OHSU-S-85-007

CLEAR TECHNICAL REPORT NO. 300

LIMNOLOGY OF THE ISLANDS REGION OF LAKE ERIE

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Prepared for

Ninth Bioscience Colloquium of the College of Biological Sciences
"Biogeography of the Islands Region of Lake Erie:
A Laboratory for Experiments in Ecology and Evolution"
The Ohio State University
Columbus, Ohio
May 1985

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INTRODUCTION

Lake Erie is one of the largest freshwater lakes in the world, ranking 9th by area and 15th by volume (Herdendorf 1984). It occupies a glacially enlarged and deepened river basin that has been etched in middle Paleozoic rocks (Carman 1946). The lake is naturally divided into three distinct topographic basins; western, central, and eastern. Numerous bedrock islands, reefs, and shoals lie along the divide separating the shallow western basin from the moderately deep central basin (Figure 1). Because the islands occupy this position, a wide diversity of habitats and environmental conditions exist which foster a wide array of aquatic plants and animals.

The nutrient-rich waters of the western basin are more turbid than the other basins because of large sediment loads from the Detroit and Maumee rivers, wave resuspension of silt and clay from the bottom, and high algal productivity. The Detroit River accounts for over 90% of the flow of water into Lake Erie and therefore controls the circulation patterns of the western basin. In this basin the water is normally isothermal from top to bottom; its shallowness precludes the formation of a permanent thermocline. Occasionally, during calm periods in the summer or when internal seiches drive central basin hypolimnetic water into the western basin, the water stratifies thermally leading to rapid oxygen depletion near the lake bottom (Bartish 1984).

Other than the island archipelago and the rising slope of a sand and gravel bar between Point Pelee, Ontario and Vermilion, Ohio, the bottom of the central basin is extremely flat. Although the central basin receives over 95% of its inflow from the western basin, the water is considerably less turbid and less biologically productive. This inflow and drainage from the Sandusky River and other tributaries are concentrated in the sub-basin and along the south shore where biological productivity and contaminants are the highest. Water temperatures in the central basin are isothermal from fall to late spring; thermal stratification normally occurs below 15 m from June until September. During the later part of the stratified period the thin hypolimnion (2-5 m) may lose all of its dissolved oxygen (Herdendorf 1983).

Because the water of the islands region is shallow, warm, relatively clear, and high in nutrients, it supports abundant forms of plankton, benthos, nekton, and aquatic avifauna. The diverse geomorphic features of the region have resulted in the establishment of several aquatic or semi-aquatic ecosystems: 1) coastal marshes and lagoon wetlands, 2) barrier beaches, 3) bedrock reefs and shoals, 4) cliffed shorelines of bedrock, lacustrine deposits and glacial till, 5) limnetic waters and profundal bottoms, and 6) disturbed shores and bottoms, including rip-rap, dredged channels, etc. Each of these ecosystems has its own distinct biotic and abiotic characteristics.

GEOLOGICAL LIMNOLOGY

Morphometry

The Islands Region (Figure 1), encompasses that part of Lake Erie between latitude 41° 25'N and 42°00'N and longitude 82°30'W and 83°10'W, an area of approximately 70 km by 60 km (4,200 km^2). Of this, about 3,600 km^2 is open water of Lake Erie and the remaining 600 km^2 is composed of mainland coast and the islands. The 6 major islands including Pelee, Kelleys, South Bass, Middle Bass, North Bass and Johnson (areas >1.0 km^2), and the 19 smaller ones account for 70 km^2 in surface area (Table 1). The bedrock islands, and associated reefs and shoals, form a natural division between the western and central basins of the lake, and therefore, the surrounding waters are influenced by the limnological characteristics of both basins. The morphometry of a lake refers to its shape or form and is usually expressed as a series of dimensions. Such information is useful in understanding how a lake was formed, how it functions ecologically, and how it will respond to environmental stresses. The major morphometric dimensions of the western and central basins and the entire lake are given in Table 2.

The western basin, lying west of a line from the tip of Point Pelee, Ontario, to Cedar Point, Ohio, is the smallest and the shallowest of the three basins, with most of the bottom at depths between 7 and 10 m (Figure 2). Topographically, the bottom is monotonously flat, except for the sharply rising islands and shoals. The maximum depths in the basin are found in the inter-island channels. The deepest sounding, 19 m, was made in a small depression north of Starve Island Reef; south of Gull Island Shoal, in another depression, a depth of 16 m has been recorded. Elsewhere in the basin these depths are not approached.

From the islands, the central basin extends over 200 km to the east where it is separated from the eastern basin by a relatively shallow sand and gravel bar between Erie, Pennsylvania, and Long Point, Ontario. The central basin has an average depth of 19 m and a maximum depth of 26 m (Figure 2). Except for the island archipelago at its western edge and the rising slopes of a sand and gravel bar (glacial moraine) extending south-southeastward from Point Pelee, Ontario, the bottom of the central basin is extremely flat (Hartley 1961). The depression in the lake bottom between the bar and the islands is known as the Sandusky sub-basin. This sub-basin has an area of approximately 1,350 km^2 and a maximum depth of 16 m.

The shores of islands are rockbound or fringed with rock rubble, chiefly rugged in character, with steep bluffs along most of their western exposures. The highest elevations also occur adjacent to the west shores with more gentle slopes found along the eastern shores giving the islands their distinctive "cuesta" shape. Small sand, cobble or boulder beaches are situated at indentations in the shoreline. The most extensive pocket beach of this type is found in the north embayment at Kelleys Island.

The islands and reefs are arranged in three roughly north-south belts or chains (Figure 3). The most westerly belt lies north of Locust Point and includes approximately 12 reefs and West Sister Island. The middle belt extends from Catawba Island (peninsula) through the Bass and Sister islands, and includes at least 14 reefs and 10 islands. The easterly belt encompasses Johnson Island, Marblehead Peninsula, Kelleys Island, Middle Island and Pelee Island, and about seven reefs and shoals. This arrangement and the cuesta shape of the islands are controlled by the structure and relative resistance of the underlying bedrock.

The bedrock exposed on West Sister Island and on reefs in the vicinity of Locust Point as far east as Niagara Reef is the lower portion of the Tymochtee Dolomite. This formation is highly variable in its resistance to weathering, a factor that may explain the lack of bedrock reefs between Niagara Reef and the Bass Islands.

The reefs (Figure 3) consist of submarine bed-rock exposures and associated rock rubble and gravel. The topography of the reef tops varies from rugged surfaces caused by bedrock pinnacles and large boulders to smooth slabs of nearly horizontally bedded rock. In places the exposed bedrock has the appearance of low stairs with the "steps" dipping slightly to the east from the fringe of the reefs to its crest. All of the bedrock formations that form the reefs are carbonate rocks which contain abundant solution cavities. Most of the reefs are conical in shape and elongated, as are many of the islands, in a northeast-southwest direction. Two factors appear to have influenced this elongation: 1) vertical joint systems in the bedrock which are oriented parallel to the elongation and 2) the elongation is in general agreement with the major trends of glacial ice movements as deduced from grooves found on the islands.

The middle and eastern belts of bedrock islands (Catawba-Bass and Johnson-Kelleys) are characterized by high elevations and cliffs at their western shorelines; elevations generally decrease eastward resulting in shelving rock along the eastern shorelines. The resulting topographic form is that of a cuesta or asymmetrical ridge, where the gentle slope agrees with the dips of resistant beds and the steeper slope is an eroding cliff maintained partly by undercutting of less resistant rocks (Figure 4). Because West Sister Island lies on the west flank of the Cincinnati Arch, the dip of the strata is also to the west. This has resulted in the development of a cuesta with its steep cliff on the east side of the island, the opposite of those formed on the more easterly islands.

Catawba and the Bass islands are underlaid by a band of resistant dolomites of the Bass Island Group. The Put-in-Bay Dolomite of this group is responsible for most of the rugged features of the shoreline. The Tymochtee Formation, which underlies the Put-in-Bay Dolomite at the base of the cliffs, is more readily eroded by waves and results in the undermining of the rock above, which falls away in large blocks, forming nearly vertical walls. The shoreline of Catawba Island consists of an alternation of rocky headlands and glacial bluffs. The dolomite headlands rise to 21 m above lake level, whereas the glacial till is much less resistant to erosion and has been cut back into coves with indentations along the coast. Pebble and cobble beaches have formed locally in the coves.

The shoreline of Catawba and the Bass islands contain many indentations and headlands which owe their origin to such solution processes. Roughly circular lagoons in the bedrock are particularly common along the west shore of Catawba Island (Figure 5). These lagoons are thought to be collapsed caves or sinkholes as evidenced by springs issuing from their bottoms. Formerly lagoons such as these provided excellent protection for coastal wetlands, but in recent years most of them have been developed as small boat harbors. A few natural lagoons still exist along the rocky shores (such as Terwilliger's Pond on South Bass Island) but even these are threatened by the rapid increase in recreational use of the region.

The resistant lower beds of the Columbus Limestone are responsible for the easterly chain of bedrock highs, including Johnson, Kelleys, and Pelee islands. Between South Bass Island and Kelleys Island three shaley formations less resistant than the Put-in-Bay Dolomite and the Columbus Limestone account for the shallow depression between the islands.

The Marblehead Peninsula shore arcs for 6 km from Lakeside to the base of Bay Point and is lined with limestone and dolomite bluffs, generally less than 6 m above lake level. Bay Point extends southward from Marblehead Peninsula for 3 km into Sandusky Bay. This point is a compound spit that is growing from sand contributed by littoral currents moving along Cedar Point and around the end of the Sandusky Harbor jetty. Johnson Island, lying in Sandusky Bay adjacent to Bay Point, is composed of low limestone and glacial till shores. The shore of this island is bordered by discontinuous cobble beaches.

Sandusky Bay also lies at the division of the western and central basins. The rocky peninsulas known as Catawba Island and Marblehead separate the bay from western Lake Erie. This 150 km^2 bay contains only one bedrock island (Johnson Island) and is the estuarine mouth of the Sandusky River. Sandusky Bay has a mean depth of less than 3 m, but is open to Lake Erie through a naturally scoured inlet (Moseley Channel) which reaches a maximum depth of 13 m between Cedar Point and Bay Point.

Sedimentology

The unconsolidated bottom sediments within the Islands Region were deposited by glaciers or settled in prehistoric and modern stages of Lake Erie.

During the Pleistocene Epoch the region was covered by several continental ice sheets and later by a series of glacial lakes resulting in the deposition of glacial till followed by the deposition of lake sediments. The surface over which the glacier moved was a stream entrenched terrain underlain by Silurian and Devonian bedrock, largely limestones, dolomites, and shales. Glaciation moderately scoured the rock surfaces during the ice advances, forming features such as the spectacular grooves on Kelleys Island and most of the other islands. The ice sheets also buried much of the preglacial topography under a blanket of till. Lacustrine sediments, largely fine sand, silt, clay, and organic deposits such as peat, now cover over 90% of the till and bedrock (Figure 6).

The bottom deposits of Lake Erie consist of silt and clay muds, sand and gravel, peat, compact glacio-lacustrine clays, glacial till, shoals of limestone and dolomite bedrock and rubble, shale bedrock shelves, and erratic cobbles and boulders composed chiefly of igneous and metamorphic rocks (Herdendorf 1968). The distribution of bottom sediments is closely related to the bottom topography. The broad, flat areas of the western and central basins have mud bottoms. Midlake bars and nearshore slopes are comprised mostly of sand and gravel or glacial till. Rock is exposed in the shoals of western Lake Erie and along the south shore of the central basin. In general, sand is limited along the shoreline, but extensive dunes have been formed at several places, most notably at the base and southwestern side of Point Pelee. These dunes were formed presumably under the influence of the prevailing southwest winds. Littoral currents have concentrated sand spits, baymouth bars, and harbor breakwalls at such places as Point Pelee, Fish Point (Pelee Island), Port Clinton, East Harbor, Bay Point, and Cedar Point.

The bottom deposits of the Ohio portion of western Lake Erie are composed mainly of mud (semifluid clay- and silt-sized particles) (58%). Sand (17%), mixed mud and sand (12%), mixed sand, gravel, and coarser material (7%), glacio-lacustrine clay (3%), and bedrock (3%) account for the remaining bottom material (Verber 1957). Peat and plant detritus occur in isolated areas along marshy shores. Sand deposits near the entrance to Sandusky Bay have been designated for commercial dredging.

The bedrock core of the reefs and shoals is commonly masked by rubble composed of both local (broken fragments of bedrock) and glacially transported material. The rubble typically ranges from small pebbles to boulders up to 2 m in diameter. On the upper portions of the reefs, isolated patches of sand and gravel commonly fill vertical joint cracks and small depressions in the bedrock; at the fringes of the reefs, sand, gravel, or glacial till lap over the rock. Generally the till consists of a random mixture of clay, silt, sand, and rock fragments.

Test borings into the subsurface bottom deposits in the vicinity of the Lake Erie Islands show a predominance of lake-deposited material with only thin glacial till overlying bedrock (Hartley 1961). Preglacial buried valleys are indicted by bedrock topography, which in places has 60 m of relief. Some boring also indicates the possibility of interglacial or postglacial buried valleys and lower lake stages. Beach deposits and peat have been found 11 to 24 m below the present lake level, buried under more recent deep-water sediments. A radiocarbon date of 6,550 years ago was obtained for a sample of oak wood buried 7 m below the lake bottom (Herdendorf and Braidech 1972). This date permits the calculation of a sedimentation rate of 0.1 m/century. Seismic reflection surveys have revealed a maximum unconsolidated sediment thickness of 84 m in the central basin and 40 m in the western basin.

Recent sedimentation in the Islands Region can be attributed to two primary sources: suspended solids from inflowing streams and bluff material contributed by shore erosion. Over 6,000,000 m tons of clay, silt, and sand are transported annually to Lake Erie from its tributaries. Shore erosion of glacial till and lacustrine clay bluffs is an acute problem at many locations along the shoreline. Maximum shore erosion based on volume of material removed occurs along the north shore of the central basin, although the low-lying south shore of Maumee Bay has experienced the maximum rate of shore recession, which has been as high as 6 m per year. Estimates of erosion rates for the Ohio shoreline indicate that about 6,000 m^3/km of bluff material erode each year. Extended for the entire shore of the lake, 8,500,000 m^3 are contributed to the lake each year, which would equate to a thickness of 0.25 mm if spread uniformly over the lake bottom (Herdendorf 1975). Because of the resistant bedrock which compose the islands, shore erosion is minimal except where wave action undermines certain formations. Such undermining is prevalent at Lighthouse Point of South Bass Island.

PHYSICAL LIMNOLOGY

Hydrology

Two rivers enter Lake Erie west of the Islands Region which dominate water quality conditions surrounding the islands. The Detroit River with a mean flow of 5,140 m^3/sec is the connecting channel for drainage from the upper Great Lakes and delivers 1.6 million tons of suspended solids and 33.6 million tons of dissolved solids to the lake each year. The Maumee River, at 137 m^3/sec is only 3% of the Detroit River flow but yields 2.3 million tons of suspended sediment and 1.4 million tons of dissolved material. This river drains 17,000 km^2 of primarily low lying farm land which accounts for its high sediment load. The high turbidity of the Maumee River significantly diminishes water clarity around the southern islands.

The Sandusky River is the largest stream flowing directly into the Islands Region. This drains an area of 3,700 km^2, has an average flow rate of 30 m^3/sec, and discharges 270,000 metric tons of suspended sediment and 450,000 metric tons of dissolved solids to Sandusky Bay annually. The only other major streams in the region are the Portage and Toussaint rivers with average discharge rates of 11 and 2 m^3/sec, respectively. These two streams yield a combined load of 130,000 tons of suspended sediment and 95,000 tons of dissolved solids to Lake Erie annually.

The average annual rainfall in the Lake Erie basin is about 90 cm. The total land area which drains into Lake Erie, excluding that above the mouth of the Detroit River, is only about twice the area of the water surface of the lake. The large expanse of water affords a great opportunity for evaporation, and the amount of water which has been lost is estimated to be between 85 and 91 cm per year. Therefore evaporation is approximately equivalent to the average annual rainfall over the lake. During dry periods more water may be evaporated from the lake than flows into it from its drainage basin. Under such conditions Lake Erie discharges to the Niagara River a smaller quantity of water than it receives from the Detroit River.

Water level changes on Lake Erie are of two principal types: 1) long period and 2) short period oscillations. Long period fluctuations are related to volumetric changes of the lake, caused principally by variations in precipitation, evaporation, and runoff. These changes include both seasonal fluctuations and those occurring over a period of several years. Short period fluctuations are due to a tilting of the lake surface by wind or by atmospheric pressure differentials. Wind tides, seiches, and harbor surges, which have periods from a few seconds to several days, are examples of short term oscillations. Verber (1960) found sun and lunar tides are negligible, resulting in maximum fluctuations of 3.3 cm.

Long-Period Water Level Fluctuations. The highest and lowest average monthly levels on Lake Erie generally occur in June and February, respectively. This seasonal variation typically ranges from 0.3 to 0.6 m. The plane of reference for charts and navigational works on Lake Erie is known as Low Water Datum (LWD), and stands at an elevation of 173.3 m above the mean at Father Point, Quebec. The water level at Father Point, known as the International Great Lakes Datum or IGLD, 1955, approximates sea level at the place where the flow from the Great Lakes enters the ocean based on water level records for the year 1955. The mean level of Lake Erie for the period of record (1900-83) is 173.9 m as measured by the U. S. Army Corps of Engineers. The highest average monthly level recorded was 174.8 m (reached in June 1973) and the lowest average monthly level recorded was 173.0 m (February 1936). This represents a change in the lake's volume of approximately 10%.

