


DEPARTMENT OF NATURAL RESOURCES

Stressors to Biological Communities in Minnesota's Lakes

February 2018


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Glossary

Cyanobacteria: bacteria that obtain their energy through photosynthesis; also known as "blue-green algae"

Epilimnion: the surface or uppermost layer of water in a thermally-stratified lake; warmest layer during the summer and typically contains the highest dissolved oxygen concentration

Eukaryotic: containing cells with membrane-bound nuclei

Floristic quality index: a measure designed to evaluate the quality of the flora, or plant community, present in a lake relative to undisturbed conditions

Hypolimnion: the dense, bottom layer of water in a thermally-stratified lake; coldest layer during the summer

Index of biological integrity: a score that compares the types and numbers of organisms observed in an ecosystem to what is expected for a healthy, undisturbed ecosystem

Insectivore: an animal that eats insects

Interspecific competition: a form of competition in which individuals of different species compete for the same resources in an ecosystem

Intolerant: sensitive to environmental perturbations

Littoral: the nearshore area in a lake where sunlight penetrates all the way to the bottom sediment, allowing aquatic plants to grow

Omnivore: an animal that eats both plants and animals

Oxythermal habitat: habitat within a preferred range of temperatures and dissolved oxygen concentrations

Stratification: the formation of water layers based on temperature

Thermocline: the transition layer of water between the epilimnion and hypolimnion; layer at which temperature changes most rapidly

Tolerant: able to withstand environmental perturbations

Stressor identification process in Minnesota lakes

Aquatic ecosystem health can be evaluated by comparing the observed diversity and composition of species to what would be expected if the ecosystem was undisturbed by anthropogenic activities. In Minnesota, the Department of Natural Resources (MNDNR) and Pollution Control Agency (MPCA) have implemented the use of indices of biological integrity (IBIs) to inform assessment decisions regarding ecosystem health and aquatic life use. Currently, the primary tool to assess the health of lakes is a fish-based IBI (FIBI), and a plant floristic quality index (FQI) is used as supporting information during the assessment process. Lakes that are identified as impaired for aquatic life use are further investigated to determine potential stressors that may be contributing to the biological impairment. Information gathered during the stressor identification process can then be used in the development of Watershed Restoration and Protection Strategies (WRAPS) and during watershed planning activities such as One Watershed One Plan (1W1P).

Causes of biological stress in Minnesota lakes

Candidate causes of biological stress are considered during the biological stressor identification process for aquatic systems. This document lists and summarizes candidate causes and possible effects to fish and aquatic plant communities in Minnesota lakes. Candidate causes of biological stress in lakes include eutrophication, physical habitat alterations, altered interspecific competition, temperature regime changes, dissolved oxygen, pesticides, ionic strength, metals, and unspecified toxic chemicals. Additional information to facilitate causal assessments in aquatic systems can be found on the U.S. Environmental Protection Agency (EPA) Causal Analysis/Diagnosis Decision Information System (CADDIS) website.

Eutrophication

Eutrophication is the enrichment of a water body with nutrients. Eutrophication has the potential to alter aquatic ecosystems by restructuring plankton and rooted aquatic plant communities (Smith 1998; Jeppesen et al. 2000; Wetzel 2001). Nutrient loading can increase abundance of aquatic plants, and at higher levels, competition for light reduces aquatic plant species richness and abundance (Capers et al. 2009). Excessive nutrient loading destabilizes plant-dominated clear-water shallow lakes and reduces the coverage of plants in deeper lakes (Scheffer et al. 1993; Zimmer et al. 2009). Aquatic plant loss results in a physical alteration to fish habitat, which can negatively affect the success of vegetation-dwelling fish species from a variety of feeding guilds (Dibble et al. 1996).

Eutrophication may lead to an unbalanced plankton community in lakes, favoring less-edible cyanobacteria over eukaryotic phytoplankton and large-bodied zooplankton that are preferred food items for forage fish and juvenile game fish (O'Neil et al. 2012). The increase in primary productivity due to eutrophication can also result in decreased light penetration. The reduced light penetration can reduce the efficiency of sight-feeding predators like Largemouth Bass *Micropterus salmoides* and Northern Pike *Esox Lucius*, ultimately resulting in lower top carnivore biomass in the fish community (Jackson et al. 2010). Eutrophication can also significantly increase depletion of summer hypolimnetic oxygen and harm coldwater fish such as Cisco *Coregonus artedi*, Lake Whitefish *Coregonus clupeaformis*, Burbot *Lota lota*, and Lake Trout *Salvelinus namaycush*.

