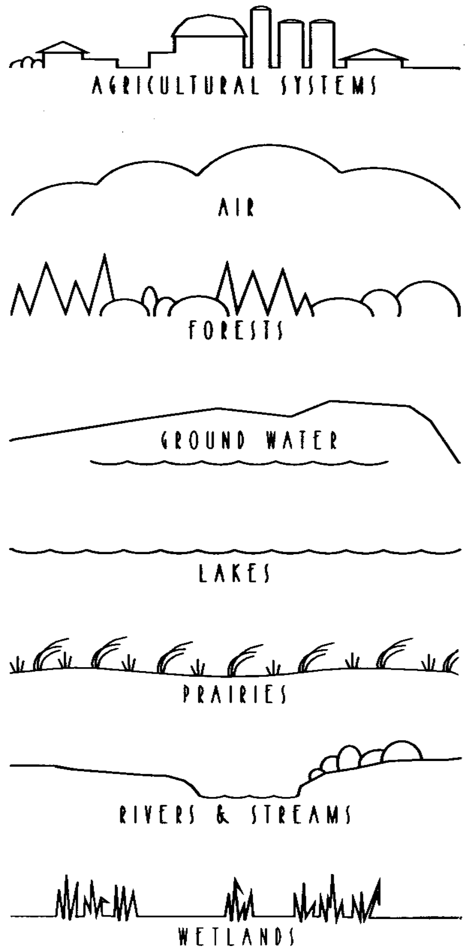
DEVELOPING ENVIRONMENTAL INDICATORS FOR MINNESOTA

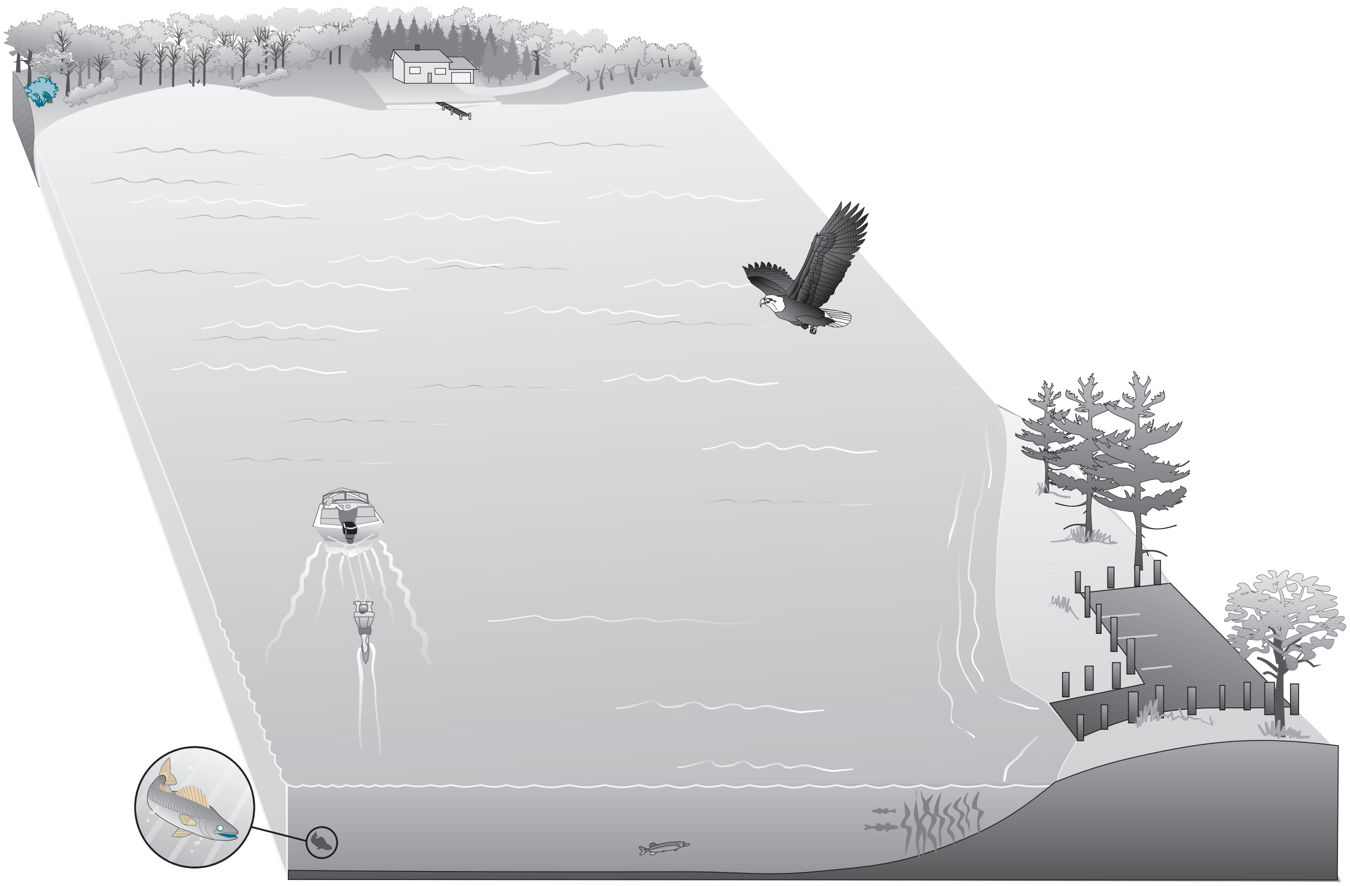


Lakes

The Environmental Indicators Initiative

State of Minnesota
Funded by the Minnesota Legislature
on recommendation of the
Legislative Commission on Minnesota Resources
Sponsored by
The Environmental Quality Board

1998



Citizens and decision makers use environmental indicators to help effectively manage and protect Minnesota's lakes. Environmental indicators answer four questions.

What is happening to our lakes?

Environmental condition can be measured by **fish community diversity, numbers of bald eagle nests, phosphorus concentrations in water**, and **relative abundance of native and exotic aquatic plants**.

Why is it happening?

Indicators of *human activities* that affect lakes include **density of lakeshore homes, removal of shoreline vegetation**, and **recreational activity**.

How does it affect us?

Changes in lake health may diminish the flow of *benefits*. Indicators of how we are affected include **fishable-swimmable waters** and **average fish size**.

What are we doing about it?

Societal strategies to maintain or restore healthy lakes include **shoreline vegetation restoration, aquatic habitat improvement**, and **environmentally sensitive use of lawn chemicals**.

In this chapter we outline important benefits from lake ecosystems, the key ecological characteristics that determine the health of lakes, the pressures affecting lakes today, the current status and trends relating to lakes, and the most significant policies and programs that affect Minnesota lakes. In this chapter we give examples of indicators that provide important information about Minnesota lakes.

HIGHLIGHTS

Benefits of Healthy Lakes

- Habitat for fish and wildlife
- Over $2 billion spent annually on hunting and fishing
- Over $715 million spent annually for wildlife observation
- Boating, swimming, hiking, and nature observation
- Domestic and industrial uses
- Storage basins for rain and floodwaters

Important Ecological Characteristics

- Regional differences in parent material, vegetation types, climate, topography, water chemistry, and land-use activity explain the regional trends in lake characteristics
- Seasonal changes in lake stratification influence temperatures, nutrients, and oxygen levels
- Nutrient and suspended sediment levels strongly influence productivity, with different fish communities occurring in lakes with different nutrient levels, water clarity, and temperature
- Open-water, near-shore, and lake-bottom areas support a diversity of plants and animals
- Lakes reflect the ecological condition of their watershed

Pressures

- Land-use activities that increase nutrient and sediment inputs or dramatically alter hydrologic regime
- Loss of native plants and animals with lakeshore development
- Fishing pressure and harvest
- Invasive species
- Environmental contaminants

Status and Trends

- Nutrient levels are lowest in northeastern lakes and highest in southwestern lakes
- Levels of DDT and PCBs in fish and birds have decreased since 1977
- The majority of Minnesota's lakes are suitable for swimming
- Fish from most of Minnesota's large lakes are edible with some restrictions
- 40-50 million pounds of fish are harvested annually, but in general fish size has declined since the 1930s
- Invasive species (e.g., Eurasian watermilfoil and purple loosestrife) continue to be introduced, although the spread has slowed with control programs
- 1/3 of lake homes are concentrated around only 50 of the state's nearly 2,000 large recreational lakes

Existing Policies and Programs

- Federal Clean Water Act aims to restore the chemical, physical, and biotic integrity of the nation's waters
- Federal Clean Lakes Program assesses lakes and develops restoration and protection plans
- MPCA Lake Water Quality Project assesses water quality for 1,400 lakes
- MPCA Clean Water Partnership Program addresses pollution problems associated with runoff from agricultural and urban systems
- MDNR Fisheries Lake and Stream Management Program assesses fish and habitat quality
- The Shoreland Management Program (MDNR and local units of government) address potential problems in the development of lake and river shorelands
- Lake associations help make local decisions and promote educational programs

BENEFITS FROM LAKES

Minnesotans fish, swim, and boat in the waters of the state's many lakes and hike and hunt along their shorelines. Many Minnesotans structure their recreation around lakes, participating in the fishing opener, canoeing on weekends, observing the fall colors, and ice fishing. Without a doubt, lakes are a treasured Minnesota resource.

