CHAPTER
Three

Ecological Vulnerability to Climate Change: Aquatic Ecosystems

The Great Lakes region is distinguished by its abundant lakes, streams, and wetlands. All of these aquatic ecosystems will be affected in some way by the direct human stresses and human-driven climate changes explored in Chapters 1 and 2.

Lake Ecosystems

Lakes in the region differ widely in size, depth, transparency, and nutrient availability, characteristics that fundamentally determine how each lake will be affected by climate change (Figure 17). A wide variety of studies have focused on the inland waters and Great Lakes, providing strong evidence of how the waters have changed and are likely to change in the future.

Higher Lake Temperatures

Warmer air temperatures are likely to lead to increasing water temperatures and changes in summer stratification in the Great Lakes[47] and in the inland lakes and streams of the region.[48] Earlier model studies project that summer surface water temperatures in inland lakes will increase by 2 to 12°F (1 to 7°C). Projections for deep water range from a 14°F warming to a counterintuitive 11°F cooling. The response in deep waters varies because warming air temperatures can cause a small, deep lake to stratify sooner in spring, at a cooler temperature. Projected changes in water temperature would be even greater using the more recent climate scenarios on which this report is based, especially by 2090. Overall, changes in temperature and stratification will affect the fundamental physical, chemical, and biological processes in lakes (see box, p.22). Higher water temperatures, for example, result in lower oxygen levels.

Lower oxygen and warmer temperatures also promote greater microbial decomposition and subsequent release of nutrients and contaminants from bottom sediments. Phosphorus release would be enhanced[49] and mercury release and uptake by biota would also be likely to increase.[50] Other contaminants, particularly some heavy metals, would be likely to respond in a similar fashion.[51] (Heavy metals such as mercury become more soluble in the absence of oxygen. Oxygen binds with these elements to form insoluble compounds that sink to the bottom.)

FIGURE 17
Impacts on Lake Ecosystems

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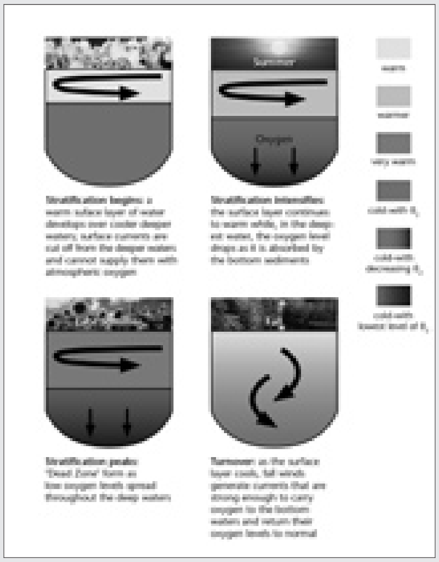
Climate Change and "Dead Zones" in Lake Erie

The fall of 2001 brought startling and discouraging news to residents around Lake Erie. Testing stations in the lake's central basin reported the most rapid oxygen depletion in nearly 20 years. "It's like going back to the bad old days when Lake Erie was dead," one aquatic biologist told the Toledo Blade. The bad old days were the 1960s when Lake Erie had been all but choked to death: massive phosphorus pollution had fertilized algal blooms and their decay was using up the dissolved oxygen needed to support fish and other aquatic life. Then, in 1972, implementation of the Great Lakes Water Quality Agreement led to billions of dollars in new sewage treatment plants, bans on phosphate laundry detergent, new farming practices that reduced fertilizer runoff, and other measures that drastically cut phosphorus input to Lake Erie. As phosphorous loading dropped, so did the extent and duration of the summer "dead zones."

FIGURE 18A

Lake Stratification and the Development of "Dead Zones"



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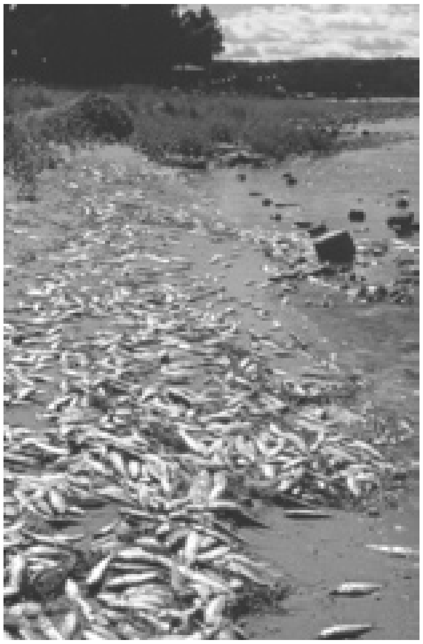
Was the massive dead zone of 2001 an anomaly or a trend, scientists and policymakers wondered? And what had caused it this time? A committee of US congressmen traveled to the lake to investigate, and researchers in the United States and Canada launched a $2 million effort to find answers. The suspected culprits ranged from ozone depletion, which allows ultraviolet light to reach deeper into the waters, to the invading zebra mussels that now line the lake bottom down to 100 feet (30 meters). Missing from most discussions, however, was the recognition that a warming climate will mean more frequent and larger dead zones in the future.

A dead zone is an area of water—in a lake or even in a part of the ocean such as the Gulf of Mexico off the mouth of the Mississippi River—that contains no oxygen to support life. Dead zones form when oxygen in the water is consumed by organisms, but these zones can only persist when the water is isolated from the atmosphere and thus from a source of new oxygen. This isolation occurs when water is stratified—that is, layered and separated with warmer surface waters acting as a lid on top of the cooler bottom waters, isolating them from the air (Figure 18a).