Eutrophic conditions favor undesirable omnivore species over predatory game fish and vegetation-dwelling species. MNDNR FIBI scores and metrics, including the number and proportions of tolerant, omnivore, and insectivore species, are strongly correlated with measures of eutrophication such as total average phosphorus (J. Bacigalupi, MNDNR, personal communication). The feeding behaviors of some omnivorous, tolerant fish such as Common Carp *Cyprinus carpio* or Fathead Minnows *Pimephales promelas* may further exacerbate eutrophication, particularly in shallow lakes, by resuspending sediments and releasing nutrients (Breukelaar et al. 1994; Zimmer et al. 2006).

Eutrophication is caused by inputs of excessive nutrients, particularly phosphorus, from activities including agriculture and urban development. Research has shown that elevated phosphorous levels significantly affect fish and aquatic plant community structure and function in Minnesota lakes (Schupp and Wilson 1993; Heiskary and Wilson 2008; Radomski and Perleberg 2012). Sources of excess phosphorus can include agricultural runoff, animal waste, fertilizer, industrial and municipal wastewater facility discharges, non-compliant septic system effluents, and urban stormwater runoff. To learn more about eutrophication and its effects to aquatic life, refer to the EPA's CADDIS nutrients website.

Types of eutrophication data

The MPCA coordinates the collection of data to measure total phosphorus, chlorophyll-a, and transparency, which are used to assess nutrient impairment in lakes. These data can also be used to evaluate eutrophication and effects to aquatic communities. Total phosphorus, chlorophyll-a, and transparency are often measured multiple times per year and are available for many lakes. The representative averages derived from a minimum number of measurements taken during the months of June through September are then compared to the eutrophication standards for Minnesota lakes and reservoirs, which can be found in Table 1.

Land use within a watershed can also be used to evaluate the potential effects of eutrophication on fish communities. Modeling in Minnesota lakes suggests that total phosphorus concentrations increase significantly over natural concentrations when land use disturbances occur in greater than around 25% of the watershed area and accelerate even further at 40% (Cross and Jacobson 2013). Land use disturbances characterized at the watershed scale are the best predictors of differences in fish and wetland plant communities, although smaller scales may be useful to explain specific responses of particular components of these communities (Brazner et al. 2007).

Table 1. Eutrophication standards for Minnesota lakes and reservoirs. Additional eutrophication standards are found in Minnesota Administrative Rules Chapter 7050.0222 Specific Water Quality Standards for Class 2 Waters of the State; Aquatic Life and Recreation.

Lake type or ecoregion	Phosphorus (µg/L)	Chlorophyll-a (µg/L)	Secchi disk transparency (m)
Designated Lake Trout lakes in all ecoregions	12	3	≥4.8
Designated trout lakes in all ecoregions, except Lake Trout lakes	20	6	≥2.5
Lakes, shallow lakes, and reservoirs in northern lakes and forest ecoregion	30	9	≥2.0
Lakes and reservoirs in north central hardwood forest ecoregion	40	14	≥1.4
Lakes and reservoirs in western corn belt plains and northern glaciated plains ecoregions	65	22	≥0.9
Shallow lakes in north central hardwood forest ecoregion	60	20	≥1.0
Shallow lakes in western corn belt plains and northern glaciated plains ecoregions	90	30	≥0.7

Physical habitat alteration

Physical habitat may refer to characteristics such as water depth, substrate size and type, aquatic and riparian vegetation cover, and bank structure (Jacobson et al. 2016). Degraded aquatic plant communities or other physical habitat in lakes can lead to changes in fish communities (Whittier et al. 1997; Jennings et al. 1999; Taillon and Fox 2004). The amount of physical habitat that occurs naturally within a lake can be altered by riparian lakeshore development, water level management, aquatic plant control, connectivity, introduction of non-native species, sedimentation, and others. To learn more about physical habitat and its effects on aquatic life, refer to the EPA's CADDIS physical habitat website.

Riparian lakeshore development

Residential development adjacent to lakes is known to have negative effects on riparian and aquatic habitat (Christensen et al. 1996; Jennings et al. 2003; Dustin and Vondracek 2017) and can alter spatial distribution patterns and community composition of fish (Jennings 1999; Radomski and Goeman 2001; Scheuerell and Schindler 2004) and plants (Hatzenbeler et al. 2004; Hicks and Frost 2011). Residential development that affects the lakeshore includes clearing of riparian vegetation for lawns and views, addition of sand blankets for swimming beaches or rip-rap for erosion control, and destruction of aquatic vegetation and placement of docks for recreation. These activities affect aquatic communities through a variety of indirect pathways and to different extents. For example, the direct destruction of aquatic vegetation reduces available habitat that indirectly influences the reproduction, survival, and abundance of some fish species (Rozas and Odum 1988; Radomski and Goeman 2001). The clearing of riparian vegetation can decrease buffering capacity and increase sedimentation, which affect physical habitat and nutrient levels that then affect ecological processes at the base of the food web (Dodson et al. 2005). Clearing of dead trees from the shoreline can also reduce habitat complexity, which is important for supporting a biologically diverse and resilient aquatic ecosystem (Christensen et al. 1996).

