-level responses to nutrient loading in both freshwater and marine systems.

Keywords: Algae; coastal marine ecosystems; estuaries; eutrophication; harmful algal blooms; nitrogen; nutrients; lakes; reservoirs; rivers; phosphorus; phytoplankton; shallow lakes; wetlands

Introduction

Humans now strongly influence almost every major aquatic ecosystem, and their activities have dramatically altered the fluxes of growth-limiting nutrients from the landscape to receiving waters. One primary cause has been the rapid intensification of agriculture (Matson et al. 1997). The global production of agricultural fertilizers alone released <10 million metric tonnes of nitrogen in 1950, but may exceed 135 million metric tonnes of N by the year 2030 (Vitousek et al. 1997). Substantial N is also applied to croplands in the form of animal manures, for which regulatory standards are generally far less stringent than those applied to human sewage (Carpenter et al. 1998a). Similarly, a small but ecologically very significant portion of agriculturally-applied phosphorus is exported from the land surface to receiving waters (Bennett et al. 2001, Kauppi et al. 1993, Rekolainen et al. 1995, Sims et al. 1998). Atmospheric loading of P to surface waters has also increased (Brunner and Bachofen 1998). In addition, humans use flowing waters as convenient wastewater disposal systems, and the loading of N and P to the world's surface waters is very strongly influenced by human population density and land use (Cole et al. 1993, Caraco 1995).

Unfortunately, these nutrient inputs can have profound effects upon the quality of receiving waters (Carpenter et al. 1998a, Correll 1998). Just as fertilizing an agricultural crop or forest can result in enhanced plant growth, the most common effect of increased N and P supplies to aquatic ecosystems is an increase in the abundance of algae and aquatic plants. However, the environmental consequences of excessive nutrient enrichment are more serious and far-reaching than nuisance increases in plant growth alone. The degradation of water resources by eutrophication can result in loss of the amenities or services that these aquatic resources provide (Postel and Carpenter 1997). In addition, the eutrophication of both freshwater and coastal marine systems causes a wide array of undesirable symptoms that are either directly or indirectly related to the nuisance growth of aquatic plants (Table 1).

Eutrophication accounts for almost one half of the impaired lake area and 60% of impaired river reaches within the United States alone (U.S. EPA 1996a), and eutrophication-related water quality impairment can have very substantial negative economic effects (Carpenter et al. 1998b, Corrales and Maclean 1995). Eutrophic drinking water supply reservoirs, for example, are much more likely to have higher treatment costs; greater

Table 1: Adverse effects of freshwater and coastal marine eutrophication

difficulties in meeting standards for disinfection by-products; consumer complaints due to objectionable taste and odor; and health hazards due to algal toxins in the finished drinking water (Cooke and Kennedy 2001). In coastal marine habitats, harmful algal blooms may render shellfish and finfish toxic, or cause massive fish and shrimp kills; by mid-1994, there were 3,164 reported incidents of human poisoning and 148 deaths in the Asia-Pacific region alone (Corrales and Maclean 1995). Economic losses may exceed \$1 million U.S. per event, and monitoring efforts may cost up to \$50,000 U.S. for each affected area (Corrales and Maclean 1995).

Because of these problems, there have concerted efforts for several decades by aquatic ecologists and civil engineers worldwide to develop a rational predictive framework to prevent and manage freshwater eutrophication (OECD 1982, Cooke et al. 1993). The U.S. EPA has recently published a series of nutrient criteria technical guidance manuals for lakes and reservoirs, rivers and streams, and marine waters (U.S. EPA 2002), and parallel attempts are being made worldwide to evaluate and to predict the responses of aquatic ecosystems to changes in nutrient loading.

As a result of global efforts to solve the eutrophication problem, we now have a firm mechanistic understanding of the relative roles of N and P as growth-limiting nutrients; we have developed models that can predict nutrient concentrations in receiving waters from watershed nutrient inputs and hydrology; and we have developed a series of models that then relate waterbody nutrient concentrations to the critical aspects of water quality that are perceived by the general public as being important and worthy of preservation. In general, an exces-

sive accumulation of algal biomass is the symptom of eutrophication that is most easily perceived and most disliked by the public. A remarkable unity in the response of algal production to eutrophication has in fact been found in most aquatic ecosystems that have been studied, and a demonstrated success in reducing algal biomass to publicly acceptable levels has been the feature held in common by all successful eutrophication control efforts (Smith 1998).

The literature on eutrophication is expanding rapidly, and cannot be reviewed comprehensively in this paper. A large number of historical and technical reviews have appeared during the past several years (e.g., Carlson and Simpson 1998, Correll 1998, Smith 1998, Smith et al. 1999, Swedish EPA 2000, U.S. EPA 2002), and this information will not be repeated here. The purpose of this mini-review is to provide a brief update of our knowledge of the effects of eutrophication on algal-related water quality in both freshwater and coastal marine ecosystems, and to suggest key areas that may be fruitful for future research efforts.

1 Eutrophication of Freshwater Ecosystems

1.1 Lakes and reservoirs

Effects of eutrophication on algal biomass. Because phosphorus has been identified as a key growth-limiting nutrient for algae in lakes and reservoirs (Schindler 1977, OECD 1982), phosphorus-based eutrophication classification systems and management schemes have been developed worldwide. An example of the Swedish eutrophication classification system for lakes is shown in Table 2.

Table 2: Swedish eutrophication classification system for freshwater lakes according to the growing season biovolume of planktonic algae (modified from Willén 2000)

Class	Designation	May-October mean biomass: mm ³ per L	August peak biomass: mm ³ per L	Lake trophic state
1a	Particularly small biomass	≤0.1	≤0.1	Ultraoligotrophic
1b	Very small biomass	0.1–0.5	0.1–0.5	Oligotrophic
2	Small biomass	0.5–1.5	0.5–2	Mesotrophic
3	Moderately large biomass	1.5–2.5	2–4	Eutrophy I
4	Large biomass	2.5–5	4–8	Eutrophy II
5	Very large biomass	>5	>8	Hypertrophy

In general, the growing season average biomass of algae in lakes is strongly dependent upon the concentration of total phosphorus (TP, $\mu\text{g/L}$) in the water. However, the relative availabilities of nitrogen and phosphorus change consistently with cultural eutrophication (Downing and McCauley 1992), and the response of algal biomass to TP is strongly modified by the total nitrogen to total phosphorus (TN:TP) ratio (cf. Forsberg and Ryding 1980, Smith 1982, Canfield 1983, Prairie et al. 1989, McCauley et al. 1989, Faafeng and Hessen 1993, Seip 1994).

The global robustness of algal biomass-nutrient relationships has been well demonstrated in many cross-sectional analyses of lakes and reservoirs (Sakamoto 1966, Lund 1970, Dillon and Rigler 1974, Jones and Bachmann 1976, Ahl and Weiderholm 1977, Nicholls and Dillon 1978, Canfield and Bachmann 1981, Chow-Fraser et al. 1994, Seip and Ibrekk 1988, Smith 1990a, Jones et al. 1998, Nürnberg 1996, Mazumder and Havens 1998, Portielje and Van der Molen 1999, Seip et al. 1992, 2000, Brown et al. 2000). Information on the responses of lake and reservoir water quality to nutrient enrichment is now available from most of the geographical regions of the world (e.g., **Africa:** Thornton 1980, Harper et al. 1993, Hecky 1993, Kebede et al. 1994, van Ginkel et al. 2000, Varis and Fraboulet-Jussila 2002; **Australia:** Ferris and Tyler 1985, Davis 1997; **Central and South America:** Quirós 1991, 1998; Salas and Martino 1991, Jones et al. 1993; **China:** Chang 2002, Dickman et al. 2001; **Europe:** Hrbáček and Popovský 1978, Vyhánek et al. 1994; Kopáček et al. 1996, Istvánovics and Somlyódy 1999; **Greece:** Danielidis et al. 1996; **Ireland and the U.K.:** Harper and Stewart 1987, Traill 1991, Sutcliffe and Jones 1992; Moss et al. 1996, Wilson 1998; **India:** Bhade et al. 2001, Kaul 1977; **Israel:** Gophen et al. 1999; **Italy:** de Bernardi et al. 1996, Heinonen et al. 2000; **Japan:** Seip and Satoh 1984, Fukushima and Muraoka 1988; **Korea:** An and Jones 2000, 2002; **Nepal:** Aizaki et al. 1987, Jones et al. 1989; **New Zealand:** Pridmore et al. 1985, McBride and Pridmore 1988, Duggan et al. 2001; **Oman:** Victor et al. 2002; **Scandinavia:** Willén 2000, Rask et al. 2002; **Sri Lanka:** Piyasiri 2001; **Thailand:** Jones et al. 2000; and **Turkey:** Tanik et al. 1999).

In general, comparative studies of freshwater eutrophication strongly suggest that efforts to control external nutrient loading to many lakes will tend to achieve similar reductions in their average algal biomass, regardless of geographical location (Seip et al. 2000; but for exceptions, see Sas 1989, Moss et al. 1996, Carpenter et al. 1999). However, the growing season or yearly average biomass of algae *per se* is probably not consciously measured or used by the users of a water body as their primary index of water quality impairment: the maximal concentrations of algal biomass that occur during transient blooms are much more easily detected, and even more strongly disliked by the public. Jones et al. (1979) reported a linear arithmetic relationship between **mean** algal biomass (estimated as chlorophyll *a*) and **maximum** algal biomass in U.S. lakes:

$$\text{Chl}_{\text{max}} = 1.7 (\text{Chl}_{\text{mean}}) + 0.2, r^2 = 0.58 \quad (1)$$

Other investigators have reported a much steeper arithmetic slope (2.6 rather than 1.7; see OECD 1982); however, the variance in the relationship of Jones et al. (1979: their Fig. 1) increases strongly with the value of Chl_{mean} , implying that empirical models based on log-transformed data should be stronger and statistically more appropriate. Stadelmann et al. (2001) have examined relationships between mean and maximum chlorophyll *a* during the growing season in Minnesota lakes, and they indeed found a very strong log-linear relationship (note that the dependent and independent variables are reversed in their analysis),

$$\log_{10} (\text{Chl}_{\text{mean}}) = 0.91 \log_{10} (\text{Chl}_{\text{max}}) - 0.20, r^2 = 0.91 \quad (2)$$

Similarly, Willén (2000) reported an empirical relationship between late-summer peak biomass and growing-season mean algal biomass (based upon algal biovolume rather than Chl *a*),

$$\text{Total Volume}_{\text{August}} = 1.65 (\text{Total Volume}_{\text{May-October}}) - 0.26, r^2 = 0.75 \quad (3)$$

In addition, she reported a strong relationship between annual peak algal biomass and growing-season mean concentrations of total phosphorus,

$$\log_{10} (\text{Annual Peak Total Volume}) = 1.512 \log_{10} (\text{TP}_{\text{March-October}}) - 1.924, r^2 = 0.76 \quad (4)$$

Phosphorus-based models can also be used to quantify the response of nuisance algal bloom frequency to reductions in nutrient loading. For example, Havens and Walker (2002) have developed predictive models relating water column TP concentrations to the frequency algal blooms in Lake Okechobee, Florida (USA), which they used to establish in-lake total phosphorus goals that will be required to reduce water quality impairment in this multiple-use lake. Similarly, Lathrop et al. (1998) have developed models to predict the phosphorus loading reductions needed to reduce the frequency of blue-green algal blooms in Lake Mendota, Wisconsin (USA).

