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Lake Erie's Fish Community: 150 Years of Cultural Stresses

H. A. Regier and W. L. Hartman

Lake Erie's biotic community is not dead, although its condition is far from the healthy state that humans find most appealing. Fortunately, the reduction of various stresses, such as nutrient loading from metropolitan waste-treatment effluents, and the prevention of major new stresses, will permit the habitat and biota to recover many of their more desirable characteristics. In no event, however, will the recovery be complete; some taxa are extinct, new taxa have colonized the lake, and parts of the habitat have been irreversibly damaged. Millions of humans will continue to use Lake Erie directly and indirectly in many ways inimical to full recovery, despite our highest resolve and best collective efforts. But perhaps full recovery is not the ultimate goal; if, for example, it meant the return of mosquitoes in their original numbers, with the attendant epidemics of malaria, few of us would choose it.

We distinguish here between natural and cultural stresses. Natural stresses result from extreme or unusual manifestations of physical, chemical, and biological variables that are largely independent of man's activities; some examples are climatic warming or cooling and unseasonably heavy precipitation. Cultural stresses, on the other hand, are the direct or indirect consequences of man's activities; two examples are commercial fishing and cultural eutrophication—the steady increase in nutrient supply that results from agricultural, industrial, and population growth in the drainage basin.

In this review we contrast primeval Lake Erie with Lake Erie today (Fig. 1), identify the major ecological stresses, consider the effects of the fishery and other cultural stresses on the lake's resources, explore the difficulties in managing common property resources, and outline current initiatives of fishery research and management.

Conflict between Nature and Culture

Lake Erie has changed greatly since 1669, when it was "discovered" by Louis Joliet; today more than 13 million people live in its watershed. Even in the late 1700's, when the human population was less than one-thousandth its present size, the land in the drainage basin still supported large stands of timber—primarily beech-birch, maple-hemlock, and oak-hickory associations. Interspersed were vast savannahs of grass and wild oats 2 to 3 meters high. Large marshes bordered the lake. The Great Black Swamp at the southwest corner of the lake was a wet forest of roughly a million hectares. Because of the thick vegetative cover, soil erosion was limited, runoff waters were generally clean and soft, stream and river bottoms were free of clayey silts, and marshes and protected shallow bays supported luxuriant aquatic vegetation. By 1870, most of the woodlands had been cleared, the savannahs burned, and some swamplands drained; these areas had been turned into rich farmlands (*1*, *2*). Exposed soil was washed into rivers and inshore lake areas, and the increased deposits of clay and fine silt covered valuable spawning grounds of many species of fish such as the walleye and the lake whitefish. Aquatic vegetation in nursery marshes and bays declined. Nearly all the swamps were eventually drained in the early 1900's, which destroyed more spawning and nursery areas. Meanwhile, hundreds of mill dams impeded or blocked walleye, sturgeon, and other fishes from their traditional river spawning areas (*1*).

The quality of Lake Erie's water when its shores were first settled was solely the result of natural processes: organic and inorganic materials were leached from the watershed; water containing low concentrations of nutrient ions and organic substances flowed into Lake Erie from the upper Great Lakes; and precipitation contributed some ions and particles. Inflow rates of nutrients were relatively low. Most lake water was clear throughout the year, and free from blooms of algae. Today, nutrients that flow into the lake at high rates feed dense blooms of planktonic algae —especially the blue-green algae that are now so prevalent and obnoxious in late summer in the shallow western end of the lake. Death of the algae periodically reduces oxygen throughout the bottom waters of the lake, especially in the large Central Basin.

At the time of settlement, the great quantity and variety of fish inhabiting the lake and its tributaries included many of the larger, preferred food and game fishes—smallmouth and largemouth bass, muskellunge, northern pike, and channel catfish inshore; and lake herring, blue pike, lake whitefish, lake sturgeon, walleye, sauger, freshwater drum, and white bass in the open lake (*3*). Even lake trout maintained a moderate population in the eastern end of the lake. Some of these species moved into tributaries to spawn and were readily captured by Indians and the early settlers. Today, the blue pike, sauger, and native lake trout are gone;

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very few sturgeon, lake herring, lake whitefish, and muskellunge remain; and the numbers of walleye and northern pike are greatly reduced (*4*). The present fish community is dominated by yellow perch, white bass, channel catfish, freshwater drum, carp, goldfish, and rainbow smelt.

Ecological Stresses: Cultural and Natural

Obviously, Lake Erie, as well as many other great lakes of the world—Washington, Huron, Michigan, Ontario, Geneva, Maggiore, Vatter, and Constance (the Bodensee), has been adversely affected by man's activities (*5*). Consequently, the development of a general classification of cultural stresses on aquatic ecosystems is a matter of practical urgency. We distinguish here the following major cultural stresses in Lake Erie: the commercial fishery as a predatory process, in which the predator has been to some extent external to the system; cultural eutrophication; the introduction of, or invasion by, nonindigenous aquatic species; tributary and shoreline restructuring (for example, mill-dam construction and marsh drainage); turbidity and siltation caused by the continuing inflow of fine, inert materials; the release of toxic materials from industrial sources, vessels, and vehicles; and the unintended introduction of biocides.