Although small changes to habitat resulting from residential development may not lead to observable changes in aquatic community structure, the cumulative effects of modifications to several components of riparian habitat will lead to changes in community structure (Jennings et al. 1999). Additionally, a lag time exists between the alteration and loss of habitat and the fish community response, which occurs over several generations of fish. Therefore the status of the current aquatic community in any lake is a reflection of the effects of the collective activities that have resulted in the loss of aquatic and riparian habitat over several decades.

Within Minnesota, the number of seasonal cabins and homes along lakeshores increased six-fold from the 1950's through the 1990's in one group of lakes with similar attributes, and about one-third of nearshore emergent and floating leaf vegetation was lost in developed areas of those lakes (Radomski and Goeman 2001). Other analyses of lakeshore development found that up to half of the shoreline and 14% of the littoral zone habitat may be lost with full build out on some of Minnesota's lakes with current shoreland development standards (Radomski 2005; Radomski et al. 2010). The cumulative effects of such development have adverse effects on the aquatic communities in those lakes. For example, decreases in FIBI metrics characterizing vegetation-dwelling and other intolerant nearshore fish species have been observed as dock density, an indicator of residential development on lakes, exceeds 10 docks per kilometer of shoreline (Dustin and Vondracek 2017; J. Bacigalupi, MNDNR, personal communication).

Types of riparian lakeshore development data

Attempts to assess the extent of riparian habitat loss have ranged from direct measurement of physical conditions to indirect indices that quantify human structures shown to be related to decreases in available habitat. Direct measurements of physical habitat can be expensive, require large amounts of time, and have lacked standard protocols. To address some of these limitations, the MNDNR Ecological and Water Resources program developed "Score the Shore" survey protocols (Perleberg et al. 2015) in 2013 to assess riparian lake habitat. These protocols have subsequently been adopted for use by the MNDNR Fisheries program beginning with the 2015 field season. Similarly, an inventory of residential docks has been used as a surrogate to measure the effects of human development on riparian areas

(Radomski et al. 2010). Alternatively, another rapid physical habitat assessment method developed by the EPA National Lakes Assessment is being investigated for greater use in Minnesota lakes.

Aquatic plant removal

Lake plant communities are degraded through human removal. Payton and Fulton (2004) documented that many Minnesota lakeshore property owners reported removing aquatic vegetation. Healthy aquatic plant communities provide important benefits to fish communities that may include spawning habitat, protection or refuge areas for juvenile fish, and foraging opportunities. Therefore, human actions that decrease plant abundance or diversity may also negatively affect fish community structure.

Control activities of aquatic plants growing in public waters in Minnesota are regulated by the MNDNR Aquatic Plant Management (APM) program. APM program rules limit the amount of removal on a given lake based on plant type and proposed removal method in order to protect fish habitat and allow lakeshore owners reasonable access. Activities that have the potential to cause damage either to fish, such as herbicide applications, or to important fish habitat, such as removal of emergent plants, require an APM permit. Other activities, such as removal of small quantities of submerged or floating-leaf plants, which are less likely to significantly alter fish habitat on a lakewide scale, do not require a permit but are covered under program rules, which can be found at the APM program website. Current APM rules that limit the total lakewide removal of vegetation are designed to limit negative effects to fish and other organisms; however, lower amounts of removal still constitute a reduction in the aquatic plant community and a loss of fish habitat (Radomski and Goeman 2001; Valley et al. 2004).

In addition to regulated removal activities, aquatic plants are destroyed through illegal activities; however, these activities are often not reported and go undocumented. Therefore, the cumulative effects of illegal activities are difficult to quantify, particularly because incremental aquatic plant community reductions and fish habitat loss can occur over a long period of time.

Types of aquatic plant removal data

The MNDNR APM program maintains records of permitted aquatic plant removal activities. These records can include number of APM permits issued, acres permitted, and quantity of pesticides approved, among others. Few records exist that document illegal plant removal activities.