Long-term variations are the result of persistent high or low precipitation. In the mid-1960s on Lake Erie and the upper Great Lakes, there was low precipitation and near record low water levels in the lakes. In 1972-73, there was a higher precipitation and extreme high water levels on Lake Erie. Over a hundred years of records at Cleveland indicate no regular, predictable cycle of levels. The interval between periods of high and low water can vary widely.

Short-Period Water Level Fluctuations. Water levels at the ends of Lake Erie (Toledo and Buffalo) have a much greater fluctuation than near the center. High water levels coupled with northeast storms have produced a maximum rise in level of 3 m above Low Water Datum at Toledo. Conversely, low water and southwest winds have lowered the level to 2 m below Datum, a range of 5 m. Under the influence of wind, currents tend to bank up water on the windward shore. This forced movement of the lake surface is known as wind tide and the amount of rise produced is the wind setup. The resulting free oscillation of the lake surface caused by the inequality of water level is called a seiche. Such free oscillations are nearly continuous in the Islands Region and most often have a period of 12 hours and amplitude of less than 0.7 m with a maximum amplitude of 2 m.

The major seiches on Lake Erie are essentially parallel to the longitudinal axis of the lake. Seiches along this axis have a period of approximately 12 to 14 hours. Seiche periods as recorded for three years at a water level gauge at Put-in-Bay on South Bass Island (Figure 7) indicated that longitudinal seiches were in operation about 44% of the year (Herdendorf and Braidech 1972). Surface winds from the southwest or northeast are likely to produce such seiches along the long axis of the lake. Wind records from Sandusky, Ohio are in agreement with the frequency of seiche periods; surface winds from these directions occur approximately 150 days (42%) of the year.

Circulation and Currents

Water movement in the western basin of Lake Erie is strongly influenced by Detroit River flow. This inflow is composed of three distinct water masses. The midchannel flow predominates and is characterized by: 1) lower temperature, 2) lower specific conductance, 3) greener color and higher transparency, 4) lower phosphorus concentration, 5) higher dissolved-oxygen content, 6) lower chloride-ion concentration, and 7) lower turbidity than the flows on the east and west sides of the river. The midchannel flow penetrates deeply into the western basin where it mixes with other masses and eventually flows into the central basin through Pelee Passage and to a lesser extent through South Passage. The side flows generally cling to the shoreline and recycle in large eddy currents.

In the central basin, the prevailing southwest winds are parallel to the longitudinal axis of the lake. Because of the earth's rotation these winds generate currents which cause a geostrophic transport of water toward the Ohio shore. This convergence of water on the south shore results in a rise in lake level which is equalized by sinking of water along this shore. At the same time the lake level is lowered along the Canadian shore as surface currents move the water offshore. The sinking along the south shore is compensated by a subsurface movement of water toward the north and an upwelling along the Ontario shore.

The central basin thermocline is approximately 10 m shallower adjacent to the north shore than on the south side of the lake. This can be interpreted as an upwelling influenced by the prevailing southwest winds (Herdendorf 1970). The resultant surface currents indicate a net eastward movement, while subsurface readings show a slight net westward movement. This can be explained by the cycle of: 1) surface transport of water toward the southeast, 2) sinking of water off the south shore, 3) subsurface transport toward the north-northwest, and 4) upwelling adjacent to the north shore. The formation of a deep thermocline in the southern half of the central basin results in a relatively thin hypolimnion which is highly susceptible to oxygen depletion by sediments with high oxygen demands. These circumstances result in the presence of anoxic bottom water, particularly in the southwestern part of the basin (Sandusky sub-basin).

The surface currents in the western half of the western basin are dominated by the Detroit River in flow (Figure 8). However, in the Islands Region, the surface flow becomes more influenced by the prevailing southwesterly winds, producing a clockwise flow around the islands. However, the surface flow is often changed by changes in wind direction and intensity. Eddy effects along the sides of the Detroit River inflow lead to sluggish movement of surface water west of Colchester, Ontario and between Stony Point, Michigan and Toledo. These eddies tend to retain waters contained within them, leading to the higher concentrations of pollutants found in these areas.

Bottom currents in much of the western basin of Lake Erie are similar to surface currents, being dominated by the Detroit River inflow (Figure 8). However, in the Islands Region the bottom currents are often the reverse of the surface currents with a counter-clockwise flow around the islands. Like the surface movement, bottom currents can also be changed by the wind, although stronger winds are required to create a major change of pattern.

Herdendorf and Braidech (1972) measured lake currents at 68 stations in the Island Region under various wind conditions during a 10-year period. When data from these measurements were plotted to create current maps, one of the most striking features is that winds from any direction will normally drive surface currents downwind, while subsurface currents are often opposed to the wind. To compensate for the loss of surface water blown downwind, a returning flow of water is created along the bottom. Wind direction, bottom topography and shoreline configuration appear to be the major factors controlling shallow-water current patterns. The average recorded velocity for surface and bottom currents was 14.4 cm/sec and 7.7 cm/sec, respectively. The highest velocities were found in restricted areas such as inter-island channels and in the vicinity of reefs. Currents in excess of 25 cm/sec were found at 35% of the stations, while currents above 50 cm/sec were measured at only one station.

All of the submerged rock exposures within the Islands Region project above the surrounding bottom, and are generally swept clean of sediments by the currents. The relatively clean surface indicates that no permanent sedimentation is taking place on the reefs. However, sediment collectors placed on the reefs indicate that a considerable amount of sediment is being transported over the reefs to be deposited in deeper water. Because the reefs project above the bottom, they are generally areas of higher energy due to the forces of waves and currents. The habitat created closely simulates the environment found in the riffles and streams. Several fish species, particularly the walleye (Stizostedion v. vitreum) which commonly spawns in streams, appear to have enjoyed success in western Lake Erie because of the availability of this type of habitat.

The wind is the over-riding force affecting water circulation of the central basin of Lake Erie. Wind-driven currents are, as the term implies, the movements of water directly caused by wind stress at the water surface. These currents are the fastest and most variable in direction of large-scale water movements. Large volumes of water can be moved in a very short time, as in wind set-up. The orientation of the central basin, with its long axis essentially parallel to the prevailing southwesterly winds makes this effect especially important which can cause dewatering of coastal marshes in the Islands Region. Also, during northeast storms, large volumes of water can be transferred into the western basin, flooding coastal wetlands.

Waves

Wave action follows wind action very closely on Lake Erie because of the shallowness of the lake. Swells, however, often continue into the next day after a storm subsides. The depth of the water and the direction, velocity, duration, and open water fetch of the wind collectively determine the characteristics of waves at a given location. The U. S. Army Corps of Engineers (Resio and Vincent 1976) estimates that off Marblehead Peninsula, with a fetch of 240 km and a wind velocity of 48 km/hr, the maximum wave for Lake Erie is developed in 20 hours. Given these conditions a wave of 3.7 m high with a 6.5 sec period can be attained. Waves of this height break offshore, but reformed waves up to 1.1 m in height can reach the shoreline.

As waves approach the shoreline the water level rises at the shore and the excess water escapes as alongshore (littoral) currents. These currents can be rapid (up to 1.2 m/sec) when waves approach the shore at angles other than perpendicular and can result in the transport of beach materials as large as cobbles (64 to 256 mm in diameter) and boulders (>256 mm). These currents are important agents of erosion, transportation, and deposition of sediments along the barrier beaches which front many of the western Lake Erie coastal marshes.

The rockbound shorelines of islands are undergoing very slow erosion by scour from waves and currents. However, during the recent period of high water many large blocks of dolomite have fallen from high cliffs of several of the islands. This problem has become particularly acute at Lighthouse Point of South Bass Island, where in 1976, it necessitated the relocation of the U. S Coast Guard navigation light tower which was in danger of falling into the lake. The highest incident of erosion appears to take place in the spring and fall. Ground water seeping into cracks and joints in the rock freezes, expands, and tends to split the rock from the cliffs, a process known as frost wedging. This process, coupled with frequent and severe storms in the spring and fall, has resulted in many offshore blocks of dolomite which ring the west shores of several of the islands.

Alongshore currents also produce excellent beaches. One of the best examples in western Lake Erie is Fish Point, a spit at the southern tip of Pelee Island. The sand has come from glacial deposits lying east and west of the island. Converging southerly currents along the east and west sides of the island have built a 3 km-long sand spit.

Thermal Structure

As a consequence of the wide range in the seasonal climatic (thermal) conditions in the Great Lakes region, Lake Erie undergoes a cycle of heat storage and heat loss which involves exchanges of vast amounts of thermal energy. The resultant seasonal cycles of lake temperatures are of great importance to many physical, chemical, and biological processes in the coastal wetlands. A principal component of the heat budget of western Lake Erie is incoming solar radiation. Table 3 contains average daily values of solar radiation received at the surface of the lake for each month.

Western Lake Erie experiences a maximum of about 15 hours of daylight in the summer and 9 hours in the winter. Therefore, the percent of possible sunshine is greatest in midsummer and least in winter. Sunshine in winter is further reduced by the cloud-producing effects of the lake. December and January ordinarily have less than 40% of possible sunshine, while June and July average more than 70%.

Lake Erie water temperatures in the western basin normally fall to 0.5^{o}C about the middle of December and remain at that level until the middle of March. Most winters, the western basin freezes over completely. Ice usually disappears from the Islands Region by late April. Shortly after ice breakup in the spring, the ice drifts eastward and accumulates in the eastern basin.

Western Lake Erie warms up more quickly in the spring heating season and cools more rapidly in fall than does the rest of the lake. The lake normally attains its highest temperature in late July or early August (Figure 9). Nearshore temperatures generally average a few degrees warmer than the open lake, but the entire basin is essentially isothermal in structure throughout the year except when rapid heating causes a temporary thermocline to form or when internal seiches transport central basin hypolimnetic water into the western basin (Bartish 1984). The thermal gradient across these thermoclines is generally less than 3 C^{o}. Prolonged periods of calm weather have produced anoxic or near-anoxic conditions in the ephemeral hypolimnions if they persist longer than a week (Carr et al. 1965). The Detroit River flow also influences the thermal structure of the basin for 10 to 15 km south of its mouth by discharging water several degrees cooler than the water mass found along the south shore (Herdendorf 1969).

The central basin typically stratifies into three distinct layers in early June and turns over in early September. The mean thickness of the epilimnion, mesolimnion, and hypolimnion are 13 m, 2 m, and 4 m, respectively. In general the central basin hypolimnion decreases in thickness, area, and dissolved oxygen throughout the stratified period, but increases in temperature. Thinning of the hypolimnion increases the bottom surface area to water volume ration, which tends to increase the effect of sediment oxygen demand (SOD) on the remaining hypolimnetic water. The SOD rate for central basin sediments is approximately 0.5 g O_2/m^2/day. Because of the shallow nature of the Sandusky sub-basin, this area is generally the first to become anoxic each summer, usually in early August.

CHEMICAL LIMNOLOGY

Suspended Solids

Water clarity, most often measured as either Secchi disk transparency or as turbidity, is an indicator of inorganic and organic particulate matter suspended in the water column as well as phytoplankton biomass. Central basin turbidity is primarily the result of the organic component, whereas in the western basin spring meltwaters carry a large component of inorganic solids to the lake. High turbidity (and conversely low transparency) occurs near the mouths of the Maumee, Portage and Sandusky rivers. In spring a significant amount of this suspended material is transported eastward along the Ohio shore to Catawba and then northward through the Islands Region before passing into the Sandusky sub-basin where considerable deposition occurs. In the late summer transparency levels in the Island Region are once again reduced during algal blooms.

Herdendorf (1983) reports that ten-years of Secchi disk measurements in the western and central basins (1973-1982) show stable conditions with small year to year variability. Typically summer western basin transparency depths range from 0.5 to 3.0 m for offshore stations. In the central basin, measurements range from 2.5 to 8.0 m, improving in an easterly direction. The euphotic zone in the western basin has an average summer thickness of 5 to 7 m, while the central basin is 15 to 18 m.

Trends in dissolved substances in Lake Erie waters can be inferred from long-term records of conductivity, measurements, and determinations of major conservative ions such as chloride. Early records from Beeton (1965) show an exponential rise in concentrations from the early 1900s until the end of the 1960s. Improved management of discharges and high water levels have resulted in significant improvements in the concentration of dissolved ions in the lake (Figure 10). Current conditions in Lake Erie in this regard are similar to those that were found in the lake in the mid-1940s.

Dissolved Solids

Major Ions. Lake Erie waters of the Islands Region are alkaline, having a total alkalinity (as $CaCO_3$) of approximately 90 mg/l and an average pH of 8.3. Total dissolved solids in the water average 182 mg/l which yields a conductivity (25^o) value of about 280 umho/cm. Mean concentrations of major ions are calcium -- 40 mg/l, sulfate -- 22 mg/l, chloride -- 18 mg/l, sodium -- 10 mg/l, magnesium -- 9 mg/l, and potassium -- 2 mg/l. In general, concentrations are slightly higher in the southern Islands Region due to the influence of the Maumee River. The northern islands are more influenced by the less mineralized water of the mid-channel flow of the Detroit River.

Nutrients

Phosphorus has been identified as a limiting nutrient for algal productivity in Lake Erie (Hartley and Potos 1971), whereas nitrogen is in sufficiently large supply in the lake waters that it is not considered limiting to plant growth. The distribution of most nutrients throughout the lake shows similar patterns. Total phosphorus, for example, is characteristically high in concentration near the mouth of major tributaries, particularly the Maumee, Portage, and Sandusky rivers (Figure 11). The Detroit River is an exception in that a large volume of upper Great Lakes water tends to dilute the nutrient load contributed by the urban and industrial complex adjacent to the river.

Annually, approximately 13,000 metric tons of phosphorus are loaded to Lake Erie via tributaries and other sources. The Detroit River accounts for about 38% of this total and the Maumee River adds another 12%. Because of the high clay content in the sediments delivered to the lake, large quantities of phosphorus are absorbed to these particles and become incorporated in the bottom sediment. Approximately 80% of the phosphorus entering Lake Erie in sedimented in this manner and only 20% is discharged via the Niagara River. Improvements in the treatment of waste water in the Detroit metropolitan area in the past decade have resulted in a reduction in phosphorus loading from the Detroit River from 12,000 metric tons in 1970 to only 5,000 in 1980. Conversely, nitrogen is the only major dissolved constituent in the waters of western Lake Erie which has shown a significant increase in the past decade, largely due to the application of chemical fertilizers in the drainage basin.

Nutrient concentrations are high and typical of eutrophic conditions in western Lake Erie whereas in central Lake Erie they are more moderate and typical of mesotrophic conditions. Therefore, the Islands Region can fluctuate depending on the movement of water masses from either basin into the region. Mean annual concentrations for western and central Lake Erie are for total phosphorus --38 and 16 ug/l, for dissolved nitrate + nitrite -- 434 and 178 ug/l, for dissolved silica -- 1.2 and 0.7 mg/l, and for chlorophyll a -- 8.4 and 3.9 ug/l, respectively (Herdendorf 1983).

In the mid 1960s, the concentration of phosphorus in influent wastewater to municipal treatment plants averaged about 10 mg/l within the Lake Erie drainage basin and the mean effluent concentration was approximately 7 mg/l. By 1980, many plants had installed phosphorus removal systems which resulted in an average effluent concentration of only 1.6 mg/l for all Ohio plants and concentrations as low as 0.6 mg/l for the Detroit sewage treatment plant in 1982. As a result, concentrations of total phosphorus in western Lake Erie have declined in the past 2 decades, particularly along the Ontario shore. In 1969, the total phosphorus concentration of the Ontario nearshore waters was about 50 mg/l but by 1979, it had dropped to 25 mg/l.

Chlorophyll pigment in water samples serves as a useful indicator of algal productivity in western Lake Erie. Concentrations are generally the highest along the western and southern shores, especially Sandusky Bay, while the lowest values are found in the water mass influenced by the Detroit River flow. Nearshore concentrations of chlorophyll a correspond to the same patterns observed for phosphorus. The most significant difference occurs in Maumee Bay where chlorophyll is high, but proportionally lower than phosphorus values. The high sediment turbidity of these waters is thought to be the major cause, resulting in reduced light levels for algal photosynthesis. In the central basin concentrations are less than half those of the western basin yielding a strong gradient east of the Islands Region.

Trace Substances. Toxic pollutants in Lake Erie generally occur in trace amounts. They are introduced to the lake through municipal and industrial wastewater discharges, atmospheric deposition, and urban and agricultural land runoff. In the Islands Region, interlake transfer via the Detroit River is also a significant source of contaminants. Ten heavy metals (Cd, Cr, Cu, Pb, Mn, Vd, Hg, Ni, Ag and Zn) and six organic pollutants (benzene, chloroform, methylene chloride, bis [2 ethylexyl] phthalate, tetra-chloroethylene, and toluene) occur in most effluents from major municipal wastewater treatment plants in the western Lake Erie basin, but none in alarming concentrations. However, high concentrations of some metals have been found in surface sediments adjacent to tributary mouths at major industrial areas. In particular, mud deposits at the mouth of the Detroit River show elevated levels of most of these metals (Drynan 1982).

Sediment cores taken at the mouth of the Detroit River and in western Lake Erie in 1971 yielded surface mercury values up to 3.8 ppm and generally decreased in concentration exponentially with depth (Walters et al. 1974). High surface values were attributed to waste discharge from chlor-alkali plants on the Detroit and St. Clair rivers which operated during the period 1950 to 1970. Several years after these plants diminished operation the area was again cored with analyses showing that recent deposits covered the highly contaminated sediment with a thin layer of new material which had mercury concentrations approaching background levels (0.1 ppm). As a result of these discharges, mercury in fish of Lake St. Clair and western Lake Erie was a major contaminant problem in the early 1970s. Fortunately, levels of total mercury in walleye declined from 2.0 ug/g in 1970 to 0.5 ug/g in 1980. The rapid environmental response subsequent to the cessation of the point source discharges can be attributed to rapid flushing of the system, the high load of suspended sediment delivered to western Lake Erie, and the high rate of biological productivity.