Although both the average and the peak biomass of algae in lakes often respond very sensitively to changes in nutrient availability, several critical site-specific factors can alter the responses of algal growth to external N and P loading. For example, variations in depth can potentially modify algal growth (Petersen et al. 1997), and deep lakes produce a lower algal biomass per unit total phosphorus than shallow lakes (Smith 1990a). For example, the May-October mean biovolume of algae in shallow, wind-mixed lakes (mean depth ≤ 3 meters) is typically twice as great as the values observed in thermally stratified, deep lakes of similar fertility in Sweden (Willén 2000). Similarly, Mazumder (1994a) noted higher levels of algal biomass (measured as chlorophyll *a*) in shallow, mixed lakes than in stratified lakes. In addition to these cross-system differences, lakes with complex physical structure can exhibit remarkable spatial variations in water chemistry and algal biomass (cf. Philips et al. 1993). For example, the *within-lake* variation observed in Table Rock, Missouri (USA) is so large that it almost matches the magnitude of *lake-to-lake* variation within the entire state (Jones et al. 1997)!

In addition to the above effects of morphometry, the hydraulic residence time of a waterbody potentially can influence the biomass of algae produced by nutrients if the water residence time is shorter than the doubling times (ca. 0.5–1.5 days) of phytoplankton algae (Reynolds 1997). Significant effects of hydraulic flushing on phytoplankton biomass have indeed been observed in the very small fraction of waterbodies that have exceptionally short water residence times (McBride and Pridmore 1988, Smith 1990a). However, in environments which experience strong seasonality in rainfall and hydrology such as southeastern Asia, dramatic changes in water quality also can occur as a result of periodic monsoons (Jones et al. 1997). Other physical factors can modify the biological expressions of eutrophication as well. For example, high rates of soil erosion in the watershed can result in elevated inorganic turbidity levels that can strongly attenuate underwater light and potentially reduce the algal biomass produced at a given concentration of total phosphorus (Canfield and Bachmann 1981, Hoyer and Jones 1982, Ferris and Tyler 1985, Carlson 1991, Jones et al. 1998, Dokulil 1994, Jones et al. 1997).

Biotic factors can also be extremely important. In shallow lakes that have the potential to develop large populations of aquatic vascular plants (macrophytes), the presence or absence of these plants can strongly modify the biomass of algae produced at a given nutrient supply level (Canfield et al. 1983). For example, Portielje and Van der Molen (1999) reported significantly lower chlorophyll *a* concentrations in shallow Dutch lakes and ponds with submersed macrophytes coverage exceeding 5% of the total surface area. Shallow lakes inherently have the capacity to develop large macrophyte populations, and also may exhibit strong internal phosphorus loading due to regeneration from the lake sediments. Such lakes may not respond to nutrient loading management in the manner predicted by simple eutrophication models (Moss et al. 1996, Carpenter et al. 1999). In some cases, shallow eutrophic lakes can alternate between two equilibrium points, in which one stable state is dominated by macrophytes, and the alternate stable state is dominated by optically thick phytoplankton communities (Scheffer et al. 1993, Scheffer 1998).

The effects of food web structure on algal biomass in lakes have also been extremely well characterized during the past 25 years (Shapiro et al. 1975, Hrbáček et al. 1978, Carpenter and Kitchell 1993, Mazumder 1994a,b, Carpenter et al. 1995, Lacroix et al. 1996, Carpenter 2002). In particular, lake-to-lake differences in the abundance and structure of fish communities can profoundly influence algal biomass by modifying the grazing pressure of zooplankton on phytoplankton. Large cladocerans such as *Daphia pulex* and *Daphnia pulex* typically become abundant in lakes having few (or no) planktivorous fish, and these large-bodied herbivores are extremely effective grazers. Lakes dominated by planktivorous (zooplankton-eating) fish thus produce a significantly higher algal biomass per unit TP than lakes dominated by piscivorous (fish-eating) fish, because the intensity of zooplankton grazing on algae is typically lowest in planktivore-dominated systems (Carpenter and Kitchell 1993, Quirós 1991,1998). However, the effects of food web

structure on algal biomass can also be modified by the physical structure of the environment (e.g., lake depth: Proulx et al. 1996, Bertolo et al. 2000).

Such trophic interactions also offer the potential for using food web manipulations (biomanipulation: Shapiro et al. 1975) as a means to reduce nuisance phytoplankton biomass in nutrient-enriched lakes. The record of biomanipulation as a management tool often has been positive, but the actual responses to deliberate fish manipulations have been highly variable (Gulati et al. 1990, Cottingham and Knight 1995, Sarvala et al. 2000, Søndergaard et al. 2000).

Effects of eutrophication on algal species composition. The biomass of phytoplankton is frequently, but not always, the primary focus of attention in lake and reservoir management. Algal species composition in many cases may be a more important facet of water quality for the users and consumers of freshwater. Bloom-forming blue-green algae (cyanobacteria) typically become dominant over other algal species in the phytoplankton of eutrophic lakes (Schindler 1977, Reynolds 1997, Smith 1990a, 2001). These cyanobacteria can form objectionable surface scums (Klemer and Konopka 1989, Paerl 1988); can cause summer fishkills (Barica 1978, Lathrop et al. 1998, Kann and Smith 1999); and can impair the quality of drinking water (Cooke and Kennedy 2001, Smith et al. 2003).

In addition, many cyanobacteria can produce highly hepatotoxic, cytotoxic, and neurotoxic compounds that are hazardous to humans, cattle, domestic animals, and aquatic consumers (Fulton and Paerl 1987, Hawser et al. 1992, Carmichael 1997, Chorus and Bartram 1999, Sivonen 2000, van Ginkel et al. 2000, Chorus 2001). Mass occurrences of toxic cyanobacteria are a global phenomenon, although the timing and duration of the bloom-forming season varies with geographic location (Sivonen 2000). In Europe alone, surveys using toxicity bioassays or high performance liquid chromatography have revealed an unexpectedly high frequency of toxic blooms (Fig. 1).

The general patterns of response by toxic cyanobacteria to eutrophication are nicely summarized in a recent comparative study by Willén et al. (2000). Both the intensity of late

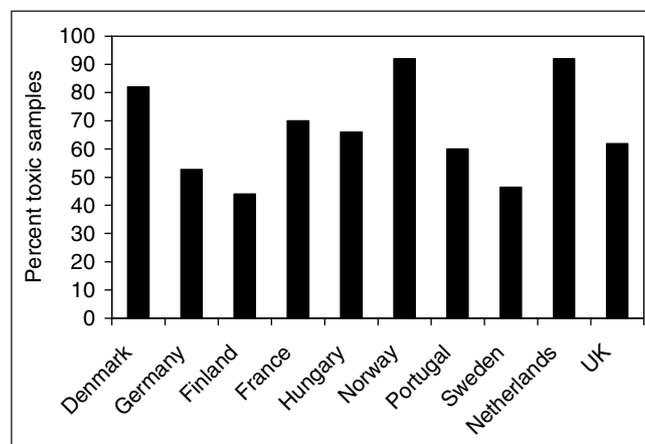


Fig. 1: Frequencies of toxic cyanobacterial blooms in 11 European countries (data from Table 2.2.1 in Sivonen 2000)

Table 3: Swedish eutrophication classification system for total phosphorus and water-blooming cyanobacteria in late summer (modified from Willén 2000)

Class	Designation	Total phosphorus, $\mu\text{g/L}$	August cyanobacterial biomass: mm^3 per L	Number of toxin-producing cyanobacterial genera
1	Very small biomass	6–12.5	<0.5	≤ 2
2	Small biomass	12.5–25	0.5–1	–
3	Moderately large biomass	25–50	1–2.5	3–4
4	Large biomass	50–100	2.5–5	–
5	Very large biomass	>100	>5	4

summer cyanobacterial blooms and the number of toxin-producing genera increase with eutrophication in Swedish lakes (Table 3). However, Willén et al. (2000) found no trend in peak cyanobacterial toxicity ($\mu\text{g/g}$ dry wt. of algae) with lake trophic state, and found that maximum cyanophyte toxicity was more closely related to species dominance than to season.

While many past studies of cyanobacteria have focused primarily on the phytoplankton of natural lakes, toxic blue-green blooms also frequently occur in enriched, turbid Australian reservoirs (Davis 1997); similarly, 10 of 15 turbid Kansas reservoirs studied by Dodds (1996) were found to contain potentially toxic, microcystin-producing cyanobacterial strains. The empirical study of Smith (1990b) and the data shown in Fig. 2 indicate that cyanobacterial dominance can increase dramatically with nutrient enrichment in turbid, man-made impoundments; however, this general response is likely to be modified by the presence of high concentrations of non-volatile suspended solids (Smith 1990b).

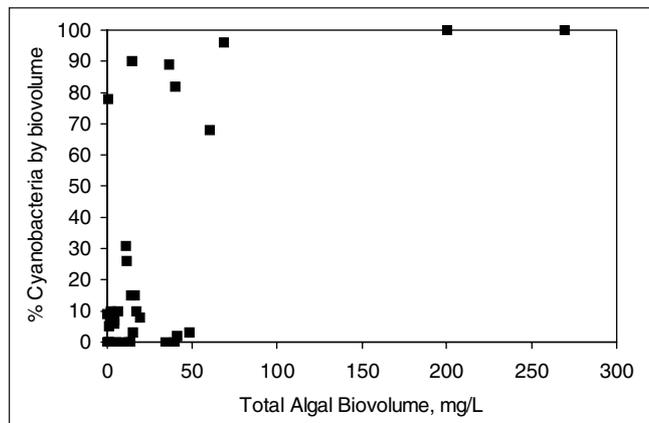


Fig. 2: Relationship between cyanobacterial dominance and trophic state (as measured by summer algal biovolume) in 39 turbid Kansas, USA reservoirs. Data from Carney (2001)

Empirical models relating the relative and absolute biomass of cyanobacteria to nutrient concentrations (Smith 1985, 1986, 1990b, Smith et al. 1987), and models to predict the response of cyanobacterial blooms to phosphorus loading reductions (Lathrop et al. 1998), have been developed. However, a lively debate is currently being waged in the literature concerning the primary mechanisms that are responsible for cyanobacterial dominance in eutrophic lakes. A number of potential mechanisms have been proposed in the literature (Shapiro 1989, Klemer and Konopka 1989), but perhaps the most contentious is the relative role of nitrogen, phosphorus (N, P) ratios. Empirical and experimental evi-

dence supporting the N:P ratio hypothesis of cyanobacterial dominance has been summarized by Smith and Bennett (1999), and the N:P ratio hypothesis has also recently been modified to include the effects of food web structure by Elser (1999). However, other researchers (e.g., Trimbee and Prepas 1987, Canfield et al. 1989, Jensen et al. 1994, Reynolds 1997, Downing et al. 2001) have concluded from their own analyses that elevated absolute concentrations of total phosphorus *per se*, rather than the presence of low TN:TP ratios, result in cyanobacterial dominance. This extremely important fundamental question remains unresolved, and is a key topic for future eutrophication research.