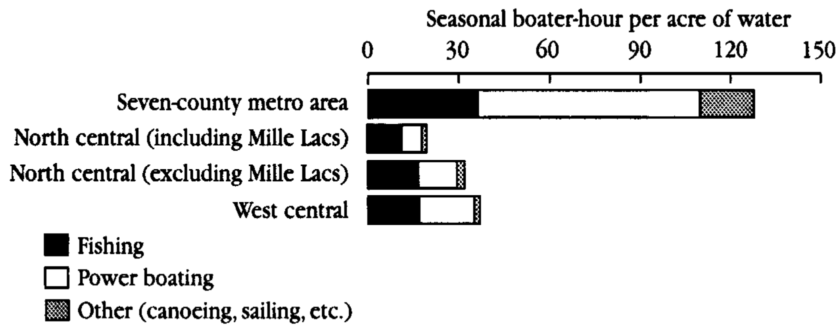
Lakes have long supported commercial operations in Minnesota. At the turn of the century, individual trappers harvested as much as 50,000 pounds of turtle meat in a single season. Today the harvest is smaller, over 42,000 pounds of turtle meat, but still significant (Tester 1995). Commercial fish harvests from 1986 to 1990 averaged over 4 million pounds each for buffalo and bullhead, over 12 million pounds for carp, and over 100,000 pounds for other species (MDNR 1994). Commercial fish harvests from Lake Superior alone were valued at over $160,000 each year from 1987 to 1991 (MDNR 1994a).

Recreational fishing and hunting, which are often centered on lakes, are popular activities for both residents and tourists. About 500,000 visitors come to Minnesota each year to fish in clean, natural settings. Among the state's residents are nearly 600,000 hunters and over 1.5 million anglers. Visitors and permanent residents spend over $1.5 billion each year on fishing-related activities, and hunting and fishing combined contribute over $2 billion each year to Minnesota's economy (USFWS 1997). The cabin and resort industry, bait and tackle shops, restaurants, and many other businesses rely on revenues derived from outdoor recreation. This is especially true in northeastern Minnesota, where nearly 8% of the economy is tied to water-related outdoor recreation spending (Kelly and Sushak 1987). In addition, the management, protection, and restoration of fish and wildlife habitat, including wetlands and lakes, are supported by hunting and fishing license fees.

Lakes are the center of many natural areas, which attract hikers, skiers, photographers, birders, naturalists,

Figure 1

Seasonal Boating Use on Lakes

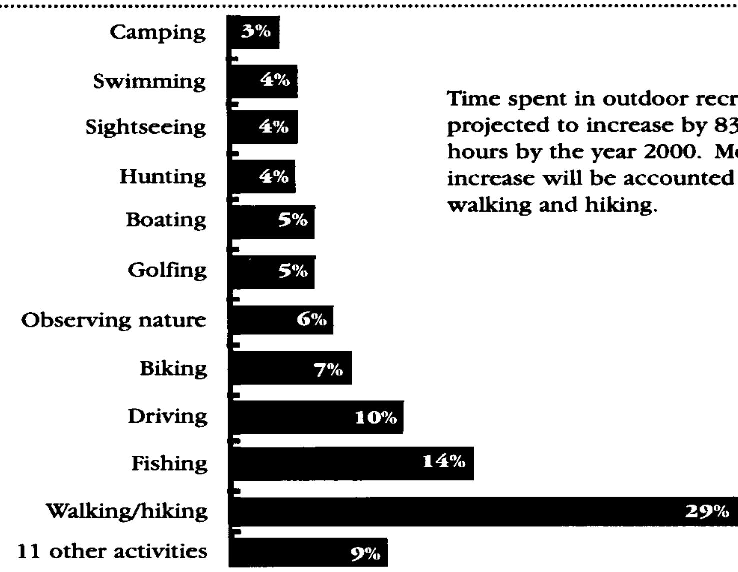


Season begins on the Saturday of Memorial Day weekend and ends Labor Day.

Source: Barstad and Karasov 1987

Figure 2

Portions of Overall Recreation Increase Accounted for by Individual Activities



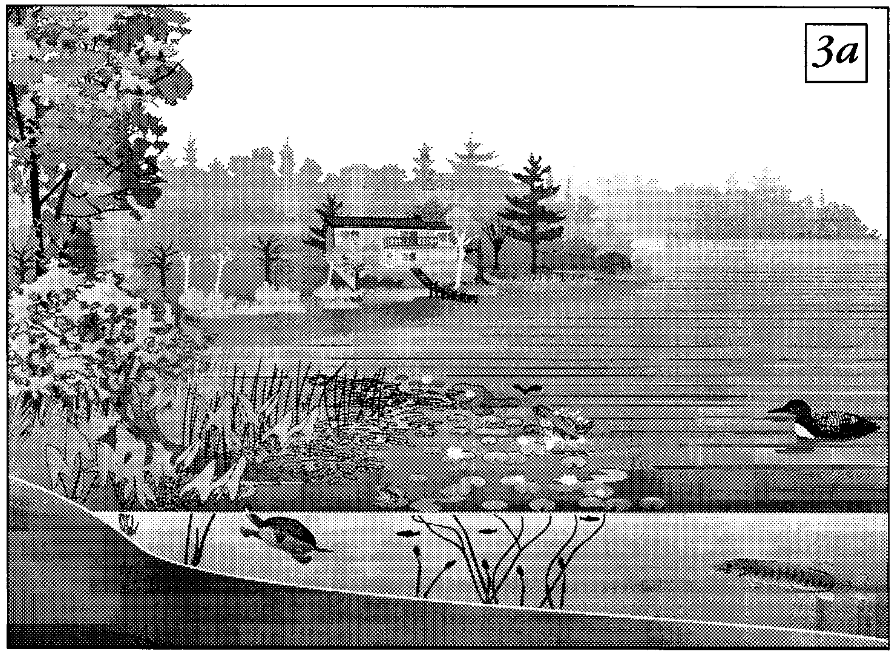
Time spent in outdoor recreation is projected to increase by 83.6 million hours by the year 2000. Most of this increase will be accounted for by walking and hiking.

Modified from MDNR and DTED 1990

educators, and campers. Each year 1.2 million residents and 0.6 million visitors to Minnesota observe wildlife, contributing more than $700 million to the state's economy. Boating is a popular pastime (Figure 1), with over 23 million hours every year spent on the state's waters. By the year 2000, the number of hours spent in outdoor activities, especially walking, hiking, and fishing, will increase significantly (Figure 2; MDNR and DTED 1990). Lakes are an important part of the hydrologic cycle. They catch and store water from rainfall and surface runoff before it evaporates back into the atmosphere. Lake basins help decrease the impacts of floods and provide permanent sources of water for wildlife, fish, and humans.