When winter ends in the Great Lakes region and surface waters become free of ice, lakes usually mix from top to bottom and the entire lake becomes saturated with oxygen. Soon after this spring mixing, however, the sun warms the surface waters and stratification sets in. Once the lake is stratified, oxygen begins to decrease (hypoxia) in bottom waters, and the race is on to see whether all the oxygen will be depleted (anoxia) and a dead zone created before the lake again mixes fully in the late fall or early winter. The more rotting biomass such as dead algae in the water, the more oxygen is consumed. In recent years, oxygen consumption has had the advantage in this race because

FIGURE 18B
Lake Michigan Fish Kill



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shorter winters have led to earlier spring stratification in many lakes, meaning that the lake bottom runs out of oxygen even sooner in the summer. For example, winters on Lake Erie have been growing shorter since the 1960s. Also, recent increases in the near-shore water temperatures for four of the five Great Lakes indicate that their summer stratification periods have increased by one to six days per decade.[25]

In a warming climate, the duration of summer stratification will increase in all the lakes in the region. Warming could also lead to a partial disappearance of the fall and spring periods of complete mixing that are typical of all the Great Lakes. This mixing resupplies oxygen and nutrients throughout the water column. In the fall, the formerly warm and buoyant surface waters cool and then sink, driving mixing. This occurs only if the surface waters cool to the temperature of maximum water density (39°F or 4°C).[52] Lake Ontario is particularly sensitive to this effect. Under some climate warming scenarios,[53] it would experience only a single, short period of complete mixing in late winter, then deep water temperatures would increase throughout the year. The deeper Great Lakes (Huron, Michigan, and Superior) would experience a similar suppression of mixing in some years, along with a significant warming of deep waters.[54] No suppression of mixing will occur in shallower bodies of water such as Lake St. Clair and the western basin of Lake Erie, because there will always be sufficient wind to stir the entire water column from top to bottom.

In the end, longer stratification periods and warmer bottom temperatures will increase oxygen depletion in the deep waters of the Great Lakes[55] and will lead to complete loss of oxygen during the ice-free period in many inland lakes of at least moderate depth.[56] Anoxia or hypoxia in deep waters will have negative impacts on most of the organisms in the lakes. Persistent dead zones can result in massive fish kills, damage to fisheries, toxic algal blooms, and foul-smelling, musty-tasting drinking water (Figure 18b).

Reduced Ice Cover

Extrapolations from 80 to 150 years of records strongly suggest that ice cover will decline in the future. Hydrologic model simulations also predict drastic reductions in ice cover on the Great Lakes[57] and on inland waters in the future (Table 1). Changes in ice cover create large ecological and economic impacts. Shorter ice cover periods, for example, can be a mixed blessing for fish. Reduced ice will lessen the severity of winter oxygen depletion in many small inland lakes,[56] thus significantly reducing winterkill in many fish populations. However, small species uniquely adapted to live in winterkill lakes go extinct locally when predatory fishes are able to invade and persist in lakes that previously experienced winterkill.[58] Reduced ice cover also allows greater storm disturbance, which increases egg mortality of the commercially valuable lake whitefish, whose eggs incubate over winter on the bottom of Great Lakes bays.[59] Increases in the ice-free period extend the shipping season on the Great Lakes but reduce ice fishing, ice boating, skiing, snowmobiling, and winter festivals such as Wisconsin's "Kites on Ice" (see box, p.15).

Changes in Lake Water Levels

Climate scenarios and lake models have consistently predicted less runoff, more evaporation, and lower water levels in both large and small lakes in the region.[60] The most recent hydrologic models continue to project lower lake and groundwater levels in the future (Table 2), despite a lack of clear trends in the historic record. Predictions based on one of the climate models used in this report (HadCM3) suggest even greater declines in late summer water levels because this model projects higher temperatures and lower summer rainfall in the region than the models used in previous studies. However, the absence of long-term trends in the historic Great Lakes water levels record[34] and increases in water in some inland areas of Wisconsin[35] suggest that lake water levels may not yet show the decline expected from long-term climate change.

Changes in Lake Productivity

The growth of algae in the water and on lake bottoms is called primary production because these planktonic plants form the base of the food web that nourishes animals from zooplankton to fish. Primary production is controlled by a combination of temperature, light (or the portion of the ice-free year when light is available), and nutrients. Excessive nutrients can

TABLE 1 **Ice Cover Expected to Decrease in the Great Lakes Region**

Lake	Current Situation	Future Scenarios By 2030	Future Scenarios By 2090
Lakes Superior and Erie (6 basins)[a]	77 to 111 days of ice cover	Decrease ice cover from 11–58 days	Decrease ice cover from 33–88 days
Lake Superior (3 basins)[a]	No ice-free winters	Increase ice-free winters from 0–4%	Increase ice-free winters from 4–45%
Lake Erie (3 basins)[a]	2% of winters are ice free	0–61% of winters are ice-free	4–96% of winters are ice-free
Small inland lakes[b]	~90–100 days of ice cover	Decrease ice cover by 45–60 days with a doubling of atmospheric CO_2	

Source: See note 61.

TABLE 2 **Water Levels Likely to Decrease in the Future** (as shown here for the Great Lakes, Crystal Lake, Wisconsin, and groundwater near East Lansing, Michigan)

Lake or Site	2 × CO_2 (range of 3-4 simulations)	2030 (range of 2 simulations)	2090 (range of 2 simulations)
Lake Superior	–0.23 m to –0.47 m	–0.01 m to –0.22 m	+0.11 m to – 0.42 m
Lake Huron/Michigan	–0.99 m to –2.48 m	+0.05 m to –0.72 m	+0.35 m to – 1.38 m
Crystal Lake, Wisconsin	–1.0 m to –1.9 m (2 simulations)		
Groundwater near Lansing, Michigan		–0.6 to +0.1 m	

Source: See note 62. Additional data on lake level declines can be found in the technical appendices: http://www.ucsusa.org/greatlakes/glchallengetechbac.html

TABLE 3 **Expected Effects of Warmer and Drier Summer Climate on Lakes and Subsequent Impacts on Algal Productivity**

Climate-Driven Change	Impact on Production	Most Sensitive Lake Type
Increases in both ice-free period and maximum summer water temperature	Increase in production	Moderate in area, depth, and nutrient concentration
Increase in duration of summer stratification and loss of fall top-to-bottom mixing period	Decrease in production caused by decrease in nutrient regeneration rates	Deep and oligotrophic (nutrient-poor; e.g., Lake Ontario)
Drought-induced decrease in lake water volume	Initial increase in production, followed by progressive decrease as the lake level declines	Small and shallow
Drought-induced decrease in annual input of nutrients (phosphorus) and dissolved organic carbon	Decrease in production resulting from nutrient limitation	Small and oligotrophic

lead to eutrophication, causing increased algal growth, including noxious algal blooms and degraded water quality. On the other hand, drops in primary production can ultimately reduce fish production in a lake.