Non-native species introduction

Non-native species can alter physical habitat in lakes via several mechanisms. Aquatic plants such as Eurasian Watermilfoil *Myriophyllum spicatum* and Curly Leaf Pondweed *Potamogeton crispus* may displace native plants and change the structure of the plant community (Madsen et al. 1991; Bouldan et al. 1994); however the effects of these changes on fish and invertebrate populations are variable and not well documented (Keast 1984; Kilgore et al. 1989; Smith and Barko 1990). Non-native invertebrates such as the Rusty Crayfish *Orconectes rusticus* graze on aquatic plants and have demonstrated an ability to reduce richness and biomass of aquatic plant communities (Lodge and Lorman 1987), which could then influence vegetation-dwelling fish species (Dibble et al. 1996). Crayfish herbivory may select against perennial plants and promote growth of pioneering plants like *Chara* spp. (Rosenthal et al. 2006). Common Carp, introduced from Europe, can also have significant detrimental effects on aquatic plant biomass and richness and can increase suspended solids in shallow lakes (Bajer et al. 2016).

Other non-native species such as Zebra Mussels *Dreissena polymorpha* change the physical structure and complexity of substrate and can indirectly increase aquatic plant growth through increases in water clarity (Mayer et al. 2001). Changes to the physical structure of the aquatic plant community may result in changes to abundance and composition of the invertebrate community that utilize that habitat (Botts et al. 1996; Ricciardi et al. 1997); however, the consequences to fish communities from these changes are generally poorly understood.

Types of non-native species data

The MNDNR Fisheries and Ecological and Water Resources programs survey aquatic plant communities in lakes. These data can provide information about the presence and prevalence of non-native aquatic plant species. Likewise the MNDNR Aquatic Invasive Species (AIS) program monitors lakes for presence and prevalence of aquatic invasive species. Information on aquatic invasive species and the current infested waters list can be found on the MNDNR AIS program website.

Water level management

Historically, managing water levels in lakes has been undertaken in response to perceived problems that humans have with the quantity of water within a lake basin at a given time. Lake outlet structures were often built with the goal of maintaining a more consistent water level with elevations set to reduce low water conditions in late summer. Little or no consideration was given to the effects that water level manipulations may have on the quantity and quality of the aquatic habitat for fish. However, research has shown that natural water level fluctuations are important for maintaining diverse aquatic plant communities that provide complex habitat beneficial to several organisms (Keddy and Reznicek 1986; Leira and Cantonati 2008). Alteration of water level regimes can reduce abundance and diversity of nearshore plants either because periods of low water no longer occur or because swings in water level become more extreme (Wilxox and Meeker 1991). The presence of aquatic plants can benefit the fish community by stabilizing lake sediments or harboring organisms used by fish as forage (Chow-Fraser et al. 1998).

In addition to direct manipulation using control structures, water levels are affected by the timing and quantity of water entering a lake basin. These factors can be influenced by climate change and hydrologic manipulation in the immediate and contributing watershed from activities including draining wetlands, tile drainage in agricultural fields, and increasing impervious surface coverage. These alterations affect how quickly lake levels rise after rainfall events as well as the elevations to which peak levels reach. Additional research is needed to quantify the effects of these changes to aquatic habitat. Likewise, limited research is available to suggest the appropriate range of lake level fluctuations for optimum fish habitat.

Types of water level data

The US Army Corps of Engineers maintains a National Inventory of Dams website, which identifies many lake outlet structures. Additionally, the MNDNR Ecological and Water Resources program maintains dam safety and permit records for all lake outlet structures within the state. The MNDNR also periodically monitors water levels in Minnesota lakes, and these data can be found for individual lakes on the water levels tab on the MNDNR lake finder website.

Connectivity loss

Natural connections between water bodies may be important to natural population and community dynamics of some fish species. Connectivity between aquatic systems can be negatively influenced by construction of dams, bridges, or culverts that may impede fish movement or alter important habitat. For example, aquatic connectivity is important for species such as Walleye *Sander vitreus*, White Sucker *Catostomus commersonii*, Northern Pike, and Lake Sturgeon *Acipenser fulvescens* that migrate to spawn in tributary streams. Although the effects of connectivity are more widely studied in flowing water systems (Fullerton et al. 2010), there has recently been increased interest in understanding the importance of connectedness to lake fish diversity. Connectivity can be an important factor in explaining some of the natural variability of species richness in some game fish lakes (Tonn and Magnuson 1982), but other geologic and hydrologic variables may better explain the observed variation (Hrabik et al. 2005). Nonetheless, connectivity can influence the number of species available to inhabit lakes and can affect the abundance of certain species (Bouvier et al. 2009). Conversely, connectivity was not significantly related to individual FIBI metrics or the overall FIBI score for Minnesota lakes assessed during FIBI development (J. Bacigalupi, MNDNR, personal communication).

