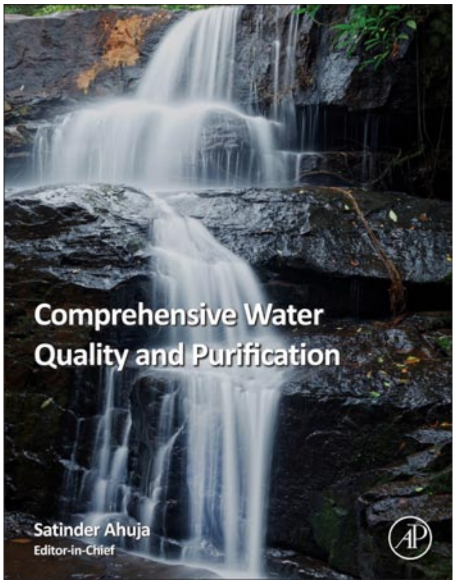

Baker L.A., and Newman R.M. (2014) Managing the Biological, Economic, and Social Aspects of Sustainability of Lake Ecosystems. In: Ahuja S. (ed.) Comprehensive Water Quality and Purification, vol. 4, pp. 76-86. United States of America: Elsevier.

4.4 Managing the Biological, Economic, and Social Aspects of Sustainability of Lake Ecosystems

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Glossary

Bioaccumulate The process by which a stable contaminant becomes concentrated as it moves through a food chain.

Dichlorodiphenyltrichloroethane It is a chlorinated hydrocarbon widely used as a pesticide until it was banned (in the US) in 1972.

Environmental Protection Agency The main federal environmental agency in the US federal government.

Eutrophic A condition of high nutrient enrichment, resulting in high algae abundance, low clarity, and often, an anoxic hypolimnion.

Eutrophication As generally used, extensive nutrient enrichment of a lake or estuary. Eutrophic waters are characterized by high algae abundance, often dominated by blue–green algae, and low concentrations of dissolved oxygen near the bottom. Eutrophication can be reversed by reducing nutrient inputs.

Hydroshed The land area that is tributary to the city through either natural topography or created infrastructure. (Baker, 14) Impaired lake, in the US, a legal definition meaning that a lake does not meet one or more water quality standards.

Impaired lake In the US, this is a legal definition under the Clean Water Act. Lake impairment is based on the concentration of specific contaminants. The designation of 'impaired' triggers legal action to restore the water.

Littoral zone The region of a lake near its shoreline. For lakes, the littoral zone is often defined as the area wherein rooted aquatic plants live, which is in turn defined by clarity of the lake.

Mesotrophic A condition of moderate nutrient enrichment.

Pathogens Microorganisms that cause disease.

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PCB Polychlorinated biphenyls, a type of chlorinated hydrocarbons widely used in transformers and electric motors. Because PCBs bioaccumulate and are toxic, they were banned (in the US) in 1979.

Trophic status The degree of biological production within a lake, usually based on the total mass of algae in a lake. Lakes are often classified as oligogtrophic (low algae abundance), mesotrophic (moderate algae abundance), and eutrophic (high algae abundance).

4.4.1 Introduction

High-quality lakes and reservoirs provide enormous benefits to human society. Some of these benefits include water storage; opportunities for recreation – fishing, swimming, and boating; highly valued home sites; wildlife habitat; and aesthetic enhancement for our often stressed-out lives. Finally, large lakes such as the Great lakes are a significant source of food. This chapter examines qualities of lakes in relation to their capacity to provide sustained benefits to human society, for both present and future generations. The authors therefore delve more broadly into the idea of 'lake quality,' going beyond 'water quality' to examine the intersection of lake ecosystems with the social and economic dimensions of human ecosystems – the triad of the modern concept of 'sustainability.' For additional information on sustainability, *see* Chapters 1.1, 1.15, 2.2, 2.16, 4.1, 4.3, and 4.18. The next section of this chapter examines the qualities of lakes in the context of various uses; the authors then turn to 'drivers of change' that alter these qualities.

4.4.2 Lake Quality in Relation to Uses

4.4.2.1 Urban Water Supply

Lakes and reservoirs store water for much of the nation's water supply, hence the quality of stored water is important. In particular, nutrient enrichment, taste and odor problems, and catastrophic events such as wildland fires can have a deleterious impact on downstream water supply (*see* Chapter 4.19).

4.4.2.1.1 Lakes as storage reservoirs

Many cities rely, at least in part, on water that has been stored in lakes or reservoirs. Lakes and reservoirs provide 68% of the water used by the nation's largest utilities (>50 000 customers; NAS, 1992). Some of these are located at considerable distance from cities, with water transmitted via canals or aqueducts from upstream 'hydrosheds'; examples include Denver, Phoenix, San Francisco, and New York City. Other, often smaller lakes and reservoirs are located on the fringe of the urban area. Many of these water supply lakes were once on the outskirts of cities but are now surrounded by urban development. Robbins et al. (1991) reported that residential land was the dominant land use in 64% of the nation's water supply reservoirs by the late 1980s.

Maintaining high-quality source water is very important for cities. Cities using conventional water treatment (flocculation/coagulation/sedimentation, followed by sand filtration and disinfection) have limited ability to remove soluble contaminants. Although water treatment plants generally are efficient at removing particles including bacteria and protozoa, high turbidity in inflow water raises the costs of chemicals (especially alum coagulant), electricity (by decreasing the backwash interval of sand filters), and sludge disposal. Hence, securing and maintaining high-quality water in storage reservoirs and lakes is an important component of a multiple barrier approach to managing municipal water production.