Research indicates that the longer ice-free periods and higher surface water temperatures expected in the future will spur greater algal growth.[63] Other aspects of climate change, however, may offset these productivity gains. Cloudy days can lower productivity by making less light available for algal photosynthesis.[64] Cloud cover has increased in the Great Lakes region recently, but future trends in cloudiness are not clear. Increased primary productivity could also be limited or even reversed by a decline in availability of nutrients, primarily nitrogen and phosphorus, necessary for plant growth. Predicted reductions in runoff and a general drying of watersheds during summer are likely to reduce the amounts of phosphorus and other dissolved materials that streams carry into lakes.[65] Finally, prolonged or stronger stratification can also lead to lower primary production in lakes by preventing the mixing that brings nutrients from bottom waters and sediments up into surface waters.[66]

Changes in the species composition of algae and in seasonal patterns of blooms are also likely consequences of climate change. Earlier ice-out (thaw of lake ice) and spring runoff will shift the timing of the spring algal bloom,[67] and earlier and longer periods of summer stratification tend to shift dominance in the algal community during the growing season from diatoms to inedible blue-green algae. If climate change causes inedible nuisance species to dominate algal productivity, or if the timing of algal production is out of synch with the food demands of fish, then all upper levels of the food chain, particularly fish, will suffer (see box, p.22).

The impacts of climate change on aquatic productivity will differ among lakes. Table 3 summarizes the likely outcomes.

River and Stream Ecosystems

The aspects of climate change that will have the greatest impact on streams are warming air temperatures and general drying of watersheds, especially during summer and autumn. This drying will result from warmer temperatures and higher rates of evaporation during a longer ice-free period. This future scenario is consistent with past trends toward longer ice-free periods, earlier spring stream flows, and more frequent midwinter breakups and ice jams.[68] Despite a general drying,

TABLE 4 **Impacts of Climate Change on Stream Ecosystems**

Climate-Driven Change	Likely Impacts on Physical and Chemical Properties	Likely Impacts on Ecosystem Properties	Intensifying or Confounding Factors
Earlier ice-out and snow melt	Peak flows occur earlier. Ephemeral streams dry earlier in the season. Backwater pools experience anoxia earlier.	The timing of fish and insect life cycles could be disrupted.	Snowmelt occurs earlier and faster in urban areas and where coniferous forest harvest has occurred.
Lower summer water levels	More headwater streams dry; more perennial streams become intermittent. Concentrations of dissolved organic carbon decrease, thereby reducing ultraviolet-B attenuation. Groundwater recharge is reduced.	Habitat decreases in extent. Hydrologic connections to the riparian zone are reduced. Groundwater recharge is reduced. Species with resting life stages or rapid colonizers dominate communities.	Impervious surfaces and impervious soils exacerbate stream drying due to reduction in infiltration and groundwater recharge.
More precipitation in winter and spring and increased water levels	Spring floods reach greater heights. Surface runoff increases. Nutrient and sediment retention decrease. Groundwater recharge potential increases.	Floodplain habitat for fish and invertebrates grows. Hydrologic connections with wetlands increase.	Precipitation occurring when soils are frozen results in higher runoff and increases flood height.
Warmer temperatures	Stream and groundwater temperatures increase.	The rates of decomposition and respiration increase. Insects emerge earlier. Primary and secondary production per unit of biomass increases when nutrients are not limited; however, total production could decrease if aquatic habitat shrinks under drought conditions.	Impervious surfaces and both natural and human-made retention basins increase water temperatures. Woody riparian vegetation can buffer stream temperatures. In areas with porous soils and active groundwater connections, temperature extremes are smaller.
More frequent heavy rainfall events	Larger floods occur more frequently. Erosion and pollutant inputs from upland sources increase. Runoff increases relative to infiltration.	Fish and invertebrate production decreases. Fish and insect life histories and food webs are disrupted by changes in the intensity, duration, and frequency of flooding.	Impervious surfaces increase runoff and stream flow. Channelized streams increase peak flow.
Elevated atmospheric CO_2		Possible changes in leaf litter quality could impact aquatic food webs.	

model predictions for the region also suggest that over the next 100 years precipitation will increase during winter and spring. This could increase the magnitude of spring floods, especially if the floods coincide with snowmelt when soils are still frozen. Stream responses to these climate-driven changes will vary greatly across the region (Table 4), mainly because of differences in the relative contribution of groundwater versus surface water to their flow patterns.[69] Direct human disturbances such as removing streamside vegetation, paving or developing land, channelizing streams, depositing nitrogen and acid from acid rain, diverting water, and introducing invasive species will undoubtedly alter the way stream ecosystems respond to climate change.

Impacts of Changes in Hydrology

Heavy rainfall events and flooding are increasing in the Great Lakes region[38] (see Figure 7, p.14), and projected increases in the frequency of these events may amplify the range of conditions that make flooding more likely in the future, such as stream channeling and land-use changes that increase the amount of impervious surfaces. The likelihood of flooding will also increase with changes in land use. Streams in the agricultural areas on fine-textured soils and flat topography at the eastern end of Lake Erie, for instance, rise quickly in response to rain and are likely to be especially vulnerable to intense summer storms.

