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# Critical Assessment of U.S. Land Derived Pollutant Loadings to the Great Lakes: A Summary

Great Lakes Basin Commission

International Reference Group on Great Lakes Pollution from Land Use Activities

Great Lakes Environmental Research Laboratory

William C. Sonzogni

Timothy J. Monteith

*See next page for additional authors*

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**Authors**

Great Lakes Basin Commission, International Reference Group on Great Lakes Pollution from Land Use Activities, Great Lakes Environmental Research Laboratory, William C. Sonzogni, Timothy J. Monteith, and William E. Skimin



**INTERNATIONAL REFERENCE GROUP  
ON GREAT LAKES POLLUTION  
FROM LAND USE ACTIVITIES**

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**INTERNATIONAL  
JOINT  
COMMISSION**

**CRITICAL ASSESSMENT OF U.S.  
LAND DERIVED POLLUTANT  
LOADINGS TO THE GREAT LAKES**

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ACKNOWLEDGEMENTS  
DISCLAIMER

## CRITICAL ASSESSMENT OF U.S. LAND DERIVED

## POLLUTANT LOADINGS TO THE GREAT LAKES

### A SUMMARY U.S. TASK D PLUARG

by

William C. Sonzogni  
Timothy J. Monteith  
William E. Skimin  
Steven C. Chapra\*

Great Lakes Basin Commission Staff  
Ann Arbor, Michigan

March 1979

To be used as a portion of the Technical Reports of the International Reference Group on GREAT LAKES POLLUTION FROM LAND USE ACTIVITIES of the International Joint Commission--prepared in partial fulfillment of U.S. Environmental Protection Agency Interagency Agreement No. EPA-IAG-78-D-X0055 with the Great Lakes Basin Commission.

\* Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan



DISCLAIMER

The study discussed in this report was carried out as part of the efforts of the Pollution from Land Use Activities Reference Group, an organization of the International Joint Commission, established under the Canada-U.S. Great Lakes Water Quality Agreement of 1972. Funding was provided through the U.S. Environmental Protection Agency. Findings and conclusions are those of the authors and do not necessarily reflect the views of the Reference Group or its recommendations to the Commission.

William C. Bonaparte  
Timothy J. Korte  
William A. Sklar  
Steven C. Doney

Great Lakes Water Quality Agreement  
Ann Arbor, Michigan

March 1979

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## EXECUTIVE SUMMARY

This report presents the findings of Subactivity 3-4 of the U.S. Task D portion of the Pollution from Land Use Activities Reference Group (PLUARG) study. The report reviews the degree of Great Lakes water quality impairment which is known or thought to be caused by pollution from land drainage. It also summarizes and integrates the overall U.S. Task D effort. Further, the report examines certain critical questions that were not answered in the PLUARG final report but were recognized as essential to implementing the PLUARG recommendations.

Based on an extensive literature review, it was concluded that, while many studies have implicated land-derived pollution as a factor in the degradation of Great Lakes water quality, there is little conclusive evidence of direct effects. It is clear that nonpoint sources are impairing the lakes, however it is often impossible to separate the effects of point and other sources to determine the specific role of nonpoint source pollution.

Impairment caused by nonpoint source sediment inputs is perhaps most easily identified, although even here the effects on water quality are not well established. Control of soil erosion upstream may significantly reduce sedimentation in harbors and thus reduce the cost of maintenance dredging.

The most important land-related factors affecting the magnitude of nonpoint source pollution from rural land are those related to the texture of the soil material, especially infiltration rate. Clay-textured soils cause the greatest nonpoint source pollution problems. Maps which have been prepared showing the distribution of surface soil texture over the entire U.S. basin, indicate that the Lake Erie basin has the greatest amount of clay-textured soils. In some areas fine-textured sub-surface soils account for significant nonpoint source problems.

Different estimates of phosphorus loads were evaluated. Good agreement exists between the different estimates, and those differences that do occur are readily accounted for. Annual diffuse tributary loads can vary as much as 30 percent due to normal year-to-year flow variations. For example, mid-1970 diffuse tributary total phosphorus loads to the Great Lakes were generally higher than can typically be expected due to high tributary flow.

A mathematical model is presented which demonstrates the importance of considering the Great Lakes as an interconnecting system. For example, Detroit River phosphorus loads have a major effect not only on Lake Erie, but also on Lake Ontario. From a water quality management perspective, the results show that uniform treatment of phosphorus sources around the basin, while politically convenient, is not economically optimal.



As a result of the integration of U.S. Task D studies, it was learned that shoreline erosion contributes about five times as much sediment to the Great Lakes as is delivered by tributaries. The biologically available fraction of the phosphorus associated with shoreline erosion is small, as low as a few percent of the total, but would be significant as other sources are reduced or when compared to the available phosphorus fraction of other sources. For example, it appears that the biologically available sediment phosphorus delivered to the Great Lakes from land runoff is also quite low, probably no more (and usually considerably less) than 40 percent of the total sediment phosphorus.

Task D also investigated the effect on the Great Lakes of the large non-point source tributary inputs that occur in early spring. Pollutants from runoff tended to disperse quickly and few water quality changes were noted immediately following runoff events. Thus the effect of nonpoint source inputs appears to be long-range and cumulative. It was noted that shore erosion and resuspension processes can be very important during the spring runoff period. Resuspension of bottom sediments was found to be quite prevalent in U.S. nearshore waters, but the effect of resuspension on water quality is not yet understood.

It is speculated that high sediment input might be related to low levels of toxic contaminants in the Great Lakes. The significantly lower levels of PCBs in Lake Erie fish compared to Lake Superior fish may be related (among other factors) to the fact that the tributary suspended sediment input to Lake Erie is over 100 times greater on a unit volume basis than to Lake Superior.



## MAJOR CONCLUSIONS

1. Very little information exists in the literature which directly links land-derived pollution with impairment of Great Lakes waters. While many studies have implicated land-derived pollution to be a cause of degradation of Great Lakes water quality, it has proved difficult to separate the effects of non-point source pollution from point source pollution. Although the physical and biological effects of pollutants on plankton, benthos and fish are becoming better known, it is difficult to determine the relative importance of the non-point source loads.
2. The amounts of solids removed by dredging from many Great Lakes river mouth areas were found to be comparable to the amount of suspended solids contributed annually by the rivers. Control of soil erosion upstream may thus have a significant benefit in terms of reducing the quantity of sedimented material that must be removed by dredging.
3. Despite often being implicated as harmful to the Great Lakes, few examples of Great Lakes impairment by road salt runoff exist. There is some speculation that subtle but derogatory changes in the species composition of phytoplankton in the Great Lakes may occur if chloride levels continue to increase. For some lakes (e.g., Ontario) chloride inputs from industrial operations are much more important than road salt runoff.
4. Despite the potential harmful impact of lead, there is currently no evidence to indicate it is causing impairment of the Great Lakes resource.
5. Pesticides currently in use do not appear to be impairing Great Lakes water quality. Pesticides used in the past, such as DDT, have been documented to be harmful to the Great Lakes ecosystem and levels still exceed some water quality objectives.
6. Texture of the soil material appears to be the most important indicator of the magnitude of nonpoint source pollution from rural land. The Lake Erie watershed has large areas of clay surface soils and consequently has the largest land-derived loading of phosphorus and sediment.
7. Substantial differences in pollutant outputs can be seen between event and stable response tributaries. The Maumee provides a good example of an event response tributary while the Grand (Michigan) is a good example of a stable response tributary.
8. Differences in the Great Lakes phosphorus load estimates made by PLUARG, the Water Quality Board and the Technical Group to Review Phosphorus Loadings are minor and/or readily accounted for.



9. Annual diffuse tributary loads can vary considerably (as much as 30 percent) due to normal year-to-year flow changes. Mid-1970 loads of total phosphorus to the Great Lakes were higher than usual, reflecting high flow conditions, particularly during 1975.

10. Waterfowl do not appear to be a significant source of phosphorus to the Great Lakes.

11. The Great Lakes should be viewed as a system in order to optimize cost-effective environmental management.

12. The response of the Great Lakes to pollution abatement, including toxic substance as well as phosphorus abatement, will likely be much more rapid than the long period (in some cases hundreds to thousands of years) previously thought by many.

13. Shoreline erosion on an annual basis contributes about five times as much sediment to the Great Lakes as is delivered by tributaries.

14. The available phosphorus input to the Great Lakes from shoreline erosion is generally small relative to other sources of total phosphorus. However, when compared to only the available phosphorus loads from other sources, or if compared to possible reduced total phosphorus loads resulting from phosphorus control measures, the shoreline erosion available phosphorus load can be quantitatively significant, at least for some lakes or lake sectors.

15. Overall, it appears that a rather large percentage (60 percent or more) of the phosphorus associated with sediments delivered to the Great Lakes via tributary suspended solids is not biologically available.

16. Roughly 40 to 50 percent or more of the tributary total phosphorus load is likely to be in a biologically unavailable form.

17. The sodium hydroxide extraction technique as conducted for PLUARG appears to give a good indication of potentially available sediment phosphorus. The readily available sediment phosphorus appears, however, to be considerably less than that measured by the sodium hydroxide extraction. Factors such as the phosphorus status of the algal population, phosphorus concentration and pH of the lake water and the residence time of the sediment particle in the water can affect the rate of uptake of biological availability of sediment phosphorus.

18. Less than 50 percent of the metals associated with tributary suspended material appear to be available.

19. During the late winter/early spring runoff period when tributary inputs are large, synoptic remote sensing indicates that shoreline erosion and sediment resuspension are also very important processes affecting suspended sediment levels in the Great Lakes.

20. The effect of large runoff inputs were not observed to cause major biological and chemical changes in Great Lakes waters immediately following the event. Rather, the effect appears to be long-range and cumulative.



21. Pollutants from a runoff event generally are quickly dispersed, with wind speed and direction playing a major role in the movement of the river plume.

22. Most of the sediment and associated pollutants which enter the western basin of Lake Erie during the early spring runoff period are apparently transported to the central basin by early summer.

23. Resuspension of Great Lakes nearshore sediments is a major contributor to suspended solids levels found in the Great Lakes. Sediments from Saginaw Bay, western Lake Erie, southern Lake Michigan and western Lake Superior have the greatest potential for affecting water quality as a result of wind-induced resuspension.

24. PCB levels in Lake Erie fish are significantly lower than levels in fish in the other lakes. This may be related, at least in part, to the high tributary sediment input to Lake Erie. For example, the tributary suspended sediment input per unit volume of lake water is over 100 times greater for Lake Erie than Lake Superior.



20. As shown in Figure 1, the sedimentation of suspended solids in the Great Lakes is a function of the wind speed and direction. The wind speed and direction play a major role in the movement of the river plume.

21. Pollutants from a runoff event generally are quickly dispersed with wind speed and direction playing a major role in the movement of the river plume.

22. Most of the sediment and associated pollutants which enter the western basin of Lake Erie during the early spring runoff period are generally transported to the central basin by early summer.

23. Resuspension of Great Lakes nearshore sediments is a major contributor to suspended solids levels in the Great Lakes. Sediments from the western basin have been shown to be resuspended in the western basin and western Lake Superior have the greatest potential for affecting water quality as a result of wind-induced resuspension.

24. PCB levels in Lake Erie are significantly lower than levels in fish in the other lakes. This may be related, at least in part, to the high sedimentation rate in Lake Erie. For example, the sedimentation rate in Lake Erie is about 100 times greater than in the other lakes.

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## INTRODUCTION

### RECOMMENDATIONS FOR FUTURE STUDY

1. The quantitative importance of wind erosion as a nonpoint source of pollutants needs to be determined. Pollutants derived from wind erosion are likely distributed to the lake surface over a wide area and thus have different ecological effects than tributary inputs which empty into river mouth areas.
2. The effect of phosphorus removal practices on concentrations of toxic substances in municipal treatment plant effluent needs to be studied.
3. The biological availability of phosphorus leaving treatment plants should be investigated for different treatment processes.
4. Availability of sediment phosphorus derived from land runoff needs further study. The kinetics of uptake by algae of sediment-bound phosphorus also needs further illumination.
5. The ecological importance of resuspension of sedimented material in the Great Lakes is a prime research need. Information is urgently needed on whether or under what conditions resuspended particulate material can take up or release contaminants.
6. The potential importance of sediment input on moderating levels of toxic contaminants in Great Lakes fish needs to be investigated. The effect of reducing sediment input through nonpoint source control programs on toxic contaminant levels should also be considered.
7. Remote sensing studies coordinated with shipboard surveys should be encouraged to provide more synoptic coverage of the Great Lakes.
8. The effect, if any, of nonpoint source sediment reductions on silica levels in the Great Lakes needs to be addressed.
9. Transmission of point and nonpoint sources, and the implications for management, needs to be better understood.



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7. Future sampling studies coordinated with air-borne surveys should be encouraged to provide more synoptic coverage of the Great Lakes.
8. The effect, if any, of nonpoint source sediment reductions on algal levels in the Great Lakes needs to be addressed.
9. Transmission of point and nonpoint sources, and the implications for management, needs to be better understood.



## INTRODUCTION

This report presents the findings of Subactivity 3-4 of the U.S. Task D portion of the Pollution from Land Use Activities Reference Group (PLUARG) study. The report critically reviews the degree of Great Lakes water quality impairment which is known or thought to be caused by pollution from land drainage. It also summarizes and integrates the overall U.S. Task D effort. Further, the report examines certain critical questions that were not answered in the PLUARG report but were recognized as essential to the implementation of the PLUARG recommendations. Some of these questions were raised by PLUARG itself, and some were raised by various review groups, including the Great Lakes Water Quality Board and the PLUARG public panels.

Since this report covers many aspects of pollution from land drainage, specific sections may be of particular interest to certain individuals. Thus, the sections have been written so they can be easily comprehended when viewed independently. However, the report does attempt to integrate the different topics, as it is necessary to look at the total picture to understand a system as complicated as the Great Lakes and its basin.

The report begins by summarizing the results of an extensive literature review of the impact of U.S. land-derived pollutant loadings on the Great Lakes. This review documents observations of Great Lakes water quality degradation linked to land-derived diffuse pollutant sources. Emphasis is given to the effect of phosphorus and sediment transported in runoff water to the lakes. The literature review is presented in its entirety in Appendix A.

"Land Factors Influencing Pollutant Loads" is the subject of the next chapter. Land drainage was a major consideration in the PLUARG study. This chapter of the report provides additional information on this subject, particularly on the relationship between soil texture and water quality. This information is essentially a follow-up on the previous work in this area conducted by the Basin Commission staff (Sonzogni *et al.*, 1978; Monteith and Skimin, 1978).

The next chapter, "Phosphorus Loadings", compares the relative importance of the different sources of phosphorus loadings to the Great Lakes. One of the major overall objectives of U.S. Task D was to provide enough information to make such comparisons. Unless the contribution of nonpoint sources is known relative to the contributions from other sources, the large expenditures and personal sacrifices that will be involved in instituting nonpoint source controls cannot be justified. This section also compares and critiques the phosphorus loading estimates made during the mid-1970s, and it considers the variability in phosphorus loads that occur as a result of natural year-to-year variations in runoff. Such information is critical, especially when evaluating the meaning



of the proposed "target phosphorus loads" found in the new 1978 U.S.-Canadian Great Lakes Water Quality Agreement.

The following chapter, entitled "Predicting Impacts on the Lakes", provides specific information on modeling the response of the lakes to changes in the phosphorus input, including changes in the land-derived portion of the input. It treats the Great Lakes as an integrated system and highlights the effects that control strategies in one portion of the lake may have on another.

The final chapter, "Summary and Evaluation of U.S. Task D, PLUARG", summarizes and integrates all the different aspects of U.S. Task D, PLUARG. The main activities of U.S. Task D include (1) Assessment of Shoreline Erosion, (2) Survey of River Sediment and Associated Water Quality, and (3) Effects of River Inputs. All of these activities are linked together, so it is necessary to look at the overall results to put the Task D effort in proper perspective. Consequently, the summary and integration provide an overview of the degree to which Great Lakes water quality has been impaired by land-derived sources of pollution. Since the question of phosphorus availability was given major attention in U.S. Task D (Subactivity 2-5), particular emphasis is given to the application of the availability results in the broad context of Great Lakes pollution control.

Throughout this report the pollutants considered are those pollutants identified in the PLUARG process as being of most concern. Phosphorus is given the most attention as it appears to be the most significant Great Lakes pollutant found in land drainage. Suspended solids is also given attention, although its effect on the lake is difficult to explicitly determine. The effects of certain dissolved solids, particularly chloride and silica, are also investigated.

While the above parameters, particularly phosphorus, are of concern with regard to the ecological health of the lakes, toxic substances continue to be the most serious and immediate concern due to their public health implications. Consequently, heavy metals and other toxic elements, industrial organics such as polychlorinated biphenyls, and pesticides are addressed in this report. However, these pollutants are generally not derived from land-associated sources of pollution or, as is the case for pesticides, are not currently thought to present a Great Lakes pollution problem.



# SUMMARY OF A LITERATURE REVIEW ON THE IMPACT OF LAND-DERIVED NONPOINT SOURCE POLLUTION ON THE GREAT LAKES

## INTRODUCTION

A review of current literature relevant to the study of the impact of land-derived nonpoint source pollution on the Great Lakes system was conducted. The review concentrated on the effects of phosphorus and suspended solids, although information was obtained on dissolved solids and toxic substances as well. Because of the length of the review, only a summary is presented here. The entire literature review is contained in Appendix A.

The process of defining the effect nonpoint source pollutants have on Great Lakes water quality is complicated by problems inherent in attempting to separate the effects of runoff-derived tributary loading from the effects of the point source component. In the case of an element such as phosphorus, the task is further complicated by the fact that not all of the phosphorus contributed is biologically available.

## EFFECTS OF NONPOINT SOURCE PHOSPHORUS

The most significant nonpoint source phosphorus pollution occurs in Lakes Erie and Ontario. Pronounced local effects have been identified in each of the other Great Lakes. Two particular areas, Green Bay, Lake Michigan, and Saginaw Bay, Lake Huron, have had a substantial amount of their water quality problems attributed to nonpoint phosphorus loading.

The primary and secondary effects of phosphorus on the abundance and species composition of plankton in the Great Lakes is well-documented. However, the relative importance of nonpoint sources in these investigations is not always clear and frequently impossible to establish.

Less information is available relating macrophyte abundance in the Great Lakes to phosphorus loading resulting from surface runoff. Abundance and productivity of Cladophora has been associated with phosphorus enriched waters. In Lake Huron, the low ambient level of phosphorus, and other nutrients, is thought to be responsible for the sparsity of Cladophora. Only in local areas enriched by nonpoint and/or point sources does Cladophora appear to proliferate in Lake Huron. Consequently, this is one of the best examples of land-derived impacts on nearshore waters.

A number of investigations have documented changes in benthic organism abundance and distribution in the Great Lakes. A shift in composition toward the more pollution-tolerant species has been observed. The role of land-derived diffuse phosphorus in these changes cannot be separated from other inputs.



Very little information currently exists relating nonpoint source phosphorus pollution to changes in fish populations.

#### EFFECTS OF FINE-GRAINED SUSPENDED SOLIDS

Estimates of fine-grained sediment inputs to the Great Lakes from the U.S. have been revised in light of recent PLUARG loading estimates. Of the five Great Lakes, Erie receives the largest load. Fine-grained suspended sediment inputs to Lake Michigan and the U.S. portion of Lake Superior are dominated by shoreline erosion, while tributary loading accounts for the greatest proportion of the U.S. load to Lakes Huron, Erie, and Ontario.

Though few studies have been conducted specifically on Great Lakes waters, the effect of high or abnormal levels of suspended solids is well documented. The presence of suspended solids causes an increase in turbidity and sedimentation affecting both plant and animal populations. Aesthetic deterioration, as well as undesirable economic effects, such as increased dredging and difficulty in purifying water supplies, may result. The amounts of solids removed by dredging from many Great Lakes river mouth areas were found to be comparable to the amount of suspended solids contributed annually by the rivers. Control of soil erosion upstream may thus have a significant benefit in terms of reducing the quantity of sedimented material that must be removed by dredging.

Several examples of the effect of turbidity on primary productivity in the Great Lakes are available. In some cases high turbidity has been associated with high plankton concentrations, possibly due to high nutrient concentrations. Also, turbidity tends to cause plankton to concentrate near the surface.

A number of authors have also observed a correlation between increased suspended sediment inputs and the disappearance of macrophytes, particularly in Lake Erie. Although the sediment load to Lake Erie has increased about threefold since the mid-1800s due to the agriculturalization of the basin, the effect cannot be easily separated from other environmental perturbations. It is speculated that a decrease in the suspended solids loads to the western Lake Erie basin may even lead to excessive macrophyte growths in the basin's shallow waters.

The effect of suspended solids on benthos has received less attention. Little is known regarding the response of these organisms to increasing rates of siltation, although increased sediment input is often implicated as deleterious to the benthos.

Most studies of Great Lakes fish populations have concentrated on Lake Erie. Turbidity, siltation, and the loss of macrophytic vegetation are among the reasons cited for the decline of its fish population. The effect of sediment on Great Lakes fish is not well established, however.

#### EFFECTS OF DISSOLVED SOLIDS - CHLORIDE AND SILICA

In the last decade, many efforts have been devoted to studying chloride



transport and estimating future chloride levels in the Great Lakes. Chloride and other dissolved solids have been implicated as a potential cause of a shift in the species distribution of plankton in the Great Lakes. Salt-tolerant organisms have already been identified throughout the Great Lakes. However, increasing levels of dissolved solids have not been conclusively linked to biological changes occurring in the Great Lakes, although a number of investigations infer that a relationship does exist.

Road salt is often being implicated as the cause of increased chloride levels in the Great Lakes. However, few examples in the literature support this belief. Perhaps the best example is Irondequoit Bay of Lake Ontario. Chloride levels in this small and restricted bay have increased five times in the last 20 years as a result of road salt drainage. Mining and industrial operations also contribute large amounts of chloride to the Great Lakes, and in some cases are the dominant source.

Silica depletion may cause a shift in algal species towards the predominately nonsiliceous forms, such as the undesirable blue-greens. Depletion may result from overproduction of diatoms, which require silica for growth, due to high phosphorus loading or restriction of the natural inflow of silica to the lakes. Future consideration should be given to the effect control of nonpoint sources may have on silica inputs.

#### EFFECTS OF LEAD

Lead is the only heavy metal strongly linked to nonpoint sources, with urban areas the greatest contributors. Excessive levels of lead in the aquatic environment have been found to inhibit photosynthesis and to bioaccumulate in both vertebrates and invertebrates, where it may produce lethal or sublethal effects. Of additional concern is the possibility of lead undergoing chemical and biological methylation to form highly toxic tetramethyl lead. Despite the potential harmful impact of lead, there is currently no evidence to indicate it is causing impairment of the Great Lakes resource.

#### EFFECTS OF PCBs

The Great Lakes have been particularly susceptible to inputs of PCBs. Atmospheric deposition on the drainage basin and subsequent runoff is a major nonpoint source of PCBs to the lakes. In addition to direct toxic effects, PCBs bioaccumulate in both invertebrates and vertebrates, with lethal and sublethal effects. Research is continuing to fully assess the impact of PCBs on the Great Lakes system.

#### EFFECTS OF PESTICIDES

With the exception of waste discharges from manufacturing plants, pesticide inputs are from diffuse sources, both atmospheric and land runoff. Continuing inputs of chlorinated hydrocarbons, such as DDT, arise mostly from residues in the soil. In addition to direct toxic effects, these insecticides tend to bioaccumulate, especially at higher levels of the food chain. It should



be noted, however, that their levels in Great Lakes waters and fish have declined rapidly since the use of chlorinated hydrocarbons was curtailed. To date, no severe problems have been identified related to the use of the new organophosphate and carbamate compounds. Herbicides are generally less toxic and less subject to bioaccumulation than insecticides. The increased use of these compounds is not expected to result in significant problems for the Great Lakes.



# LAND FACTORS INFLUENCING POLLUTANT LOADS

## INTRODUCTION

Earlier in this report land use activities were identified as a significant source of phosphorus, lead, PCBs and sediment inputs to the lakes. This chapter discusses the various land factors that influence the magnitude of the land-derived input of these pollutants to the lakes. Information is also presented on the distribution of soil texture classes throughout the U.S. portion of the basin, as well as the results of several statistical studies designed to examine the relationship between land factors and water quality.

Land-derived inputs of pollutants are most often expressed in terms of annual unit area loads, calculated by dividing the total annual load from a given area by the size of that area. Unit area loads based on data collected in the PLUARG pilot watershed studies (summarized in PLUARG 1978 and 1978a) show differences between land use categories for several parameters. Those figures indicate that unit area loads of sediment and phosphorus from urban and cropland are of the same order of magnitude. In contrast, unit loads from forested areas for those parameters are 10 to 100 times less. In the case of lead, however, the pattern is quite different. Unit area loads of lead are generally of the same order of magnitude for forest and agricultural lands (ranging from 0.002 to 0.08 kg/ha/yr). Urban areas, with heavy vehicular traffic and industrial air emissions, on the other hand, show average unit area loads for lead ranging from 0.06 to 7.0 kg/ha/yr.

The great variability in unit area contributions of pollutants from different land use activities, and indeed within a given activity, is a reflection of the wide range of factors that influence the amount of material moving from land to the lakes. Some of these, such as soil texture and parent material, are related to the naturally occurring physical fabric of the area. Others reflect human activities: amount of connected impervious surface, tillage practices, application of fertilizers and pesticides, removal of the natural land cover and scarification of the soil. Finally, overlying the above factors is the variability of meteorological conditions around the basin: annual precipitation, intensity and duration of rainfall events, timing of the spring thaw, etc. Long-term variations in river mouth loads related to climatic factors are discussed further in subsequent chapters.

## Land Form and Physical Fabric

As was mentioned, there are a number of factors related to the natural physical characteristics of an area that affect the extent of nonpoint source loads derived from it. The most important of these, based on the results of PLUARG studies, is the texture of the soil material--a measure of the distribution of particle sizes in a given soil type. In general, fine-textured soils--those with a



high percentage of clay -- have higher unit area loads of sediment and sediment-related pollutants (such as phosphorus) than do coarse (sandy) or medium-textured soils. There are several reasons for this. First, percolation and infiltration rates are generally lower in fine-textured soils, promoting higher runoff rates, most noticeable where fine soils are found over the full horizon. Second, clay particles are more easily dislodged from the soil surface than are larger particles. Also, once they are entrained in overland flow, they are less likely to settle out than are larger particles. Similarly, they are less apt to settle out in tributary flow. Finally, because of their relatively high adsorption capacity, they are an important transport mechanism for certain nutrients, heavy metals and organic compounds.

Another factor important in determining the unit area load of a particular pollutant for a given area is the chemical composition of the soil mineral and organic constituents. For example, the natural fertility of calcareous soils, measured by its phosphorus content, results in high unit area loads of dissolved phosphorus. In fact, natural fertility may be much more important than added fertilizers in determining loads in some areas.

Numerous other land form factors also influence unit area loads. These include slope and physiography, drainage density, presence of wetland areas, depth and quality of groundwater and sub-soil condition.

#### Land Use and Management Factors

The magnitude of the effect that land use and management has on unit area loads can be seen by comparing the relative sediment yields of different land cover classes (EPA, 1973):

Forest	:	1
Grassland	:	10
Cropland	:	200
Construction Site	:	2000

Data collected through the PLUARG pilot watershed studies showed a similar pattern for sediment and phosphorus, as shown in Table 1 (PLUARG, 1978a).

TABLE 1

PILOT WATERSHED UNIT AREA LOADS (kg/ha/yr)

	<u>Suspended Sediment</u>	<u>Total Phosphorus</u>	<u>Filtered Reactive Phosphorus</u>
Forest	1 - 820	0.02 - 0.67	0.01 - 0.10
Cropland	20 - 5,100	0.2 - 4.6	0.05 - 0.40
General Urban	210 - 1,750	0.3 - 2.1	0.05 - 0.30
Developing Urban	27,500	23	0.10

It is interesting to note that unit area loads of filtered reactive phosphorus show much less variability than either total phosphorus or suspended sediment.



One of the most important factors resulting in high unit area loads is the removal of land cover, either natural or crop, leaving the soil exposed to wind and water erosion. Studies by PLUARG investigators and others show that maintenance of a protective cover, either vegetative or crop residue, is one of the most effective ways of reducing soil and related contaminant losses. Timing of tillage of operations, so that a ground cover is maintained during the spring thaw and runoff period, is especially important in some portions of the basin.

Although the natural fertility of the soil is important, the application of manure, chemical fertilizers and pesticides may also affect unit area loads from a given land area. Rapid incorporation of manure and fertilizers into the soil is needed to prevent excessive nutrient losses, for example.

Other factors that influence the magnitude of rural unit area loads include animal density and location of feedlot operations with respect to stream channels, use of tile drains and the application of various soil conservation practices.

Interconnected impervious surfaces and hydrologically efficient stormsewer systems result in high unit area loads from urbanized areas. Deposition and subsequent washoff of vehicular exhausts, industrial emissions, animal wastes, and decaying leaves are some of the sources of pollutants in urbanized areas.

There are a number of other land use or management activities that may also increase pollutant loads where they occur. Examples of these activities include solid and liquid waste disposal, on-site waste disposal systems, and combined sewers. The relative contribution of these activities to pollutant loads has not been determined.

#### LAND FACTOR DATA BASE

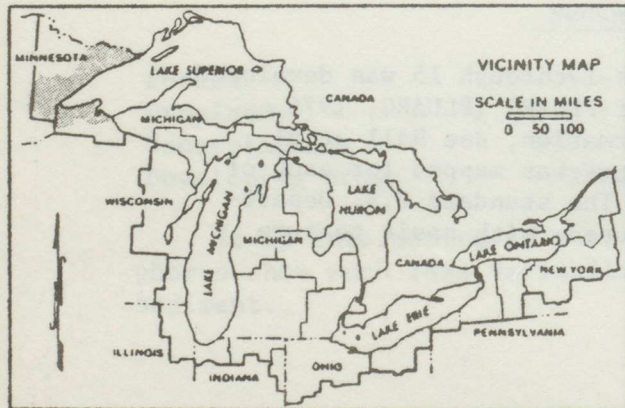
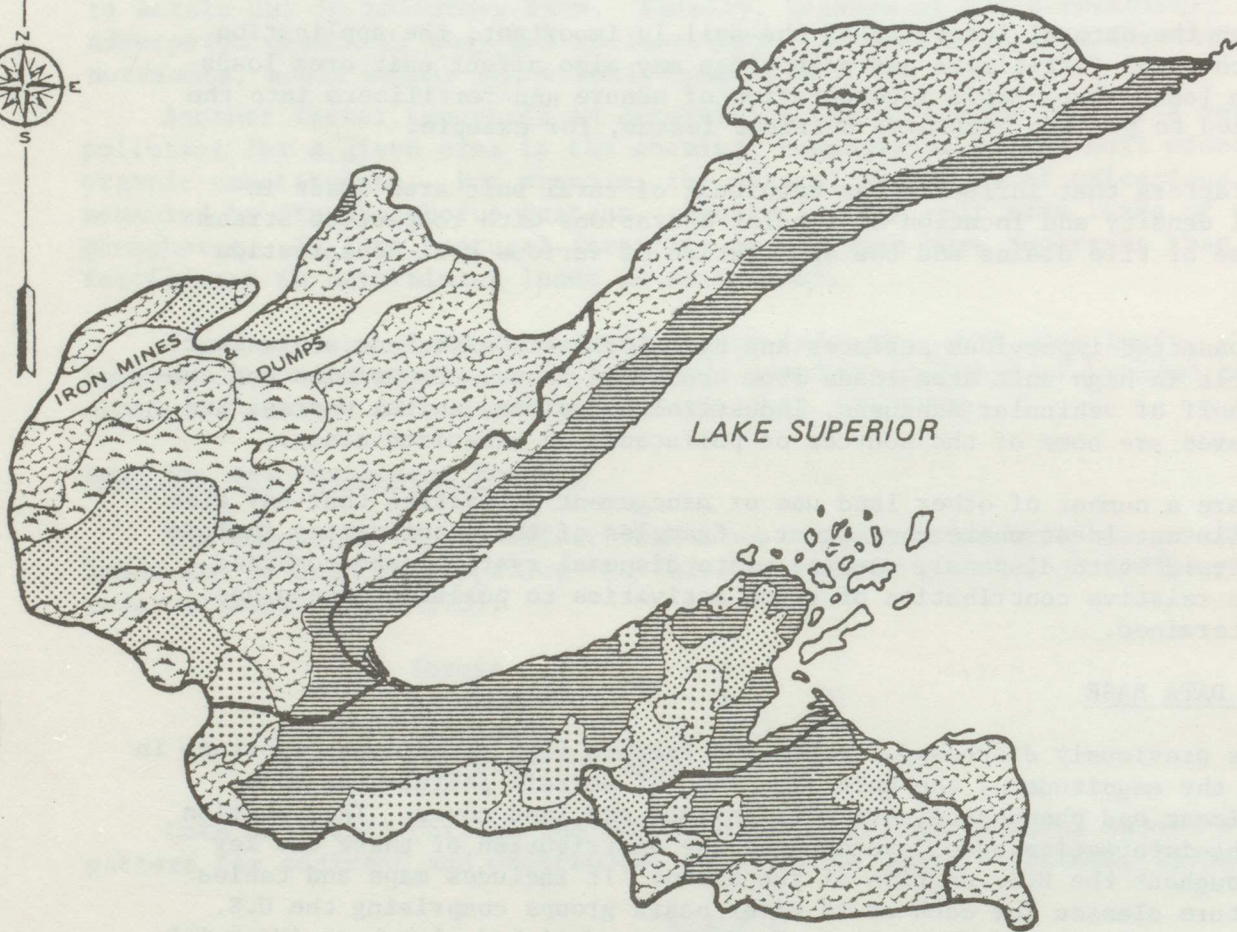
As was previously discussed, two of the factors felt to be most important in determining the magnitude of the unit area load of certain pollutants, most notably sediment and phosphorus, are soil texture and land cover. This section describes the information base developed on the distribution of these two key factors throughout the U.S. portion of the basin. It includes maps and tables of soil texture classes for each of 15 river basin groups comprising the U.S. basin. It also reviews briefly data on land cover published elsewhere (Monteith and Jarecki, 1978). Finally, there are brief discussions of the accuracy of the data and their possible applicability to other study efforts. The discussion also includes suggestions as to what might be done to improve them.

#### Soil Texture







The soil texture information displayed in Figures 1 through 15 was developed on the basis of soils data collected by U.S. Task B of PLUARG (PLUARG, 1976, for more detailed political and hydrological map information, see Hall *et al.*, 1976). Information on the dominant surface soil texture was mapped for each of the soil associations identified in the Task B maps. The standard U.S. Department of Agriculture soil texture classification was used, with basic texture classes summarized as shown in Table 2.