No natural stress that has waxed and waned during the past 200 years has had a more profound, long-term, direct effect than any one of the above cultural stresses. Certainly a violent storm that causes a pronounced seiche may have marked effects on a system, some of which may persist for a considerable period. Short-term climatic effects are also widely recognized as being ecologically important. It has often been argued that a gradual increase of from 1° to 2°C in the average annual air temperature, recorded since about 1920 in the Lake Erie region (*6*), may have seriously stressed certain species of fish that approach their southernmost zoogeographic limits in this lake (*7*). For various reasons, we doubt that such natural stresses have been *primarily* responsible for most of the imbalance in the lake's ecosystem or in any major component of it. In the presence of pronounced cultural stresses, however, the severity of natural stresses may be compounded. Thus, if the spawning grounds of a species have been progressively reduced to a few vulnerable locations by intensive fishing or by environmental degradation, small climatic deviations may then lead to periodic failures of the reproductive process. Of course, climatic fluctuations alone may inhibit the reproductive process as well as reproductive success.

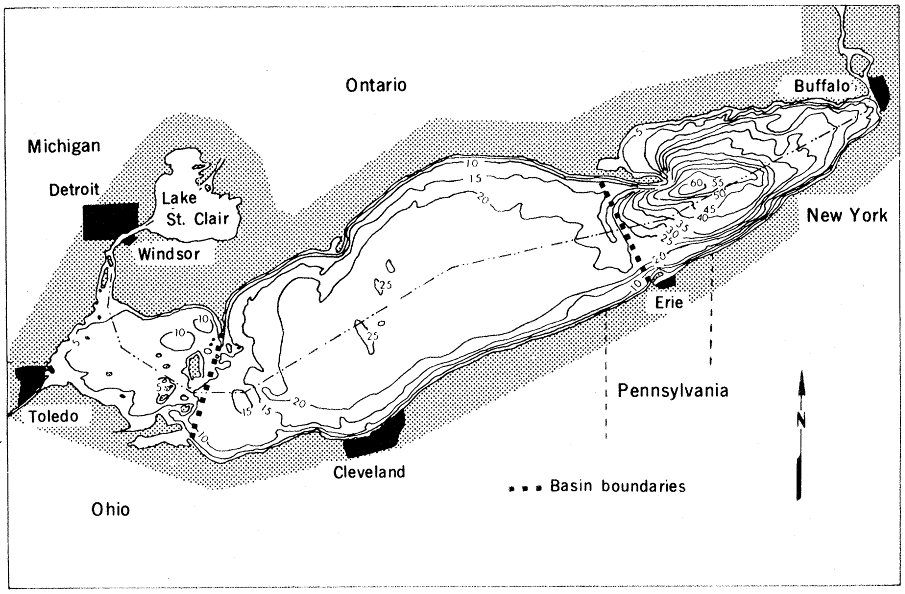

Fig. 1. Lake Erie, with depth contours shown in meters. Dashed lines separate the Central Basin from the Western and Eastern basins.

The Commercial Fishery

The commercial catch of fish from Lake Erie over the past 150 years has exceeded that of the other four Great Lakes combined. The fisheries for lake herring, lake whitefish, blue pike, and now yellow perch and rainbow smelt have been outstanding: total fish harvests have averaged about 9 kilograms per hectare per year.

The commercial fishery began after the War of 1812, while the south shore of Lake Erie was being rapidly settled and development of the north shore was advancing at a more deliberate pace. Subsistence fishing was practiced in the streams and coves of the lake. At the outset, populations of towns were small, the preferred species were readily caught, and transportation systems were inadequate; consequently, no market or commercial fishing of appreciable scope developed until about 1820. During the ensuing 70 years, however, social, economic, and technological developments were so rapid that the catches increased at an average rate of about 20 percent per year (Fig. 2). (The intensity of fishing—although not the size of the catches—continued to increase, with some minor dips, long beyond 1890, and probably did not peak until the late 1950's.)

Transportation was improved, and new markets were made available by the opening or improvement of canals: the Erie Canal linking the Niagara River at Buffalo and the Hudson River was completed in 1825, the Welland Canal which directly linked lakes Erie and Ontario was opened in 1829, and the Erie-Ohio Canal to the Maumee River upstream from Toledo was opened in 1832.

The efficiency of fishing gear improved rapidly during this early period. Before 1850, fishermen used hooks, seines, and small stationary gear, such as traps and weirs. Gill nets and pound nets first came into use in the 1850's. The American Civil War then spurred development of the Lake Erie fishery; gill nets and pound nets began to be used progressively further offshore, and by 1880 fishing gear was being operated throughout the lake.

The lake sturgeon was the species most seriously affected in the 1860's, as it became a serious problem to the early gill-net fishery, which was directed chiefly at lake trout, lake herring, and lake whitefish (*8*). Because the sturgeon was large (sometimes over 80 kg) and had external bony armor, it readily tore the nets set for smaller species. Fishermen then devised heavier nets with large mesh to capture sturgeon and destroyed the fish caught with them—often by piling them like cordwood on the beaches, dousing them with oil, and burning them. As this species grows slowly, does not mature until it is 15 to 25 years old, and is highly vulnerable to most fishing gear, it was rapidly reduced to commercial insignificance. Lake Erie fishermen saw no value in this fish until the 1860's, when an immigrant from Europe arrived with a knowledge of how to smoke it, render its oil, manufacture caviar from its eggs, and make isinglass from its air bladder. By 1870 the sturgeon had become a valued species, but also a much less abundant one. Although stream and marsh populations were probably damaged by other cultural stresses, some sturgeon spawned toward the eastern end of Lake Erie, where environmental conditions must have remained nearly ideal long after sturgeon had dwindled to insignificance. A few are still taken in commercial gear each year.