Types of connectivity data

The MNDNR is developing an inventory of culverts within the state and the US Army Corps of Engineers maintains a National Inventory of Dams website that can be used to evaluate loss of connectivity; however, there is still an important need to identify small dams or other obstructions not included in the National Inventory of Dams. Similarly, the MNDNR Watershed Health and Assessment Framework website contains aquatic connectivity health scores based on the density of physical structures on stream systems in each of Minnesota's major watersheds.

Sedimentation

Sedimentation is the deposition of suspended solid materials. Sedimentation has the potential to change substrate characteristics within lakes, which may negatively affect richness and abundance of aquatic plants as well as vegetation and substrate-dependent fish species. Suspended sediment can also reduce light penetration, therefore limiting primary production and possibly affecting richness and biomass of vegetation-dwelling and sight-feeding fishes (Dibble et al. 1996; Jackson et al. 2010).

Sedimentation can be caused by a variety of anthropogenic activities. Human development along lakeshores can result in significant changes to the sediment characteristics in a lake (Francis et al. 2007). Destruction of nearshore aquatic plant communities and removal of woody material, which help to stabilize substrates, can lead to resuspension and redistribution of sediments (Dieter 1990; Horppila and Nurminen 2001). Non-native Common Carp also contribute to the loss of aquatic vegetation by dislodging plants, which leads to the resuspension of bottom sediments (Breukelaar et al. 1994). To learn more about sediment and its effects on aquatic life, refer to the EPA's CADDIS sediments website.

Types of sediment data

The MPCA coordinates collection of water samples to measure total suspended solids; however, these measurements are rarely collected for lakes and are generally unavailable. Secchi transparency measurements can be used to understand suspended sediment in aquatic systems; however, determining the type of suspended material is important for determining the appropriate stressor.

Few MNDNR surveys have documented the condition of substrate in Minnesota lakes historically; however, in select circumstances, these data have been collected by local partners and may be used to help evaluate changes in substrate that may be caused by sedimentation. Likewise, measures of embeddedness could provide additional information to evaluate sedimentation in Minnesota's lakes.

Altered interspecific competition

Competition between species for resources can result in changes to community composition. Changes within aquatic systems that result in elevated levels or unnatural forms of interspecific competition may include introductions of non-native species in lakes outside of the species' native range, introductions of species into lakes within the species' native range, and manipulations to population size and structure.

Several examples of non-native fish that compete with native species for resources are Common Carp (Weber and Brown 2011), Rainbow Smelt *Osmerus mordax* (Hrabik et al. 1998), and Round Gobies *Neogobius melanostomus* (French and Jude 2001). Presence of these fish species outside of their native range has led to dramatic changes in the forage base of many aquatic ecosystems. Similarly, Smallmouth bass *Micropterus dolomieu* introduced beyond their native range in northeast Minnesota may have negatively impacted native fish assemblages as in other Precambrian Shield lakes (Jackson 2002; Vander Zanden et al. 2004).

Game fish such as Walleye and Muskellunge *Esox masquinongy* are examples of species that have been widely introduced to lakes within their geographic range. Effects of these introductions to the game fish community may be negligible (Knapp et al. 2012) or may be species-specific (Fayram et al. 2005). Other observed effects on the fish community have included homogenization of species assemblages (Radomski and Goeman 1995), reductions in native minnow diversity (Whittier et al. 1997), or declines in important forage species such as Yellow Perch *Perca flavescens* (Anderson and Schupp 1986; Pierce et al. 2006). Strong Yellow Perch year-classes are thought to buffer small-bodied fishes like minnows and darters to the Walleye predation (Forney 1974; Lyons 1987), therefore declines in Yellow Perch density could adversely affect other forage species. Additionally, introduced predators have the potential to affect the community by replacing an existing predator or by adding to total predator density. However, unless the prior fish community was predator free, fish community structure in lakes can be influenced more strongly by spatial, environmental, and habitat variables than by the introduction of a predatory species (Trumpickas et al. 2011).

Density and population structure of native game fish species can also be manipulated by management activities, resulting in potential changes to fish community structure. The effects of management activities such as harvest regulations or supplemental stocking to increase density or improve population structure are largely unknown. However, regulations that result in excess harvest of predators may result in increases in prey abundance and other changes to fish community structure (Jacobsen et al. 2014).

