ECOLOGICAL CONCEPT OF THE COASTAL ZONE IN THE GREAT LAKES*

Claire L. Schelske

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INTRODUCTION

Ecology of the coastal zone is obviously too broad or general an area to discuss more than generally in a limited amount of time. For the purposes of this conference, however, generalities and principles may be more appropriate than detailed scientific discussions.

It would be appropriate to provide a definition of the coastal zone in the Great Lakes, but I hope this paper may provide some insight as to why it may not be possible or desirable to establish a rigid definition. Depending on scientific disciplines, legal aspects, recreational uses and other interests, one may have many definitions. As an ecologist, I can list a number of factors that influence the limits of the coastal zone. Among these are depth of water, season of the year, proximity to tributaries and harbors, concentrations of nutrients in inflowing waters, and other environmental factors. The coastal zone, generally speaking, is an area from the shore to some distance offshore over which there are transitional environmental characteristics. At times it may not be present as such and at other times it may extend for miles offshore. The limits of the zone will probably not be the same for all environmental characteristics.

The use of the term, ecology, in this paper should be clarified also. If ecology is considered from the standpoint of basic environmental processes, we can see that biological functions of environmental systems or ecosystems are dependent on transformation of solar energy by green plants (Fig. 1). Solar energy is transformed into plant protoplasm by photosynthetic plants. In deep lakes, plants are microscopic and are called phytoplankton. Phytoplankton, like other green plants, require light, carbon dioxide and nutrients for photosynthesis. In aquatic systems, the rate of photosynthesis and growth of phytoplankton may be controlled by the supply of nutrients. As the supply of nutrients increases,

the system becomes more productive and this process is called eutrophication. Eutrophication is a natural process but its rate in the Great Lakes has been accelerated by the activities of man.

Because the basic processes of the ecosystem are dependent on phytoplankton, we can generalize and state that other biological properties will be dependent or related to the phytoplankton. In other words environmental disturbances, perturbations, and other changes will be reflected in the amounts and kinds of phytoplankton. Therefore, I will not discuss additional biological components of the ecosystem and other links in the food chain except primary producers.

Eutrophication of the Great Lakes is controlled by the supply of essential nutrients for photosynthesis and plant growth and by non-essential factors that affect the subtle interrelationships among the many species and disrupt the ecological balance. Essential nutrients are those elements that are required for plant growth. By definition, at any one time, one essential nutrient is termed the limiting nutrient. The limiting nutrient is that essential element which is present in concentrations too low in relation to other essential nutrients to provide an adequate supply for plant growth. Phosphorus, nitrogen and certain trace elements may be limiting nutrients in aquatic ecosystems.

The role of non-essential and conservative elements in eutrophication has not been documented as fully as that of limiting nutrients. Conservative elements are those whose concentrations in water are not changed appreciably by chemical, biological, and other environmental factors. As examples, sodium is required or is essential for growth of blue-green algae (Evans and Sorger 1966) and is probably not required or is required in much smaller amounts by other algae, and concentrations of chloride in the water determine whether the flora and fauna are freshwater, brackish water or marine. None of this discussion is

concerned with acute toxicity of non-essential and essential elements. Acute toxicity in the Great Lakes apparently is not a serious large-scale problem due to the large dilution capacity of the systems.

In the remaining time, I will consider physical and chemical factors, assimilation capacity, and the coastal zone concept in relation to ecological processes in the Great Lakes.

. PHYSICAL AND CHEMICAL FACTORS

Water temperature and water movement affect ecological processes in the nearshore environment. Thermal stratification, upwelling, and the thermal bar are physical phenomena of interest. The relationship of physical factors to eutrophication in larger lakes has been discussed (Mortimer 1969).

Temperature Phenomena

In lakes smaller than the Great Lakes, the annual temperature cycle and distribution are well known and predictable depending primarily on the season of the year and the morphometry of the lake basin and surrounding basin. In these lakes solar radiation warms the surface of the water, and wind mixes a layer of water near the surface. By early summer three layers of the lake are identifiable on the basis of temperature: epilimnion, thermocline, and hypolimnion (Fig. 2a). At the surface is the epilimnion, the warmest layer; at the bottom is the coldest layer, the hypolimnion; and between these is the thermocline, the layer with the largest temperature gradient. Vertical temperature stratification of this type is found also in the Great Lakes; but upwelling and the thermal bar are horizontal temperature phenomena peculiar to the nearshore environment of large freshwater lakes.