SOIL TEXTURE  
River Basin Group 1.1



Predominant  
Soil Texture

-  SAND
-  COARSE LOAM
-  MEDIUM LOAM
-  FINE LOAM
-  CLAY
-  MUCK

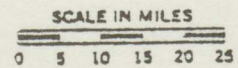
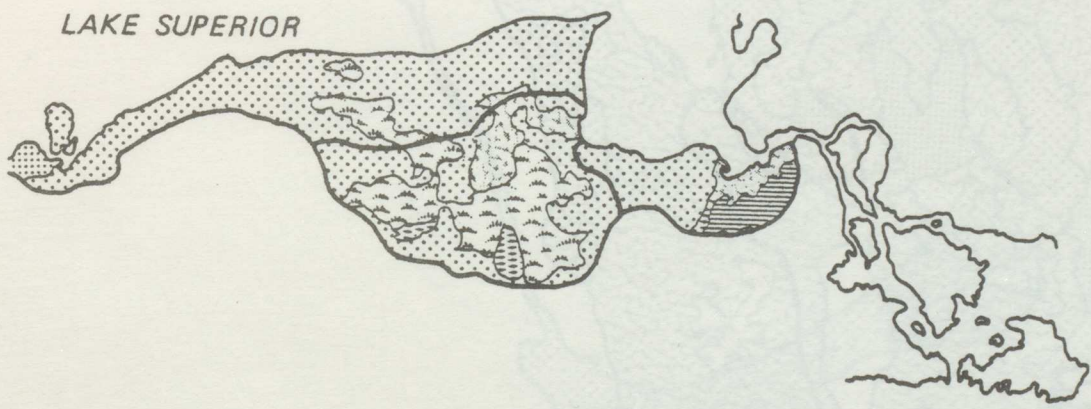
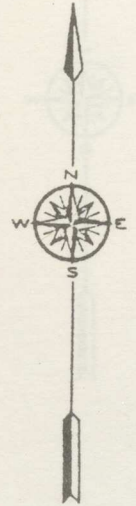
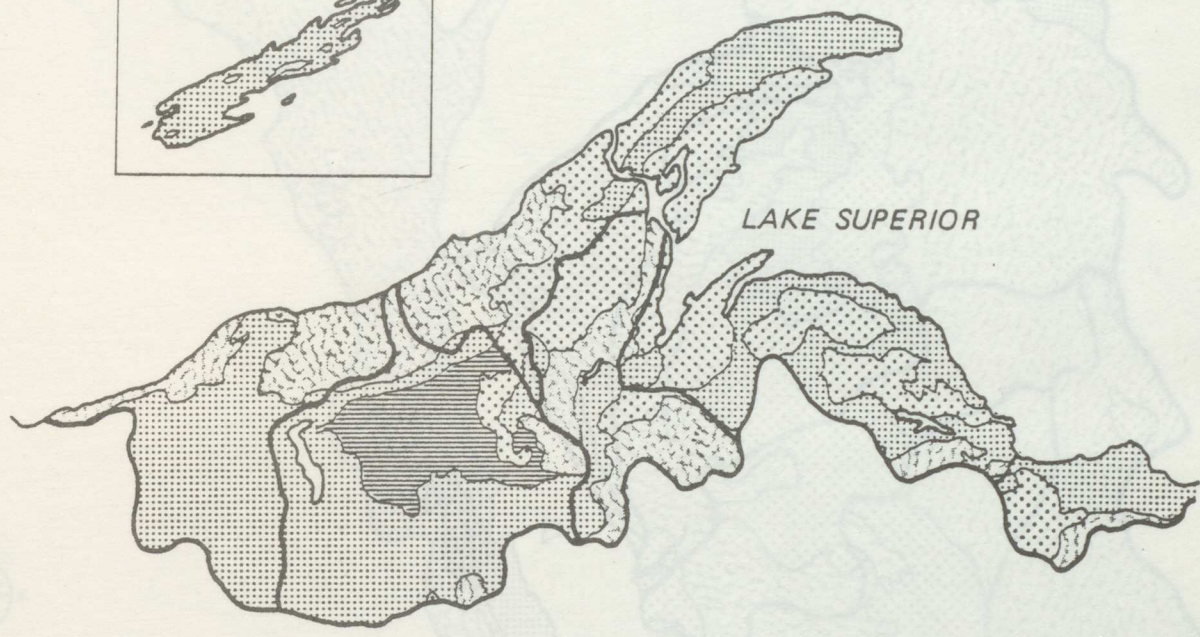
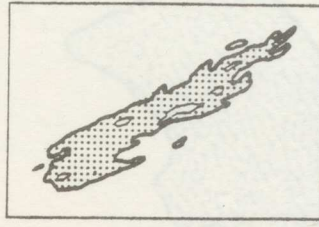




FIGURE 2  
 SOIL TEXTURE  
 River Basin Group 1.2



Predominant Soil Texture

- SAND
- COARSE LOAM
- MEDIUM LOAM
- FINE LOAM
- CLAY
- MUCK

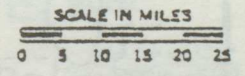
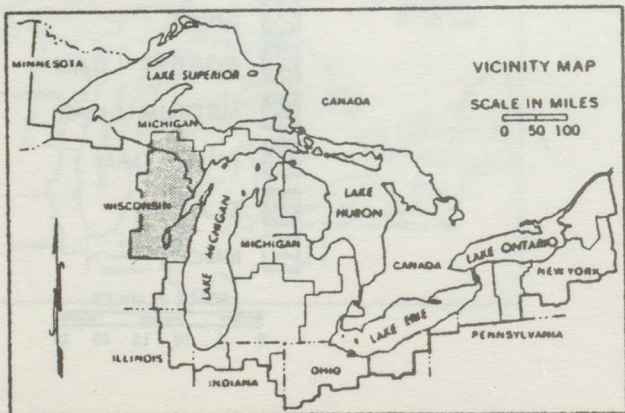
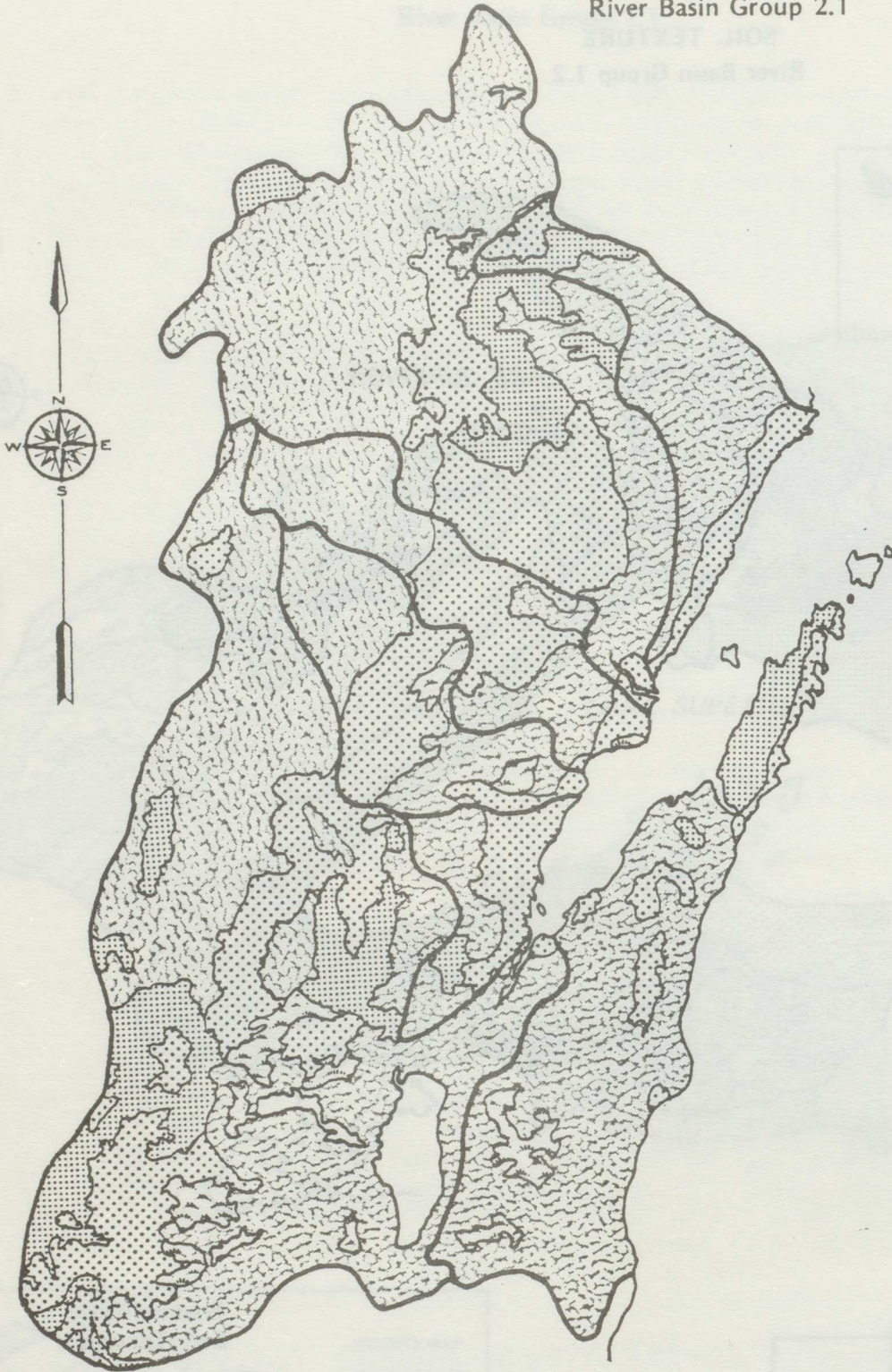




FIGURE 3  
**SOIL TEXTURE**  
 River Basin Group 2.1



**Predominant Soil Texture**

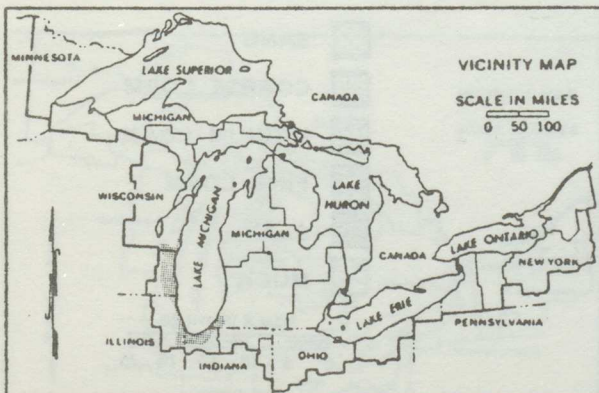
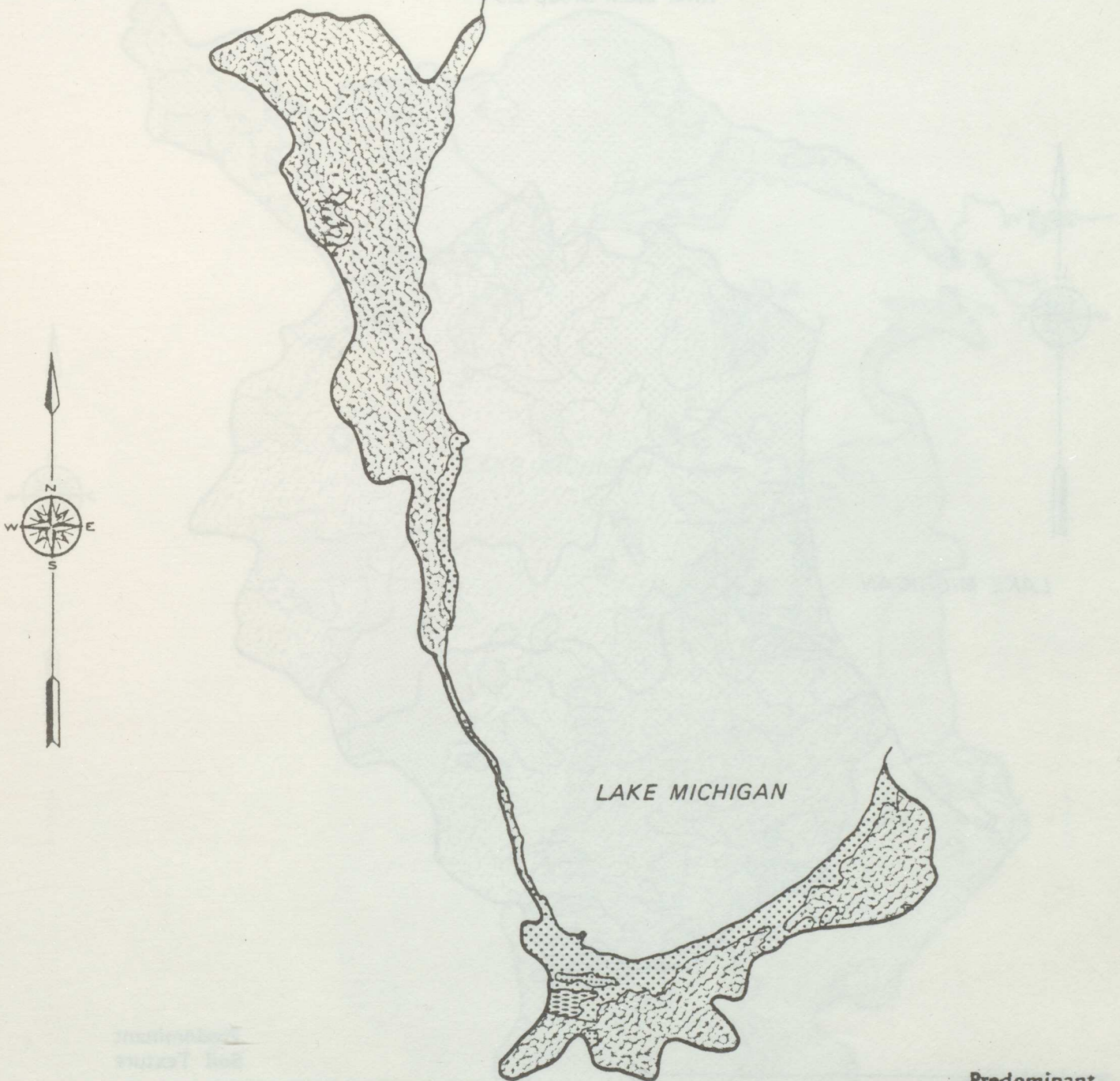
- SAND
- COARSE LOAM
- MEDIUM LOAM
- FINE LOAM
- CLAY
- MUCK











FIGURE 4

SOIL TEXTURE  
River Basin Group 2.2



Predominant  
Soil Texture

-  SAND
-  COARSE LOAM
-  MEDIUM LOAM
-  FINE LOAM
-  CLAY
-  MUCK

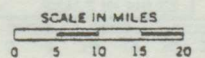
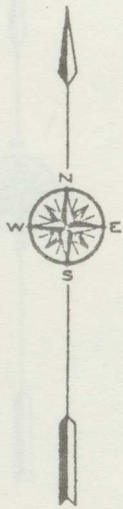


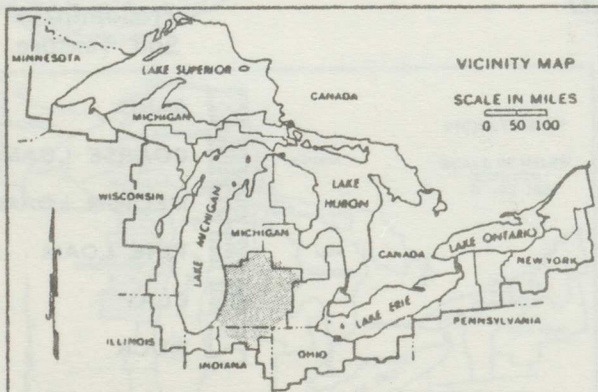
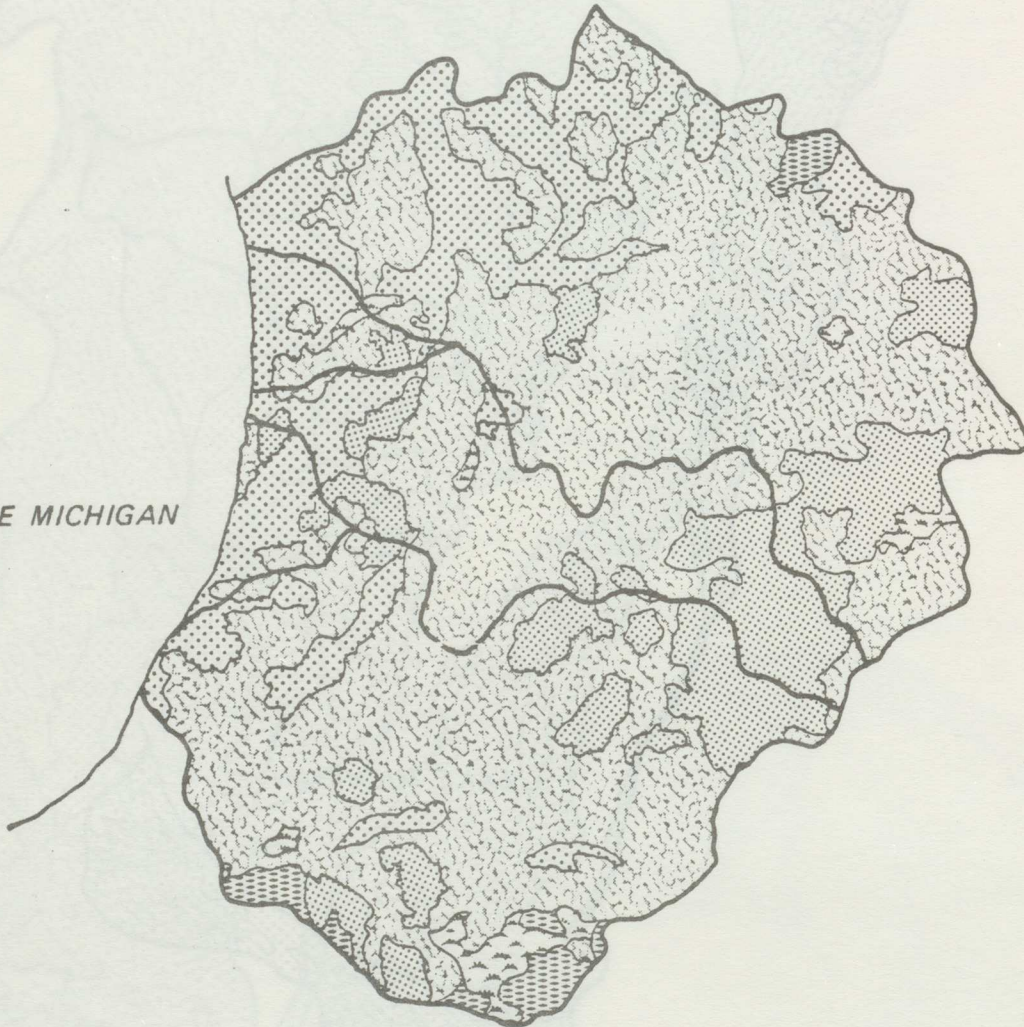


FIGURE 5







SOIL TEXTURE  
River Basin Group 2.3



LAKE MICHIGAN



Predominant  
Soil Texture

-  SAND
-  COARSE LOAM
-  MEDIUM LOAM
-  FINE LOAM
-  CLAY
-  MUCK

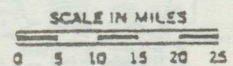




FIGURE 6  
 SOIL TEXTURE  
 River Basin Group 2.4

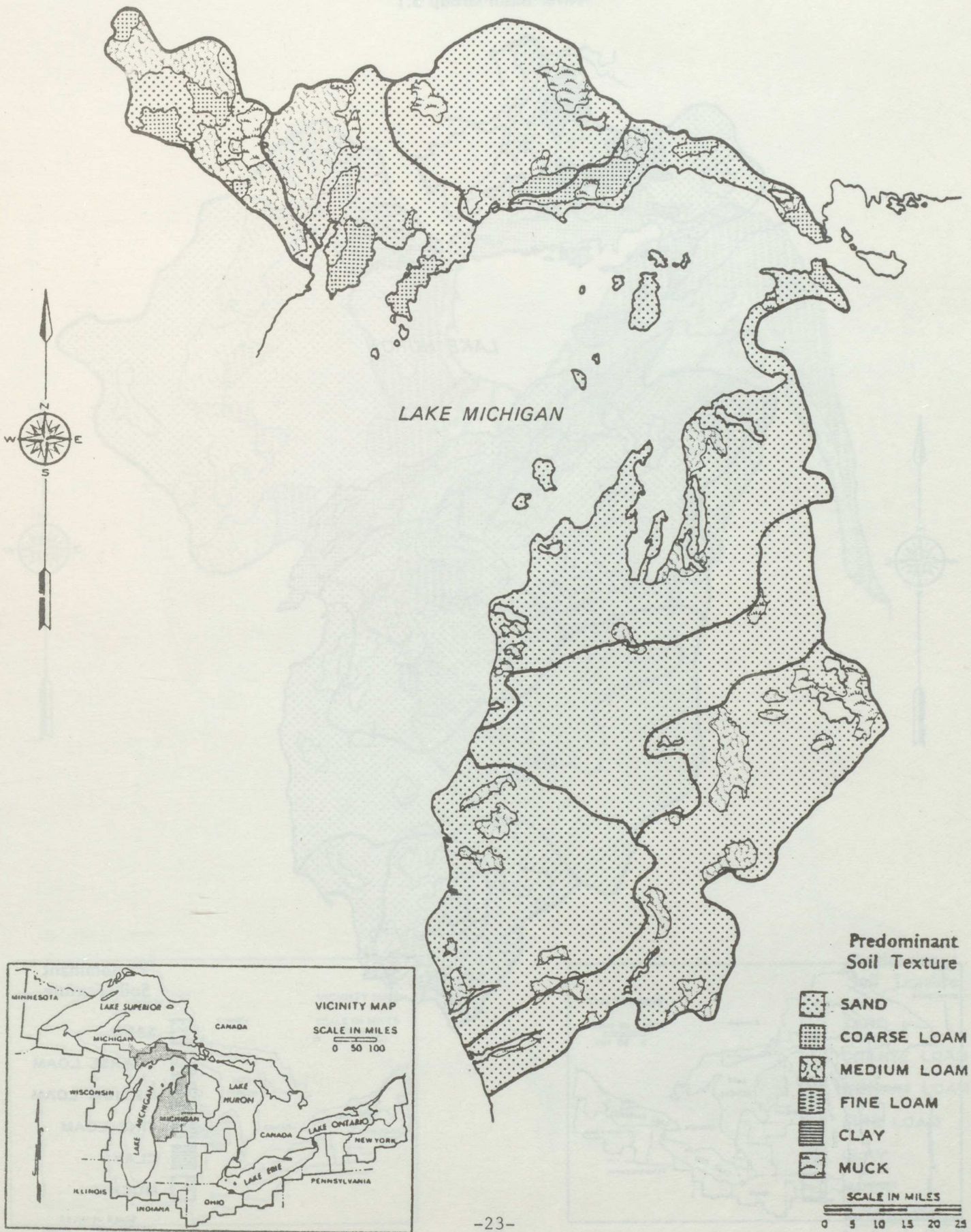
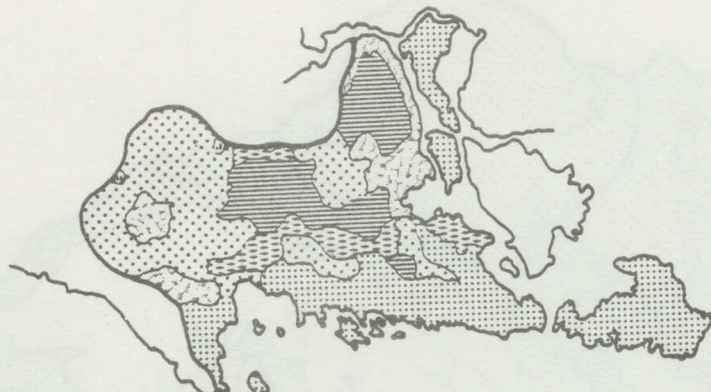
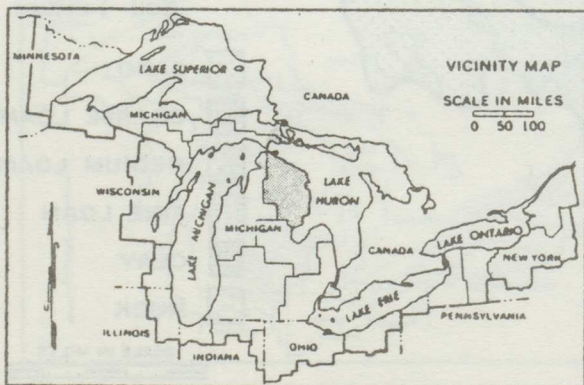
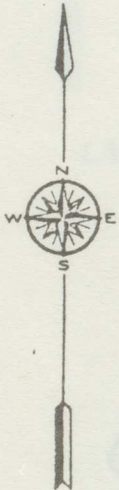
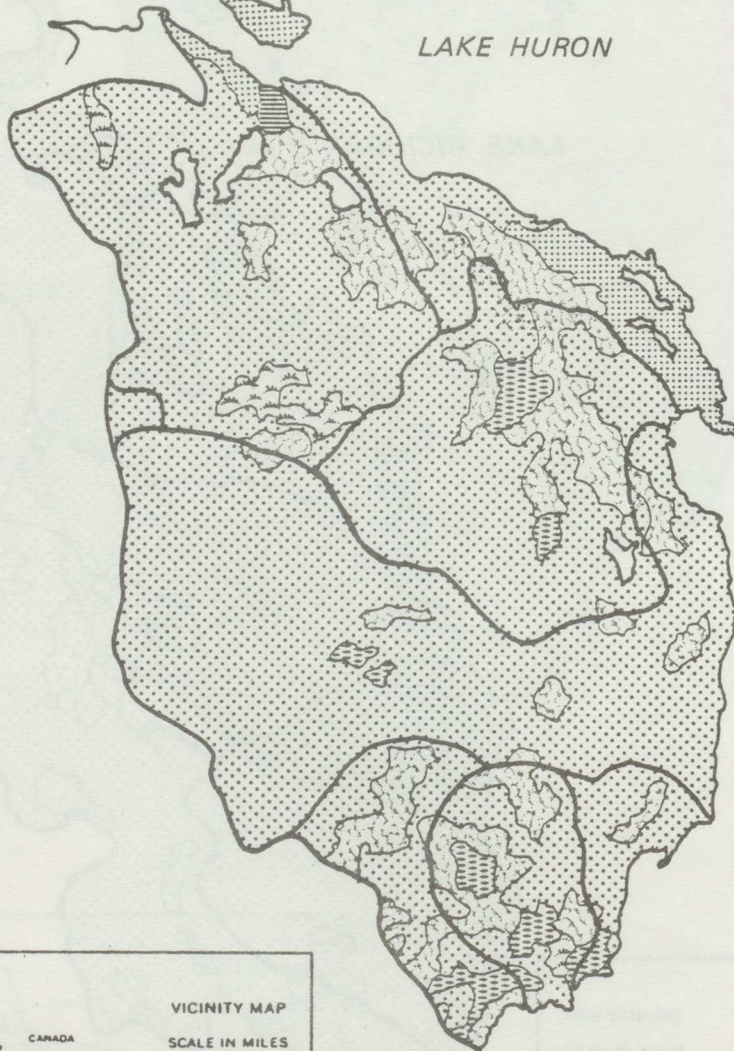






FIGURE 7  
SOIL TEXTURE  
River Basin Group 3.1



LAKE HURON



Predominant  
Soil Texture

-  SAND
-  COARSE LOAM
-  MEDIUM LOAM
-  FINE LOAM
-  CLAY
-  MUCK

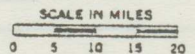
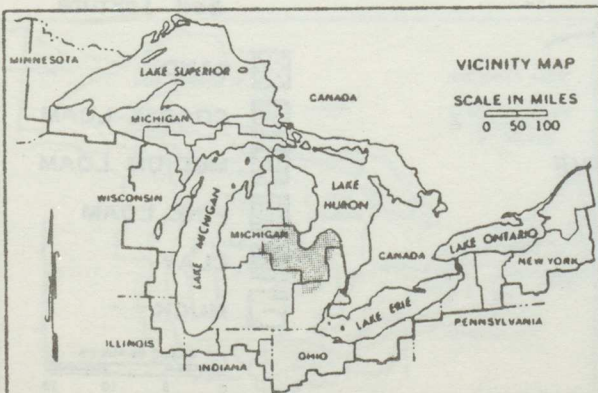
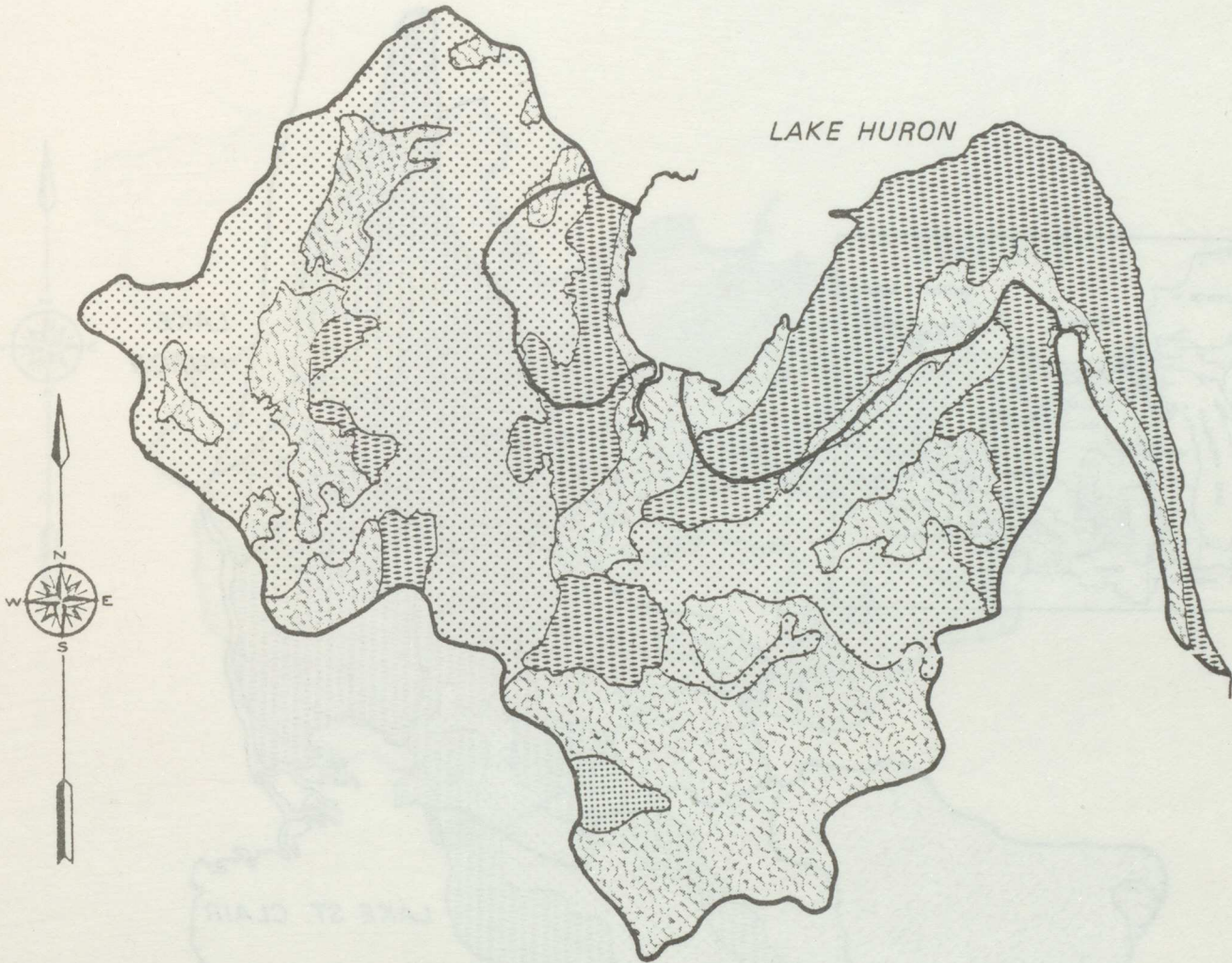





FIGURE 8  
 SOIL TEXTURE  
 River Basin Group 3.2



Predominant Soil Texture

-  SAND
-  COARSE LOAM
-  MEDIUM LOAM
-  FINE LOAM
-  CLAY
-  MUCK

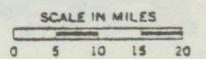




FIGURE 9

SOIL TEXTURE  
River Basin Group 4.1

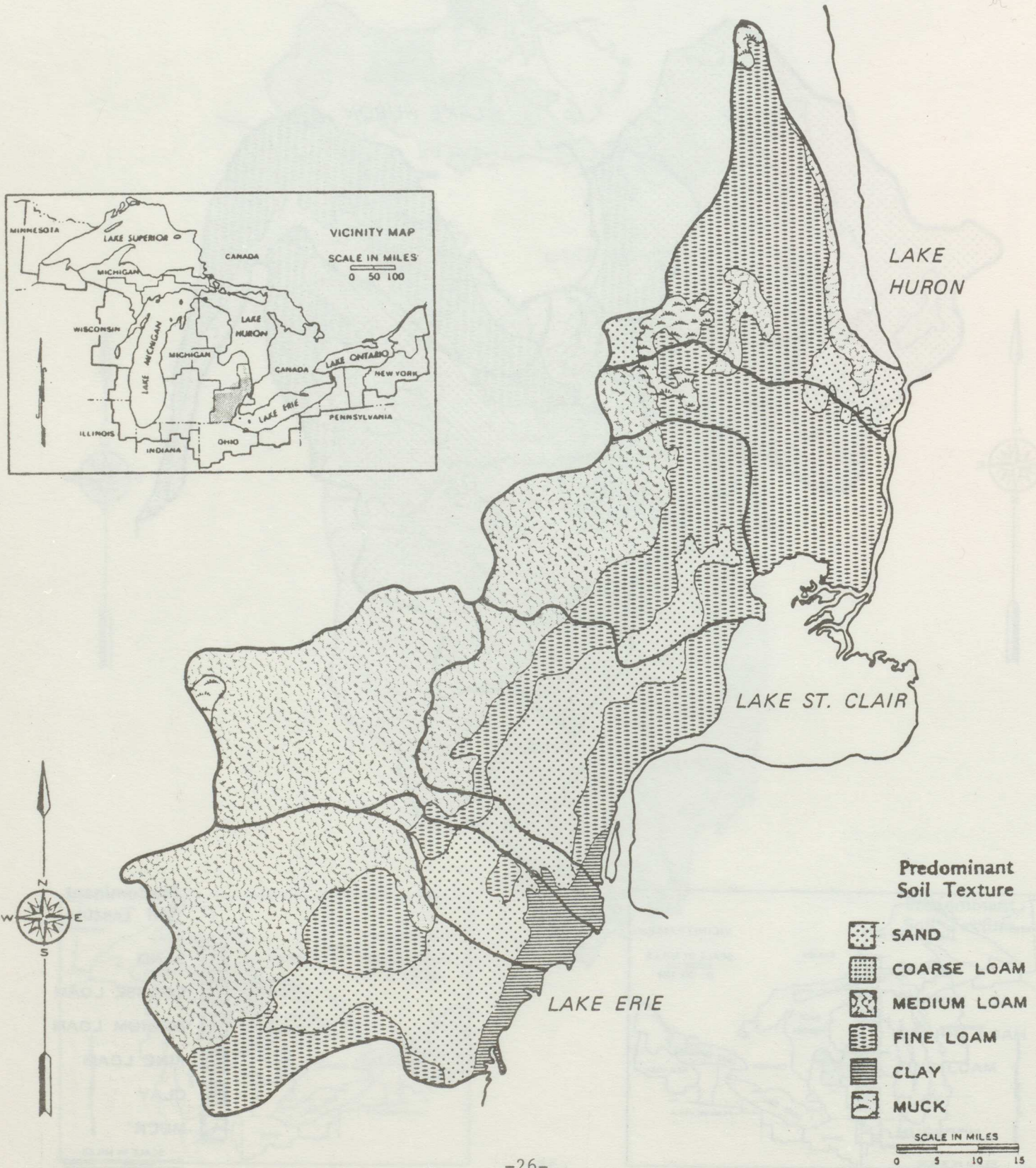
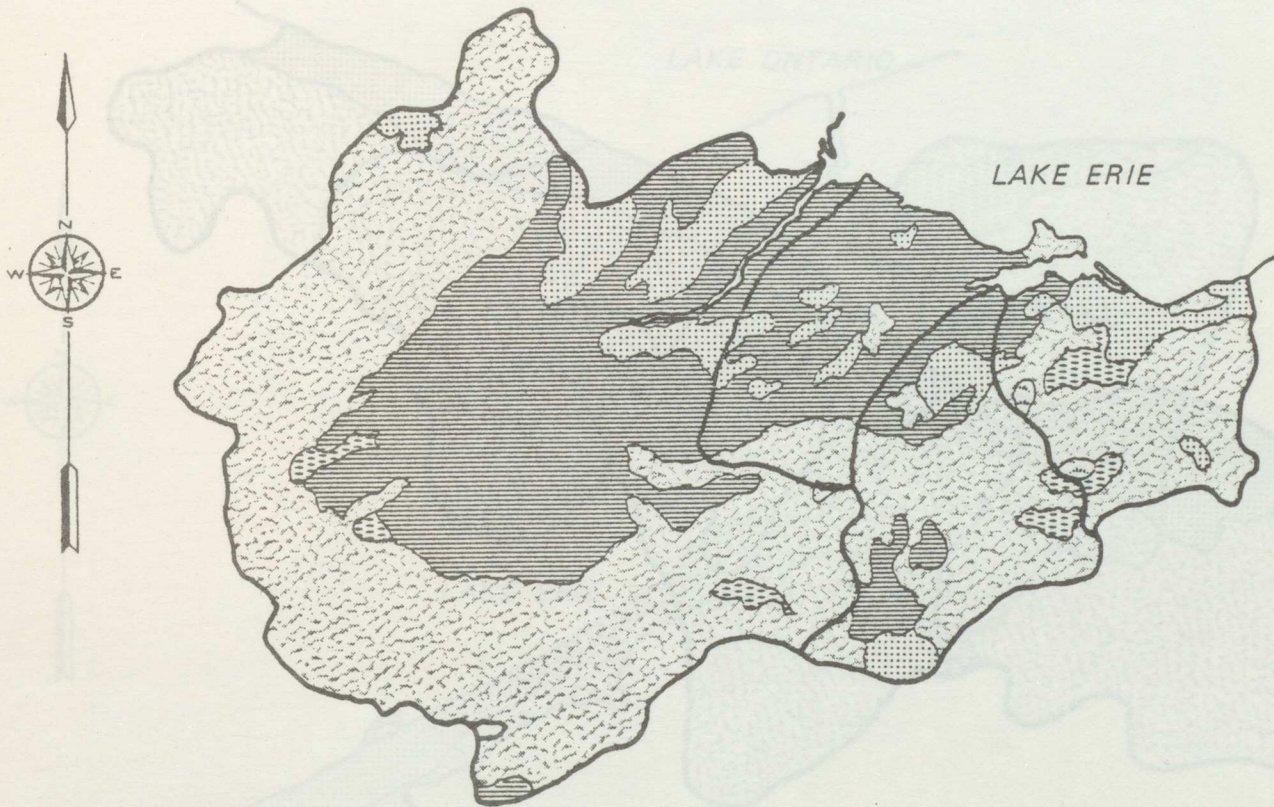