In the mid-19th century, construction of railroads released the fishery from its dependence on canal transport and greatly expanded the market for fish. The development of reliable methods of refrigeration soon reduced the need for smoking and salt curing. New fishing gear suited to nearshore and offshore waters were introduced from Europe and New England and modified for local conditions. Steamboats large enough to weather almost all Lake Erie storms began to operate, and steam power was also soon applied to the laborious task of setting and hauling gear (*9*). Capital investments were apparently large, and the industry gradually moved from a labor-intensive to a capital-intensive state; much of the capital was under the control of a relatively small number of American firms.

After the near destruction of the sturgeon population, the fishing for lake trout became excessively intense in the 1880's (*10*) and for lake whitefish about 1890 (*11*). Lake trout catches diminished rapidly. Lake whitefish and lake herring catches fluctuated for some decades, being supported in each case by a number of exceptionally large year classes, and ultimately became insignificant (Fig. 2).

The United States dominated the Lake Erie fishery until rather recently. In the early years, U.S. catches were much greater than those in Canadian waters (*12*) because of the earlier development of the fishery in the United States, some fishing by Ohio and New York fishermen in Canadian waters (originally with Canadian concurrence), and some direct offshore commerce between Canadian fishermen and dealers from the United States. Fishing in Canadian waters and the offshore commerce were officially discouraged beginning in the 1880's and largely discontinued by 1920, not without some objections from both sides of the border. Thereafter, U.S. dealers generally purchased Canadian catches at Canadian ports and transported them overland. (During the past two decades fishing in Lake Erie has been dominated by Canadians, in part because of lower labor costs, a more innovative industry, government price supports, and the greater stocks of marketable species in Canadian waters; in addition, the increasing popularity of water recreation has led to a substantial shift in user demands in U.S. waters.)

It was inevitable that undesirable economic and ecological effects would result from the combination of large markets, a technologically advanced fishery which had a free choice of fishing practices, unrestrictive regulations, and the lack of effective breeding programs to compensate for high rates of fish removal. As early as the 1890's, some U.S. fishing enterprises on Lake Erie collapsed because of low catch rates of preferred species. The intensity of fishing by other companies remained high, and the abundance of various species soon began to oscillate irregularly. During the 1890's a number of fishery experts worked strenuously for regulations that would have effectively reduced fishing intensity. Some regulations were in effect by 1905, but full acceptance of stringent restrictions was impossible to achieve. The fish culturists' faith in their approach was pitted against the conservationists' faith in regulations.

The intense debate about stringent fishing regulations versus hatcheries in the period 1890 to 1910 apparently assisted anglers in their attempts to reserve certain species in U.S. waters as sport fish. In Lake Erie these species included smallmouth bass, largemouth bass, nothern pike, and muskellunge. Canadians lagged in this respect, partly because Ontario is well blessed with small inland lakes that satisfy local sportsmen and also because it has no large population centers on Lake Erie.

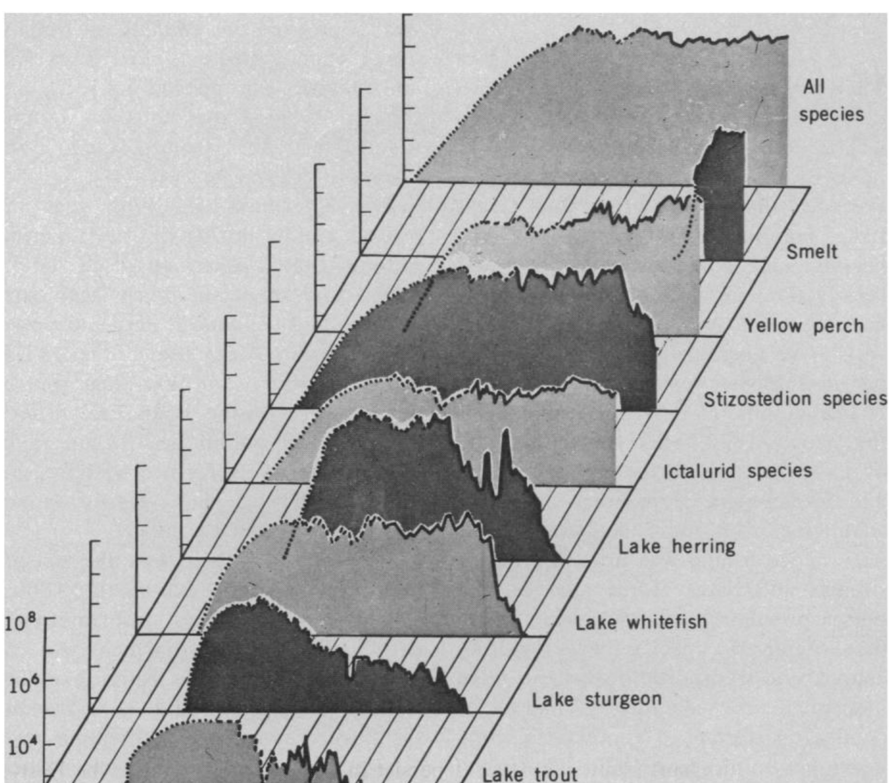

Fig. 2. Annual catches of selected species, and of all species combined, by the Lake Erie commercial fishery since 1820. The vertical scale is logarithmic. Continuous lines represent data reported annually by commercial fishermen, dashed lines represent less firm data that involve considerable interpolation, and dotted lines are based on a number of semiquantitative accounts. *Stizostedion* species include walleye, blue pike, and saugers; *Ictalurid* species include channel catfish and bullhead.