Levels of PCB and DDT in spottail shiners (Notropis hudsonius) and in herring gull (Laurus argentatus) eggs have declined in the past decade, illustrating a system-wide response to controls on production and use of these compounds. PCB levels in shiners at Point Pelee dropped from 844 ng/g in 1975 to 150 ng/g in 1980 while during the same period DDT fell from 92 to 21 ng/g (International Joint Commission 1981).

Dissolved Gases

Dissolved oxygen in the surface waters of the Islands Region varies considerably in concentration depending on the time of day and the season. Most O_2 is supplied to the surface water by absorption from the atmosphere and is transferred to the lower layers by wind-generated mixing until the saturation level is reached for the temperature of the particular water mass. Supersaturation commonly occurs as a result of photosynthetic activity of phytoplankton.

Bartish (1984) reported that stratification of western Lake Erie normally occurs 3 to 5 times per year by two process: 1) meteorological conditions (calm, warm weather) and 2) hydromechanical movement of central basin hypolimnetic water into the western basin. Meteorological stratification can result in anoxia within 2 to 9 days due to the small thickness and volume of the hypolimnion. However, hydromechanical stratification can result in immediate anoxia if the entering water mass is already in this condition.

Low concentration of dissolved oxygen, particularly in the central basin hypolimnion is one of major environmental problems still plaguing Lake Erie (Figure 12). Small areas of anoxic water in the Sandusky sub-basin east of Kelleys Island were observed as early as 1930 (Fish 1960). The size of the summer anoxic region of the lake continued to grow until 1973, when approximately 94% of the hypolimnion (11,270 km^2) had oxygen concentrations below 0.5 mg/l. The International Joint Commission has set a level of 6.0 mg/l as the minimum concentration of O_2 for a healthy aquatic environment. In response to reduced nutrient loading through management efforts, the anoxic region in 1982 was only 47% of the hypolimnion (5,470 km^2). The rate of oxygen consumption in the central basin hypolimnion is about 0.1 mg/l/day.

Other gases important to biological productivity, such as carbon dioxide are in small concentrations in Lake Erie waters (normally <0.5 mg/l). However, because the lake has a relatively high alkalinity (90 mg/l mostly bicarbonate) a source of carbon for primary productivity is readily available. During periods of high productivity the dissolved carbon dioxide is continually depleted, removing buffering capacity and driving the normal 8.3 pH up to >9 pH which in turn results in the release of CO_2 from the bicarbonate in solution.

BIOLOGICAL LIMNOLOGY

Plankton

Phytoplankton. Planktonic algae are the dominant primary producers in the nearshore and open waters of western Lake Erie. Although not as important as macrophytes, algae are also significant producers of organic matter in the marshes, converting the sun's energy into chemical compounds that in turn are used as food by animals and nonphotosynthetic micro-organisms. Phytoplankton production and distribution are influenced by sunlight, temperature, lake morphometry, water movements, grazing by zooplankton, nutrients, and other factors.

Many inorganic elements are required for algal cell growth, including nitrogen, phosphorus, silican (diatoms) and many major ions and trace elements. Algae reproduce rapidly when phosphorus is added to the water, and continue to reproduce as more phosphorus is added. However, nitrogen and other nutrients must also be present if algal production is to continue. Sawyer (1954) concluded that when inorganic nitrogen concentrations of 0.30 mg/l (sum of NH_3-N, NO_2-N, and NO_3-N) and orthophosphate-phosphorus concentrations of 0.01 mg/l (PO_4-P) were present in bodies of water at the start of the active growing season, nuisance algal blooms could be anticipated. Measurements in western Lake Erie indicate concentration well in excess of these limits.

The first comprehensive investigation of phytoplankton in the vicinity of western Lake Erie coastal marshes was initiated in 1929 (Wright et al. 1955). Samples were collected from the estuaries of the Detroit, Raisin, Maumee, and Portage rivers. Distinct differences were observed between phytoplankton communities of the Detroit River and the smaller tributaries. The sheltered Maumee Bay maintained a greater standing crop than the other locations. The algal abundance decreased markedly with increased distance from the mouth of the Maumee River. Herdendorf et al. (1977) observed a similar pattern in spring phytoplankton populations in Maumee Bay, except locations nearest the river mouth showed some reduction in numbers due to the high turbidity caused by spring runoff. Chandler (1942) also found turbidity to have a negative effect on plankton and submersed macrophytes photosynthesis near South Bass Island.

Taft and Taft (1971) published an exhaustive study of the algae in western Lake Erie, exclusive of diatoms. Their collections included sites within emergent plant marshes on the Lake Erie Islands and Catawba Peninsula (East, Middle, and West harbors). The richness of the algal flora of these localities is indicated by the more than 300 species found in South Bass Island coastal marshes (Table 4). Hohn (1969) studied the diatoms in Fishery Bay, a shallow embayment of South Bass Island containing dense beds of wild celery (*Vallisneria americana*). *Asterionella formosa* populations were relatively consistent throughout the year at approximately 1,000 cells/ml. *Diatoma tenue* exhibited the highest population in the spring at slightly more than 5,000 cells/ml.

Britt et al. (1973) observed that phytoplankton investigations from the late 1920s through the 1960s all indicated that diatoms were the dominant group in the nearshore waters of western Lake Erie, except in early summer.

Reutter and Reutter (1977) studied the phytoplankton community associated with submerged aquatic plants in Fishery Bay of South Bass Island (Figure 13). The dominant groups were diatoms (Bacillariophyceae), green algae (Chlorophyceae), and blue-green algae (Myxophyceae). Diatoms comprised the greatest percentage of the total phytoplankton population with a major pulse in the spring and a smaller pulse in the fall. Diatoms were the only abundant group during the winter. All the diatom genera which occur in large numbers, such as Melosira, Fragilaria, Asterionella, and Synedra, are indicators of eutrophic conditions. The planktonic green algae became most plentiful during midsummer as the lake water warmed up. This group was the most diverse member of the phytoplankton community and the dominant genus was Pediastrum. Also a considerable amount of fragments of the filamentous, attached green algae Cladophora glomerata, which covers the rocky shoreline, occurs in the plankton. Blue-green algae were most common during late summer. Blooms of Aphanizomenon often occurred during the calm "dog days" of August.

The basin-wide blooms of planktonic blue-green algae (Microcystis, Aphanizomenon, and Anabaena) in western Lake Erie and massive growths of an attached, filamentous green algae (Cladophora glomerata) which were so prevalent in the mid-1960s, decreased in intensity and number in the 1970s. No basin-wide blooms have been reported in recent years. Open lake phytoplankton analysis between 1970 and 1980 indicates a reduction in total phytoplankton biomass and a composition shift toward more oligotrophic species. Eutrophic species (i.e. Melosira granulata, Stephanodiscus tenius, and S. niagara were less abundant in 1979 than in 1970, and oligotrophic species (i.e. Dinobryon divergens and Ochromonas scintillans) were first observed in 1979 (International Joint Commission 1981, Munawar 1981).

Zooplankton. By definition, plankton are floating organisms whose movements are more or less dependent on currents. However, some zooplankters exhibit active swimming movements that aid in maintaining vertical position. Zooplankters are diverse in their feeding habits. Herbivores graze on phytoplankton, periphyton, and macrophytes within the Islands Region. Carnivores prey on attached protozoans and other zooplankters, while omnivores feed at all trophic levels. In turn, zooplankton are important fish and waterfowl food. Every fish species and many duck species utilizing the wetlands in this region eat zooplankters during some portion of their life cycle.

The animal component of the lake plankton is dominated by three groups: protozoans, rotifers, and microcrustaceans (primarily cladocerans and copepods). Landacre (1908) was the first to study the zooplankton in Sandusky Bay marshes. He observed that the plankton in open Sandusky Bay and Lake Erie was sparser than expected due to the shallowness and high amount of sediment in the water when agitated by the wind. But, the marshes and beach pools were unusually rich, particularly in protozoans where duckweed was abundant. Landacre reasoned that the zooplankton was poor in rhizopods (amoeboid protozoans) because their favored wetland plant, Sphagnum, was absent from Lake Erie marshes.

Wright et al. (1955) conducted studies of the plankton at several nearshore localities in western Lake Erie (Table 5). Zooplankton abundance followed a similar pattern to that of the phytoplankton, in that the Detroit River mouth had the lowest population, the south shore estuaries had the highest numbers, and the Islands Region had intermediate densities. Ahlstrom (1934) investigated the rotifer populations of a marshy embayment on South Bass Island known as Terwilliger's Pond. He found 91 planktonic species and attributed this high number to the protected nature of the embayment. The number of rotifers per unit volume increased from the entrance of the pond to the more static interior end. He classified about 75% of rotifer species in the pond as "pseudoplanktonic", living on aquatic plants or bottom debris, and being adventitious in the plankton. Ahlstrom observed both a spring and fall pulse, with the largest population (4,600 organisms/l) occurring in early June.

Reutter and Reutter (1975) analyzed the zooplankton populations in Fishery Bay on South Bass Island. This bay lies between the open lake and Terwilliger's Pond, and is rich in submerged plants such as wild celery and curly pondweed (Potamogeton crispus). The total zooplankton population reached a peak of 590/l in June and decreased to a low of 50/l in January (Figure 13). The rotifer populations in Fishery Bay followed the same pattern as the total zooplankton population, reaching a peak of 300/l in June. The mean numbers for all months were higher than those for copepods and cladocerans. The monthly mean copepod population, including nauplii, also reached its peak in June at 270/l and declined to 10/l in December. The decrease was much more pronounced than the total zooplankton population. When the copepod population is subdivided into calanoids (filter feeders which graze on small phytoplankton and detritus), cyclopoids (omnivorous particulate feeders, vectors for aquatic parasites, and known to attack larval fish), and nauplii (immature stages), the latter group was dominant from April through December. Cyclopoids were slightly more numerous than nauplii during the early months. The calanoid populations were low (<10/l) throughout the year. The cladocerans had by far the lowest populations of the major zooplankton groups, rarely exceeding 30/l.

The results of the work by Reutter and Reutter (1975) are generally consistent with the findings of Chandler (1940) and Hubschman (1960), with the exception of the calanoid population. The latter two studies were conducted farther offshore, and showed calanoid populations which, at times, surpassed the cyclopoid populations.

Herdendorf and Monaco (1983) observed an interesting association between a phytoplankter and a zooplankter in Fishery Bay. During a blue-green algal bloom of up to 20,000 cells/ml in July 1980, filaments of Anabeana flos-aqua were interwoven to form spherical masses. As many as 66 epiphytic ciliates/ml were found on the algal filament. The contractile stalks of Vorticella campanula were attached to the outer filament segments forming a pulsating corona around the entire algal mass. The pulsating feeding behavior of Vorticella produced a distinct gliding motion of the algal colony. Pratt and Rosen (1983) speculated that the "swimming" motion created by sessile protozoans on algae may be advantageous in maintaining nutrient flow past the algal cells.

Sessile Algae

Periphyton. The term periphyton generally refers to microfloral growth (particularly algae), on submerged substrate. Modifiers are normally used to indicate type of substrate: epipelic--growing on sediment, epilithic--growing on rock, epiphytic--growing on macrophytes, and epizooic--growing on animals. The periphyton of western Lake Erie consists of predominantly littoral communities, most commonly associated with wetland vegetation and rockbound shores. A greater number of species occur in the littoral zone than in the limnetic zone of the lake due to the greater diversity of habitats available in the nearshore region.

Millie (1979) examined the epiphytic diatom flora of aquatic macrophytes in several western Lake Erie marshes. Three common species of wetland macrophytes were studied as hosts, narrow-leaved cattail (Typha angustifolia), white water lily (Nymphaea tuberosa), and swamp smartweed (Polygonum cocineum). Of the 247 diatom taxa identified (38 genera), 157 were new distributional records for Lake Erie. Centric forms, such as Stephanodiscus subtilis, and keel-pennate forms, such as Nitzschia palea, were the most common taxa, but each marsh possessed a distinct flora and successional pattern. Millie attributed this heterogeneity to the diversity of littoral habitats in the marshes, particularly differences in chemical and physical factors.

Benthic algae. The filamentous, epilithic green alga Cladophora glomerata is well-adapted to rocky littoral reaches of Lake Erie, as evidenced by its profuse growth. This alga has been reported in Lake Erie since the late 1800s, but in the past few decades it has become increasingly abundant. Massive growths of Cladophora have created nuisance accumulations and obnoxious odors along recreational shores. It may also clog water intakes, foul fishing nets and submerged structures, and impede navigation due to growths on boat hulls. Thomas (1975) suggests that the Cladophora starts to become a nuisance at phosphorus concentrations of 15 ug/l, and it is only above this level that it interferes with certain water uses, especially recreation and drinking water. However, Lorenz (1981) and Monaco (1985) found that beds of Cladophora play an important role in the ecology of the nearshore region by supporting a wide diversity of organisms. Because of the high concentrations of phosphorus in the nearshore waters of Lake Erie, the distribution and abundance of Cladophora is largely limited by the lack of suitable substrate. The most extensive growths of Cladophora are located in the Islands Region.

Stoneworts (Characeae) are large epipelic algae with whorled branches that attain heights of over 0.3 m in western Lake Erie coastal marshes. Chara grows in water rich in calcium carbonate which is incorporated into their hard, brittle branches. This feature spares them from grazing by invertebrates, except for certain water beetles (Halipus and Peltodytes). Stonewort supports a diverse epiphytic flora and serves as food for waterfowl. These plants grow on firm marsh sediment and some rocky bottoms. Nitella and Tolypella are less calcareous stoneworts that have been reported in East Harbor Marsh on Catawba Island and Haunck's Pond on Middle Bass Island (Taft and Taft 1971).

The depth to which Cladophora grows on the island shelves and reefs varies from up to 7 m at Colchester reef near the Ontario shore to less than 2 m off Catawba Island. Correspondingly, Secchi disk transparencies are greatest and the extinction coefficients of light are smallest in the northern portion of the Islands Region. The vertical distribution of Cladophora, therefore, is limited by light attenuation in the water column. Photosynthetically active radiation below approximately 50 $uE/m^2/sec$ limits colonization (Monaco 1985).

Cladophora in the infralittoral zone (0.5 - 7 m) exhibits a bimodal biomass pattern. Growth is generally observable from April to July, with a peak standing crop of up to 240 g/m^2 (dry weight). After the water reaches a temperature of about 25°C, growth ceases and the filaments begin to atrophy. In October, as the lake cools, a smaller autumn pulse in growth occurs. Splash zone (0.5 m below to 0.5 m above lake level) Cladophora is present as a lush green growth during the entire growing season.

Lorenz and Herdendorf (1982) documented the occurrence and growth patterns of several other species of filamentous, benthic algae in the Island Region of Lake Erie (Figure 14). The most common genera include the green (Chlorophyta) algae Alothrix, Stizeoclonium, and Tetraspora, the blue-green (Cyanophyta) algae Oscillatoria, and the recent red (Rhodophyta) algae invader, Bangia. All of these taxa grow attached to the bedrock substrate but none attain the biomass of Cladophora.

Macrophytes

Over 300 species of vascular plants have been identified in the aquatic and wetlands habitats of the Islands Region (Stuckey and Duncan 1977). Distributions of 24 of the most important of these species are illustrated in Figure 15. In the open water of the lake and larger bays, aquatic vascular plants are few and limited mostly to rooted submersed species (Figure 16), such as wild celery (Vallisneria americana), sago pondweed (Potamogeton pectinatus), curly pondweed (Potamogeton crispus), water-milfoil (Myriophyllum spicatum), and water star-grass (Heteranthera dubia). These species and a few others, among them coontail (Ceratophyllum demersum), water-weed (Elodea canadensis), Richardson's pondweed (Potamogeton richardsonii), and the submersed form of the flowering-rush are the major submersed species in the bays and shallow water near the shoreline (Stuckey 1968).

The flora of the ponds shows considerable diversity. In addition to having most of the species already mentioned, small floating plants such as the duckweeds (Lemnaceae) form dense mats in quiet, stagnant water. In some places the floating water fern, (*Azolla caroliniana*) also forms dense reddish mats. Species with large floating leaves, white water lilies (*Nymphaea tuberosa*), and the American water-lotus (*Nelumbo lutea*) are not common, but where they do grow they may form extensive colonies, as does the large emersed-leaved spatter-dock or yellow water lily (*Nuphar advena*). Emergent species with showy flowers or large distinctively-shaped leaves, such as cattails (*Typha* spp.), bur reed (*Sparganium eurycarpum*), flowering rush (*Butomus umbellatus*), arrowhead (*Sagittaria latifolia*), swamp rosemallow (*Hibiscus mosheutos*), water smartweed (*Polygonum punctatum*), and pickerel weed (*Pontederia cordata*) line the edges of the coastal lagoons, often in segregated zones. Along the dryer margins of the marshes, three-square bulrush (*Scirpus pungens*), bluejoint (*Calamagrostis canadensis*), prairie grass (*Phragmites australis*), reed-canary grass (*Phalaris arundinacea*), and rush (*Juncus effusus*) are common.