Floods exert their greatest physical influence by reshaping river channels, inundating floodplains, and moving large woody debris and sediments. Flooding can degrade water quality when untreated human, commercial, or agricultural wastes overflow from treatment facilities or when soils are eroded from agricultural fields treated with pesticides and fertilizers.[70] High water flow also diminishes the capacity of a stream to recycle nutrients and sequester suspended or dissolved organic matter.[71] Channelized urban and agricultural streams have little capacity to retain water, and the anticipated increases in spring runoff by the end of the century will result in increased height of spring floods and lower nutrient and sediment retention in these streams.

Not all impacts of flooding are negative, of course. Aquifer recharge is one benefit. Floods also transport fine sediments downstream, increasing the quality and quantity of habitat for some fish and invertebrates. In addition, several important fish species move upstream into the Great Lakes tributaries to reproduce during spring (sturgeon, walleye, and white sucker) or fall (steelhead, Chinook salmon, and brook trout), cued by either increased flow or day length. Although changes in the frequency and severity of disturbances such as floods can disrupt some aquatic communities, many fish and invertebrate species coevolved with seasonal flood pulses to take advantage of the expanded habitat for spawning and nursery sites.[72] In the Great Lakes region, these species include bass, crappie, sunfish, and catfish.[73]

FIGURE 19

Impacts on Stream Ecosystems

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Apart from extreme events, summer rainfall is expected to decline in the future, especially in the southern and western portions of the region (see Figure 13, p.18). Drier conditions will translate into lower summer stream flow and less stream habitat.[74] Headwater streams, which often make up more than 75 percent of the river miles in a watershed, are probably the most vulnerable of all aquatic ecosystems under warmer and drier conditions (Figure 19).[75] Drought effects can lead to warmer water temperatures, depleted oxygen, higher concentrations of contaminants as water volume declines,[76] reduced transport of nutrients and organic matter,[77] and disruption of food webs.[78] Regions with intensive agricultural production on fine soils and flat topography, such as those found at the eastern end of Lake Erie,[69] will be most vulnerable to extreme events and reduced summer rainfall, since their hydrology is controlled largely by surface water. In small streams where flow comes primarily from surface runoff, one study predicts that 50 percent of the streams will stop flowing if annual runoff decreases by 10 percent.[79]

One consequence of periodic droughts is that sulfates and acidity are mobilized during post-drought rains and can deliver a strong acid pulse to streams and lakes in the watershed. Because of this phenomenon, climate warming may slow or even halt the recovery of many acid-stressed aquatic ecosystems.[80] Streams most susceptible to acid rain include those on the Canadian shield of Ontario, along the higher-gradient reaches of New York, and in northern Michigan, Minnesota, and Wisconsin.

Impacts of Higher Water Temperature

Across the watershed, stream temperatures will closely mirror increasing air temperatures, although the warming may be modified by shade from riparian forests and other vegetation and by water storage in wetlands.[81] Locally, cool groundwater seeps will provide some buffering for streams against warming air temperatures. Warmer water will affect stream organisms from plankton to insects and fish (fish are discussed below). In response to warmer waters, some insect species increase growth rates, emerge earlier, are smaller at maturity, alter their sex ratios, or reduce fecundity.[82] Plankton productivity tends to increase with warmer temperatures and longer growing seasons,[83] but reductions in water volume, coupled

TABLE 5 **Impacts of Climate Change on Wetland Ecosystems**

Climate-Driven Change	Likely Impacts on Physical Properties	Likely Impacts on Ecosystems	Intensifying or Confounding Variables
Earlier ice-out and snow melt	Wet periods are shorter, especially in ephemeral wetlands.	Fast-developing insect and amphibian species are favored, as are species with resting stages. The timing of amphibian and insect life cycles could be disrupted.	Snowmelt occurs earlier and faster in urban areas and where coniferous forest harvest has occurred.
Lower summer water levels	Isolation and fragmentation within wetland complexes increase. Fens store less carbon. Reductions in dissolved organic carbon result in less attenuation of ultraviolet-B radiation.	Habitat and migration corridors are reduced, as are hydrologic connections to riparian zones and groundwater recharge. Emergent vegetation and shrubs dominate plant communities. Amphibian and fish reproduction fails more often in dry years. Organisms with poor dispersal abilities become extinct.	Agricultural and urban development exacerbate fragmentation effects.
Warmer temperatures	Evaporative losses increase. Fens and bogs store less carbon.	The rates of decomposition and respiration increase. Insects emerge earlier. Primary and secondary production per unit of biomass increase when nutrients are not limited. Species at the southern extent of the range become extinct.	Impervious surfaces increase water temperature. More competition from invasive species may accelerate extinctions.
More frequent heavy rainfall events	Wetlands increase in extent.	Habitat area increases. Ground-nesting birds may be lost during floods.	Wetland losses from development reduce flood storage capacity.
Elevated atmospheric CO_2		Possible changes in leaf litter quality could impact aquatic food webs.	

with possibly intermittent flow in smaller streams, should lead to reductions in overall aquatic production.

The effects of increasing water temperature would be compounded by forest harvest (especially of conifers), which opens up the canopy and promotes earlier snowmelt.[84] Northern Michigan, Minnesota, Wisconsin, and western Ontario will be most vulnerable to this phenomenon. Urban areas also experience earlier and faster snowmelt than do rural areas.