4.4.2.1.2 Nutrient enrichment

Nutrient enrichment of storage lakes is therefore a major problem for lakes that store municipal source water. Nutrient enrichment results in high algae abundance, hence turbidity. Both phosphorus (P) and nitrogen (N) can limit algae growth, although P limitation is generally thought to be more common for freshwaters (Schindler, 2006). Eutrophication also causes hypolimnetic oxygen depletion, causing problems with reduced compounds (Fe^{2+}, Mn^{2+}, and H_2S). These constituents degrade the aesthetic quality of municipal water, impairing its taste, and, for Fe^{2+} and Mn^{2+}, causing stains in sinks. All three constituents can be removed in a conventional water treatment plant, but doing so adds to the cost.

4.4.2.1.3 Tastes and odors (T&O) in stored water

A more widespread problem is the occurrence of T&O caused by algae. In a national survey of drinking water quality, 52% of respondents reported that they are concerned about the 'smell or taste of water' (WQA, 2001). Musty/moldy problems caused largely by algae affect nearly a quarter of all municipal water suppliers using surface water (Suffet et al., 1996). A wide variety of chemicals can cause taste and odor problems in water supplies, but the problem is often caused by metabolites produced by blue–green algae (cyanobacteria), mainly 2-methylisoborneol (MIB) and geosmin. Both planktonic and attached algae can cause T&O problems. Although T&O problems have been correlated with indicators of trophic status (Walker, 2000), this is not always the case. Baker et al. (2006) found no correlation between concentrations of MIB and chlorophyll in three mesotrophic reservoirs in Arizona. One reason for the lack of general relationship between T&O problems and gross metrics of algae abundance is that few species of algae contribute T&O compounds to water: it is the presence of these specific species, often blue–green algae, that is correlated with concentrations of T&O compounds. Moreover, taste and odor problems are sometimes caused by benthic algae, especially in reservoirs (Taylor et al., 1994).

There is considerable economic motivation for water utilities to reduce T&O problems in source waters because removal of T&O compounds within water treatment plants is very expensive. Some of these techniques include selective treatment with copper sulfate, selective withdrawal from reservoirs to avoid strata containing T&O compounds, temporary cessation of withdrawals to allow degradation of T&O compounds, and destratification (Westerhoff et al., 2005; Baker et al., 2006; Taylor et al., 1994).

4.4.2.1.4 *Impact of catastrophic events*

Catastrophic events, such as wildland fires, flooding, and droughts, can also alter water quality in lakes and reservoirs in ways that affect urban water use. These events alter both the hydrology and transport of chemicals in watersheds, often resulting in large pulses of water, nutrients, sediments, and other chemicals. One particular concern is the impact of wildland fires on municipal source waters. In the US, the number of wildland fires and acres burned on forest service lands have increased dramatically since the mid-1980s (Calkin et al., 2005). These lands alone provide water for water utilities serving 60 million people. Briefly, the effects of wildland fires on water quality include increased water yield and loadings of sediment and nutrients, with mixed findings with respect to metals (Smith et al., 2011; Landsberg and Tiedemann, 2000). The increase in sediment export from burned areas can exceed 1000 times that of unburned areas (Smith et al., 2011). Water from burned areas is often intercepted by storage impoundments. Impoundments may improve water quality, for example, by sedimentation, which would reduce turbidity of water delivered downstream. Conversely, impoundments can exacerbate fire impacts; for example, the pulse of nutrients released from a burned watershed can cause rapid eutrophication of impoundments, with associated impacts on urban water supply (Section 4.4.2.1.2). Water treatment plants below a burned watershed may have to modify their water treatment, switch to other sources (e.g., groundwater), or require residents to boil water (Smith et al., 2011). Given the potential for growing impact of wildland fires on municipal water supplies, there is remarkably little research on upstream mitigation strategies.

4.4.2.2 Fishing

Even in the age of the Internet, one-third of all Americans over the age of 16 years enjoy fishing, making it one of the most important recreational activities in the US (NSRE, 2002). Both water and habitat qualities are important determinants of the fish community, and the quality of fishing in lakes and fishing is a *de jure* use protected by the Clean Water Act.

4.4.2.2.1 *Economic impact of fishing in the US*

Fishing is an important recreational activity: there are 25 million freshwater anglers in the US, who spend 419 million days angling, generating $87 billion in economic output (ASA, 2008). Much of this fishing occurs in lakes and reservoirs (Hatch, 2008).

4.4.2.2.2 *Trophic status in relation to fishing quality*

Fish and sport fish communities composition are often related to trophic status (Ryder and Kerr, 1978). Trout and salmon (*Salvelinus* sp. and *Oncorhynchus* sp.) fisheries are associated with oligotrophic lakes, perch (*Perca flavescens*) and walleye (*Sander vitreus*) with mesotrophic lakes, and bass (*Micropterus* sp.) and sunfish (*Lepomis* sp.) with eutrophic lakes. Hypereutrophic lakes support less desirable communities of carp (*Cyprinus carpio*) and bullhead (*Ameiurus* sp.) (Heiskary and Wilson, 2008). In North America, the most desired fish communities are associated with the best water quality (oligotrophic); eutrophication can shift fisheries to less desirable species or to a community different from that historically present. Fish productivity and fishery yields are positively related to trophic status, and mesotrophic and eutrophic lakes can thus support more harvest than nutrient-poor lakes (Wagner, 2008). However, with the exception of relatively pristine and higher altitude lakes, excess nutrients rather than a lack of nutrients is the typical problem, and eutrophication associated with human activities may result in undesirable shifts in fish community, with some lakes losing desirable walleye populations or shifting from bass and panfish to carp and bullhead.