With exception of Pelee Island, none of the Lake Erie Islands have extensive marshlands. Because all of the islands are rockbound, the only opportunity for marshes to develop exists in protected embayments, coastal ponds, and where converging sand bars form a lagoon at the base of a spit. Noteworthy examples of these wetlands include the Put-in-Bay embayment on South Bass Island where extensive beds of submerged macrophytes occur in Fishery Bay, and on North Bass Island, Manila Bay, where emergent forms are more common. Coastal ponds and lagoons occur on Kelleys Island (Carp Pond), Middle Bass Island (Haunck's Pond), South Bass Island (Terwilliger's Pond), North Bass Island (Manila Bay, Fox's Pond, and Smith's Pond), East Sister Island (East Sister Swamp), and Pelee Island (Lake Henry and Fish Point Swamp). Each has its own distinct flora, but in general, floating-leaved plants are best developed in these isolated habitats. The largest island marshes are found on Pelee Island where sand spits at both its north and south tips have formed lagoons similar to the formation of Point Pelee on the Ontario shore. Lake Henry, on the north, has been breached by high water storms and is now in danger of being engulfed by Lake Erie.

Haunck's Pond provides an excellent example of aquatic plant zonation in response to water depths. The basin containing the marsh appears to have been formed by sand spits (double tombolo) which now connect two rocky outcrops of Middle Bass Island. Eight zones have been identified extending from open water to a shrub shoreline by Wood (1966). Each of these zones is transitional in nature, and in no zone does one species dominate to the exclusion of all other species:

1. open water
2. water lily
3. dock
4. cattail
5. cutgrass
6. jewelweed
7. tall grass
8. shrub zone

Zone 1. Major species occurring in the open water zone are unattached floating plants such as duckweeds (Lemna minor, L. trisulca), large duckweed (Spirodela polyrhiza), and watermeal (Wolffia columbiana); and submersed aquatic plants such as sago pondweed (Potamogeton pectinatus), water-milfoil (Myriophyllum exalbescens), waterweed (Elodea canadensis), and coontail (Ceratophyllum demersum). Summer water depth in this zone is about 1 m.

Zone 2. Major species composing the water lily zone are spatterdock (Nuphar advena) and white water lily (Nymphaea tuberosa). Species associated with this zone included water-plantain (Alisma plantago-aquatica), arrowhead (Sagittaria latifolia), and pickerel weed (Pontederia cordata). The water lily zone is actually several disjunct zones, together occupying a major portion of the wetland. Summer water depth in this zone ranges from 50 cm to 1 m.

Zone 3. Two species of dock (Rumex crispus and R. verticillatus) comprise the major cover of the dock zone. Plants thriving under the dock cover include spatterdock, white water lily, sedges, and in some areas rice cutgrass (Leersia oryzoides). Occasional hummocks support swamp-loosestrife (Decodon verticillatus) and buttonbush (Cephalanthus occidentalis). Summer water depth in this zone ranges from 15 to 50 cm.

Zone 4. Narrow-leaved cattail and broad-leaved cattail are co-dominant species of the cattail zone. Thriving as associates in this zone are sedges (Carex cristatella, Scirpus atrovirens, and S. validus), soft rush (Juncus effusus), bur reed (Sparganium eurycarpum), cutgrass, and river bulrush (Scirpus fluviatilis). Early summer water depth in this zone ranges from 0 to 15 cm. However, this zone is predominantly a mudflat.

Zone 5. In early summer, 5 to 15 cm of water covers the cutgrass zone. At this time water-plantain and spatterdock are common associates of cutgrass. As water levels fall, associated species are limited to sedges (Carex cristatella, C. comosa, Cyperus strigosus, Scirpus atrovirens, and S. validus), spike-rushes (Eleocharis intermedia and E. obtusa), and ditch stonecrop (Penthorum sedoides).

Zone 6. The jewelweeds, Impatiens capensis, and I. pallida, occur in the jewelweed zone nearly to the exclusion of other species. However, in wetter areas cutgrass, spatterdock, and dock occur. Additional associates of this zone include cattail, sedges, rushes, monkey flower (Mimulus ringens), skullcap (Scutellaria epilobiifolia), and Iris sp.

Zone 7. The tallgrass zone is primarily composed of reed-canary grass (Phalaris arundinacea), bluejoint grass (Calamagrostis canadensis), which in some areas attained a height of 2 m. Jewelweed and cattail are the only herbaceous associates. Small hummocks in this zone support white ash (Fraxinus americana), hackberry (Celtis occidentalis), and choke cherry (Prunus virginiana).

Zone 8. The shrub zone is composed primarily of saplings of species found in the nearby swamp forest such as bur-oak (Quercus macrocarpa), hackberry, slippery elm (Ulmus rubra), white ash (Fraxinus americana), and white mulberry (Morus alba). Low growing plants occurring in this site include choke cherry, prairie rose (Rosa setigera), and common elderberry (Sambucus canadensis).

Small swamps, dominated by woody vegetation, also occur in low wet areas along the islands shores. Because of continued fluctuating levels, this vegetation type is not as extensive as the marshes. Willows (Salix spp.), cottonwood (Populus deltoides), sycamore (Platanus occidentalis), and ashes (Fraxinus spp.) are the dominant trees. Formerly, American elm (Ulmus americana) was more prevalent, but most of these trees have since been destroyed by the Dutch elm disease. Shrubs are mostly dogwoods (Cornus spp.), elderberry (Sambucus canadensis), willows, buttonbush (Cephalanthus occidentalis), and roses (Rosa spp.). Diversity of herbaceous species in the swamps is low. Among those more commonly occurring during the summer are shade-tolerant plants such as nettles (Urticaceae), false-nettle (Boehmeria cylindrica), and spotted touch-me-not (Impatiens capensis). An excellent example of a shoreline swamp can be found on Fish Point, Pelee Island.

Many of the macrophytes in the Islands Region which are exposed to natural water level fluctuations can be considered "pioneer species." They are the type that first colonize a low, wet, denuded area. If the habitat becomes too stable (i.e. constant water levels within a controlled marsh) they soon become crowded by other species and eventually disappear. However, the seeds of these species have considerable longevity and are able to again germinate when the environment is disturbed.

At the time of Wisconsin glacial retreat, streams were either enlarged or formed anew as meltwater became abundant. The bare soil of moraines and alluvial deposits characterized the landscape. Stranded bodies of water between the receding ice front and terminal moraines formed lakes such as the former stages of Lake Erie in northwestern Ohio and southeastern Michigan. Stuckey (1972) describes this "glacial sidewalk" as a perfect avenue for migration and colonization by pioneer plants. A good example is marsh cress (Rorippa palustris var. hispida) which survived glaciation in refugia in the Rocky Mountains. It doubtlessly spread rapidly eastward as the ice receded, carried by wind and water to the fresh barren soils, germinated, and grew in abundance. This plant is not found south of the limit of Wisconsin glaciation, presumably because environments were more stable to the south and already vegetated. This species, as do many other pioneer plants, continues to persist in Lake Erie coastal marshes because of the frequent storms and constantly changing water level regime (Vesper and Stuckey 1977).

Local changes in the aquatic flora have been very evident during the past decade, a period of record high water levels for Lake Erie. This temporary environmental condition has affected the aquatic flora by reducing the size of populations of most of the emergent shoreline species, forcing them to migrate shorewards, and increasing the size of populations of some submersed and floating-leaved species. Jaworski et al. (1981) developed a plant community displacement model which predicts responses of wetland vegetation to changes in water levels in Lake St. Clair. This model (Figure 17) has been modified for use on Lake Erie. The model illustrates the shoreward movement of begetation zones under rising water level conditions. For a typical marsh, a rise of 1 m in water level will result in a 15,000 m shoreward advance for each zone.

However, environmental changes due to human activity can be more devastating and dramatic changes have occurred in the aquatic flora in the past 85 years. In Put-in-Bay harbor, 50% (20 out of 40) of the species of aquatic vascular plants have disappeared (Stuckey 1971). The flora of the bays, in particular, have been disturbed severely because of increased turbidity of the water, building of retaining walls and docks, use of herbicides, dredging operations, and man's multi-uses of these aquatic habitats ranging from recreation to dumping grounds for wastes. Many of the lagoons and embayments have been destroyed to build marinas and housing developments. In those coastal lagoons that remain, most of the submersed aquatic species still survive and represent one of the few refuges for this segment of the flora.

Benthic Invertebrates

Other than the planktonic protozoans, rotifers, and microcrustaceans, most of the invertebrates in the Islands Region are benthic or epiphytic forms for at least part of their life cycle. The sessile communities of the lake bottom and the coastal marshes are accumulations of diverse and at time abundant organisms. These organisms occur on and in a variety of substrates, including;soft mud, hard clay, sand, gravel, rock, organic debris, and aquatic plants. Burrowing forms such as the oligochaete worms and certain mayfly nymphs are most common in soft, mud bottoms, whereas dragonflies and certain snails are most often found in shallow water with emergent vegetation, and some caddisflies and water penny beetles are most abundant on rocky bottoms. The species and abundance of the organisms are dependent not only on substrate, but also water quality, particularly temperature, dissolved oxygen and the presence of toxic substances. Since this group is less mobile than either the plankton or nekton, they are most affected by local environmental changes.

Shelford and Boesel (1942), Carr and Hiltunen (1965), and Britt et al. (1973) studied the nearshore and open lake bottom fauna of western Lake Erie. Figure 18 illustrates the benthic communities in the Lake Erie Islands region. It is interesting to note that on this map depicting 1937 populations, the majority of the bottom was inhabited by the mayfly Hexagenia limbata. However, Britt et al. (1973) indicates that mayflies had been virtually extirpated from the benthic fauna by the late 1960s. The open lake benthic populations are now dominated by oligochaetes (sludge worms) and chironomids (midge larvae), which have replaced the former mayfly-caddisfly community.

The nearshore open waters of the bay contain a benthic community dominated by oligochaete worms and chironomid (midge) larvae (Herdendorf and Lindsay 1975, Lindsay 1976). Three species of oligochaetes (Branchiura sowerbyi, Limnodrilus hoffmeisteri, and Peloscolex ferox) and three species of chironomids (Chironomus plumosus, Procladius culiciformis, and Coelotanypus scapularis) comprise 90% of the benthic fauna. In all, at least 50 benthic taxa are common, including other annelids and dipterans, crustaceans, gastropods, pelecypods, larval insects, hydrozoans, bryozoans, and sponges.

All of the oligochaetes in Sandusky Bay burrow in the mud, some constructing tube cases. They all feed by ingesting mud from which they extract soluble organic material and microorganisms. There appears to be commensal feeding among the oligochaetes. The feces of one species serves as the food for another. Brinkhurst (1974) found that these worms tend to migrate toward different worm species rather than their own species. Of the three species of chironomids common in the bay, Procladius bellus and Coelotanypus scapularis are carnivorous predators. The third species, Chironomus plumosus, feeds primarily on plankton, periphyton and aquatic plant tissue. Chironomus constructs a definite burrow in soft sediments, while the other two species do not. The predators feed on other chironomids and frequently inhabit the burrows of their prey.

The importance of aquatic vegetation as a habitat for aquatic invertebrates is often overlooked. Krecker (1939), working in wetlands on the Lake Erie islands, noted that submerged, leafy types of vegetation are more densely populated than are the emergent, hard surfaced, non-leafy types. He examined seven species of submersed plants (Figure 16) for both the composition and quantity of the animal population. Representatives of 29 taxa were found among these plants (Table 6), ranging from a maximum of 26 on Elodea and 4 on Vallisneria. An entirely different picture is presented when the plants are compared on the basis of individuals present per linear meter of plant. Myriophyllum with mean populations of 440 invertebrates per meter and Potamogeton crispus with 347 led all the others by a wide margin. Midge larvae (Chironomidae) and freshwater annelids (Oligochaeta) together made up 59 to 93% of the invertebrates on all plants except Elodea. On this plant, midges and annelids only comprised 29%, while the sessile rotifer, Melicerta, made up 50% of the epiphytic invertebrates.

Gastropods. Well-vegetated portions of unpolluted embayments, marshes, beach ponds, and sluggish tributary mouths are the most productive localities for freshwater snails in western Lake Erie. They live on submerged vegetation, on rocks and on the bottom at the water's edge and out to a depth of several meters. Two subclasses, Prosobranchia and Pulmonata, are well represented in Lake Erie coastal marshes. The former group is characterized by internal respiratory gills (ctenidia), or as in Valvata, external gills and an operculum used to seal the shell aperature. The latter group does not have gills, but obtains oxygen through a "lung-like" pulmonary cavity. Pulmonate snails, which have descended from land snails, must come to the surface periodically to take air into the lung. Dennis (1938) reported that pulmonates in the Bass Islands region were always found where there was considerable wave action or near the surface, while gilled snails were found in deeper more stagnant waters.

Most aquatic snails are vegetarians. The veneer of living algae which covers most submerged surfaces is the chief food, but dead plant and animal material is frequently ingested. Dissolved oxygen is an important limiting factor; most gilled species require high concentrations, with limpets such as Ferrissia being found only where the water remains near saturation (Pennak 1978). However, Campeloma decisum and Amnicola limosa have been collected in water with less than 2 ppm oxygen (Harman 1974). The concentration of dissolved solids in western Lake Erie, particularly calcium carbonate at 95 ppm, provides adequate essential materials for shell construction.

Pelecypods. The bivalved molluscan fauna of western Lake Erie consists of three families. The majority of the species belong to the Unionidae (freshwater mussels or naiades) and Sphaeriidae (fingernail clams). The third family, Corbiculidae (little basket clams), is represented by an introduced Asiatic species. Bivalves are most abundant nearshore, especially in water less than 2 m deep. Stable gravel and sand substrates with a good current support the largest populations. Commonly mussels inhabit substrates free of rooted vegetation, but there are numerous exceptions, including Anodonta grandis and Quadrula quadrula.

Stomach contents of unionid mussels are commonly mud, desmids, diatoms, and other unicellular algae, protozoans, rotifers, flagellates and detritus. The largest populations of mussels develop below areas where disintegration of rich vegetation is occurring, such as Fishery Bay of South Bass Island.

The female pocket-book mussel (Lampsilis ventricosa) is capable of extending and pulsating the posterior edge of the mantle in such a way that it resembles an injured minnow (Clarke 1981). This activity attracts several marsh-associated fish species such as bluegill, white crappie, smallmouth bass, and yellow perch, and increases the opportunities for juvenile mussels (glochidia) to attach themselves to a fish after they have been ejected from the parent. The larvae are released by the parent when its light sensitive spots are stimulated, for example, by the shadow of a passing fish. Several unionid bivalves possess special mantle structures adapted to lure fish into their vicinity. The glochidia of each species of freshwater mussel must attach to the gills and fins of a particular fish species or small group of species (Table 7) before further development can take place. Most glochidia never accomplish this, but those that do succeed remain attached for a few weeks as they metamorphose into tiny mussels. The young mussels then drop from the fish to take up an independent life on the lake bottom, moving about and siphoning water for respiration and for obtaining plankton as a source of nourishment.

Crustaceans. Throughout Lake Erie Gammarus fasciatus is an important food organism for yellow perch, walleye, freshwater drum, catfish, and other fish species. This amphipod is one of the dominant macrozoobenthic forms in the coastal waters of the Islands Region. Gammarus is well equipped to cling to aquatic vegetation; each of its 14 pereiopods has a terminal claw which is used to grasp plant stems and seize prey. Clemens (1950) found that during the summer and fall in western Lake Erie, Gammarus was most common on beds of submerged vegetation, particularly Potamogeton crispus, Vallisneria, Myriophyllum, and Cladophora glomerata. These 8 to 10 mm long crustaceans are omnivorous in their feeding habits. Plant and animal matter, both living and dead, are readily devoured. Aquatic plants (especially submerged forms), dead leaves, zooplankton (Daphnia, Leptodora, and Cyclops), fellow members of this species, and their own moults and fecal pellets are the most common food items. Populations of these scuds also occur in deeper, offshore portions of western Lake Erie, but not in as great a density as in the vegetated areas.

Other notable crustaceans in the Islands Region include copepods and cladocerans (water fleas), isopods (aquatic sowbugs), ostracods (seed shrimp), and decapods (crayfish and shrimps). Because of the great variety of ecological niches available, the shallow littoral zone of western Lake Erie is rich in cyclopoid and calanoid copepods. Harpacticoid copepods are more restricted to bottom debris in the wetlands. Cladocerans are important limnetic (open water) organisms in Lake Erie, but several species, including Daphnia pulex and Sida crystallina, are abundant among the vegetation in the coastal marshes. Bacteria, algae, protozoans and organic detritus are the chief foods of these filter feeders. Both of these microcrustacean groups, as well as protozoans, are trapped and ingested by bladderwort (Utricularia vulgaris) plants in the coastal marshes. Isopods seldom enter open water but prefer niches under vegetation, debris, and rocks. Asellus racovitzai is the common species in western Lake Erie. The nature of the substrate appears to have little influence on the distribution of ostracods. In many cases, the same species can be found on algae, decaying vegetation, rooted aquatics, and mud. Crayfish are generally inhabitants of shallow water. Species such as Orconectes immunis live in the water during warm months, but in the autumn they construct burrows along the edge of the marsh and live in them until the lake level rises and the weather becomes warmer in the spring (Pennak 1978).

Insects. The most conspicuous invertebrates associated with the coastal waters are the myriad of insects. The dipterans (true flies) are the most abundant and include the midges, mosquitoes, and crane flies. Mayflies, dragonflies, and damselflies are also abundant groups of organisms which have an aquatic larval stage and then emerge to fly and mate over the marsh. The hemipterans (true bugs) are represented by diverse forms including the water strider, backswimmer, water boatman, and giant water bug (Belostoma sp.), which preys on tadpoles and small fish (Weller 1981). Also important insect groups of the marshes include the caddisflies and beetles. The former (Triaen sp. and Oecetis sp.) builds a case from bits of vegetation and sand. The latter includes the predaceous diving beetle (Dytiscus sp.) and the gregarious whirlygigs (Gyrinus sp.).