FIGURE 10  
 SOIL TEXTURE  
 River Basin Group 4.2



Predominant  
 Soil Texture

- SAND
- COARSE LOAM
- MEDIUM LOAM
- FINE LOAM
- CLAY
- MUCK

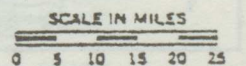
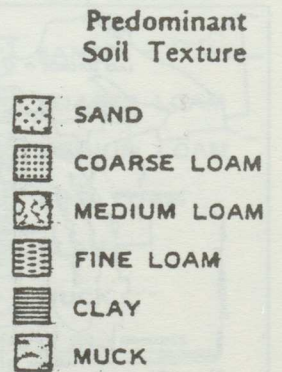
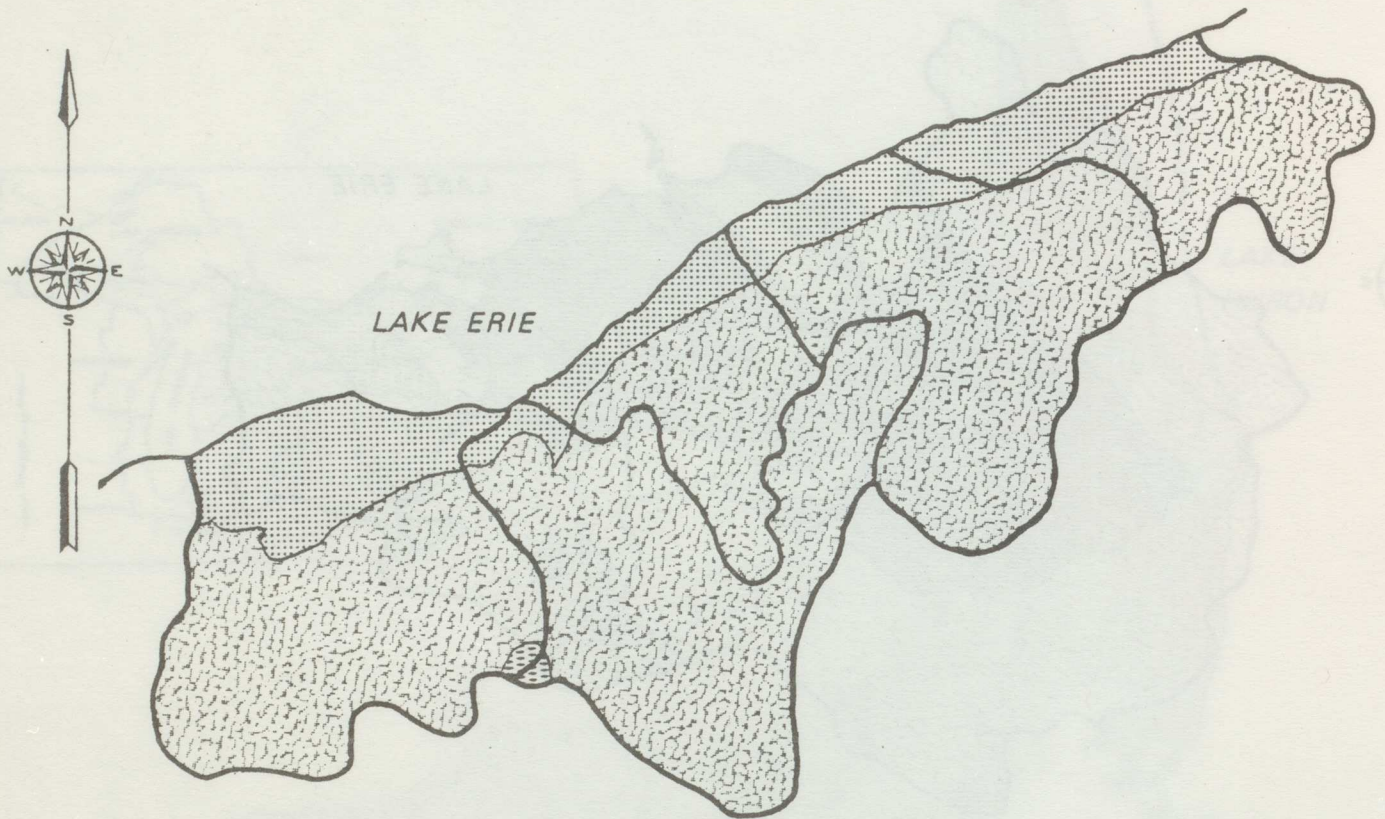




FIGURE 11

SOIL TEXTURE  
River Basin Group 4.3

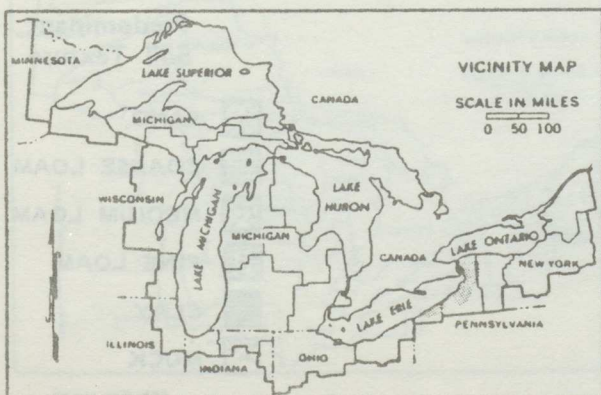
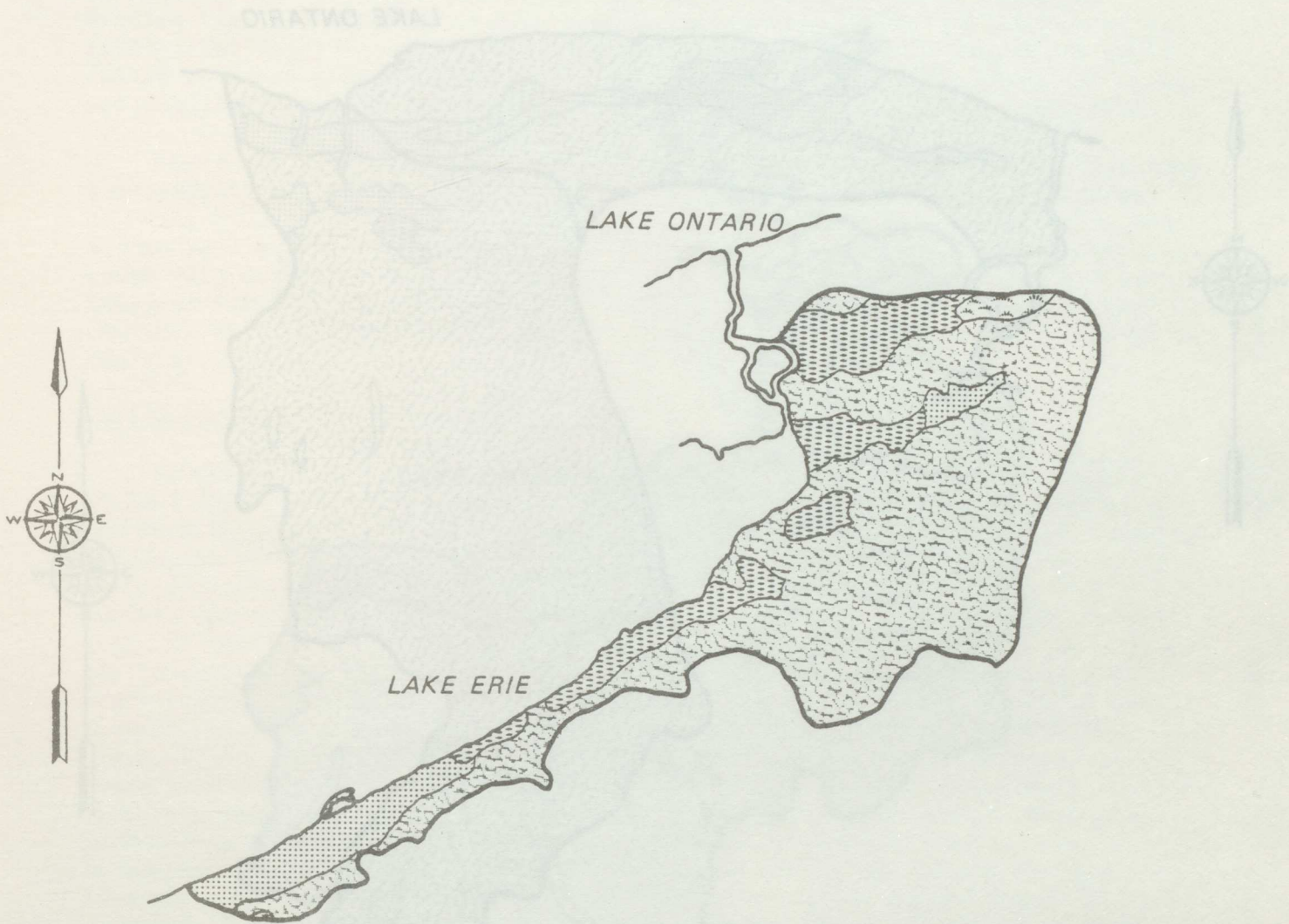


SCALE IN MILES









FIGURE 12

SOIL TEXTURE  
River Basin Group 4.4



Predominant  
Soil Texture

-  SAND
-  COARSE LOAM
-  MEDIUM LOAM
-  FINE LOAM
-  CLAY
-  MUCK

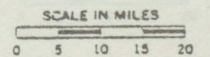
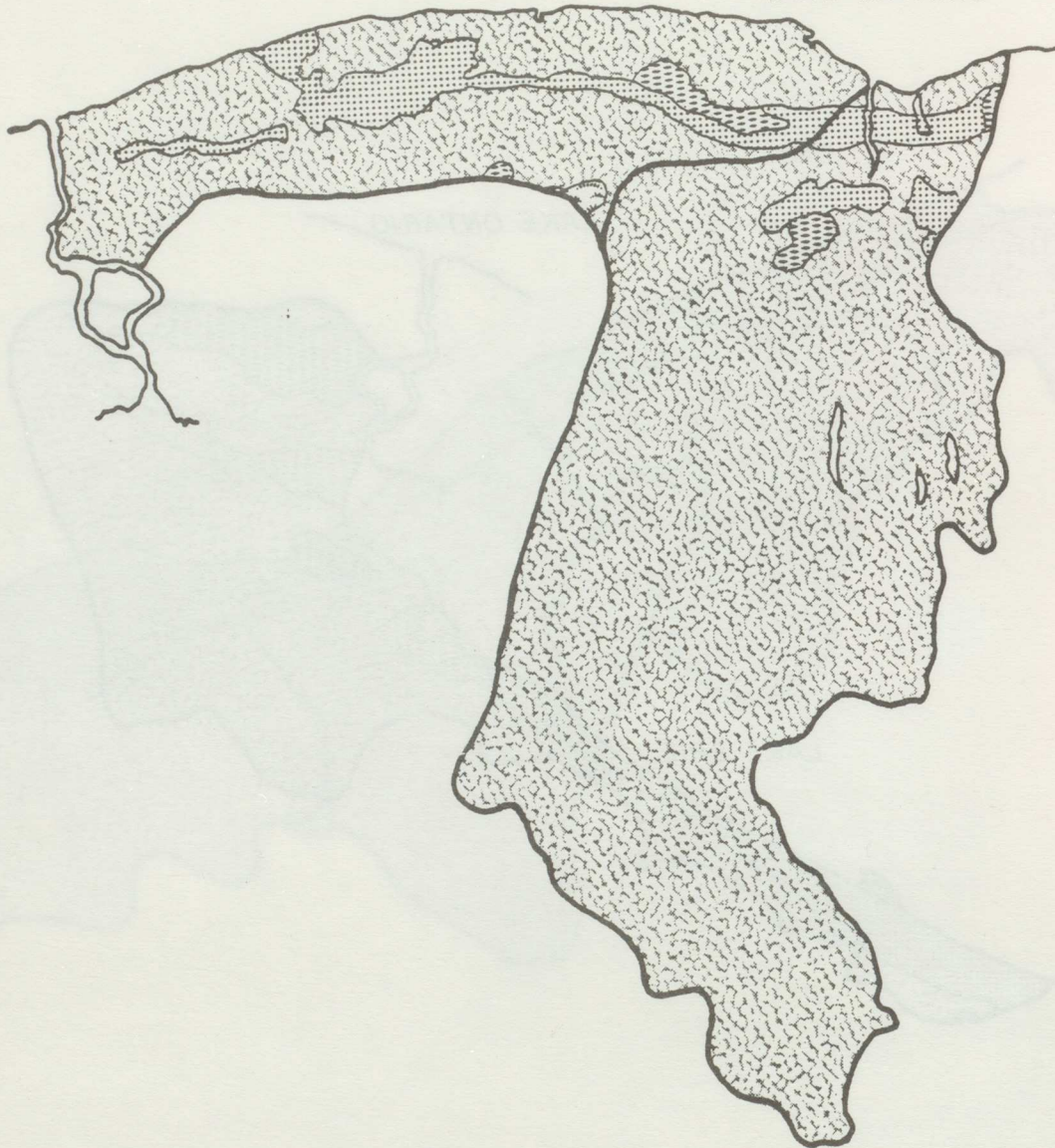
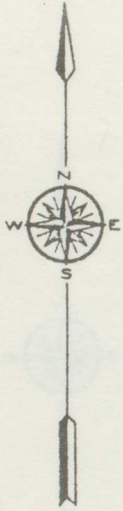










FIGURE 13

SOIL TEXTURE  
River Basin Group 5.1

LAKE ONTARIO



Predominant  
Soil Texture

-  SAND
-  COARSE LOAM
-  MEDIUM LOAM
-  FINE LOAM
-  CLAY
-  MUCK

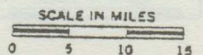
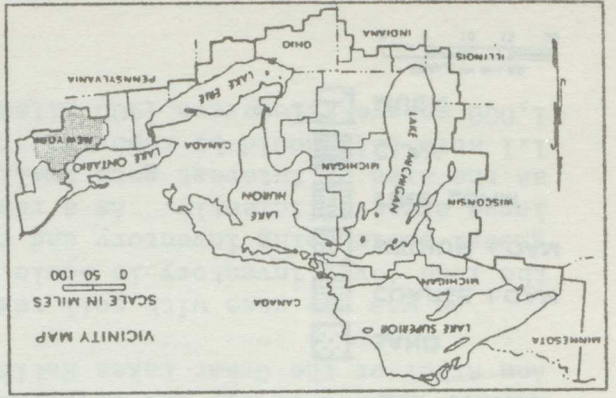
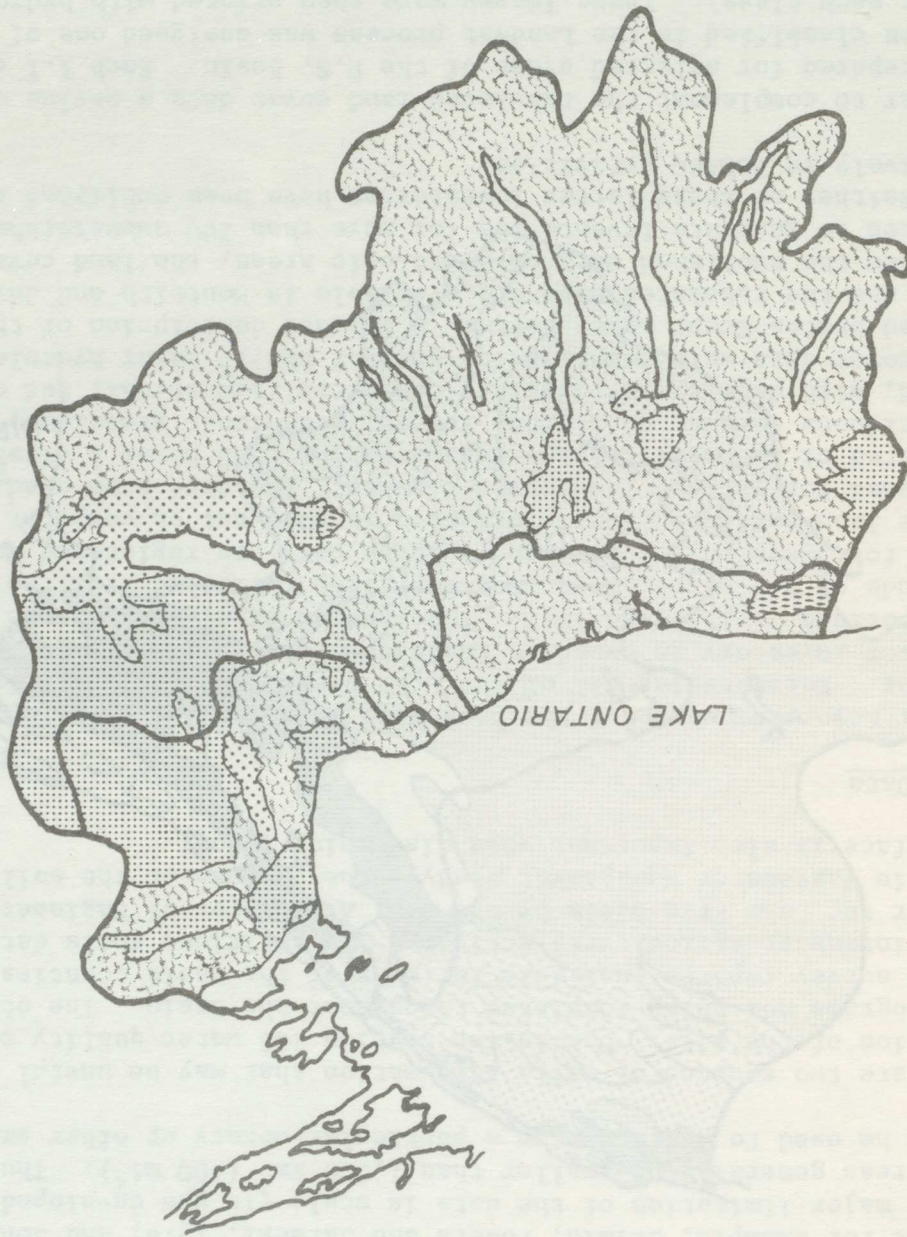




FIGURE 14

SOIL TEXTURE  
River Basin Group 5.2

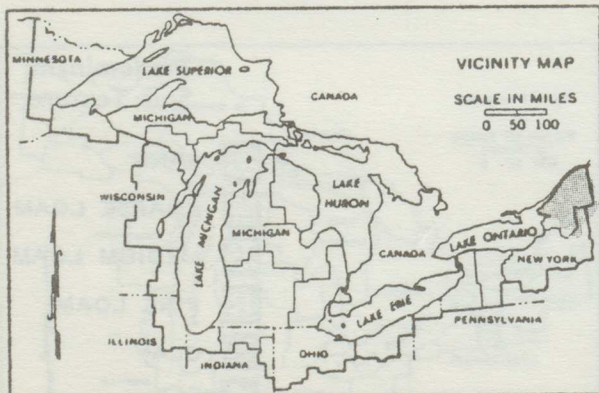
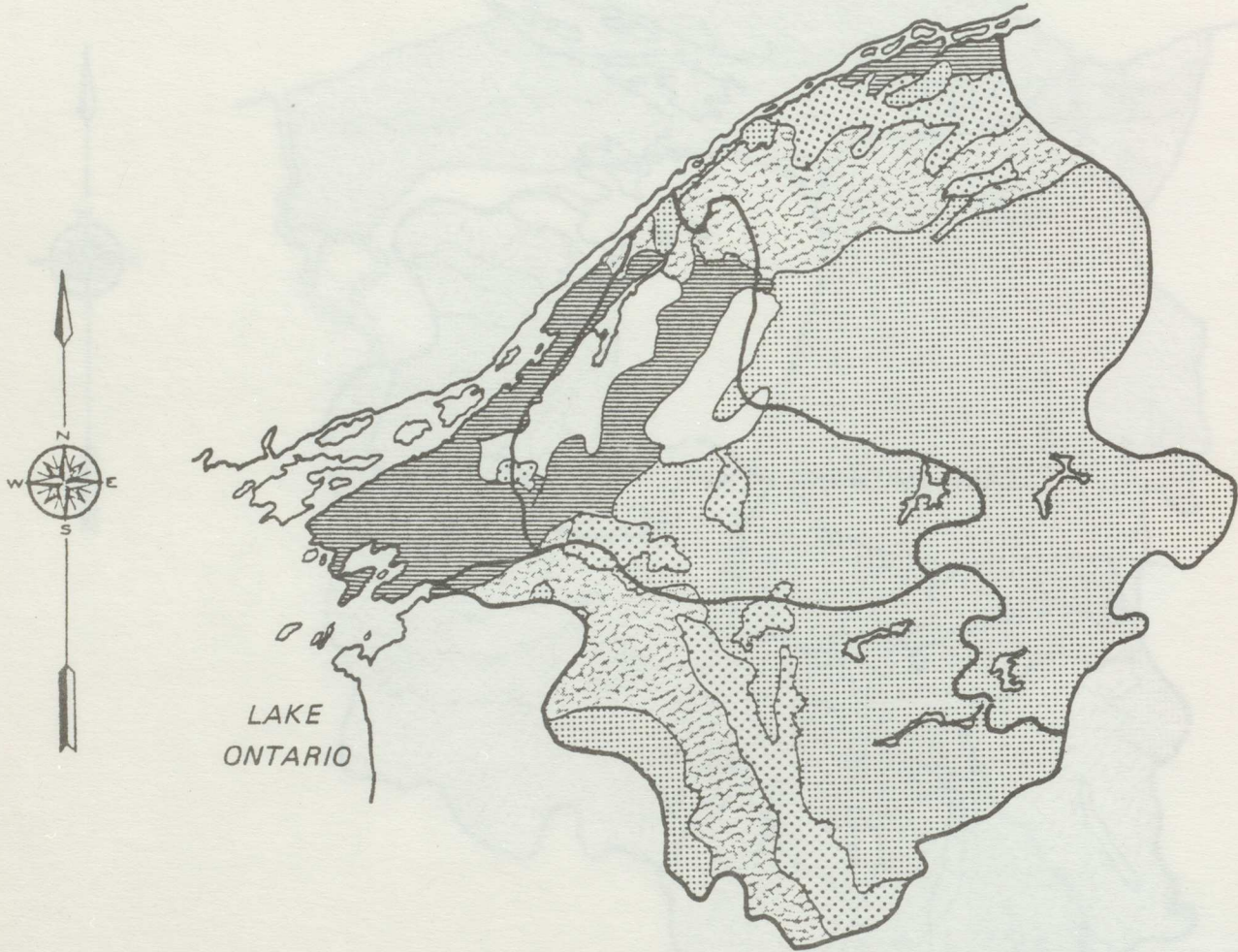


SCALE IN MILES  
0 5 10 15 20







- Predominant  
Soil Texture
- SAND
  - COARSE LOAM
  - MEDIUM LOAM
  - FINE LOAM
  - CLAY
  - MUCK



FIGURE 15  
 SOIL TEXTURE  
 River Basin Group 5.3



Predominant Soil Texture

-  SAND
-  COARSE LOAM
-  MEDIUM LOAM
-  FINE LOAM
-  CLAY
-  MUCK

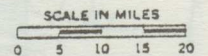




TABLE 5  
U.S. DEPARTMENT OF AGRICULTURE  
RAPID SOIL TEXTURE CLASSIFICATION SYSTEM

The soil texture data developed by PLUARG is by necessity very general in nature. It has, however, been useful in a number of PLUARG technical studies (see for example, Skimin, Powers and Jarecki, 1978; and Johnson *et al.*, 1978). The major limitation of the data is scale--it was developed for application to areas generally no smaller than 1,000 km<sup>2</sup> (400 mi<sup>2</sup>). Thus, it could not readily be used to characterize a particular county or other small area.

There are two sources of soils information that may be useful in improving the resolution of the data. One is the Section 208 water quality management planning programs now being completed throughout the basin. The other is the modern soil survey reports available for many of the basin counties, especially those with intensive agricultural activity. In addition, soils data has been compiled for the Lake Erie basin by the U.S. Army Corps of Engineers as part of the Lake Erie Wastewater Management Study. The texture of the soil material in the sub-surface is also important when discussing runoff.

#### Land Cover Data

Another major component of the basinwide data base is a current inventory of land cover. Encompassing all of the U.S. portion of the Great Lakes basin, the land cover inventory is based on Landsat satellite imagery collected during the spring periods of 1976 and 1977. Two Landsat satellites circle the earth at an altitude of 570 miles, measuring the light reflected from the earth's surface for four wavelengths of light. These data are registered for every 1.1 acres on the land surface. The information is then put on computer tapes that can be analyzed for various land cover classes. The data base used in this study consisted of 10 major classes (based on the USGS Level 1 classification): wetland, deciduous forest, coniferous forest, brushland, grassland, barren, plowed field, high density residential, commercial/industrial, and open water. These land cover data were compiled for each of the 72 major hydrologic areas in the United States Great Lakes basin. A further description of the Landsat methodology and the tabulated data are available in Monteith and Jarecki (1978). In addition to the published data on hydrologic areas, the land cover data have also been used to generate inventories for more than 200 subwatersheds and 191 counties. Neither of these latter inventories have been published but have been used extensively in PLUARG activities.

In order to complement the tabulated land cover data a series of six color maps were prepared for selected areas of the U.S. basin. Each 1.1 acre cell that had been classified in the Landsat process was assigned one of ten colors (a color for each class). These images were then printed with hydrologic and political map overlay information. Only two sets of these maps were prepared and are available for use at either the Great Lakes Basin Commission office in Ann Arbor or the Great Lakes National Program Office of the U.S. EPA in Chicago.

As was the case with soil texture data, the major limitation on the use of the land cover inventory is scale. The data were developed to be used on a regional scale using inventory and classification procedures suitable for covering large areas efficiently. As a result, the accuracy of the tabulated data declines as the area of interest gets smaller. Although the classification for a single 1.1 acre cell could be reported, the practical limit of resolution is around 1,000 square kilometers (400 miles<sup>2</sup>) or a single county.



TABLE 2

U.S. DEPARTMENT OF AGRICULTURE  
 BASIC SOIL TEXTURE CLASSIFICATION SYSTEM

General Terms		Basic Soil Textural Class Names
Common Names	Texture*	
Sandy soils	Sand	Sandy
		Loamy sands
Loamy soils	Coarse Loam	Sandy loam
		Fine sandy loam
	Medium Loam	Very fine sandy loam
		Loam
		Silt loam
	Fine Loam	Silt
Clay loam		
Clayey soils	Clay	Sandy clay loam
		Silty clay loam
		Sandy clay
		Silty clay
		Clay

\* Included on soil texture maps



A comparison was made between the PLUARG data and existing 208 planning data for developed land in the U.S. coastal counties. For the PLUARG information, developed land was defined as the high density residential and the commercial/industrial groups. A linear regression, with the independent variable being the PLUARG data and the dependent variable the 208 data, provided a good correlation with  $r=.93$ . The analysis showed that in areas with high densities of developed land the PLUARG data tends to overestimate the amount of land in that class due to the dominance of the light reflected from man-made structures. In areas where very low amounts of developed land are present, the PLUARG data tends to underestimate the amount of developed land due to the interference of adjoining classes such as forest and grassland. Overall, however, a very good fit was found for those areas studied in the developed land category. Since this is perhaps one of the most difficult classes to determine from the satellite information, it was seen that the PLUARG data base did provide a good general overview of the developed classes.

#### Other Land Factor Information

Although the soil texture and land cover data described above is useful in analyzing nonpoint source inputs to the lakes, it is not the only information available. As was mentioned above, for example, many of the Section 208 water quality management planning agencies are developing much more detailed inventories of soil and land cover as well as other factors related to nonpoint sources. There is also additional information available from PLUARG, particularly Task B.

This section briefly describes the information that is available at present or will be used to augment the existing data.

Current Information. In addition to the soils information that formed the basis for the soil texture maps, U.S. Task B of PLUARG compiled an inventory of information useful in assessing nonpoint source problems on a regional scale. Several specific items should be mentioned at this time. One is an inventory of materials applied to the land (Doneth, 1975), with annual usage rates, by county, for fertilizers, manures, pesticides, and road salts (base years range from 1969 to 1973). Regional and basinwide overviews are also included in the report. The information in this report represents a good starting point from which to base an evaluation of the effects of material applications on nonpoint source loads.

Another useful set of information available from the U.S. Task B activities is an inventory of specialized land uses (PLUARG, 1975); intensive livestock operations, solid and liquid waste disposal operations, and deepwell disposal sites in particular. Estimates, based on 1970 census figures, are also included for on-site waste disposal system density. Although there may be a need to update some of this information, it does nonetheless present a good regional overview.

Additional information has also been compiled by U.S. Task D. Detailed maps and tables are available concerning shoreline recession rates, volume of eroded material, and chemical inputs from shoreline erosion (described in Seibel, Armstrong and Alexander, 1976; and Monteith and Sonzogni, 1976). This material,



while not directly applicable to assessing nonpoint source loads, is useful in evaluating the overall material balance of the lakes.

A great deal of information has also been compiled concerning point source loadings, both directly to the lakes as well as to tributaries; this information has been used in the evaluation of pollutant transport reported elsewhere in the report. Information of this kind is essential if nonpoint source inputs are to be measured and evaluated relative to other sources of pollutants. It is also important if the information base is to be used in making management decisions. As was pointed out in the PLUARG final report, both point and nonpoint source inputs must be evaluated in a management framework.

Other Information. Since PLUARG completed its report a great deal of information related to both point and nonpoint source pollution has become available--primarily from the state and regional Section 208 water quality planning programs. It includes the detailed land cover and soils data mentioned earlier as well as population projections, point and nonpoint source problems, and management plans. Efforts are presently underway to collect this information and summarize it in a form useful to resource planners and policymakers. Also included in this effort will be information from other pertinent sources, such as the Corps of Engineers Lake Erie Wastewater Management Study.

#### ANALYSIS OF LAND FACTOR/WATER QUALITY RELATIONSHIPS

The first section of this chapter briefly outlined the relationships between land factors and water quality. These relationships are generally well supported from both theoretical and empirical perspectives. This section presents the results of several studies designed to characterize this relationship in more detail through the application of statistical procedures. The discussion is presented in three parts: a brief review of the literature, including those studies carried out as a part of PLUARG; a comparison of two major tributaries, the Maumee and Grand rivers; and an overview of land factor-pollutant load relationships on a basinwide basis.

#### Review of Related Literature

The most comprehensive study dealing with the influence of land factors on water quality using statistical techniques seen to date was recently completed by EPA (Omernik, 1977). Using data collected at more than 900 locations nationwide, correlation and regression techniques were used to examine the strength of the relationship between "macro-drainage area characteristics" (particularly land use) and stream nutrient concentrations (total and inorganic forms of nitrogen and phosphorus). Important products of the study were predictive equations and nationwide maps of predicted stream nutrient concentrations. The best predictor of nutrient concentrations was found to be percent of the watershed in contributing land use (% urban + % agriculture, with correlation coefficients ranging from 0.50 to 0.75). The regression equations were functions of the form:

$$\log_{10} \text{ concentration} = b + a \cdot [\% \text{ contributing area}].$$



No significant improvement in predictive capability was gained using more complicated models. It was also found that "differences in nutrient loads in streams associated with different land use categories were not as pronounced as differences in nutrient concentrations."

Another study, carried out by U.S. Geological Survey researchers for EPA (Lystrom et al., 1978), used multiple regression to assess the relationship between water quality and land factors in the Susquehanna River basin. Seventeen water quality characteristics and 57 basin factors related to climate, topography, geology, soils, stream flow and land use were included in the evaluation. Regression equations were developed for 14 of the water quality variables, with coefficients of determination ( $r^2$ ) ranging from 56 to 89 percent. The equations were each of the form:

$$\log y = a_1 \log X_1 + a_2 \log X_2 + \dots + a_n \log X_n + \log b.$$

Equations for suspended sediment predictions included terms related to the amount of land in agriculture. Phosphorus equations all had terms related to urban land area (which may reflect point source inputs) and fertilizer P applications.

The Lake Erie Wastewater Management Study, LEWMS, being conducted by the Corps of Engineers is also making use of correlation and regression techniques in their analysis of pollutant loads to Lake Erie. Using data collected during storm event periods, researchers have developed linear predictive equations based on flow for suspended solids, total phosphorus and nitrate-nitrite concentration for a number of U.S. Lake Erie tributaries (Corps of Engineers, 1975). Correlation coefficients for these relationships ranged from zero to 0.96, indicating that additional factors need to be considered.

Several statistical studies were performed in support of PLUARG investigations. One such study conducted by Canadian Task C investigators (PLUARG 1978a) developed predictive equations for unit area loads (kg/ha/yr) of total phosphorus (TP) and suspended solids (SS):

$$\begin{aligned} \text{TP} &= 0.149 + 0.000655 (\% \text{ clay})^2 + 0.000162 (\% \text{ row crops})^2 & (r^2 = 0.92) \\ \text{SS} &= 204.0 + 7.9 (\% \text{ clay}) + 11.0 (\% \text{ row crops}) & (r^2 = 0.64). \end{aligned}$$

It is interesting to note that the strength of the relationship between the independent variables (% clay and % row crops) and the predicted unit area yields is much greater for total phosphorus than for suspended solids, as indicated by the coefficient of determination,  $r^2$ . It is also interesting to observe that the relative contributions made by the two independent variables change between the two equations; in predicting total P, the percent of the watershed with clay soils dominates, while the percent of the watershed in row crops is more significant in predicting sediment unit area loads.

Several statistical techniques were utilized in another PLUARG study done by Ongley (1978). Although this study did not develop predictive relationships between land factors and water quality, it did present results designed to measure the strength of relationships between them.

One of the major difficulties encountered in examining the relationship between land factors and water quality (represented by pollutant concentration



or unit area load) is the tremendous variability observed in the dependent (water quality) variables, even when land factors are held constant. The Task C results described earlier demonstrated the extent of this variability: unit area loads of suspended solids from cropland ranged from 20 to 5,100 kg/ha/yr, while total phosphorus loads of 0.2 to 4.6 kg/ha/yr were observed. A large portion of this variability may be accounted for if other physical factors were included, such as soil texture class. Other important sources of variation include land management and cropping practices, physiographic factors, and local climate variations.