1.2 Streams and rivers

Although eutrophication research in streams and rivers has lagged behind that of lakes and reservoirs, the nutrient enrichment of streams and rivers is nonetheless of great concern (Behrendt 1993, Biggs 2000). In the U.S., concerns about hypoxia in the Gulf of Mexico led to a White House-commissioned task group on the effects of reduced nutrient loading on surface water quality in the Mississippi River basin (Brezonik et al. 1999). In Europe, investigators have reported extensive eutrophication of the Bure River system in the United Kingdom (Moss et al. 1989, Moss and Balls 1989); Köhler and Gelbrecht (1998) have documented significant eutrophication in several major rivers in Germany; and Billen et al. (1994) have demonstrated strong differences in algal development at different sites in the Oise and Marne river system in France. The concept that flowing waters are almost always nutrient-saturated, and the conclusion that physical factors such as light-limitation and short hydraulic residence times consistently prevent or restrict any potential algal responses to nutrient enrichment in rivers, both no longer appear to be tenable (Smith et al. 1999). As will be reviewed in separate sections below, the nutrient enrichment of flowing waters strongly modifies the biomass and community structure of both suspended and benthic algae.

Several nutrient classification systems have been proposed for flowing waters. For example, McGarrigle (1993) concluded that maintaining a mean annual dissolved inorganic phosphorus concentration <47 $\mu\text{g/L}$ was necessary to prevent the nuisance growth of attached algae and to preserve water quality suitable for salmonid fishes in Irish rivers. The U.K. Environment Agency (1998) has used annual mean values of soluble reactive phosphorus (SRP, $\mu\text{gP/L}$) as the boundaries for four trophic state categories in streams and rivers: oligotrophic (20 $\mu\text{gP/L}$); mesotrophic (60 $\mu\text{gP/L}$); mesoeutrophic (100 $\mu\text{gP/L}$); and eutrophic (200 $\mu\text{gP/L}$). In contrast, Dodds et al. (1998) have proposed trophic state

Table 4: Suggested boundaries for trophic classification of temperate streams (Dodds et al. 1998)

Trophic state category	Mean benthic Chl <i>a</i> , mg/m ²	Maximum benthic Chl <i>a</i> , mg/m ²	Suspended Chl <i>a</i> , µg/L	TN, µg/L	TP, µg/L
oligotrophic	<20	<60	<10	<700	<25
mesotrophic	20–70	60–200	10–30	700–1500	25–75
eutrophic	>70	>200	>30	>1500	>75

boundaries for temperate streams using concentrations of total nitrogen (TN, µg/L) and total phosphorus, which may be more directly compared to those for lakes (Table 4). The general issue of establishing nutrient criteria in streams is discussed by Dodds and Welch (2000).

Effects of eutrophication on suspended algal biomass. The production of suspended algae per unit total phosphorus is often significantly lower in rivers than in lakes and reservoirs (Dokulil 1994, Soballe and Kimmel 1987, Van Nieuwenhuysse and Jones 1996). This reduced response to nutrients may be caused in some systems by the high washout rate that the flowing water imposes on suspended algal biomass. For example, a very strong inverse relationship was observed between suspended chlorophyll *a* concentrations and discharge in the Hungarian Danube (cf. Fig. 4 in Schmidt 1994). In addition, the potential for high algal productivity in nutrient-rich, well-mixed systems may not be realized if the presence of suspended soils greatly reduces underwater light availability (Dokulil 1994). To my knowledge, light attenuation by suspended inorganic particulates has not been explicitly included in previous empirical models linking nutrient concentrations to suspended algal biomass in fluvial ecosystems. However, data from the Mississippi River (Fig. 3) do not reveal a consistent reduction in the yield of suspended chlorophyll *a* at stations containing high concentrations of non-volatile suspended solids (NVSS, mg/L), and this question should be explored further in additional river systems.

An important prediction of Fig. 3 and other empirical nutrient-chlorophyll models for streams and rivers (e.g., Basu and Pick 1996, Van Nieuwenhuysse and Jones 1996, Lohman and Jones 1999, Champion and Currie 2000) is that reductions in suspended algal biomass should generally occur in rivers that experience significant TP reductions following the imposition of point and non-point source controls. A strong reduction in suspended chlorophyll *a* (Fig. 4) indeed appears

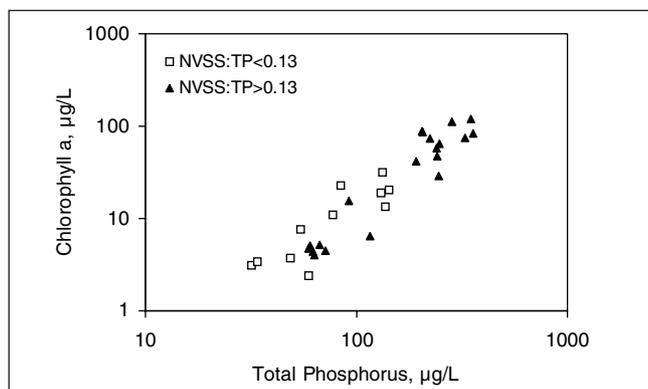


Fig. 3: Relationship between suspended algal biomass and total phosphorus in the Mississippi River. NVSS, TP ratios greater than 0.13 indicate high levels of inorganic turbidity, and potential shading inhibition of algal growth in the river. Data from Heiskary and Markus (2001)

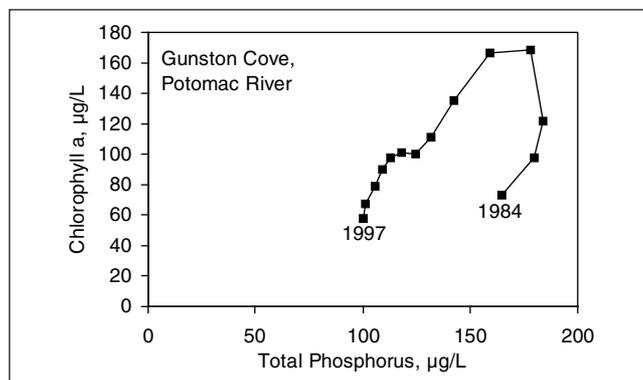


Fig. 4: Response of Gunston Cove in the tidal freshwater Potomac River, USA, to reductions in point source phosphorus loading. Note that the response appears to be hysteretic. The data shown are estimates of annual means derived from LOWESS fits to the entire dataset by Jones (2000)

to have occurred in the tidal freshwater Potomac River (USA) as a result of point source phosphorus loading controls (Jones 2000). Also of very great interest in Fig. 4 is an apparent hysteresis in this chlorophyll-phosphorus relationship; such hysteretic responses to changes in nutrient loading can be seen in lakes (e.g., Lake Washington, USA; see Smith 1998), and can significantly complicate the recovery of aquatic ecosystems from eutrophication (Carpenter et al. 1999).

Effects of eutrophication on suspended algal community structure. As in lakes, nuisance blooms of cyanobacteria can seriously degrade the water quality of fluvial ecosystems (Paerl et al. 1990, Prygiel and Leitao 1994, Ha et al. 1998, Mitrovic et al. 2000). Heiskary and Markus (2001) provide data that allow an initial test of the hypothesis that eutrophication causes predictable and directional shifts in the community structure of suspended algae in flowing waters. An analysis of their data (Fig. 5) suggests that cyanobacterial dominance in large rivers increases strongly and predictably with phosphorus enrichment, just as it does in eutrophic lakes and reservoirs.

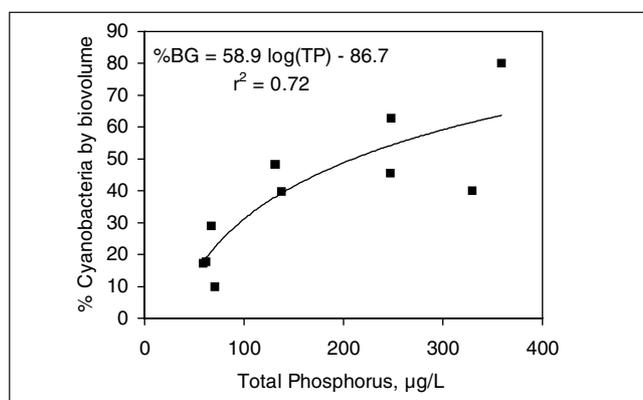


Fig. 5: Relationship between blue-green algal dominance and total phosphorus in the Mississippi River. Data from Heiskary and Markus (2001)

Phytoplankton dynamics in rivers thus may not be so different from those observed in shallow lakes (Reynolds 1994), with traditional biotic interactions between algae and nutrients perhaps being dampened or modified by fluvial conditions, but not totally unexpressed.

Effects of eutrophication on benthic algal biomass. As is true of periphyton in lakes (Eloranta 2000, Herve 2000), benthic algae on natural substrates in flowing waters can respond sensitively to anthropogenic nutrient enrichment (Welch et al. 1992). A recent meta-analysis of nutrient enrichment experiments in streams by Francoeur (2001) has confirmed that benthic algal biomass can be significantly increased by the addition of either N or P, and Borchardt (1996) published a review of the literature on nutrients and stream periphyton communities. Krewer and Holm (1986) and Horner et al. (1990) observed a strong curvilinear dependence of periphyton growth on phosphorus in artificial laboratory channels, and this general relationship has been confirmed for lotic ecosystems by Dodds et al. (1997, 2002). Similar to the nitrogen-phosphorus interactions documented in Section 1.1 above for lakes, and consistent with the strong N, P interactions documented in Francoeur's (2001) stream meta-analysis, the biomass of benthic algae growing on natural substrates appears to be dependent upon both TN and TP concentrations in the stream water (Fig. 6).

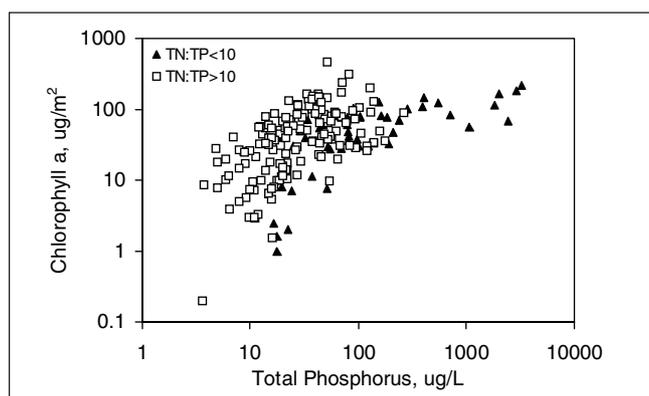


Fig. 6: Relationship between benthic algal biomass and total phosphorus in streams. As is true of phytoplankton in lakes (Smith 1982), the yield of periphytic algae in flowing waters appears to be reduced when the TN:TP ratio is <10, 1 by mass. Note: these data are based only upon algal samples collected from natural substrates, and errors in the database have been corrected from the dataset analyzed in Dodds et al. (2002)

Effects of eutrophication on the community structure of benthic algae. Shifts in community structure along nutrient supply gradients are a common feature of most aquatic ecosystems, and attached algae in streams are no exception. Whether these communities are influenced by exotic species (e.g. *Hydrodictyon reticulatum*: Hall and Cox 1995, Hall and Payne 1997), or are undisturbed by exotic invaders, nutrient availability often has a strong selective role in determining the species composition of benthic algal communities. Epilithic diatoms can be used as sensitive indicators of streamwater total nitrogen and total phosphorus concentrations (Winter and Duthie 2001), and Chételat et al. (1999) reported marked directional shifts in overall community composition as the total biomass of benthic algae increased. The proportion of green algae (Chlorophyta), for example,

increased with benthic chlorophyll *a* and was highest at moderately eutrophic sites. These studies suggest that predictive models similar to those developed for phytoplankton communities in lakes, and for suspended algae in rivers (see Fig. 5), can be developed for benthic algae.