Warmer temperatures should enhance decomposition and nutrient cycling in streams, allowing microbes to break down human and agricultural wastes into nutrients that fuel greater primary productivity. However, other impacts of climate change, such as prolonged low flows combined with higher temperatures, may lead to oxygen depletion, which will slow decomposition and waste-processing functions.[85]

Impacts on Biodiversity and Food Webs

A warmer climate will combine with land-use change and the introduction of invasive species to pose great threats to aquatic biodiversity in the coming century. Native plant and animal species will differ widely in their responses to changing stream temperature and hydrology. Some will respond by adapting to warmer temperatures, or expanding their ranges northward, or seeking refuge in areas where temperatures and flow patterns remain suitable. Others will decline to extinction.[86] Insects and plants that have resistant or mobile life history stages (larvae, cysts, seeds) will survive better than other organisms during reduced water flows.[87] Fish species presumed to be at higher risk of extinction are those that have small geographic ranges, require steady water flows or slack water habitats, reproduce at an older age, or require specific foods. Of 146 fish species in Wisconsin, 43 percent have two or more of the above traits, indicating potential sensitivity to global warming. Darters and sea lampreys are among the species that are especially sensitive.[86]

FIGURE 20

Impacts on Wetland Ecosystems

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Another potential impact on stream food webs and the biodiversity they support comes directly from increasing atmospheric CO_2 levels. Some studies indicate that plant leaves grown under elevated CO_2 have lower food value.[88] If these changes in leaf chemistry turn out to be significant, they could slow microbial decomposition of plant material that falls into streams—a major source of energy and nutrients in many aquatic ecosystems—and also reduce growth and survival in some stream insects that feed on the leaves.[89] Any such impacts would be magnified up the food chain.

Wetland Ecosystems

Because of low topography or the presence of impervious soils, the Great Lakes region historically harbored extensive expanses of wetlands, particularly in the prairie regions of Minnesota and Illinois, the boreal regions of northern Minnesota and Ontario, and the low-lying fringes of Lake Michigan (Figure 20) and Lake Erie, including the Great Black Swamp in western Ohio. For more than a century, however, these wetlands have been extensively modified or drained for urban development and agricultural production, resulting in 40 to 90 percent losses in wetland area in the Great Lakes states and Ontario.[90] These losses are especially apparent in the southern portion of the region.

Wetlands near the Great Lakes occur as three distinct types: fringing coastal marshes that are directly impacted by lake levels and wave action, riverine wetlands that are partially influenced by both lake and river, and protected lagoons or barrier beach systems that are hydrologically connected to the lake only via groundwater.[91] Where they have not disappeared, coastal marshes in the southern part of the basin, particularly on Lake Erie and southern Lake Ontario, have been extensively diked to protect them from water level fluctuations. Coastal wetlands such as those in Saginaw Bay and large estuaries such as Green Bay are hot spots of primary productivity because nutrients and sediments from throughout the

Climate and Bird Diversity on Michigan's Upper Peninsula

One of the most popular bird-watching destinations in the Midwest is Michigan's Upper Peninsula, a densely forested neck of land that stretches 384 miles east from the northern Wisconsin border into the heart of the Great Lakes. Although parts of the peninsula lie farther north than Montreal, the climate is moderated by Lakes Superior, Michigan, and Huron, which create a continuous 1,700-mile shoreline around the Upper Peninsula. This shoreline and the peninsula's 16,500 square miles of largely unfragmented forest contain a rich diversity of terrestrial and aquatic habitats that provide refuge for more than 300 bird species. About 25 to 30 percent are year-round residents; the rest are migratory species that arrive in the Upper Peninsula each spring to breed or each fall to winter. A warming climate will drive complex changes in habitat, quality, and timing of food resources, and other factors that are likely to diminish bird diversity on the Upper Peninsula in the future. Hardest hit will be the migratory and wintering species.

FIGURE 21A
Songbird Declines Expected

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Habitat changes, particularly the expected northward shift of boreal forest species such as spruce and fir, will have profound impacts on bird communities. Spruce, fir, and hemlock are vital to a number of species such as crossbills, siskins, grosbeaks, and breeding warblers (Figure 21a). The nature of a peninsula will also make it more difficult for plant communities to respond quickly to changes since the land is isolated from sources of new colonists. Human land-use changes such as second-home development and logging will interact with climate to exacerbate habitat loss or degradation.

A number of resident bird species might, however, benefit from warming, including mockingbirds, chickadees, woodpeckers, titmice, and northern cardinals. For example, northern cardinals, chickadees, and titmice might be able to start breeding earlier and raise more broods within a season than they do now.[92] More important, reduced winter-related mortality might increase populations of these year-round residents. It may also enable some cold-intolerant species such as the Carolina wren and sharp-shinned hawks to expand their range northward.[93]

The prospects are less rosy for songbirds that migrate to the Upper Peninsula from the tropical forests of Central and South America to breed. Food may be scarce along the route if trees leaf out and insects hatch earlier than normal in response to warming. More vital in the Upper Peninsula may be any change in the spring emergence of aquatic insects along the shoreline and in the wetlands, since this flush of insects serves as the primary food supply for arriving migrants.

Another concern arises from the fact that different parts of North America are warming and will probably continue to warm at different rates. Spring temperatures immediately to the south of the

Great Lakes region are warming less than spring temperatures observed in the region itself. If these areas to the south continue to be cooler relative to areas further north, migratory birds may face a dilemma: They need to arrive earlier on their northern breeding grounds, but may be unable to migrate because food resources such as caterpillars are not yet adequate to allow them to fatten up for the flight from their more southern staging areas. Already some warblers such as the yellow-rumped warbler seem to be arriving earlier on their breeding grounds, as expected if they are responding to earlier springs, whereas other species such as the chipping sparrow are arriving later, perhaps in response to colder springs immediately to the south of the region.[94]

FIGURE 21B

Climate Change Impacts on Waterfowl

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If some year-round resident birds do thrive and expand in a warming climate, their success may further reduce the food available to populations of migratory songbirds breeding in the region, especially if the "pulse" of midsummer insects is also reduced. Forest bird diversity in the Great Lakes is highest in northern areas such as the Upper Peninsula largely because of the increased diversity of migratory species. Warming therefore may reduce forest bird diversity if fewer resources are available to migratory songbirds. One study projects that the Great Lakes region could lose more than half its tropical migrants, although new bird species colonizing from outside the region could cut the net loss in bird diversity to 29 percent. Waterfowl are also expected to decline. Studies based on earlier and milder warming forecasts than those used in this report project 19 to 39 percent declines in duck numbers by the 2030s in response to lost breeding and migratory habitats as well as declines in the aquatic plants on which ducks feed.[95]

Loss of bird diversity will have economic as well as ecological consequences. Wildlife watching—principally bird watching—is a $3.5 billion (US) a year industry in northern Michigan, Minnesota, and Wisconsin. In addition, hunting—including waterfowl hunting—is a $3.8 billion (US) industry in these three states (Figure 21b). Besides these potential economic losses, a decline in birds will mean a loss in ecological services such as seed dispersal and insect control.

watershed are deposited there, and these systems support rich plant, bird, and fish communities.[96]

Inland wetlands are even more diverse and range from entirely rain-driven systems such as bogs to riparian wetlands fed by contributions from both surface and ground water. Bogs and fens cover extensive areas in the northern Great Lakes region and contain a wide variety of acid-loving plants, including the widely known pitcher plant.