Fishing and fisheries management can also alter lake trophic state via trophic cascades or top–down control. Removal of top predators such as bass can result in increased algal abundance and decreased water clarity (Carpenter and Kitchell, 1988). Similarly, stocking of planktivorous trout can also degrade water clarity (Hembre and Megard, 2005). Ward and Newman (2006) suggested that overabundant sunfish can suppress Eurasian watermilfoil herbivores and thus allow dominance of this invasive macrophyte. Removal of predators such as northern pike (*Esox lucius*) or bass, or even large sunfish by anglers may thus promote the invasive Eurasian watermilfoil (*Myriophyllum spicatum*) and further reduce water quality.

4.4.2.2.3 *Chemical contaminants of fish*

Chemical contaminants affect fishing by making the fish unhealthy to eat and by impairing the fish themselves. Contaminants that impair the health of fish in lakes at levels commonly found in lake include free aluminum (in acidic lakes), free chlorine, chloride (from road salt and other sources), mercury, polychlorinated biphenyls, dichlorodiphenyltrichloroethane, and ammonia. Probably the most common chemical condition affecting fish populations is the lack of a chemical oxygen. Near-zero oxygen levels are often found in the hypolimnion of eutrophic lakes during the summer and under the ice of many shallow lakes in the winter, limiting habitat for fish. Winterkills caused by oxygen depletion can render a lake devoid of fish. Principles of fish toxicology and many case studies are presented by Di Giulio and Hinton (2008) (*see* Chapter 4.7).

4.4.2.2.4 *Importance of shoreline quality*

Shoreline quality is important to lake fisheries indirectly via its effects on nutrient and sediment loading, and directly via alteration of fish habitat. Lakeshore development can result in soil erosion and sedimentation (Jennings et al., 2001) that can alter lake trophic state and also eliminate spawning habitat. Borman (2007) found that shoreline development alters macrophyte communities, favoring larger statured plants that can become invasive. Reduced emergent and floating leaf macrophytes related to shoreline development are also correlated with reduced abundance of northern pike and sunfish (Radomski and Goeman, 2001). Reduction of natural wood inputs and removal of woody debris to facilitate lake access can reduce spawning habitat. Nest density and nesting success of largemouth bass (*Micropterus salmoides*) and black crappie (*Pomoxis nigromaculatus*) are reduced as shoreline development and number of residences increases (Wagner et al., 2006; Reed and Pereira, 2009).

4.4.2.3 Nonfishing Recreation

Lakes are universally appreciated for their recreational appeal. In Minnesota, with its 10 000 (nominal) lakes, 77% of respondents to a major survey of lake users reported that they engaged in some type of lake-based recreation for an average of 55 days per year (Anderson et al., 1999). Several quality aspects of lakes that affect nonfishing recreation include the presence or potential presence of pathogens, algal toxins, and aesthetic qualities.

4.4.2.3.1 Pathogens

The presence of pathogens can affect recreational use, either because the detection of pathogen indicators (*Escherichia coli* or fecal coliform) results in beach closures or because pathogens actually cause illness. Beach monitoring for the Great lakes over the period 2006–2010 shows that 13–15% of the 406 beaches monitored exceeded bacterial limits for recreational use. During the same period, there were 3766 days of beach closings and several extended closings (NRDC, 2011). Beach closings for lakes within states are not uniformly reported across states or even within states. However, the occurrence of disease caused by swimming in lakes is fairly rare. There were 10 outbreaks of waterborne diseases associated with lake recreation throughout the US in 2005, with a total of 99 cases and no deaths (Yoder et al., 2008).

4.4.2.3.2 Algal toxins

A second health-related aspect of recreational swimming is the presence of algal toxins. These cause allergic reactions to some swimmers resulting in rashes; eye irritation; respiratory symptoms; and in some cases gastroenteritis, liver and kidney failure, or (rarely) death (USEPA, 2009). Algal toxins occasionally kill dogs and farm animals that drink contaminated lake water (Lindon and Heiskary, 2008). The World Health Organization has three indicators of human health risk to algal toxins, two indirect (total chlorophyll and cyanobacteria) and one direct (microcystin) (USEPA, 2009). In their National Lake Survey, Environmental Protection Agency (EPA) reported that 12% of lakes exceeded the high-risk threshold for chlorophyll; 7% exceeded the high-risk level for cyanobacteria; but only 0.2% exceeded the high-risk level for microcystin (*see* Chapter 4.8).

4.4.2.3.3 Aesthetic qualities

In addition to water quality, aesthetic qualities of lakes are important for recreation utilization. Anderson et al. (1999) reported that 4 of the top 10 reasons for visiting their favorite lakes were related to aesthetic features – 'scenic,' 'good fishing,' 'quiet,' 'good water quality,' 'wildlife in area,' 'good swimming,' and 'size preference' (**Figure 1**). Other factors included habit ('have gone for years'), social interaction ('friends on lake' and 'few people' fared equally well; **Figure 1**), and finally, convenience and expense. An important management implication of this survey is that the aesthetic features of the shoreline region are at least as important as water quality itself. The same survey revealed that respondents use their 'most visited lake' in multiple ways: 'socializing' and 'appreciating nature' are just as important as fishing, swimming, and nonfishing boating (**Figure 2**).