Non-fish species such as Zebra Mussels may shift energy flows between benthic and pelagic communities (Riley and Adams 2010) and Spiny Water Flea *Bythotrephes longimanus* may reduce native zooplankton, which are important prey for native fish (Boudreau and Yan 2003). Rusty Crayfish prey on eggs and juvenile fish, and also eliminate aquatic vegetation that may be important physical habitat for vegetation-dwelling fish species (Wilson et al. 2004).

Anthropogenic sources of non-native species that compete with native fish species in lakes may include unauthorized bait bucket introductions or unintentional transport in livewells, on trailers, or on other equipment. Sources of introduced game fish species or artificially elevated densities of game fish species include introductory and supplemental stocking activities by management agencies or private parties. Likewise, sources of manipulated population structure include angler harvest and associated harvest regulations established by management agencies.

No significant relationships between FIBI scores or metrics and the number of species stocked, relative abundance of stocked species, or Walleye stocking density have been observed in Minnesota lakes (Drake and Pereira 2002; J. Bacigalupi, MNDNR, unpublished data). However, effects in individual lakes are possible as management activities can vary considerably based on individual lake characteristics and communities.

Types of interspecific competition data

The MNDNR Fisheries program surveys fish communities in lakes managed for fishing on a rotational basis. These data can provide information about the presence and prevalence of non-native fish species.

Likewise the MNDNR AIS program monitors lakes for fish and other aquatic invasive species. Information on aquatic invasive species and the current infested waters list can be found on the MNDNR AIS program website.

The MNDNR Fisheries program maintains stocking records for lakes managed for fishing, establishes regulations to manage harvest, and also periodically conducts creel surveys on a small number high-use lakes to estimate angler effort and harvest. These data can provide information about the magnitude and frequency of stocking events as well as management objectives related to harvest.

Temperature regime changes

Fish species exhibit preferences for specific temperature ranges, outside of which they may experience increased metabolic needs, reduced fitness, or lower survival (Jobling 1981; Wood and McDonald 1997). Consequently, changes in the temperature profile, along with dissolved oxygen concentrations, of a lake may result in changes to fish assemblages over time. For example, coldwater species such as Cisco, Lake Whitefish, Burbot, and Lake Trout have very specific thermal requirements and begin to experience physiological stress at water temperatures exceeding 59–68 °F (Coutant 1977). Fewer than 1,000 lakes in Minnesota currently support coldwater fish communities (Jacobson et al. 2010), and hypolimnia of these lakes may be particularly susceptible to reduced availability of adequate oxythermal habitat and longer periods of summer thermal stratification. Prolonged thermal stratification and reduced oxythermal habitat during the summer months can result in summer kill events for these coldwater species.

Fish community composition in shallower lakes and in the epilimnia of deeper lakes can be affected by and therefore experience stress caused by increases in water temperature, shorter ice cover periods, and longer growing seasons. Changes to the fish community resulting from increasing temperature may include increases in tolerant species richness and abundance or decreases in intolerant species richness and abundance (Jacobson et al. 2017). Water temperature changes can also shift species' geographic distributions and alter timing of key behaviors such as migration and spawning (Lynch et al. 2016). Plankton assemblages may shift towards communities dominated by cyanobacteria, which have a competitive advantage in warmer water and during longer periods of thermal stratification (O'Neil et al. 2012). An increase in cyanobacteria may negatively affect small non-game and juvenile game fish that prefer to prey on eukaryotic phytoplankton and zooplankton (Kamjunke et al. 2002).

Aquatic plant species abundance and distribution change with temperature and ice duration changes. Longer growing seasons may result in greater biomass and distribution of aquatic plants (Alahuhta et al. 2010; Bornette and Puijalon 2011).

Climate change—the result of anthropogenic emission of greenhouse gases—is the primary human-induced cause of temperature regime changes in lakes (Hondzo and Stefan 1993). Other natural factors that affect the temperature regime of a lake include geographical location, bathymetry, morphometry, and water clarity (Read et al. 2014). Other stressors that influence water temperature include actions that result in water clarity changes (Read et al. 2014), such as non-native species introductions (MacIsaac 1996), excess nutrients inputs, or sedimentation (Swift et al. 2006). Lake water level dynamics may also change due to hydrologic changes caused by climate change (Dadaser-Celik and Stefan 2007). To learn more about temperature and its effects on aquatic life, refer to the EPA's CADDIS temperature website.

Types of temperature data

Surface or profile temperature data have been collected by the MNDNR and MPCA and are available for many lakes. Continuous temperature data have been collected and are available for a much smaller subset of lakes.