The composition of the benthic macroinvertebrate communities of western Lake Erie has improved since 1967. Samples taken in 1979, when compared with 1967 data, show that the bottom is still dominated by pollution tolerant tubificids (Limnodrilus hoffmeisteri, L. cervix, and L. maumeensis); however, other less tolerant taxa of tubificids (Peloscolex spp.) are also common. The density of tubificid worms declined sharply at the mouth of the Detroit River between 1967 (13,000/m^2) and 1979 (2,400/m^2), while the number at the mouth of the Maumee River has remained relatively stable. Midge (Chironomidae) larvae represented only 6% of the benthic population in 1967 but rose to 20% by 1979, replacing some of the tubificids (Ontario Ministry of Environment 1981). A modest reestablishment of the burrowing mayfly (Hexagenia limbata) has also been observed at the mouth of the Detroit River and adjacent areas of western Lake Erie. This species was extirpated from the western basin in the mid-1950s following periods of anoxia in this normally unstratified portion of the lake. Prior to 1953, bottom sediments yeilded about 400 nymphs/m^2 in the Islands Region (Britt et al. 1973). In 1979, 20 nymphs were collected near the mouth of the Detroit River and for the past several years a small emergence of adults has been observed on South Bass Island.

Fish

Lake Erie supports a greater diversity of fish stocks and a higher biomass of fish per unit area than the other Great Lakes. The western basin, and in particular the Islands Region, has long been considered the most valuable fish spawning and nursery grounds in the lake. At least 95 species of fish have been reported from the lake waters surrounding the islands. About 40 of these species are presently or have formerly been of significant commercial or recreational value. The diversity and abundance of fishes in the Islands Region is attributed to its southernmost (warmest) position in relation to the other Great Lakes, its shallow, nutrient-rich waters, and its variety of aquatic habitats, especially the bedrock reefs and the extensive coastal marshes surrounding the western basin (Figure 19).

Trautman (1981) is the primary source of information regarding fish in Lake Erie and their life histories, habitat associations, and utilization of coastal wetlands. He provides detailed location maps for each species. Other useful works on western Lake Erie fisheries include; Barnes (1979), Edmister (1940), Fraleigh et al. (1975), Goodyear et al. (1982a,b), Hartley and Herdendorf (1975), Herdendorf et al. (1981), Langlois (1954, 1965), Price (1963), and Van Meter and Trautman (1970). Spawning and nursery grounds for important western Lake Erie fish species are depicted in Figure 20.

Since the advent of European colonization of the Lake Erie shore approximately 200 years ago, fish communities and habitats in the lake have been radically changed by a series of largely cultural stresses. The original native fish communities of the lake were characterized by a much greater predominance of coldwater and coolwater species, including lake sturgeon (Acipenser fulvescens), lake trout (Salvelinus namaycusch), lake whitefish (Coregonus clupeaformis), lake herring (Coregonus artedii), northern pike (Esox lucius), muskellunge (Esox masquinongy), yellow perch (Perca flavescens), walleye (Stizostedion v. vitreum) and blue pike (Stizostedion vitreum glaucum), than at present. Many warm water species such as white bass (Morone chrysops), white crappie (Pomoxis annularis), black crappie (Pomoxis nigromaculatus), largemouth bass (Micropterus salmoides), and smallmouth bass (Micropterus dolomieui) were also more abundant than at present. Intensive commercial exploitation of the originally abundant salmonid, esocid, and percid populations was largely responsible for significant depletions or extirpations of these populations. In addition, the introduction or invasion of exotic species such as sea lamprey (Petromyzon marinus), alewife (Alosa pseudoharengus), rainbow smelt (Osmerus mordax), carp (Cyprinus carpio), goldfish (Carassius auratus), and white perch (Morone americana) which competed with or altered the habitats of native species, had deleterious effects on many native populations. Cultural development along Lake Erie resulted in the alteration or elimination of essential habitats and spawning areas due to agricultural siltation, industrial waste discharge, draining and filling of marshes, and channelization or damming of tributaries used by lake-run spawners. Limnological changes associated with a climatic warming trend and increasing cultural nutrient loading resulted in accelerated eutrophication and accompanying dissolved oxygen depletion, increased plankton densities, and increased deposition of organic sediments.

Cultural stresses to Lake Erie were greater than in the other Great Lakes because of the relatively small size and volume of the lake and the extensive agricultural and urban-industrial development in its watershed. Such stresses continue to affect the lake, although they are now strictly regulated and partly abated or reversed by scientific land use, water quality, and fisheries management practices. The coldwater salmonid component of the original fish communities of the lake has been largely eliminated, and remaining valuable coolwater species such as yellow perch and walleye are heavily exploited. Warmwater species such as gizzard shad (Dorosoma cepedianum), carp, spottail shiner (Notropis hudsonius), channel catfish (Ictalurus punctatus), brown bullhead (Ictalurus nebulosus), white bass, and freshwater drum (Aplodinotus grunniens) comprise the largest and most stable component of the fish communities of the lake. Carp, channel catfish, and white bass are currently important commercial and recreational fishes. Other warmwater species such as largemouth and smallmouth bass and white and black crappies have declined in abundance due to a combination of intense exploitation and habitat loss. Species favored by the warmer, more turbid condition of the lake, including gizzard shad and freshwater drum, have proliferated, yet have minimal current economic values.

Wetlands in the Islands Region are important to fish production because they provide spawning and nursery habitat for wetland-dependent species, cover for juvenile and forage fish, and feeding areas for predator fish. Approximately 43 species of fishes are or once were associated with the coastal marshes of Lake Erie. Twenty-six of these species are currently of significant recreational, commercial, or prey value. Fish associated with coastal marshes can be divided into two categories: 1) species directly dependent on coastal marshes as adult habitats or spawning and nursery areas, and 2) coastal marshes, apparently making opportunistic use of them as spawning, nursery, and feeding areas. The first category includes species such as northern pike, longnose gar (Lepisosteus osseus), bowfin (Amia calva), bullheads, and crappies, whose dependence on aquatic vegetation has been well established. The second category includes common nearshore and bay species such as gizzard shad, quillback (Carpiodes cyprinus), white sucker (Catostomus commersoni), white bass, white perch, channel catfish, and yellow perch, which have been shown by qualitative surveys and observations of marsh managers to be seasonally common or abundant as young or adults in coastal marshes, although the literature indicates that they have no strict dependence on aquatic vegetation.

Most of the fish fauna inhabiting wetlands appear to consist of non-salmonid, warmwater or coolwater species such as carp, northern pike, bullheads, and buffalos. Because of the predominance of clayey and organic-rich substrates in wetlands, there is a prevalence of bottom feeders (e.g., bullheads, channel catfish, carp, and buffalo). Often as much as 90% of the standing fish crop of coastal marshes consists of forage species such as carp and freshwater drum. Large predator fish, such as northern pike, rely on visual contact for locating their prey and require clear water as do some species, including carp, bullheads, and buffalo which are tolerant of turbidity and siltation. Siltation due to agricultural development of northwestern Ohio has eliminated much of this type of environment. As the waters have become more silt-ladened, the clear water fish have been replaced by other species, including carp, bullheads, and buffalo which are tolerant of turbidity and siltation. Northern pike usually broadcast their eggs in shallow sedge marshes or in flooded fields. Carp also broadcast their eggs over vegetation and debris in warm, shallow embayments and marshes. Because many fish species spawn only on specific substrate types, modification of wetlands through direct habitat loss, addition of suspended solids, and alteration of flow regime has resulted in the elimination or degradation of wetland spawning environments.

The introduction of externally-derived detritus, including particulate organic matter, along with algae, duckweeds, and other aquatic plants provide food for herbivorous fish and other forage species. In turn, the abundance of these forage fish, as well as large numbers of juvenile fish resulting from spawning activities, attract predator fish to wetlands for feeding. Predator fish, such as northern pike, may feed at dusk and at dawn in shallow waters, but usually return to somewhat cooler or deeper waters for resting during the day. Thus, links between open waters and the shallow wetlands are essential. Spring floods, seiches, and other high-water periods provide access to the wetlands for feeding and spawning fish. In contrast, during periods of low or obstructed flow, links to adjacent wetlands are broken and the isolated wetland populations may suffer from higher water temperatures, reduced dissolved oxygen, and a concentration of chemical effluents. Carp Pond on Kelleys Island is typically barred across in late summer and suffers these problems.

The annual sport angler harvest of fish in the Ohio waters of Lake Erie increased from 5.2 million kg in 1975 to 7.3 million kg in 1982, an increase of 40%. During this 8-year period, yellow perch harvests rose from 3.7 million kg to 5.5 million kg while walleye production jumped from 0.5 million kg to 1.4 million kg. The increased walleye production has been attributed to good young-of-the-year recruitment and international management approaches to control sport and commercial harvests. The abundance of walleye in western Lake Erie increased dramatically from 1970 to 1982. During the 1960s and early 1970s the "fishable" population of walleye, 37 cm in length and larger, was estimated at or below 2 million individuals. In 1983, the fishable population in western Lake Erie was estimated at over 25 million walleyes (Ohio Division of Wildlife 1984).

Amphibians and Reptiles

Amphibians and reptiles form two distinct classes of vertebrate animals found in the Islands Region. Both groups are cold-blooded, deriving heat from outside sources and controlling their body temperatures by moving to cooler or warmer environments as necessary. Amphibians, including salamanders, newts, toads, and frogs, have moist, glandular skins and their toes are devoid of claws. Their young pass through a larval stage, usually aquatic, before they metamorphose into the adult form. By comparison, reptiles, including turtles, snakes, and lizards are clad in scales or plates, and their toes bear claws. Young reptiles are miniature replicas of their parents, although some differ in color patterns from adults.

Mudpuppies (*Necturus maculosus*) are fairly common in embayments with soft bottoms and aquatic plants. Its name comes from the doglike head with wavy red gills which look somewhat like ears. The body of this large salamander is mottled brown with black spots, slimy, and about 30 cm. They burrow into mud during the day and crawl along the bottom at night, feeding on water insects, snails, fish eggs, and small fish.

The smaller spotted (*Ambystoma maculatum*), tiger (*Ambystoma tigrinum*), Jefferson (*Ambystoma jeffersonianum*), and smallmouth salamanders (*Ambystoma texanum*) belong to the mole salamander family (Ambystomidae), spending most of their lives underground. At the early spring breeding time, they take to the icy lake water. The eggs are usually laid in large clusters and attached to submerged sticks or wetland debris. The marshes of Middle Bass and North Bass islands are especially good locations to observe mole salamanders.

The northern dusky salamander (*Desmognathus f. fuscus*) and the red-backed salamander (*Plethodon c. cinerus*) belong to a family of lungless salamanders (Plethodontidae). They breathe through the throat membrane and the skin, which must be kept continually moist. These slender salamanders often live among the rocks of sheltered shoreline or in moist caves.

Newts are not as slimy as most salamanders; their skin is rougher. The red-spotted newt (*Notophthalmus viridescens*) lives in water during the beginning and end of its life, while the time between is spent on land. The young newts, called red efts, live in the woods for a year or longer, then mature into newts which return to the water to live and breed.

Toads live on land most of the time, but in spring, after leaving their winter shelter under rocks and logs, they seek ponds and sheltered wetland embayments. The American toad (Bufo americanus), is common in the IslandsRegion.

Most of the year, frogs in the treefrog family (Hylidae) live on land, but in spring they find their way to ponds and marshes to mate and lay their eggs. The spring peepers (Hyla c. crucifer) are among the first to come out of hibernation followed by the western chorus frog (Pseudacris t. triseriata), sometimes called the swamp treefrog. The cricket frog (Acris crepitans) belongs to the treefrog family, but pads on their toes are too small for them to climb trees. Most of the time they live along the cattail and rush borders of ponds and marshes.

Members of the true frog family (Ranidae), include the pickerel frog (Rana palustris), leopard frog (Rana pipiens), and the bullfrog (Rana catesbeiana). They are the typical frogs of ponds and marshes; all have long legs, smooth skin, separated fingers, and toes joined by webs.

The snapping turtle grows to over 70 cm long and may weigh more than 18 kg. This is the largest reptile in western Lake Erie and makes its home in ponds, marshes and embayments of the lake. When catching food, including fish, frogs, insects, crayfish, and ducklings as well as some aquatic plants, the snapping turtle darts its head forward and snaps with powerful jaws. They hibernate in the mud bottoms of the ponds and marshes.

The map (Graptemys geographica), spotted (Clemmy guttata), midland painted (Chrysemys picta marginata), box (Terrapene carolina), and Blanding's (Emydoidea blandingi) turtles all belong to the water and box turtle family (Testudinidae). The map turtle prefers water and places where aquatic plants are thick. Spotted turtles are scarce in the Islands Region and have been placed on the Ohio Endangered Species List. The midland painted turtle always lives near the water since it does all its eating under water. The box turtle is mostly terrestrial, but sometimes enters the water to cool off or escape from an enemy. The Blanding's turtle is primarily aquatic aquatic and seldom wanders far from the lake or marshes. Soft-shelled turtles (Trionyx spinifera) are odd-looking aquatic reptiles which prefer rivers. They are scarce in the region having only been reported from Catawba Island marshes (Langlois 1964).

The Lake Erie water snake (Nerodia sipedon insularum) is the snake most often seen in or near the lake throughout the Islands Region. It is a uniform green-brown color without the distinct light and dark brown of its close relative, the northern water snake (*Nerodia s. sipedon*) which inhabits the mainland shore and some of the islands. The rarer Kirtland's water snake (*Clonophis kirtlandii*) has only been observed on South Bass Island. When alarmed, this snake can flatten its body making itself almost ribbon-like and rigidly immobile. It is a good swimmer but the least aquatic of the water snakes. Water snakes grow to a length of about 1.3 m. They catch and eat small animals which live in or near water, such as fish, frogs, insects, and mice. Water snakes are not poisonous, but they will hiss, coil, and strike if annoyed. They also secrete a foul smelling substance from musk glands as a defense mechanism. Late in summer, the female has from 15 to 40 young which she bears live. The Lake Erie water snake is fairly common around the islands, particularly the uninhabited ones, and can be seen swimming along the shore with its head above water or sunning on flat rocks near the water's edge.

In addition to the water snakes, there are seven other common species of snakes on the island which belong to the Colubrid family. The garter snake (*Thamnophis sirtalis*) is sometimes found near water where it eats frogs, toads, salamanders, crayfish, and minnows. It grows to 1 m long and its back is brown with three yellow stripes; underneath it is light yellow. The fox snake (*Elaphe vulpina gloydi*) is a resident of the marshes which border western Lake Erie and the adjacent upland areas. This attractive snake is boldly patterned with background colors varying from yellowish to light brown, to reddish and the dark spots and blotches from chocolate to black. The black rat snake (*Elaphe o. obsoleta*) is a plain, shiny black reptile. Its habitats range from rocky, wooded cliffs to marshy shorelines; an excellent climber, it sometimes takes up residence in cavities high up in hollow trees. It constricts rats, mice and birds in it strong coils as does its close relative the fox snake. The northern brown or Dekay's snake (*Storeria dekayi*) is small, generally not over 30 cm, gentle, and very common throughout the Islands Region. It can be found near the marshes, in the moist woods, and near the rocky shoreline.

Avifauna

The habitats of the Lake Erie islands support a diversity of bird life. Resident and migratory species of waterfowl, waterbirds, wading birds, shore birds, gulls and terns, raptors and perching birds use the region for nesting, feeding, and resting. Noteworthy migratory species which utilize the shoreline environment include the bald eagle (*Haliaeetus leucocephalus*), and osprey (*Pandion haliaetus*). Waterfowl commonly observed in the wetlands are mallards (*Anas platyrhynchos*), wood ducks (*Aix sponsa*), black ducks (*Anas rubripes*), blue-winged teal (*Anas discors*), and pintails (*Anas acuta*).

The character of the western Lake Erie shores varies from clay bluffs, to sand and gravel beaches, and from rocky headlands to coastal marshes. The beaches attract spotted sandpipers (*Actitis macularia*) in summer, small flocks of shorebirds in migration, and patrolling gulls year around. The coastal marshes, mud flats associated with the larger streams, and embayments where algal mats accumulate are the places where waterbirds gather. The mud flats and algal accumulation frequently occur in the autumn, when Lake Erie water drops from its summertime high level.

The coastal marshes and the wetlands associated with the mouth of streams along the Lake Erie shore have a rich array of breeding species. The extensive stands of cattail (Typha spp.) and other emergent plants, and the open shallow water area provide habitat for many summer residents including pied-billed grebe (Podilymbus podiceps), American bittern (Botaurus lentiginosus), Canada goose (Branta canadensis), mallard, blue-winged teal, Virginia rail (Rallus limicola), American coot (Fulica americana), common moorhen (gallinule) (Gallinula chloropus), marsh wren (Cistothorus palustris), common yellowthroat (Geothylpis trichas), and red-winged blackbird (Agelaius phoeniceus). Swampy woodlands are often associated with the larger coastal wetlands. In addition to the landbirds these areas support, the following waterbirds most commonly nest in the wooded habitats: great blue heron (Ardea herodias), black-crowned night-heron (Nyticorax nyticorax), green-backed heron (Butorides striatus), great egret (Casmerodius albus), wood duck, American woodcock (Scolopax minor), belted kingfisher (Ceryle alcyon), bald eagle, and osprey.

The Lake Erie islands are nesting sites for many species of birds including herons, ducks, gulls and terns that feed along the shore and in the coastal marshes. Colonies of these birds completely cover many of the smaller, rocky islands and shoals, several of which are designated as nature reserves or wildlife sanctuaries. Protected islands include Green and West Sister islands in Ohio and East Sister, Middle Sister, Hen and Chicken islands in Ontario. Species known to nest on these islands include the great blue heron (Figure 21), black-crowned night-heron, great egret, double-crested cormorant (Phalacrocorax auritus), herring gull (Larus argentatus), ring-billed gull (Larus delawarensis), common tern (Sterna hirundo), and Caspian tern (Sterna caspia).