1.3 Wetlands

Effects of eutrophication on algal biomass and community structure. Wetlands (areas where water saturation is the dominant factor determining the nature of soil development, and structuring the associated plant and animal communities: Wolff 1993) are a very common feature of many landscapes worldwide. However, as noted by Crosbie and Chow-Fraser (1999), the impact of human land use and nutrient loading on the water quality of freshwater wetlands has seldom been documented. Given the consistency of algal responses to nutrient enrichment in lakes, it might be expected that similar nutrient-algal biomass relationships would be observed for wetlands. A plot of data from 22 marshes in the Great Lakes Basin of Ontario, Canada (Crosbie and Chow-Fraser 1999), confirmed that suspended chlorophyll *a* in these wetlands responded strongly to increases in average water column total phosphorus (TP) concentrations (Fig. 7):

$$\log_{10}(\text{Chl}_{\text{mean}}) = 1.14 \log_{10}(\text{TP}_{\text{mean}}) + 1.17, r^2 = 0.72 \quad (5)$$

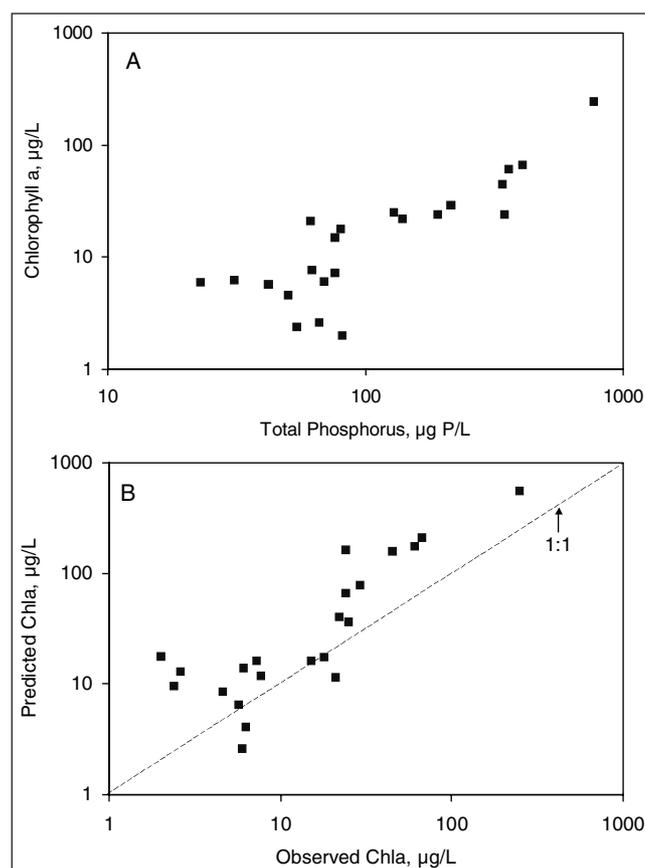


Fig. 7: **A.** Relationship between suspended chlorophyll *a* and total phosphorus concentrations in 22 marshes near Ontario, Canada. Each data point represents the mean of two sampling trips during the growing season. **B.** Predicted versus observed chlorophyll *a* concentrations for the 22 marshes above, using Equation 4 in Table 2 of Lund (1998)

Moreover, the algal biomass in these 22 marshes covaried with the predictions of a new empirical model developed for wetlands located on the Swan Coastal Plain of Australia (Lund 1998), although the predicted algal biomass consistently exceeded the observed values. This prediction bias may be due in part to the original model specification: the empirical chlorophyll-phosphorus model of Lund (1998) was developed using a mixture of data from lakes (permanently inundated), sumplands (seasonally inundated), and artificial wetlands. Nonetheless, the data in Fig. 7 suggest that the biomass of suspended algae in wetlands tends to respond strongly and predictably to changes in nutrient inputs.

The possibility also exists that algal communities in nutrient-enriched wetlands experience directional shifts in species composition that parallel those found in lakes, reservoirs, and large rivers. For example, a recent survey of 32 Kansas (USA) wetland areas by Carney (2002) revealed that the planktonic algae were dominated by cyanobacteria in the most eutrophic wetlands. Efforts to develop new models for suspended and attached algae in both freshwater and coastal marine wetlands would be a valuable new area for future eutrophication research; such models could provide objective, quantitative guidance in the restoration and protection of wetlands from excess nutrient loading.

2 Eutrophication of Estuarine and Coastal Marine Ecosystems

A very large fraction of the nutrients exported from the land surface to streams and rivers ultimately makes its way to the sea, and as a result, estuaries receive more nutrient inputs per unit surface area than any other type of ecosystem (Howarth 1993). More than half of the world's human population resides within 60 kilometers of the coast, and more than 90% of the world's fisheries depend in one way or another on estuarine and near-shore habitats (Hobbie et al. 2000). Increased nutrient loading results in a wide variety of changes in the structure and function of coastal marine ecosystems (cf. Fig. 2 in Schramm 1999), and protecting these systems from the many adverse effects of eutrophication is extremely important (U.S. EPA 1996b, National Research Council 2000, Rabelais and Nixon 2002). As can be seen in Table 5, the Swedish EPA has developed a nutrient-based classification scheme for coastal marine ecosystems that strongly resembles the trophic state categories presented earlier in Tables 2–4 for freshwater ecosystems.

The possibility of applying a limnological approach to the management of coastal marine eutrophication was noted in

the literature over two decades ago (Schindler 1981, Lee and Jones 1981). However, although freshwater eutrophication management can be considered a success story in ecosystem science (Smith 1998), it has recently been questioned in the literature whether the limnological experience can be repeated for estuaries and coastal marine ecosystems (Sharp 2001). Rapidly accumulating evidence suggests that the answer to this critically important question is an increasingly confident *yes!* While estuarine and coastal marine systems can often be hydrologically and spatially complex, the biomass of phytoplankton in these systems nonetheless tends to respond predictably to changes in the water column concentrations of total nitrogen and total phosphorus.

An analysis of Danish coastal waters by Nielsen et al. (2002) is an excellent example of recent successes in coastal zone eutrophication modeling. Nielsen et al. (2002) analyzed a very large dataset from 162 stations located in 27 Danish fjords and coastal waters, and developed empirical models for total nitrogen (TN, $\mu\text{g/L}$), chlorophyll *a* (Chl, $\mu\text{g/L}$), suspended matter (W_{susp} , mg dry wt./L), and Secchi disk transparency (SD, m) that should help to provide objective guidance for water quality management in Danish coastal waters,

$$\ln(\text{Chl}) = 0.963 \ln(\text{TN}) - 4.186, r^2 = 0.30 \quad (6)$$

$$\ln(\text{SD}) = -0.444 \ln(\text{Chl}) - 0.367 \ln(W_{\text{susp}}) + 2.686, R^2 = 0.81 \quad (7)$$

$$\ln(\text{SD}) = -0.894 \ln(\text{TN}) + 6.818, r^2 = 0.48 \quad (8)$$

Additional models based upon either total phosphorus or total nitrogen have been developed for coastal marine ecosystems in the Adriatic Sea (Vollenweider et al. 1992); Canada (Champion and Currie 2000, Meeuwig et al. 1998); Mexico (Contreras and Kerekes 1993); Scandinavia (Håkanson and Wallin 1991, Borum 1996, Meeuwig et al. 2000, Elmgren and Larsson 2001, Nielsen et al. 2002); and the USA (Boynton et al. 1996, Bowen and Valiela 2001). Efforts have also been made to apply the OECD's critical load concept to Norwegian marine waters (Hessen et al. 1992), and Janicki (2001) has developed a chlorophyll *a*-based trophic state index for Florida (USA) estuaries that parallels the highly successful trophic state index created by Carlson (1977) for lakes. Even more importantly, improvements in coastal marine water quality tend to follow reductions in external nutrient loading (Smith et al. 1999, Boesch et al. 2001, Elmgren and Larsson 2001), as has been documented in many freshwater lakes.

However, as stressed by Richardson (1996), scientists cannot be expected to identify and recommend courses of ac-

Table 5: Swedish eutrophication classification system for coastal marine surface water (modified from Swedish EPA 2000; nutrient concentrations have been rounded from the original molar values)

Class	Nutrient Pollution Level Designation	Summer TN, $\mu\text{g/L}$	Summer TP, $\mu\text{g/L}$	August Chlorophyll <i>a</i> , $\mu\text{g/L}$
1	Very low	<252	<15	≤ 1.5
2	Low	252–308	15–19	1.5–2.2
3	Moderate	308–364	19–24	2.2–3.2
4	High	364–448	24–31	3.2–5.0
5	Very high	>448	>31	>5.0

tion to combat coastal zone eutrophication in the absence of clear goals for environmental conditions desired in a given area. Objective water quality targets can be defined by using one or more of the following methods:

1. By applying quantitative water quality criteria developed by local, regional, or federal environmental protection agencies, such as the empirical boundaries for TN, TP, and Chl *a* concentrations in eutrophic waterbodies that have been proposed for coastal waters (e.g. Håkanson 1994);
2. By using historical data, time series data, or reference region data to establish reference values that reflect pristine water quality conditions completely free of any effects of human activity (e.g., Table 2b in Swedish EPA 2000); or
3. By using robust survey methods that allow local users of the water resource to generate quantitative estimates for the value of a key water quality variable (the Quality Variable of Concern, *sensu* Reckhow and Chapra 1983), that represents their perception of the critical point at which undesirable water quality is present.

Once target goals have been established, quantitative relationships between water quality and nutrients can be used to calculate the critical water column nutrient concentrations that must be attained in order to reach these target conditions. This information then can be linked to macro-scale models of nutrient and water fluxes to the coastal zone (e.g., Valiela et al. 1997) in order to identify the corresponding nutrient loading rates that must be achieved to obtain desirable water quality in the receiving waters being managed (for example, cf. Fig. 9 in Valiela et al. 2000). However, many critical questions still remain regarding the actual development and implementation of measures to protect coastal marine ecosystems from eutrophication, and answering these questions will require thoughtful, trans-disciplinary efforts (cf. Elmgren and Larsson 2001).

3 Conclusions and Outlook

A remarkable unity is evident in the global response of algal biomass to nitrogen and phosphorus availability in lakes and reservoirs; wetlands; streams and rivers; and estuaries and coastal marine waters. The species composition of algal communities inhabiting the water column appears to respond similarly to nutrient loading, whether in lakes, reservoirs, or rivers. As is true of freshwater ecosystems, the recent literature suggests that marine ecosystems respond positively to nutrient loading control efforts.