Impacts of Changes in Hydrology

All wetland types are sensitive to alterations in hydrology that are likely to accompany climate change (summarized in Table 5, p.28).[97] A warmer and drier climate will threaten both inland and coastal wetlands, although higher precipitation during winter and spring and intense storm events may at times offset the generally decreased water levels.[98] The largest impact should be on rainfalldependent wetlands, since systems that are largely recharged by ground water are more resistant to climate-driven changes.[99] Projected declines in summer rainfall in the southern and western portions of the region (Figure 12, p.18) will also cause drying of prairie potholes and similar depressional wetlands.

Some impacts will be positive. Although dropping water levels will cause wetlands to shrink, new vegetation may colonize formerly open-water habitats on some exposed shorelines, creating new types of habitat.[100] In wetlands fringing the Great Lakes, shoreline damage and erosion are likely to decrease as water levels drop.[101]

The impacts of climate change will often exacerbate continuing direct human disturbances such as dredging and filling, water diversion, and pollution.[102] As demands for public drinking water supplies and irrigation water increase, for example, groundwater pumping may pose the greatest threat to ephemeral wetlands. Also, the spread of invasive species such as phragmites, purple loosestrife, and Eurasian water milfoil poses an added threat to many wetland communities, especially when habitat or ecological processes are disrupted.[103]

> Climate change will exacerbate human disturbances such as dredging and filling, water diversion, and pollution.

Ecosystem Functioning

Wetlands serve as the main interface for moving nutrients, pollutants, and sediments from land to water. Decreased runoff from the land, particularly in summer, will decrease the deposition of material from uplands into wetlands. The material that does enter wetlands will be retained longer, however, before high-water pulses flush it downstream into lakes and rivers. Although decomposition rates will increase with warmer temperatures, fluctuating water levels combined with warmer temperatures are likely to reduce the capacity of wetlands to assimilate nutrients and human and agricultural wastes.

Fluctuations in water levels and soil moisture also influence the release of nutrients and heavy metals.[104] Lower water levels expose more organic wetland soils to oxygen, which may reduce exports of mercury (mercury binds with oxygen and is immobilized), but also may reduce the breakdown of nitrate by denitrifying bacteria in wetland soils. Increased oxygen concentrations in exposed soils, especially when accompanied by acid precipitation, may release other metals such as cadmium, copper, lead, and zinc,[51] and wetlands downstream of industrial effluents could face increased risk of heavy metal contamination during periods of low water.

Carbon stored in wetland soils may also be lost to the atmosphere in a warmer climate. Northern peatlands such as those found in Minnesota and Ontario form when cold temperatures and waterlogged soils limit the rate of decomposition of carbon-rich plant organic matter.[105] Warmer temperatures are likely to increase the rate of organic matter decomposition and accelerate carbon release to the atmosphere in the form of CO_2. Carbon release from wetlands in the form of methane, which is 25 times more potent than CO_2 as a greenhouse gas, will be enhanced by warmer temperatures and higher water levels.[106]

Reduced stream flow in summer will also decrease the amount of dissolved organic carbon washed from land into surface waters. Less dissolved organic carbon results in clearer water, which allows higher doses of ultraviolet-B radiation to penetrate further through the water column.[107] Organisms such as frogs living in shallow waters will be at greatest risk because UVB penetration is generally restricted to the top two to eight inches of the surface water.[108] In deeper waters, organisms can find refuge from the harmful radiation.[109]

Impacts on Biodiversity

Wetland plant and animal communities are continually adapting to changing water levels, although extreme events such as drought or flooding can result in persistent disturbance to community structure and functions such as decomposition rates and productivity.[110] Climate warming is likely to cause some wetland species to shift their ranges to accommodate their heat tolerances. Because of differences in breeding habits, age to maturity, or dispersal rates, some species are more vulnerable than others to disturbance and change.[111] Earlier spring or summer drying of ephemeral wetlands, for example, will threaten reproductive success of certain species such as wood frogs and many salamanders in the Great Lakes region (Figure 22).[112]

In times of drought, when individual wetlands are isolated from one another, deep wetlands serve as a safe haven or "refugia" for plants and animals until water levels are restored in dried-out wetlands. Loss of these refugia during longer or more severe droughts will threaten populations of amphibians and other less-mobile species. Landscape fragmentation exacerbates this situation, leaving refugia scarcer and more isolated.[113]

Wetland loss and degradation also threaten to drive the yellow-headed blackbird locally extinct in the Great Lakes region. This songbird's habitat is restricted to a small subset of marshes that have suitable vegetation in any given year as a result of fluctuations in water level. Land-use changes have greatly reduced the amount of suitable habitat, and further changes in water levels caused by increases in spring rain or summer drying could render remaining marshes unusable (see box, p.30).

Finally, most aquatic birds in the region depend upon seasonal flood pulses and gradual drops in water levels. Changes in the timing and severity of the flood pulse will affect the availability of safe breeding sites for birds and amphibians. Midsummer "spike" floods, for example, can flood bird nests in small wetlands and attract predators such as raccoons to areas where birds and amphibians breed. Changes in the timing of the spring melt also greatly alter migratory pathways and timing. Canada geese, which formerly wintered in flocks of hundreds of thousands in southern Illinois, now mainly winter in Wisconsin and further north in Illinois. The availability of seasonal mudflats for migratory shorebirds and endangered, beach-nesting species such as the piping plover will be affected by the drying or loss of wetlands.