Even so, water clarity is an important aesthetic quality. The expectation of how clear lakes 'should be' depends on

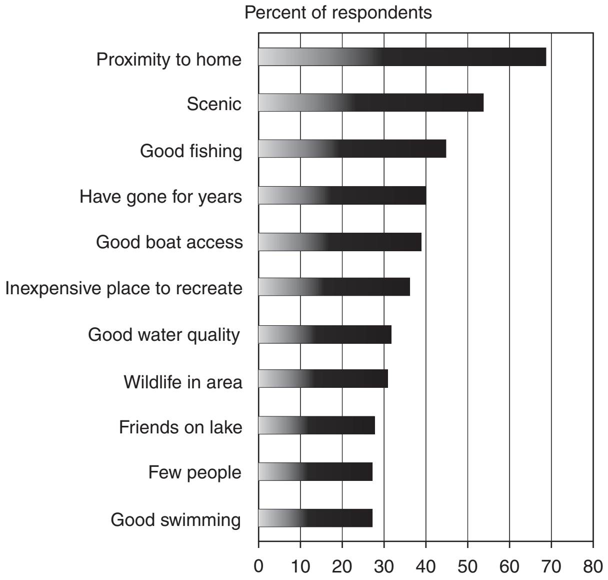

Figure 1 Percentage of respondents selecting top 10 reasons that they prefer their most-visited lake.

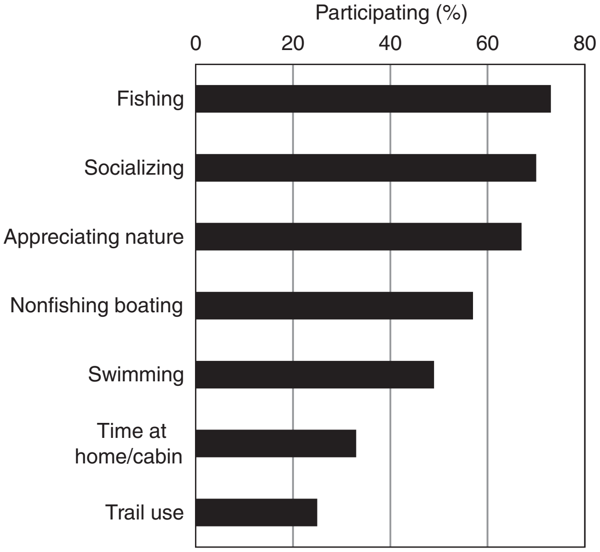

Figure 2 Participation in various activities of respondents in the 'Treasures Under Pressure' survey of Minnesota lakes.

where one lives. Heiskary and Wilson (2005) found that survey respondents from the northern part of Minnesota (the Northern Lakes and Forest ecoregion), where lakes are generally quite clear, 2-m Secchi disk clarity was perceived as 'slight impairment,' whereas users of lakes in the Central Hardwood Forests region (the middle part of the state, where lakes are naturally more eutrophic) perceived that 1.2-m clarity was perceived as slight impairment (**Table 1**). In Minnesota, there is a perception that the desirable qualities of lakes have been diminished (**Table 2**). This is also true in Wisconsin, where respondents to a lake survey associated an increase in shoreline development with decreased water quality, even though monitoring data showed no downward trend in lake clarity associated with development (Stedman and Hammer, 2006).

Loss of lake clarity has been linked to economic loss due to reduced recreation. Using a stated preference method, Vesterinen et al. (2010) concluded that the loss of 1 m clarity in Finnish lakes would result in a loss of 29–87 million Euros per year from reduced swimming and 38–113 million Euros from reduced fishing; conversely, improving water quality (increased clarity) would increase the value of lakes for swimming and fishing. Loss of clarity has also been linked to lower property values (see Section 4.4.2.5).

4.4.2.4 Spiritual and Religious Qualities of Lakes

Lakes often have spiritual and even religious qualities that are deeply embedded in our culture, at least in lake-rich regions. Water, and often lakes, is important in nearly every major religion; it is often part of creation stories and is used in cleaning rituals. In the modern world, sectarian values that might have been associated with water in Old World cultures have been transmogrified into secular spirituality that remains powerful (Strang, 2004). In a young America settled by Europeans, Thoreau's On Walden Pond was the 'bible' of the American naturalist movement and Walden Pond (now a Massachusetts state park) has become its shrine, although far more prosaic lakes have spiritual value (Gordon, 2010; Klessig, 2010). More than 250 000 people visit Minnesota's Boundary Waters Canoe Area each year, many seeking a spiritual retreat from modern life.

Lakes have more direct religious value to Native American religions. Many tribes consider specific lakes to be the source of life. Examples include Mille Lacs in Minnesota (Mde waken, 'spirit water' to the Ojibway tribe), Lake Tahoe (do-wa-ga, 'center of existence' to the Washoe), and Devil's lake, Wisconsin (Minnewaukan, 'holy waters' to the Dakota). Food sources associated with lakes may also have spiritual connections. A notable example is wild rice (manoomin; *Zizania palustris*), widespread along the shorelines of many lakes in the northern Midwest, which is central to Ojibway culture and religion (Vennum, 1988). The spiritual value of wild rice has recently come into focus in the context of an ongoing reevaluation of a unique 'wild rice' standard for sulfate at the Minnesota Pollution Control Agency (*see* Chapter 4.17).