As can be seen in the above review, our understanding of freshwater eutrophication and its effects on algal-related water quality is extremely strong and is advancing rapidly. Unfortunately, however, our understanding of the effects of eutrophication on estuarine and coastal marine ecosystems is much more limited, and this gap represents an important future research need. While estuarine and coastal marine systems may often be hydrologically complex, numerous empirical analyses that have been performed worldwide indicate that the biomass of marine phytoplankton responds sensitively and predictably to changes in the external supplies of nitrogen and phosphorus. These models in turn sug-

gest that efforts to manage nutrient inputs to the seas will result in significant improvements in coastal zone water quality. Efforts should be made to develop new models that quantitatively link ecosystem-level responses to nutrient loading in both freshwater and marine systems.

References

- Ahl T, Wiederholm T (1977): Swedish water quality criteria. Chemicals causing eutrophication. SNV PM 918, Stockholm, Sweden. 124 pp
- Aizaki M, Terashima A, Nakahara H, Nishio T, Ishida Y (1987): Trophic status of Tilitso, a high altitude Himalayan lake. *Hydrobiologia* 153, 217–224
- An K-G, Jones JR (2002): Reservoir responses to the Asian monsoon with an emphasis on longitudinal gradients. *J Freshwat Ecol* 17, 151–160
- An K-G, Jones JR (2000): Factors regulating bluegreen dominance in a reservoir directly influenced by the Asian monsoon. *Hydrobiologia* 432, 37–48
- Barica J (1978): Collapses of *Aphanizomenon flos-aquae* blooms resulting in massive fish kills in eutrophic lakes: effect of weather. *Verh Internat Verein Limnol* 20, 208–213
- Basu BK, Pick FR (1996): Factors regulating phytoplankton and zooplankton biomass in temperate rivers. *Limnol Oceanogr* 41, 1572–1577
- Behrendt H (1993): Point and diffuse loads of selected pollutants in the River Rhein and its main tributaries. International Institute for Applied Systems Analysis (IIASA) working paper, Index No RR-93-001, Laxenburg, Austria
- Bennett EM, Carpenter SR, Caraco NF (2001): Human impact on erodible phosphorus and eutrophication: A global perspective. *BioScience* 51, 227–234
- Bertolo A, Lescher-Moutoué F, Lacroix G (2001): Interaction effects of depth and planktivorous fish on plankton biomass. *Verh Internat Verein Theor Angew Limnol* 27, 1747–1751
- Bhade C, Unnit KS, Bhade S (2001): Limnology and eutrophication of Tawa Reservoir, MP State, India *Verh Internat Verein Theor Angew Limnol* 27, 3632–3635
- Biggs BJF (2000): Eutrophication of streams and rivers: dissolved nutrient-chlorophyll relationships for benthic algae. *J N Amer Benthol Soc* 19, 17–31
- Billen G, Garner J, Hanset P (1994): Modelling phytoplankton development in whole drainage networks: the RIVERSTRAHLER Model applied to the Seine river system. *Hydrobiologia* 289, 119–137
- Boesch DF, Burroughs RH, Baker JE, Mason RP, Rowe CL, Siefert RL (2001): Marine pollution in the United States: Significant accomplishments, future challenges. Pew Oceans Commission, Arlington, VA, USA. p 137
- Borchardt MA (1996): Nutrients, p 183–227. In: RJ Stevenson, ML Bothwell, and RL Lowe, Eds, *Algal Ecology: Freshwater Benthic Ecosystems*. Academic Press, San Diego, CA, USA
- Borum J (1996): Shallow waters and land/sea boundaries, p 179–203. In: BB Jørgensen and K Richardson, Eds, *Eutrophication in Coastal Marine Ecosystems*, Coastal and Marine Studies 52. American Geophysical Union, Washington, DC, USA
- Boynton WR, Murray L, Hagy JD, Stokes C, Kemp MR (1996): A comparative analysis of eutrophication patterns in a temperate coastal lagoon. *Estuaries* 19(2B), 408–421
- Bowen JL, Valiela I (2001): The ecological effects of urbanization of coastal watersheds: historical increases in nitrogen loads and eutrophication of Waquoit Bay estuaries. *Can J Fish Aquat Sci* 58, 1489–1500

- Brezonik PL, Bierman VJ, Jr, Alexander RA, Anderson J, Barko J, Dortch M, Hatch L, Keeney D, Mulla D, Smith VH, Walker C, Whitledge T, Wiseman W, Jr (1999): Effects of reducing nutrient loads to surface waters within the Mississippi River basin and the Gulf of Mexico. Topic #4, Gulf of Mexico Hypoxia Assessment. NOAA Coastal Ocean Program Decision Analysis Series, NOAA Coastal Ocean Office, Silver Springs, MD, USA
- Brown CD, Hoyer MV, Bachmann RW, Canfield DE, Jr (2000): Nutrient-chlorophyll relationships: an evaluation of empirical nutrient-chlorophyll models using Florida and north-temperate lake data. *Can J Fish Aquat Sci* 57:1574–1583
- Brunner U, Bachofen R (1998): The biogeochemical cycles of phosphorus: a review of local and global consequences of the atmospheric input. *Technol Environ Chem* 67, 171–188
- Canfield DE, Jr (1983): Prediction of chlorophyll *a* concentrations in Florida lakes: the importance of phosphorus and nitrogen. *Water Resources Bull* 19, 255–262
- Canfield DE, Jr, Bachmann RW (1981): Prediction of total phosphorus concentrations, chlorophyll *a*, and Secchi depths in natural and artificial lakes. *Can J Fish Aquat Sci* 38, 414–423
- Canfield DE, Jr, Langeland KA, Maceina MJ et al. (1983): Trophic state classification of lakes with aquatic macrophytes. *Can J Fish Aquat Sci* 40, 1713–1718
- Canfield DE, Jr, Philips E, Duarte CM (1989): Factors influencing the abundance of blue-green algae in Florida lakes. *Can J Fish Aquat Sci* 46, 1132–1237
- Caraco NF (1995): Influence of human populations on P transfers to aquatic ecosystems: A regional scale study using large rivers. In: H Tiessen, Ed, Phosphorus in the Global Environment. John Wiley and Sons, New York, New York, p 235–244
- Carlson RE (1991): Expanding the trophic state concept to identify non-nutrient limited lakes and reservoirs, p 59–71. In: Enhancing the States' Lake Management Programs. Monitoring and Lake Impact Assessment. North American Lake Management Society, Madison, WI, USA
- Carlson RE (1977): A trophic state index for lakes. *Limnol Oceanogr* 22, 361–369
- Carlson RE, Simpson JT (1998): A coordinator's guide to volunteer lake monitoring methods. North American Lake Management Society, Madison, Wisconsin, USA
- Carmichael WW (1997): The cyanotoxins. *Adv Bot Res* 37, 211–256
- Carney E (2002): The Kansas wetland survey, p 6. In: Central Plains Aquatic Bioassessment and Biocriteria Symposium, 18–19 September 2002, Lawrence, KS, USA (abstract)
- Carney E (2001): Lake and wetland monitoring program report. Kansas Department of Health and Environment, Division of Environment, Bureau of Field Services, Topeka, KS, USA
- Carpenter SR (2002): Ecological futures: Building an ecology of the long now. *Ecology* 83, 2069–2083
- Carpenter SR, Kitchell JF, Eds (1993): The trophic cascade in lakes. Cambridge, UK
- Carpenter SR, Ludwig D, Brock WA (1999): Management of eutrophication for lakes subject to potentially irreversible change. *Ecol Appl* 9, 751–771
- Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH (1998a): Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol Appl* 8, 559–568
- Carpenter SR, Bolgrien D, Lathrop RC, Stow CA, Reed T, Wilson MA (1998b): Ecological and economic analysis of lake eutrophication by nonpoint pollution. *Australian J Ecol* 23, 68–79
- Carpenter SR, Christensen DL, Cole JJ, Cottingham KL, He X, Hodgson JR, Kitchell JF, Knight SE, Pace ML, Post DM, Schindler DE, Voichick N (1995): Biological control of eutrophication. *Environ Sci Technol* 29, 784–786
- Champion M, Currie DJ (2000): Phosphorus-chlorophyll relationships in lakes, rivers and estuaries. *Verh Int Ver Theor Angew Limnol* 27, 1986–1989
- Chételat J, Pick FR, Morin A, Hamilton PB (1999): Periphyton biomass and community composition in rivers of different trophic status. *Can J Fish Aquat Sci* 56, 560–569
- Chang WYB (2002): Chinese great lakes: their changes and impacts. *Verh Int Ver Theor Angew Limnol* 28, 3:7–310
- Chorus I, Ed (2001): Cyanotoxins: Occurrence, causes, consequences. Springer-Verlag, Heidelberg, Germany
- Chorus I, Bartram J, Eds (1999): Toxic cyanobacteria in water – A guide to their public health consequences. E and FN Spon, London, England
- Chow-Fraser P, Trew DO, Findlay D, Stainton M (1994): A test of the hypothesis to explain the sigmoid relationships between total phosphorus and chlorophyll concentrations in Canadian lakes. *Can J Fish Aquat Sci* 51, 2052–2065
- Cole JJ, Peierls BL, Caraco NF, Pace ML (1993): Nitrogen loading of rivers as a human-driven process, p 141–157. In: MJ McDonnell and STA Pickett, Eds, Humans as Components of Ecosystems. Springer-Verlag, New York, USA
- Cooke GD, Kennedy RH (2001): Managing drinking water supplies. *J Lake Reservoir Manage* 17, 157–174
- Cooke GD, Welch EB, Peterson SA, Newroth PR (1993): Restoration and management of lakes and reservoirs. Lewis Publishers, Boca Raton, Florida, USA
- Contreras F, Kerekes J (1993): Total phosphorus-chlorophyll relationships in tropical coastal lagoons in Mexico. *Verh Int Ver Theor Angew Limnol* 25, 448–451
- Corrales RA, Maclean JL (1995): Impacts of harmful algae on sea farming in the Asia-Pacific areas. *J Appl Phycol* 7, 151–162
- Correll DL (1998): The role of phosphorus in the eutrophication of receiving waters: A review. *J Environ Quality* 27, 261–266
- Cottingham KL, Knight SE (1995): Effects of *Daphnia* on the response of mesotrophic lakes to experimental enrichment. *Wat Sci Technol* 32, 157–163
- Crosbie B, Chow-Fraser P (1999): Percentage land use in the watershed determines the water and sediment quality of 22 marshes in the Great Lakes Basin. *Can J Fish Aquat Sci* 56, 1781–1791
- Danielidis DB, Spartinou M, Economou-Amilli A (1996): Limnological survey of Lake Amvrakia, western Greece. *Hydrobiologia* 318, 207–218
- Davis JR, Ed (1997): Managing algal blooms: Outcomes from CSIRO's multi-divisional blue-green algal program. CSIRO, Canberra, ACT, Australia
- de Bernardi R, Calderoni A, Mosello R (1996): Environmental problems in Italian lakes, and lakes Maggiore and Orta as successful examples of correct management leading to restoration. *Verh Int Ver Theor Angew Limnol* 26, 123–138
- Dickman MD, Pu PM, Zheng CS (2001): Some consequences of hypereutrophication and wind-induced mixing for the limnology of Lake Tai in eastern China. *Verh Int Ver Theor Angew Limnol* 27, 3669–3673
- Dillon PJ, Rigler FH (1974): The phosphorus-chlorophyll relationship in lakes. *Limnol Oceanogr* 19, 767–773
- Dodds WK (1996): Assessment of blue-green algal toxins in Kansas. Kansas Water Resources Research Institute Report G2020-02. Contribution 320, University of Kansas and Kansas State University, 36 pp
- Dodds WK, Jones JR, Welch EB (1998): Suggested classification of stream trophic state: Distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus. *Water Res* 32, 1455–1462
- Dodds WK, Smith VH, Lohman K (2002): Nitrogen and phosphorus relationships to benthic algal biomass in temperate streams. *Can J Fish Aquat Sci* 59, 865–874
- Dodds WK, Smith VH, Zander B (1997): Developing nutrient targets to control benthic chlorophyll levels in streams: A case study of the Clark Fork River. *Water Research* 31, 1838–1750