Figure 3

Potential Changes in Lakes During Development and Restoration

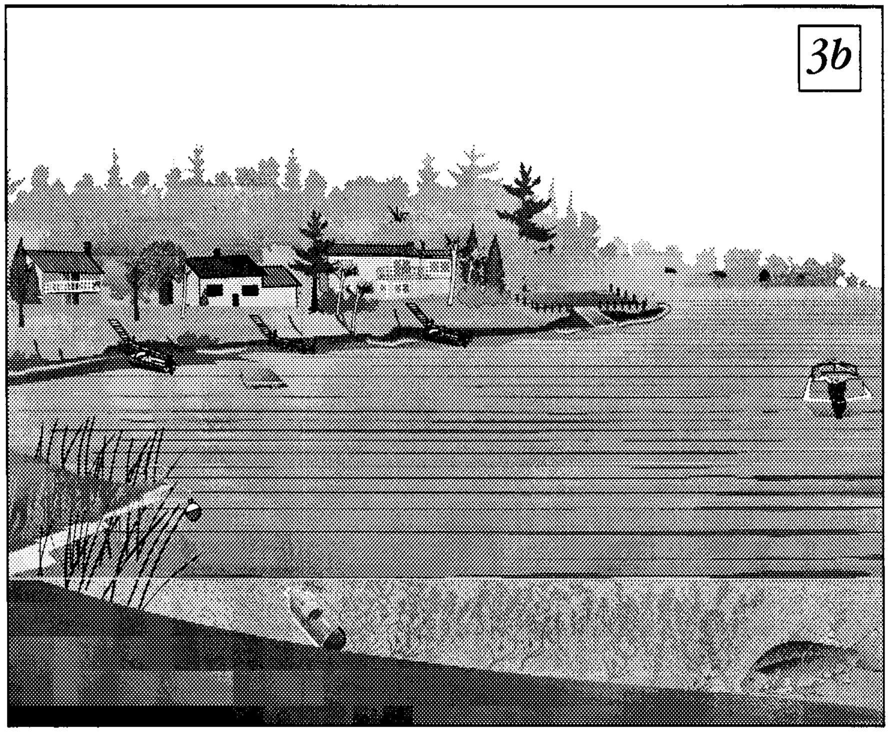


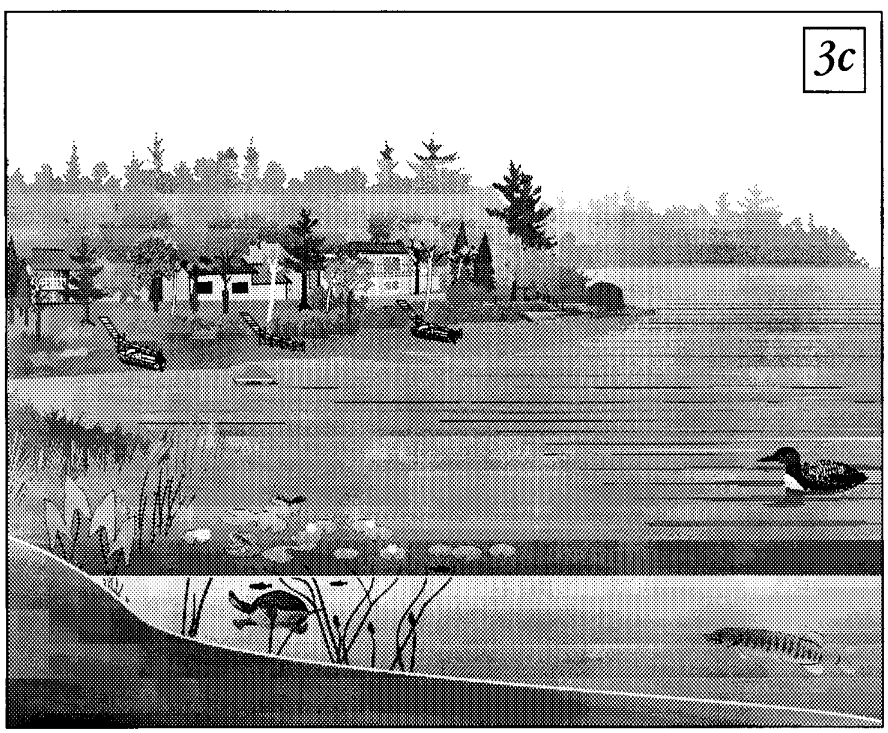
ENVIRONMENTAL INDICATORS

What are environmental indicators, and how can they help us maintain healthy lakes? Indicators are measures of the environment or of human activities that affect the environment. They help us understand the condition of our lakes, alert us to potential problems, and point to ways to prevent or fix problems before they become crises. The following scenario demonstrates the value of environmental indicators.

Many state residents and nonresidents build vacation homes on remote northern lakes. Initially, lakeshore development is limited to a few isolated cabins with docks in the water (Figure 3a). The removal of a few trees and bulrushes, wild rice, or cattails from a small area of shoreline accommodates swimming and other activities. The shoreline remains stable, and wildlife and fish habitat is plentiful. Fish community diversity and average fish size are high. Animals that depend on littoral habitats (reptiles and amphibians) are abundant. Bald eagles nest in tall lakeshore trees, and red-necked grebes and loons are common. Fishing is excellent, and moose occasionally visit the lakeshore.

A highway is built near the lake, and more homes appear; lawns, sand beaches, and boat docks gradually replace more of the rushes, shrubs, and trees along the lakeshore (Figure 3b), and eventually there are more docks, boat ramps, and manicured





lawns than natural vegetation. Habitat for fish and waterfowl is scarce. Red-necked grebes, loons, and bald eagles are rare. Erosion undercuts the shoreline, sediments cloud the water, and nutrients from septic systems and lawn chemicals feed algal blooms. Undesirable aquatic plants flourish, and rough fish are abundant. More people are fishing, swimming, and boating, but they are having less fun, and the lake is less beautiful than it used to be.

The lakeshore development scenario is representative of the complex issues affecting our lakes. The EII framework provides insights into the relationships between human activities and environmental change and helps select indicators that measure progress toward solving complex problems. Some *human activities* adversely affect ecosystem health and diminish the flow of benefits. In the lakeshore development scenario, indicators of human activities include the **density of lakeshore homes**, the **number of septic systems, removal of littoral and shoreline plant communities, conversion of seasonal homes to permanent homes**, and **recreational activity on the lake**. These activities are pressures that cause changes in *environmental condition*. Indicators of environmental condition include the **relative abundance of native and exotic plant species**, the **number of red-necked grebes, loons, and bald eagles, shoreline erosion, water quality, algal productivity, average fish size, fish community composition**, and **reptile and amphibian population sizes**.

Table 1

Examples of Indicators from a Shoreline Development Scenario

HUMAN ACTIVITIES	ENVIRONMENTAL CONDITION	BENEFITS	SOCIETAL STRATEGIES
• Density of lakeshore homes • Runoff of fertilizers, pesticides, and road salts • Removal of shoreline and littoral vegetation • Number of septic systems • Recreational activity • Conversion of seasonal homes to year round residences	• Diversity of aquatic birds • Lakeshore and upland erosion rates • Water quality • Fish community diversity • Reptile and amphibian population sizes • Bald eagle nests • Algal productivity • Relative abundance of native and exotic plant species	• Opportunities for recreation • Fishable-swimmable waters • Average fish size	• Restoration of littoral plant communities • Septic system maintenance • Environmentally sensitive use of lawn chemicals • Planned development

Indicators can describe desired conditions (stable shorelines, diverse wildlife, healthy game fish populations, low housing density). They also can be used to guide restoration efforts by monitoring progress in returning the lake to a healthier state (Figure 3c). *Strategies* for improving conditions may include management activities that **restore native littoral plant communities, retain native vegetation**, and **reduce inputs from lawn chemicals and septic systems**. Such strategies help restore and maintain the health of the lake, increase the quality of lake experiences, and ensure that the *benefits* we look for from lakes are sustainable. These strategies are effective in large part because they address the human activities that cause declines in the health of the lake. An integrated set of indicators helps us understand how our actions alter ecosystems and their ability to provide the benefits we depend on.

LAKE ECOLOGY

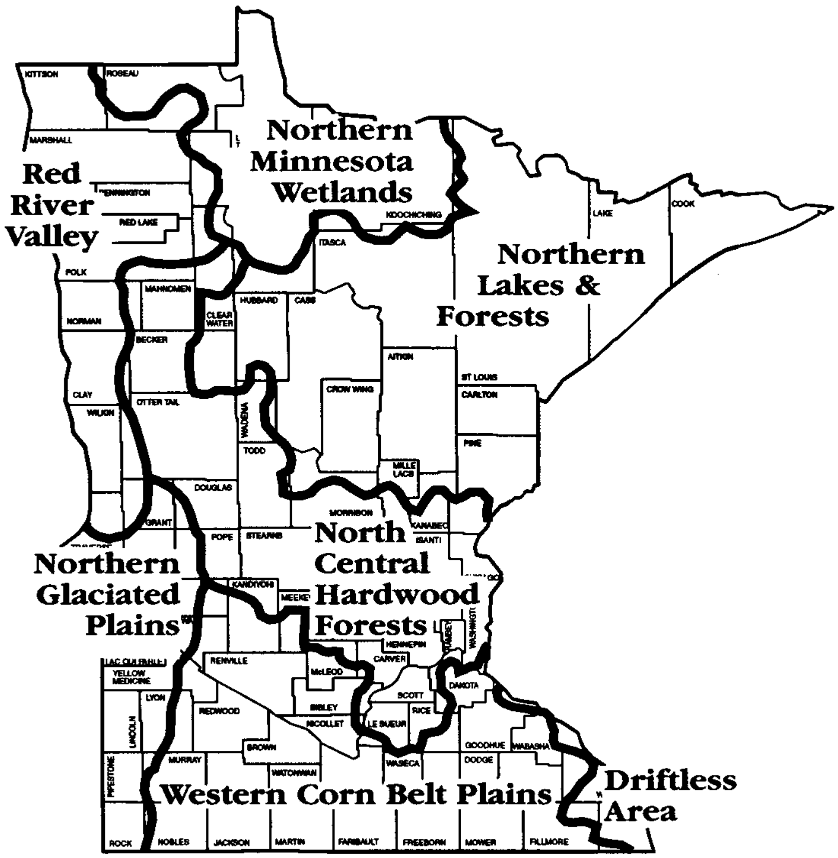
Physical and chemical characteristics of lakes

Retreating glaciers left a legacy of lakes with a wide range of sizes, shapes, and chemistry. Approximately 12,000 lakes in the state are larger than 10 acres. These lakes are unevenly distributed throughout the state; 98% occur in four of Minnesota's seven ecoregions: the Northern Lakes and Forests, North Central Hardwood Forests, Northern Glaciated Plains, and Western Corn Belt Plains (Figure 4; Omernik 1987).