During the last half of the 19th century, with the new problems, new approaches to fishery management began to develop. Because of concern over the depletion of valued stocks in other areas and of lake trout and lake whitefish stocks in Lake Erie, a number of government fishery agencies were created in Canada and the United States in the 1860's and 1870's. Each state and province soon had its own agency, whose interests turned to the collection of catch statistics, fish culture, the introduction of new species of fish, catch regulations, and other methods of fishery management. A need for catch statistics was felt, not only because certain Lake Erie fishes were dwindling, but also because international disputes were developing on the Atlantic Coast and elsewhere in the 1870's. Governments concerned with potential disputes over Lake Erie apparently wished to have adequate data from which to bargain, and therefore created the agencies to collect them.

A voluminous literature on all aspects of fish and fisheries in Lake Erie documented these activities in the period 1870 to 1900. (By comparison the literature on activities during the 1900 to 1930 period is scant; modern fishery science in North America dates from about 1930.)

France in 1850 developed a new technology—the use of fish hatcheries—with the aim of improving the natural reproduction of fish (*13*). The glowing hopes of European fish culturists infected North Americans, including the Lake Erie fishermen, who knew even in 1870 that the most preferred fish were becoming increasingly difficult to take. Consequently, one of the first, and ultimately the most extended, responses of government agencies to falling catch rates in Lake Erie was the development of hatchery and fish stocking programs. Between 1867 and 1920, some 18 hatcheries were constructed on or near Lake Erie. They continued to operate for varying lengths of time, from a couple of years to half a century. All but one have been quietly phased out, because studies in various waters, including Lake Erie, failed to find evidence of significant returns from the stocking of fish fry.

A great enthusiasm for exporting and importing organisms was closely associated with the hatchery program. Many fish species were put into or taken out of Lake Erie. These early introductions were not preceded by careful study, nor were they subsequently monitored (*14*). The great majority failed completely, a few had catastrophic effects on the native fish population, others proved harmless, and some have been generally acclaimed as great successes.

During World War I, laissez faire and partial regulation were superseded by incentives to increase fish production. Fish prices rose, and the industry began to thrive.

Development of new gear and materials greatly increased fishing efficiency, partly by reducing the degree to which each gear was selective for a particular species. A very efficient, large, gill net—the so-called bull net—was introduced in 1905 and soon became widely used. Because of its efficiency, particularly in taking immature whitefish, the net was considered excessively wasteful. Between 1929 and 1934, its use was outlawed in one jurisdiction after another. The U.S. fisheries then became dominated by Ohio trap netters, who were more conservative in their fishing practices. The Canadians concentrated on the use of gill nets and pound nets.

The efficiency of gill nets, originally made of cotton or linen, improved markedly—by a factor of at least 2 or 3—when nylon materials were introduced in the early 1950's. Nylon had a further important advantage: because few microorganisms attack nylon, it is not necessary for fishermen to rack and dry the nets every few days. Consequently, effective fishing time per unit of gear also increased significantly.

When Canadian fishermen experienced high catch rates with nylon gill nets, Ohio fishermen increased their fishing effort with this new gear, without reducing the number of trap nets. The result was the most intensive fishing in Lake Erie's history for walleye, blue pike, and yellow perch in the mid- and late 1950's. By 1960, the stocks of blue pike and walleye had been depleted, and commercial catches in gill nets and trap nets consisted primarily of medium-value fish such as yellow perch, smelt, and white bass. Bottom trawling for smelt was successful in Canadian waters, and sizable landings of low-value fish such as carp, goldfish, and freshwater drum were made with haul seines in the shallow bays. Unfortunately, during the 1960's, large numbers of immature walleye continued to be caught in gill nets with the yellow perch and white bass. This added further stress to the depleted stocks of walleye (*15*).

Other Cultural Stresses

Another powerful cultural stress exerted on Lake Erie has been the nutrient loading of the aquatic environment from agricultural, industrial, and metropolitan sources. Its effects have differed considerably in different parts of the lake, because of differences in the morphometry of the three main basins and in their proximity to the sources of nutrients.

The Western Basin is the smallest and shallowest. It has an average depth of 7.4 m and encompasses only 13 percent of the total area of the lake and 5 percent of its volume. The many shoals and rocky reefs in this basin continue to be swept clean by storms, but deeper areas are filling with recent sediments. This basin has long been considered to have the most valuable fish spawning and nursery grounds in the lake and is the site of extensive boating, fishing, and other recreational activities. Because of its small size and proximity to the large urban areas of Detroit and Toledo, however, it has been especially vulnerable to pollution and nutrient loading. The Detroit River, for example, contributes 6×10^9 liters of industrial and domestic waste per day. This basin seldom stratifies thermally during the summer because of its small size and shallow depth and the large inflows from the Detroit, Raisin, and Maumee rivers.