Decreased dissolved oxygen

Dissolved oxygen (DO) is the concentration of oxygen gas in water. It is critical to sustain fish and other aquatic organisms. All fish require oxygen to respire and survive, although some species are much more sensitive to low or variable DO concentrations. Inadequate DO can result in suffocation or can affect locomotion, growth, and reproduction (Kramer 1987) to the extent that changes in the fish community can occur. Reductions, or increased variability, in DO in lakes can shift the fish community towards one characterized as having more tolerant and fewer intolerant species.

Several processes facilitate dissolution of oxygen into water including direct absorption from the atmosphere and production of oxygen by aquatic plants during photosynthesis (Davis 1975). DO concentrations can be reduced by excess nutrients (i.e., eutrophication), which can result in an increased biological oxygen demand on a system from increased rates of planktonic and bacterial respiration (Davis 1975) and organic material decomposition (Nürnberg 1995), especially in the hyplimnion. Additionally, reduced vertical mixing of water as a result of climate change could reduce dissolved oxygen within the hypolimnion (Lofgren and Gronewold 2014).

DO concentrations in lakes vary naturally depending on time of day and season (Davis 1975); however, hypolimnetic oxygen concentrations are less susceptible to diel fluctuations and may provide a more stable measure of coldwater fish habitat. Regardless, anthropogenic activities that contribute excess nutrients to lakes or result in increased water temperatures (e.g., climate change) may amplify these fluctuations to the extent that fish community changes occur. To learn more about dissolved oxygen and its effects on aquatic life, refer to the EPA’s CADDIS dissolved oxygen website.

Types of DO data

Surface or profile DO data have been collected by the MNDNR and MPCA and are available for many lakes.

Increased ionic strength

Ionic strength is the strength of the electric field in a solution, and it is primarily influenced by the amount of dissolved salts and minerals present. Although dissolved salts and minerals occur naturally in aquatic systems, elevated or imbalanced levels can negatively affect aquatic health. Chloride is one such naturally occurring chemical which, at high concentration, can be toxic to aquatic organisms (Corsi et al. 2010; Van Meter and Swan 2014). High concentrations of dissolved salts can also contribute to a greater likelihood of meromixis (i.e., lack of mixing) in small, deep, sheltered lakes (Sibert et al. 2015).

Human induced changes to ionic strength in aquatic systems are primarily the result of road salt and de-icing products; however, other sources may include industrial runoff and discharges, urban stormwater and agricultural drainage, and wastewater treatment plant effluent (Dugan et al. 2017). To learn more about ionic strength and its effects on aquatic life, refer to the EPA’s CADDIS ionic strength website.

Types of ionic strength data

The MPCA coordinates collection of specific conductance readings and water samples to measure chloride in lakes. Measurements taken in lakes are compared with the MPCA chronic standard for chloride (230 mg/L), per the Guidance Manual for Assessing the Quality of MN Surface Waters for Determination of Impairment (MPCA 2014).

Pesticide application

Pesticides are substances or mixtures of substances used to prevent, destroy, repel, or mitigate harmful or undesirable organisms. Herbicides (i.e., pesticides that target plants) and insecticides (i.e., pesticides that target insects) are used throughout the landscape, including in and around lakes. In aquatic systems, herbicides may reduce the aquatic plant community, which is important habitat for vegetation-dwelling fish species. If the treatment area is large, the decomposition of the aquatic plants may create a high biological oxygen demand and reduce DO to levels that affect fish adversely (Solomon et al. 2013). Herbicide applications in riparian areas may also reduce or eliminate terrestrial vegetation that may serve as a buffer or eventually contribute to in-lake habitat (e.g., coarse woody habitat). In addition, herbicides may be toxic to non-target organisms including fish (de Oliveira-Filho et al. 2004; Solomon et al. 2013). Insecticides intended to be lethal to insects may also have the potential to negatively affect fish and other aquatic organisms (Haya 1989; Wijngaarden et al. 2004).

Herbicides can be applied to eliminate undesirable terrestrial or aquatic vegetation. A majority of terrestrial herbicides are applied to row crop agriculture, however they are also applied to lawns, parks, golf courses, and other suburban and urban areas. Aquatic herbicide treatments are most often used to remove aquatic vegetation that interferes with recreational use (Folmar et al. 1979) or to control algae (e.g., copper-based herbicides) and must be first approved by the MNDNR APM program. Approval by the MNDNR APM program also fulfills the MPCA's National Pollutant Discharge Elimination System Permit requirements. Insecticides are also applied to row crop agriculture and in developed settings to control nuisance insects. Mechanisms for pesticides to enter aquatic systems include spray drift, runoff, leaching, and direct application. To learn more about pesticides and their effects on aquatic life, refer to the EPA's CADDIS herbicides and insecticides websites.