Because of the widely fluctuating character of the data, an analysis of the patterns of variability may be a more fruitful approach to the problem. This approach was used previously to examine differences among watersheds around the Great Lakes (Monteith and Skimin, 1978). Various subsets of the total sample, which included suspended sediment data for 25 tributaries, were defined based on the dominant land cover (forest versus agriculture) and soil texture (clay, loam or sand) found in each watershed. Frequency distributions for sediment concentration were developed for each subset and comparisons made. For example, Figure 16 shows three frequency distributions for forested watersheds with sand, loam and fine-textured soils, respectively. In a similar fashion, Figure 17 shows frequency distributions observed for forested and agricultural watersheds. Similar patterns were found by Omernik (1977) on the basis of phosphorus and nitrogen concentration.

#### Comparison of the Grand and Maumee

Daily concentration and load estimates for total phosphorus and suspended sediment covering periods of approximately 15 months were used to compare the Grand River of Michigan and the Maumee River of Ohio. Comparisons were made using the frequency distributions of the loads, as well as general patterns in the seasonal nature of the two rivers. Although the watersheds are similar in terms of size (14,660 km<sup>2</sup> versus 17,100 km<sup>2</sup> for the Grand and Maumee, respectively) and general climate, the two differ markedly in dominant soil texture (see Figures 5 and 10), intensity of agricultural activity and importance of point source inputs.

The results presented additional evidence that streams with extensive areas of clay in their watersheds behave very differently than watersheds with relatively little clay. Based on the sample data for the Grand and Maumee rivers, these differences extend to the general distribution of flow and pollutant load values as well as relationships among flow and the concentration of pollutants. Specifically, the results showed that the sample distributions of flow, sediment load and total phosphorus load for the two rivers are significantly different. Large differences between mean and median values showed that high load events are much more significant on the Maumee than on the Grand.

Substantial differences were also found in the flow and concentration. In the Grand, phosphorus concentration remains essentially stable throughout much of the year, regardless of variations in flow. Nor are there apparent relationships between sediment concentration and either flow or phosphorus. The Maumee data, on the other hand, show a fairly high correlation between flow



FIGURE 16

FREQUENCY POLYGONS FOR SEDIMENT CONCENTRATION  
FROM FORESTED WATERSHEDS

Key

- : Sand Watersheds
- - - : Loam Watersheds
- : Fine Textured Watersheds

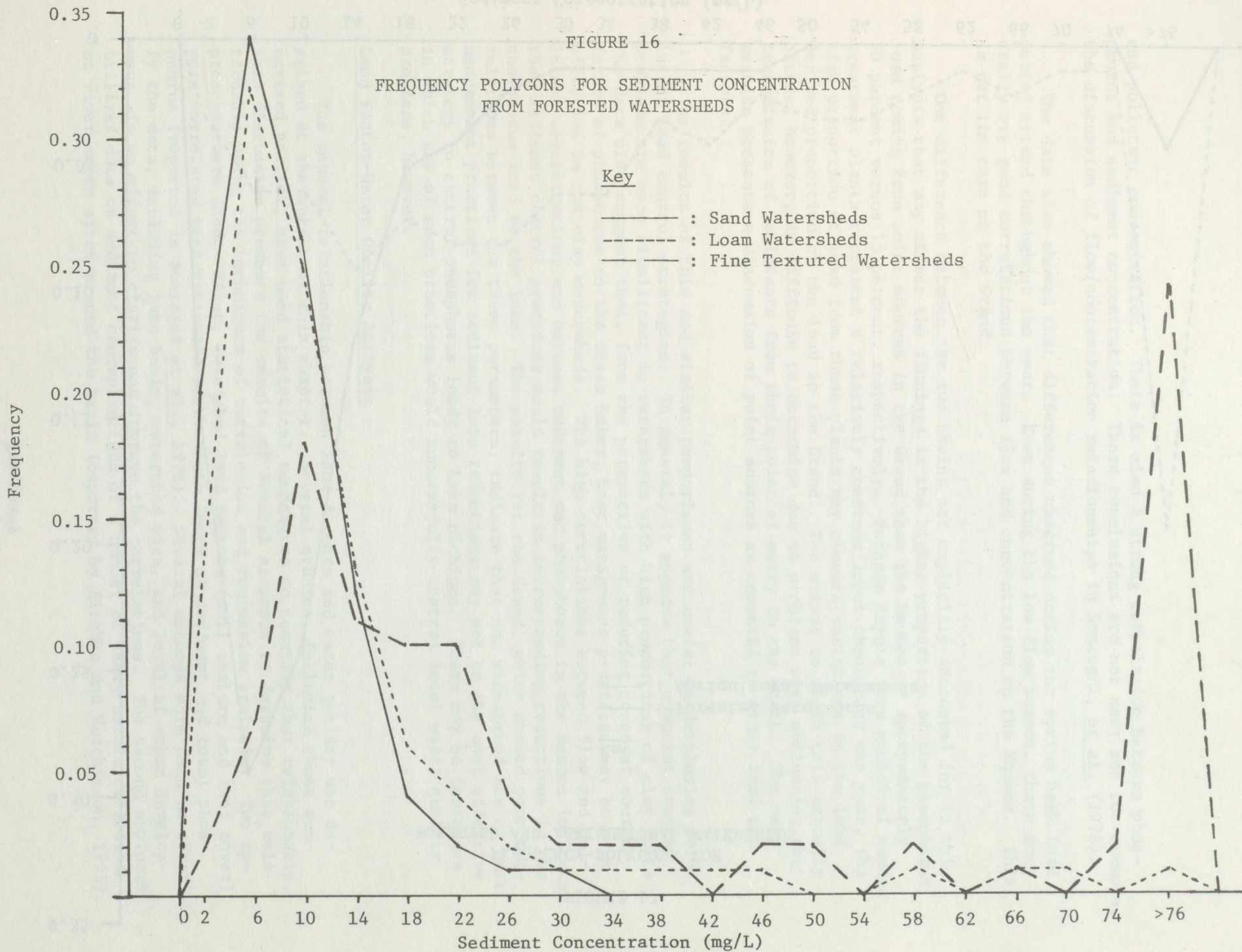
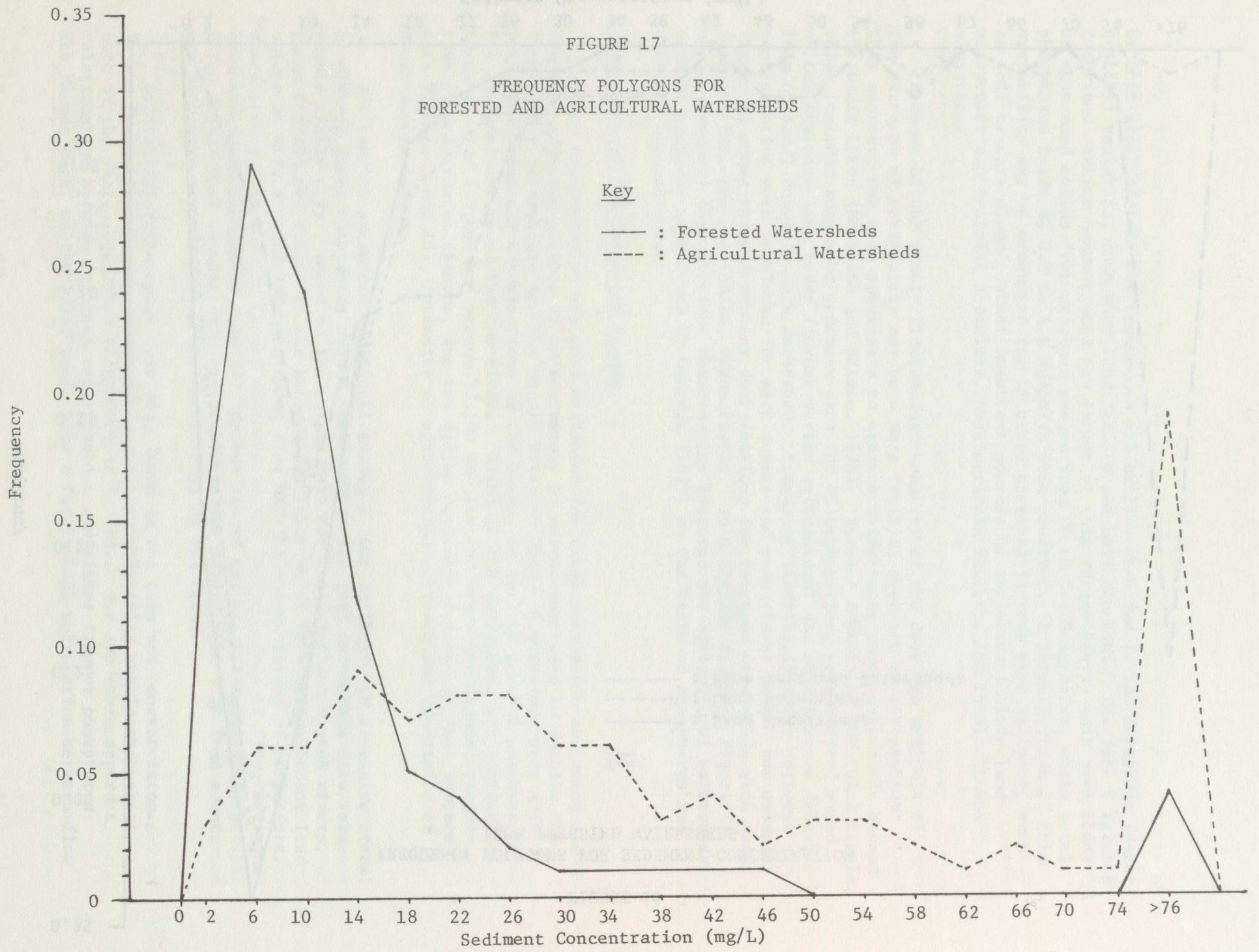




FIGURE 17  
FREQUENCY POLYGONS FOR  
FORESTED AND AGRICULTURAL WATERSHEDS





and pollutant concentration. There is also a strong correlation between phosphorus and sediment concentration. These conclusions are not new; see for example, the discussion of flow/concentration relationships in Sonzogni, et al. (1978).

The data also showed that differences observed during the spring peak load period extend throughout the year. Even during the low flow season, there generally are good correlations between flow and concentration on the Maumee. This is not the case on the Grand.

One difference between the two basins not explicitly accounted for in this analysis that may affect the findings is the higher proportion of the phosphorus load coming from point sources in the Grand than the Maumee -- approximately 50 percent versus 15 percent, respectively. Because inputs from municipal sewage treatment plants represent a relatively constant input throughout the year, the high proportion of load from these plants may obscure variations in the land derived proportion of the load in the Grand. The extent to which this actually occurs, however, is difficult to determine due to problems with evaluating the transmission of pollutants from their point of entry to the mouth. The next section presents a discussion of point sources as compared to other land use factors.

The results of this and similar comparisons are useful in developing pollutant load control strategies. In general, it appears that nonpoint source problems are more significant in watersheds with high proportions of clay soils. The data also suggest that, from the perspective of reducing nonpoint source inputs of phosphorus to the Great Lakes, best management practices may be more effective in the clay watersheds. The high correlations between flow and pollutant concentration, and between sediment and phosphorus in the Maumee indicate that sediment control practices would result in corresponding reductions in the phosphorus load to the lake. The results for the Grand, which showed poor correlations between the three parameters, indicate that the widespread use of best management practices for sediment loss reductions may not be the most effective strategy to control phosphorus loads to Lake Michigan. There may be instances in which use of such practices would successfully control local water quality problems, however.

#### Land Factor-Water Quality Analysis

The general relationship between land factors and water quality was described at the outset of this chapter. Several studies, including those summarized earlier, have used statistical techniques to quantify that relationship. This discussion presents the results of several attempts to describe that relationship using the techniques of correlation and regression analysis. Two approaches were used. First, watershed land factors (soil texture and land cover) were correlated with estimated river mouth loads of sediment and total phosphorus (reported in Sonzogni et al., 1978). Several methods were used to stratify the data, including lake basin, watershed size, and level of urban development, in an effort to clarify and improve the correlations. The second approach utilized data on sediment concentrations of a number of heavy metals collected at river mouth sites around the basin (reported by Fitchko and Hutchinson, 1975).



The results of these analyses are summarized below.

### Sediment and Total Phosphorus

Several past attempts to relate observed water quality conditions to various land factors using statistical techniques were described earlier. Two in particular, those prepared by Omernik (1977) and Lystrom *et al.* (1978), illustrate two different approaches to the same problem. Omernik utilized data from more than 900 sites collected across the nation. In an attempt to develop predictive equations for phosphorus concentration in the receiving waters, the best results were found using the "percent contributing area" (% urban + % agriculture) as the independent variable in a function of the form:

$$\log [P] = b + a (\% \text{ urban} + \% \text{ agriculture}).$$

Although some improvement was noted when the data were stratified by region (west, center or east), or had a term added for the percent of the area in forest cover, coefficients of determination ranged from 0.27 to 0.56.

Lystrom *et al.*, on the other hand, utilized water quality and associated land factor data collected at 80 stream sites in one river basin, the Susquehanna. With the detailed data base described earlier, they were able to select from a wide range of factors that may have significant influence on water quality. Of the 17 water quality parameters included in their sample, 14 were significantly related to land factors using regression analysis on logarithmically transformed data. Coefficients of determination for phosphorus and sediment equations ranged from 0.56 to 0.84. Thus, while there is some improvement in the predictive capability of the equations over those developed based on nationwide data, there is still an unexplained variance of up to 44 percent.

The analysis performed in this study used suspended sediment and total phosphorus loads for 1975 and/or 1976 for 71 and 86, respectively, U.S. tributaries to the Great Lakes (from Sonzogni *et al.*, 1978). The data were transformed to a unit area basis to minimize the effect of watershed area. Land factors used in the analysis included the following (expressed in terms of the percent of the watershed in each class): coarse soils, loamy soils, fine soils, forest, grassland, plowed fields and urban area (land cover data from Monteith and Jarecki, 1978). In addition to analyzing the data set in toto, the following stratification schemes were used in an attempt to remove possible sources of added variance: lake basin, watershed size and degree of urban development.

The correlations were generally better (i.e., more significant) with the phosphorus data than with the suspended sediment data. Regression equations were developed for selected cases using a linear form with one or more independent variables. Coefficients of determination ranged from 0.53 to 0.84. In comparison to similar studies with more observations or a wider range of independent variables, these results are about as good as could be expected.

In general, the best correlations for total phosphorus were found in the Lake Superior and Huron basins. One possible explanation for this may be the



## PHOSPHORUS LOADS

fact that both are relatively "simple" in terms of potential pollutant sources; neither one is dominated by major urban areas or extensive areas of agriculture on fine-textured soils. This may result in a more clear-cut link between land factors and resultant water quality conditions.

There are, of course, other factors which may be involved in the Lake Superior and Huron results. For instance, many of the streams in the Lake Superior basin are relatively short, with small drainage areas. In another part of this analysis, it was found that the best correlations between total phosphorus load and land factors was for watersheds of less than 500 km<sup>2</sup>. In the Lake Huron basin, many of the streams drain forested areas with coarse-textured soils. These streams would tend to be non-event responsive, with much more stable flows and a relatively narrow range of phosphorus concentration values. This could also improve the correlation results.

The importance of urban areas was suggested in the results for Lake Michigan, where percent urban area was the variable most highly correlated with total phosphorus load. The analysis indicates that, as the level of urban development in a watershed increased, the relationship between total phosphorus load and other land factors became less clear. This may reflect the importance of constant point source inputs from municipal treatment plants relative to the variable inputs from the land surface.

As was stated at the outset of this discussion, the analysis of loads as a function of land factors using statistical methods often does not yield clear-cut results, even when the empirical evidence for such a relationship is quite strong. Limitations on the capability of statistical methods in this context do not appear to have been overcome by increased observations or the addition of more independent variables.

An analysis was also conducted of data on the concentration of heavy metals associated with Great Lakes river mouth data which was presented in Fitchko and Hutchinson (1975). Once again, little additional insight was gained from this analysis. There did seem to be a correlation between river mouth sediment metal concentrations and urban area. However, based on the data available, the relative importance of point versus nonpoint inputs could not be established.



fact that both are relatively "stable" in terms of potential nutrient sources; neither one is dominated by major urban areas or extensive areas of agriculture or livestock. The results in a more direct and less complex form of factors and nutrient sources are available.

These are, of course, other factors which may be involved in the low nitrogen performance results. The influence of the nitrogen in the low nitrogen basin is particularly evident. It is possible that the low nitrogen basin is a watershed area. The watershed area is a basin of low nitrogen and low factors. The watershed area is a basin of low nitrogen and low factors. The watershed area is a basin of low nitrogen and low factors.

These streams would tend to be somewhat responsive. This would mean that a relatively narrow range of phosphorus concentration values. This could also improve the nitrogen concentration. The nitrogen concentration is also improved. The nitrogen concentration is also improved. The nitrogen concentration is also improved.

The importance of these areas was suggested in the results for the low nitrogen basin. The nitrogen concentration is also improved. The nitrogen concentration is also improved. The nitrogen concentration is also improved. The nitrogen concentration is also improved.

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With this (analysis) was also improved. The nitrogen concentration is also improved. The nitrogen concentration is also improved. The nitrogen concentration is also improved.

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## PHOSPHORUS LOADS

One of the primary objectives of U.S. Task D was to determine the importance of land-derived pollutant sources relative to other sources. In order to make this determination all sources of phosphorus, which is the most significant Great Lakes pollutant derived from land drainage, have been investigated. These sources include municipal and industrial point sources, diffuse tributary, atmospheric, shoreline erosion, and sources generally not considered, such as waterfowl excretion. The year-to-year variability of the sources and a comparison of different loading estimates by major studies are addressed. A discussion is included on movement of point and nonpoint inputs to the tributary system and how assumptions on transmission may affect the relative importance of point versus nonpoint sources.

### DIFFERENCES IN GREAT LAKES PHOSPHORUS LOAD ESTIMATES MADE BY PLUARG, WATER QUALITY BOARD, AND THE FIVE YEAR REVIEW GROUP

Inconsistencies have occurred in the phosphorus load estimates made in major studies. The results of three of these studies made in 1976 are shown in Table 3.

TABLE 3

#### 1976 ESTIMATED TOTAL PHOSPHORUS LOADS FOR THE GREAT LAKES (MT/YR)

<u>Lake</u>	<u>Water Quality Board</u> <sup>1</sup>	<u>Task Group</u> <sup>2</sup>	<u>PLUARG</u> <sup>3</sup>
Superior	3600	3600	4200
Michigan	6600	6700	6400
Huron	4800	4300	4900
Erie	15,400	19,700	17,500
Ontario	12,700	12,800	11,800

1. International Joint Commission (1977f)
2. International Joint Commission (1978)
3. Pollution from Land Use Activities Reference Group (1978a)



Inconsistencies are to be expected given the large amount of data that must be synthesized and the constantly changing status of this information. Differences may also occur as a result of boundary definitions (e.g., between basins or between direct and indirect point sources). Nevertheless, the load estimates currently compiled are agreeable, especially when reasons for the differences are understood.

From a management perspective, it is important not to put great significance on small differences in load estimates. Differences of a few hundred metric tons of total phosphorus input, or in the case of Lake Erie, even as much as a thousand metric tons, are small relative to inherent errors in the estimate. Loads need not be known with super accuracy and precision to develop sound control strategies, nor would it be cost-effective to obtain loads with an extremely high degree of accuracy and precision. Natural year-to-year variability in the load from diffuse sources due to climatic variations (probably 10-15 percent of the total load) exemplifies this point.

Table 4 shows the sources of data used by the different studies for making phosphorus loading estimates. As indicated in Table 4, U.S. tributary loading data used by PLUARG was based on a report prepared by the Great Lakes Basin Commission staff (Sonzogni and Monteith, (1978). This report includes a comparison

TABLE 4

SOURCES OF DATA FOR PHOSPHORUS LOAD ESTIMATES

---

Tributary and Municipal/Industrial Loads

Water Quality Board -- derived from data submitted by State or Province.

Task Group -- basically updated Water Quality Board data except for Saginaw Bay (U.S. EPA data) and Lake Erie (U.S. Army Corps of Engineers' Lake Erie Wastewater Management Study estimates).

PLUARG -- U.S. tributary data for all lakes except Erie based on PLUARG report prepared by Great Lakes Basin Commission which utilized state data, university data, PLUARG data, etc. Erie tributary data based on U.S. Army Corps of Engineers information.

Atmospheric Loads

Water Quality Board and Task Group atmospheric data essentially the same. PLUARG atmospheric load based on a recent report by the Great Lakes atmospheric loading experts and is in effect an update of Water Quality Board/Task Group estimates.

---



of estimates by the Basin Commission and Water Quality Board and emphasizes the difference in the rivers investigated and the number of measurements upon which the loads were based. This report should be consulted for more detailed information.

Listed below is a summary of the difference in total phosphorus load estimates (sum of all sources) for each of the lakes.

#### Lake Superior

Little difference exists between load estimates for Lake Superior. PLUARG reported a slightly higher total load, largely as a result of a higher atmospheric phosphorus loading estimate.

#### Lake Michigan

Little difference exists between the total load estimates. The somewhat lower PLUARG estimate is likely due to a more accurate estimate of the total tributary input.

#### Lake Huron

Little difference exists between the total load estimates. The lower Task Group estimate is largely a result of the Saginaw Bay load. The Task Group's Saginaw Bay load was based on detailed data collected for a specialized study of the Bay conducted by the U.S. Environmental Protection Agency. Another reason for the difference is that EPA's data was based on the calendar while PLUARG's estimates were based on the water year. Differences in precipitation and runoff over these time spans could have contributed to the differences in the load estimates.

#### Lake Erie

The largest discrepancy between the load estimates exists for Lake Erie. The Water Quality Board estimate is likely underestimated due to the limited number of data used in their calculations. In particular, the results of the extensive event tributary monitoring program conducted as part of the Lake Erie Wastewater Management Study (U. S. Army Corps of Engineers, 1975) were not used in their estimates.

Disregarding the Water Quality Board estimates, attention is focused on the differences in the estimates of the Task Group and PLUARG. Table 5 compares the phosphorus loads reported by these two sources.



TABLE 5

SUMMARY COMPARISON OF LAKE ERIE 1976 TOTAL PHOSPHORUS LOADS AS  
DETERMINED BY THE TASK GROUP AND PLUARG

(METRIC TONS/YEAR)

	<u>Total Tributary</u>	<u>Direct</u>	<u>Atmospheric</u>
U.S.			
Task Group	7,732	6,957	
PLUARG	7,732	5,699	
Canada			
Task Group	2,544	245	
PLUARG	1,911	234	
U.S./Canada			
Task Group			1,119
PLUARG			774

Note that the major differences between the Task Group and the PLUARG report are with the Canadian total tributary load, the U.S. direct load, and the atmospheric input. Aside from the atmospheric inputs (the difference is due to more current atmospheric loading data available to PLUARG) and the Canadian tributary inputs (Task Group Canadian tributary loads were based on an estimate made by U.S. Army Corps of Engineers), the main difference is in the U.S. direct load. The PLUARG U.S. direct sources estimate is over 1,000 metric tonnes lower than the Task Group estimate. Table 6 summarizes different estimates made of direct inputs to U.S. Lake Erie. Note that the Task Group (i.e., U.S. Army Corps of

TABLE 6

1976 TOTAL PHOSPHORUS LOAD ESTIMATES TO LAKE ERIE  
FROM DIRECT SOURCES

	<u>metric tons/year</u>
Task Group (U.S. Army Corps of Engineers, 1975)	6,957
Great Lakes Basin Commission (early estimate, unpublished)	6,500
Great Lakes Basin Commission (revised estimate used in overview modeling; Johnson <u>et al.</u> , 1978)	6,750
PLUARG	5,588
Water Quality Board	5,661



Engineers estimates) and Great Lakes Basin Commission estimates are fairly close. The PLUARG estimate is similar to the Water Quality Board estimate. Since the Water Quality Board estimate is not based on as detailed information as that of the Basin Commission or the Corps of Engineers, the PLUARG estimate is probably low. This low direct source estimate, along with the Canadian tributary load difference and the atmospheric load difference accounts for the main difference between the PLUARG and the Task Group estimate. Consequently, the Task Group estimate is believed to be the more reasonable.

#### Lake Ontario

Little difference exists between the total load estimates for Lake Ontario. The lower PLUARG estimate is largely due to a lower figure for the atmospheric phosphorus input. Since PLUARG's atmospheric input estimates were based on the most current information (not available to the other studies), the PLUARG estimate should carry the greatest weight.

#### MID-1970 PHOSPHORUS LOADS

A more detailed look at total phosphorus loadings to the Great Lakes during the mid-1970's is presented in Table 7. These figures were based on the estimates of the three sources discussed previously, as well as information from other summary sources. (Chapra, in press; Andren *et al.*, 1977; Casey and Salbach, 1974; Johnson *et al.*, 1978; U.S. Army Corps of Engineers, 1975; Monteith and Sonzogni, 1976; Sonzogni *et al.*, 1978). The majority of the information was available for water years 1975 and 1976.

In Table 7 point sources have been differentiated as direct inputs (generally located below river mouth monitoring stations or direct to the lakes) and tributary inputs (discharging to tributaries at a location upstream of the river mouth). Diffuse sources include tributary and atmospheric inputs. The tributary diffuse input consists of both land runoff and base flow (ground water inputs). Total phosphorus inputs associated with Great Lakes shoreline erosion have also been included in Table 7.

Point source loads include both municipal and industrial sources, although the industrial inputs of phosphorus are relatively minor. Point source inputs to tributaries were assumed to be completely transmitted to the Great Lakes. A further discussion on transmission and its effect on estimating the distribution between point and nonpoint source contributions is given in a subsequent section.

In order to provide insight into year-to-year variability of land runoff sources, upper and lower bounds of the diffuse tributary loads were estimated (Table 7). These bounds were derived by assuming that the mean annual diffuse tributary load varies directly with mean annual flow. The range corresponds to plus or minus two standard deviations in mean annual flow (Sonzogni *et al.*, 1978, Water Survey of Canada 1977) multiplied by the average concentration of each lake's tributaries (corrected for point sources). These ranges are designed to illustrate that the diffuse tributary loads to each of the lakes can vary significantly from one year to another, depending on meteorological and runoff conditions. In this regard, flow from tributaries during the mid-70's (water years 1975 and 1976) was generally higher than the mean discharge over the historical



TABLE 7

ANNUAL TOTAL PHOSPHORUS LOADS  
TO THE GREAT LAKES FOR THE MID-1970's  
(Does not Include Interlake Exchange Loads)  
(Metric Tons Per Year)

	Point Direct	Point Tributary	Diffuse Tributary <sup>1</sup>	Atmospheric	Total Loading <sup>2</sup>	Shoreline Erosion
Lake Superior	300	200	2,400	1,100	4,000	3,800
U.S.	150	150	1,000(750-1200)			3,800
Canada	150	50	1,400(1100-1900)			minimal
Lake Michigan	1,850	1,400	2,000(1400-2000)	1,700	6,950	3,700
Lower Green Bay	450	300	400	50	1,200	minimal
Upper Green Bay	minimal	minimal	150	50	200	100
Main Lake	1,400	1,100	1,450	1,600	5,500	3,600
Lake Huron	250	725	2,500	1,100	4,575	700
U.S.	100	550	1,200(700-1100)			300
Canada	150	175	1,300(900-1400)			400
North Channel	50	minimal	600	50	700	minimal
Georgian Bay	50	25	500	300	875	minimal
Saginaw Bay	50	550	800	25	1,425	25
Main Lake	100	150	600	725	1,575	675
U.S.	50	minimal	400			275
Canada	50	150	200			400
Lake Erie	7,000	1,350	9,000	800	18,150	10,450
U.S.	6,750	1,150	6,700(3600-6800)			1,000
Canada	250	200	2,300(1300-2700)			9,450
Western Basin	5,950	650	4,400	100	11,100	250
U.S.	5,700	550	3,900			150
Canada	250	100	500			100
Central Basin	900	500	2,700	500	4,600	9,200
U.S.	900	500	2,200			450
Canada	minimal	minimal	500			8,750
Eastern Basin	150	200	1,900	200	2,450	1,000
U.S.	150	100	600			400
Canada	minimal	100	1,300			600
Lake Ontario	2,250	1,150	2,800	450	6,650	1,300
U.S.	1,100	1,000	1,700(800-1400)			500
Canada	1,150	150	1,100(700-1400)			800

<sup>1</sup>Range in parenthesis is an estimate of the likely range in diffuse tributary loading due to year to year flow variations.

<sup>2</sup>Excluding shoreline erosion.



period of record, except for Lake Superior tributaries whose flow was close to normal. This is consistent with the mid-1970 diffuse tributary loads in Table 7, which, except for Lake Superior, were near or even exceeded the upper end of the estimated normal range. The high Lake Huron and Lake Ontario U.S. Tributary loads reflect extremely high U.S. tributary flow to these lakes during the water year, flows that were greater than two standard deviations from the mean. The year-to-year variability will be discussed more fully in the following section.

The diffuse tributary loads to each of the lakes account for a significant portion of the total load (excluding shoreline erosion), especially for Lakes Superior, Huron and Erie (Table 7). The majority of this diffuse load is derived from agricultural land, except in the Lake Superior basin which drains mostly forested land.

As discussed in Pollution from Land Use Activities Reference Group (1978) and Sonzogni *et al.*, (1978) lands with predominantly fine-texture soils (i.e., clay soils) tend to be the largest contributors of phosphorus from agricultural land. Urban land, which on a unit area basis can contribute more phosphorus than agricultural land, comprises only about four percent of the basin, so that the total contribution from urban areas is relatively small. As shown in Table 7, the largest diffuse tributary loads, as well as the largest total loads, are delivered to Lake Erie.

Despite the fact that total phosphorus is a useful parameter for modeling lake trophic response, it should be understood that not all of the total phosphorus input, especially not all of the particulate phosphorus fraction, is biologically available. Based on recent information which will be discussed in a later chapter of this report, approximately 50 percent or more of the total phosphorus contributed by tributaries is unavailable for plant growth. A large fraction of the unavailable phosphorus is associated with suspended particles.

The total phosphorus derived from shoreline erosion is even less available (probably less than ten percent). Consequently, for modeling purposes shoreline erosion has not been considered as part of the total load but rather as a steady state background input not able to be controlled. This is consistent with other treatments of shoreline erosion (International Joint Commission Technical Group to Review Phosphorus Loadings, 1978; PLUARG, 1978).

#### YEAR-TO-YEAR VARIABILITY IN GREAT LAKES TOTAL PHOSPHORUS DIFFUSE TRIBUTARY LOADS

The importance of the year-to-year variability in total phosphorus loads was discussed briefly in the previous section. The following discussion provides more detail on how the range of the diffuse tributary load, given in Table 7, was determined.

#### Variability of Tributary Flow

Rather dramatic changes in annual river flow can occur from one year to the next. These flow fluctuations, resulting from differences in the amount, intensity, and time of occurrence of precipitation, can greatly affect loads of land-derived pollutants to the Great Lakes.



To illustrate the fluctuations that can occur in flow, all gaged flows for U.S. and Canadian rivers were summed for the years 1958 through 1977 and plotted in Figure 18. The gaged flow was then extrapolated linearly to the ungaged area to produce a total land runoff for each year over the 20 year period. In this figure it can be seen that a high of 250,000 cfs occurred in 1969, and a low of 156,000 cfs occurred in 1963. This is an increase (from 1963 to 1969) of 60 per cent over only a six year period. The flow fluctuation is also illustrated (Figure 19) by the flow out of the St. Lawrence River, which drains the Great Lakes.

FIGURE 18

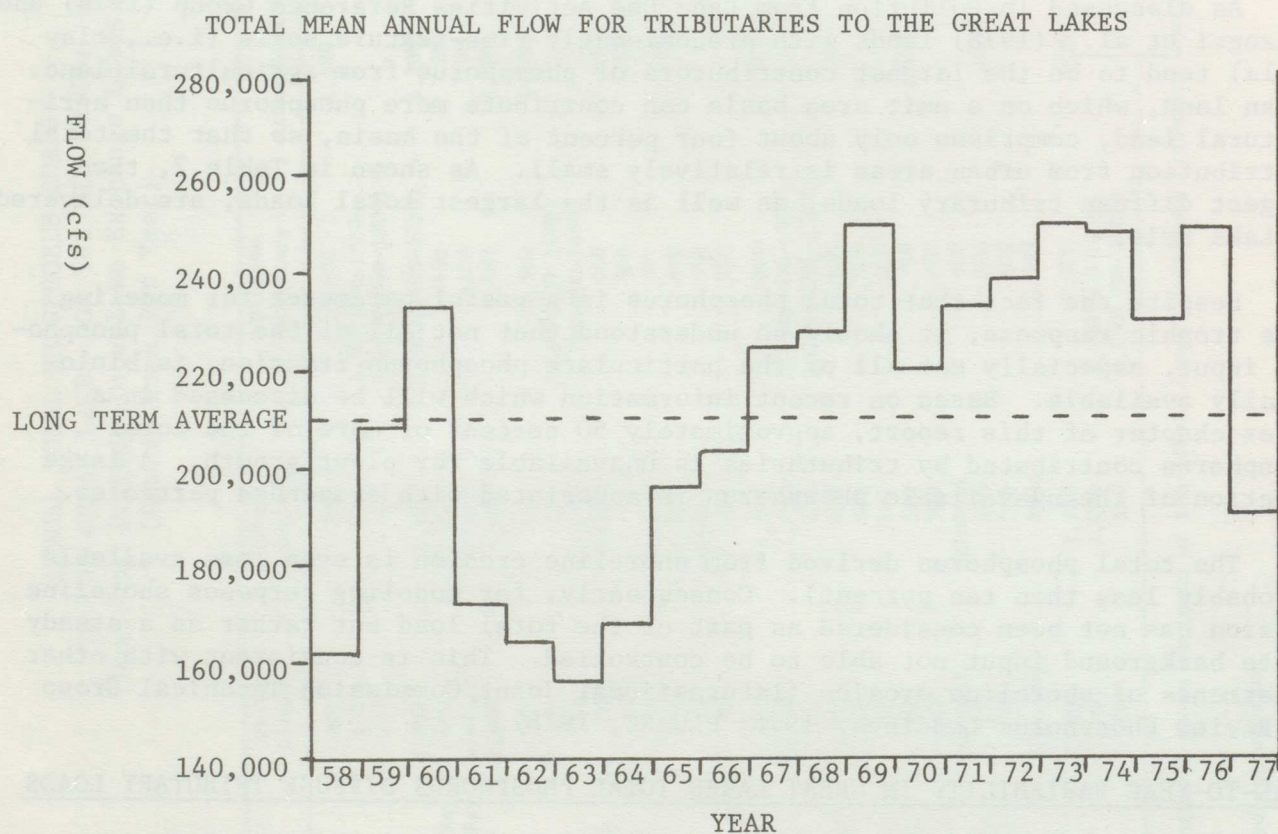
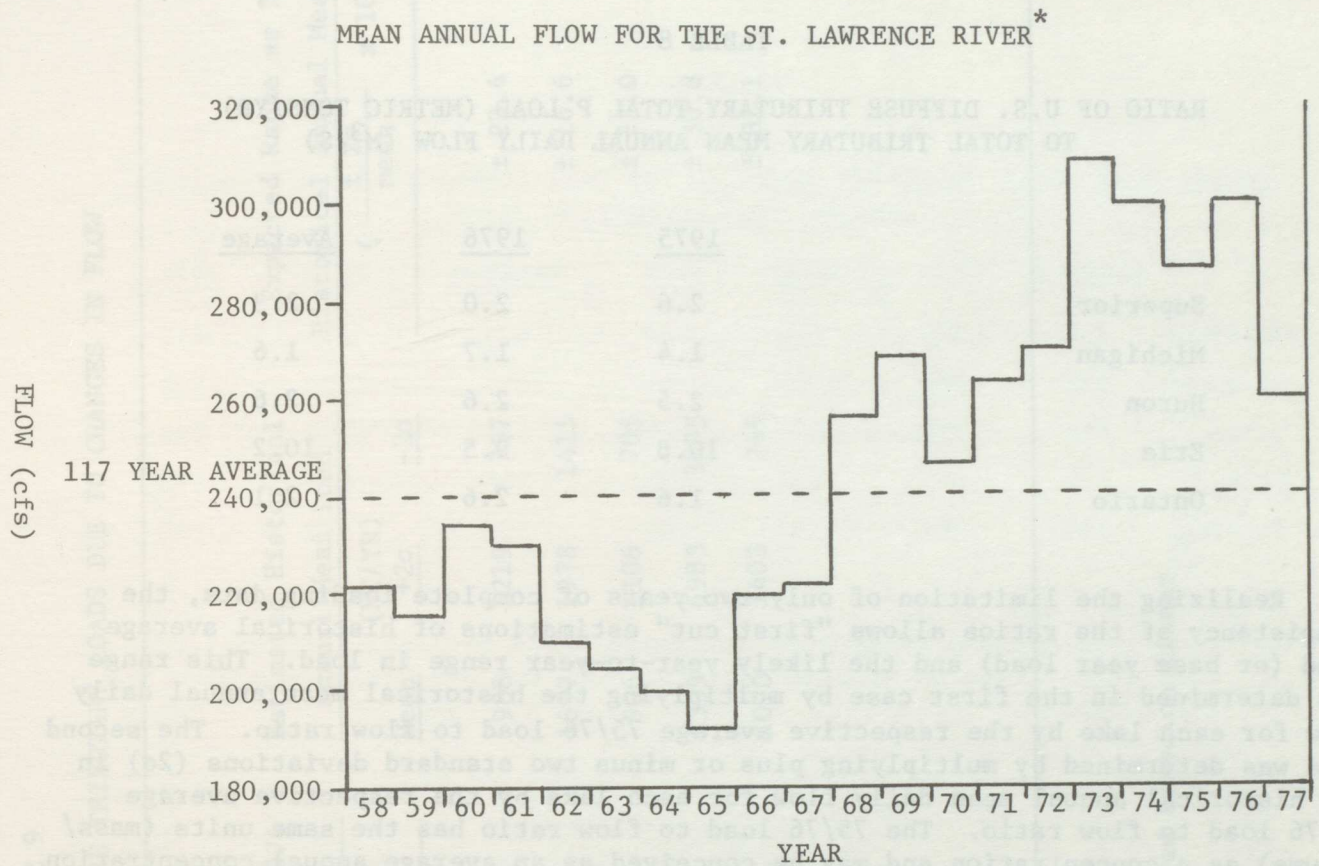




FIGURE 19



\*USGS Station #04264331 at Cornwall, Ontario. State of New York records.