Pelee Island, has two nature reserves which feature coastal marsh habitats. At the northeast tip of the island, Lighthouse Point Provincial Nature Reserve includes Lake Henry which is separated from Lake Erie by a narrow barrier beach. Here dead trees standing in the lake provide nesting sites for colonies of double-crested cormorants and herring gulls. Lake Henry is also a favored foraging area for herons and egrets. The southernmost extremity of the island is a sand spit which lies within Fish Point Provincial Park Reserve. The mature swamp forest which has developed here supports a large heronry. Great egrets, cattle egrets (Bubulcus ibis), black-crowned night-herons, and yellow-crowned night-herons (Nyctanassa violacea), king rails (Rallus elegans) and common moorhens as well as a variety of shorebirds have been recorded from the lagoons and ponds at the base of the spit (Goodwin 1982). Offshore and on the extreme end of the spit, double-crested cormorants, great black-backed gulls (Larus marinus), herring gulls, Caspian terns, and piping plovers (Charadrius melodus) occur regularly.

The Lake Erie islands lie along the path of two bird migration corridors which comprise the Mississippi and Atlantic flyways. Each corridor, in turn, is a web of routes as opposed to a single, narrow band rigidly followed by waterfowl. In general, fall movements of dabbling ducks, (e.g. mallard and blue-winged teal) are from the northwest to the Gulf Coast of Texas and Louisiana. Diving ducks exhibit a more east-west migration pattern but may winter in either the Gulf or Atlantic coasts (Bellrose 1968).

As waterfowl migrate between breeding grounds and wintering areas, they stop to rest and feed in coastal wetlands of the Islands Region with an abundance of food, low wave energy, and little human disturbance (Figure 22). Canvasbacks, redheads, American widgeon, goldeneye, and mergansers (Figure 23) prefer crayfish, small fish, and other animal foods. Black ducks, mallards, pintails, teals, scaup, and buffleheads, select from both plant and animal foods. Canada geese and mallards also feed heavily on waste grains in agricultural fields.

All of the 11 species of common wading birds in western Lake Erie belong to the family Ardeidae. They occupy two habitats in the region--the rockbound Lake Erie Islands and the coastal marshes. The colonial nesting species known to inhabit the islands include: great blue heron, great egret, black-crowned night-heron, and cattle egret (Parris 1979). The green-backed heron is a solitary nester that prefers the coastal wetlands but also inhabits the islands. American bittern and least bittern (*Ixobrychus exilis*) are secretive, non-colonial nesters that are best known from the coastal marshes of the mainland. In addition to these species, four others are residents of the coastal wetlands; yellow-crowned night-heron, snowy egret (*Egretta thula*), tricolored heron (*Florida caerulea*), and little blue heron (*Egretta tricolor*). Typically, herons and egrets arrive in the western Lake Erie region in early March and migrate southward in October. A small population of great blue herons may over-winter in this region.

Wading birds usually forage on the shorelines of the tributary streams and Lake Erie, and within the coastal marshes. Their diet is primarily fish, but crayfish and insects are also eaten. Fish species most often consumed include: carp, goldfish, yellow perch, gizzard shad, and freshwater drum.

Meeks and Hoffman (1980) found that in 1979, West Sister Island had the largest nesting populations of herons and egrets in the region. Great blue heron nests numbered 950, black-crowned night-herons 1,000 nests, great egrets 50 nests, and cattle egrets 13 nests. They conducted surveys of heron and egret movement into and out of Navarre Marsh at Locust Point. Over 95% of the movements were in NNW or SSW directions, a direct alignment with West Sister Island located 15 km offshore. In general, herons and egrets are crepuscular in nature, being more active during early morning and evening surveys. The period of highest activity was 0600-0800 hours and 1800-2000 hours. They concluded that the West Sister Island nesting colonies used the mainland coastal marshes as feeding sites while they raised their young in the seclusion provided by the islands.

Gulls and terns, family Laridae, are the other principal colonial nesting species using the Lake Erie islands. Herring gulls are the most abundant species, but ring-billed gulls are becoming more common. Common terns have a history of nesting upon the Lake Erie Islands, but are now restricted to the diked spoil areas near Toledo harbor. In western Lake Erie, gulls utilize the Lake Erie shoreline, its bays and inlets, and to a lesser extent open water areas of coastal marshes until freeze-up. At this time gulls use sanitary landfills as a site for food, and also follow the lake ice edge using it as they would the shoreline (Meeks and Hoffman 1980). Herring gulls are typically scavengers feeding on dead fish, refuse, and other organic debris along the shoreline. They are also known to be predators upon the young of wetland birds whenever the opportunity presents itself. Herring gulls are especially prevalent in marshes during migration periods. Wherever reduced water levels concentrate small fish sufficiently to cause them to "surface" due to an oxygen stress, gulls can be found feeding on these moribund fish.

The double-crested cormorant, family Phalacrocoracidae, is another colonial nesting bird that occurs on the Lake Erie islands. This species is the most abundant cormorant in North America and feeds almost entirely upon fish which they obtain from the open lake. Cormorant colonies are most common on the Canadian islands.

Mammals

The cattail marshes of western Lake Erie provide excellent food and building material for furbearers such as the muskrat (*Ondatra zebethicus*). Many other mammalian species in the region, such as raccoon (*Procyon lotor*) and white-tailed deer (*Odocoileus virginianus*), occupy multiple habitats of which wetlands function as one. Eastern cottontail (*Sylvilagus floridanus*), woodchuck (*Marmota monax*), and striped skunk (*Mephitis mephitis*) chiefly utilize the earthen dikes of managed marshes. Fox squirrels (*Sciurus niger*) are found most commonly in the wooded margins of the wetlands. Long-tailed weasels (*Mustela frenata*), mink (*Mustela vison*), and red fox (*Vulpes fulva*) are occasional visitors to Lake Erie wetlands, feeding on rodents and marsh birds. The Norway rat (*Rattus norvegicus*) is a common predator on muskrats in the marshes (Bednarik 1956). In total, about 30 species of mammals can be found in the coastal marshes of western Lake Erie. The mammalian fauna of the Lake Erie islands wetlands generally have a lower diversity than the mainland marshes.

Several structures observed in Lake Erie coastal marshes are associated with the activity of muskrats (Bednarik 1956). The most noticeable structure is the muskrat "house", a dome-shaped pile of emergent vegetation. The average house varies in size from 1 to 2.5 m in diameter at the base and from 0.5 to 3 m in height. They are located in stands of emergent vegetation or along the periphery of such stands. Houses are often constructed on protuberances in the marsh bottom, utilizing plants in the immediate area. The majority of houses are constructed in October and November. Building activity occurs mainly during periods of darkness.

Muskrats have a wide range of feeding behavior patterns and consume a wide variety of food items. They usually select plant species which are immediately available to them. Narrow-leaved cattail (Typha angustifolia) and giant bur reed (Sparganium eurycarpum) are the first and second most important food items, respectively, throughout the year. Because muskrats appear to prefer the tender-most growing shoots, other plant species are consumed more frequently when they are in early stages of growth. The authors have often observed muskrats feeding on the pale-green to white basal stems of wild celery (Vallisneria americana) in Fishery Bay of South Bass Island.

Energy Flow and Biological Productivity

The ultimate source of energy for the Lake Erie ecosystems is the sun. Only a small fraction of the total available energy from the sun enters the food chain and passes this energy from one organism to another along a food chain made up of trophic levels. In most ecosystems, food chains form complex food webs involving many different types of organisms. The first step in the food chain is always a primary producer, which in the Lake Erie ecosystems consists of three basic types: 1) phytoplankton, 2) benthic microalgae, and 3) macrophytes.

Producers far outweigh consumers, over 90% of all living organic matter in the lake is made up of plants, especially algae. Energy enters the animal segment of the lake population largely through the activities of the herbivores. Of the organic material consumed by herbivores, much is excreted undigested with most of the chemical energy used for heat, motion, or digestive processes, and only a small fraction is converted to animal biomass.

The next levels in the food chain, the secondary and tertiary consumers, involve carnivores. Again only a small part of the organic substance present in the body of a herbivore becomes incorporated into the body of a carnivore. The decomposers, primarily bacteria and fungi, break down dead and discarded organic matter, completing the oxidation of the compounds formed by photosynthesis. As a result of the metabolic work of the decomposers, waste products (detritus, feces, dead plants, and animals) are broken down to inorganic substances that are returned to the lake sediment and water to be recycled.

The flow of energy through a food chain is often represented by a pyramid which illustrates the quantitative relationships among the various trophic levels (Figure 24). Juday (1943), one of the earliest investigators to introduce trophic levels, developed the concept from studies of freshwater ecosystems. He found dissolved organic matter composed about 60% of the total pyramid, the fish, only 0.5%, and the other animals slightly less than 5% of the total.

The western Lake Erie ecosystems possess two basic complexes of interrelationships: 1) invertebrates, fish, birds, and mammals which utilize living plant tissues, and 2) organisims which utilize detritus or dead plant tissues. Living plant tissue (e.g. diatoms, reed grass, cattail rhizomes) serve as food for phytophagous (plant eating) animals such as stem boring and leaf mining insects as well as certain microcrustaceans. Many species of waterfowl graze extensively on plant material, and muskrats are important plant consumers. The next higher trophic level in the first complex consists of animals which prey upon the phytophagous organisms. Predatory beetles, dragonflies, certain fishes, frogs, birds, and small insectivorous mammals are important organisms of this upper trophic level. In western Lake Erie, submergent vegetation tends to be inhabited and grazed more heavily than emergent forms (Krecker 1939) because the former type of aquatic macrophytes lack the more impenetrable structural tissues prevalent in the emergent type.

The second complex consists of a vast number of insect larvae which rely on organic detritus as a direct energy source or by stripping microbial populations from the surface of organic particles. Gastropods and annelids are also important organisms in this detritophagous complex. Whatever residual not utilized by these animals is subjected to further decomposition by bacterial and fungal populations. As with the phytophagous complex, there exists in the detritophagous complex a wide spectrum of animals which prey on the detritus-feeding organisms. Several species of insects, amphibians, mammals and waterfowl compose this level, and many of these species are not selective in their prey, utilizing organisms from both complexes.

The detritus food chain of Sandusky Bay is illustrated by the benthic fauna (see Figure 34 in Ecosystems section). Of the six dominant benthic macroinvertebrate species present, three are detritivores, one is a grazer, and two are predacious. The three species of oligochaete detritivores function in a commensal aggregation to exploit the allochthanous and autothanous inputs to the bay. Additionally they use the bacteria that utilize detrital inputs for substrates, and the products of bacterial activity. The one grazer is the larva of the chironomid Chironomus plumosus. It exploits the plankton, primarily diatoms and other algae, by entrapment on a spun net, which it ingests along with the plankton. Chironomus also grazes on diatoms, other periphyton, aquatic plant tissue, and decaying organic matter. The two predator species are also chironomids. Coelotanypus is a voracious predator on other chironomid larvae while Procladius is a more general carnivore. Coelotanypus preys on both Chironomus and Procladius, and members of its own species at times. Procladius feeds on other chironomids and also utilizes the three species of oligochaetes.

Several studies of phytoplankton productivity (Table 8) have been conducted in western Lake Erie (Cody 1972, McQuate 1954, Sheffield and Carey 1980, and Verduin 1962). McQuate (1954), working in Sandusky Bay observed that small bays and open pockets within the beds of rooted aquatic vegetation provided "excellent cultural grounds" for plankton which are carried into the bay and eventually reach the waters of Lake Erie. He measured a photosynthetic rate of approximately 1,400 mg of carbon assimilated per day. This rate compares favorably with nearshore measurements made by other investigators in western Lake Erie, and as would be expected, is higher than values for offshore locations, the islands area, and central Lake Erie. Considering relative biomass, phytoplankton is not as important as the macrophytes in the total primary production occurring within the coastal marshes. However, it is significant in the zooplankton-fish larvae food chain within the marshes. Conversely, in the offshore portions of the lake, phytoplankters are the dominant primary producers.

McMillian (1951) studied the photosynthetic rate of filamentous algae (Cladophora glomerata and Ulothrix zonata) attached to littoral boulders and rocky shorelines of Fishery Bay, South Bass Island. She found that this association which included abundant periphytic diatoms, had an average carbon fixation rate of 567 mg C/m^2/day during a 4-month growing season. This rate is comparable to that obtained by Cody (1972) for phytoplankton (742 mg C/m^2/day) in the same bay. McMillian determined the average yield of attached algae in this habitat to be 144 g/m^2. Lorenz and Herdendorf (1982) obtained maximum standing crop values for Cladophora at South Bass Island of 214 g/m^2. Monaco (1985), continuing this study found that the vertical distribution of Cladophora was limited by light attenuation to a depth of about 2 to 3 m near the Bass Islands. Mean productivity at 2 m was 30 mg C/g (dry wt)/day.

Coastal Marshes and Lagoon Wetlands

In large bodies of water such as Lake Erie, the shifting of sediments by nearshore currents can form basins where wetlands eventually develop. If sediments are deposited across the mouth of an embayment, a tributary outlet, or freshwater estuary, the blockage may result in the formation of a new pond or lagoon. Wave activity, too, has formed bars of sand and gravel, which likewise have closed off the mouths of embayments.

The usual way in which a lagoon capable of supporting a wetland is formed is by accretion of a bar across some irregularity or indentation of the coastline. The term bar is used here in a generic sense to include the various types of submerged or emergent embankments of sand and gravel built on the lake bottom by waves and currents. One of the most common types of bars associated with wetlands in Lake Erie is a spit. This feature is a sand ridge attached to the mainland at one end and terminating in open water at the distal end. Spits that have extended themselves across or partially across embayments are termed baymouth or barrier bars. Commonly the axis of a spit will extend in a straight line parallel to the coast, but where currents are deflected landward or unusually strong waves exist, growth of a spit may be deflected landward, resulting in the creation of a recurved spit or hook. Several stages of hook development may produce a compound recurved spit with a series of ponds separated by beach ridges. These ponds have provided excellent sites for wetland development along the shores of western Lake Erie.

Lake Erie is noted for its severe northeast and northwest storms and the resultant wave attacks and rapid fluctuations in water level at the shoreline. The high energy produced at the shore by these storms precludes the development of fringing coastal wetlands. Only where some type of natural or artificial protection is available against these harsh coastal processes of erosion, scour, and rapid transport or deposition of beach material and sediments can marshes become established and continue to exist. Settling of the shore surrounding the western end of Lake Erie has greatly altered the natural shoreline. Kaatz (1955), points out that in the 1790s much of the western basin shoreline was fronted by barrier beaches, which protected lagoons and massive wetlands (Figure 25). Today these low shores are armed with stone dikes or protected with bulkheads. Sandy shores are now restricted to a few spits, such as Cedar Point and Bay Point (Figure 26) in Ohio, Woodtick Peninsula, Michigan, and Pelee Island in Ontario, and places where littoral currents converge, such as East Harbor on Catawba Island, Ohio.

Based on these considerations, the coastal marshes of western Lake Erie fall into three categories depending on the type of protection available to the wetland vegetation. As mentioned earlier, at one time protection afforded by barrier bars or other natural features of the shoreline to form quiet lagoons and coastal embayment was the most important type. Very few natural wetlands of this type still exist in western Lake Erie. One of the best remaining examples is the lagoon ("east bay" of Sandusky Bay) stabilized by Cedar Point sand spit (Figure 26). Other examples of natural-protection wetlands which still persist are those formed by rock-bound embayments in the Islands Region of western Lake Erie. Unfortunately many of these embayments have been disturbed by the construction of small boat harbors (Figure 6).

Most of the lagoon-type coastal marshes, if they have not been drained or filled or engulfed by the lake, have been replaced by the second type, managed waterfowl marshes which are now protected by earthen and rip-rap dikes. The high wave energy of Lake Erie and the record high water levels of 1972-1973 have taken a toll on the barrier beaches, necessitating the construction of armored dikes along much of the western basin shoreline. Large areas of wetlands are now protected in this manner by federal, state and local agencies as well as private shooting clubs.

The third type of protection is the natural isolation from lake storms provided by the estuaries of virtually all of the tributaries entering the western end of Lake Erie. At places, such as the Sandusky River, the estuarine aspects of the drowned river mouth extend upstream at least 10 km. Large wetlands have developed along most of the estuaries where disturbance has been minimal. Estuarine coastal marshes form the majority of the naturally protected wetlands bordering the mainland, whereas lagoons are more common on the islands.

By their very nature, which most generally includes a diversity of emergent, floating-leaved, and submersed aquatic plants, coastal marshes provide more food and shelter for wildlife than any other coastal or offshore habitat in western Lake Erie. Invertebrates, particularly the crustaceans, insects, and gastropods, are abundant on and among wetland vegetation. These organisms are important food items and cover for several fish species and some of the mammals which dwell at the marshes edge. Some waterfowl and other birds rely on the marsh plants for sustenance, nesting sites, and cover, while others utilize the fish and invertebrates which inhabit the marshes.

Lake Erie coastal marshes and embayments are excellent habitat for Odonata (dragonfly) because of their quiet waters and abundant food supply. Kennedy (1922) studied the distribution of dragonfly species in relation to the occurrence of coastal marshes on the Lake Erie islands. He observed a distinct species preference for wetlands in different successional stages. Of the nine wetlands investigated, Put-in-Bay Harbor on South Bass Island was the most open, exposed area, and Fox Marsh on North Bass Island was the most closed or advanced successionally. Figure 27 illustrates a succession gradation both in marsh development and species preference for the wetlands and the 25 species of dragonfly that occur in them. Kennedy concluded that the more advanced marsh species supplant the more primitive open lake species as the marshes mature or become more closed. The marsh species have all developed egg stages which can withstand intermittently dry conditions.