Minerals leached from rocks and soils and carried into the lake via surface runoff and groundwater strongly influence water chemistry. As a result, lakes in western and southwestern Minnesota, where deposits of limestone-rich glacial till are deep, are high in calcium and other minerals. In contrast, lakes in northeastern Minnesota, where the glaciers left thin deposits of glacial till and exposed igneous and metamorphic rocks, are low in calcium and tend to have low pH.

Sediment washes into all lakes, especially those in watersheds with steep topography and naturally high erosion, and is an important source of nutrients for algae and other

Figure 4
Minnesota's Ecoregions



microorganisms at the bottom of the food web. Vegetation regulates sediment inputs by intercepting raindrops that loosen soils, by trapping soil particles, and by physically holding soils in place. Conversely, the removal of vegetation often increases the movement of soil and nutrients. Interactions between the size of the watershed and the volume of the basin also help determine lake water chemistry and clarity. For a given watershed area, large lakes more effectively dilute sediment and chemical inputs than do small lakes. Indicators of lake integrity must be sensitive to natural variability in the factors that determine lake water quality. For example, indicators that measure **water chemistry** (e.g., **pH**) need to account for the naturally high acidity in the northeastern part of the state as well as naturally high erosion in watersheds with steep slopes.

Nutrient cycling in lakes

Nutrients that enter lakes by way of eroded soils and dead plant material are essential for maintaining productivity. But once in lakes, nutrients (and contaminants) tend to settle to the bottom, out of reach of most plants and animals. Some of these chemical compounds remain on the lake bottom, but bottom-dwelling bacteria and invertebrates consume and recycle useful nutrients. Wind- and weather-induced mixing also helps recirculate nutrients. In many lakes, summer sunlight heats the upper waters of the lake, creating a less dense layer (epilimnion) that floats on the cool lower waters (hypolimnion). Oxygen levels are often higher near the surface and depleted deeper down. These layers are separated by the metalimnion, a zone in which temperature decreases rapidly with depth. When lakes are thermally stratified, there is little mixing between the layers, and nutrients remain out of reach of many organisms. During spring and fall, however, the temperature is fairly uniform throughout the water column, and the water mixes freely when stirred by the wind. Lake mixing brings oxygen-rich water to the bottom of the lake, and nutrients to the surface for use by algae, rooted plants, and other organisms.

We know from changes in nutrient availability associated with lake stratification that nutrients play an important role in the health of a lake. They influence plant productivity and oxygen levels, and these in turn affect habitat quality for fish and other lake-dependent animals. Indicators that help us monitor changes in nutrient levels, particularly

concentrations of nitrogen and phosphorus, algal productivity, and **oxygen depletion**, help assess lake health.

Biological productivity

Because plants need light for photosynthesis, light availability strongly influences ecosystem productivity. Algae, rooted plants, organic material, suspended sediments, and water itself limit sunlight penetration in lakes. Organic acids from bogs and soils also reduce light penetration. Although some plants thrive in low light conditions, plant growth is usually greatest in shallow areas where sunlight penetration is most abundant.

Nutrient availability also limits productivity. Oligotrophic lakes are severely nutrient limited and generally have scarce aquatic vegetation, small populations of algae, and well-oxygenated hypolimnions. They commonly support populations of trout and whitefish (Table 2). In eutrophic lakes, nutrients are abundant. These lakes have a high sediment accumulation rate, dense aquatic vegetation, and large populations of algae and commonly support populations of sunfish, crappie, and largemouth bass. During years of especially high algal production, bacteria and other bottom-dwelling organisms may use up all the oxygen in the deep waters. Eutrophic lakes are more common in the southwestern part of the state. Hypereutrophic lakes have excessive nutrients, very dense algal populations, and support nongame fish species such as bullhead, carp,

Table 2

Characteristics of Oligotrophic & Eutrophic Lakes

OLIGOTROPHIC LAKES	EUTROPHIC LAKES
Deep w/ steep banks	Shallow w/ broad litoral zone
Epilimnion small compared to hypolimnion	Epilimnion to hypolimnion ratio greater
High transparency	Low transparency
Blue or green water	Green to yellow or brownish green water
Low nutrient content	High nutrient content
Organic matter content low in sediments	Organic matter content high in sediments
Oxygen abundant at all levels at all times	Oxygen often depleted in hypolimnion
Production to respiration ratio low	Production to respiration ratio high
Rooted plants limited	Rooted plants abundant
Low phytoplankton population	High phytoplankton population
Algal blooms rare	Algal blooms common
Diverse but sparse bottom fauna	Few species but abundant bottom fauna
Trout and whitefish in hypolimnion	No trout or whitefish in hyolimnion

From Tester 1995

and buffalo. In general, fish production mirrors overall lake productivity and ranges from about 4 pounds per acre per year in oligotrophic lakes to as much as 700 pounds per acre per year in hypereutrophic lakes.

Of Minnesota's 12,000 lakes, 15% are oligotrophic, 33% are mesotrophic (intermediate nutrient concentrations), 35% are eutrophic, and 17% are hypereutrophic (Heiskary and Wilson 1990). Most of Minnesota's lakes were oligotrophic when formed 10,000 to 12,000 years ago. As they aged, sediments and nutrients accumulated, and they became more productive. Given enough time, lakes become wetlands by filling completely with sediment, organic matter, and living vegetation. The rate at which this natural process occurs depends on climate and on the physical and chemical characteristics of the lake and watershed. Human activities that increase the input of nutrients to lakes may hasten succession by creating hypereutrophic conditions.

Indicators that measure **changes in productivity** (**oxygen depletion, frequency of algal blooms, fish population sizes,** and **community structure**) can help identify lakes subject to excessive **nutrient and sediment inputs** from human activities and assess overall lake health.

Biological diversity

Lakes support a variety of plant and animal communities. The littoral (nearest the shoreline) community consists of rooted plants and many species of insects, snails, fish, and aquatic mammals. Littoral areas are spawning habitat, feeding areas, and refuge from predation for juvenile fish and invertebrates. The pelagic (open-water zone) community is dominated by algae, the zooplankton that feed on the algae, and fish species such as cisco, walleye, and northern pike. The profundal community occupies the dark and cold waters deep in the lake. Small invertebrates that live on the organic remains of plants and animals live in the lake-bottom sediments and the water above and are a primary source of food for fish. Many other animals, including waterfowl, songbirds, birds of prey, frogs, turtles, raccoons, minks, otters, deer, moose, coyotes, and wolves, depend on lakes to some degree.

Although several species of aquatic plants and animals are listed as endangered, threatened, or of special concern, efforts to inventory the distribution and habitat preferences of these species have been few. Listed aquatic species (Pfanmuller and Coffin 1989) include 4 species of mollusks, 7 reptiles and amphibians (Blanding's turtle), 9 birds (e.g., bald eagle), 16 fish (e.g., lake sturgeon), and 12 plants (e.g., small white-water lily).
Plants and animals are sensitive to changes in turbidity, oxygen levels, nutrients, contaminant levels, temperatures, habitat quality, and invasive species. When environmental conditions change, species that are tolerant of degraded conditions increase in number while species that do not fare well in the new conditions decline. The plant and animal communities of undisturbed, healthy lakes are a good benchmark for comparison. Indicators which compare the biological diversity of a lake to that in similar but undisturbed lakes help identify which environmental conditions have changed.