#### Variability of Tributary Load

In order to provide an insight into the year-to-year variability of land run-off inputs of total phosphorus to the Great Lakes, upper and lower bounds of the diffuse tributary loads were estimated based on historical flow data. These bounds were derived by assuming that the mean annual load varies directly with the mean annual flow. The appropriateness of this assumption was initially determined by calculating the ratio of the estimated U.S. diffuse total P tributary load to the flow in each of the Great Lakes (Table 8). Data for these calculations were derived principally from Sonzogni et al. (1978) and Table 7.

Note that Table 8 shows relatively good consistency in the load to flow ratio between 1975 and 1976. Also, average ratios were all between 1.6 and 3.0 except for Lake Erie, which had a significantly higher load to flow ratio. This higher ratio is probably the result of the characteristic of the Erie watershed (high clay content; event response tributaries). Less intensive sampling of non-Lake Erie tributaries and a consequent underestimation of the tributary load (see Sonzogni et al., 1978, for further explanation) may also contribute to the difference in ratios between Erie and the other lakes.



TABLE 8

RATIO OF U.S. DIFFUSE TRIBUTARY TOTAL P LOAD (METRIC TONS/YR)  
TO TOTAL TRIBUTARY MEAN ANNUAL DAILY FLOW (M<sup>3</sup>/S)

	<u>1975</u>	<u>1976</u>	<u>Average</u>
Superior	2.6	2.0	2.3
Michigan	1.4	1.7	1.6
Huron	2.5	2.6	2.6
Erie	10.8	9.5	10.2
Ontario	1.6	2.6	2.1

Realizing the limitation of only two years of complete loading data, the consistency of the ratios allows "first cut" estimations of historical average load (or base year load) and the likely year-to-year range in load. This range was determined in the first case by multiplying the historical mean annual daily flow for each lake by the respective average 75/76 load to flow ratio. The second case was determined by multiplying plus or minus two standard deviations ( $2\sigma$ ) in the historical annual mean daily flow for each lake by the respective average 75/76 load to flow ratio. The 75/76 load to flow ratio has the same units (mass/volume) as a concentration and may be conceived as an average annual concentration of total phosphorus for all tributaries to a given lake. Data used in the calculations described above are summarized in Table 9.

It should be reemphasized that these estimates are extremely rough and involve many implicit assumptions. For example, it assumes that flow from gaged areas can be extrapolated linearly to give a total basin tributary flow and that the loading estimates are equally accurate for each of the lakes. Perhaps the most significant assumption is that the load to flow ratio determined from 1975 and 1976 is representative under all flow conditions; that is the concentration remains constant with variation in flow on a large scale. The data show that this assumption is reasonable, at least on the scale considered. Even if attempts to estimate loads from historical flow data are disregarded, simply considering the range in flows can provide a qualitative appreciation of the variability expected from diffuse inputs due to meteorological (and runoff) conditions.

Flow from Great Lakes tributaries during the 1975 and 1976 water years was generally higher than the mean discharge over the historical period of record, except for Lake Superior whose flow was close to normal. This is demonstrated from the data compiled in Table 10. The mid-1970 diffuse tributary phosphorus loads (see Table 7) are also, except for Lake Superior, near the upper end of the estimated normal range. Table 10 shows that flow during water year 1976 was near the maximum flow over the period of record for Huron and Ontario. Consequently, from a management perspective it is important to realize that the mid-1970 diffuse tributary total phosphorus loads are probably not representative of "base" or "average" conditions.



TABLE 9

## FLUCTUATIONS IN TOTAL PHOSPHORUS U.S. DIFFUSE TRIBUTARY LOADS DUE TO CHANGES IN FLOW

Lake	Historical Total Tributary Annual Mean Daily Flow <sup>1</sup> (m <sup>3</sup> /s)			Average 1975 and 1976 Load to Flow Ratio ( $\frac{\text{MT/YR}}{\text{m}^3/\text{s}}$ )	Estimated Historical Annual Mean Load (MT/YR)			Expected Range as % of Historical Annual Mean Load ( $\frac{\pm 2\sigma}{\text{mean}} \times 100$ )
	Mean	+2 $\sigma$	-2 $\sigma$		Mean	+2 $\sigma$	-2 $\sigma$	
Superior	424	523	325	2.33	988	1219	757	± 23.4
Michigan	1067	1244	890	1.59	1697	1978	1415	± 16.6
Huron	350	427	272	2.59	906	1106	705	± 22.0
Erie	526	688	364	10.15	5339	6983	3695	± 30.8
Ontario	505	662	361	2.12	1070	1403	765	± 31.1

1. Flows are for total basin; flow from ungauged areas estimated based on linear extrapolation from gauged areas.



TABLE 10

ANNUAL MEAN DAILY TRIBUTARY FLOW<sup>1</sup> (M<sup>3</sup>/S) DATA COMPARISONS (U.S. only)

	<u>Minimum</u>	<u>-2σ</u>	<u>Mean</u>	<u>+2σ</u>	<u>Maximum</u>	<u>1975</u>	<u>1976</u>
Superior	224	325	424	523	623	475	417
Michigan	538	890	1067	1244	1699	1229	1305
Huron	170	272	350	427	538	429	499
Erie	170	364	526	688	906	645	674
Ontario	330	361	505	662	823	555	767

1. Flow from ungaged areas were estimated based on linear extrapolation from gaged areas to give an estimate of total U.S. tributary flow for each basin.

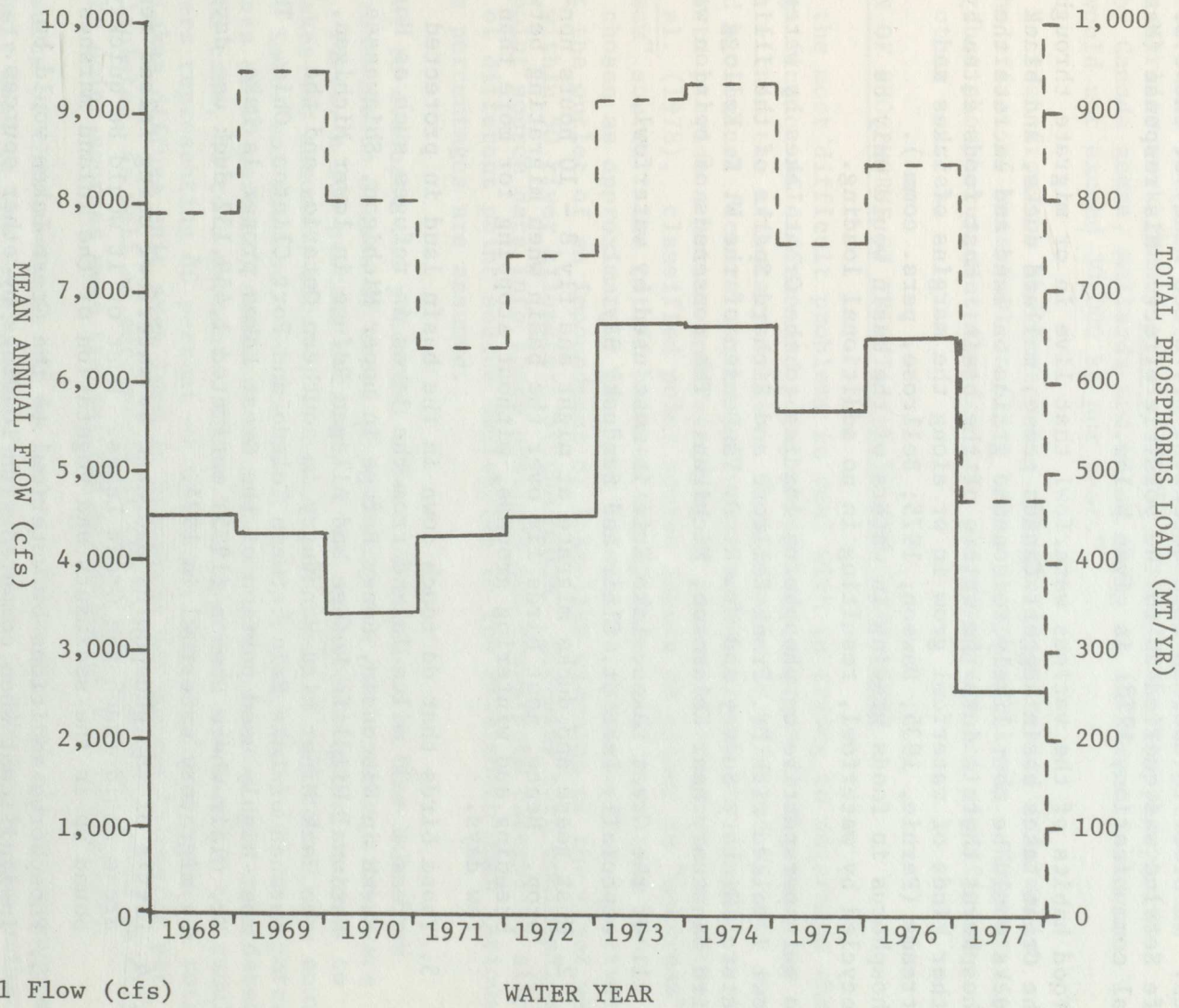
A similar analysis was conducted for Canadian tributaries. Generally, less flow data is available for Canadian tributaries, both in terms of the percent of the basin gaged and the period of record. Nonetheless, estimates of total flow into the Great Lakes from each of the four Canadian Great Lakes basins were made. The range in load was then calculated as described above (see Table 7 for results).

The above analysis has been done for groups of tributaries, since for individual tributaries the relationship between flow and concentration would generally be expected to be more variable. Trends in the load/flow relationship can still be seen clearly for individual rivers. Figure 20 shows how flow from the Grand River in Michigan has varied over the last few years. It can be clearly seen from this figure that, in most cases, the load increases with the flow. The historical mean annual flow for 51 years of record is approximately 113 cubic meters per second (4,000 cubic feet per second). The flow for the Grand River for water years 1975 and 1976, as can be seen in Figure 20, were well above the historical average flow and, in fact, were some of the highest on record. The corresponding loads, then, were likely to be some of the highest delivered by the Grand River. Comparing 1976 and 1977, note that the flow dropped from 6500 cubic feet per second to a little more than 2500 cubic feet per second, a drop of 62 percent. The corresponding load decreased from 850 tonnes per year to 470 tonnes per year, a drop of 44 percent. The difference between 1976 and 1977 further illustrates the importance of considering the year-to-year variability of flow when evaluating the characteristics of a tributary load for a single year or a short period of record.



FIGURE 20

GRAND RIVER, MICHIGAN  
FLOW AND TOTAL PHOSPHORUS LOAD AT THE MOUTH



KEY

- Mean Annual Flow (cfs)
- - - Total Phosphorus Load for the Year (MT/YR)



3. About 35,000 black ducks winter along Lake St. Clair, the Detroit River, and the marshes of Lake Erie.

While precise estimates of phosphorus added by all waterfowl to the the Great Lakes per year are fraught with uncertainties, by reference to some earlier work (Manny *et al.*, 1975), I would say the phosphorus added by Canada geese, mallards and black ducks to the Great Lakes basin would not exceed 30,000 kg per year."

As can be seen from the above response, little quantitative information exists on the effect of waterfowl on Great Lakes phosphorus loads. However, it does appear that phosphorus contribution from waterfowl are not significant relative to other sources.

#### TRANSMISSION OF PHOSPHORUS BY TRIBUTARIES TO THE GREAT LAKES

One of the most difficult problems to deal with in trying to determine the relative significance of diffuse and point phosphorus sources is the question of transmission within the tributary system. Transmission is affected by many physio-chemical and biological factors as the pollutant moves through the fluvial system. In an effort to provide a better understanding of potential transmission losses, Sonzogni *et al.* (1978), classified point source inputs as either an "upstream" or "downstream" source. The cutoff between the upstream and downstream source was arbitrarily chosen as approximately 50 river kilometers upstream from the river mouth, or at the outlet of an impoundment or lake-like widening of the river where such occurs within 50 river kilometers of the mouth. Grouping both municipal and industrial point source data into these upstream and downstream categories allows calculation of different point source deliveries to the rivermouth when various transmission percentages are assumed.

In order to evaluate the potential effect on the load at the lake from different transmission losses of total phosphorus, two basic assumptions were considered. First, a 100 percent delivery of all downstream point sources to the Great Lakes was assumed; second, 50 percent delivery of all downstream sources to the Great Lakes was assumed. In the first case, a range from 100 to 0 percent (in increments of 10 percent) delivery of upstream point sources was considered; in the second case, 50 to 0 percent. Using this approach and summing the results for 110 rivers representing 80 percent of the total U.S. drainage basin, a total U.S. Great Lakes diffuse unit area load in kilograms per square kilometer per year was calculated, as well as percentage of the total load that would be diffuse if indeed the point sources were transmitted according to the assumptions.

The results of this analysis can be seen in Table 11. If all point sources delivered their load to the Great Lakes from any place in the basin, approximately 70 percent of the total tributary load to the Great Lakes would be diffuse, with the remaining 30 percent due to those point sources. If, in the other extreme, none of the upstream point sources were delivered and only half of the downstream point sources were transmitted to the Great Lakes, 96 percent of the tributary load would be diffuse. Over a long period of time (e.g., 20 years) most of the point source material will likely reach the lakes, unless major impoundments or other sinks are found along the river course. Thus, ultimately most nutrients, solids, and toxics should be transmitted (though they may be in a different



TABLE 11

## TRANSMISSION OF POINT SOURCE TOTAL PHOSPHORUS TO THE GREAT LAKES

DIFFUSE AND POINT SOURCE LOADS - TOTAL P - U.S. GREAT LAKES 1975

<u>Point Source Delivery</u>		<u>Percent Diffuse</u>	<u>Diffuse U.A. (KG/KM2/YR)</u>
<u>Percent Upstream</u>	<u>Percent Downstream</u>		
100.0	100.0	69.7	39.1
90.0	100.0	71.9	40.3
80.0	100.0	74.2	41.5
70.0	100.0	76.4	42.8
60.0	100.0	78.6	44.0
50.0	100.0	80.8	45.2
40.0	100.0	83.0	46.5
30.0	100.0	85.2	47.7
20.0	100.0	87.4	49.0
10.0	100.0	89.6	50.2
0.0	100.0	91.8	51.4

<u>Point Source Delivery</u>		<u>Percent Diffuse</u>	<u>Diffuse U.A. (KG/KM2/YR)</u>
<u>Percent Upstream</u>	<u>Percent Downstream</u>		
50.0	50.0	84.9	47.5
40.0	50.0	87.1	48.8
30.0	50.0	89.3	50.0
20.0	50.0	91.5	51.2
10.0	50.0	93.7	52.5
0.0	50.0	95.9	53.7

TOTAL P - U.S. GREAT LAKES 1975

244257. KM2 ARE MONITORED OUT OF A TOTAL AREA OF 304690. KM2.

THIS GIVES A COVERAGE OF 80.2 PERCENT

THE TOTAL MONITORED RIVER MOUTH LOAD IS 13682. METRIC TONS PER YEAR.

THE STANDARD ERROR IS 273. MT/YR WITH 182.09 EFFECTIVE DEGRESS OF FREEDOM

3391 SAMPLES WERE USED FOR 110 RIVERS



## PREDICTING IMPACTS ON THE LAKES

physical-chemical form) to the Great Lakes. In event response tributaries, due to their more flashy nature, there is a greater potential for the system to be flushed. Thus, they have a higher and more rapid transmission potential.

Uncertainty about the effect of impoundments on riverine pollutant transport is particularly acute for streams draining into eastern Lake Michigan. Many of these streams have been impounded and, most importantly, have lake-like widenings at their mouth. Because of the estuarine exchange with the open lake, it is difficult if not impossible to determine the effect of these lake-like widenings on transmission. In fact, for many tributaries the closest monitoring station is upstream from the lake-like widening. Because many of these widenings probably do reduce delivery of certain pollutants, some tributary inputs for these areas are likely overestimated.

Many factors besides impoundments must be considered in understanding transmission. For a given watershed if most point source discharges occur in the upper portion of the watershed, overall transmission of point sources is likely to be smaller than if point source discharges occurred near the mouth. Such is the case for several tributaries draining into eastern Lake Michigan. Transmission loss may be more important when the ratio of point source contributions to non-point source contributions is high. When point sources are high, transmission losses may be relatively high, since point source inputs occur all year, including the low flow period when transmission loss potential is the highest. On the other hand, nonpoint source contributions occur when flows are highest and transmission loss is minimal. When point source inputs are low relative to nonpoint source input, point source delivery losses on an annual basis can be a small percentage of the total load. Thus, transmission losses may be more pronounced in streams receiving high point source inputs relative to nonpoint source inputs.

It also is likely that some pollutants from upstream point sources are immobilized by in-stream sediments. However, this is probably only a temporary sink. During high flow runoff events, these pollutants are likely delivered as part of the diffuse source pollutant load of the tributary.

The above analysis illustrates the importance of understanding transmission phenomena when trying to determine the impact of either point or nonpoint source controls on phosphorus loadings. Variations in transmission from river to river must be recognized as a significant obstacle to pinpointing the effectiveness of any type of control. Controls also must be evaluated over a long period of time, for it is impossible to understand transmission with one or two years of data.



RESEARCH ON SEVERAL FACTORS WHICH AFFECT THE RATE OF TRANSMISSION OF  
 THE SIGNAL TO THE RECEPTOR AND THE EFFECT OF THE SIGNAL ON THE  
 RECEPTOR

It is impossible to underestimate the importance of the above-mentioned factors for any type of control. Control also must be exercised over a long period of time and must be exercised in a systematic manner. The effectiveness of control is dependent on the nature of the signal and the nature of the phenomenon upon which it acts. The nature of the signal is dependent on the nature of the phenomenon upon which it acts. The nature of the phenomenon is dependent on the nature of the signal and the nature of the control.

It also is likely that some signal will be received from sources and transmitted by the system without the signal being received and likely delivered to the system without the signal being received and likely

receiving high speed source input relative to independent source input of the total system. The transmission of these signals to the system is dependent on the nature of the signal and the nature of the system. The nature of the signal is dependent on the nature of the phenomenon upon which it acts. The nature of the phenomenon is dependent on the nature of the signal and the nature of the control. The nature of the control is dependent on the nature of the signal and the nature of the phenomenon upon which it acts.

Many factors besides impedance must be considered in understanding transmission and reception of signals. The nature of the signal is dependent on the nature of the phenomenon upon which it acts. The nature of the phenomenon is dependent on the nature of the signal and the nature of the control. The nature of the control is dependent on the nature of the signal and the nature of the phenomenon upon which it acts. The nature of the signal is dependent on the nature of the phenomenon upon which it acts. The nature of the phenomenon is dependent on the nature of the signal and the nature of the control.

RESEARCH ON SEVERAL FACTORS WHICH AFFECT THE RATE OF TRANSMISSION OF  
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# PREDICTING IMPACTS ON THE LAKES

## GREAT LAKES TOTAL PHOSPHORUS BUDGET MODEL

### Introduction

The primary objective of this Chapter is to synthesize recent information in a total phosphorus budget model of the Great Lakes system for the mid-1970s. The Great Lakes are a complicated series of interacting lakes and embayments and it is necessary to view the lakes from a systems perspective rather than as a series of individual, isolated entities. Using the model, the effect on the Great Lakes system of different management options, including control of land-derived phosphorus inputs, can be addressed. The model discussed below is also being used in the Great Lakes Basin Commission's Great Lakes Environmental Planning Study.

### Theory

Segmentation. A previous attempt to model Great Lakes total phosphorus budgets (Chapra, 1977) idealized each lake as a completely-mixed system. The present model has been expanded to explicitly model the major embayments.

Budget Model. A general phosphorus budget equation, as formulated by Vollenweider (1969) with modifications by Chapra, (Chapra, 1975; 1979) is written for each segment of the Great Lakes as

$$V \frac{dp}{dt} = W + Q_b p_b - Qp + E'(p_b - p) - VA_s p \quad (1)$$

where

- $V$  = segment volume,  $\text{km}^3$
- $p$  = total phosphorus concentration of the segment,  $\mu\text{g/L}$
- $t$  = time, yr
- $W$  = direct mass loading of total phosphorus to the segment, metric tons/yr (mta)
- $Q_b$  = advective water flow from an adjacent segment,  $\text{km}^3/\text{yr}$
- $p_b$  = total phosphorus concentration in the adjacent segment,  $\mu\text{g/L}$
- $Q$  = advective outflow of water from the segment,  $\text{km}^3/\text{yr}$
- $E'$  = the bulk dispersion coefficient, which parameterizes turbulent transport with an adjacent segment,  $\text{km}^3/\text{yr}$
- $v$  = the apparent settling velocity of total phosphorus. For dimensional consistency, the units of  $v$  in Equation 1 are  $\text{km}/\text{yr}$ . In the remainder of the text, the more conventional units of  $\text{m}/\text{yr}$  are used.
- $A_s$  = the segment's surface area,  $\text{km}^2$



In cases where the segment is adjacent to more than one other segment (for example, Upper Green Bay has interfaces with both Lower Green Bay and Lake Michigan), additional advection and diffusion terms are included. Equation 1 is then written for each of the lake segments resulting in a set of ordinary differential equations. By assuming a steady state ( $dp/dt = 0$ ), these equations reduce to a set of linear, algebraic equations that constitute the budget model and are used to estimate losses of phosphorus to the sediments of each segment and to calculate intersegment effects.

Sediment losses. Over an annual cycle, a fraction of a lake's phosphorus loading is retained by its bottom sediments. The apparent settling velocity (Chapra, 1975) is an appropriate mass transfer coefficient to parameterize this process since it normalizes the loss to the lake's surface area. It is thus acknowledged mathematically that the sediment sink is a heterogeneous reaction. A previous attempt to model Great Lakes phosphorus budgets (Chapra, 1977) used a value of 16 m/yr for all segments and found it to yield adequate results. In the present case, since all the other terms in the budget are either measured or estimated, an apparent settling velocity can be directly calculated for each segment by rearranging Equation 1 at steady state to yield

$$v = \frac{W + Q_b p_b - Q_p + E'(p_b - p)}{A_s p} \quad (2)$$

Intersegment effects. The estimation of intersegment effects is based on an approach developed by Thomann (1963, 1972) to model dissolved oxygen distribution in estuaries. By again assuming a steady state, Equation 1 can be rewritten as

$$ap - a_b p_b = W \quad (3)$$

where  $a$  and  $a_b$  are coefficients of the form

$$a = Q + E' + vA_s \quad (4)$$

and

$$a_b = Q_b + E' \quad (5)$$

Equation 3 is written for all the segments and the resulting set of equations is expressed in matrix form as

$$[A] (p) = (W) \quad (6)$$

where

[A] = the  $n \times n$  matrix of all the coefficients,  $\text{km}^3/\text{yr}$

(p) = the  $n \times 1$  vector of phosphorus concentrations for the segments,  $\mu\text{g}/\text{L}$

(W) = the  $n \times 1$  vector the direct mass loadings of total phosphorus to the segments, tonnes/yr



The solution vector (p) is then obtained formally by inverting the [A] matrix to yield

$$(p) = [A]^{-1}(W) \quad (7)$$

where

$[A]^{-1}$  = the inverted matrix which is termed the steady state system response matrix, ( $\mu\text{g/L}$ )/(tonnes/yr)

A useful property of  $[A]^{-1}$  is that its elements represent the response of a segment (as represented by phosphorus concentration) to a unit loading to any other segment in the system. For example, the appropriate element of  $[A]^{-1}$  would indicate how many  $\mu\text{g/L}$  of phosphorus concentration in Eastern Lake Erie would result from the addition of a metric ton of phosphorus to Western Lake Erie.

### Data

Phosphorus loading. Great Lakes total phosphorus loadings used in the model are representative of mid-1970s conditions. They are shown in Table 7 which was presented earlier in the report. As discussed, the loads are based on an accumulation of information from many summary sources, and take advantage of the recent work conducted by PLUARG and other studies. The majority of the information was available for water years 1975 and 1976.

Morphometry and water movements. Data on the morphometry and water movements of the Great Lakes (Tables 12 and 13) were derived from a variety of sources (Great Lakes Basin Framework Study, 1976; IJC 1976a, 1976b; Burns, 1976) as well as by direct estimation from navigation charts and U.S. Geological Survey Reports.

The bulk dispersion coefficient was either determined empirically from conservative substance budgets using the method described by Chapra (1979) or was estimated from direct measurements or calculations (Arnsbrak and Ragotzkie, 1970; Daneek and Saylor, 1975; IJC 1976a, 1976b; Quinn, 1977). In certain cases, bulk dispersion was omitted even though an open boundary existed between two of the segments. For example, the gradients that exist between Georgian Bay, the North Channel and Lake Huron are small enough to justify the omission of diffusive transport across their interfaces. In the case of Lake Erie, calculations based on a hydrodynamic model suggest that advective transport is much more important than diffusive transport as an exchange process between the basins (Burns, 1976).

Phosphorus concentrations. Mean annual concentrations of total phosphorus are taken from a variety of sources (Dobson *et al.*, 1974; Patterson *et al.*, 1975; Tierney, 1976; IJC, 1976a, 1976b; Smith, 1977; Chapra, 1979) as well as by analyzing data from the Environmental Protection Agency's STORET system and data from the Canada Centre for Inland Waters. The results for the period from 1974 through 1976 are summarized in Table 12.

### Results

Apparent settling velocities. Using Equation 2 along with the data from Tables 7, 12 and 13 yield the apparent settling velocities in Table 12. As can



TABLE 12

PHYSICAL AND CHEMICAL DATA FOR THE GREAT LAKES FOR THE MID-1970s  
(ALSO INCLUDING LONG-TERM AVERAGE OUTFLOWS)

Segment	Mean Depth m	Surface Area km <sup>2</sup>	Volume km <sup>3</sup>	Advective Outflow		Phosphorus Concentration µg/L	Apparent Settling Velocity m/yr
				1974-76 km <sup>3</sup> /yr	Long-Term Average km <sup>3</sup> /yr		
Lake Superior	147.70	82100.0	12125.00	68.5*	67.2	4.6	9.8
Lake Michigan	86.10	57800.0	4976.00	50.9	36.0		
Lower Green Bay	9.00	953.0	8.50	5.4	5.4	40.0	12.7
Upper Green Bay	18.00	3260.0	58.70	10.7	10.8	15.0	11.2
Main Lake	91.60	53587.0	4909.00	50.9	36.0	8.0	12.3
Lake Huron	60.40	59600.0	3597.00	186.7	160.8		
North Channel	23.30	3950.0	91.90	43.9	45.4	5.5	26.6
Georgian Bay	44.70	15108.0	675.00	21.8†	17.9	4.5	11.4
Saginaw Bay	5.85	1376.0	8.05	7.0	4.7	30.9	13.5
Main Lake	72.10	39166.0	2822.00	186.7	160.8	5.5	11.7
Lake Erie	19.90	25212.0	501.00	220.6	182.0		
Western Basin	8.80	3680.0	32.00	202.3	171.1	39.1	29.3
Central Basin	19.10	15390.0	294.00	214.0	177.5	19.4	28.0
Eastern Basin	28.50	6150.0	175.00	220.6	182.0	17.2	26.5
Lake Ontario	86.80	18960.0	1649.00	262.6	211.7	21.0	12.4

\*23 km<sup>3</sup>/yr goes to North Channel while 45.5 km<sup>3</sup>/yr goes to Main Lake Huron.

†3.2 km<sup>3</sup>/yr goes to North Channel while 18.6 km<sup>3</sup>/yr goes to Main Lake Huron.



TABLE 13

BULK DISPERSION COEFFICIENTS  
FOR TURBULENT EXCHANGE BETWEEN SEGMENTS

Interface	Bulk Dispersion Coefficient km <sup>3</sup> /yr
Lower Green Bay/ Upper Green Bay	20
Upper Green Bay/ Main Michigan	30
Main Michigan/ Main Huron	70
Saginaw Bay/ Main Huron	25



be seen, Lake Erie and the North Channel have higher  $v$ 's than the other segments. The Lake Erie case has been noted elsewhere (Burns, 1976) and may be partly due to the large amounts of suspended sediments in its tributaries. The North Channel case may be due in part to year-to-year variability and/or inaccuracies in loading estimates which range from 401 mta (IJC Technical Group to Review Phosphorus Loadings, 1978) to 1068 mta (IJC, 1976a).

The geometric mean of Great Lakes settling velocities is 15.7 m/yr, with a range corresponding to  $\pm 1$  standard deviation from 10.2 to 24.0. This is slightly larger than the value of 11.4 m/yr ( $\pm$  standard deviation from 3.4 to 38.1) determined for other North Temperate lakes (Chapra, 1978). However, a Kruskal-Wallis rank test was used to determine that the two populations were not significantly different.

It should be noted that deviations from steady state could bias the settling velocity calculations. The only part of the Great Lakes where a trend is evident is Lake Ontario where total phosphorus concentration has been dropping at an approximate yearly rate of 1  $\mu\text{g/L}$  since 1973 (H.F.H. Dobson, Canada Centre for Inland Waters, personal communication). Such a trend would tend to cause the present calculation to underestimate the settling velocity and the actual value for Lake Ontario would be about 18 m/yr. Nevertheless, for the other parts of the system, the values in Table 12 represent the best estimates that are possible on the basis of the existing data.

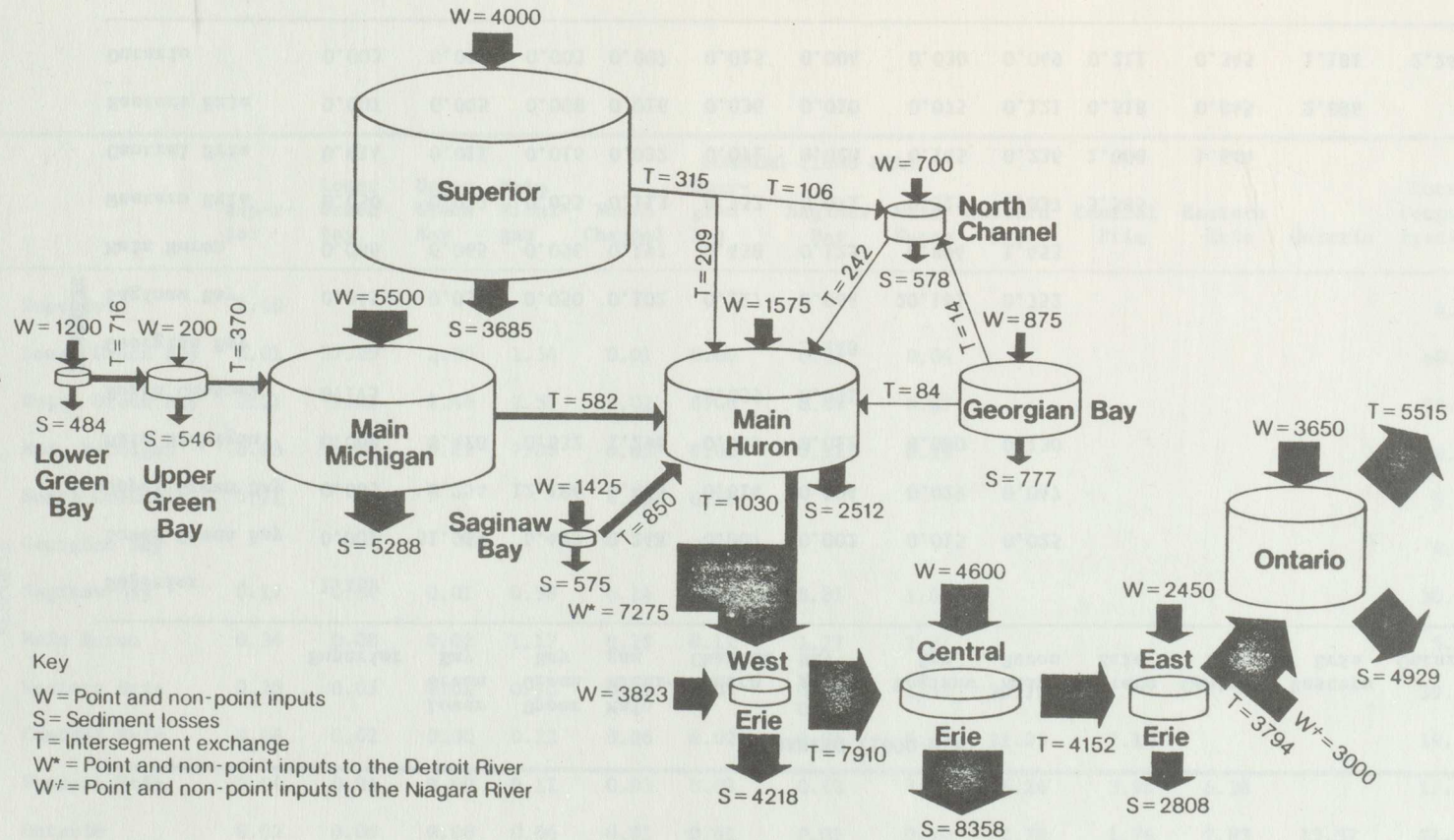
Phosphorus budget. Using the apparent settling velocities and the data in Tables 7, 12 and 13, a total phosphorus budget for the Great Lakes is constructed and presented in Figure 21. The most striking feature of this diagram is the intense pressure on the Lower Great Lakes and the impact of the Detroit River phosphorus loading. Not only does the Detroit River loading constitute the major component of the intense pressure on the Western Basin of Lake Erie, but the large water flow through the Lower Lakes tends to propagate its influence through the remaining basins of Lake Erie and on to Lake Ontario. This is in contrast to the Upper Great Lakes (Superior, Michigan and Huron) where low flow-volume ratios tend to minimize interlake effects and, in general, a large fraction of the loading is retained by each lake. These effects are given quantitative expression in the next section.