An analysis of energy flow in the coastal marshes reveals that the entire heterotrophic component of the wetlands is dependent on organic matter produced through photosynthesis. One way that this material is utilized is through grazing of living tissues. Several species of waterfowl feed on various parts of aquatic macrophytes. The seeds of pondweed, sedges, smartweed, water shield, wild rice, and bulrush are preferred foods as well as the foliage of pondweed, wild celery, naiad, duckweed, and water weed, and tubers or rootstocks of wild celery and sago pondweed. Many mammals, including muskrat, browse heavily on several of the aquatic macrophytes. Phytophagous (plant eating) insects, such as leafminer beetles, are the food supply for several species of marsh birds, fishes, reptiles and mammals.

Another form of plant utilization is the direct consumption of organic detritus and the ingestion of the microbial populations associated with this particulate organic matter. Many benthic invertebrates rely completely on such food sources. These organisms in turn form the food supply for many vertebrates in the coastal marshes. In addition to plants being a direct or indirect food source for many species of animals, macrophytes provide cover and nesting areas for waterfowl. Several species of fish, such as northern pike, spawn in vegetated wetlands and muskrats prefer emergent vegetation for construction of their feeding platforms and houses (Tilton et al. 1978).

Barrier Beaches and Bars

Although sand beaches are scattered and not extensive along the western Lake Erie shoreline they do provide an important function in protecting coastal marshes from direct exposure to lake waves (Figure 28). The sand deposits are low, not forming extensive dunes (Figure 29). Consequently, they are particularly vulnerable to fluctuating water levels, continuous wave action, and erosive action by ice in winter. Most of the sand beaches are now used for recreation as swimming and camping areas. Because of these natural and artificial disturbances, most of the plant species unique to this type of habitat have disappeared (Core 1948, Stuckey and Duncan 1977). Distinctive herbaceous species now rare or extirpated are sea rocket (*Cakile edentula*), seaside spurge (*Euphorbia polygonifolia*), beach pea (*Lathyrus japonicus*), sand grass (*Triplasis purpurea*), sand dropseed (*Sporobolus cryptandrus*), beach grass (*Ammophila breviligulata*), wormwood (*Artemisia caudata*), prickly pear (*Opuntia humifusa*), and Schweinitz's and Houghton's cyperus (*Cyperus schweinitzii* and *C. houghtonii*). Distinctive shrubs that are today also rare or eliminated are sand-dune willow, sand cherry (*Prunus pumila*), buffalo berry (*Shepherdia canadensis*), ground juniper (*Juniperus* communis), kinnikinick (Arctostaphylos uva-ursi), and Canadian milk-vetch (Astragalus canadensis).

Common trees present are cottonwoods, willows, dogwoods, and ashes, and among these are often thick growths of lianas including wild grape (Vitis spp.), Virginia creeper (Parthenocissus vitaceae), poison ivy (Rhus radicans), bittersweet (Celastrus scandens), and trumpet-creeper (Campsis radicans). In the open areas on the sand beaches, herbaceous species such as Russian thistle (Salsola kali), winged pigweed (Cycoloma atriplicifolium), umbrella-wort (Mirabilis nyctaginea), and sandbur grass (Cenchrus pauciflorus) formerly not present, now form a new distinctive beach flora. Ubiquitous European "weeds" have also invaded, including crab grass (Digitaria sanguinalis), pigweed (Amaranthus spp.), white sweet clover (Melilotus alba), catnip (Nepeta cataria), and mullein (Verbascum thapsus).

Gravel beaches and bars are a common habitat on the Lake Erie islands (Figure 30). Because these beaches are subjected to severe ice scouring and wave wash, no permanent vegetation becomes established on this continuously agitated shore. Mats of the alga Cladophora often wash ashore, die, and decay on the gravel beaches. Farther up on the beach where waves reach only during storms and periods of high water, willows, cottonwood, dogwood, and ashes are dominant woody members. Lianas, such as wild grape, poison ivy, and Virginia creeper become entangled on the beach. Herbaceous species are few, but usually germander (Teucrium canadense) and smartweeds are present.

The harsh environment resulting from lake waves breaking on these beaches and bars precludes extensive colonization by benthic invertebrates. However, the shoreward slope of submerged sand bars do provide some protection, and in places such as Locust Point, dense populations of unionid mussels (Figure 31) have been observed on the slopes above the silt-ladened troughs between successive offshore bars.

Bedrock Reefs and Shoals

Many of the predator fish species of the Islands Region, particularly walleye, smallmouth bass, and white bass rely on sight to find their prey (Regier et al. 1969). Efficient sight feeding, especially for a large fish seeking moving prey, requires sufficiently clear water to discern the prey at some distance. Such relatively clear water is found over the bedrock reefs in the Islands Region. Fish populations are found concentrated around clean, hard bottoms, such as rocky reefs, gravel or clean sand, and at the edge of weed beds. Cladophora beds harbor emerging insects and zooplankters. Zooplankton attract small fish, usually shiners, upon which walleye prey.

Scuba divers who have inspected reefs in western Lake Erie have observed walleye lying motionless on the rocky bottom during daylight. This daily "resting requirement" may tend to limit them to reefs and other hard bottoms. Silty or muddy bottoms with high organic concentrations tend to have lower oxygen concentrations. This is especially true during calm periods when currents and water mixing are slight. Walleye prefer not to rest in these areas because of their additional requirement for high oxygen concentrations.

Walleye commonly spawn over rock, rubble or gravel in streams, shallow offshore reefs or along shorelines of lakes (Eschmeyer 1950). Spawning runs of walleye persist in only two major Ohio streams, the Sandusky and Maumee rivers. In the 1800s and the early part of this century many of the lake's other tributaries were productive spawning sites (Langlois 1954), but the construction of dams, siltation, excessive pollution, and irregularity of stream flow due to man's activities have destroyed the spawning sites. Today, the major existing spawning grounds in Lake Erie are found on the reefs of the Islands Region. These reefs are free from oxygen-consuming mud due to the scouring of breaking waves. These waves and currents also simulate the riffle habitat of the spawning streams.

Researchers have postulated that walleye fry imprint some essential characteristics of their birthplace and that most sexually mature adults return to that birthplace to spawn (Regier et al.1969). These factors would also favor the continued utilization of the reefs by future walleye populations.

The benthic fauna of the shoal waters of western Lake Erie, both in the density of population and variety of its forms, depend upon the type of substrate, character of the vegetation, and depth of the water. Krecker and Lancaster (1933) found that such physical factors as temperature, oxygen, carbon dioxide, and pH were in general so uniform in the nearshore waters that they did not appear to be critical factors. The densest population was in less than 1 m of water. Half of the animals represented occurred in maximum numbers within the 15 cm contour although, due to great numbers of chironomids (midge larvae), the largest total population was at the 50 cm contour. Shelving rock shores were the most densely populated because of great numbers of chironomid larvae and Lymnaea but rubble shores had the greatest variety of animals present in maximum numbers. The smallest number of forms occurred on sand bottoms, the largest variety on rubble.

Among the plants, bulrush was most densely populated, again due to great numbers of chironomids, but it also was inhabited by the smallest variety of invertebrates. However, both Potamogeton spp. and Cladophora sp. had more diverse animal populations (11 taxa). Because the benthic populations are dependent on water depth, a definite zonation occurs that rapidly adjusts, through a succession process, when water levels fluctuate.

Western Lake Erie has a combination of characteristics of large rivers (i.e. Detroit, Maumee, and Sandusky) and several small streams. This (i.e. Detroit, Maumee, and Sandusky) and several small streams. This situation, in conjunction with it being accessible to both faunal elements, has resulted in an unusual mixture of large river and headwater species in the fauna of the lake and coastal marshes. Stansbery (1960) found that as a result of this circumstance, the molluscan fauna of the Islands Region has intergraded. Relatively strong, persistent, alongshore currents (simulating stream conditions) are associated with rapid growth of unionid mussels, whereas quiet waters result in stunting. Consequently, mussels in Lake Erie nearshore waters are more commonly found on shallow gravel shoals than in the protected cattail marshes and the quiet deepwater habitats (Stansbery 1960). Fishery Bay of South Bass Island (Figure 32) possesses abundant gravel shoals which foster dense unionid populations.

Cliffed Shorelines

The lake bluffs of the Islands Region consist of unconsolidated sediments, such as lacustrine deposits and glacial till, and resistant bedrock. Perhaps the most dramatic of the shoreline habitats are the high, rugged limestone and dolomite cliffs (Figure 33). These are mostly confined to the north and west shores of most of the islands. These cliffs have two vegetation zones--one along the wave-splashed lower portion of the cliffs and the other on the drier upper portion. Plants inhabiting the lower portion, which are also characteristic of the low shelving rocky shores, are filamentous algae, mainly the green alga *Cladophora* and an invading marine, red alga *Bangia*. Distinctive herbaceous vascular plants observed by Stuckey and Duncan (1977) are Dudley's rush (*Juncus dudleyi*), Kalm's lobelia (*Lobelia kalmii*), St. John's wort (*Hypericum kalmianum*), prairie and winged loosestrife (*Lysimachia quadriflora* and *Lythrum alatum*), mountain mint (*Pycanthemum virginianum*), heath aster (*Aster pilosus*), grass-leaved goldenrod (*Solidgo graminifolia*), golden ragwort (*Senecio pauperculus*), and beardtongue (*Penstemon hirsutus*). On the upper portion are such distinctive herbaceous species as ivory sedge (*Carex eburnea*), nodding onion (*Allium cernuum*), purple and hairy rockcress (*Arabis drummondii* and *Arabis pycnocarpa*), harebell (*Campanula rotundifolio*), and smooth cliff brake fern (*Pellaea glabella*). Bluegrass (*Poe compressa*) is abundant above the splash zone. Xeric mosses and foliose lichens are pioneers in this habitat. Shrubs and small trees line most of the tops of the cliffs. Among the more common ones are ninebark (*Physocarpus opulifolius*), choke cherry (*Prunus virginiana*), staghorn sumac (*Rhus typhina*), hackberry (*Celtis occidentalis*), dogwoods (*Cornus* sp.), hop hornbeam (*Ostrya virginiana*), and red cedar (*Juniperus virginiana*). Dense growths or lianas, such as poison ivy, Virginia creeper, and wild grapes, cover large portions of the cliffs.

Limnetic Waters and Profundal Bottoms

The limnetic zone composes the open waters of Lake Erie surrounding the islands. It is sometimes referred to as the euphotic zone and extends from the surface down to the light compensation level (1% of incident light at the surface of the lake). Typically this zone is 3.5 times the Secchi disk transparency and usually ranges from less than 3 m west of the islands to over 15 m east of the islands. The profundal zone of the lake adjacent to the islands refers to the bottom and deep-water areas beneath the light compensation level. The limnetic environment is dominated by the planktonic and nektonic organisms discussed earlier, whereas the profundal bottoms are characterized by benthic macroinvertebrates which prefer soft sediments.

Verduin (1962) concluded that western Lake Erie is an area of relatively high primary productivity, averaging 500 mg/C/m^2/day in summer. He observed that the lake has a high vertical turbulence which is generated by wind and seiche-generated currents. This turbulence (eddy diffusivity of 25 cm^2/sec) contributes importantly to the ecology of this area by promoting vertical transport of the products of photosynthesis and respiration and the phytoplankton into and out of the euphotic zone at frequent intervals. He determined an extinction coefficient of 0.13 relating depth of light penetration in m to concentration of suspensoids in mg/l (dry weight). Verduin found the CO_2 and O_2 economy of the western Lake Erie ecosystem to be almost a closed system, with CO_2 produced by respiration of the aquatic community serving as the CO_2 supply for the autotrophic component, and the O_2 produced by the autotrophs serving as the supply for the total community. A slight net gain in CO_2 from the atmosphere was established, but it represents less than 3% of the daily CO_2 budget.

In the limnetic zone, zonation has been demonstrated for larval fish populations (Figure 20) in western Lake Erie. A series of studies in the estuaries and open waters of western Lake Erie have shown that the estuaries of the Maumee River and Sandusky River contained the highest densities of larval fish when compared with other nearshore and offshore areas (Cooper et al. 1981a,b, 1983, 1984 and Mizera et al. 1981). Gizzard shad, white bass, and freshwater drum dominated the estuarine populations. The highest density of yellow perch was found in nearshore areas associated with sandy bottoms, particularly in the vicinity of Locust Point. The following depth/density relationship was observed for this species:

Water depth (m)	Maximum number/100m^3
0 - 2	157.0
2 - 4	19.3
4 - 6	7.7
6 - 8	5.2
8 - 10	5.0
> 10	3.7

Variations in year-class strength (YCS) of western Lake Erie fishes is related to the availability of plankton food to the larval fish as they enter the limnetic waters. For example, walleye, which spawn in large numbers on western Lake Erie shoals (Cooper et al. 1981a,b), show highly variablity in YCS. A strong correlation exists between the rate of spring warming of the nearshore waters and the number of young-of-the-year walleye captured during fall stock assessment surveys (Busch et al. 1975). This suggests that increased recruitment under more rapid warming (earlier in the spring) may be a result of temperature effects on critical food resources, such as the zooplankton.

Temperature also strongly affects the production of zooplankton. Culver and DeMott (1978) studied the seasonal variation of biomass, production, and species composition of zooplankton in western Lake Erie and found that the plankton communities undergo a switch from domination by copepods in the spring to domination by cladocerans as the water warms. Because this transition occurs near the beginning of the planktivorous phase of many larval fish, the effect of temperature on the transition may strongly affect the availability of the larger zooplankton (particularly cladocerans) for young fish.

Larval fish studies conducted in the vicinity of Locust Point in the mid-1970s (Mizera et al. 1981) show that all fish taxa appeared in the ichthyoplankton samples prior to the June increase in zooplankton production. Consequently, the YCS of fishes recruited during this time period was poor.

The soft-bottom community of the open lake offshore from the islands is less diverse than the organisms occurring in the rock and gravel community. The species present are dependent upon the silt-clay substrate, availability or organic material, sediment chemistry, and water quality (particularly dissolved oxygen). Oligochaetes and chironomids occur most often and most universally. The tubificid oligochaete, _Limnodrilus_, dominates the bottom fauna, comprising 60% of the total soft mud fauna (Figure 34). Chironomid larvae make up about 20% and sphaeriid (fingernail) clams 10% (Britt et al. 1973). The remaining 10% of the profundal community includes leeches, amphipods, isopods, polychaete worms, gastropods, and other invertebrates (Table 9).

Disturbed Shores and Lake Bottoms

The waters of most of the bays and marshes have become muddy and turbid within the past century. These conditions have come about by: 1) the extensive erosion of the soil in the once-forested uplands of the watershed, 2) dredging, diking, and drainage of large portions of the marshes for private, industrial, agricultural, and wildlife areas, 3) construction of docks and bulkheads that, in combination with dredging channels, have altered many of the bays for commercial or recreational purposes and, 4) introduction of carp, a species of fish that uproots and destroys aquatic plants and contributes to the overall turbidity by stirring up the bottom silt and keeping it in suspension. These physical changes, silted conditions, and continued high turbidity levels have brought about a situation in which sensitive plant species of open clear water are eliminated or are drastically reduced in numbers, thereby resulting in a decline in species diversity. Submersed plants are more sensitive, particularly northern species such as pondweeds, waterweeds, and wild celery which prefer clear, cool, well-oxygenated waters (Stuckey 1975).

The managed marshes which are surrounded by dikes (Figure 35), provide excellent habitats for a great variety of wildlife, although their principal function is the attraction and production of waterfowl and furbearers. Ironically, these attractive and productive areas are presently of little value as spawning and nursery areas for economically important Lake Erie fish populations. The historical importance of Lake Erie's wetlands in supporting fish populations in the open lake has long been recognized. At least 40 species of fish, 25 of which are significant game or commercial species, are dependent to some degree on the lake's wetlands as spawning and nursery areas. Notable among these are northern pike, muskellunge, carp, bullheads, sunfishes, crappies, and largemouth bass. Species such as gizzard shad, emerald shiner, spottail shiner, channel catfish, white bass, yellow perch, and freshwater drum seem to make opportunistic use of wetlands, but their degree of dependence is not known.

As late as 150 years ago, the western end of Lake Erie was surrounded by an extensive marsh-swamp forest system known as the Black Swamp. Settlement of the area proceeded at a rapid pace after the War of 1812. Between 1850 and 1920 most of the wetlands were drained and filled to provide agricultural land and sites for urban and commercial development. Adverse environmental conditions to some extent engendered by this development, especially agricultural siltation, wave erosion, and water level fluctuations, contributed to wetland losses during this period. At the same time, the reputation of Lake Erie's wetlands as quality waterfowl hunting areas was spreading.

About 1920, groups of wealthy sportsmen and state and federal agencies, alarmed at the rate of wetland loss, purchased most of the remaining wetland areas. These areas were enclosed by dikes to protect them from wave erosion, siltation, and water level fluctuation. Gates, pumps, and flumes of various types were installed to control water levels within the marshes. This made it possible to produce the right types and amounts of aquatic vegetation used by wildlife, thus enhancing the quality of the marshes as waterfowl and furbearer habitats. The result was the present system of controlled, managed marshes. Without controls, siltation and erosion would quickly eliminate most of the marshes.