FIGURE 22

Leopard Frog in Wisconsin Wetland

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Fish Responses to Climate Change

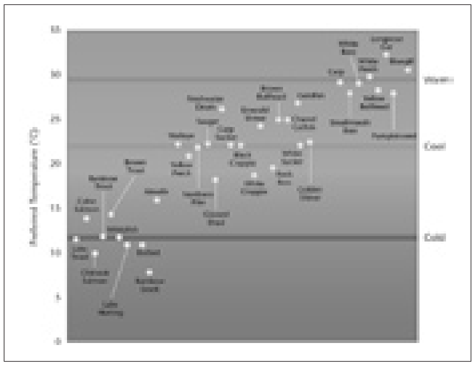
The body temperature of a fish is essentially equal to the temperature of the water in which it lives, and each species has a characteristic preferred temperature. Rates of food consumption, metabolism, and growth rise slowly as the preferred temperature is approached from below, and drop rapidly after it is exceeded until reaching zero at the lethal temperature. Common species of fish can be grouped according to their preferred temperatures into "guilds" (Figure 23). Fish will respond strongly to changes in water volume, water flow, and water temperatures, either by shifts in distribution or in overall productivity.

Changes in Fish Distribution

Individual fish actively select and rapidly change living areas based on suitable temperatures, oxygen concentrations, and food availability. Cold-water fish actively avoid temperatures that exceed their preferred temperature by 3.5 to 9°F (2 to 5°C, depending on the species) and seek out refuges provided by sources of cooler water such as groundwater or seepage areas and headwater streams.[114] Physical constraints such as drainage patterns, waterfalls, and land-locked areas play a large role in determining the boundaries of a species' range and the rate at which it may respond to changing conditions. For example, temperature constraints prevented white perch from the Atlantic coast from invading Lake Ontario until the 1930s. Then, a series of warm winters over a 20-year

FIGURE 23

Temperature Groupings of Common Great Lakes Fish



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for full-size color image of this figure period permitted this species to spread through the Hudson River and Erie barge canal and into Lake Ontario by 1950.[115] Table 6 summarizes the potential impacts of climate warming on the distribution of fish species in the Great Lakes region.

Populations living near the edge of the species' range often exhibit greater year-to-year variation in abundance than populations living near the center of the range.[116] Thus, when a southern boundary retracts northward, populations with historically stable abundances may become more variable. Populations living at the northern edge of the range tend to exhibit lower growth rates and greater sensitivity to exploitation. Thus, when a northern boundary extends northward, populations near the old boundary may become less sensitive to exploitation and exhibit more stable abundance.

Many studies have forecast a potential northward expansion of the distribution of smallmouth bass, a typical warm-water species that is native to the southern part of the Great Lakes basin.[117] Recent work indicates that the consequences of that expansion could include local extirpation of many native minnows and negative impacts on native top predators, particularly lake trout, in newly invaded lakes.[118] These findings clearly demonstrate the ecological disruptions that will occur throughout the region as cold-water species disappear and warm- and cool-water species vie to take their place in a warmer world.

These disruptions are likely to be compounded by invasions of nonnative organisms, many of which are capable of totally restructuring existing food chains and causing significant consequences for native fish communities.[119] The zebra mussel and European carp invasions in the Great Lakes region are perhaps the best examples of such major disruptive events. Climate warming is likely to permit zebra mussels and common carp to expand their existing ranges northward in the Great Lakes region.

As noted earlier, higher summer surface water temperatures and increased summer anoxia in deeper waters may lead to greater release of mercury from sediments.[120] That would lead to higher mercury levels in fish, which would harm not only fish populations but human consumers as well.[50]

TABLE 6 Changes Observed, Predicted, and Possible in the Ranges of Fish Species in the Lakes and Rivers of the Great Lakes Basin

Distributional Changes	Impacts on Species
Extension at northern limit	Perch, smallmouth bass: Predicted 300-mile extension of existing boundary across Canada with 7°F increase in mean annual air temperature[a]
	Smallmouth bass, carp: Predicted 300-mile extension of existing boundary in Ontario with 9°F increase in mean annual air temperature[b]
	Minnows (8 species), sunfishes (7 species), suckers (3 species), topminnows (3 species): Predicted extension into Great Lakes basin possible with warming[c]
Retraction at southern limit	Whitefish, northern pike, walleye: Predicted retraction because of northward shift in sustainable yields expected to result from climate change[d]
	Lake trout and other cold-water species: Retraction predicted in small shield lakes at southern limit because lower O_2 levels will shrink deep-water refuges from predation in summer[e]
	Brook trout: Retraction predicted for streams at lower elevations throughout the southern edge of the range because of expected increases in groundwater temperatures[f]
Barrier release and range expansion	White perch: Observed invasion and spread through Great Lakes basin when 1940s warming of Hudson River and Erie barge canal waters effectively removed thermal barrier and permitted access[g]
	Striped bass: Predictions indicate that warming may permit this species to invade the Great Lakes basin and thus expand its range eastward[h]

Sources: See note 121.