Intersegment effects. The steady state system response matrix,  $[A]^{-1}$ , is calculated and presented in Tables 14 and 15. Table 14 (based on long-term average flows) expresses the conventional form of the matrix; i.e., each element represents the response of a segment in  $\mu\text{g/L}$  to a unit loading change of 1,000 mta to any other segment. It can be used to answer such a question as: what would be the improvement in Lake Ontario, if the loading to Central Lake Erie were reduced by 1,000 mta? The element corresponding to the loading to Central Lake Erie and the response of Lake Ontario shows that a 0.345  $\mu\text{g/L}$  improvement would result from such a measure. It should also be noted that because the model is linear, to derive the response to a 2,000 mta reduction of the Central Lake Erie loading, one would simply double the matrix element; i.e. a 0.690  $\mu\text{g/L}$  improvement would result. Furthermore, another advantage of linearity is that superposition holds and any combination of control measures can be analyzed and the results are additive.



FIGURE 21

GREAT LAKES TOTAL PHOSPHORUS BUDGET FOR THE MID-1970'S  
WITH MAJOR FLUXES SHOWN IN METRIC TONS PER YEAR \*



\* The cylinders used to represent each segment are proportional in size to the actual body of water with a 1000:1 distortion in depth; the width of the arrows is proportional to annual mass flux.



TABLE 14

## STEADY STATE SYSTEM RESPONSE MATRIX FOR THE GREAT LAKES BASED ON MEAN LONG-TERM FLOWS

Elements are in  $\mu\text{g/L}$  and correspond to the response of each segment (row) due to a loading of 1000 metric tons per year to every other segment (column)

	LOADING (1000 MTA)											
	Superior	Lower Green Bay	Upper Green Bay	Main Michigan	North Channel	Georgian Bay	Saginaw Bay	Main Huron	Western Erie	Central Erie	Eastern Erie	Ontario
RESPONSE Superior	1.152											
Lower Green Bay	0.001	31.069	6.499	0.248	0.007	0.002	0.015	0.025				
Upper Green Bay	0.003	8.254	12.186	0.465	0.014	0.004	0.029	0.047				
Main Michigan	0.008	0.428	0.632	1.296	0.039	0.011	0.080	0.130				
North Channel	0.173				6.639	0.091						
Georgian Bay						5.248						
Saginaw Bay	0.045	0.034	0.050	0.102	0.227	0.064	20.181	0.752				
Main Huron	0.086	0.065	0.096	0.197	0.438	0.123	0.894	1.453				
Western Erie	0.050	0.037	0.055	0.113	0.252	0.071	0.515	0.837	3.585			
Central Erie	0.014	0.011	0.016	0.032	0.071	0.020	0.145	0.236	1.008	1.644		
Eastern Erie	0.007	0.005	0.008	0.016	0.036	0.010	0.075	0.121	0.518	0.845	2.896	
Ontario	0.003	0.002	0.003	0.007	0.015	0.004	0.030	0.049	0.211	0.345	1.181	2.24



TABLE 15

## STEADY STATE SYSTEM RESPONSE MATRIX FOR THE GREAT LAKES FOR THE MID-1970s

Elements are the response of each segment in  $\mu\text{g/L}$  to the actual loading to every other segment

	LOADING (1000 MTA)											Total Concentration	
	Superior	Lower Green Bay	Upper Green Bay	Main Michigan	North Channel	Georgian Bay	Saginaw Bay	Main Huron	Western Erie	Central Erie	Eastern Erie		Ontario
Superior	4.60												4.6
Lower Green Bay	0.01	37.29	1.30	1.34	0.01	0.00	0.02	0.04					40.0
Upper Green Bay	0.01	9.91	2.44	2.52	0.01	0.00	0.04	0.07					15.0
Main Michigan	0.03	0.50	0.12	7.00	0.03	0.01	0.11	0.19					8.0
North Channel	0.71				4.69	0.10							5.5
Georgian Bay						4.50							4.5
Saginaw Bay	0.17	0.04	0.01	0.58	0.14	0.06	28.81	1.09					30.9
Main Huron	0.34	0.08	0.02	1.17	0.29	0.12	1.27	2.21					5.5
Western Erie	0.20	0.05	0.01	0.70	0.17	0.07	0.76	1.33	35.79				39.1
Central Erie	0.06	0.02	0.00	0.22	0.06	0.02	0.24	0.42	11.23	7.13			19.4
Eastern Erie	0.04	0.01	0.00	0.12	0.03	0.01	0.13	0.23	6.26	3.98	6.38		17.2
Ontario	0.02	0.00	0.00	0.06	0.01	0.01	0.06	0.10	2.78	1.76	2.83	13.37	21.0



Table 15 (based on mid-1970 flows) presents the system response matrix in an alternative way by multiplying each column by the actual measured loadings. In this case, each row in the matrix represents a breakdown of what every segment contributes to the phosphorus concentration of every other segment. This can be demonstrated by the response row for Eastern Erie, where it can be seen that a large portion (6.26  $\mu\text{g/L}$  or 36 percent) of its phosphorus concentration of 17.2  $\mu\text{g/L}$  is due to the loadings to Western Erie.

### Discussion

By demonstrating that the segments of the Great Lakes cannot be considered as isolated entities, the foregoing analysis shows that Great Lakes eutrophication should be approached from a system's perspective. A further advantage of the "systems" approach is that it can form the basis of an economic optimization of the phosphorus reduction program for the basin.

To date, the eutrophication control program on the Great Lakes has been developed from more of a legalistic than economic perspective in that phosphorus reduction measures have been applied with a certain equanimity across the basin. For example, the present strategy limits the effluents of all major treatment plants to less than 1 mg/L. While such a strategy has legal or political advantages in its implementation (i.e., all wastewater treatment plants are "created equal"), it is suboptimal in a systems engineering sense. It does not consider the effectiveness (or benefits) to be achieved by the level of treatment in the various segments of the system nor does it optimize the effects on the Great Lakes for a given level of cost. In other words, money might be better spent on a non-uniform control strategy.

This can be demonstrated using Table 14 to contrast point source control for Lake Superior with that for Lake Erie. The removal of 500 mta from the Lake Superior load would result in only a 0.6  $\mu\text{g/L}$  improvement in its own concentration (although some local or nearshore improvement could occur) with minimal benefit to the rest of the Great Lakes system. Removal of the same amount from Western Lake Erie, on the other hand, would result in improvements of 1.8, 0.5 and 0.3  $\mu\text{g/L}$  to the Western, Central and Eastern Basins, respectively, as well as a 0.1  $\mu\text{g/L}$  improvement in Lake Ontario. Additionally, the cost of the removal would be different in each basin and it also might be considered more beneficial to improve the degraded, highly populated Lower Great Lakes than to spend money removing nutrients from unfertile Lake Superior.

With regard to the Lower Great Lakes, it is clear that they receive a large phosphorus input relative to their size compared to the other Great Lakes. Western Lake Erie in particular receives a large phosphorus input. Thus, it is not surprising that Lake Erie is the most eutrophic of the Great Lakes and has the highest phosphorus concentrations. However, the amount of reduction in loading that can be practically achieved is also greater for Lake Erie. For example, limiting Detroit River municipal point sources to the 1 mg/L P level will reduce the phosphorus delivered to the western basin by several thousand metric tons. As discussed above, this would have a measureable effect not only on the rest of Lake Erie, but also on Lake Ontario.



While the present model would be a somewhat crude basis for a detailed cost-benefit analysis, it does show how mathematical models can be used in such an analysis as a link between the causes and effects of water quality control programs. Hopefully, future management of Great Lakes water quality will adopt a similar perspective as it becomes increasingly apparent that environmental needs must vie with other societal priorities (such as energy, education and health care) for limited public funds.

## RESPONSE TIMES

### Phosphorus

Although the previous discussion of the total phosphorus budget model does not explicitly consider response times, the time of response to smaller phosphorus loadings is extremely important. Further, it is important to understand that a decreased phosphorus loading to an upper lake segment will have a delayed effect on a downstream lake segment. Currently, work is continuing to generate a matrix of response times for the system (i.e., the time to reach a certain percent of the new steady state in any segment of the system due to a step decrease in loading in any other segment).

While response times of intersegment reactions to phosphorus input reductions have not yet been computed, estimates are available on the response time of individual lakes (Sonzogni et al., 1978a).

These estimates of response times, reflective of current information, are much more optimistic than previous estimates which called for relatively slow improvement of the lakes following phosphorus control. The response times for Saginaw Bay and Lake Erie are now estimated to be in the order of one to two years or less. The response time for Lake Ontario is estimated to be about six to seven years. The response time for Lake Superior is estimated to be about 15 to 20 years, while Lakes Michigan and Huron are thought to have response times of about five years. Thus, it appears that phosphorus controls may have a rapid effect despite the size of the lakes.

While such predictions are optimistic, it must be again remembered that the current phosphorus models do not consider the availability of total phosphorus inputs. Disproportionate control of available versus nonavailable phosphorus inputs may cause lake recovery to differ from what might be predicted from the change in total phosphorus loads alone. More work is needed on understanding and modeling the biological availability of phosphorus inputs to the Great Lakes.

### Toxic Substances

Of the toxic substances which have found their way into the Great Lakes, the insecticide DDT, and the fire retardant PCB, are perhaps the best known and most studied. Both chemicals have seriously contaminated organisms in the Great Lakes system. Great Lakes fish have been particularly affected and, in some cases, accumulation of the substances in the fishes has led to their being unfit for regular human consumption.



Although firm actions have been taken to reduce or prevent further inputs of DDT and PCBs into the Great Lakes, a major question facing planners and managers is how long dangerously high contamination levels will persist. Many have thought that recovery would be extremely slow due to the stability of these contaminants. However, recent evidence points to the possibility of a more rapid recovery. Much of this expectation is based on the considerable decrease in the levels of DDT found in Great Lakes fish. This new data, based on a monitoring program that has been carried out since a ban was placed on the use of the pesticide in the basin, indicates DDT should disappear completely from fish in the lakes in 25 years or less (Bierman and Swain, 1978). Previous scientific estimates ranged up to 100 years. Permanent trapping of DDT in the bottom sediments appears to be the mechanism which accounts for the loss from fish.

The rapid disappearance of DDT has also sparked some optimism for rapid removal of at least some of the PCBs in Great Lakes fishes. Based on research conducted at the University of Wisconsin (Weininger, 1978), it is estimated that about 80 percent of the PCBs in fish could be permanently lost to bottom sediments in a matter of years. The other 20 percent will probably remain in the system for a long time due to constant recycling from sediments.

The PCB problem is complicated by the fact that, although major controls have been placed on PCB use, considerable quantities are still finding their way into the lakes. Nevertheless, the fact that a good portion of the PCBs in the system may disappear rather quickly once sources are eliminated or reduced provides a good deal of hope for the future.



## SUMMARY AND EVALUATION OF U.S. TASK D, PLUARG

In the detailed PLUARG study plan (International Joint Commission, 1974), Task D is defined as "diagnosis of the degree of impairment of water quality in the Great Lakes, including an assessment of contaminants contained in sediments, in fish, and in other aquatic resources." It states further that "Task D is devoted to the boundary waters, their effect upon water quality and their significance in these waters in the future and under alternative management schemes." Consequently, a separate study plan was developed for U.S. Task D (International Joint Commission, 1976c) to put a perspective on these questions and to answer them to the extent possible, based upon available information developed in the Task D study or elsewhere.

The degree of impairment of water quality in the Great Lakes is not only a function of nonpoint pollution derived from land sources, but is the result of all types of pollution loadings, including municipal and industrial inputs, atmospheric sources, shore erosion, and internal loadings. Since all sources of pollution combine to contribute to the impairment of water quality in the lakes, it is often difficult to separate out the individual effects of the pollution sources. However, it is possible to look at the comparative loadings of all sources and to evaluate the relative importance of each source on Great Lakes water quality. The emphasis of the U.S. Task D effort was to look at all sources of pollutants in order to determine the relative importance of nonpoint source loadings to the lakes. This chapter attempts to summarize and integrate the results of the U.S. Task D activities and in so doing determine, to the extent possible, the relative significance to the Great Lakes of pollution from land drainage.

Pollution from land sources is principally of the diffuse type; not concentrated at any one point. For example, fish are mobile and can pick up contamination from many different locations within the Great Lakes. Despite the inherent difficulties, a number of studies within Task D and elsewhere have attempted to assess the degree of contamination of fish, sediments, and other Great Lakes aquatic resources. But a definitive answer as to how and to what extent Great Lakes water quality has been degraded due to land-derived pollutants (one of the charges to Task D) is not possible at this time. The International Joint Commission has been trying to answer questions such as these since its inception in 1909.

U.S. Task D was divided into three major activities. The first activity was designed to answer the question of whether shore erosion is a significant pollutant source to the lakes. In order to do this, estimates of the quantity of shoreline erosion were made for the entire U.S. shoreline. In addition,



estimates were made of the loadings of the total amounts as well as the biologically available amounts of chemicals associated with the eroded shoreline material.

The second major activity of U.S. Task D was designed to determine the tributary loading to the Great Lakes as measured from river mouth stations. This was accomplished by first assessing the data available on the U.S. side and then calculating river mouth loadings from the available data. In order to determine the input from land drainage, the point source component was determined and the nonpoint source input estimated by difference (total loading minus point source loading). This part of the study was also designed to answer the extremely important question of what percent of the total tributary loading of pollutants, particularly those associated with suspended sediment, are likely to be (or become) biologically available in the Great Lakes.

The third major activity of Task D dealt with how river inputs derived from land drainage affect the lakes. Remote sensing data was utilized along with ground truth information to determine the impact that Great Lakes tributaries have on the lakes as a result of spring runoff events. In addition, the dispersion of pollutants derived from runoff was also investigated. In order to determine the importance of land-derived pollutants, particularly in the case of suspended material, comparisons were made of the impact from resuspension of bottom sediments in the lakes. Again, it is important to know the relative impact of nonpoint sources compared to other influences or factors affecting Great Lakes water quality in order to determine the proper significance of land-derived sources. Another aspect of this part of the study was to determine if Great Lakes organisms below tributary outfalls are measurably affected by nonpoint source inputs, such as would occur during periods of high flow. Finally, the last part of this activity (and the subject of this report) is the integration of all aspects of Task D in order to determine the likely impairment of water quality resulting from land drainage.

#### SHORELINE EROSION

The PLUARG study was probably the first major effort to consider the impact of shore erosion on the water quality of the Great Lakes. Shore erosion was not only investigated as a source of sediment pollution, but also as a potential source of contaminants, such as phosphorus, which are associated with the eroded shoreline material.

#### Shoreline Erosion Sediment Input

Shoreline erosion loading of sediment to the Great Lakes from the U.S. shoreline is estimated to be about 40 million metric tons for an average year (Monteith and Sonzogni, 1976). Since erosion is intensified as a result of high lake levels, loadings during the recent period of high lake levels may be significantly higher--as much as 70 million metric tons per year. In general, estimating loadings during periods of maximum erosion were found to be four to six times greater than the minimum erosion rate which occurs during low water periods, and about twice as great as the rate under average erosion conditions.



The input of sediment from U.S. shoreline erosion is high relative to other sources, especially for the upper lakes. Considering only the fine-grained portion of the shoreline sediment input (the coarse-grained material is likely to settle rapidly with little ecological effect), the load is considerable. The lower lake shoreline erosion input also becomes more important when the Canadian shoreline load is considered. For example, Thomas and Haras (1979) report that Canadian shoreline erosion contributes approximately 9,000 to 14,000 metric tons of sediment per year to Lake Erie. Over 20 percent of this Canadian input was reported to be fine-grained (clay sized). Consequently, it is clear that shoreline erosion is a major, and in some cases the major, source of sediment to the Great Lakes, even when only the ecologically important fine-grained fraction is considered.

The amount of sediment contributed to the Great Lakes by shore erosion varies widely from one shoreline county to another. Leelanau County, Michigan (on Lake Michigan), contributes the largest total amount of sediment via U.S. shoreline erosion. Bayfield County, Wisconsin (on Lake Superior), contributes the next largest amount. In terms of loading per kilometer of U.S. shoreline, Allegan County, Michigan (which borders Lake Michigan), has the highest loading rate. Canadian researchers (Thomas and Haras, 1979) reported 80 percent of the total sediment loading to Lake Erie from Canadian shoreline erosion was contributed by one reach from Rondeau to Long Point (roughly one-third of the Canadian shoreline). On a lake basis for the U.S. side, Lake Michigan shorelines have the highest erosion rate per kilometer of shoreline, followed by Superior, Erie, Ontario, and Huron, respectively. Lake Michigan shorelines were found to have the highest percentage of sandy soils, while U.S. Lake Superior shorelines were found to have the highest percentage of loamy and clayey soils. Consequently, the quantity and quality of eroded material is not equally distributed along the shoreline.

The relative importance of shoreline erosion as a source of sediment is further illustrated by Table 16. As shown, shoreline erosion on a total Great Lakes basis contributes almost five times as much total sediment as the tributary input. Thus, shoreline erosion, at least in terms of bulk quantity, is a considerably greater source of sediment than the combined input of sheet and gully erosion, streambank erosion, point sources and wind erosion. The importance of wind erosion as a source of particulate matter deserves further study, however.

#### Water Quality Effects

Because of the large amount of sediment contributed to the Great Lakes from shoreline erosion, some effects on water quality are likely to occur, although little direct documentation of effects was found. Principal physical effects of eroded material are likely related to problems associated with turbidity and sediment accumulation. Turbidity would be most important in areas where the shoreline soils consist of finely divided particles such as in clay soils. In areas where the shoreline consists mostly of sand, the effect of turbidity may be relatively small since coarse-grained sand particles settle rapidly. In general, shoreline erosion probably contributes larger sized soil particles to the lakes than sheet erosion which would likely contribute fine-sized particles.



TABLE 16

COMPARISON OF SEDIMENT INPUT FROM SHORELINE EROSION WITH INPUT FROM TRIBUTARIES<sup>a</sup>

<u>Lake</u>	<u>10<sup>3</sup> metric tons/yr.</u>	
	<u>Total Tributary (1976)</u> <u>(suspended sediment)</u>	<u>Shoreline</u> <u>Erosion.</u>
Superior (U.S. only)	1,400	11,300
Michigan	700	21,800
Huron	1,100	1,800
Erie	6,500	11,100
Ontario	1,600	3,200
TOTAL	11,300	49,200

a. Adapted from PLUARG, 1978.



Further, the more exposed and biologically active surface soils are removed in sheet erosion, while in shore erosion the entire profile is eroded.

Because of the large volume of material eroded from the bluffs along the U.S. Great Lakes shoreline, the loadings of the total forms of various chemicals associated with the eroded material is relatively high, at least for certain parameters. Undoubtedly, a large percentage of the chemicals associated with the eroded shoreline material is rapidly lost to the lake sediments and does not interact to any degree with lake waters. Further, the uptake by the eroded particulate material of constituents dissolved in lake waters, such as phosphorus or heavy metals, could be just as important environmentally as the release of contaminants.

Phosphorus. Because of the large volume of material contributed to the Great Lakes by shoreline erosion, the loadings of total phosphorus associated with the shoreline material is high. However, the potentially biologically available fraction of phosphorus appears to be small relative to the total. Based on data from U.S. Task D studies (Armstrong *et al.*, 1979), the available phosphorus associated with recessional shoreline samples ranged from one to eleven percent of the total phosphorus. Thomas and Haras (1979) reported the available phosphorus fraction of the Lakes Huron, Erie, and Ontario shoreline erosion phosphorus load to be considerably higher, ranging from about 10 to 40 percent. Despite this relatively high fraction of available phosphorus, Thomas and Haras concluded that the available phosphorus from shoreline erosion represents only a small portion of the combined load of total phosphorus from other sources.

Although most investigators discount shoreline erosion as a source of phosphorus, a closer look at the data indicates it deserves more attention. Table 17 compares the estimated available phosphorus shoreline erosion with other sources. Note that, compared to the total phosphorus loads from all sources (except shoreline erosion), the available phosphorus shoreline erosion load is small. However, if current loads are reduced to meet target loads, for example, the relative importance of shoreline erosion increases. Also, if the available portion of the total phosphorus load from the different sources were considered, the shoreline erosion load would be more significant. Assuming 40 percent of the diffuse tributary phosphorus load is available, the shoreline erosion available phosphorus load takes on new meaning (Table 17). In fact, Canadian shoreline erosion is shown to be a larger source of available phosphorus than Canadian diffuse tributary inputs. If the available phosphorus component of the atmospheric or point source load were estimated (or better known), the relative significance of the shoreline erosion phosphorus load could be even better assessed.

Since the shoreline erosion sediment input is not evenly distributed, localized shoreline erosion phosphorus inputs may be relatively important to the mass balance of inputs, especially where other sources are small. For example, the available phosphorus loading to Lake Superior from U.S. shore erosion is estimated to be in the same range as the reactive phosphorus contributed annually by both U.S. and Canadian tributaries to Lake Superior (Monteith and Sonzogni, 1976). Recently, Bahnick *et al.* (1978) reported that indeed the shoreline erosion contribution of phosphorus, at least to the southwest portion of Lake Superior, is probably significant.



TABLE 17

IMPORTANCE OF SHORELINE EROSION AVAILABLE PHOSPHORUS INPUTS  
 RELATIVE TO OTHER INPUTS FOR LAKE ERIE  
 (based on mid-1970 data)  
 MT/YR

	Total Phosphorus Load from all sources not including shoreline erosion	Total Phosphorus Target Load not including shoreline erosion	Total Phosphorus Diffuse Tributary Load	Estimated Available Phosphorus Tributary Load <sup>c</sup>	Available Phosphorus from Shoreline Erosion
Canada	--	--	2,300	920	1,350 <sup>a</sup>
U.S.	--	--	6,700	2,680	50 <sup>b</sup>
Total	18,150	11,000	9,000	3,600	1,400

- a. Based on erosion during high water years of 1972 and 1973, non-apatite phosphorus is assumed to be available; Thomas and Haras, 1979.
- b. Assume 5 percent of U.S. shoreline erosion total phosphorus load in available form.
- c. Assume 40 percent of the total phosphorus diffuse tributary load is available.



Other Parameters. The estimated nitrogen loadings to the Great Lakes from shoreline erosion were judged to be small relative to nitrogen loadings from other sources. Organic carbon loadings were estimated, but no conclusions could be reached from the data. Silica was not measured in this study, but because silica is a major component of soils, particularly sandy soils, the total contribution would be expected to be relatively large. The fraction of this silica that becomes available for diatom growth is unknown, however.

In general, metals associated with eroded shore materials were not judged to be important as a source of pollutants to the Great Lakes. While levels of the total forms of some metals may be significant relative to other sources, the amount of the total metal that is available to biota is probably low. Anthropogenic sources of metals have undoubtedly a much more important influence on Great Lakes water quality. Highest loadings of metals would probably be found in areas of shoreline with high clay content, such as the red clay area of the Lake Superior coastline. Total loadings of iron and manganese appear to be significant relative to estimated total tributary loadings for Lake Huron and Lake Superior, but the ecological significance is not known. Overall, shoreline erosion inputs of sediment and phosphorus, and possibly silica, are probably of most importance ecologically.

#### Overall Impact

The shore erosion process has been occurring for thousands of years along the Great Lakes, and loadings from shoreline erosion must be considered a natural occurrence and not man-derived. Undoubtedly, large percentages of chemicals associated with the eroded shoreline material are rapidly lost to the lake sediments and do not interact to any degree with lake waters. Further, in some cases the eroded particulate material may actually remove dissolved constituents, such as phosphorus or heavy metals, from lake water through sorption or ion exchange processes. Nevertheless, shore erosion can contribute to turbidity, sedimentation and, in the case of phosphorus, can measurably contribute to the available phosphorus input. Thus, despite the fact that shore erosion is a natural process, it is important to understand its impact so that the significance of other land-derived sources of pollutants, such as runoff, can be put in proper perspective.

#### TRIBUTARY LOADING

Activity 2 of the U.S. Task D study concentrated mostly on defining the U.S. tributary input to the Great Lakes. The relative importance of point versus nonpoint sources, as well as the biological availability of the parameters, was emphasized.

#### Estimation of Tributary Loads

In determining tributary loads it is extremely important to demarcate watershed boundaries consistently. On the U.S. side, the Great Lakes basin was divided into 15 river basin groups (Hall *et al.*, 1976). These river basin groups were then subdivided into smaller hydrologic areas consisting of a single large river basin or a complex of small river basins. Their hierarchy generally followed the one developed as part of the Great Lakes Basin Framework study. Such an



organization formed the basis for all tributary loading work, since without consistent watershed boundaries meaningful and comparable loading data cannot be developed.

River mouth sampling data from 550 tributaries to the Great Lakes were identified. Data considered included soluble and particulate nutrients, pesticides, heavy metals, and refractory organics (i.e., persistent organics, such as PCBs, not normally classified as pesticides), water discharge and sediment.

Approximately 30 percent of the tributaries considered were found to have sufficient water quality data to calculate annual loadings. About 14 percent of these tributaries were gaged at a representative river mouth gaging station; however, this represents a gaged area of 65 percent of the total U.S. drainage area. Of the 550 tributaries identified, 102 were considered to be major tributaries, the remaining being relatively minor streams that individually are not likely to have a major influence on the Great Lakes (except for possible local effects).

In general, there is a good water quality data record for Great Lakes tributaries from the standpoint of monthly monitoring. However, flow data generally lag behind water quality data in terms of the number of tributaries adequately monitored. Also, the information that is available on many tributaries can lead to an underestimation of total loadings of at least some parameters due to the lack of data during high flow periods, when a large portion of the total annual loading can occur. Very few streams were found to have data available specifically for runoff events.

Few data were found for heavy metals, pesticides, and refractory organics from which loading calculations could be made. Most data on these parameters are based on grab-type samples. A number of tributaries were also found to be deficient in dissolved reactive phosphorus data. In general, however, key loading parameters, such as suspended solids, nitrogen species, total phosphorus, and chloride, have been routinely monitored in most sampling programs.

As a result of Task D's investigation of available data, it was decided that additional monitoring should be carried out on a representative tributary. The Grand River, due to its importance to Lake Michigan and its watershed characteristics, was chosen for additional study. Daily samples were collected and analyzed for over a year, providing one of the best data sets on tributary inputs to the Great Lakes. Unfortunately, a report was never prepared specifically on this monitoring program. However, the data has been used extensively in the Task D, as well as the overall PLUARG, analysis.

The Grand River proved to be an excellent choice for additional study since it provided a contrast to tributaries draining Lake Erie, which also have been extensively studied. Based on the Grand River investigation, the concept of event versus stable response tributaries was developed. "Stable response" tributaries are not dominated by runoff events as are event response tributaries, since their concentrations of materials do not vary greatly with the tributary flow and because their flow is less erratic. Stable response tributaries, such as the Grand River and many other eastern Lake Michigan tributaries, tend to have



relatively small annual diffuse river mouth unit area loads. Event response tributaries, e.g., many of the Lake Erie tributaries, tend to have high annual diffuse river mouth unit area loads for phosphorus and suspended solids. Although many factors influence whether a stream fits either an event response or stable response classification, the type of soil in the watershed is perhaps the most important factor. Event response tributaries tend to drain watersheds whose soils have a high proportion of fine-grained clay particles, while stable response tributaries have watersheds with relatively coarse-grained, sandy soils.

A major accomplishment of U.S. Task D was the estimation of annual tributary loads. Loads were estimated not only for total phosphorus, but also for soluble ortho phosphorus, suspended solids, total nitrogen, nitrate nitrogen, ammonia nitrogen, and chloride. Loads were calculated for water years 1975 and 1976. All loads for monitored tributaries were calculated using the ratio-estimator calculation method except for Lake Erie tributary loads which were obtained from the Lake Erie Wastewater Management study. In order to provide complete coverage of the basin, loads from unmonitored watersheds were estimated from unit area loads determined from similar and usually adjacent monitored watersheds.

The tributary loading estimates developed in U.S. Task D served as the basis for the U.S. PLUARG loading estimates (PLUARG, 1978) as well as the "overview modeling" work (Johnson *et al.*, 1978). The Task D tributary loads have thus contributed heavily to the loading objectives currently proposed in the 1978 U.S.-Canadian Water Quality Agreement. Phosphorus tributary loading estimates have been compared, summarized and put in perspective relative to other sources earlier in this report.

One of the original objectives of U.S. Task D was to determine how land use combines with other factors to affect water quality. While this was not dealt with as a separate project during the Task D effort, the importance of factors other than land use, notably soil texture, evolved from the Task D study as well as other PLUARG studies. This was one of the most significant conclusions of the Task D effort and PLUARG as a whole.

#### FACTORS AFFECTING POLLUTION FROM LAND

The most important land-related factors affecting the magnitude of pollution from land use activities in the Great Lakes basin were found to be land form (the natural physical and chemical characteristics of the land, such as soil texture), land use intensity (e.g., the intensity in which a land is farmed), and materials usage (e.g., manure application). A knowledge of these factors and how they affect nonpoint source pollution is fundamental. While it was obvious before the Task D study that certain land uses within the same region generally contributed more pollutants than others per given area, the reasons for differences among sites of the same land use were unclear. Since given land uses often follow land form characteristics, such as soil and geological patterns, many past studies have mistakenly identified land use as the cause of nonpoint source problems when, in fact, other characteristics, such as land form, were the cause. A major conclusion of the study was that land factors such as land form must be considered along with land use when evaluating a land area as a nonpoint source.



From an overall perspective the single most important indicator of high unit area loads was found to be land form, particularly soil texture (soil particle size). Overland runoff is more prevalent on fine-grained soils than coarse, sandy soils since sandy soils tend to have higher water infiltration rates. Clay soils generally have more associated pollutants due to their chemical and physical characteristics. Clay-sized particles are easily suspended but usually settle very slowly, so the probability of transport over the land and down the river is high. Those sections of the Great Lakes basin which have sandy soils (e.g., upper Lake Michigan basin) have relatively good water quality, while those with clayey soils (e.g., Lake Erie basin) tend to have poorer water quality.

The relationship between soil texture and water quality has also been discussed extensively in a previous chapter: "Land Factors Influencing Pollutant Loads." Maps showing the textural distribution of soils in the Great Lakes basin have been included. This information forms the basis for the important PLUARG conclusion that across-the-board measures for nonpoint source pollution control is not warranted, and that specific action needs to be taken only in those areas where a problem can be expected, notably those with fine-grained surface soils.

#### Biological Availability of Pollutants

The question of biological availability was of paramount importance to the Task D study. Despite the fact that total forms of pollutants such as phosphorus and metals are useful parameters for assessing water quality, knowledge of the biologically available fraction is needed. Knowledge of biologically available forms is particularly important when considering control strategies. Control of a source that is highly available will have more impact than controlling a source from which the pollutant has low biological availability.

At the present time only a limited amount is known concerning biological availability of different pollutants. Part of the phosphorus associated with any soil particle may be chemically or physically bound to the particle in such a way that it cannot be used by aquatic plants in the growth process. The availability undoubtedly varies widely from season to season and from stream to stream. The availability also depends on the chemical and biological nature of the receiving water. For example, anoxic conditions, such as found in the central basin of Lake Erie, would cause additional pollutants to be released from sediment transported there. Also, some pollutants associated with sediment may not be immediately available, but available forms can be released gradually over time.

Despite the complexity of the availability questions, certain general observations can be made based on Task D and other work. Overall, it appears that a rather large percentage of the pollutants associated with sediments delivered to the Great Lakes is not biologically available, both over the long and short term. Since river mouth loads are an integration of pollutants derived from various sources, and the pollutants are subject to exchange or equilibrium reactions between dissolved and solid phases prior to reaching the river mouth, the ultimate source or origin of the available versus non-available sediment associated pollutants is unclear.



Phosphorus. Based on studies of a limited number of rivers in the Great Lakes basin during runoff events (Armstrong et al., 1979; Logan et al., 1979), 40 percent or less of the suspended sediment phosphorus was estimated to be in a "biologically available" form. For many rivers the "available" fraction of the phosphorus associated with the suspended solids is probably considerably less than 40 percent.

Based on river mouth data, the soluble phosphorus fraction contributed to the lakes is roughly 25 percent of the total phosphorus load. This percentage can vary considerably from year to year and from stream to stream; event response tributaries will generally have a lower percentage of soluble phosphorus than stable response tributaries. The remaining 75 percent is principally particulate phosphorus. The soluble phosphorus fraction is essentially all readily available. However, given the limited availability of the particulate phosphorus which comprises the bulk of the total phosphorus load from tributaries, it appears that 40 to 50 percent or more of the total phosphorus load contributed by tributaries is unavailable for plant growth. Since a significant portion of the soluble phosphorus load (and the readily available particulate phosphorus) is likely tied to point sources, particularly for some of the Great Lakes, a considerable fraction of the diffuse source total phosphorus load must be biologically un-available.

The Task D availability studies were complemented by similar work conducted for the Lake Erie Wastewater Management Study (Logan et al., 1979). The Lake Erie study results indicated that biologically available phosphorus, as measured by NaOH extraction, was on the order of 14-40 percent of the total inorganic sediment phosphorus in sediments. Sediments from tributaries in New York State had about half as much available phosphorus as sediments from Michigan and Ohio tributaries (on a percent of total inorganic phosphorus basis).

Logan et al. (1979) concluded that the available phosphorus associated with suspended sediment reflects the chemical and biological reactivity of native soil phosphorus in basin soils, fertilizer additions, possible phosphorus enrichment because of preferential clay transport and the uptake of soluble phosphorus contributed by point sources. They indicated the higher percent biologically available phosphorus in the western portion of the Lake Erie basin reflects the high clay content of the soils in the watershed.

Logan et al. (1979) also indicate that fertilizer addition over the last 40 years has not increased the total phosphorus content of the soil to any significant degree (no more than 10 percent). However, the available phosphorus fraction has increased in fertilized soils (although the extent of the increase is not clear). This may be the result of overfertilizing the soil. That is, it may be due to applying phosphorus fertilizer in excess of what is required for optimum plant growth.

The sodium hydroxide (NaOH) extraction technique (see Armstrong et al., 1979, for details) is a widely used indicator of short-term biologically available sediment phosphorus. It contains the most exchangeable (labile) phosphorus which is mainly associated with the Fe and Al hydrous oxides. It has also been correlated with the fraction of sediment phosphorus available for algal uptake as



measured by bioassay techniques (Sagher *et al.*, 1975). The NaOH extractable phosphorus closely corresponds to non-apatite inorganic phosphorus, which is often cited as the available phosphorus fraction.

Despite its usefulness, Armstrong *et al.* indicated the NaOH extraction was probably a measure of the maximum available inorganic phosphorus content of the sediment, at least over the short term. Available phosphorus as measured by an anion exchange resin method, which removes part of the NaOH extractable phosphorus, was interpreted to represent more readily available phosphorus. Phosphorus measured by the anion exchange method was generally about 50 percent of the NaOH fraction. Only at very low solution phosphorus concentrations ( $< 1\mu\text{g/L P}$ ) does it appear that all of the NaOH-fraction could be available. Thus, as indicated by Armstrong *et al.*, the availability of sediment phosphorus transported to the Great Lakes via tributaries is likely considerably less than even the NaOH fraction. Consequently, the readily available phosphorus is probably considerably less than 40 percent of the tributary suspended sediment total phosphorus.

Logan *et al.* (1979) also concluded that NaOH extractable phosphorus is only a measure of the potentially available phosphorus. However, this conclusion was based on bioassay tests (Logan *et al.*, 1979), which indicated that the rate of phosphorus removal from sediment by algae may limit biological uptake. They deduced that exchange kinetics may, in fact, be more limiting than the amount of available phosphorus associated with suspended sediment. Due to experimental difficulties with kinetic studies of algal uptake of phosphorus, this research area needs further evaluation. Nevertheless, possible kinetic limitations are another reason to expect the available fraction of phosphorus associated with suspended sediment to be quite low.

Metals. Limited studies on suspended solids from Great Lakes tributaries indicate that 20 to 70 percent of the particulate metals, such as copper, zinc and lead, were estimated to be in an "available" form. The percent available varies considerably, depending on the river system, size fraction and specific metal. In most cases it would appear that metal availability is less than 50 percent of the total particulate metal.