The dikes and management practices essential to maintaining productive marshes prevent fish from entering and using the marshes as spawning and nursery areas (Johnson 1984, Snyder and Johnson 1984). Drastic declines over the last 50 to 60 years in the abundance of marsh-dependent fish populations have been attributed in large part of the wholesale draining and filling of marshes before 1920 and subsequently to the inability of fish to enter the remaining marshes because of dikes. Dikes are constructed of a solid clay base, covered with rip-rap (Figure 35), and are placed such that water can enter or leave the marshes only through specially constructed channels. Screens are placed over flumes and gates to exclude carp. These screens also keep desirable fishes from entering and leaving the marshes.

Regulatory and management agencies concerned with protecting Lake Erie fish populations generally oppose construction of dikes around shallow, bottomland areas because they keep fish from reaching spawning and nursery areas. This is a justifiably cautious approach to protecting an important resource. However, without dikes these bottomland areas are little more than flooded mud flats with little aquatic vegetation. The importance of these flooded mud flats as fish spawning areas is a topic which needs further study.

Another problem of a totally different nature may also present itself by the end of the decade. Lake Erie sport fish production is at an all-time high. This production, primarily in the Islands Region and along the south shore of the central basin is nurtured by high nutrient concentrations and associated high rates of primary/secondary productivity. As international water quality management programs become more and more effective in controlling phosphorus inputs to the lake and thereby limiting algal production, the anoxic region of the central basin is being reduced. However, at the same time the food base for such important fish species as walleye and yellow perch may be eroded. As the 1980s proceed, it will become increasingly important to consider the balance between western basin fish production and central basin hypolimnetic oxygen content.

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TABLES AND FIGURES

Table 1. Islands and major reefs of Lake Erie

ISLANDS

Ohio Islands	Area (km^2)	Shore Length (km)
Kelleys	11.32	18.3
South Bass	6.35	17.2
Middle Bass	3.29	12.4
North Bass	2.85	8.4
Johnson	1.17	5.3
West Sister	0.31	2.1
Rattlesnake	0.26	2.6
Sugar	0.13	1.4
Green	0.08	1.3
Ballast	0.05	1.1
Mouse	0.03	0.8
Gibraltar	0.02	0.8
Starve	<0.01	0.3
Buckeye	<0.01	0.2
Rattles	<0.01	0.1
Lost Ballast	<0.01	<0.1
Gull	<0.01	<0.1
Ontario Islands		
Pelee	42.70	37.2
Middle	0.42	2.6
Middle Sister	0.25	1.7
East Sister	0.23	1.9
Hen	0 07	0.7
North Harbor	0.03	0.3
Big Chicken	<0.01	<0.1
Little Chicken	<0.01	<0.1
TOTAL	69.56	116.7

Table 1. (concluded)

REEFS

Ohio Reefs and Shoals	Area (km^2)	Least Depth (m)	Maximum Depth (m)
West Reef	5.31	1.2	3.0
Niagara Reef	2.49	0.9	6.0
Gull Island Shoal	2.05	0.0	6.0
Kelleys Island Shoal	1.92	0.6	7.5
Scott Point Shoal	1.48	3.0	6.4
Middle Harbor Reef	1.40	0.3	4.5
Toussaint Reef	1.23	0.9	3.3
Locust Point Reef	0.93	1.5	4.0
Round Reef	0.88	2.1	4.0
Mouse Island Reef	0.85	2.7	6.0
Crib Reef	0.85	0.6	4.5
Little Pickerel Reef	0.72	4.6	6.7
Starve Island Reef	0.67	2.1	6.0
Cone Reef	0.67	3.0	6.0
Lakeside Reef	0.05	3.7	6.0
TOTAL	21.50	MEAN 1.8	5.3

Data Sources: Herdendorf and Braidech (1972), Cooper and Herdendorf (1977)

Table 1. Morphometry of the western and central basins of Lake Erie

Dimension	Western Basin	Central Basin	Eastern Basin	Entire Lake
Maximum length (km)	80	212	137	388
Maximum breadth (km)	64	92	76	92
Maximum depth (m)	18.9	25.6	64.0	64.0
Mean depth (m)	7.4	18.5	24.4	18.5
Area (km^2)	3,284	16,138	6,235	25,657
Volume (km^3)	25	305	154	484
Shoreline length (km)	438	512	430	1,380
Percent of area (%)	12.8	62.9	24.3	100
Percent of volume (%)	5.1	63.0	31.9	100
Percent of shoreline (%)	31.7	37.1	31.2	100
Development of volume (ratio)	1.2	2.2	1.1	0.9
Development of shoreline (ratio)	2.3	1.3	1.7	2.1
Water storage capacity (days)	51	635	322	1,008
Drainage basin land area (km^2)	37,000	15,000	7,000	59,000
Mean elevation (m)	173.86	173.86	173.86	173.86
Highest monthly mean elevation (m)	174.58	174.58	174.58	174.58
Lowest monthly mean elevation (m)	172.97	172.97	172.97	172.97
Mean tributary inflow (m^3/sec)	5,300	200	200	5,700
Mean outflow (m^3/sec)	5,300	5,500	5,700	5,700
Highest mean monthly outflow (m^3/sec)	6,600	6,900	7,200	7,200
Lowest mean monthly outflow (m^3/sec)	3,100	3,200	3,300	3,300

Table 2. Mean daily solar radiation received at the surface of Lake Erie

Month	Solar Radiation Per Day (langleys)	(kcal/m^2)	Radiant Flux Energy Per Sec (joules/m^2)	Irradiance Per Sec (uE/m^2)	(quanta/cm^2)
Jan	110	1,100	136	576	3.5×10^{20}
Feb	190	1,900	211	894	5.4×10^{20}
Mar	290	2,900	284	1,202	7.2×10^{20}
Apr	390	3,900	342	1,448	8.8×10^{20}
May	450	4,500	359	1,519	9.1×10^{20}
Jun	550	5,500	420	1,778	10.7×10^{20}
Jul	550	5,500	429	1,813	10.9×10^{20}
Aug	470	4,700	394	1,667	10.0×10^{20}
Sep	370	3,700	342	1,448	8.7×10^{20}
Oct	240	2,400	250	1,057	6.4×10^{20}
Nov	130	1,300	154	652	3.9×10^{20}
Dec	90	900	115	486	2.9×10^{20}

Conversion Factors:

1 langley = 1 cal/cm^2

1 cal = 4.19 joules

1 joule/m^2/sec = 1 watt/m^2

1 joule = 4.23 ueinsteins (mean for visible light)

1 ueinstein = 6.02×10^{17} quanta

Data Source: Mateer (1955)

Table 4. Relative abundance of algal species in aquatic habitats on western Lake Erie islands

Taxanomic Unit (Class)	South Bass Is	Middle Bass Is	North Bass Is	Kelleys Island	Pelee Island	Catawba Island
	Locality					
Chlorophyceae (green algae)	238	194	101	80	46	86
Charophyceae (stoneworts)	8	4	-	-	-	9
Xanthophyceae (yellow-green algae)	6	7	7	3	7	1
Euglenophyceae (euglenoids)	11	6	4	4	1	-
Chrysophyceae (golden algae)	19	15	10	4	-	2
Dinophyceae (dinoflagellates)	3	5	2	-	1	1
Cryptophyceae (cryptomonads)	1	-	-	-	-	-
Myxophyceae (blue-green algae)	56	36	20	15	6	22
Rhodophyceae (red algae)	1	-	1	1	-	-
TOTAL	342	267	145	117	61	121

Data Source: Taft and Taft (1971)

Table 5. Comparison of phytoplankton and zooplankton populations for localities in western Lake Erie

Date (1930)	Abundance by Locality: Detroit River Mouth	River Raisin Mouth	Maumee Bay	Portage River Mouth	Bass Islands
Phytoplankton (thousands of algal units per liter)					
July 1-15	26	154	431	206	42
July 16-31	39	352	406	212	104
Aug 1-15	31	453	970	419	110
Aug 16-31	25	700	1452	701	155
Sept 1-15	95	1347	2128	783	200
Sept 16-30	71	1500	2174	935	544
Mean	48	751	1260	543	193
Zooplankton (microcrustacean individuals per liter)					
July 1-15	3	77	81	76	43
July 16-31	3	58	52	67	40
Aug 1-15	3	61	56	82	63
Aug 16-31	5	71	70	--	32
Sept 1-15	1	25	81	48	29
Sept 16-30	1	13	28	37	20
Mean	3	51	61	62	38

Data Source: Wright et al. (1955)

Table 6. Invertebrate animals found on common aquatic plants in the Islands Region of Lake Erie

Invertebrate Taxa	Population Per Linear Meter of Submerged Plants													
	E.c.		N.f.		M.s.		V.a.		P.z.		P.p.		P.c.	
	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max
ANNELIDA														
Aeolosoma	<1	<1	1	4	1	5	-	-	-	-	-	-	-	-
Chaetogaster	2	3	3	9	8	51	-	-	5	5	2	3	6	21
Dero	1	3	-	-	-	-	-	-	-	-	-	-	<1	2
Nais	12	34	52	98	133	596	4	4	125	125	59	78	78	217
Ophidonais	-	-	-	-	5	37	-	-	-	-	-	-	-	-
Stylaria	10	28	6	22	27	69	-	-	1	1	2	3	11	55
ARTHROPODA														
Crustacea														
Amphipoda	1	2	1	5	27	111	-	-	-	-	1	1	1	5
Insecta														
Anisoptera	<1	1	-	-	<1	<1	-	-	-	-	-	-	<1	<1
Chironomidae	21	61	27	47	110	213	2	2	15	15	64	67	95	296
Coleoptera	<1	<1	<1	1	-	-	-	-	-	-	-	-	2	9
Ephemeridae	<1	<1	6	21	19	79	-	-	-	-	1	1	1	3
Hydroptila	<1	1	1	1	8	41	1	1	1	1	3	5	5	23
Leptoderidae	<1	<1	-	-	1	6	-	-	-	-	-	-	1	4
Zygoptera	5	9	3	8	20	61	-	-	1	1	2	2	5	13
MOLLUSCA														
Amnicola	-	-	-	-	<1	1	-	-	-	-	-	-	-	-
Ancylus	1	3	<1	1	1	2	-	-	-	-	-	-	6	29
Goniobasis	<1	1	<1	1	-	-	-	-	-	-	-	-	-	-
Helisoma	7	12	5	6	25	59	-	-	-	-	6	11	8	22
Physella	1	2	<1	1	1	4	-	-	<1	<1	-	-	1	3
Snail Eggs	-	-	-	-	-	-	-	-	2	2	-	-	<1	<1
PLATYHELMINTHES														
Planaria	4	8	2	3	7	34	-	-	-	-	1	1	6	24
Stenostomum	12	37	6	9	22	48	1	1	1	1	2	2	14	27
BRYOZOA														
Plumatella	1	2	<1	<1	1	4	-	-	-	-	1	2	10	52
Urnatella	-	-	1	2	-	-	-	-	-	-	-	-	-	-
ROTIFERA														
Melicerta	80	188	<1	<1	1	6	2	2	18	18	-	-	80	180

Table 6. (Concluded)

Invertebrate Taxa	Population Per Linear Meter of Submerged Plants													
	E.c.		N.f.		M.s.		V.a.		P.z.		P.p.		P.c.	
	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max
NEMATODA	4	16	<1	<1	17	113	-	-	-	-	-	-	1	7
COELENTERATA														
Hydra	7	15	1	2	6	20	-	-	5	5	1	1	15	52
PORIFERA														
Spongilla	<1	1	-	-	-	-	-	-	-	-	-	-	-	-
CHORDATA														
Vertebrata														
Fish Eggs	2	6	<1	2	-	-	-	-	-	-	<1	<1	-	-
Total	172		116		440		9		174		143		347	

Key: E.c. = *Elodea canadensis* N.f. = *Najas flexilis*
M.s. = *Myriophyllum spicatum* V.a. = *Vallisneria americana*
P.z. = *Potamogeton zosteriformis* P.p. = *Potamogeton pectinatus*
P.c. = *Potamogeton crispus*

Data Source: Krecker (1939)

Table 7. Western Lake Erie unionid bivalves and their glochidial host fish

Fish Hosts	Unionid Clams AMB	FUS	QUA	ELL	ALA	LAS	SIM	ANO	STR	TRU	PRO	CAR	LEP	ACT	LIG	LAM
Northern pike	X															
Carp						X		X								
Golden shiner								X								
Creek chub								X	X							
White sucker					X											
N hog sucker					X											
N Sh redhorse					X											
Bl bullhead			X													
Ye bullhead								X								
Br bullhead			X													
Ch catfish	X		X													
Bk stickleback								X								
White bass	X							X						X		X
Rock bass	X				X			X						X		X
Gr sunfish	X					X		X				X		X		
Pumpkinseed	X															
Or-sp sunfish												X				
Bluegill	X	X						X				X		X	X	X
Sm bass														X		X
Lm bass	X					X		X			X			X	X	X
Wh crappie	X	X	X	X		X		X				X		X	X	X
Bl crappie	X	X		X				X						X		X
Iowa darter								X								
Johnny darter					X			X								
Ye perch				X				X						X		X
Walleye																X
Freshwater drum								X		X	X		X			
Mottled sculpin					X											
Mudpuppy (amphibian)							X									

AMB - *Amblema plicata*
FUS - *Fusconaia flava*
QUA - *Quadrula quadrula* and *Q. pustulosa*
ELL - *Elliptio dilatata*
ALA - *Alasmidonta viridis* and *A. marginata*
LAS - *Lasmigona complanata* and *L. costata*
SIM - *Simpsoniconcha ambigua*
ANO - *Anodonta grandis grandis* and *A. imbecilis*
STR - *Strophitus undulatus*
TRU - *Truncilla donaciformis* and *T. truncata*
PRO - *Proptera alata*
CAR - *Carunculina parva*
LEP - *Leptodea fragilis*
ACT - *Actinonaias carinata*
LIG - *Ligumia recta*
LAM - *Lampsilis radiata siliquoidea* and *L. ventricosa*

N- northern
Sh- shorthead
Bl- black
Ye- yellow
Br- brook
Gr- green
Or-sp- orange-spotted
Sm- smallmouth
Lm- largemouth
Wh- white

Data Sources: Clarke (1981), Fuller (1974)

Table 3. Carbon assimilation by phytoplankton productivity in Lake Erie

Measurement Location	Photosynthic Rate (mg/C/m^2/day)	Data Source
Western Lake Erie		
Pointe Mouillee	2,197	Sheffield and Carey (1980)
Pigeon Bay, Pt. Pelee	1,775	Sheffield and Carey (1980)
Sandusky Bay	1,438	McQuate (1954)
Locust Point	1,223	Sheffield and Carey (1980)
Niagara Reef	833	Cody (1972)
South Bass Island:		
Fishery Bay	742	Cody (1972)
offshore, west coast	512	Verduin (1962)
Central Lake Erie		
Old Woman Creek, offshore	820	Sheffield and Carey (1980)

Table 9. Benthic macroinvertebrates common in profundal bottoms of western Lake Erie

Species
Phylum Porifera (sponges)
Class Demospongia
Spongilla spp.
Phylum Coelenterata
Class Hydrozoa
Hydra spp.
Phylum Bryozoa
Class Ectoprocta (moss animalcules)
Pectinatella magnifica
Plumatella emarginata
Phylum Annelida (segmented worms)
Class Oligochaeta (aquatic earthworms)
Family Tubificidae
Bothrioneurum vejdovskyanum
Branchiura sowerbyi
Limnodrilus hoffmeisteri
Peloscolex ferox
Class Polychaeta (fan worms)
Manayunkia speciosa
Class Hirudinea (leeches)
Glossiphonia complanata
Helobdella stagnalis
Phylum Mollusca (soft-bodies animals)
Class Gastropoda (snails)
Subclass Pulmonata (lunged snails)
Family Physidae
Physa sp.
Family Planorbidae
Heliosoma sp.
Planobula armigera

Table 9. (Continued)

Species
Family Ancylidae
Ferrissia sp.
Family Lymnaeidae
Bulimnea megasoma
Subclass Prosobranchia (gilled snails)
Family Viviparidae
Campeloma decisum
Viviparus malleatus
Family Valvatidae
Valvata sp.
Family Pleuroceridae
Goniobasis livescens
Pleurocera acuta
Family Hydrobiidae
Amnicola sp.
Family Bithymidae
Bithynia tentaculata
Class Pelecypoda (bivalves)
Family Unionidae
Amblema plicata
Anodonta grandis
Carunculina parva
Elliptio dilatatus
Lampsilis radiata siliquoidea
Leptodea fragilis
Obliquaria reflexa
Propter alata
Quadrula pustulosa
Quadrula quadrula
Truncilla donaciformis
Truncilla truncata
Family Sphaeriidae (fingernail clams)
Pisidium henslowanum
Sphaerium transversum

Table 9. (Concluded)

Species
Phylum Arthropoda (joint-legged animals)
Class Crustacea
Order Amphipoda (scuds)
Gommarus fasciatus
Hyalella azteca
Order Cladocera (water fleas)
Leptodora kindtii
Order Decapoda (shrimps, crayfishes)
Palaemonetes exilipes
Order Isopoda (aquatic sowbugs)
Asellus racovitzai
Class Insecta
Order Diptera (flies)
Family Chaoboridae (phantom midges)
Chaoborus flavicans
Family Ceratopogonidae (biting midges)
Palpomyia tibialis
Family Chironomidae (midges)
Subfamily Chironominae
Chironomus plumosus
Polypedilum sp.
Pseudochironomus richardsoni
Subfamily Tanypodinae
Coelotanypus scapularis
Procladius bellus
Procladius culiciformis
Tanypus sp.
Order Ephemeroptera (mayflies)
Hexagenia limbata
Caenis sp.
Order Tricoptera (caddisflies)
Oecetis sp.

Data Sources: Britt et al. (1973), Herdendorf and Lindsay (1975), Lindsay (1976), Wolfert and Hiltunen (1968)