Upwelling occurs after the lake is stratified thermally, and when sufficient warming and mixing have occurred to establish a three-layered lake with a

temperature profile as shown in Fig. 2a. An offshore wind then can move warm surface or epilimnetic water to the windward shore, literally piling the warm water on one side of the lake. If enough surface water is moved, pressure differences force cold bottom water to the surface on the lee shore, replacing the warmer wind-transported surface water (Fig. 2b). Upwelling is significant to the recreation industry since it may bring uncomfortably cold water to bathing beaches.

Because bottom water is richer in nutrients than surface water, upwelled water stimulates the growth of phytoplankton (Schelske, Stoermer, and Feldt 1971). It is significant that upwelling moves deep offshore lake water into the nearshore zone by physical processes. Nutrients in the upwelled water originated from nearshore sources and were diluted or assimilated into the lake previously. In this case, the effect of dilution may be somewhat different than one would predict without adequate knowledge of physical processes in the system.

A thermal bar is established in the spring and fall because shallow nearshore areas warm and cool faster than deeper offshore areas. The shallower areas warm faster than the deeper areas because less solar radiation is required for a given temperature increase in the smaller mass of water present per unit area than in the deeper offshore environment. In the spring, therefore, the water is warmer near the shore than in the deeper parts of the lake (Fig. 2c). The thermal bar persists in the spring until the temperature offshore water exceeds 4°C, the temperature of maximum density of water (Rodgers 1965). After this time, vertical temperature stratification will begin and will persist over most of the lake until late in the fall. In the fall, the inshore waters cool faster than the offshore waters and the reverse of the spring thermal bar may occur, although the fall thermal bar may not be as pronounced as the one in the spring.

Nutrients and other materials flowing into the lakes are trapped in the nearshore environment by the thermal bar. When inflows to the lake are trapped in this manner, the expected or calculated dilution for the entire volume of the lake may not be realized as rapidly as anticipated and biological and other environmental processes related to concentrations of different factors will be affected accordingly.

Sources and Fate of Nutrients

Generally speaking, there are two sources of nutrients for ecological processes in a lake: (1) from materials entering the lake from stream or tributary inputs (including materials naturally present as well as pollutants), direct outfalls, atmospheric inputs, and discharges from ships; and (2) from materials present in the lake due to recycling mediated by biological, chemical and physical phenomena within the lake. Nutrient cycles are processes that tend to result in accumulation of materials in the system at the expense of dilution processes.

The fate of nutrients and other dissolved materials introduced into the lake from tributary inputs depends on the season of the year. In the spring, inflowing waters warmer than the offshore lake waters are trapped by the thermal bar and can be utilized by phytoplankton in the nearshore zone (Fig. 2c). After the disappearance of the thermal bar, nutrients are diluted into the epilimnetic waters (Fig. 2a) where they can be utilized by phytoplankton near the source of input. In the fall and early winter, the inflowing waters are colder than the lake waters and tend to sink to the bottom due to density differences. Nutrients in these waters may not be utilized immediately by phytoplankton if they sink to depths where light is not adequate for photosynthesis. During the winter and early spring the lake becomes homothermous and, presumably wind action mixes the lake, resulting in the most uniform distribution of dissolved

substances that is found at any season of the year. During the winter, maximum amounts of dilution are achieved, but unfortunately, from the ecological standpoint, the cold winter period may be the least critical for most biological processes.

ASSIMILATION CAPACITY

Two different approaches will be used to question whether the assimilation or dilution capacity of the Great Lakes, exclusive of Lake Superior, has been exceeded. Available data indicate that for the entire lake system the amounts of some dissolved substances may be decreasing in Lake Superior (Beeton 1969). Amounts may be decreasing due to the large quantities of materials transported into the lake during glaciation and lower concentrations of materials in present tributary streams and rainfall. Even though dilution of these materials may be occurring presently, Lake Superior has only about one third the concentration of dissolved solids found in Lake Michigan. This fact alone is an indication that the dilution capacity of Lake Michigan has been exceeded. The two main lines of evidence, however, are changes in conservative elements and accelerated eutrophication.