#### EFFECT OF RIVER INPUTS ON THE GREAT LAKES

The extent of dispersion in the Great Lakes of particulate and soluble material contributed by tributaries, particularly during high flow conditions, and the effect of land-derived pollutant material on the water quality of the lake offshore of the river mouths was a major focus of U.S. Task D. In order to help address the above questions, a pilot study was initiated to determine the dispersion and fate of selected Maumee River pollutants in Lake Erie utilizing a combination of shipboard water quality measurements and high altitude remote sensing measurements. This study successfully provided useful information on the effects of river loadings under non-event conditions and on the dispersal of the tributary-derived pollutants. In addition, an experimental program utilizing the transmission of remotely sensed data to surface vessels to aid in planning strategic vessel sampling locations was found to be very beneficial to the overall program. The aircraft imagery was also very useful for extrapolating shipboard measurements over a large area.



Because of the general success of the pilot study on the Maumee River and Lake Erie, similar studies were designed for the river mouth areas of four other U.S. tributaries. These tributaries included the Genesee River in New York, the Grand River in Michigan, the Menomonee River in Wisconsin, and the Nemadji River in Wisconsin. In addition, a more detailed continuation study of the Maumee River in Ohio was conducted.

The objectives of each river mouth study were as follows:

1. Survey the quality of water offshore of a river mouth following a runoff event such as occurs during the spring thaw. Contaminants considered included suspended sediment, nutrients and some toxic substances.
2. Identify general distribution patterns and transport mechanisms of contaminants contributed by the river, particularly those contaminants thought to be derived from land drainage.
3. Determine whether resuspension of sedimented materials is likely to be significant relative to the tributary input of suspended material in the near-shore area of the river under study.
4. Assess the general impact of wind-induced resuspension of suspended material on the water quality of the area under study.
5. Assess the general impact of the tributary loading to the lake under event conditions.

Importantly, essentially no data existed on river mouth water quality during the spring runoff, much less on the effect of the event on the lake. Since during the spring period a large percentage of the total land drainage load can be delivered to the lake, the study addressed perhaps the primary objective of PLUARG--namely, the assessment of the effect of land drainage on the Great Lakes.

The river mouth study results are summarized below under specific points relevant to Task D and PLUARG. The results of the five river mouth field studies (Sydor and Oman, 1977; Bannerman *et al.*, 1977; Eadie, 1976; Herdendorf and Zapotosky, 1977; Wyeth *et al.*, 1976), as well as the remote sensing counterpart to the field investigations (Raquet *et al.*, 1977), were used in developing the analysis below. The results of the Task D study on the frequency and extent of wind-induced resuspension of bottom material in U.S. Great Lakes nearshore waters (Chesters and Delfino, 1978) were also used in the analysis.

#### General Conclusions

Overall, the combination of ship surveys and remote sensing proved useful for determining the effect of river inputs on Great Lakes water quality. The study showed that the dispersal of pollutants and the effect on the lake by a particular tributary is very site dependent. However, the results of each of the studies showed that the tributary input was not the only factor affecting lake quality during the spring. Shoreline erosion and resuspension were also found to be important inputs, and in some situations were quantitatively more significant than the river input.



## Immediate Impact of Runoff Events on Great Lakes Water Quality

Despite the relatively detailed studies, very few immediate effects of the river input on the lake were directly established. This does not mean that the large land drainage input of material during the spring is not important, but that its effect is subtle and more long-term.

The Nemadji River study (Sydor and Oman, 1977) found that loads of 15 and 12 metric tons of total phosphorus and total organic nitrogen, respectively, were distributed over the lake three days after the peak spring river flow. Concentrations of total phosphorus and total organic nitrogen were much higher near the Nemadji river mouth than near the St. Louis river mouth, presumably the result of the high land-derived sediment contributed by the Nemadji. During certain wind conditions the Nemadji input is trapped in extreme western Lake Superior. This appears to be a major factor in the relative abundance of aquatic organisms in this area.

The Menomonee study indicated that the inner Milwaukee harbor, into which the Menomonee River as well as Milwaukee and Kinnickinnic Rivers discharge, did not show a major response to runoff events. Only suspended solid and total organic nitrogen concentrations showed an increase over non-event conditions. Further, the nearshore zone of Lake Michigan outside the harbor exhibited virtually no changes in concentrations of pollutants following runoff events. Based on the result of the event surveys, it was concluded that current patterns in the harbor (e.g., those caused by seiche effects) and harbor structures (a large breakwater exists between the outer harbor and the nearshore zone) played a major role in hindering transport of land-derived pollutants to the nearshore zone of Lake Michigan. In fact, it was estimated that 70 percent of the suspended solids discharged from the Menomonee River during runoff events was retained in the inner part of the harbor each year.

Despite high flows from the Grand River into Lake Michigan during the spring runoff period, no major effects were observed. Algal biostimulation, which could be attributed to the river input, was only observed on one cruise. It was estimated that about 25 percent of the 1976 annual loading of suspended material, nutrients and trace metals occur during the spring runoff period. This percent input for the stable response Grand River is probably relatively low compared to most event response tributaries. For example, 90 percent of the annual sediment load to Lake Erie from the Maumee River occurred during spring runoff in 1976. Chlorophyll levels in western Lake Erie were somewhat elevated during this spring runoff period according to the Maumee river mouth survey. Presumably this high algal production is related to the nutrient input from the Maumee, although no direct evidence exists.

### Dispersion of Pollutants Contributed by Runoff Events

The transport and dispersion of river inputs was closely investigated in each of the river mouth studies. Movement of the inputs in mass or as a plume appeared to be relatively limited except for the input of the Maumee to the western basin of Lake Erie. Here it was observed that resuspension tended to move solids contributed by the Maumee into the central basin over a several



month period. The plume from the Nemadji River during maximum spring discharge was observed approximately 30 miles into western Lake Superior. In general, however, the input from rivers during the spring runoff period tended to disperse with the rest of the lake rather quickly.

Wind direction was found to play an important role in dispersion of the pollutant input from the Nemadji River. Variable winds appear to trap pollutants associated with the runoff in the extreme western basin, while long fetch westerly winds tend to disperse the pollutants and purge the area. Sydor and Oman (1977) report that under average erosion conditions a patch of turbidity 1 km in diameter would disperse in about one week to background levels. Long fetch northeasterly winds which tend to produce high turbulence in western Lake Superior tend to cause currents which normally move easterly along the Wisconsin shore to reverse. Consequently, Nemadji runoff moves along the Minnesota shore and out to extreme western Lake Superior. Under other wind conditions, however, effluents from the Duluth-Superior area and the St. Louis River are transported toward the Wisconsin shore.

In the Menomonee study measurements indicated that the runoff event flow from the Menomonee, Milwaukee and Kinnickinnic Rivers did not significantly affect transport patterns. Rather, lake and harbor seiches seemed to be more significant. These seiches were found to cause an oscillation of flow between the river mouth area and the nearshore water outside the harbor. Consequently, pollutants tended to move out of the harbor in pulses. Apparently, the pollutants from the runoff had a long residence time in harbor, allowing many of the pollutants, particularly those associated with the particulate matter, to settle out in the harbor. The harbor thus appeared to serve as a trap for pollutants contributed during runoff. Only during exceptionally large flows could runoff-derived pollutants be expected to move outside the harbor into Lake Michigan proper.

Once in the nearshore area of Lake Michigan (outside the harbor), the dispersion of pollutants was found to be highly variable and dependent on wind conditions. There was also evidence that a subsurface plume can exist along the thermocline. Such a plume would not be readily detected through remote sensing.

The Grand River spring flow was also found to have a relatively minor effect on the transport of pollutants in Lake Michigan. In other words, the physical condition of the lake, such as whether it is stratified, the magnitude of the longshore current, and upwelling conditions appear to be much more important than river flow as a transport mechanism. The plume of the Grand thus dissipated very quickly and the river-borne materials were rapidly mixed into the lake.

The large spring input of sediment from the Maumee River was found to be initially deposited in the western basin. However, as mentioned previously, the material moves easterly into the central basin as a result of wind-induced mixing. Most of the sediment and associated pollutants which enter the lake during the early spring runoff period appear to be transported to the deeper portions of the western basin or to the central basin by late spring or early summer. It is significant that sediment is transported to the central basin,



since anoxic conditions there could cause a release of pollutants associated with the particulate material in an otherwise unavailable form.

In the Genesee river mouth study it was found that wind direction played a very significant role in the movement and dispersion of the river plume in Lake Ontario. Layering of the spring input on the surface due to the low density cold water input during the spring, which had been suggested, was not found. As was generally found in the other river mouth studies, river inputs become dispersed in the lakes relatively rapidly.

#### Transboundary Movement of Pollutants

The synoptic remote sensing coverage allowed a broad coverage of pollutant movement which would not have been possible otherwise. For example, using remote sensing images it was possible to trace the movement of solids from the western to the central basin of Lake Erie. It also provided information on areas other than the five river mouth areas specifically studied. For example, Lake St. Clair was observed to contribute large amounts of sediment to Lake Erie during certain times of the year. Also, a major sediment plume was observed flowing into Lake Ontario via the Niagara River and the Welland Canal. Apparently, a major source of this material was shoreline erosion along the Canadian Lake Erie coast. It is a good example of transboundary movement of land-derived pollutants, although the source appears to be natural and not a result of man-induced pollution.

#### Importance of Resuspension and Shoreline Erosion During the Spring Runoff Period

During the spring runoff period resuspension and shoreline erosion contribute major amounts of sediment to the Great Lakes. During the spring period some of the most intense storms occur, causing resuspension and shoreline erosion to compete with river sediment as a source of particulate and soluble materials to the lakes.

Remote sensing proved to be extremely valuable in identifying suspended solids levels over a large area. The fact that turbid waters were depicted in the imagery even though no significant river discharge was occurring clearly demonstrated the importance of resuspension and shoreline erosion. However, it was difficult to separate shoreline erosion from resuspension based on the remote sensing data, and in many cases the role of resuspension versus shoreline erosion could not be deciphered.

Of the five river mouth areas investigated, shoreline erosion appeared most predominant along the south shore of the western arm of Lake Superior. The sediment plume of the Nemadji River, while observable, was in fact dwarfed by the shoreline erosion input. Also, based on numerical modeling and remote sensing data, it is estimated that roughly 50 percent of fine particulates from the Nemadji River runoff which settle out in the nearshore zone are resuspended.

Resuspension and shoreline erosion are also seen to have a major effect relative to the Menomonee River, whose sediment discharge is mostly trapped in Milwaukee Harbor. High levels of suspended sediment were observed in the



nearshore waters adjacent to the Milwaukee Harbor during periods of no runoff, indicating resuspension and shoreline erosion are a major source of sediment to the lake. At the Genesee and Grand Rivers, shoreline erosion and resuspension are believed to be significant at certain times.

The importance of resuspension in shallow western Lake Erie has already been discussed. U.S. shore erosion did not appear to be significant, at least relative to resuspension. Most of the shore erosion inputs to Lake Erie arise from the Canadian shoreline.

#### Frequency and Extent of U.S. Nearshore Resuspension

Chesters and Delfino (1978) found that the magnitude of sediment resuspension is related closely to the occurrence of wind-generated waves strong enough to resuspend bottom sediments. Sediment type is also important as fine sediments (i.e., clayey sediments as found in the western basin of Lake Erie) are more easily suspended than more coarse-grained (i.e., sandy) sediments.

Based on the limited data available, it was estimated that the quantity of sediment resuspension per unit area in the Great Lakes varies in the order of: Superior>Michigan>Erie>Huron>Ontario (Chesters and Delfino, 1978). Calculated resuspension quantities did appear to be in the same order of magnitude as observed data.

The susceptibility of nearshore areas was also determined by Chesters and Delfino (1978) based on the annual frequency and quantity of sediment resuspension. In Lake Superior the western basin, including the Duluth-Superior area, and Whitefish Bay are particularly susceptible. The susceptible areas of Lake Michigan include the eastern and southern basin. Saginaw Bay and the St. Clair River are particularly susceptible portions of Lake Huron. In Lake Erie, the western basin is more susceptible than the central and eastern basins, even though the frequency of conditions conducive to resuspension is greater for the central and eastern basins. The eastern nearshore areas of Lake Ontario have the greatest resuspension potential.

Critical areas in the U.S. nearshore zone were also delineated by Chesters and Delfino (1978). These areas were Saginaw Bay, western Lake Erie, southern Lake Michigan and the Duluth-Superior and northern segments of Lake Superior. These critical areas are based on the quality of the sediments as well as the frequency of resuspension. Consequently, due to taconite tailing disposal and the associated asbestos problem, northern Lake Superior was considered a critical area even though the potential for resuspension is low. Further, resuspension frequency does not necessarily correspond with resuspension quantity.

It should be clear that resuspension of sedimented material is quantitatively very important in the Great Lakes. Sly (1977), for example, has emphasized that resuspension of particulates is far more significant quantitatively than the disposal of dredged materials. However, the significance to water quality of resuspension is not clear. Obviously, resuspension increases turbidity, but its effect on levels of phosphorus, heavy metals, organic toxicants, etc., is essentially unknown. For example, resuspension of bottom sediments could cause



soluble nutrients in interstitial waters to be reintroduced into the water column. Conversely, resuspended particulate material could scavenge soluble materials through sorption and thereby remove pollutants from the water column. Since it is now evident that resuspension is an important process in the Great Lakes, more work will have to be undertaken to determine its importance to the chemical and biological regime.

#### Effect of Toxics on Organisms in River Mouth Areas

In general, relatively little direct effect on organisms has been observed during or immediately following runoff events. This is particularly true for toxic substances, which are mostly derived from point sources rather than non-point sources (PLUARG, 1978; Suns et al., 1978). The literature on the effect, or possible effect, of contaminants derived from land runoff on organisms in the Great Lakes in the vicinity of river mouths has been reviewed extensively elsewhere in this report.

Jerger et al. (1978), in a study conducted for U.S. Task D, measured the levels of toxic pollutants in macroinvertebrates collected in the outfall areas of four U.S. tributaries. These tributaries included the Menomonee (Wisconsin), Grand (Michigan), Maumee (Ohio) and Vermillion (Ohio). Benthic macroinvertebrates were thought to provide a good indicator of the effect of tributary inputs since their mobility is restricted to the area of interest.

A large number of toxic contaminants were analyzed, even though not all of these contaminants were expected to be derived from land runoff. Table 18 presents results from this study (Jerger et al., 1978) as well as a similar Canadian study (Suns et al., 1978). Unfortunately, no quality control or statistical evaluation of the data was reported by Jerger et al. (1978), so it is difficult to analyze the results. It does appear that many values reported by Jerger et al. (1978) are much higher than reported by Suns et al. (1978) or in other studies of contaminant levels in organisms (Konasewich et al., 1978). For example, PCB levels in Jerger et al. are two to three orders of magnitude higher than normally reported in the literature. A concentration of PBB reported by Jerger et al. in Grand River benthic macroinvertebrates (0.01 mg/g; sample not shown in Table 18), was higher than the concentration found in many condemned cattle in the State of Michigan (Waybrant, 1978). The metal levels reported by Jerger et al. may also be high. While there is little data on metal accumulations in Great Lakes benthic organisms for comparison, concentrations reported in fish (Konasewich et al., 1978) tend to be one or more orders of magnitude lower than reported by Jerger et al. On the other hand, Jerger et al.'s values for benthic organisms are in the same range as metal values found in Great Lakes surficial sediments (Konasewich et al., 1978).

Jerger et al. (1978) also reported on an experiment whereby live-boxes containing freshwater clams were used to measure uptake of toxic contaminants near the mouth of the Vermillion River (Lake Erie). The only parameter that showed a large increase in concentration over the control was zinc. The significance of this increase is not clear, however.



TABLE 18

REPORTED HEAVY METAL AND ORGANOCHLORINE RESIDUES  
IN BENTHOS IN THE NEARSHORE BIOTA OF THE GREAT LAKES  
( $\mu\text{g/g}$ )

Parameter	Vermillion <sup>1</sup> River	Maumee <sup>1</sup> River	Grand <sup>1</sup> River	Menomonee <sup>1</sup> River	Oakville <sup>2</sup> River	Grand <sup>2</sup> River
Copper	8.9	23	18	9.4		
Cadmium	4.3	7.1	2.3	1.3		
Lead	10.0	11	19	31		
Zinc	89.0	84	162	126		
Arsenic	57.0	18	15	7.5		
Selenium	<1	2	2	<1		
Mercury	<0.1	<0.1	<0.1	0.8		
BHC	.17	0.02	.11	0.51	.007 $\pm$ .001	.006 $\pm$ .003
Heptachlor	<0.01	<0.01	0.01	<0.03	ND	ND
Dieldrin	0.14	0.06	0.07	0.06	.006 $\pm$ .001	.003 $\pm$ .001
Endrin	<0.03	<0.03	<0.04	0.03	ND	ND
p,p <sup>1</sup> DDD	0.03	0.16	0.09	0.34	.002 $\pm$ .001	--
Methoxychlor	0.07	0.04	0.11	<0.01		
Chlordane	<0.1	0.1	0.7	<0.1	.002 $\pm$ .001	<.001
PCB	14	12	9	43	.040 $\pm$ 8	.005 $\pm$ 6
PBB			<0.02			
Total Pthalate	45	28	64	3		

1. From Jerger *et al.* (1978); data predominantly from samples taken in river mouth area.

2. From Suns *et al.* (1978); samples taken upstream from river mouth.

ND. No Data Available.



While current pesticide use is not considered a threat to the Great Lakes, residues of formerly used pesticides, such as DDT and its derivatives, continue to move off the land and into the lakes. A recent evaluation of hazardous chemicals in Lake Ontario (Waller and Lee, 1979) shows that levels of DDT and its derivatives (dominant form was DDE) are about ten times higher than water quality objectives set by the U.S. Environmental Protection Agency (EPA) and the International Joint Commission (IJC). The objectives, which were set under the rationale that such levels could potentially result in bioaccumulation in fish and subsequently cause harm to humans and fish eating birds, actually approach or are below the current analytical detection level. Waller and Lee (1979) also point out that, despite the fact that total DDT levels in water were above the EPA and IJC objectives, concentrations in fish were generally below the 5 ppm limit set by the U.S. Food and Drug Administration for fish used for human consumption. The dominant form of the DDT group in Lake Ontario water and fish was DDE. Unfortunately, Jerger *et al.* reported no data for DDE, so the significance of their DDT group data cannot be determined.

Overall, due to lack of a comparative statistical evaluation of the data, it appears the data of Jerger *et al.* (1978) is questionable. Hence, it cannot be used with any confidence to assess organism contamination off Great Lakes river mouths. However, even with more reliable data, it is doubtful that specific effects of river inputs, and especially the nonpoint component, can be clearly established. Apparently, nonpoint inputs are diffuse not only because of their source, but also because of their effect on the lake. The Task D effort has shown that nonpoint inputs must be viewed cumulatively with other inputs to assess overall loads to the Great Lakes.

An interesting point with regard to toxic substance pollution of the Great Lakes is that sediment derived from nonpoint sources may help ameliorate the toxic substances problem. Large sediment input may help bind toxic pollutants and make them biologically unavailable or carry them to the sediment. Sediment input may also help dilute and "bury" toxic materials in lake sediment.

It is perhaps not coincidental that Lake Erie has the lowest PCB concentrations in fish (Konasewich *et al.*, 1978), yet receives by far the largest tributary sediment load. The ratio of tributary sediment input to lake volume is given in Table 19. Note Lake Erie receives over 100 times as much tributary sediment input as Lake Superior on a volumetric basis. While other factors are involved which apparently make Lake Erie less susceptible to PCB and toxic substances pollution relative to the other Great Lakes (e.g., productivity, sediment temperature, oxygen content, water residence time, particulate settling rate, the composition of the fishery), the sediment input is likely an important factor.

Data from Suns *et al.* (1978) show that organisms in the lower reaches of the Grand River (Canadian Lake Erie tributary) generally had lower contaminant levels than organisms in the lower reaches of Oakville Creek which drains into Lake Ontario. Yet no significant differences in dissolved contaminant levels were noted in the water from each river. The Grand River watershed is large, highly agriculturalized and contains several intense urban areas. It carries a relatively large sediment load. The Oakville Creek watershed is comparatively



TABLE 19

RATIO OF GREAT LAKES TRIBUTARY  
SUSPENDED SOLIDS LOAD<sup>a</sup> TO LAKE VOLUME

Lake	Tributary Suspended Solids Input (metric tons/yr)	Normalized to Lake Superior
	Lake Volume (km <sup>3</sup> )	
Superior	113	1.0
Michigan	144	1.3
Huron	298	2.6
Erie	13,523	119.7
Ontario	916	8.1

a. Tributary Suspended Solids Load from PLUARG, 1978 .



small and mostly rural. Its sediment load is relatively small. Thus, the lower toxic levels in the Grand River may be related to the different sediment loads.

The possibility that sediment load is related to toxic levels leads one to speculate on the effect that reducing sediment loads may have on toxic contaminant levels. Perhaps a reduction of land runoff will improve the trophic status of Lake Erie, but in turn cause the lake to suffer more severe toxic pollution problems. Clearly, the question is potentially a significant one, and deserves further attention.



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GREAT LAKES BASIN COMMISSION STAFF  
Ann Arbor, Michigan

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Section 1.1. The purpose of this report is to provide a comprehensive review of the literature on the impact of land use changes on water quality in the Great Lakes region.

Section 1.2. This report is organized into several chapters, each focusing on a different aspect of the problem. Chapter 2 discusses the sources of nonpoint source pollution, while Chapter 3 examines the effects of land use changes on water quality.

Section 1.3. The report is intended to provide a comprehensive review of the literature on the impact of land use changes on water quality in the Great Lakes region. It is hoped that this report will be useful to researchers and policymakers alike.

Section 1.4. The report is organized into several chapters, each focusing on a different aspect of the problem. Chapter 2 discusses the sources of nonpoint source pollution, while Chapter 3 examines the effects of land use changes on water quality.

Section 1.5. The report is intended to provide a comprehensive review of the literature on the impact of land use changes on water quality in the Great Lakes region. It is hoped that this report will be useful to researchers and policymakers alike.

## APPENDIX A

Section 1.6. The report is intended to provide a comprehensive review of the literature on the impact of land use changes on water quality in the Great Lakes region. It is hoped that this report will be useful to researchers and policymakers alike.

# A LITERATURE REVIEW ON THE IMPACT OF LAND DERIVED NONPOINT SOURCE POLLUTION ON THE GREAT LAKES

Section 1.7. The report is intended to provide a comprehensive review of the literature on the impact of land use changes on water quality in the Great Lakes region. It is hoped that this report will be useful to researchers and policymakers alike.

William J. Gburek  
Thomas J. Gburek  
William E. Gburek  
William M. Gburek  
Robert M. Gburek

GREAT LAKES WATER QUALITY CENTER  
The State University of New York at Buffalo



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## APPENDIX A

### SUMMARY AND CONCLUSIONS

1. Very little information exists in the literature which directly links land-derived pollution with impairment of Great Lakes waters. While many studies have alluded to land-derived pollution as a cause of degradation of Great Lakes water quality, it has been very difficult to separate the effects of nonpoint source pollution from point source pollution. Nevertheless, the indirect evidence is strong that nonpoint pollution does contribute significantly to the degradation of Great Lakes water quality.

2. Although the physical and biological effects of pollutants on plankton, benthos and fish are becoming better known, it is difficult to determine what percentage of the impairment results from nonpoint source pollution as opposed to point source pollution. Further, the biological availability of land-derived pollutants remains an incompletely answered question.

3. One of the clearest examples of specific land-derived impacts is the Cladophora accumulations in Lake Huron. Due to the low ambient nutrient concentrations in the lake, Cladophora flourishes only in specific areas which are enriched from local nonpoint or point pollution.

4. The amounts of solids removed by dredging from many Great Lakes river mouth areas were found to be comparable to the amount of suspended solids contributed annually by the rivers. Control of soil erosion upstream may thus have a significant benefit in terms of reducing the quantity of sedimented material that must be removed by dredging.

5. Sediment contributed by land runoff is often implicated in being deleterious to macrophytes, benthic organisms and fish in the Great Lakes, particularly Lake Erie. The effect of sediment is not easily separated from other environmental perturbations, however.

6. Despite often being implicated as harmful to the Great Lakes, few examples of Great Lakes impairment by road salt runoff exist. There is some speculation that subtle but derogatory changes in the species composition of phytoplankton in the Great Lakes may occur if chloride levels continue to increase.

7. Since silica may cause a shift in algal species towards the nonsiliceous forms, such as the undesirable blue-greens, the effect that nonpoint source control may have on reducing silica inputs to the Great Lakes should be considered.

8. Despite the potential harmful impact of lead, there is currently no evidence to indicate it is causing impairment of the Great Lakes resource.



## SUMMARY AND CONCLUSIONS

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The present study was designed to determine the effect of the treatment of Great Lakes water with activated carbon on the removal of organic matter and the subsequent effect on the growth of the bacterium *Micrococcus luteus*. The results of the study are summarized in Table I. It is concluded that the treatment of Great Lakes water with activated carbon results in a significant reduction in the amount of organic matter present in the water. This reduction in organic matter results in a corresponding reduction in the growth of *Micrococcus luteus* in the treated water. The results of this study indicate that the treatment of Great Lakes water with activated carbon is an effective method for reducing the amount of organic matter present in the water and for controlling the growth of *Micrococcus luteus*.

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The results of the present study are summarized in Table I. It is concluded that the treatment of Great Lakes water with activated carbon results in a significant reduction in the amount of organic matter present in the water. This reduction in organic matter results in a corresponding reduction in the growth of *Micrococcus luteus* in the treated water. The results of this study indicate that the treatment of Great Lakes water with activated carbon is an effective method for reducing the amount of organic matter present in the water and for controlling the growth of *Micrococcus luteus*.



## INTRODUCTION

The U.S. Task D portion of the International Joint Commission's Pollution from Land Use Activities Reference Group (PLUARG) aimed to assess how land derived runoff and its associated pollutants have affected the Great Lakes. To supplement the information gathered specifically for the Task D effort, a review of the current literature was conducted. The purpose of this review was to determine what evidence exists in the literature of impacts on the Great Lakes from land derived nonpoint source pollution. At the start of the review it was realized that direct observations of effects on the lakes would be very limited; nonetheless, it was felt to be important to establish just what is known or inferred about how nonpoint sources are affecting the Great Lakes.

The review concentrated on phosphorus and suspended solids, the two most prevalent pollutants derived from land drainage with a potential effect on the Great Lakes. Information was also sought on chloride, silica, and dissolved solids in general. Impacts associated with toxic substances, such as heavy metals, pesticides, and industrial organics, were also considered, but only cursorily, since these pollutants are not generally from nonpoint sources, according to recent PLUARG studies. Of the toxics, greatest attention was placed on those trace toxic substances derived from land runoff which have been a problem in the past (e.g., hard pesticides, such as DDT) or are a potential problem (e.g., lead from urban runoff).

Most of the literature reviewed was specifically related to the Great Lakes. Some papers on the effects of nonpoint source pollution on other lakes, particularly large lakes, were considered. While a very large number of references were reviewed, only those most representative of work being done in this area are discussed below. A complete file of all references reviewed is available at the Great Lakes Basin Commission headquarters. Annotated summaries of pertinent information regarding nonpoint source pollution are included in this reference file.

Effects on the total Great Lakes system and local effects (e.g., nearshore effects off a river mouth) were both sought during the review. Impacts sought were concentration changes and general water quality parameter changes, and effects on plankton, macrophytes, benthos and fish.



INTRODUCTION

The U.S. Food & Drug Administration (FDA) is pleased to announce the results of the first phase of the Great Lakes Water Quality Study (GLWQS). The purpose of this study was to determine what additional actions are needed to improve the water quality in the Great Lakes. At the start of the study it was realized that direct observation of water quality in the lakes would be very difficult. It was felt to be important to establish just what is known or believed about the nonpoint sources and other factors affecting the Great Lakes.

The review concentrated on phosphorus and suspended solids, the two most prevalent pollutants having the most dramatic and potential effect on the Great Lakes. Information was also sought on chlorides, nitrate, and dissolved solids in general. Reports associated with toxic substances, such as heavy metals, pesticides, and industrial organics, were also considered, but only cursorily, since these pollutants are not generally from nonpoint sources. According to recent EPA studies, of the various greatest attention was placed on those toxic substances having the most serious effects which have been a problem in the past (e.g., herbicides, such as DDT) or are expected to be a problem (e.g., lead from lead paint).

Part of the literature reviewed was specifically related to the Great Lakes. Some papers on the effects of nonpoint source pollution on other lakes, basins, and large lakes, were considered. While a very large number of references were reviewed, only those most representative of work being done in this area are discussed below. A complete list of all references reviewed is available as the Great Lakes Basin Conference Proceedings. Numerous summaries of pertinent information regarding nonpoint source pollution are included in the reference file.

Effects on the total dissolved solids, suspended solids, and total phosphorus (TSP) were both sought during the review. Reports on the effects of a river mouth and general water quality parameter changes, and effects on plankton, sedimentation, fisheries and fish.



# PHOSPHORUS

## GENERAL IMPACT

Of the pollutants associated with nonpoint source pollution from land, phosphorus has perhaps been studied the most, as it is regarded by most as the key to the eutrophication process. Most of this work has documented the contribution of the nonpoint source phosphorus load to tributaries relative to the total tributary load (e.g., see Sonzogni *et al.*, 1978). Unfortunately, it is very difficult, if not impossible, to separate out the effects on Great Lakes Water Quality of the runoff derived fraction of the tributary phosphorus load from the effects of the point source fraction, since these inputs are often quickly diffused within the lakes.

One way of estimating the importance of phosphorus emanating from nonpoint sources is to measure the percent mass contribution from these sources (Table A1). Inferences on the effect of nonpoint source phosphorus are often based on these mass loading estimates. However, the actual effect of diffuse input cannot be determined strictly from the magnitude of mass input, as much of it may enter the lakes in a short period of time during spring runoff.

TABLE A1

PERCENT CONTRIBUTION OF DIFFUSE TRIBUTARY SOURCES  
TO THE TOTAL PHOSPHORUS LOAD TO THE GREAT LAKES

<u>Lake</u>	<u>Total Load<sup>1</sup></u> <u>Mid 1970's(MT/YR)</u>	<u>%</u> <u>Diffuse<sup>2</sup></u>
Superior	4,000	60
Michigan	6,950	29
Huron	4,580	55
Erie	18,150	50
Ontario	6,650	42

<sup>1</sup> Shoreline erosion not included

<sup>2</sup> Assumes 100 percent delivery of point sources. Data are presented in the "Phosphorus Loads" chapter, Table 4.



Assessment of the effect of nonpoint source phosphorus is further complicated by the fact that not all of the phosphorus delivered to the Great Lakes is biologically available for plant growth. It appears that 40 to 50 percent or more of the total phosphorus contributed by tributaries is unavailable (Armstrong *et al.*, 1978; Logan, 1978). Since a large fraction of the unavailable phosphorus is associated with suspended soil particles, much of the phosphorus from land runoff is likely to be unavailable. Since the question of availability was a major area of investigation in U.S. Task D, this topic was discussed in more detail earlier in this report.

Early studies of the effect of diffuse phosphorus inputs on the Great Lakes, which were generally focused on eutrophic Lake Erie, often underestimated the importance of land derived pollution. Baker and Kramer (1973), after monitoring diffuse and point sources to the Sandusky River (a tributary to western Lake Erie), concluded that the diffuse phosphorus loading factor generally applied for Lake Erie at that time (U.S. Department of the Interior, 1968b) was less than half of the value they found. This conclusion is consistent with other information on diffuse phosphorus inputs found for the entire U.S. Lake Erie basin (U.S. Army Corps of Engineers, 1975).

Since a large fraction of the annual land derived phosphorus input may enter the lakes during the spring runoff period (Burwell *et al.*, 1975; U.S. Army Corps of Engineers, 1975; Sonzogni *et al.*, 1978), a major portion of the U.S. Task D (PLUARG) work was devoted to measuring impacts of phosphorus and other pollutants during this period. Studies were conducted using a combination of shipboard analysis and remote sensing offshore of five major U.S. tributaries. These studies were discussed in more detail in the chapter which integrates and summarizes the total U.S. Task D effort.

Some additional observations in the literature on the general effects of land derived phosphorus inputs on each of the lakes are discussed below.

#### Lake Superior

Nonpoint phosphorus inputs do not likely have a major effect on the lakes as a whole and few studies of nonpoint inputs have been undertaken. Although Lake Superior receives the largest percentage of diffuse tributary phosphorus input relative to other lakes, the nonpoint load is lowest of any of the Great Lakes. Furthermore, due to the large volume of Lake Superior (over half the total volume of the Great Lakes), the volumetric percentage is small. For example, the average U.S. tributary derived phosphorus load to Lake Superior is about 0.2 metric tons/yr-km<sup>3</sup>. This value is over 175 times smaller than the U.S. tributary phosphorus load to Lake Erie! Edmondson (1961, 1969) has indicated that dilution factors and input concentrations, as can be implied from the above comparison, need greater consideration in evaluating the effects of nutrient loads on the lakes. Since much of the Lake Superior drainage is forested, the diffuse load is probably composed, to a large extent, of base flow (ground water input to streams) and represents near-natural or background conditions.



Some local effects, such as at Duluth-Superior Harbor or offshore of the red clay erosion area on the western shore of Lake Superior (Monteith and Sonzogni, 1976), can occur. Bahnick (1977) studied the input of phosphorus associated with red clay erosion in the southwestern Lake Superior basin. While the input was not large compared to point sources, the relative importance of this nonpoint source is expected to increase as point sources decrease in the future. The solids derived from land runoff in this area may have more significant impact than phosphorus productivity. This topic will be discussed later under "Biological Effects of Suspended Solids."

### Lake Michigan

Relative to its total loading, Lake Michigan receives the smallest diffuse tributary input of any of the Great Lakes. This accounts in part for the relatively oligotrophic conditions in most of the lake. Some eutrophic local conditions exist in the southernmost portions of the lake and in Green Bay. A large part of the load to southern Green Bay is accounted for by point sources.

Most data to document changes within Lake Michigan has been based on samples from water intakes at major urban centers. Though phytoplankton and nutrient information gleaned from such samples should not be interpreted as representative of the whole lake, it may be indicative of local conditions arising, at least in part, from diffuse tributary loadings. It has been projected that any long-term trends noted on the basis of such information might represent increasing nutrient loading of inshore areas (Holland and Beeton, 1972). Unfortunately, the impacts from tributary point sources, which make up the majority of the input to southern Lake Michigan, and from diffuse tributary sources, are not readily separable.

Schelske (1978) measured various parameters (nutrients, phytoplankton, etc.) at increasing distances from river mouths along the eastern shore of Lake Michigan. Distinct differences were observed between inshore and offshore waters and, in some cases, between river mouth areas. Though the data has not yet been completely evaluated, the effect of diffuse tributary sources will be difficult to separate from point sources, shoreline erosion and resuspension (Schelske, 1978).

Green Bay is one of the primary areas of concern in Lake Michigan with regard to deteriorating water quality. The primary tributary to the bay and largest contributor of total phosphorus is the Fox River, whose waters spread into the lower 15 to 20 km of the Bay (Schraufnagel, 1966; Sonzogni *et al.*, 1978). The large contribution from the Fox is not surprising in light of the extensive and highly urbanized and agricultural land area which this tributary drains (Skimin *et al.*, 1978).

Sager and Wiersma (1975) indicated that, while nonpoint phosphorus inputs were estimated to contribute about one-half of the annual total phosphorus load in 1970-1971, these inputs were less significant than others since they entered the lake at a time (spring) when algal populations were low. However, it would appear that the phosphorus could be stored or would still be available for late spring and summer blooms.



During certain periods, Green Bay exhibits a hypolimnetic oxygen demand. This results from the oxygen demand exerted by algae stimulated by excess phosphorus, and from organic wastes generated by industry. The most severe dissolved oxygen depletions occur during low flow conditions of the Fox River in late summer. Also, during January-to-April ice cover, severe oxygen depletion throughout 150 square miles of lower Green Bay has occurred (Patterson *et al.*, 1975). The role of nonpoint sources in this case is not obvious, but they undoubtedly contribute to the overall problem.

#### Lake Huron

A large proportion of the total phosphorus load delivered to Lake Huron by U.S. tributaries is of diffuse origin. Except for the lower Saginaw Bay and Thumb area, most of this drainage is from forested areas and thus represents a near-natural load (Manny and Owens, 1978). Productivity values tend to be low (Glooschenko *et al.*, 1974) in Lake Huron, reflecting this relatively natural diffuse load.