The Central Basin is the largest. It averages 18.5 m in depth and has a large, flat, muddy plain at a depth of between 18 and 24 m. It makes up 63 percent of both the area and the volume of the lake. In contrast to the Western Basin, the Central Basin is deep enough so that it stratifies in summer, but not so deep that its bottom waters have a large reserve of dissolved oxygen at the onset of summer stratification, which is the period of isolation from atmospheric recharging.

The Eastern Basin has an average depth of 24.4 m and a maximum depth of 64 m. It encompasses 24 percent of the lake's surface area and 32 percent of its volume. Only here do the glacial relict, benthic populations of the opossum shrimp, *Mysis relicta*, and the burrowing amphipod, *Pontoporeia affinis*, persist in significant numbers. The Eastern Basin has received less sediment and nutrients than the other basins because most of the material that flows into the lake is deposited in the Western and Central basins.

Cultural eutrophication has caused

several marked changes in Lake Erie. Among these is the great increase in total concentrations of most major ions over the past 50 years (*16*). Total dissolved solids have risen from 133 to 183 milligrams per liter, and concentrations of calcium, chloride, sodium plus potassium, and sulfate have risen by 8, 16, 5, and 11 mg/liter, respectively. The nutrient ions, nitrogen, and phosphorus, appear to have increased threefold since 1930.

The algae of Lake Erie have also undergone enormous changes (*17*). Average summer densities have increased only threefold, but the broad extension of spring and fall maximum densities are reflected in the nearly 20-fold increase since 1919 in the algal biomass produced annually. Qualitative changes have also occurred. Oligotrophic forms of *Asterionella* and *Synedra* once dominated the phytoplankton pulses in spring and fall; then the eutrophic *Melosira* and *Fragilaria* began to dominate the spring pulses, and by 1970 the fall pulses were dominated by three eutrophic blue-green algae—*Anabaena*, *Microcystis*, and *Aphanizomenon*.

The fallout of dead organic material from greatly increased phytoplankton pulses has had profound effects on the bottom fauna. By 1953 the chemical oxygen demand in the sediments of the Western Basin was so high that after a 28-day period of calm weather in midsummer, during which the water was thermally stratified, dissolved oxygen in the bottom waters dropped from the usual concentration of about 9 mg/liter to about 1 mg/liter (*18*). As a consequence, the dominant benthic form, the large burrowing mayfly, *Hexagenia*, which requires adequately oxygenated water for survival, was nearly eradicated (*19*). Nutrient loading continued, phytoplankton pulses enlarged, and oxygen demands in the sediments increased, until by 1963 only 5 days of hot, calm weather in summer were required for dissolved oxygen concentrations in bottom waters to drop to extremely low levels. *Hexagenia* has now been replaced primarily by oligochaetes and chironomids, which have a low oxygen tolerance.

The impact of nutrient loading and oxygen depletion on the fish community of Lake Erie has been most clear-cut in the Central Basin. Some reductions in hypolimnetic oxygen concentrations were first noted in 1929 in the heavily enriched southwest end, and by the late 1950's large areas of the basin's hypolimnion were becoming anoxic for weeks during mid- and late summer. The area and duration of hypolimnial anoxia has increased progressively since then (*20*). In the small, deep Eastern Basin, the oxygen in the cold bottom waters is only now reaching low concentrations in late summer.

The metalimnion and hypolimnion of the Central and Eastern basins were summer sanctuaries for many valued cold-water fishes—lake trout, lake herring, lake whitefish, and blue pike. During this century, catches of all these species have fluctuated greatly and all populations have declined to commercial extinction (the first three species) or possible biological extinction (the blue pike).

We suspect that the increasing fluctuations in the catches of these cold-water species have been due partly to year-to-year differences in oxygen regimes and algal food as the environment worsened because of accelerated eutrophication. The variability may also have been generated or reinforced by periodic intense predation (including cannibalism) by an occasional large year class (cohort) in succeeding year classes. The flexible, opportunistic, and intense fishing, which was already heavily stressing the fishery resources, probably acted in concert with the developing environmental stresses to increase the fluctuations in catches and extend them to a series of species.

Eutrophication of the Central Basin prior to 1900 should have caused a marked increase in the production of fish, accompanied by a gradual trend toward an increase in numbers of the more pelagic species. As the areas of low oxygen content increased, mobility of the fish should have increased, and this greater mobility should have brought about higher catch rates in stationary gear. Published catch statistics show that the largest catches usually immediately preceded the great declines. Abundance estimates based on these higher catch rates were probably excessive, however, when compared with those based on catch rates in earlier times of less environmental stress and normal fish mobility.

The major effect of eutrophication may have been a gradual restriction of suitable spawning, resting, and feeding habitats—a process that tended to make the affected species more vulnerable to other stresses. Thus the abundance of blue pike, whitefish, and lake herring, like that of lake trout and lake sturgeon, might eventually have become greatly reduced, even in the absence of fishing. If rainbow smelt (discussed below) had not invaded the lake, however, and if the fishing had been suitably regulated, it seems likely that all these preferred species would still be present in at least moderate numbers.