- Dodds W K, Welch EB (2000): Establishing nutrient criteria in streams. *J N Amer Benthol Soc* 19, 186–196
- Dokulil MT (1994): Environmental control of phytoplankton productivity in turbulent turbid systems. *Hydrobiologia* 289, 65–72
- Downing JA, McCauley E (1992): The nitrogen:phosphorus relationship in lakes. *Limnol Oceanogr* 37, 936–945
- Downing JA, Watson SB, McCauley E (2001): Predicting Cyanobacteria dominance in lakes. *Can J Fish Aquat Sci* 58, 1905–1908
- Duggan IC, Green JD, Thomasson K (2001): Do rotifers have potential as bioindicators of lake trophic state? *Verh Int Ver Theor Angew Limnol* 27, 3497–3502
- Elmgren R, Larsson U (2001): Eutrophication in the Baltic Sea area: Integrated coastal management issues, p 15–35. In: B von Bodungen and RK Turner, Eds, *Science and Integrated Coastal Management*, Dahlem University Press, Berlin, Germany
- Eloranta P (2000): Use of littoral algae in lake monitoring, p 97–104. In: P Heinonen, Z Giuliano, and A Van der Beken, Eds, *Hydrological and Limnological Aspects of Lake Monitoring*, Wiley and Sons, Ltd, West Sussex, England
- Elser JJ (1999): The pathway to noxious cyanobacterial blooms in lakes: the food web as the final turn. *Freshwat Biol* 42, 1–7
- Faafeng B, Hessen DO (1993): Nitrogen and phosphorus concentrations and N:P ratios in Norwegian Lakes: perspectives on nutrient limitation. *Verh Int Verein Theor Angew Limnol* 25, 465–469
- Ferris JM, Tyler PA (1985): Chlorophyll-Total phosphorus relationships in Lake Burragorang, New South Wales, and some other Southern Hemisphere lakes. *Aust J Mar Freshwater Res* 36, 157–168
- Forsberg C, Ryding S-O (1980): Eutrophication parameters and trophic state indices in 30 Swedish waste-receiving lakes. *Arch Hydrobiol* 89, 189–207
- Francoeur SN (2001): Meta-analysis of lotic nutrient amendment experiments: detecting and quantifying subtle responses. *J N Amer Benthol Soc* 20, 358–368
- Fulton RS, Paerl HW (1987): Toxic and inhibitory effects of the blue-green alga *Microcystis aeruginosa* on herbivorous zooplankton. *J Plankton Res* 9, 837–855
- Fukushima T, Muraoka K (1988): Simple model to predict water quality in 90 Japanese lakes. *Verh Int Ver Theor Angew Limnol* 23, 812–827
- Gophen M, Smith VH, Nishri A, Threlkeld ST (1999): Nitrogen deficiency, phosphorus sufficiency, and the invasion of Lake Kinneret, Israel, by the N₂-fixing cyanobacterium *Aphanizomenon ovalisporum*. *Aquat Sci* 61, 293–306
- Gulati RD, Lammens EHRR, Meijer J-L, van Donk E, Eds (1990): *Bio-manipulation – Tool for Water Management*. Kluwer, Belgium
- Ha K, Kim HW, Joo GJ (1998): The phytoplankton succession in the lower part of hypertrophic Nakdong River (Mulgum), South Korea. *Hydrobiologia* 253, 1–11
- Håkanson L (1994): A review of effect-dose-sensitivity models for aquatic ecosystems. *Int Rev Ges Hydrobiol* 79, 621–667
- Håkanson L, Wallin M (1991): An outline of ecometric analysis to establish load diagrams for nutrients/eutrophication. *Environmetrics* 2, 49–68
- Hall J, Cox N (1995): Nutrient concentrations as predictors of nuisance *Hydrodictyon reticulatum* populations in New Zealand. *J Aquat Plant Manage* 3, 68–74
- Hall J, Payne G (1997): Factors controlling the growth of field populations of *Hydrodictyon reticulatum* in New Zealand. *J Appl Ecol* 9, 229–236
- Hansson L-A, Annadotter H, Bergman E et al. (1998): Bio-manipulation as an application of food chain theory: constraints, synthesis and recommendations for temperate lakes. *Ecosystems* 1, 558–574
- Harding WR (1992): A contribution to the knowledge of South African coastal vleis: the limnology and phytoplankton periodicity of Princess Vlei, Cape Peninsula. *Water SA* 18, 121–130
- Harper DM, Stewart WDP (1987): The effects of land use upon water chemistry, particularly nutrient enrichment, in shallow lowland lakes: comparative studies of three lochs in Scotland. *Hydrobiologia* 148, 211–229
- Harper DM, Phillips G, Chilvers A, Kitalka N, Mavuti K (1993): Eutrophication prognosis for Lake Naivasha, Kenya. *Verh Int Ver Theor Angew Limnol* 25, 861–865
- Havens KE, Walker WW, Jr (2002): Development of a total phosphorus concentration goal in the TMDL process for Lake Okeechobee, Florida (USA). *J Lake Reservoir Manage* 18, 227–238
- Hawser SP, O'Neil JM, Roman MR, Codd GA (1992): Toxicity of blooms of the cyanobacterium *Trichodesmium* to zooplankton. *J Appl Phycol* 4, 79–86
- Hecky RE (1993): The eutrophication of Lake Victoria. *Verh Int Ver Theor Angew Limnol* 25, 39–48
- Heinonen P, Guiliano Z, Premazzi G (2000): Use and impact of monitoring results for water protection management, p 351–363. In: P Heinonen, Z Giuliano, and A Van der Beken, Eds, *Hydrological and Limnological Aspects of Lake Monitoring*, Wiley and Sons, Ltd, West Sussex, England
- Heiskary S, Markus H (2001): Establishing relationships among nutrient concentrations, phytoplankton abundance, and biochemical oxygen demand in Minnesota, USA, rivers. *Lake Reservoir Manage* 17, 251–262
- Herve S (2000): Chemical variables in lake monitoring, p 41–54. In: P Heinonen, Z Giuliano, and A Van der Beken, Eds, *Hydrological and Limnological Aspects of Lake Monitoring*, Wiley and Sons, Ltd, West Sussex, England
- Hessen DO, Vadstein O, Magnusson J (1992): Nitrogen to Marine Areas: on the Application of a Critical Load Concept. Background document to the workshop 'Critical Loads for Nitrogen' in Loekeberg, Sweden, 6–10 April 1992. Environment Canada and Nordic Council of Ministers, NORD, 1992, 41. 33 pp
- Hobbie JE, Ed (2000): *Estuarine science: A synthetic approach to research and practice*. Island Press, Washington, DC
- Horner RR, Welch EB, Seeley MR, Jacoby JM (1990): Reponses of periphyton to changes in current velocity, suspended sediment and phosphorus concentration. *Freshwat Biol* 24, 215–232
- Howarth RW (1993): The role of nutrients in coastal waters, p 177–202. In: *Managing wastewater in coastal urban areas*. Report from the National Research Council on Wastewater Management for Coastal Urban Areas. National Academy Press, Washington, DC, USA
- Howarth RW, Anderson D, Cloern J, Elfring C, Hopkinson C, Lapointe B, Malone T, Marcus N, McGlathery K, Sharpley A, Walker D (2000): Nutrient pollution of coastal rivers, bays, and seas. *Issues in Ecology* 7, Ecological Society of America, Washington, DC, USA
- Hoyer MV, Jones JR (1983): Factors affecting the relation between phosphorus and chlorophyll *a* in midwestern reservoirs. *Can J Fish Aquat Sci* 40, 192–199
- Hrbáček J, Desortová B, Popovský J (1978): Influence of the fishstock on the phosphorus-chlorophyll ratio. *Verh Int Ver Theor Angew Limnol* 20, 1624–1628
- Istvánovics V, Somlyódy L (1999): Load-response relationships in the Upper Kis-Balaton Reservoir – The role of spatial variability. *Freshwat Biol* 41, 1–19
- Janicki AJ (2001): TMDL's in the Tampa Bay estuary. *ERF Newsletter* 24(2), 14. Estuarine Research Foundation, Port Republic, MD, USA
- Jensen JP, Jeppesen E, Olrik K, Kristensen P (1994): Impact of nutrients and physical factors on the shift from cyanobacterial to chlorophyte dominance in shallow Danish lakes. *Can J Fish Aquat Sci* 51, 1692–1699
- Jones G (1997): Limnological study of cyanobacterial growth in three south-east Queensland reservoirs, p 51–66. In: JR Davis, Ed, *Manag-*