Types of pesticide data

The Minnesota Department of Agriculture (MDA) and Minnesota Department of Health (MDH) monitor concentrations of common pesticides in groundwater as well as on select streams and a limited number of lakes. Measurements taken in lakes are compared with MPCA surface water standards for pesticides (Table 2), per the Guidance Manual for Assessing the Quality of MN Surface Waters for Determination of Impairment (MPCA 2014). Additional information and benchmarks for pesticides can be found at the EPA's aquatic life benchmarks and ecological risk assessments for registered pesticides website.

MNDNR APM permit data can also be used to indirectly evaluate the extent of herbicide treatments on individual lakes.

Table 2. Summary of MPCA surface water standards for pesticides.

Pesticide	Chronic class 2A* (cold water)	Chronic class 2B (warm/cool water)	Maximum standard 2A and 2B
Acetochlor (µg/L)	3.6	3.6	86
Alachlor (µg/L)	3.8	4.2	800
Atrazine (µg/L)	3.4	3.4	323
Chloropyrifos (µg/L)	0.041	0.041	0.083
Metolachlor (µg/L)	23	23	271

*Chronic standards for aquatic organisms are protective for exposure duration of four days

Metal contamination

Elevated concentrations of metals (e.g., mercury, lead, copper, and cadmium) in aquatic systems can adversely affect fish and other aquatic life, particularly because of their toxicity (Membane et al. 2012), accumulation in the environment (Mackenthun and Cooley 1952), and in some instances, transferability through the food chain (Dallinger et al 1987). Several adverse effects include reductions in survival, physiological function, growth, and reproduction (Atchison et al. 1987; Scott and Sloman 2004) that may lead to shifts in community structure (Rygg 1985; Weis et al. 2001).

Mining operations, industrial sites, firing ranges, urban runoff, landfills, junkyards, and copper-based pesticide treatments are examples of contributors to elevated levels of metals in aquatic systems. To learn more about metals and their effects on aquatic life, refer to the EPA's CADDIS metals website.

Types of metals data

Currently only mercury levels in fish tissue are monitored through a partnership between the MNDNR, MPCA, and MDH. Measurements taken in lakes are compared with the MPCA mercury numeric water quality standards (Table 3), per the Guidance Manual for Assessing the Quality of MN Surface Waters for Determination of Impairment (MPCA 2014). Additionally, fish tissue mercury concentrations for MDH's levels of consumption advice are found in Table 4.

Table 3. Mercury numeric water quality standards for Minnesota lakes.

	Standard
Human health-based statewide standard	6.9 ng/L
Wildlife-based standard (Lake Superior Basin)	1.3 ng/L

Table 4. Fish tissue mercury concentrations for Minnesota Department of Health's levels of consumption advice.

Minnesota fish consumption advisory for mercury	Mercury Concentration in Fish, ppm			
	<0.05	0.05–0.2	>0.2–1.0	>1.0
Consumption advice*	Unlimited	1 meal/week	1 meal/month	Do not eat

*Consumption advice for young children and women of child-bearing age.

Unspecified toxic chemical contamination

A number of additional toxic chemicals exist that affect aquatic life and can enter the aquatic environment through a variety of pathways. Negative effects to fish communities range from direct lethal effects on individuals, altered food webs from effects to forage organisms, and reduced fitness from chronic exposure (Scott and Sloman 2004). Some examples of toxic chemicals include endocrine disrupting chemicals, halogens and halides, organic solvents, and other hydrocarbons.

Sources of toxic chemicals to aquatic systems include industrial, agricultural, mining, logging, urban and residential activities, landfills, spills and illegal dumping, and discharges from industries, municipal treatment facilities, and animal husbandry operations. To learn more about toxic chemicals and their effects on aquatic life, refer to the EPA's CADDIS unspecified toxic chemicals website.

Types of unspecified toxic chemical data

The MPCA monitors and assesses lakes for PCBs and occasionally PFCs via fish tissue samples. A list of impaired lakes can be found on Minnesota's Impaired Waters List website. The MDH also conducts limited testing on fish tissue for select toxic chemicals such as dioxins and PCBs, however these data are often unavailable for most lakes. Lastly, the EPA National Pollutant Discharge Elimination System Enforcement and Compliance History Online website also contains information and reports for facilities that are permitted to discharge pollutants through a point source into water.

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