Natural disturbances

Seasonal and interannual fluctuations in lake water levels are characteristic of Minnesota lakes and help maintain their biological diversity and productivity. For example, high water levels in spring make adjacent wetlands accessible to spawning northern pike. Alternating periods of low and high water allow a variety of plant species to become established and maintain themselves. Suppression of natural water level fluctuations and the artificial manipulation of lake water levels, on the other hand, may be detrimental to lake biota. Long-term water withdrawals, similar to prolonged drought, may increase the concentration of nutrients and minerals in the basin, alter water chemistry, and affect plant and animal communities in shallows and deep-water zones. Prolonged flooding and unnaturally high water levels eliminate littoral vegetation that is intolerant of deep water, changing habitat and food resources for fish and aquatic birds.

The maintenance of natural water level regimes is essential to maintaining lake ecosystem integrity. Indicators that monitor **changes in lake levels over time**, especially those that result from unnatural causes, can identify those changes that are outside the range of natural variation and that may have long-term or widespread impacts on lake communities.

PRESSURES ON MINNESOTA'S LAKES

Landuse impacts

Change in land cover is one of the simplest (although most critical) indicators of ecosystem health. Forest harvesting, intensive agricultural practices, urban development, and highway construction within a lake's watershed increase nutrient and sediment inputs to the lake. These and other activities have the potential to alter patterns of water flow and infiltration and to eliminate native plant and animal communities associated with lakes (Pfannmuller and Coffin 1989). Where lakeshore vegetation and shallow-water wetlands are removed to facilitate other activities, inputs of nutrients and sediment may increase dramatically. Despite restrictions on shoreline development, housing, especially high-density, and commercial development around lakes significantly alter their character.

Excessive harvest and use

While fishing pressure on Minnesota's lakes has increased dramatically for many decades, populations of large sport fish have not (and could not have) increased at the same rate. On Lake Winnibigoshish, fishing increased more than 700% from 1939 to 1977, but walleye harvest increased only 150% (MDNR 1989). Average walleye size declined from 2.2 pounds in 1939 to 1.3 pounds in the 1950s to 1.1 pounds in the 1980s (MDNR 1994a). As the number of anglers increases and techniques for catching fish improve, larger fish become increasingly rare, and anglers keep smaller fish. Over harvesting large walleye may reduce angling quality for other fish as well, including largemouth bass, smallmouth bass, northern pike, muskellunge, and trout (MDNR 1989). Although stocking may provide additional angling opportunities, increase fish diversity, and overcome some of the impacts of habitat degradation, it does not increase the size of fish caught.

Table 3

Occurrences of Exotic Species of Concern in Minnesota Lakes

SPECIES	1997 OCCURRENCE
Eurasian watermilfoil	80 lakes
Purple loosestrife	559 lakes
Flowering rush	10 lakes
Curly-leaf pondweed	65 of 87 counties
Zebra mussel	Duluth harbor, Lake Pepin
Rusty crayfish	>12 counties
Ruffe	Duluth harbor

From MDNR Exotic Species Program 1997

LAKE MONITORING PROGRAMS

Since 1985, the Minnesota Pollution Control Agency (MPCA) has maintained a database on approximately 90 lakes chosen to be representative of Minnesota lakes: 30 in the Northern Lakes and Forests ecoregion, 38 in the North Central Hardwood Forests, 12 in the Western Corn Belt Plains, and 10 in the Northern Glaciated Plains (MPCA 1996). All of these reference lakes are minimally affected by human activities, have no point-source wastewater discharges, and have no large urban areas in the watershed. Data collected from reference lakes provide an important basis of comparison for assessing impacts in other lakes. The MDNR Section of Fisheries conducts regular fish population surveys on 600 lakes. The highest priority lakes are surveyed once every 3 to 5 years. The state's eleven largest lakes (e.g., Mille lacs, Superior, Lake of the Woods) are surveyed annually as part of the Large Lakes Monitoring Program established in 1983. In 1973, Dr. J. Shapiro at the University of Minnesota established a citizen-led lake monitoring program (Klang 1996). With the help of these volunteers, the MPCA regularly monitors nearly 2,000 lakes across the state. The MDNR Division of Waters also enlists the help of many lake-monitoring volunteers. In addition, a citizen-volunteer group supervised by the Metropolitan Council collects data on nearly 200 metropolitan-area lakes.

Lakes also face increasing use by boaters, swimmers, and hunters. Minnesotans spend more than 23 million hours each year boating for pleasure, and countless hours at swimming beaches and in hunting blinds. As lake-related outdoor recreation increases, so will problems of overuse.

Non-native species

Many introduced species promote economic growth (by increasing the quality or quantity of food or recreational fishing, for example). However, from 1906 to 1991, 79 aquatic and terrestrial introduced non-native species were estimated to cost the United States about $97 billion (Bjergo et al. 1995). In aquatic systems they may interfere with swimming, boating, fishing, industrial water use, and commerce, with significant ecological and economic costs. But many of the costs associated with non-native species arise from their impact on ecosystems, and these are difficult to measure economically. Some non-native species spread rapidly because they are unchecked by natural predators and displace native species. Some exotic plants outcompete native species but provide poor habitat for fish and wildlife. Globally, non-native species have been responsible for 68% of the fish extinctions during the past 100 years and 70% of the declines in fish listed in the Endangered Species Act (Lassuy 1994).

Minnesota has been working to prevent the spread of non-native, invasive species since 1987 through the Exotic Species Program (1996). The program initially focused on control of purple loosestrife but now also addresses problems associated with Eurasian watermilfoil, flowering rush, curly-leaf pondweed, sea lamprey, zebra mussel, rusty crayfish, ruffe, and round goby (Exotic Species Program 1996; Table 3).

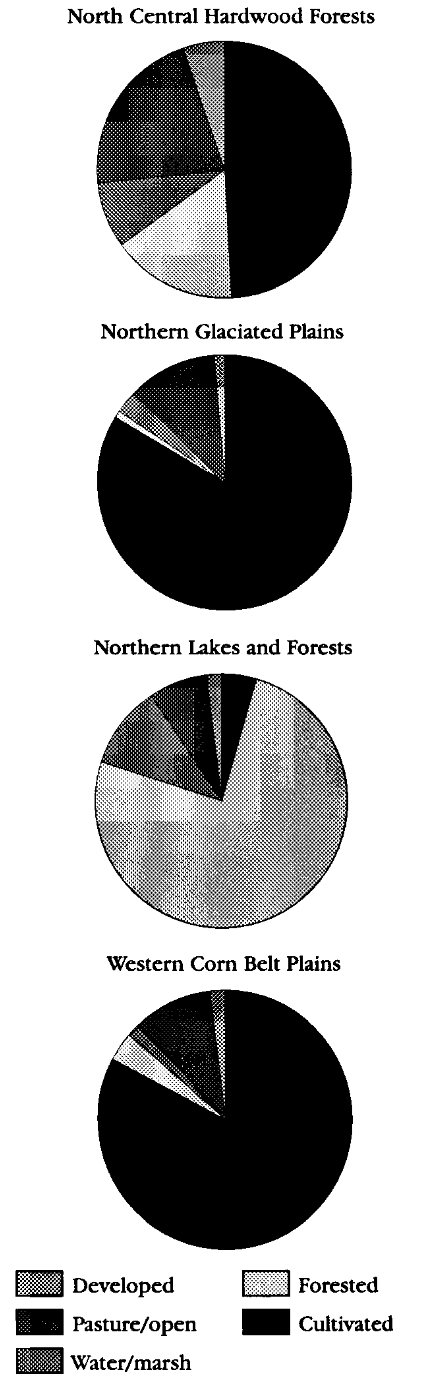
Environmental contaminants

Lakes accumulate contaminants from point sources (e.g., industrial discharge, municipal sewage, storm sewage), nonpoint sources (e.g., surface runoff from urban and rural areas), and the air (e.g., factory smokestacks, waste incinerators, smelters, cars and trucks, herbicide and pesticide spraying). Mercury, cadmium, chromium, lead, copper, DDT, dioxin, and PCBs are of particular concern because they persist in toxic forms for long periods. Over time, contaminants may accumulate in undisturbed lake sediments. However, biomagnification, beginning with sediment-dwelling insects and worms, may concentrate contaminants in fish and waterfowl. At high levels, environmental contaminants interfere with reproduction, reduce longevity, and cause physical deformities that interfere with feeding and mating.

Biomagnification also threatens anglers who consume the fish they catch. The MPCA, MDNR, and MDH collaborate in an interagency fish contaminant monitoring program to measure contaminants in fish and issue fish consumption advisories. Women of childbearing

Figure 5

Land Use in Minnesota by Ecoregions



Modified from Heiskary and Wilson 1989

age, children under age six, and people who eat fish more than once a week have the highest risk of adverse health effects from contaminants in fish (MDH 1996).