- ing Algal Blooms: Outcomes from CSIRO's Multi-divisional Blue-green Algal Program. CSIRO, Canberra, ACT, Australia
- Jones JR, Bachmann RW (1976): Prediction of phosphorus and chlorophyll levels in lakes. *J Water Pollut Control Fed* 48, 2176–2182
- Jones JR, Knowlton MF, Kaiser MS (1998): Effects of aggregation on chlorophyll-phosphorus relations in Missouri reservoirs. *Lake Reservoir Manage* 14, 1–9
- Jones JR, Knowlton MF, An K-G (1997): Developing a paradigm to study and model the eutrophication process in Korean reservoirs. *Korean J Limnology* 30(Suppl), 463–471
- Jones JR, Knowlton MF, Swar DB (1989): Limnological reconnaissance of waterbodies in central and southern Nepal. *Hydrobiologia* 184, 171–189
- Jones JR, Lohman K, Umaña VG (1993): Water chemistry and trophic state of eight lakes in Costa Rica. *Verh Int Ver Theor Angew Limnol* 25, 899–905
- Jones JR, Perkins BD, Witt A, Jr, Kaiser MS, Thamasara S, Siriworakul M, Benyasut P (2000): Limnological characteristics of some reservoirs in Thailand. *Verh Int Ver Theor Angew Limnol* 27, 2158–2166
- Jones RA, Rast W, Lee GF (1979): Relationships between summer mean and maximum chlorophyll a concentrations in lakes. *Env Sci Technol* 13, 869–870
- Jones RC (2000): Long-term trends in phytoplankton chlorophyll *a* in the tidal freshwater Potomac River, USA: Relationship to climatic and management factors. *Verh Int Ver Theor Angew Limnol* 27, 2959–2962
- Kann J, Smith VH (1999): Estimating the probability of exceeding elevated pH values critical to fish populations in a hypereutrophic lake. *Can J Fish Aquat Sci* 56, 1–9
- Kaul V (1977): Limnological survey of Kashmir lakes with reference to trophic status and conservation. *Int J Ecol Envir Sci* 3, 19–44
- Kauppi L, Pietiläinen O-P, Knuuttila S (1993): Impacts of agricultural nutrient loading on Finnish watercourses. *Water Sci Technol* 28, 461–471
- Kebede E, G-Mariam Z, Ahlgren I (1994): The Ethiopian Rift Valley lakes: chemical characteristics of a salinity-alkalinity series. *Hydrobiologia* 288, 1–12
- Klemer AR, Konopka A (1989): Causes and consequences of blue-green algal (cyanobacterial) blooms. *Lake Reservoir Manage* 5, 9–19
- Köhler J, Gelbrecht J (1998): Interactions between phytoplankton dynamics and nutrient supply along the lowland river Spree, Germany. *Verh Int Ver Theor Angew Limnol* 26, 1045–1049
- Kopáček J, Stuchlík E, Vyhňálek V, Závodský D (1996): Concentration of nutrients in selected lakes in the High Tatra Mountains, Slovakia: effect of season and watershed. *Hydrobiologia* 319, 47–55
- Krewer JA, Holm HW (1982): The phosphorus-chlorophyll *a* relationship in periphytic communities in a controlled ecosystem. *Hydrobiologia* 94, 173–176
- Lacroix G, Lescher-Moutoué C, Pourriot R (1996): Trophic interactions, nutrient supply, and structure of freshwater pelagic food webs, p 162–179. In: M Hochberg, J Clobert, and R Barbault, Eds, *Aspects in the Genesis and Maintenance of Biological Diversity*. Oxford University Press, Oxford, UK
- Lathrop RC, Carpenter SR, Stow CA, Soranno PA, Panuska JC (1998): Phosphorus loading reductions needed to control blue-green algal blooms in Lake Mendota. *Can J Fish Aquat Sci* 55, 1169–1178
- Lee GF, Jones RA (1981): Application of the OECD eutrophication modeling approach to estuaries, p 549–568. In: BJ Nielsen and LE Cronin, Eds, *Estuaries and nutrients*. Humana Press, Clifton, NJ, USA
- Lohman K, Jones JR (1999): Nutrient-estuarine chlorophyll relations in northern Ozark streams. *Can J Fish Aquat Sci* 56, 124–130
- Lund MA (1998): Are Australian wetlands less productive than Northern Hemisphere wetlands under the same nutrient conditions? *Verh Int Ver Theor Angew Limnol* 27, 1661–1665
- Lund JWG (1970): Primary production. *Wat Treat Exam* 19, 332–358
- Matson PA, Parton WJ, Power AG, Swift MJ (1997): Agricultural intensification and ecosystem properties. *Science* 277, 504–509
- Mazumder A (1994a): Phosphorus-chlorophyll relationships under contrasting herbivory and thermal stratification: Patterns and predictions. *Can J Fish Aquat Sci* 51, 390–400
- Mazumder A (1994b): Patterns of algal biomass in dominant odd-versus even-link lake ecosystems. *Ecology* 75, 1141–1149
- Mazumder A, Havens KE (1998): Nutrient-algae relationships in temperate and tropical lakes. *Can J Fish Aquat Sci* 55, 1652–1662
- McBride GB, Pridmore RD (1988): Prediction of [chlorophyll-*a*] in impoundments of short hydraulic residence time: mixing effects. *Verh Int Ver Theor Angew Limnol* 23, 832–836
- McCauley E, Downing JA, Watson S (1989): Sigmoid relationships between nutrients and chlorophyll among lakes. *Can J Fish Aquat Sci* 46, 1171–1175
- Meeuwig JJ, Rasmussen JB, Peters RH (1998): Turbid waters and clarifying mussels: Their moderation of Chl, nutrient relations in estuaries. *Mar Ecol Progr Ser* 171, 139–150
- McGarrigle ML (1993): Aspects of river eutrophication in Ireland. *Annals Limnol* 29, 355–364
- Meeuwig JJ, Kauppila P, Pitkänen H (2000): Predicting coastal eutrophication in the Baltic: a limnological approach. *Can J Fish Aquat Sci* 57, 844–855
- Mitrovic SM, Hawkins PR, Bowling LC, Buckney RT, Cheng DMH (2000): Low nitrate concentrations in a tidally mixed river coincide with replacement of chlorophytes by the cyanophyte *Microcystis*. *Verh Int Ver Theor Angew Limnol* 27, 924–929
- Moss B, Hooker I, Balls H, Manson K (1989): Phytoplankton distribution in a temperate floodplain lake and river system. I. Hydrology, nutrient sources and phytoplankton biomass. *J Plankton Res* 11, 813–835
- Moss B, Balls H (1989): Phytoplankton distribution in a temperate floodplain lake and river system. II. Seasonal changes in the phytoplankton communities and their control by hydrology and nutrient availability. *J Plankton Res* 11, 836–867
- Moss B, Madgewick J, Phillips G (1996): A guide to the restoration of nutrient-enriched shallow lakes. Broads Authority, Norwich, UK. 180 pp
- Myers N (1995): Environmental unknowns. *Science* 269, 358–360
- Nicholls KH, Dillon PJ (1978): An evaluation of phosphorus-chlorophyll-phytoplankton relationships for lakes. *Int Revue ges Hydrobiol* 63, 144–154
- National Research Council (2000): Clean coastal waters: Understanding and predicting the effects of nutrient pollution. National Academy Press, Washington, DC, USA
- Nielsen SL, Sand-Jensen K, Borum J, Geertz-Hansen O (2002): Phytoplankton, nutrients, and transparency in Danish coastal waters. *Estuaries* 25, 930–937
- Nürnberg G (1996): Trophic state of clear and colored, soft-and hardwater lakes with special consideration of nutrients, anoxia, phytoplankton and fish. *Lake Reservoir Manage* 12, 432–447
- OECD (1982): Eutrophication of waters: Monitoring, assessment and control. Organisation for Economic and Cooperative Development, Paris, France
- Paerl HW (1988): Nuisance phytoplankton blooms in coastal, estuarine, and inland waters. *Limnol Oceanogr* 33, 823–847
- Paerl HW, Mallin M, Rudek J, Bates P (1990): The potential for eutrophication and nuisance algal blooms in the lower Neuse River, NC. Albemarle-Pamlico Estuarine Study Report 90-15. North Carolina Natural Resources and Community Development, Raleigh, NC

- Petersen JE, Chen CC, Kemp WM (1997): Scaling aquatic primary productivity: experiments under nutrient- and light-limited conditions. *Ecology* 78, 2326–2338
- Phlips EJ, Aldridge FJ, Hansen P, Zima PV, Ihnat J, Conroy M, Ritter P (1993): Spatial and temporal variability of trophic state parameters in a shallow subtropical lake (Lake Okeechobee, Florida, USA). *Arch Hydrobiol* 128, 437–458
- Piyasiri S (2001): Increasing eutrophy in Kotmale Reservoir, Sri Lanka: A 5-year study. *Verh Int Ver Theor Angew Limnol* 27, 3604–3607
- Portielje R, Van der Molen TT (1999): Relationships between eutrophication variables: from nutrient loading to transparency. *Hydrobiologia* 408/409, 375–387
- Postel SL, Carpenter SR (1997): Freshwater ecosystem services, p 195–214. In: G Daily, Ed, *Nature's services*. Island Press, Washington, DC, USA
- Prairie YT, Duarte CM, Kalff J (1989): Unifying nutrient-chlorophyll relationships in lakes. *Can J Fish Aquat Sci* 46, 1176–1182
- Pridmore RD, Vant WN, Rutherford JC (1985): Chlorophyll-nutrient relationships in North Island lakes (New Zealand). *Hydrobiologia* 131, 181–189
- Proulx M, Pick FR, Mazumder A, Hamilton PB, Lean DRS (1996): Effects of nutrients and planktivorous fish on the phytoplankton of shallow and deep aquatic systems. *Ecology* 77, 1556–1572
- Prygiel J, Leitaio M (1994): Cyanophycean blooms in the reservoir Val Joly (Northern France) and their development in downstream rivers. *Hydrobiologia* 289, 85–96
- Quirós R (1998): Trophic cascade effects in a continuous series of temperate-subtropical waterbodies. *Verh Int Ver Theor Angew Limnol* 26, 2315–2319
- Quirós R (1991): Empirical relationships between nutrients, phyto and zooplankton, and relative fish biomass in lakes and reservoirs of Argentina. *Verh Int Ver Theor Angew Limnol* 24, 1198–1206
- Quirós R (1990): Factors related to variance in residuals in chlorophyll-phosphorus regressions in lakes and reservoirs of Argentina. *Hydrobiologia* 200/201, 343–355
- Rabelais N, Nixon SW, Eds (2002): Dedicated issue. Nutrient over-enrichment in coastal waters: Global patterns of cause and effect. *Estuaries* 25(4b), 639–900
- Rask M, Olin M, Horppila J, Lehtovaara A, Väisänen A, Ruuhiarvi J, Sammalkorpi I (2002): Zooplankton and fish communities in Finnish lakes of different trophic status: responses to eutrophication. *Verh Int Ver Theor Angew Limnol* 28, 396–401
- Reckhow KH, Chapra SC (1983): *Engineering Approaches for Lake Management*. Vol 1, Data Analysis and Empirical Modeling. Butterworth, Boston, MA, USA
- Rekolainen S, Pitkänen H, Bleeker A, Felix S (1995): Nitrogen and phosphorus fluxes from Finnish agricultural areas to the Baltic Sea. *Nordic Hydrol* 26, 55–72
- Reynolds CS (1997): Vegetative processes in the pelagic: A model for ecosystem study. Ecology Institute, Oldendorf/Luhe, Germany. 371 pp
- Reynolds CS (1994): Are phytoplankton dynamics in rivers so different from those in shallow lakes? *Hydrobiologia* 289, 1–7
- Richardson K (1996): Conclusion, research and eutrophication control, p 243–267. In: BB Jørgensen and K Richardson, Eds, *Eutrophication in Coastal Marine Ecosystems*, Volume 52, American Geophysical Union, Washington, DC, USA
- Sakamoto M (1966): Primary production by phytoplankton in some Japanese lakes and its dependence on lake depth. *Arch Hydrobiol* 62, 1–28
- Salas HJ, Martino P (1991): A simplified phosphorus trophic state model for warm-water tropical lakes. *Water Research* 25, 341–350
- Sarvala J, Helminen H, Karjalainen J (2000): Restoration of Finnish lakes using fish removal: changes in the chlorophyll-phosphorus relationship indicate multiple controlling mechanisms. *Verh Int Ver Theor Angew Limnol* 27, 1473–1479
- Sas H (1989): Lake restoration by reduction of nutrient loading: Expectations, experiences, extrapolations. Academia Verlag, Richarz, St. Augustin, Germany
- Scheffer M (1998): *Ecology of shallow lakes*. Chapman and Hall, London, UK
- Scheffer M, Hosper H, Meijer M-L, Moss B, Jeppesen E (1993): Alternative equilibria in shallow lakes. *Trends Ecol Evol* 8, 260–262
- Schindler DW (1981): Studies of eutrophication in lakes and their relevance to the estuarine environment, p 71–82. In: BJ Nielson and LE Cronin, Eds, *Estuaries and Nutrients*. Humana Press, Clifton, NJ, USA
- Schindler DW (1977): Evolution of phosphorus limitation in lakes. *Science* 195, 260–262
- Schmidt A (1994): Main characteristics of the phytoplankton of the Southern Hungarian section of the River Danube. *Hydrobiologia* 289, 97–108
- Schramm W (1999): Factors influencing seaweed responses to eutrophication: some results from EU-project EUMAC. *J Appl Phycol* 11, 69–78
- Seip KL (1994): Phosphorus and nitrogen limitation of algal biomass across trophic gradients. *Aquat Sci* 56, 16–28
- Seip KL, Jeppesen E, Jensen JP, Faafeng B (2000): Is trophic state or regional location the strongest determinant for Chl-*a*/TP relationships in lakes? *Aquat Sci* 62, 195–204
- Seip KL, Sas H, Vemij S (1992): Nutrient-chlorophyll trajectories across trophic gradients. *Aquat Sci* 54, 58–76
- Seip KL, Ibrekk H (1988): Regression equations for lake management – how far do they go? *Verh Int Ver Theor Angew Limnol* 23, 778–785
- Seip KL, Satoh T (1984): The impact of nutrient load on total biomass and species succession in Lake Suwa, Japan. *Verh Int Ver Theor Angew Limnol* 22, 1142–1149
- Sharp JH (2001): Marine and aquatic communities, stress from eutrophication, p 1–11. In: *Encyclopedia of Biodiversity*, volume 4. Academic Press, New York, USA
- Shapiro J (1989): Current beliefs regarding dominance by blue-greens: The case for the importance of CO₂ and pH. *Verh Int Ver Theor Angew Limnol* 24, 38–54
- Shapiro J, Lamarra V, Lynch M (1975): Biomanipulation: an ecosystem approach to lake restoration, p 85–96. In: PL Brezonik and JL Fox, Eds, *Proceedings of a Symposium on Water Quality Management through Biological Control*. University of Florida, Gainesville, FL, USA
- Sims JT, Simard RR, Joern BC (1998): Phosphorus loss in agricultural drainage: Historical perspective and current research. *J Environ Quality* 27, 277–297
- Sivonen K (2000): Toxic cyanobacteria, p 81–96. In: P Heinonen, Z Giuliano, and A Van der Beken, Eds, *Hydrological and Limnological Aspects of Lake Monitoring*. Wiley and Sons, Ltd, West Sussex, England
- Søndergaard M, Jeppesen E, Jensen JP, Lauridsen T (2000): Lake restoration in Denmark. *Lakes Reserv Res Manage* 5, 151–159
- Smith VH (2001): Blue-green algae in eutrophic fresh waters. *LakeLine* 21(1), 34–37
- Smith VH (1998): Cultural eutrophication of inland, estuarine, and coastal waters, p 7–49. In: ML Pace and PM Groffman, Eds, *Successes, Limitations and Frontiers in Ecosystem Science*, Springer-Verlag, New York, USA
- Smith VH (1990a): Phytoplankton responses to eutrophication in inland waters, p 231–249. In: I. Akatsuka, Ed, *An Introduction to Applied Phycology*. SPB Academic Publishing, Amsterdam
- Smith VH (1990b): Effects of nutrients and non-algal turbidity on blue-green algal biomass in North Carolina reservoirs. *Lake Reservoir Manage* 6, 125–131