Although eutrophication of the Central Basin, together with intense fishing, has been implicated in the fluctuations and collapse of the dominant species in the hypolimnion, the analysis cannot end there. All these species also inhabited the Eastern Basin, which only now is approaching the degree of hypolimnetic anoxia that directly stresses mature fish. However, fishing and eutrophication were not responsible for the *final* collapse of the dominant fish populations. We suggest that the final collapse was caused by predation by smelt, cannibalistic interactions between year classes of blue pike, predation of blue pike on other species, and species desegregation (*21*)—all intensified by the effects of the fishery.

The rainbow smelt invaded Lake Erie around 1931. Its numbers increased rapidly in the late 1940's, and it became extremely abundant by 1951. Smelt generally occupy pelagic areas of Lake Erie down to the metalimnion during the summer thermal stratification in the Central and Eastern basins (*22*). Young smelt feed on plankton and crustaceans, and yearling and older smelt feed to some extent on small fish. By 1950, the stocks of lake whitefish and lake trout were greatly reduced, and during the late 1950's the blue pike and sauger had almost disappeared and the stocks of walleye were decimated. When predatory pressure on the smelt from trout, blue pike, and sauger was relieved, it became the most abundant fish in the pelagic area of central and eastern Lake Erie. Consequently, the predatory stress exerted on the young of other species by ever-increasing numbers of smelt during the 1950's and 1960's was a significant factor in the severe reduction or extirpation of the young of the remnant stocks of lake herring, sauger, blue pike, lake whitefish, and walleye (*15*).

The sea lamprey invaded Lake Erie via the Welland Canal (*23*) sometime before its first capture in 1921, but it has never become a serious parasite there. It appeared after the major losses of lake trout, lake sturgeon, and lake whitefish, although it probably killed some of each species. Of greater significance is the fact that spawning grounds for the sea lamprey in tributary streams are sharply limited; consequently, lampreys may never become a serious problem—even if the fish communities of Lake Erie are restructured to include large numbers of salmonids, which are the favored prey of sea lampreys in other lakes (*24*).

An additional cultural stress on Lake Erie biota, of unknown effect, is that of toxic pollutants. Persistent biocides, toxic metallic materials, and various organic compounds are found in the flesh of fish in the lake. The discovery in walleye and white bass of concentrations of mercury higher than those deemed acceptable by the U.S. Food and Drug Administration and its Canadian counterpart has led to sharp restrictions in the commercial fishery in the Western Basin. Although the effects of the current levels of DDT, mercury, or selenium in Lake Erie fish on their growth, fecundity, and mortality are suspected to be small, research on this matter is far from complete.

Having mentioned a variety of cultural stresses, we now tentatively list them in order of their net effects on the fish community of Lake Erie, from greatest to least: an opportunistic, uncontrolled fishery; erosion and nutrient loading; invading species; stream destruction and shoreline restructuring; and toxic pollutants and biocides. The adverse effects of exploitation have been relatively sharp, whereas those of nutrient loading, for example, have developed slowly and subtly (although their damage to the fish community may recently have become fully as great).

Common Property Resources: Lake Erie and the Bodensee

When citizens share a resource, its management has generally been very difficult, especially when the responsibility has been divided between two or more jurisdictions. This situation has characterized the management of such resources as water, land, forests, and village commons (*25*)—and certainly the fishery resources of the Great Lakes. In Lake Erie, four U.S. states sovereign in these matters (Michigan, Ohio, Pennsylvania, and New York) and one Canadian province (Ontario), acting generally for Canada, share in the management of fishery resources. Although certain sedentary inshore populations, such as those of smallmouth bass and channel catfish, may rarely move across political boundaries, most of the valued fishes, like lake whitefish and walleye (and perhaps yellow perch), wander or migrate long distances, at least within each of the lake's basins.

Competition between jurisdictions for the same stock has complicated the usual problems of common property that occur within sovereign jurisdictions. The difficulty is further compounded when other users of the lake, like campers, swimmers, boaters, and water skiers, also demand high-quality aquatic resources. Additional complexities arise from the uses of Lake Erie for disposal of wastes, water level regulation, ship channel dredging, ship transport, and other activities that can produce harmful effects across boundaries.

Many attempts have been made, at state and at international levels, to develop institutional mechanisms to deal with the problem of managing Lake Erie as a resource; most have failed (*26*). No attempt has been effective enough to halt the progressive degradation of water quality. The Great Lakes Fishery Commission was established in 1955 to implement a program of sea lamprey control, to formulate and coordinate research programs, and to advise governments on measures to improve fisheries. Yet, regulatory powers remain vested with the various states and Canada, and these powers continue to be jealously guarded; consequently the few multilateral, international measures adopted have failed to adequately protect the common fishery resources in Lake Erie from overexploitation.

Some headway is being made towards regulating a number of transboundary processes inimical to water quality and fish habitat. The International Joint Commission was set up in 1911 to prevent disputes regarding the use of boundary waters and to settle other transboundary questions as they arose. The commission has frequently coordinated investigations by various agencies, and its recent activities have culminated in the "Agreement between Canada and the United States of America on Great Lakes Water Quality" of 15 April 1972. The announced objectives of this agreement were the protection and rehabilitation of the water quality of the Great Lakes, and programs were planned to operate within a specified time period. Although the agreement was signed by President Nixon and Prime Minister Trudeau, ratification and funding by the legislatures of the respective governments have yet to take place.

Lake Erie's degraded state is typical of that of many waters near population centers in North America. By way of contrast, we point to the rehabilitation of the Bodensee in central Europe, where international management of shared fishery resources and water quality has been more successful.