Environmental indicators help demonstrate the relationships between human activities and the health of lake ecosystems and suggest needed management and regulatory activities. For example, **increases in non-native species** and the associated degradation of wildlife habitat prompted aggressive programs to slow their spread. Similarly, high levels of **environmental contaminants in sediments and fish tissue** stimulated legislation to reduce emissions and programs that minimize risk to human health.

LAKE STATUS AND TRENDS

Surrounding land cover and use are primary determinants of lake water quality (Heiskary and Wilson 1989). For example, the 46% of Minnesota's lakes that occur in the Northern Lakes and Forests ecoregion generally have high quality water. In this ecoregion, 75% of the land is forested, 10% is open water and marsh, 7% is pasture and open field, and about 5% is cultivated. Lake phosphorus concentrations are low, and water clarity is high (Heiskary and Wilson 1989). In only 6% of the region's lakes is swimming limited by excess algae.

In the North Central Hardwood Forests ecoregion, where 40% of the state's lakes occur, land use is primarily urban, suburban, pasture, and tilled, and lakes lie in deposits of glacial till. Lake phosphorus concentrations are high, and water clarity is low. In about 44% of these lakes, algal growth limits recreational use. In the Western Corn Belt Plains ecoregion about 83% of the land is cultivated, 10% is pasture and open field, and less than 1% is forested (Figure 5). Nutrient concentrations are very high, and water transparency is very low.

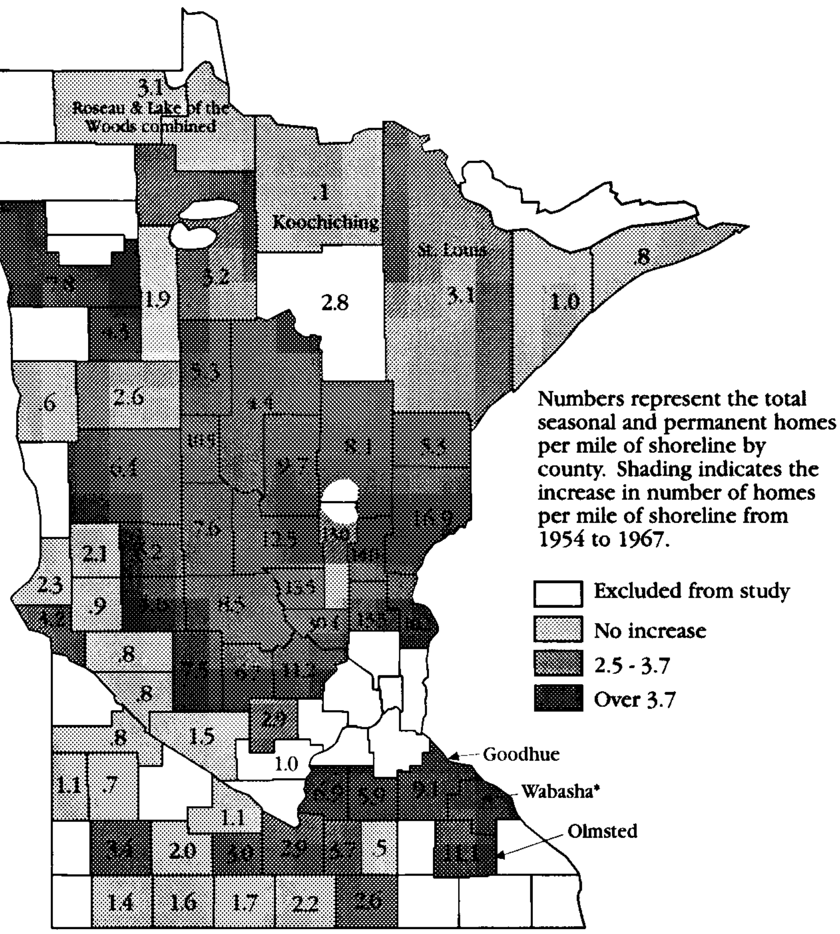
Lakeshore development

Nationwide and in Minnesota, development on lakes has increased dramatically since World War II. In Minnesota the number of lakes homes increased by 88% between 1954 and 1967; (Borchert et al. 1970). The number of lake homes increased from 33,500 in 1954 to 110,000 in 1984 (Figure 6). About one-third of these homes were constructed on lots approximately 100 feet wide (smaller than some urban lots) on 50 of the state's lakes. Development was greatest on lakes within 1/4 mile of a paved highway or within 5 miles of an urban area, on lakes supporting permanent game-fish populations, and on lakes having forested, sandy shorelines (Cohen and Stinchfield 1984).

In 1970, 60% of lake homeowners were 45 to 64 years old, and 30% were 65 or older. Lake homeowners chose sites that were close to permanent homes or work, offered isolation, and contained lakes and surrounding natural resources in good condition (Table 4; Borchert et al. 1970). The need for accessibility initially promoted very concentrated development around the Twin Cities metropolitan area, but the improvement and expansion of highways later increased access to more remote areas.

Growth in the number of people 45 and older was moderate during the 1970s but will increase as baby boomers age and may result in increased demand for lakeshore homes. Smaller, more remote lakes will face more development pressure as available space on the more accessible lakes decreases. Demand for urban facilities, service centers, and expanded highways will likely increase as more people convert lakeshore homes to permanent residences. Environmental indicators, such as **percentage of remaining littoral vegetation** or **density of development in the watershed**, provide a means to understand the relationships between lake

Figure 6
Lakeshore Homes in Minnesota, 1967



*Data for Wabasha County included in Goodhue and Olmsted Counties.
Data for Roseau County included in Lake of the Woods County.
Homes on the south shore of Rainy Lake in northeastern Koochiching County included in Lake County.

From Borchert et al. 1970

development pressures and the ecological health of lakes.

Fish harvests

The statewide fish harvest has been fairly stable at 40 to 50 million pounds of fish per year for the past 30 years. In contrast, the average size of kept fish has declined noticeably. For example, in an annual fishing contest in Park Rapids, Minnesota, the number of large-size fish and the average weight of all caught fish declined significantly from 1930 to 1987 (Olson and Cunningham 1989).

Regulation, habitat protection, and fish stocking to meet demands for quality fishing have been in place for more than 100 years (Minnesota Department of Conservation 1964; MDNR 1989, 1994a). In the late 1800s, stocking of lakes was a widespread practice, and popular fish were introduced to lakes that lacked appropriate habitat. Today supplemental stocking with hatchery-raised fish is selectively used to augment populations in which natural reproduction is inadequate to support the fishery.

While stocking will remain a component of the state's fisheries management program, habitat protection and restoration and experimental angling programs are increasingly important in the effort to improve angling. The MDNR's Section of Fisheries manages 5,400 lakes for sport fishing in Minnesota. Detailed management plans based on ecological assessments, stocking histories, and habitat availability define short- and long-term fisheries management goals for 3,000 of these lakes. Experimental regulations designed to restore fishing quality (size and catch rates) are being evaluated on 76 lakes and 12 streams.

Non-native species

Eurasian watermilfoil was first discovered in a Minnesota lake in 1987 (Exotic Species Program 1997). Although it has spread to at least 79 other lakes since then, the rate of spread has decreased during the past five years. In 1997, Eurasian watermilfoil was documented in four lakes in the Twin Cities, but in only one new lake (Ruth Lake, Crow Wing County) outside of the Twin Cities area. Purple loosestrife was documented at 1,841 sites in Minnesota. The majority of those sites (68%) are lakes (559) wetlands (561), and rivers (149). Purple loosestrife was documented in 12

Table 4
Lakeshore Home Selection Criteria

Percentage of those responding

%	Selection criteria
42%	**Accessibility**—driving distance from permanent residence or work; local road conditions
19%	**Physical site**—scenery; water and shore characteristics
14%	**Familiarity**—familiar with area and people
13%	**Isolation**—distance from crowded and commercial areas
4%	**Other nearby recreation**—other lakes, skiing, hunting, etc.
3%	**Climate**—cleaner air, temperature
2%	**Service availability**—near shopping facility and good community
2%	**Price investment**—initial cost; resale value
1%	**Other**—taxes, retirement

Modified from Borchert et al. 1970

new lake sites in 1997, increasing the total number of infested lakes to 559. Purple loosestrife control includes the use of herbicides and biological controls (two species of leafleating beetles and two species of weevils). Herbicides appear successful at controlling small populations, but less successful at controlling large populations with well established seed banks (Exotic Species Program 1997).