4.4.2.5 Qualities of Lakes Associated with Property Value

Humans derive substantial pleasure from simply seeing lakes, from shorelines, and shorelines from lakes. Studies of landscape preferences consistently reveal that humans prefer landscapes that contain water features compared to similar landscapes that lack water features (Kaplan and Kaplan, 1989). This aesthetic value translates directly to economic value. Hedonic analysis of home prices in the Twin Cities found that a shoreline location increased property value by $111 000 and even being within 200 ft of a lake added $61 000 to a property's value (Moscovitch, 2007). In a study of several cities in the Netherlands, 'overlooking water' added 8–10% to the value of a house, and a 'garden facing water' added 28% (Luttik, 2000). Lansford and Jones (1995) concluded that recreational and aesthetic values reflected by hedonic analysis – amounted to 15% of the total property value within 2000 ft of Lake Travis. Some wetlands also increase the value of nearby property. Doss and Taff (1996) reported that property values increased with proximity to open water wetlands but not forested wetlands.

Given the large premium on property values associated with proximity to lakes, there has been surprisingly little analysis of environmental qualities of lakes in relation to property value. The few studies that have been done have focused primarily on the relationship between water clarity and property value, using hedonic analysis (Steinnes, 1992; Michael et al., 1996; Boyle et al., 1998; Gibbs et al., 2002;

Table 2 Perceptions of lake qualities for most-used lake from respondents in Minnesota's 'Treasures Under Pressure' survey

	Improved	*Worsened*
Overall	12	21
Water quality	11	24
Scenic quality	9	18
Keeper fish	8	30
Motorized watercraft	1	58
Wildlife diversity	4	11
Algae scum	5	34

Summary report on public perceptions of the impacts, use, and future of Minnesota lakes: results of the 1998 Minnesota lakes survey. Report SH-1, Minnesota Sea Grant Program and the Minnesota Department of Natural Resources, Office of Management and Budget Services.

Table 1 Perception of suitability for recreation on the basis of Secchi disk clarity (m) for two Minnesota ecoregions[a]

Ecoregion (clarity, 25th–75th percentiles for reference lakes)	*Clear and beautiful*	*Not quite crystal clear and minor aesthetics*	*Definite algal green/ slight impairment*	*High algal levels and no swimming*	*Severely high algal levels and no swimming or boating*
NLF (2.4–4.6)	3.8	3.0	2.0	1.6	1.2
CHF (1.5–3.2)	2.8	1.9	1.2	0.8	0.5

[a] CHF, Central Hardwood Forests; NLF, Northern Lakes and Forest.

Krysel et al., 2003). The effect of a loss of 1 m clarity varies among lakes and can range from a few percent to as much as 34% (Long lake, in Michael et al., 1996). Gibbs et al. also reported that clarity influenced purchasing decisions of 46% of survey respondents. Dodds et al. (2009) estimated annual US lakeshore property value losses because of eutrophication of $0.3–$2.8 billion per year. To our knowledge, there are no hedonic model studies to relate lake clarity to property values in urban areas, and few that relate property values to other aspects of lake aesthetics, although some studies have evaluated effects of invasive species. For example, Horsch and Lewis (2009) found property values dropped an average of 13% after Eurasian watermilfoil (*M. spicatum*) invasion in Wisconsin lakes.

4.4.3 Drivers of Quality

How lakes are used and valued depends very much on the quality of both the water and biota. From a regulatory standpoint, water quality has generally been the driving factor, often with a focus on nutrients. Hence, the EPA has encouraged states to adopt nutrient standards for lakes, providing a mechanism by which lakes can be classified as 'impaired,' triggering a regulatory Total Daily Maximum Load process that attempts to reverse nutrient enrichment. The biotic qualities of lakes (other than algal abundance, which is tied to nutrient enrichment) are generally not part of regulatory processes at either the federal or state levels but are often a concern of state natural resource departments and even municipalities, which benefit from high-quality lakes within their borders.

4.4.3.1 Nutrient Dynamics

Nutrient dynamics are important in lakes because they help determine fish communities and overall productivity (see Section 4.4.2.2.2) and because nutrients cause eutrophication of lakes with associated undesirable features (see Section 4.4.2.1.2). With the application of input–output models in the 1970s and the acceptance of the idea that P is generally the limiting nutrient in lakes, lake management has sometimes been reduced to a modeling exercise to determine the maximum loading of P that a lake can receive to stay within a target level of algae, P, or clarity. This section examines several complexities associated with lake nutrient management, including nutrient limitation, internal nutrient loading, the role of food chain dynamics on nutrient status, and the role of littoral processes.

4.4.2.1.1 Nutrient limitation

Nutrients play an important role in in-lake water quality because algal abundance is generally limited by either N or P. Key sources include municipal wastewater, agricultural drainage, septic systems, and urban runoff. Although it is generally considered that most freshwaters are P limited (Schindler, 2006), new studies show that N and P are generally colimiting in freshwaters (e.g., Elser et al., 2007). Nevertheless, the P limitation paradigm is so deeply entrenched in lake management science that the word 'nitrogen' does not appear in the index of one of the most popular lake management books (Cooke et al., 2005).

One reason that the P paradigm has become embedded in lake management science is that it appears to work: numerous studies (many summarized in Cooke et al., 2005; Cullen and Forsberg, 1988) show that reducing inputs of P to lakes often reduces both total P concentrations and metrics of algal abundance. Several reasons might explain the apparent lack of N colimitation. First, many early studies that showed apparent response to P reduction were based on diversion of sewage from lakes, which would reduce both N and P. Second, the conclusion that reduction in algae is associated with decreased P, rather than N, may reflect the fact that many studies simply did not measure; hence no conclusion regarding N limitation could be reached. Third, if a lake were colimited, reducing only P inputs would still lead to reduced algae to the point where N became limited.