The Bodensee, the largest lake in Europe, is about 50 kilometers long, 10 km wide, and more than 252 m deep. On the southern edge of Germany, it is bordered by two German states, two Swiss cantons, and one Austrian state. The lake's most valuable commercial fish has been the Blaufelchen, a whitefish not unlike the lake herring of the Great Lakes.

Since World War II, industry, tourism, and the resident populace have all grown rapidly in the watershed of the Bodensee. The effluent wastes that were generated added greatly increased quantities of the chief algal growth agents, phosphorus and nitrogen, to the lake. Water quality of the Bodensee became degraded, and the valuable commercial fishery declined and was nearly lost (*27*).

In 1935, the Bodensee had not yet been seriously affected by cultural stresses: phosphorus was almost undetectable, and the nitrate level was about 600 micrograms per cubic meter; open-lake Blaufelchen were the most abundant commercial species, while yellow perch were confined to the shallow-water zones; and most of the Blaufelchen, which were more than 310 millimeters long and being caught in 38-mm mesh gill nets, were sexually mature and had already spawned once.

By 1963, cultural stresses had brought about drastic changes: phosphate concentrations had reached 26 $\mu g/m^3$ and nitrate levels more than 800 $\mu g/m^3$; phytoplankton had increased 20-fold, and a late winter oxygen deficit at the bottom was beginning to occur; intensified fishing pressure, cultural eutrophication, and proliferation of yellow perch and roach in pelagic zones contributed to the decline of the Blaufelchen; both the growth rate of Blaufelchen and their length at maturity had increased, so that by 1960 few 310-mm Blaufelchen were sexually mature, and by 1963 almost none of them were; finally, the age of Blaufelchen in the catch had considerably decreased—whereas most Blaufelchen caught in 1935 were 5 years old, most taken in the 1950's were 2 to 3 years old, and nearly 80 percent of those caught in the early 1960's were less than 2 years old.

The crisis for Blaufelchen and the

commercial fishery had obviously arrived by 1963. As recently as 1956, the catch of Blaufelchen was 839,000 kg, but by 1963 it had dwindled to 100,000 kg—the lowest recorded catch since the recording of catch statistics began in 1922. Of even greater gravity was the virtual absence of sexually mature fish among those taken during the 1963 fall fishing season. Nearly all of the more rapidly growing Blaufelchen were being caught before they reached sexual maturity. The Blaufelchen was headed toward complete collapse.

The International Commission for the Bodensee Fishery, at its annual meeting in 1963, heard the International Biological Subcommission recommend the closing of the Blaufelchen fishery in 1964 and an increase in the gill net mesh size to 43 mm, a size in which Blaufelchen of a minimum length of about 350 mm can be caught. After the 1-year moratorium, 400,000 kg of Blaufelchen were caught in 1965, and the catch has slowly increased since then. The age of fish in the catch has increased and the proportion of sexually mature Blaufelchen in the catch has climbed sharply.

The International Water Protection Commission for the Bodensee recommended in the 1960's that the discharge of pollutants into the lake be limited uniformly. All bordering states and cantons have enlarged their mechanical and biological sewage treatment works. In addition, chemical plants are being constructed that will soon eliminate 90 percent of the phosphorus entering the lake in domestic wastes.

This example of successful multilateral international coordination of fishery and water management, with biological evidence and recommendations contributed by scientific advisors, complements a very few successful multilateral programs for marine fish and mammals. The jurisdictional mechanisms needed to duplicate this program in the Great Lakes of North America are available. Only the requisite resolve and action by the responsible parties is lacking.

Fishery Research Initiatives

There is, of course, general agreement that species interact in Lake Erie, that environmental changes may favor a new species over an established one, and that great reductions in one species because of overexploitation or other stresses can favor proliferation of less intensely stressed species. Yet, most fishery research on Lake Erie to date has dealt with single-species problems, or with a particular variety of stress. This type of research will always be necessary. But we infer from the story of Lake Erie and similar lakes (*5*) that broader and more comparative studies of the structure and dynamics of ecosystems are necessary if we are to achieve the insight into the roles of cultural and natural stresses required for predicting the consequences of fishery and environmental management. We need to understand the *mechanisms* that control the flow of energy and material within ecosystems under growing or diminishing stresses.

The environmental degradation of Lake Erie and its effect on the fishery resources has resulted in other new research. Concentrations of such contaminants as mercury, DDT, and polyvinyl chlorides in the flesh of fish will continue to be monitored. Other contaminants may be added to the list. The trophic paths taken by these contaminants must be understood so that it will not be necessary to treat each one as unique.

The historical sequence of eutrophication in western Lake Erie is generally agreed upon, but more analyses of the Central Basin are needed. The rate of healing—the reversal of the stress sequence which should follow intensive international programs for the abatement of nutrient loading and water pollution—can then be more accurately predicted.

The fish community will respond to pollution abatement. Oligotrophication—the recovery process that will accompany substantial reductions in nutrient loading from metropolitan waste effluents—is now under way in a series of lakes in Europe and North America (*28*). Continued and expanded monitoring of the abundance, distribution, and biological characteristics of fish species is critically necessary for making short-term predictions. During oligotrophication, the recovery sequences in Lake Erie can be compared with those in similar lakes to provide broad inferences about the characteristics and rates of response of the ecosystem (*29*).