Water quality

The MPCA has assessed 1,813 lakes at least once between 1970 and 1993 to determine if they are swimmable (MPCA 1994). High nutrient levels and excessive algal growth prevent swimming in 20% of these lakes and limit swimming during some part of the season in 16%. Long-term (10-25 year) studies on some of these lakes illustrate regional differences in lake water quality. Lakes in the Northern Lakes and Forests and North Central Hardwood Forests ecoregions showed improvements in water quality (MPCA 1994), while lakes in other ecoregions did not. However, monitoring data from a statewide database of over 1,000 lakes show that average water quality in lakes was largely unchanged in most regions from 1989 to 1995 (Heiskary and Wilson 1989; MPCA 1996).

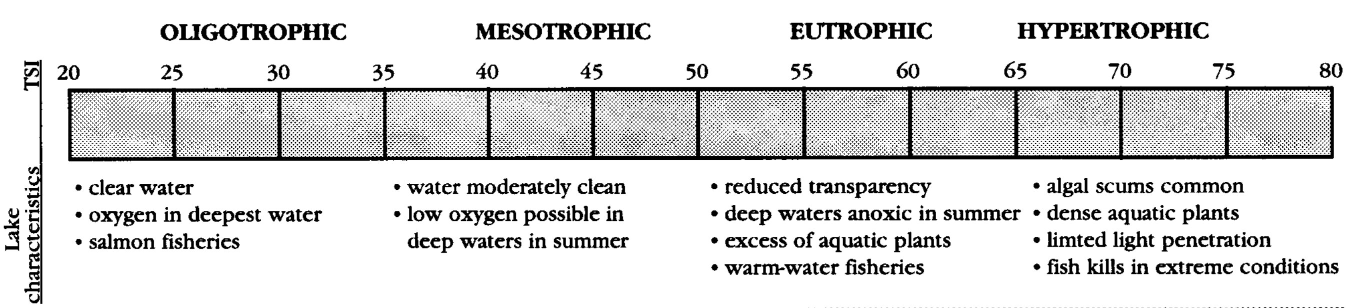
Table 5
Transparency of Lakes in Meters

ECOREGION	1989	1994
Northern Lakes and Forests	1.8-3.9	2.0-5.5
North Central Hardwood Forests	0.8-2.2	0.9-2.5
Western Corn Belt Plains	0.3-0.9	0.4-0.9
Northern Glaciated Plains	0.3-1.2	0.5-1.4

MPCA 1996

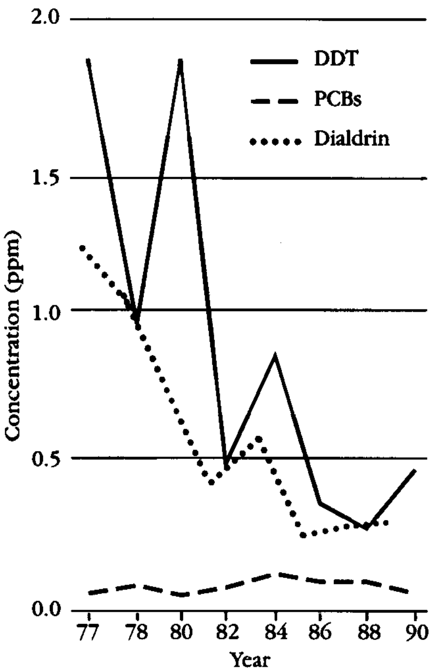
Lakes in the Western Corn Belt Plains and Northern Glaciated Plains ecoregions typically receive higher sediment and nutrient inputs than do other lakes in the state, and most are eutrophic to hypereutrophic (Figure 7). These lakes are characterized by warmer waters, dense aquatic plants, occasional algal blooms, and lower lake transparencies (Table 5). Lakes in the Northern Central Hardwood Forests ecoregion are primarily

Figure 7
Carlson's Trophic State Index (TSI)



Modified from Heiskary and Wilson 1989

Figure 8
Contaminant Levels in Lake Superior Trout



From Hesselberg and Gannon 1995

mesotrophic to eutrophic. These lakes may be oxygen depleted in deeper waters and can support dense aquatic plants that interfere with recreational activities. Most oligotrophic lakes are likely to occur in the Northern Lakes and Forests ecoregion. These lakes are characterized by lower nutrient levels and productivity, clear water, and higher transparency.

Environmental contaminants

Fish from over 700 lakes and more than 45 rivers in Minnesota have been tested for contaminants. In the past five years approximately 75 new lakes have been tested each year. Some level of mercury is detected in every fish tested. PCBs are found in fish from rivers, from some lakes near industrial sources of PCBs, and from Lake Superior. An advisory is issued for various sizes of fish of several species from specific lakes and river reaches. An increase in the number of advisories reflects increased sampling, not necessarily an increase in environmental contamination. The MDH uses the concentration of contaminants in the edible portion of fish to determine consumption advice. This advice is in terms of the number of fish meals that are safe to eat over a specific period of time and ranges from 'unlimited consumption' to 'do not eat.' For the general population, 35% of the advisories indicate that consumption poses no health hazard. The general population does not include children under age six and women in child-bearing years. Sixty percent of the advisories for this sensitive population recommend limiting consumption to one meal per month.

Mercury contamination in fish is somewhat higher in the Northern Lakes and Forests ecoregion and in the Twin Cities metropolitan area than the rest of the state. PCB contamination in fish is low in all areas except the Twin Cities metropolitan area and southeastern Minnesota (MDNR 1994b).

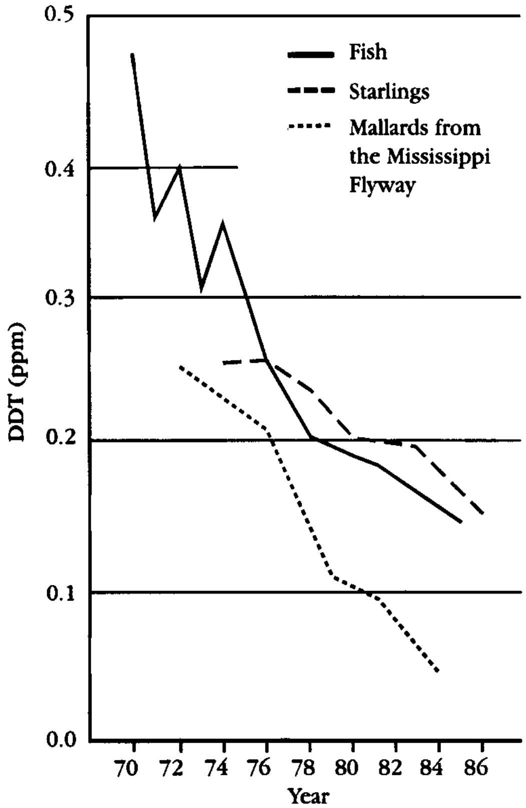
From 1977 to 1990, levels of DDT and PCBs in Lake Superior trout declined (Figure 8) and were the lowest among all the Great Lakes. Sediment concentrations of the heavy metals cadmium, chromium, and lead, in general, are greater in the Western Corn Belt Plains ecoregion than in the North Central Hardwood Forests or Northern Lakes and Forests ecoregions (Table 6; Heiskary 1996).

Since the 1970s, DDT use nationally has decreased, and DDT breakdown products in fish and bird tissues have also declined (Figure 9). Environmental concentrations of PCBs also declined while the number of bald eagles increased (Figure 10). Concentrations of mercury in fish declined from 1969 to 1974 (LaRoe et al. 1995) following reduction in point-source discharges of mercury.

Some long-lived toxic chemicals that are transported through the atmosphere continue to be a problem. Airborne mercury (from incinerators and coal-fired power plants), for example, appears to be the primary source of this contaminant in lakes. Atmospheric deposition of mercury in Minnesota's lakes has increased approximately 350% since the mid-1800s (Swain et al. 1992). Mercury deposition in Minnesota was even higher in the 1960s and 1970s but has decreased because of a combination of decreased U.S. emissions and increased long-range atmospheric transport due to taller stacks. Regional sources have declined to 40% of total deposition, and global sources have increased to 60% (Engstrom and Swain 1997).