4.4.2.1.2 Internal loading

The effect of reducing external P loading may be partly counterbalanced by internal P loading from sediments (Carpenter, 2005). Internal loading often occurs by the release of P from the sediments, typically under anoxic conditions in the hypolimnion. In some lakes, the annual internal load or release is greater than the annual external load and reductions in external loading may have little effect on summer P levels or water quality. A classical case study is Shagawa lake, Minnesota. Installation of advanced P removal to a wastewater treatment plant was expected to result in quick reversal of eutrophication, but instead, water clarity improved slowly over a period of 25 years (Baker and Schussler, 2007). The reason for the slow improvement was that internal loading from P-rich sediments provided enough P to maintain algal abundance for many years (Larsen et al., 1981). Hypolimnetic aeration has been used with various degrees of success to reduce summertime P release from sediments and thus maintain water clarity (Cooke et al., 2005). More widely used and generally successful is the application of P-binding elements such as iron and aluminum to prevent P release from the sediments. Aluminum salts, such as alum, perform best because they are not affected by redox conditions. Alum has been used successfully to reduce water column P in numerous lakes with treatments being effective from only 1 or 2 years to more than 20 years (Welch and Cooke, 1999). Hypolimnetic and littoral applications of alum can thus improve water clarity and quality when used in conjunction with other best management practices to reduce external loading (Huser et al., 2011). More recently, other approaches to reduce internal loading have been investigated and shown to have varying degrees of success. These include hypolimnetic oxygenation (Prepas and Burke, 1997; Beutel and Horne, 1999; Liboriussen et al., 2009), nitrate addition (Søndergaard et al., 2003; Beutel et al., 2008), and alum microfloc injection (Moore and Christensen, 2009). Critical to long-term success is control of external loading and perhaps also a balanced biotic community with high zooplankton and low carp abundance (see Section 4.4.2.1.3).

4.4.2.1.3 Effect of biotic interactions on trophic level: Top–down controls

Biotic interactions or top–down control also can alter nutrient budgets and the abundance of algae. Grazing by zooplankton, particularly large-bodied *Daphnia* can keep algal abundance and chlorophyll levels in check, below what might be expected based on nutrient supply alone (Carpenter and Kitchell, 1988). The addition (e.g., by stocking) of piscivorous fish, such as bass and northern pike, can reduce the abundance of smaller, planktivorous fish (such as bluegill, *L. macrochirus*), which in turn leads to an abundance of zooplankton and a decline in algal abundance and increased water clarity. Conversely, removal of piscivorous fish (e.g., by overfishing) can lead to increased abundance of planktivorous fish and a decrease in zooplankton abundance, leading to increased algal abundance and reduced clarity.

4.4.2.1.4 Littoral zone controls

The littoral zone, by definition, is the area of the lake that can support growth of rooted and benthic plants, often called macrophytes (in contrast to planktonic and periphytic algae). Macrophyte depth distribution is largely limited by light. The rooted plants must obtain sufficient light to grow to stay within the photic zone. Emergent plants, such as cattails (*Typha* spp.), sedges (*Carex* spp.), and bulrush (*Scirpus* spp.), are found along the shoreline and in very shallow water; their roots are submersed but photosynthesis occurs largely above the surface. Floating leaved plants, such as water lilies (*Nuphar* and *Nymphaea*), and some pondweeds (*Potamogeton* spp.) occupy somewhat deeper waters, up to 1–2 m in depth. Submersed macrophytes, such as sago pondweed (*Stuckenia pectinata*), water celery (*Vallisneria americana*), coontail (*Ceratophyllum demersum*), and Eurasian watermilfoil, can grow to depths of 2–6 m, depending on water clarity. In addition to light, macrophytes require suitable sediment with some organic matter and nutrients; macrophytes get most of their nutrients from the sediments (Barko et al., 1991). Rocky or sandy substrates typical of extremely oligotrophic lakes support few macrophytes, or low-growing forms called isotids (Borman et al., 2009), but most other lakes have sediment capable of sustaining macrophyte growth. Most lakes with good water clarity can thus support extensive macrophyte growth to depths of 4–6 m and lakes with poor clarity (<1 m Secchi depth) will support fewer plants and only to depths of 1–2 m (Scheffer et al., 1993). High water column nutrient levels tend to favor planktonic algae that reduce light availability to the macrophytes. Lower water column nutrient levels and more available light will favor the rooted macrophytes that get nutrients from the sediments.

In shallow systems with a high proportion of littoral area, macrophytes maintain water clarity by several mechanisms (Scheffer, 1998). They stabilize the sediments and reduce water velocity, decreasing resuspension and increasing sedimentation rates. They provide refuge from planktivorous fish to zooplankton that graze algae. And they may also compete for nutrients and release allelochemicals, which inhibit algae. Thus, macrophytes in shallow lakes can sustain a stable state of low planktonic algae, good clarity, and abundance of rooted macrophytes (Scheffer et al., 1993). If the macrophytes are lost because of management (e.g., harvesting), climate change, or biotic interactions, the lake can shift to a turbid state dominated by algae (**Figure 3**). Macrophyte growth is inhibited by the lack of light due to planktonic algae, and the lack of plants further allows sediment resuspension and nutrient release to the water column, further reducing clarity by algae and suspended sediments. This, along with the lack of zooplankton refuge and allelochemic suppression of algae by macrophytes, results in a stable state of high chlorophyll levels, poor water clarity, and few macrophytes (Scheffer et al., 1993; Scheffer, 1998).