- Smith VH, Sieber-Denlinger J, deNoyelles F, Jr, Campbell S, Pan S, Randtke SJ, Blain GT, Strasser VA (2003): Managing taste and odor problems in a eutrophic drinking water reservoir. *J Lake Reservoir Manage* (in press)
- Smith VH, Willén E, Karlsson B (1987): Predicting the summer peak biomass of four species of blue-green algae (Cyanophyta/Cyanobacteria) in Swedish lakes. *Water Resources Bull* 23, 397–402
- Smith VH (1986): Light and nutrient effects on the relative biomass of blue-green algae in lake phytoplankton. *Can J Fish Aquat Sci* 43, 148–153
- Smith VH (1985): Predictive models for the biomass of blue-green algae in lakes. *Water Resources Bull* 21, 433–439
- Smith VH (1982): The nitrogen and phosphorus dependence of algal biomass in lakes: An empirical and theoretical analysis. *Limnol Oceanogr* 27, 1101–1112
- Smith VH, Tilman GD, Nekola JC (1999): Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environ Pollut* 100, 179–196
- Smith VH, Bennett SJ (1999): Nitrogen, phosphorus supply ratios and phytoplankton community structure in lakes. *Arch Hydrobiol* 146, 37–53
- Soballe DM, Kimmel BL (1987): A large-scale comparison of factors influencing phytoplankton abundance in rivers, lakes, and impoundments. *Ecology* 68, 1943–1954
- Sorvala J, Helminen H, Karjalainen J (2000): Restoration of Finnish lakes using fish removal: changes in the chlorophyll-phosphorus relationship indicate multiple controlling mechanisms. *Verh Int Ver Theor Angew Limnol* 27, 1473–1479
- Sutcliffe DW, Jones JG, Eds (1992): *Eutrophication: Research and application to water supply*. Freshwater Biological Association, Ambleside, United Kingdom
- Stadelmann TH, Brezonik PL, Kloiber S (2001): Seasonal patterns of chlorophyll *a* and Secchi disk transparency in lakes of East-Central Minnesota: Implications for design of ground- and satellite-based monitoring programs. *J Lake Reservoir Manage* 17, 299–314
- Swedish EPA (2000): Environmental quality criteria: Coasts and seas. Swedish Environmental Protection Agency Report 5052, Stockholm, Sweden. 138 pp
- Tanik A, Beler Baykal B, Gonenc IE (1999): The impact of agricultural pollutants in six drinking water reservoirs. *Water Sci Technol* 40, 11–17
- Thornton JA (1980): A comparison of the summer phosphorus loadings to three Zimbabwean water-supply reservoirs of varying trophic states. *Water SA* 6, 163–170
- Traill I (1991): Loch Lomond: A eutrophication study 1987–1989. Clyde River Purification Board Technical Report 96. Scottish Environment Protection Agency, East Kilbride, Scotland
- Trimbee AM, Prepas EE (1987): Evaluation of total phosphorus as a predictor of the relative biomass of blue-green algae with emphasis on Alberta lakes. *Can J Fish Aquat Sci* 4, 1337–1342
- UK Environment Agency (1998): Environmental Issues Series – Aquatic eutrophication in England and Wales. UK Environment Agency Consultative Report, December 1998
- US EPA (2002): <http://www.epa.gov/waterscience/criteria/nutrient/guidance/index.html>
- US EPA (1996a): Environmental indicators of water quality in the United States, US EPA 841-R-96-02, Office of Water (4503F), US Government Printing Office, Washington, DC, USA
- US EPA (1996b): National nutrient assessment workshop. Proceedings, December 4–6, 1995. US EPA 822-R-96-004, Office of Water, US Government Printing Office, Washington, DC, USA
- Valiela I, Collins G, Kremer J, Lajtha K, Geist M, Seely B, Brawley J, Sham CH (1997): Nitrogen loading from coastal watersheds to receiving estuaries: New method and application. *Ecol Appl* 7, 358–380
- Valiela I, Tomasky G, Hauxwell J, Cole ML, Cebrián J, Kroeger; KD (2000): Operationalizing sustainability: Management and risk assessment of land-derived nitrogen loads to estuaries. *Ecol Appl* 10, 1006–1023
- Van Ginkel CE, Silberbauer MJ, Vermaak E (2000): The seasonal and spatial distribution of cyanobacteria in South African surface waters. *Verh Int Ver Theor Angew Limnol* 27, 871–878
- Van Nieuwenhuysse EE, Jones JR (1996): Phosphorus-chlorophyll relationship in temperate streams and its variation with stream catchment area. *Can J Fish Aquat Sci* 53, 99–105
- Varis O, Fraboulet-Jussila S (2002): Analysis of eutrophication level and critical loads of Lac de Guiers, Senegal. *Verh Int Ver Theor Angew Limnol* 28, 462–466
- Victor R, Al Ujaily SR (1999): Water quality and management strategies of mountain reservoirs in arid northern Oman, p 307–350. In: MFA Goosen and W Shaaya, Eds *Water Management, Purification, and Conservation in Arid Climates*, Vol 1. Technomic Publ Co Inc, Lancaster, UK
- Vitousek PM, Aber J, Howarth RW, Likens GE, Matson PA, Schindler DW, Schlesinger WH, Tilman GD (1997): Human alteration of the global nitrogen cycle: Causes and consequences. *Ecological Applications* 7, 737–750
- Vollenweider RA (1992): Coastal marine eutrophication, principles and control, p 1–20. In: RA Vollenweider, R Marchetti, and R Viviani, Eds, *Marine Coastal Eutrophication. The Response of Marine Transitional Systems to Human Impact: Problems and Perspectives for Restoration*. Science of the Total Environment Supplement 1992. Elsevier Scientific, Amsterdam, The Netherlands
- Vollenweider RA, Rinaldi A, Montanari G (1992): Eutrophication, structure and dynamics of a marine coastal system: results of a ten-year monitoring along the Emilia-Romagna coast (North-west Adriatic Sea), p 63–105. In: RA Vollenweider, R Marchetti, and R Viviani, Eds, *Marine Coastal Eutrophication. The Response of Marine Transitional Systems to Human Impact: Problems and Perspectives for Restoration*. Science of the Total Environment Supplement 1992. Elsevier Scientific, Amsterdam, The Netherlands
- Vyhnálek V, Fott J, Kopáček J (1994): Chlorophyll-phosphorus relationship in acidified lakes of the High Tatra Mountains (Slovakia). *Hydrobiologia* 274, 171–177
- Welch EB, Quinn JM, Hickey CW (1992): Periphyton biomass to point-source nutrient enrichment in seven New Zealand streams. *Water Research* 26, 669–675
- Willén E (2000): Phytoplankton in water quality assessment – An indicator concept, p 57–80. In: P Heinonen, Z Giuliano, and A Van der Beken, Eds, *Hydrological and Limnological Aspects of Lake Monitoring*. Wiley and Sons, Ltd, West Sussex, England
- Willén E, Ahlgren G, Söderhielm A-C (2000): Toxic cyanophytes in three Swedish lakes. *Verh Int Ver Theor Angew Limnol* 27, 560–564
- Wilson JG, Ed (1998): *Eutrophication in Irish waters*. Royal Irish Academy, Dublin, Ireland
- Winter JG, Duthie HC (2000): Epilithic diatoms as indicators of stream total N and total P concentrations. *J N Amer Benthol Soc* 19, 32–49
- Wolff WJ (1993): Netherlands-Wetlands. *Hydrobiologia* 265, 1–14

Received: August 29th, 2002

Accepted: December 4th, 2002

OnlineFirst: December 6th, 2002