Figure 9

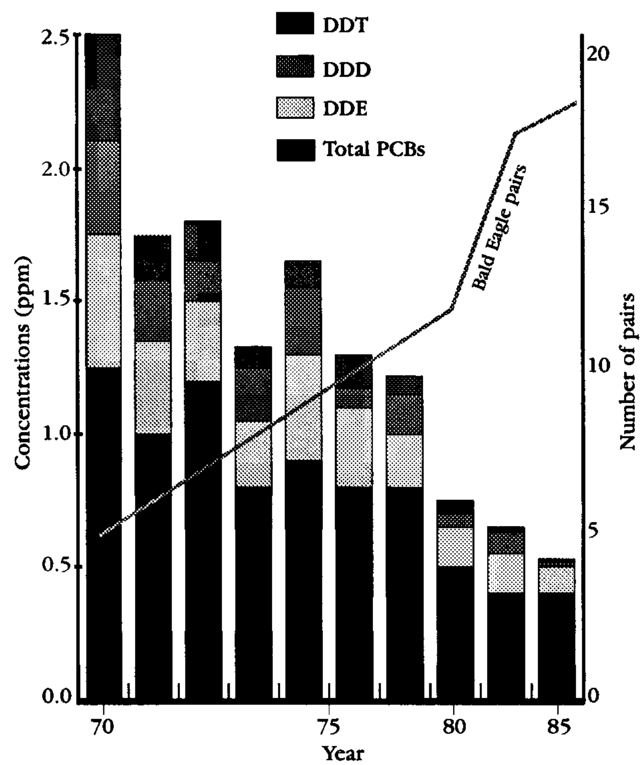
Nationwide Trends in Levels of Contaminant in Fish & Birds



Modified from Schmitt and Bunck 1995

Figure 10

Concentrations of Chemical Contaminants & Changes in Bald Eagle Populations



* Concentrations measured in fish 1970 - 1986.

From Schmitt and Bunck 1995

Table 6

Contaminant Levels in Minnesota's Lake Sediment

Parameter (mg/kg)	Biological effects begin at:	Effects are severe at:	Northern Lakes and Forests	North Central Hardwood Forests	Western Corn Belt Plains
Mercury	0.2	2	<0.12	0.07 - 0.08	0.07 - 0.08
Cadmium	0.6	10	<0.5	0.5 - 1.7	2.8 - 3.1
Chromium	26	110	15 - 38	13 - 33	42 - 48
Lead	31	250	30 - 38	16 - 56	61 - 68
Copper	16	110	13 - 46	10 - 22	19 - 36
TP	600	2,000	987 - 2,030	930 - 1,160	878 - 988
PCBs	70	—	—	215 - 385	—

From Heiskary 1996

CASE STUDY: LAKE SUPERIOR STATUS AND TRENDS

Lake Superior is the largest freshwater lake in the world, with 10% of the world's supply of fresh water, nearly 3,000 miles of shoreline, 31,280 square miles of surface area, and a maximum depth of 1,333 feet. The shoreline and lake basin are rocky basalt about 1 billion years old, and the waters are cold and well oxygenated. Nutrient levels in the lake are very low, in part because of the bedrock material but also because industrial activity and development in the watershed are limited. Plant and animal diversity and productivity are low compared to other lakes. (Lake Superior produces about 0.8 pounds of fish per acre of surface area, compared to over 200 pounds of fish per acre of surface area in Minnesota's nutrient-rich southern lakes.)

Introductions of non-native species, over-fishing, pollution, and land-use changes in the watershed (Schreiner 1995) have caused dramatic changes in the relative abundance of native fish species since the late 1880s. During the first half of the twentieth century, fishing reduced the number of lake trout. Populations of lake trout and other predatory fish declined again following introduction of the sea lamprey in the 1940s. Poisoning sea lamprey larvae effectively reduced its numbers and allowed tout and other sport fish to increase.

Combined efforts to reduce sea lamprey, stock lake tout, and limit sport and commercial harvest promoted self-sustaining populations of lake trout. Coho salmon and chinook salmon were introduced during the 1970s to help reduce fishing pressure on lake trout and to diversify sport fishing. Today populations of lake trout provide excellent recreational fishing. Approximately 10,500 fish were harvested annually from 1991 to 1995 (Halpern et al 1996). Coho salmon has become naturalized and is the second most popular sport fish today. Rainbow trout (steelhead), first introduced in 1895, have since become self-sustaining (Halpern et al. 1996). Angling success peaked in the mid-1900s but has declined over the last 10 to 15 years. Airborne contaminants and the introduction of exotic species continue to be important issues in Lake Superior.

Fish consumption advisories warn of high levels of PCBs, DDT, dieldrin, and toxaphene levels in the lake. These contaminants enter the lake primarily through precipitation and deposition on the lake surface of dry, windblown material. Partly in response to these problems, the United States and Canada established the Binational Program to Restore and Protect the Lake Superior Basin with the goals of maintaining the lake as a demonstration area where no point source of any persistent toxic substance will be permitted and providing leadership in the protection and restoration of ecosystem health in Lake Superior and its watershed (Steedman and Kavetsky 1996). Minnesota and other Great Lake states have joined with the U.S. Environmental Protection Agency in the Great Lakes Water Quality Initiative to protect aquatic life, human health, and wildlife from harmful pollutants. The MPCA, industry, and concerned citizens also are collaborating in this effort.

EXISTING POLICIES AND PROGRAMS

The Clean Water Act aims to restore and maintain the chemical, physical, and biological integrity of the nation's waters. The 1972 law mandated zero discharge of pollutants by 1985, and fishable and swimmable waters. Recent changes to the Clean Water Act protect lakes and enhance restoration efforts by emphasizing the importance of watersheds in determining water quality.

The Endangered Species Act of 1973 provides for the conservation of ecosystems on which threatened and endangered species of fish, wildlife, and plants depend, both through federal action and by encouraging the establishment of state programs.

The Clean Lakes Program was established in 1972 as part of the Water Pollution Control Act. The program facilitates diagnosing the current condition of individual lakes and their watersheds, determining the extent and sources of pollution, developing feasible lake restoration and protection plans, and implementing those plans. The program also supports statewide lake assessments.

The Minnesota Lake Water Quality Assessment analyzes data collected by the MPCA's Citizen Lakes Monitoring Program and the Lake Assessment Program to provide baseline information on the state's lakes. The 1987 Clean Water Partnership Program, administered by the MPCA, addresses pollution problems associated with runoff from agricultural and urban areas by providing local governments with financial resources to protect and improve lakes, streams, and groundwater.

Development adjacent to lake and river shorelines is subject to state regulations enforced by the MDNR Division of Waters and the Board of Water and Soil Resources. The Shoreland Management Act regulates all land within 1,000 feet of a lake and 300 feet of a river or the designated floodplain.

The MDNR Shoreland Management Program focuses on enhancing water quality and preserving scenic resources along Minnesota's lakes and rivers. The MDNR and local units of government work together to address potential problems in the development of lake and river shorelands. Throughout the state local groups such as lake associations are playing an increasingly active role in guiding lakeshore development.

EXAMPLE INDICATORS

Table 7 collects the indicators used in this chapter. The indicators are organized within the EII framework, which helps illustrate relationships among human activities, environmental condition, the flow of benefits from the environment, and strategies for sustaining a healthy environment. The indicators used in the chapter are examples that illustrate how indicators may help assess lake health. The process of developing a comprehensive set of indicators that assess lake health and inform environmental decisions is ongoing. Developing indicators will require collaboration with stakeholders interested in their use, testing, refinement, and standardization of measurement techniques.

Table 7

Example Indicators

HUMAN ACTIVITIES	ENVIRONMENTAL CONDITION	SOCIETAL STRATEGIES
Land conversions • Density of lakeshore homes • Conversion of seasonal homes to permanent homes • Change in land cover in watershed **Point- and nonpoint-source pollution** • Number of leaky septic systems • Toxic contamination from point and nonpoint sources **Introduction of exotic species** • Distribution and abundance of non-native species **Shoreline alterations** • Percentage of shoreline in native vegetation **Recreation** • Trends in recreation on lakes • Trends in fish harvest	**Productivity** • Oxygen depletion • Contaminants in fish and waterfowl • Fish population sizes and community structure • Water quality (sediment levels, algal blooms) • Average fish size **Diversity** • Number of red-necked grebes and bald eagles • Diversity of lakeshore birds • Biological diversity of a lake relative to what would be expected in a similar but undisturbed lake • Abundance of exotic species **Nutrient cycling** • Shoreline erosion • Lakeshore and upland erosion rates • Algal productivity • Water chemistry • Concentrations of nitrogen and phosphorus **Natural disturbances** • Changes in lake levels relative to historic variation	**Management actions** • Application of Shoreland Best Management Practices • Environmentally sensitive cluster housing development • Restoring native littoral communities • Environmentally sensitive use of lawn chemicals • Exotic species control via biological and chemical means • Regulation of toxic emissions **Policy and legislation** • Clean Water Act • Endangered Species Act

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