Changes in concentrations of conservative elements have been documented by Beeton (1969). Chloride, sulfate, sodium and magnesium have increased since 1900. To illustrate, only chloride will be discussed. In Lake Michigan, concentrations of chloride have increased 6 ppm, while concentrations in Lake Erie and Lake Ontario have increased about 20 ppm (Weiler and Chawla 1969). As water moves through the Great Lakes, concentrations of chloride increase, and the amounts of chloride actually flowing out increase even more. About 800 million pounds are discharged annually from Lake Michigan, whereas more than ten times that amount flows out of Lake Erie and Lake Ontario (Table 1). Data in Table 1

indicate that 80 percent of the outflow from Lake Ontario represents additions due to pollution of the Great Lakes since 1900; or, in other words, that 10 billion pounds (5 million tons) of chloride from pollution are discharged annually. Even more staggering is that residual chloride from pollution sources in Lake Ontario alone, 80 percent of 100 billion pounds, represents 40 million tons and that there is about the same amount of residual chloride in the combined totals of Lake Michigan, Lake Huron and Lake Erie.

Concentrations of chloride have not increased in Lake Huron as much as in the other three lower lakes because a large part of the water flowing into the lake is outflow from Lake Superior (Table 1). It also is difficult to discuss Lake Huron because large amounts of chloride are introduced in Saginaw Bay (Tiffany and Winchester 1969) in the southern part of the Lake near the outflow, the St. Clair River.

Concentrations of chloride in Lake Erie and Lake Ontario have doubled twice or increased from 7 to 28 ppm (Table 1) in less than 70 years and possibly in the last 50 years. If this rate of increase is maintained, concentrations will be larger than 100 ppm in the next 50 years. Presently these lakes have only one thousandth the salinity of the oceans, but if rates of inputs of chloride continue the waters will become brackish and floral and faunal changes will result. Concentrations of chloride in Lake Michigan also appear to have doubled in the last 50 years.

Direct effects of conservative elements, such as chloride, are difficult to assess but the replacement of freshwater species by brackish or marine species is one effect that has been noted. Pollution of the Great Lakes by essential elements, on the other hand, is easily recognized by environmental changes that have resulted from accelerated eutrophication. It is now generally accepted that the essential nutrient present in limiting amounts has been phosphorus, or

that inputs of phosphorus have been a prime cause of accelerated eutrophication.

Our own studies of Lake Michigan have shown that, of the essential elements, inputs of phosphorus have controlled the rate of eutrophication (Schelske and Stoermer 1971). Inputs of phosphorus probably control the rate of eutrophication in Lake Superior and Lake Ontario also. In Lake Erie and Lake Ontario sufficient phosphorus has been added to accelerate eutrophication to the point that it is now no longer a question of what essential nutrient is limiting but whether eutrophication can be reversed by management decisions. Eutrophication was reversed in Lake Washington by diverting sewage inputs around the lake (Edmondson 1970). It is not practical or desirable to divert tributary inputs containing nutrients from the Great Lakes; to control eutrophication, inputs of phosphorus will have to be controlled at their sources.

COASTAL ZONE CONCEPT IN THE GREAT LAKES

The Great Lakes, with nearly 10,000 miles of shoreline, have many coastal zones of different types. Legislatively the coastal zone of the Great Lakes and marine environments have been lumped together. Environmentally, the freshwater and marine coastal zones are not similar and the differences between the two are important from the standpoint of management decisions. Six of these differences are discussed below as examples.

(1) Obviously the salinity of the Great Lakes is much less than in the marine coastal zone. Concentrations of NaCl in Lakes Erie and Ontario are only 0.1% of the marine average of 35 parts per thousand. As indicated above, these two lakes have the largest concentrations of chloride of the five Laurentian Great Lakes (Table 1).

(2) Residence times of water in the Great Lakes are long. For example at the present rates of outflow, it would take 100 years to empty Lake Michigan and 190 years to empty Lake Superior provided all inflows including rainfall

could be stopped. Flushing rates in estuaries and bays are more rapid, meaning that waste introduced into marine coastal systems will be removed more rapidly than in the Great Lakes.