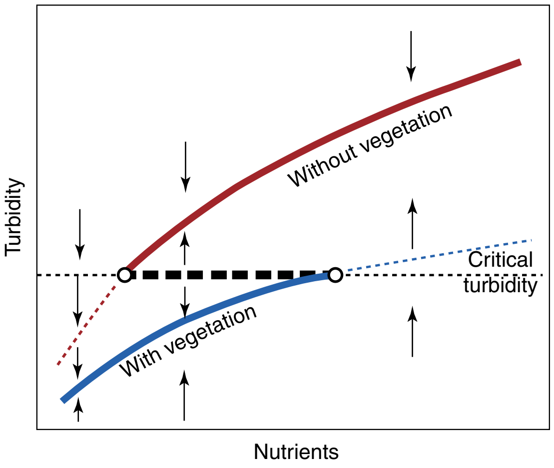

Figure 3 Conceptual illustration of alternative stable states in macrophyte communities as influenced by nutrients and clarity (turbidity). The critical turbidity represents the level of clarity (light) required to support plants, the solid lines represent alternative stable states, and the shifts between lines illustrate the change in state. Reproduced from Scheffer, M., Carpenter, S., Foley, J. A., Folke, C. and Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature* **413**, 591–596, with permission from Nature.

A key aspect of these alternative stable states is that the transitions are not linear; there is a hysteresis due to the self-reinforcing conditions of each state (Scheffer et al., 1993, 2001). Thus, once in the turbid state, a reduction in nutrient levels well below the level that resulted in the loss of macrophytes is needed before they will return (**Figure 4**). Similarly, in the clear state, nutrient levels can be increased considerably before macrophytes are lost due to their ability to sequester nutrients, keep sediment out of the water column, and prevent excess growth of planktonic algae.

In addition to human activities, such as chemical control or boating, that can reduce macrophyte abundance, benthic fish can be important. Benthic fish can root in sediment, destroying plants, suspending sediment, and releasing nutrients (Scheffer, 1998). Common carp can eliminate rooted vegetation and decrease water clarity (Bajer et al., 2009) and thus return a lake to a turbid state. Then, in addition to controlling nutrient loading, management of benthivorous fish is required to return the lake to a clear, 'macrophyte' state.

4.4.3.2 Invasive Species

Invasive species are nonnative species that cause or have the potential to cause economic, environmental, or human health harm. They are one of the main threats to biodiversity and in addition to altering ecosystem function, they often disrupt recreational and commercial uses of lakes. Once established, this biological pollution can be difficult and expensive to control, and the effects can persist for decades. Control

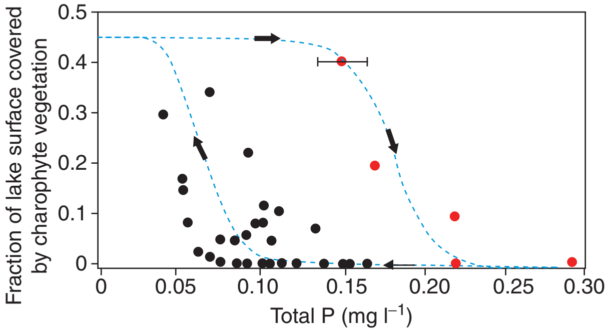

Figure 4 Response of submersed lake vegetation to changing P concentration, illustrating alternative stable states. Reproduced from Scheffer, M., Carpenter, S., Foley, J. A., Folke, C. and Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature* **413**, 591–596, with permission from Nature.

measures can also be controversial, particularly the use of biocides, and measures to reduce introduction can further disrupt recreation and commercial use.

4.4.2.2.1 Impact of invasive species

Invasive species have many direct and indirect effects on lake quality. Invasive common carp have indirect effects by reducing native macrophyte communities and promoting poor water clarity (Bajer et al., 2009). Invasive aquatic plants such as Eurasian watermilfoil and curly leaf pondweed (*Potamogeton crispus*) have direct effects on native plant communities, inhibit boating and swimming, and reduce aesthetics; they can also have indirect effects on water clarity and fisheries (Smith and Barko, 1990; Bolduan et al., 1994). Zebra mussels (*Dreissena polymorpha*) can improve water clarity, but their filtering activity can reduce food for zooplankton and sport fish (Strayer, 2009), and their shells make beaches unusable (Mills et al., 1993) (*see* Chapter 4.17).

4.4.2.2.2 Spread of invasives

Some invasive species were intentionally introduced, often well before the negative effects of introduced species were realized. Common carp were intentionally introduced throughout North America in the late 1800s (Bajer et al., 2009). They might also have been a vector for curly leaf pondweed, which likely was spread via movement of fish from fish hatcheries (Bolduan et al., 1994). Other invasives such as Eurasian watermilfoil and Hydrilla (*Hydrilla verticillata*) were likely introduced to the country via aquarium trade but then spread to other systems via boaters (Smith and Barko, 1990). Zebra mussels and spiny water flea (*Bythotrephes longimanus*) were likely introduced via ballast water (Mills et al., 1993). Once established, they are further spread to new systems by boaters (e.g., Bossenbroek et al., 2007), although hydrologic movement within river and reservoir systems is also important (Whittier et al., 2008). Boat use, proximity to nearest infestation, and suitable environment are the main determinants of establishment of new infestations (Bossenbroek et al., 2007; Whittier et al., 2008; Roley and Newman, 2008). If conditions are suitable (e.g., sufficient calcium for zebra mussels or water clarity and sediment for Eurasian watermilfoil), the invasives can become established and problematic. The negative aspects of invasives combined with lack of cheap controls can result in conflict between lakeshore owners that wish to restrict access (and thus likelihood of introduction) and agencies and the general public that expect access to public water bodies (Homans and Newman, 2011). Boater inspections and access restrictions thus further reduce lake quality for external users.