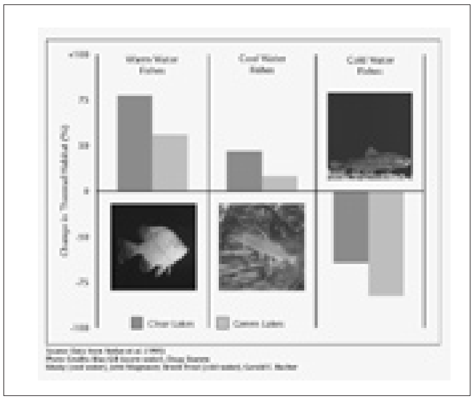
Changes in Fish Productivity

Within a lake, the productivity of a fish population is related to the amount of suitable living space, that is, the volume of thermally suitable water. Studies of walleye, lake trout, and whitefish have demonstrated that the abundance and productivity of fish increase with increased time spent at the optimal temperature.[122] There is also a trade-off between the positive effect of warmer temperatures on fish production and the negative effect of lower lake levels due to drying. For example, given a scenario where annual air temperature rises 5°F (3°C) and lake depth drops 3 feet, data from North American lakes suggest that fish production will decrease in lakes with a mean depth of 10 feet or less and increase in lakes with a mean depth greater than 10 feet.[123]

Production of several species of sport fish (lake trout, walleye, and pike) and commercially harvested fish (whitefish) in the region currently varies with the amount of thermally suitable habitat[122] (Figure 24). Predictions are that climate warming will greatly reduce the amount of thermally suitable habitat for lake trout in many inland lakes.[56] This would effectively eliminate lake trout from almost all shallow lakes in the region because of "summerkill," a lethal combination of high surface water temperatures and decreased oxygen in bottom waters. This forecast is consistent with earlier work that predicted cold-water fish living in large, cold lakes will be the most secure against the negative impacts of climate change.[124]

In contrast, other studies predict less winterkill of warm- and cool-water fish living in shallow inland lakes because shorter periods of ice cover would eliminate winter oxygen deficits.[56] Most northern lakes are likely to develop more suitable temperatures for walleye, a typical cool-water species in Ontario. However, a few southern lakes are likely to become less suitable, with summer temperatures reaching levels too warm for optimal growth.[26]

FIGURE 24
Water Temperature and Fish Distribution Changes



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Economic Consequences of Climate and Ecological Change in Aquatic Systems

Water Levels, Shipping, and Hydropower Generation

Decreases in water levels have broad implications for both ecological and human systems in and around the large lakes. Ship clearance in channels and harbors is reduced, requiring ships to carry less weight in order to ride higher in the water. The Great Lakes Carriers Association estimates that with a one-inch drop in lake level, a 1,000-foot ship loses 270 tons of cargo capacity.[125] An earlier assessment based on milder projections of warming found that shipping costs could increase by 5 to 40 percent as a result of lower lake levels.[126] A potential counter to this negative impact is that reduced ice cover will lengthen the shipping season on the Great Lakes.

Stepped-up dredging of channels and harbors is often used to increase ship clearance in times of low water, incurring both direct economic costs and environmental costs. The direct costs of dredging could exceed $100 million (US) annually.[125] But dredging often stirs up buried pollutants, which may impose additional costs on society. The estimated costs for a four- to eight-foot drop in water level range from $138 million to $312 million (US), and the price for extending water supply pipes, docks, and stormwater out-falls to the new waterline would add another $132 million to $228 million (US).[125]

Decreased water levels could reduce hydropower generation by as much as 15 percent by 2050, an estimate that is likely to be conservative because it was based on older climate models.[126] Hydropower accounts for almost 25 percent of the electricity generated in Ontario,[16] while in the United States, significant hydropower is generated at the Moses Niagara Plant in New York State (Figure 25). Demand for more hydropower will be created in the future by the need

TABLE 7 **Climate Change Impacts on Fish Ecology and Consequences for Fisheries**

Climate Change Impacts on Fish Ecology	Consequences for Fisheries
Change in overall fish production in a particular aquatic ecosystem	Change in sustainable harvests for all fish populations in the ecosystem
Change in relative productivity of individual fish populations in a particular aquatic ecosystem	Change in the relative levels of exploitation that can be sustainably directed against the fish populations of the ecosystem
Large-scale shifts in geographic distribution of species	Change in mixture of species that can be sustainably harvested within a specific geographic area Change in location of profitable fishing grounds
Small-scale shifts in the spatial distribution of members of a specific population	Change in sustainable harvest for the population Change in efficiency of fishing gear, leading to change in sustainable levels of fishing effort

to reduce CO_2 emissions from fossil fuel-fired power plants. As hydropower opportunities decline in the Great Lakes region, pressure may increase to build such projects elsewhere, such as in the James Bay region.

Water withdrawals from the Great Lakes are already subject to contentious debate, and political leaders in the region have opposed further withdrawals, especially for water to be shipped out of the basin. Given projections for drier summers in the region, pressure to increase water extraction for irrigation, drinking, and other uses will grow even within the basin. One study found that the synergistic effects of predicted decreases in runoff and increases in irrigation could be devastating to the region's streams.[127]

FIGURE 25
Water Changes Affect Hydropower

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for full-size color image of this figure

Fisheries

Climate-driven changes in fish populations and communities will produce a variety of impacts on existing fisheries (Table 7). Most of these impacts will stem from two mechanisms: (1) the sustainable harvest of fish will rise and fall with shifts in overall aquatic productivity, and (2) sustainable harvests from a specific population in a specific location may increase substantially or fall to zero, depending on how new climate conditions and species-specific temperature needs interact.

The commercial fishing sector in the region is relatively small. Landed catches in the late 1990s were valued at about $47 million (US), including $33 million taken by Canadian fishers and $14 million taken by US fishers. Most of the commercial catch in Canada comes from Lake Erie and that in the United States from Lake Michigan.

In contrast, the recreational fishing sector is quite large in both countries. In the 1990s, 7.7 million recreational anglers spent $7.6 billion (US) on fishing in US waters[13] and 2 million anglers spent $3 billion (Cdn) on fishing in Canadian waters.[128] These anglers spent about 9 million fishing days on the Great Lakes alone, not counting fishing on inland lakes, rivers, and streams. Large changes in the distribution and productivity of fish species in the region will significantly impact the nearly 10 million anglers that actively fish these waters.

These dollar figures do not reflect the full value of ceremonial and artisanal fisheries practiced by Native Americans and First Nations in many settlements scattered throughout the Great Lakes basin. Fishing plays an important role in the traditional social structures of these communities, a role that defies easy quantification and will not be reflected in cost accountings of impacts that are based purely on market measures.