Finally, much research remains to be done to provide a firmer basis for an interpretation of present surveys and analyses. Historical studies can be done in archives and libraries; biological samples from earlier years now stored in museums and laboratories have not been fully examined; and more historical samples are still in the sediment layers of the lake.

Fishery Management Initiatives

Fishery management initiatives in Lake Erie are being shaped by the forces of cultural stress on the environment and fishery resources of the lake; by the growing demands for use of the resources by sport fishermen, especially in U.S. waters; and by the proposed massive lake cleanup.

The current management objective in Lake Erie is not full restoration of historical fish communities. Such restoration is impossible for several reasons: (i) Viable spawning populations of certain valued fish cannot be easily reestablished because lake tributaries are blocked by dams or silted in, marshes have been destroyed by drainage, and many inshore lake spawning grounds have been covered with silt. (ii) Predation by rainbow smelt (now the most abundant pelagic species of fish) would probably inhibit restoration of lake whitefish and lake herring, or a percid like the blue pike if it were to be introduced. (iii) The existing large populations of freshwater drum (the most abundant nonpelagic species in western Lake Erie), carp, and goldfish might effectively resist the reintroduction of such species as northern pike, lake whitefish, and lake herring.

The current management objective, on the other hand, is the conservation of existing valued species, such as the walleye, yellow perch, and white bass, and an effective restructuring or engineering of new fish communities.

Recreational angling is expanding rapidly in U.S. waters. Competition for certain species—particularly walleye—between American anglers and commercial fishermen from both the United States and Canada is reaching serious proportions. Canadian anglers are also beginning to develop an interest in Lake Erie. Nevertheless, a viable commercial fishery worth millions of dollars still persists in the lake. Perhaps fishery management agencies will further modify their laissez-faire policies. For several decades, they maintained that no regulation was justified unless the need in a particular system was convincingly shown. Their stance was buttressed by an unwillingness to consider fully the data and inferences from Lake Erie and similar lakes, and changes in policy came slowly. But some regulatory measures are being reinstated. Obviously, all fishery managers must be cognizant of, and respond to, the shift in user demands toward angling in both American and Canadian waters.

To respond to the increased demands of anglers, the American states have released hundreds of thousands of fingerling Pacific salmon in Lake Erie—coho since 1968 and chinook since 1971. The results have been mildly encouraging. Growth has been satisfactory, and some mature adults have returned to the streams where they were released, along the south shore of the lake. Yet an open-lake sport fishery has not developed in U.S. waters. Evidently the salmon move north in the summer into Canadian waters, where they remain at depths of about 15 to 20 m, in the coldest waters that still have adequate oxygen. A problem is that some of these salmon are caught by commercial fishermen, particularly in Canadian waters. One proposed solution is regulation of the fisheries so that these salmon are unlikely to be caught. This proposal has not been popular with Ontario fishermen, however, because it might severely restrict Canadian landings of other species.

Species other than the Pacific salmon are being considered as replacements for fish that have been severely reduced or lost during the past century due to cultural stress. Lake trout, steelhead trout, and striped bass lead the list. The abundance of these fish, with the possible exception of striped bass, can be closely regulated by adjustments in stocking because natural spawning areas for such fish are now virtually absent in the lake and its tributaries.

Massive U.S. and Canadian programs to reduce nutrient loading from municipal sewage and detergents have already begun. Reduction of air pollution has already diminished outfall into the lake. If programs proposed in the water quality agreement signed in April 1972 by the United States and Canada are supported by the respective legislatures and adequately funded, the water quality of Lake Erie will improve markedly within the next decade or so. The initial goal of a reduction in nutrient loading is to reduce plankton production sufficiently to ensure that the oxygen in the Central Basin's bottom waters is not reduced to nil in the late summer. Higher standards may be necessary if a satisfactory response by the fish community is to be assured. Once the cold bottom water again becomes available to cold-water fish during the summer, a more desirable fish community may be possible.

Epilogue

With the advent of oligotrophication in Lake Erie, our partial understanding of the effects of 150 years of eutrophication should prove useful in defining variables to be monitored and in making short-term and long-term predictions. Fish are in many ways integrators of our insults to their environment. A clearer understanding of the separate and joint effects of cultural and natural stresses is now developing.

Fisheries, whether recreational or commercial, must be regulated in a way that is meaningful in an ecological, as well as a social, context. The operative principal of recent decades—that very simple regulations with an absolute minimum of constraints are best—is now thoroughly discredited. International and interstate regulatory mechanisms must be strengthened and supported; the tragedies that have resulted from laissez-faire management must be averted in the future.

The separate and joint ecological implications of the demands of various users on Lake Erie must be more clearly identified. Some demands are inconsistent with others, and thus some must be ruled inappropriate. Large amounts of toxic industrial wastes and plant nutrients from domestic sources cannot be accommodated in the future. Many other uses can be fitted together, sometimes in mutually beneficial ways. Recreational and commercial fisheries should be complementary; enlightened and energetic fishery managers can develop regulations to make them so.

In general, the opportunities to use Lake Erie will increase when the opportunism of those who have abused the lake in the past is effectively constrained, and when all agencies involved in protection, wise use, and enhancement of the fishery and associated aquatic resources move forward together in the task with far greater resolve and cooperation than ever before.

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