4.4.2.2.3 Controlling invasives

In addition to the direct negative effects of invasive species on use and aesthetics, approaches to control can be controversial and expensive. For most invertebrates such as zebra mussel and spiny water flea, there are no environmentally acceptable controls for lake populations. Municipalities and industry spend millions each year to control zebra mussels within their intakes and plants (Connelly et al., 2007) but in-lake controls are experimental and not well developed.

Invasive aquatic plants can be controlled by chemical treatment, mechanical harvesting, and small-scale physical removal, or by the use of barriers (Getsinger et al., 2005). Effective biological controls have been developed for water hyacinth, but biological control of Eurasian watermilfoil and hydrilla is less predictable and operational (Cuda et al., 2008). Mechanical harvesting can be effective but is expensive and must be repeated regularly (Getsinger et al., 2005); it can also affect fish and biological control agent populations (Newman and Inglis, 2009). Chemical controls can be quite effective (Getsinger et al., 2005) but can also be controversial due to concerns for the use of herbicides in water. Objections to herbicide use have often split lake associations and user groups, sometimes resulting in no control measures being taken. In addition, the aquatic plants, even if invasive, provide fish habitat and often help maintain water clarity; thus anglers and governmental agencies are concerned that chemical controls be targeted to minimize effects on desirable plants. Some whole-lake treatments have resulted in the loss of most aquatic vegetation and a persistent turbid state (e.g., Valley et al., 2006). Because chemical control is also expensive, the issue of who should pay becomes contentious. Governmental agencies will often conduct control of new infestations but may only cost share for some control on waters accessible to the public. Lakeshore owners may be expected to cover costs of local control, and the methods and extent of control may be further limited by regulations designed to protect fisheries habitats and water quality (Homans and Newman, 2011). It is estimated that more than $400 million is spent on control of Eurasian watermilfoil in the USA each year (Pimentel, 2005), and Florida alone spends $10 million annually to control hydrilla (Lach, 2007).

Lake managers are increasingly realizing that invasive species and methods to control them can have important effects on water quality, and that more holistic management of invasives and water quality is required to sustain desirable outcomes. For example, control of common carp may be necessary to reduce internal loading, enhance water clarity, and restore aquatic plant communities (Bajer et al., 2009). However, improved water clarity associated with carp removal or reduction of external or internal loading may result in increased abundance of nuisance macrophytes such as curly leaf pondweed or Eurasian watermilfoil. Thus, strategies to prevent introduction or control these plants should be a part of the management plan.

Furthermore, effects of invasive control on fish habitat and water clarity must also be considered to ensure the lake is not shifted to a turbid state lacking necessary fish habitat. Finally, the effects of fishing should also be considered. For example, biological control of Eurasian watermilfoil in many North American lakes appears to be limited by high densities of sunfish that eat the control agents (Ward and Newman, 2006). High densities of stunted sunfish are often the result of high angling pressure removing the large sunfish and predators. Overabundant sunfish can also affect water clarity through predation on *Daphnia*; thus, holistic lake management should consider the effects of fishing and the fish community as well as invasive species, macrophyte management, and internal and external loading on water quality.

4.4.3.3 Social and Economic Drivers of Lake Quality

Active 'lake management,' often focused on reversing eutrophication of lakes, must be seen in the context of broader changes occurring on the shorelines and in the watersheds of lakes. Shoreline development itself is often not sufficient to alter water clarity, simply because the potential input of nutrients from shoreline housing is often small relative to watershed inputs. As a general rule, watershed P inputs are probably more important than lakeshore inputs when the watershed-to-lake ratio is greater than 20 (Baker et al., 2008). Even if shoreline development does not cause eutrophication, it can profoundly alter the littoral ecosystem (Radomski and Goeman, 2001), with impacts on fishing and aesthetics. Poor lakeshore zoning can also reduce the aesthetics of the shoreline region. For many lakes, the more important drivers of algal abundance and clarity are activities in their watersheds. One of these is changing agricultural practices. In much of the country, small family farms have been replaced with far larger operations that are likely much more efficient and, for animal operations, more heavily regulated. For example, Bundy and Sturgul (2001) reported that P use efficiency on Wisconsin's cropland increased from 50% in 1975 to 85% in 1995. Other watershed changes that have likely affected downstream lakes on a fairly widespread basis include improved treatment of municipal sewage, improved regulation of septic systems, and the adoption of bans on phosphate-containing laundry detergents by many states (Baker et al., 2008).

4.4.4 Conclusions

Lake management has often been focused on water quality, especially on nutrient loading and eutrophication (*see* Chapters 4.18 and 4.11). The goals of lake management should be much broader and have discussed qualities of lakes in relation to human utilization in very broad terms, including the impact of invasive organisms, factors associated with fishing quality, aesthetic factors, and even spiritual values. In the aggregate, these qualities comprise 'lake sustainability.' Activities of humans on shorelines and in watersheds alter lake ecosystems; these alterations have important reciprocal effects on the sustainability of the human–lake ecosystem.

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