(3) There is one circulation period per year in the Great Lakes. Circulation occurs in the winter and mixes coastal waters with offshore waters and surface waters with deep waters. Mixing, in some respects, eliminates the coastal zone. Considering winter circulation, periodic upwelling, and other aspects of the Great Lakes, one would have to conclude that the coastal zone has many transitory characteristics seasonally. Circulation patterns and periods vary for different types of estuaries, which are influenced by freshwater runoff and depth.

(4) Biological productivity in the Great Lakes, particularly the three upper Great Lakes, is low in comparison to many marine coastal zones. At the turn of the century, all of the Great Lakes had characteristics of oligotrophy, indicating low supplies of nutrients and low biological productivity. Now only Lake Superior can be considered oligotrophic. Management policies for the Great Lakes should and now are beginning to reflect this fact, resulting in present efforts to control inputs of phosphorus. Some estuaries are at the other extreme, being among the most productive biological systems. There is evidence that photosynthesis in some estuaries may be limited by light, not by any one nutrient and certainly not by phosphorus. Pomeroy, Reimold and Roffmann (In press) have developed a model of phosphorus fluxes in a salt marsh estuary which shows levels of productivity would be maintained for hundreds or thousands of years without additional inputs of phosphorus. Large amounts of biological production are natural characteristics of these systems, and such estuaries should be managed to maintain high rates of biological productivity (Schelske and Odum 1962).

(5) Limiting nutrients are different in the Great Lakes and marine systems,

particularly in terms of management. Phosphorus must be controlled to maintain water quality in the Great Lakes (Schelske and Stoermer 1971), whereas it may never have been a limiting nutrient in certain coastal areas. Ryther and Dunstan (1971) have recently stated that nitrogen, not phosphorus, is the critical limiting factor and that management decisions to remove phosphates would not affect eutrophication in marine coastal zones.

(6) The Great Lakes have a characteristic that is peculiar to rivers in that the flow of water is generally directed to the ocean. All the water that flows out of Lake Michigan and Lake Superior, except that evaporated and lost by other means, would naturally flow through Lake Huron, Lake Erie and Lake Ontario in that order. Pollutants such as chloride, therefore, become more concentrated as the water passes by areas of urbanization and industrialization and moves toward the St. Lawrence River and Atlantic Ocean. Unidirectional flow of this type is not a characteristic of marine coastal zones.

In summary, the coastal zone of the Great Lakes may be similar to the marine coastal zone in many respects, but in terms of ecological processes it must be viewed as part of the lake ecosystem and cannot be treated separately. It therefore follows that to study the coastal zone adequately, one must study the entire lake ecosystem and for some types of problems, such as chloride pollution, one must consider the five Great Lakes as a system.

FIGURE CAPTIONS

Fig. 1. Components of a self-sufficient ecosystem (After Clarke 1954).

Fig. 2. Schematic representation of temperature phenomena in the Great Lakes. Isotherms are designated in degrees Celsius in each horizontal transect. a. Summer stratification, b. thermal bar, c. upwelling caused by wind-induced disruption of summer stratification.

TABLE 1. Morphometric and discharge data for the Great Lakes in relation to concentrations and discharges of chloride

Lake	Area ¹ (mi ²)	Avg. Depth ¹ (ft)	Discharges ¹ (ft ³ /sec)	Chloride (ppm) ^{2,3}		Present outflow ⁴ (10 ⁹ lbs Cl/yr)	Present residual ⁵ (10 ⁹ lbs Cl)
				Pre-1900	Present		
Superior	31,820	487	73,300	2	2	.29	54
Michigan	22,420	276	55,000	2	8	.86	86
Huron	23,010	195	178,000	4	7	2.8	55
Erie	9,930	58	195,000	6	26	9.98	26
Ontario	7,520	283	234,000	6	28	12.9	104

¹Beeton and Chandler (1963)

²Beeton (1969)

³Weiler and Chawla (1969)

⁴Present outflow is the annual discharge of chloride in billions of pounds and is obtained from the product of the annual discharge times the present concentration of chloride.

⁵Present residual is the amount of chloride in billions of pounds in each lake and is obtained from the product of the volume (area X average depth) times the concentration.

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SUMMER STRATIFICATION

THERMAL BAR

UPWELLING