The Saginaw River largely determines the water quality of Saginaw Bay, carrying large amounts of industrial, municipal, and agricultural runoff. About 95 percent of the total phosphorus load entering the bay from tributaries (Sonzogni *et al.*, 1978) is derived from the Saginaw River. When all municipal and industrial inputs are considered, approximately 70 percent of the Saginaw River's total phosphorus load is of nonpoint origin (Sonzogni *et al.*, 1978).

In 1974, measurements of total phosphorus from tributaries, dustfall, and rainfall were collected and utilized in a eutrophication model of Saginaw Bay (Canale and Squire, 1976). It was concluded that control of both point and nonpoint sources of pollution would be necessary to effect dramatic improvements in water quality. For example, according to the model, an 80 percent removal of all point source phosphorus contributions would only result in a 30 percent decrease in phosphorus concentrations near the mouth of the Saginaw River and would change outer bay concentrations to a small degree, if at all.

It was reported by Freedman (1974) that higher concentrations of phosphorus and potassium along coastal portions of the outer bay might be indicative of agricultural runoff from all rivers and shore areas, combined with interaction with the sediments in shallower waters. As is the case with most other such statements, no specific evidence was available to conclusively link these higher concentrations to agricultural runoff.

#### Lake Erie

Lake Erie receives by far the largest phosphorus load and the largest tonnage of nonpoint source phosphorus. Tributaries in the U.S. western basin, such as the Maumee and Sandusky Rivers, contribute a large part of the total nonpoint phosphorus load. Herdendorff and Zapotosky (1977), as part of the U.S. Task D (PLUARG) studies, investigated the impact of Maumee River spring runoff events on western Lake Erie. A major conclusion of their work was that a significant amount of phosphorus is contributed during the spring and ultimately affects the whole lake due to transport in an easterly direction. Further discussion of this work is presented in the section on the Summary and Evaluation of U.S. Task D.



Burns et al. (1976a) stated that high phosphorus concentrations observed along the south shore of Lake Erie in 1970 were a result of heavy U.S. loadings from the southern basin. They specifically indicated the high values were not due to nutrients released from the sediments by wave action. It would appear then that nonpoint sources could be linked, at least in part, to the high levels. Gächter et al. (1974), however, projected that high total phosphorus along the south shore reflects point source discharge of sewage from Cleveland, Ohio, and Erie, Pennsylvania. Similarly, Glooschenko et al. (1974) noted high phytoplankton populations have been observed along the south shore, with the water off of Erie, Pennsylvania, exhibiting particularly high primary production in contrast to the eastern half of the lake. Undoubtedly, the higher values result from a combination of point and nonpoint sources, and it is difficult to separate out individual influences on the lake.

If all point sources of phosphorus were eliminated, would nonpoint sources of phosphorus still be sufficient to cause anoxic conditions in Lake Erie? It has been estimated that a loading of 9,500 metric tons per year or less would be necessary to eliminate the development of anoxic conditions (IJC Technical Group to Review Phosphorus Loadings, 1978). It appears that nonpoint total phosphorus loads are close to or less than this value. If a significant amount is not biologically available, and this appears to be the case, then nonpoint sources of phosphorus alone would not cause anoxic conditions in Lake Erie.

#### Lake Ontario

Nonpoint phosphorus sources also contribute a major percentage of the phosphorus load to Lake Ontario. The largest source of phosphorus to Lake Ontario is the Niagara River, which connects Lake Erie to Lake Ontario. U.S. Lake Ontario drainage is dominated by three tributaries with large drainage areas--the Genesee, Black and Oswego Rivers. Other parts of the U.S. drainage are dominated by small tributaries (east and central part of the southern basin) or tributaries draining undeveloped land (northeastern part of the basin). Although land drainage probably comprises a significant amount of the total load to Lake Ontario from these areas, it probably has a relatively small impact on the lake.

#### EFFECTS OF NONPOINT SOURCE PHOSPHORUS INPUTS ON BIOTA

##### Plankton

Numerous studies have linked high levels of phosphorus with greater plankton abundance and changes in species composition. In some areas these effects have been associated with land drainage, but the usual difficulty of distinguishing between nonpoint source and point source effects remains. Water from the Muskegon and Kalamazoo Rivers, tributaries to Lake Michigan, has been found in laboratory studies to increase photosynthesis by about twofold as compared to Lake Michigan water (Schelske et al., 1975). Approximately 90 percent and 35 percent of the annual total phosphorus load during 1975 and 1976 for the Muskegon and Kalamazoo Rivers, respectively, was derived from nonpoint sources. Approximately 40 percent of the total phosphorus load is in soluble form, and over 40 percent of this can be accounted for by point sources. During the period of sampling (summer) the point source load may have been a larger percent of the



total than the annual average (and an even larger percentage of the soluble component of the total phosphorus load). Consequently, the role of land drainage in stimulating the increased photosynthesis is not clear, but it conceivably could have been a contributing factor.

As discussed previously, water intake data is a major source of information on the Great Lakes and can give an indication of local conditions as affected by tributaries. Two annual peaks of plankton abundance were recorded for Gary, Indiana, and Chicago, Illinois, intakes, whereas only one peak of plankton abundance occurred at the Milwaukee intake (Damaan, 1945; Holland and Beeton, 1972). It has been suggested that the bimodal maximum apparent in extreme southern inshore waters of Lake Michigan is the result of "special circumstances" and that the unimodal maximum is the more general case for most of the lake basin (Stoermer and Kopczynsky, 1967). This bimodal maximum has also been observed in Green Bay (Holland, 1969). It is a reasonable conjecture that the cycle may be characteristic of more eutrophic areas in the Great Lakes, possibly due in part to nonpoint source inputs. However, southern Lake Michigan receives major industrial inputs, often directly from the plants, particularly in the area of Burns Ditch, the Indiana Harbor Canal and the Calumet River. It is probable that municipal and industrial effluents may be more important in southern Lake Michigan in contributing to the "special circumstances" alluded to by Stoermer and Kopczynsky (1967).

Deterioration of the benthic fauna in the south end of Lake Michigan has been noted with respect to oligochaete and amphipod abundance (Mozley and Alley, 1973). Nearshore zooplankton of southeastern Lake Michigan is of a very distinct nature as compared to pelagic fauna (Roth and Stewart, 1973). Differences are in part attributed to high inshore primary productivity. Point source nutrient effluents in this area are probably most significant in determining secondary effects on zooplankton populations.

Stoermer (1968) investigated nearshore phytoplankton populations in Lake Michigan near the mouth of the Grand River during thermal bar conditions. He found that total algal cell counts were often nearly six times as high in the inshore waters as in the offshore. Nearshore phytoplankton species composition was found to be influenced by the Grand River to a substantial degree. The primary influence was thought to be enrichment of nearshore waters by the river. Thermal effects were believed to be secondary, in this case defining circulation patterns and sharply delineating nearshore waters from offshore waters (i.e., thermal bar). The Grand River contributes approximately one-fourth of the annual tributary loading of phosphorus to Lake Michigan with diffuse loading responsible for about 50 percent of this load (Sonzogni *et al.*, 1978). The impact of the non-point source component was not (and perhaps cannot be) separated out.

Marked differences in diatom flora were observed in the east (Ludington) and west (Milwaukee) nearshore areas of Lake Michigan during certain months of the year (Holland and Beeton, 1972). These differences were postulated to be associated in part with agricultural runoff within the drainage basins of the Pere Marquette and the Milwaukee Rivers (which empty into Lake Michigan at Ludington and Milwaukee, respectively), along with direct nutrient inputs from



sewage treatment plants. It was observed that inshore waters off of Milwaukee differed considerably from offshore waters, exhibiting higher concentrations of nutrients and greater diatom populations with different species compositions. In contrast, nearshore waters off of Ludington were fairly similar to offshore waters with respect to nutrients. However, tributary loading from Milwaukee is much higher than from the Ludington area (Sonzogni *et al.*, 1978). Tributary drainage from the Milwaukee area is also of an urban nature and is complicated by the presence of a large sewage treatment plant in the harbor area.

Other investigations have been conducted which directly indicate secondary effects of Milwaukee River water on the Great Lakes. Stemberger (1974) investigated the responses of zooplankton communities to a nutrient concentration gradient of high inshore nutrient conditions off of the Milwaukee River mouth to low nutrient conditions in offshore waters. The study showed that nutrient enrichment from the Milwaukee River not only resulted in high primary production but increased production of planktonic rotifers. Zooplankton species composition has also been found to be affected by Milwaukee River mouth conditions. In Milwaukee Harbor, calanoid copepods were found to comprise only 5 percent of the total micro-crustacean fauna (Gannon, 1972), an indication of eutrophic conditions.

The relative importance of nonpoint sources in causing these conditions is again not clear. It is obvious, however, that in the Milwaukee area diffuse source loads of phosphorus (about 200 tonnes/year) are less significant in their effects on algal flora than loads from the Milwaukee sewage treatment plant (about 550 tonnes/year). Most likely the bulk of this point source load is in the form that is biologically available, whereas diffuse source loads are likely much less than 100 percent available.

The biota of Saginaw Bay reflect high phosphorus concentrations. Studies and surveys (Beeton *et al.*, 1967) have noted that phosphorus levels are sufficient to support excessive algal blooms, provided other conditions are conducive. The highest chlorophyll "a" values observed in the Great Lakes as of 1971 were found in Saginaw Bay between April and December of that year (Glooschenko *et al.*, 1974). Very sharp gradients of chlorophyll "a" were also observed within the bay along with the highest primary production values observed in Lake Huron. Schelske *et al.* (1974) also found higher phytoplankton standing crops in Saginaw Bay during a survey in September of 1972 as compared to the open lake. Further, more diatoms were found in Saginaw Bay than in the open lake. These high standing crops tended to decrease with distance from shore on the transects, implying some influence from tributaries and possibly nonpoint sources. Other factors, such as resuspension of bottom sediment, are probably also important. Saginaw Bay does receive the largest overall loading compared to other parts of the lake, and the largest phosphorus input from land drainage (Sonzogni *et al.*, 1978). Consequently, it is not surprising to see higher plankton concentrations in the bay compared to elsewhere.

It was found (Manny and Owens, 1978) that over 90 percent of the total phosphorus load added to Lake Huron by the tributaries flowing into the northwestern part of the lake came in during a four- to six-week period in March and April, immediately prior to the occurrence of high phytoplankton



densities. Brown (1977) further documented temporal fluctuations of phytoplankton in the Hammond Bay area (northwestern Lake Huron) from August, 1973, through July, 1975. Algal population densities were found to increase significantly in May, peaking in June. Heberger (1977) investigated the seasonal population density and composition of crustacean zooplankton populations in Hammond Bay. He found that some taxa were significantly more abundant in nearshore than in offshore areas. This was theorized to be a response to the more eutrophic nature of nearshore waters (Beeton, 1965).

In nearshore transects sampled to the north and south of Hammond Bay in September of 1972 (Schelske *et al.*, 1974) diatom assemblages characteristic of large oligotrophic lakes (Hutchinson, 1967) were observed. This is consistent with observed phosphorus input, which is largely land drainage and which is a "natural" load due to the mostly undisturbed nature of the land and the predominantly sandy soils.

Many studies have documented the familiar 'east-west' gradient of increasing algal standing crop in Lake Erie (Hentley and Potos, 1971; Glooschenko *et al.*, 1973; Munawar and Munawar, 1976). In conjunction with this gradient, qualitative differences in phytoplankton species composition have also been noted (Davis, 1969; Verduin, 1964; Snow and Thompson, 1968; Michalski, 1968). The central and eastern basins are more similar in species composition than the western basin. Ceratium hirundinella, Peridinium sp, Pediastrum sp and Staurastrum sp were found to predominate in the eastern basin, whereas the western basin lacked significant populations of these taxa, exhibiting a more eutrophic flora (Michalski, 1968).

Since over 70 percent of the U.S. land draining into Lake Erie drains into the western basin, land runoff is certainly a factor in this plankton distribution. Further, the soils in the basin have an extremely high clay content, which is conducive to runoff and phosphorus pollution. However, it is difficult to separate out the point and nonpoint source effects, since the Detroit River and, in particular, municipal discharge from the City of Detroit, have a major impact on the western basin.

There is some indication that plankton are directly affected by tributary discharge. The Maumee River, which contains a large nonpoint source component (although the City of Toledo contributes a large point source load at the mouth of the Maumee), has been found to stimulate algae production in Maumee Bay. As early as 1933, phytoplankton standing crops near the mouth of the Maumee were found to be greater than in open waters, decreasing with increasing distance from the mouth of the river (Wright and Tidd, 1933). Recent work by Herdendorff and Zapotosky (1977) also indicate stimulation of algae offshore of the Maumee River following runoff events. With respect to zooplankton, Diapatomus siciloides and Cyclops vernalis, good indicators of eutrophic conditions (Gannon, 1972) were first found in the extreme western end of Lake Erie in 1930 at the mouths of the Detroit and Maumee Rivers (Wright, 1955). It was projected by Curl (1959) that plankton populations within the western basin of Lake Erie could even be potentially maintained by phosphorus inputs solely from the Maumee River. However, in light of the importance of the Detroit River input and improved loading information, this seems very unlikely.



The general decline in abundance of certain species of zooplankton in Lake Erie has also been partially attributed to the occurrence of anoxic conditions in the central basin which is a result, at least in part, of the diffuse phosphorus load. For example, Limnocalanus macrurus, a plankter characteristically inhabiting colder, deeper waters of all the main lakes, has declined in distribution and abundance in Lake Erie since 1930.

In Lake Ontario there is a distinct difference in phytoplankton abundance and composition in nearshore vs. offshore waters in the spring, due to a pronounced thermal bar which prevents mixing (Rodgers, 1965). As a result of this condition, some insight on the effects of tributary loadings on the localized nutrient concentrations can be gained. Nalewajko (1966, 1967) found that certain algal species, particularly Stephanodiscus tenuis, reach high abundance in nearshore waters, persisting until mixing occurs later in the season. Other investigators have also noted inshore-offshore differences in phytoplankton abundance and composition (Ogawa, 1969; Glooschenko et al., 1974). For example, it has been observed that phytoplankton abundance is very high along the shore of Lake Ontario from Toronto (at the mouth of the Niagara River), along the shore of the lake and up the eastern shore of the North Channel (Ogawa, 1969).

The eutrophic indicator species, Bosmina longirostris, was found to be associated with urban development, also reaching higher densities in shoreline areas (Shiomi and Chawla, 1970). Especially high levels were exhibited off of the Oswego River in August of 1972 and were interpreted as being influenced by the agricultural nutrient load of the river as much as by the city of Oswego itself. The primary impact of the nutrients is upon the phytoplankton whose growth is reflected by an abundance of certain zooplankton species--in this case, B. longirostris, which grazes on larger algal forms. These relations are speculations only; no data is available to verify the relationships.

### Macrophytes

Very little information is available linking land runoff phosphorus sources with macrophyte abundance in the Great Lakes. However, some studies associate greater Cladophora abundance with high phosphorus loads. The sources of these loads were not determined.

Lin (1971) indicated that stored phosphorus Cladophora growing in Milwaukee Harbor and to the north in Lake Michigan substantially increased after a heavy rainfall. This increase was attributed to runoff via storm sewers and increased river flow (urban drainage). Cladophora growth was reported to be greatest in lower Green Bay in the vicinity of the Fox River, diminishing in abundance and productivity along the shore of the bay toward the lake (Fitzgerald, et al., 1975). Net photosynthesis of Cladophora was measured at several sites in lower Green Bay during the summer of 1971 (Adams, 1973). It was found that productivity was higher at sites receiving the greatest amounts of Fox River water (Ahrnsbark and Ragotzkie, 1970). No specific link to nonpoint sources was made, however.

Cladophora has been observed (Robinson, 1974) to grow abundantly from Tawas City to Bay City, and east of Caseville around the Thumb to Harbor Beach,



where suitable substrate is present. It was surmised that these growths were stimulated by local enrichments from Saginaw Bay, which receives a considerable nonpoint phosphorus load. In Lake Ontario, high phosphorus loading has also been linked with dense growths of Cladophora. Once again, it does not appear that the enrichment from nonpoint sources can be disaggregated from the cumulative impact of the total phosphorus load from all sources.

Very recent research on Cladophora growth in Lake Huron (Canale and Auer, 1978) that shown that, given the proper substrate, the presence of this alga is associated with local sources of nutrients, including both urban and rural nonpoint sources. Canale and Auer have hypothesized that the normally low phosphorus levels in Lake Huron limit Cladophora growth except in areas enriched by an external source. Apparently, relatively small nutrient inputs can increase nearshore nutrient levels in the vicinity of the source to the extent that the density, areal distribution and tissue nutrient content of Cladophora are affected. The wider distribution of Cladophora in Lakes Erie and Ontario may be the result of higher ambient nutrient levels in these lakes. Cladophora is thus not dependent in these lakes on external sources, as appears to be the case in Lake Huron.

The initial data of Canale and Auer provides a good example of a specific local pollutant impact. Continued investigations along these lines should provide beneficial information as to the effect of nonpoint and small point sources on Lake Huron.

#### Benthos

A number of investigators have documented changes in benthic organism abundance and composition throughout the last few decades. Changes involve a shift in species composition toward an abundance of pollution-tolerant Oligochaeta and Chironomidae, while the mayfly, Hexagenia, has decreased to less than one percent of its former abundance (Beeton and Howmiller, 1970, 1971). It has been observed that even pollution-tolerant organisms are becoming largely absent from sediments in lower Green Bay (Balch et al., 1956; Schraufnagel et al., 1968). These species shifts in abundance and distribution are related to nutrient input, degree of organic pollution, and deoxygenation, although the individual influence of nonpoint derived phosphorus has not been experimentally studied.

Actinomycete (a bacteria) populations, known for their nuisance odor-causing properties, have also been observed to be very high in Green Bay along with other nutrient enriched areas of the Great Lakes (Tierney et al., 1976). Laboratory results indicated that the presence of organic materials increased actinomycete growth. It was concluded that both point and non-point source organic enrichment of northern Green Bay directly enhances conditions for increased actinomycete growth.

Gannon and Stemberger (1978) found that rotifer abundance near the Saginaw River mouth was 40 times higher than in offshore waters of southern Lake Huron. This abundance was interpreted as a response to nutrient loading, both point and nonpoint.



According to information compiled by Freedman (1974) from several different surveys, Saginaw Bay has restricted fauna in the inner bay with pollution-tolerant organisms predominating along the south and southeastern coasts. Pollution-tolerant oligochaeta were the dominant organisms. Highest concentrations were found at the mouth of the Saginaw River (25,000/m<sup>2</sup> of lake bottom) and along the southeastern shores of the bay. It is interesting to note that the highest phosphorus concentrations have been monitored at the mouth of the Saginaw River, though oligochaete distribution may also be related to bottom type. The southeasterly shore distribution of oligochaetes may be partially due to the organic loading of the Kawkawlin River. The Saginaw River and the discharges of sugar beet and milk plants in the Sebewaing area may also be influencing factors (Freedman, 1974). The mayfly Hexagenia, once common in Saginaw Bay, has completely disappeared. This is probably an indirect result of high phosphorus loading, both point and nonpoint.

Benthos populations in the vicinity of the Maumee River mouth have reflected increasing nutrient loads. Carr and Hilttunen (1965) documented changes in Lake Erie benthos between 1930 and 1961. It was observed that the taxa Gastropoda and Sphaeriidae were rare near the mouths of the Maumee and Raisin Rivers and the western side of the Detroit River, and that leeches (Hirundinea) were adversely affected by polluted conditions near river mouths. A large portion of the Maumee River load is of nonpoint source origin.

Extremely high phosphorus loadings may indirectly result in anoxic conditions in the late summer in the central basin of Lake Erie, due to the decay of large algal standing crops (Burns et al., 1976). A classic result of this condition is the widespread disappearance of the burrowing mayfly, Hexagenia (Carr and Hilttunen, 1957). The loss of Hexagenia is very significant in that it was a fish forage item, though its trophic importance is not precisely understood (Christies, 1974). Although nonpoint sources of phosphorus alone could probably not account for the anoxic problem, they have certainly contributed to it.

### Fish

It is difficult to assess the extent to which eutrophication, and more specifically nonpoint nutrient sources, has brought about changes in fish species composition, and little reference has been made to it in the literature.

Regier et al., (1969) has suggested that Lake Erie oxygen depletion had direct effects on blue pike and walleye stocks, increasing their mobility and concentration with a consequent increased vulnerability to the fishery. In Lake Ontario, Cladophora in nearshore waters, probably stimulated by nonpoint as well as point source phosphorus, provides suitable habitat for large populations of the amphipod, Gammarus; this organism, in turn, supports large populations of yellow perch (Christies, 1973). Yellow perch multiplied within the eastern basin of Lake Ontario following the whitefish population crash, and an abundance of littoral benthos, perhaps linked to point and nonpoint phosphorus inputs, may have been a contributing factor (Christie, 1973).



Christie also projected that, in highly productive areas where many species share common food resources, eutrophication may stress the competitive abilities of more specialized fish species. For example, the specialized diet of the smallmouth bass on crayfish may be affected by increasing eutrophic conditions in the Bay of Quinte.







TABLE A2

REVISED ESTIMATES OF FINE-GRAINED SEDIMENT INPUT  
 TO THE U.S. PORTION OF THE GREAT LAKES  
 (10<sup>3</sup> tonnes/year)

Sediment Sources	Lake					
	Superior	Michigan	Huron	Erie	Ontario	
Total Tributary <sup>a</sup> (1975-1976 avg.)	1,000	700	600	6,000	1,300	
Tributary Point <sup>a</sup> (1975-1976 avg.)	50	30	10	60	60	
Direct Point	30	140	50	330	30	
Shoreline Erosion	U.S. Canada	6,900 <sup>b</sup>	2,900 <sup>b</sup>	300 <sup>b</sup>	1,400 <sup>b</sup>	800 <sup>b</sup>
					2,500 <sup>c</sup>	1,000 <sup>d</sup>
Atmospheric	40 <sup>c</sup>	900 <sup>f</sup>	400 <sup>e</sup>	1,800 <sup>c</sup>	1,300 <sup>d</sup>	
Autochthonous Loading				1,000 <sup>c</sup>	200 <sup>d</sup>	
Inerconnecting Channels				1,400 <sup>c</sup>	4,600 <sup>d</sup>	

- a. derived from Sonzogni et al., 1978  
 b. derived from Monteith and Sonzogni, 1976  
 c. derived from Kemp et al., 1976  
 d. derived from Kemp and Harper, 1976  
 e. derived from International Joint Commission, 1977f  
 f. derived from Eisenreich et al., 1977



the results of this compilation. Numbers in Table A2 should be viewed as first approximations of fine-grained inputs, since in some cases fine-grained loads were estimated from total sediment loads.

By providing an overview of the relative contributions of various fine-grained sediment sources, Table A2 allows a rough estimate of the effectiveness of various sediment control strategies. Data in Table A2 is also useful for identifying potential trouble spots, such as Lake Erie, which clearly receives the largest fine-grained sediment load. Comparison of the amount of fine-grained input to total sediment input (Monteith and Sonzogni, 1976; and Sonzogni *et al.*, 1978) indicates the pollution potential of the total sediment load, since fine-grained particles are likely to carry more chemical contaminants than coarse-grained particles. At the same time, fine-grained particles also have a greater potential for removing contaminants from solution.

### Lake Superior

The input of tailings to Lake Superior from Reserve Mining is significant (Plumb and Lee, 1975; International Joint Commission, 1977d), but the amount actually distributed throughout the lake is unclear. Consequently, it has not been included in the following discussion and estimates of solids loads to Lake Superior.

Shoreline erosion is the major source of fine-grained suspended sediment to Lake Superior, the bulk of it being received by the western arm of the lake. Monteith and Sonzogni (1976) indicate that approximately 30 to 50 percent of the total annual U.S. shoreline erosion load to Lake Superior is derived from this relatively small red-clay area in Wisconsin. This shoreline erosion load makes up 25 to 30 percent of the total suspended sediment loading to Lake Superior from all sources. In addition, it is estimated that 75 percent of the U.S. tributary load of suspended sediment is delivered to the western arm via streams draining the red-clay area of Wisconsin and the Ontonogon area of Michigan. To summarize, 35 to 45 percent of the total suspended solids input to Lake Superior from the U.S. side can be attributed to erosion of a relatively small area of northwest Michigan and Wisconsin.

### Lake Michigan

Although shoreline erosion loads to Lake Michigan are extremely high (especially along the eastern shore), much of the material is coarse-grained, due to the sandy texture of lakeshore bluffs. Nevertheless, fine-grained suspended sediment inputs to Lake Michigan are still dominated by shoreline erosion (approximately 60 percent).

Tributary loads make up about 15 percent of the total loading, with highest unit area loads present along a stretch of basin from Milwaukee to the Indiana-Michigan border. The intensive urbanization of this area may account for the greater loads. Other portions of the Lake Michigan basin have consistently low unit area loads, probably due to the predominately sandy surface soils of the basin.



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Other significant sources of fine-grained suspended solids are direct point sources and dredge spoil disposal. Both are highest in southern Lake Michigan (Milwaukee to Michigan-Indiana line). Loads from this area make up about 90 percent of the total direct point source inputs and approximately 30 percent of the total dredge spoil input. Much of the direct point source load is from the Indiana Harbor Canal and Calumet River.

#### Lake Huron

Contributions of fine-grained suspended sediments from the U.S. portion of the Lake Huron basin are greatest from tributary sources, with the largest inputs being from the Saginaw River and Thumb area of Michigan. Shoreline erosion loadings of fine-grained particles are rather small compared with the other lakes, primarily due to the sandy nature of the eroded material, the predominately westerly winds, which minimize erosion on the U.S. shoreline, and the large proportions of bedrock- and wetland-dominated shoreline. The shoreline erosion which does contribute fine-grained sediment is concentrated largely along the eastern side of the Thumb of Michigan. Here the shallowness of the water and the associated wave action tend to keep fine particles in suspension, allowing transport to Lake St. Clair and, ultimately, to Lake Erie.

Atmospheric inputs of particulate matter are more significant in Lake Huron than in the other lakes. This indicates the overall low fine-grained input to Lake Huron.

#### Lake Erie

Perhaps the best data available on sources and sinks of fine-grained sediment is that for Lake Erie (Kemp *et al.*, 1974, 1976, 1977). Tributary inputs make up a large percentage of the U.S. sediment contribution, with the Maumee and Detroit Rivers being the largest tributary sources. Both are influent to the shallow, turbid western basin. Almost all of this tributary load is derived from diffuse sources, including soil erosion in the Maumee basin. The highest unit area loads of suspended sediment in the Great Lakes basin are associated with the rivers which flow into the central and eastern basins of Lake Erie. Again, almost all of this load is derived from nonpoint sources.

U.S. shoreline erosion appears to be a significant source of fine-grained sediment along portions of the Ohio shoreline, but is relatively minimal in the western basin where tributary inputs are dominant. Canadian shoreline erosion, concentrated along the central and eastern shoreline, is by far the largest contributor of fine-grained sediment to Lake Erie (Kemp *et al.*, 1977), but has little impact on the western basin. Further, according to Kemp *et al.* (1977), sediment from the Canadian shoreline has little effect on the U.S. side of eastern and central Lake Erie, but is either deposited in the deeper portions of the eastern basin or carried into Lake Ontario via the Niagara River. Sediment transported from the western basin is generally moved north of the island area into the central and eastern basins.



Other significant sources of fine-grained sediment are dredging, autochthonous loadings due to biological productivity, and atmospheric inputs. Of these, harbor dredging has perhaps the greatest effect, though the significance of its impact is probably masked by the cooccurrence of other sources. Dredging mainly occurs in harbors at the mouths of U.S. tributaries with very high sediment loads.

### Lake Ontario

The largest source of fine-grained sediment to Lake Ontario is the Niagara River, which, according to Kemp and Harper (1976), accounts for 50 percent of the total sediment load to the lake from all sources. This estimate seems reasonable in light of recent tributary loading data (Sonzogni *et al.*, 1978). Most Niagara River sediment comes from Lake Erie, which is, therefore, the primary source of suspended materials for Lake Ontario. United States tributaries, shoreline erosion, and the atmospheric inputs add approximately equal amounts of fine-grained sediment to the lake and account for much of the remainder of the fine-grained sediment input.

The Niagara River inputs generally affect only the western portions of the lake, especially adjacent to the mouth. Sediment input from other sources is thought to be rather rapidly diluted by lake waters and quickly transported to the offshore basins. Kemp and Harper (1976) find only a thin, discontinuous fine-grained sediment cover in the nearshore zones, a fact which they interpret as indicative of the transitory nature of these localized deposits.

## PHYSICAL EFFECTS OF NONPOINT SOURCE SOLIDS INPUT

### Turbidity

A primary effect of increased sediment loading to lakes is increased turbidity and a resultant decline in water transparency. Pinsak (1976) presents mapped transparency data for the Great Lakes, which can be related to areas of high nonpoint source inputs of particulates.

A consistently turbid area is present in western Lake Superior adjacent to the highly erosive red-clay land and shoreline area. Bahnick *et al.* (1972) found that suspended solids concentrations are high in these nearshore waters compared with the open lake (3-60 mg/L vs. 0.2-0.5 mg/L), and that concentrations of several sediment-related chemical parameters are generally elevated. No clearly established clay or mud bottom exists in the nearshore waters, an indication that suspended sediment is scoured and transported to offshore areas before deposition. Another area of relatively lower transparency in Lake Superior persists along the shoreline south of Silver Bay, Minnesota; this is probably due to the extremely large particulate loading from Reserve Mining Company's disposal of taconite tailings. The Ontonagon River's clay input also seems to be related to an area of somewhat turbid nearshore waters, though this relationship is not clearly established.

Pinsak's data does not indicate any serious turbidity in Lake Michigan,



though the data is incomplete. An area of low transparency is present at the outflow from Green Bay to the open lake, but this may be attributable to high phytoplankton productivity in the bay. Cook and Powers (1964) present the average spring concentration of volatile suspended solids near the mouth of the St. Joseph River as 10 mg/L, but the river's influence on this value is not clear.

The lowest transparency in Lake Huron has been observed in Saginaw Bay and around the periphery of the lake (Pinsak, 1976) and is most noticeable in regions of greatest runoff and wave action. Turbidity patterns generally reflect the flow of clear lake water into Saginaw Bay along the northwestern shore, mixing with turbid Saginaw River water, and outflow along the southeast shore, with additional input of suspended sediment from Thumb area tributaries. Other turbid areas are noted along the eastern side of the Thumb (probably shore erosion) and in the southern portion of Lake Huron, due to the combined influence of Saginaw Bay, shoreline erosion, Canadian inputs, and resuspension of bottom sediments in this relatively shallow area.

The western basin of Lake Erie consistently has the highest turbidity values reported for the Great Lakes. High phytoplankton production, particulate loads from the Maumee and Detroit Rivers, and resuspension due to wave motion in this shallow basin all can be related to the low transparency. Turbidity plumes from the Detroit River are associated with resuspension of sediment in Lake St. Clair (Herdendorf and Zapotosky, 1977). Because shoreline erosion is minimal compared with tributary inputs of particulates to the western basin, it is evident that river loads are a primary source of inorganic suspended matter. Inorganic matter makes up from 50 to 95 percent of the total suspended solids loading (Chandler, 1942). Other areas of high turbidity in Lake Erie are within the nearshore regions of the central and eastern basin, especially in proximity to tributary influxes (Pinsak, 1976).

The U.S. portion of Lake Ontario, like Lake Erie, has relatively high concentrations of suspended solids compared with the three upper lakes. Turbidity is highest off the mouths of the Niagara and Genesee Rivers, with the latter source increasing in significance during spring runoff. Large, well-defined turbidity plumes were frequently observed at the mouth of the Niagara River in Landsat images (Pluhowski, 1975). Outflow of suspended solids from Lake Erie is estimated at 4.5 million MT/yr (Kemp et al., 1977).

#### Dredging and Drinking Water Supplies

The amount of bottom sediment dredged for navigation, harbor facilities, and resource extraction totalled 67 million cubic meters for the entire Great Lakes during the period 1966 through 1972. Of this total, 79 percent was dredged from U.S. waters (International Joint Commission, 1975), and over half of the U.S. volume was removed from Lake Erie ports and channels. Stream sedimentation is one of the principal sources of dredged material, though littoral drift and, in some cases, point sources can contribute significant quantities of sediment.

In attempting to understand the importance of tributary solids input, it



is of interest to compare tributary sediment load and the amount of material removed by dredging. Raphael *et al.* (1974) found that estimated tributary loads accounted for only a small amount of the material dredged each year. They attributed this to high point source inputs or a poor weight/volume conversion factor for dredged materials. However, examination of the Raphael *et al.* (1974) study indicates their estimated tributary loads were based on relatively old data, which often underestimates suspended sediment input. Using the most recent estimates of tributary suspended solids loads (Sonzogni *et al.*, 1978 and Raphael *et al.*, 1974), the sediment inputs from many tributaries actually account for a large percentage of the amount dredged. This relationship is shown in Table A3.

Where dredged quantities exceed tributary inputs, as is the case for certain harbors, such as Manistee, Racine, Cleveland and Buffalo, other factors may explain the difference, such as accumulations of material caused by littoral drift. For example, Buffalo Harbor's location at the outlet of Lake Erie could account, at least in part, for the relative high dredged material to stream input ratio because materials tend to be transported to the eastern part of the Erie basin.

Although it is difficult to predict the changes in harbor sedimentation rates which would occur if tributary sediment loads were reduced, very rough estimates have been prepared for comparative purposes. If the assumption is made that a stream load reduction will result in a reduction in maintenance dredging requirements on a ton-for-ton basis, lessening the total U.S. Great Lakes tributary sediment load by 25 percent could result in a decrease in the amount of maintenance dredging required (for the 22 harbors listed in Table A3) by as much as 1.4 million cubic meters per year. Assuming a dredging and confined disposal cost of \$6.77/cu yd or \$8.85/m<sup>3</sup> (U.S. General Accounting Office, 1977), as much as \$12 million per year savings could be realized in lowered dredging costs for this sample of Great Lakes harbors. Reduced dredging would also lessen the potential for adverse environmental impact from removal and disposal of dredged materials.

Another economically important effect of suspended solids is water quality problems at water supply intakes. For example, high turbidity levels in Lake Superior off Cloquet, Minnesota, resulting at least in part from tributary input, have caused water intake problems (Monteith and Sonzogni, 1976). Suspended solids concentrations have been found to exceed recommended limits for drinking water supplies 53 percent of the time (Sydor, 1975).

#### BIOLOGICAL EFFECTS OF SUSPENDED SOLIDS

##### Plankton

The decrease in light penetration caused by increased turbidity reduces the numbers of primary producers (phytoplankton, periphyton, and macrophytes). This reduction may cause a shift among primary consumers from herbivores to detritus feeders. Sherk *et al.* (1976) found that carbon assimilation of laboratory cultures of phytoplankton was reduced by 50-90 percent by addition and



TABLE A3

## COMPARISON OF SUSPENDED SOLIDS LOADS AND MATERIAL REMOVED BY DREDGING

Harbor	Tributary	Stream Load (MT/YR) <sup>1</sup>		Average 1961-1970 <sup>2</sup>
		1975	1976	Maintenance Dredging (MT/YR)
Duluth/Superior	St. Louis	70,000	27,000	73,500
Ontonagon	Ontonagon	580,000	150,000	18,400
Manistee	Manistee	20,000	18,000	30,600
Manistique	Manistique	12,000	16,000	6,100
Manitowoc	Manitowoc	23,000	5,000	24,500
Menominee	Menominee	13,000	16,000	4,900
Oconto	Oconto	7,300	10,000	2,450
Racine	Root	13,000	9,000	18,400
St. Joseph	St. Joseph	82,000	110,000	53,300
Alpena	Thunder Bay	6,000	6,900	6,100
Au Sable	Au Sable	11,000	14,500	18,400
Clinton R.	Clinton	18,000		18,400
Saginaw	Saginaw	120,000	360,000	306,400
Buffalo	Buffalo R.	122,000		367,600
Cleveland	Cayahoga	630,000		747,600
Fairport	Grand	570,000		245,100
Lorain	Black	240,000		183,800
Monroe	Raisin	150,000		122,500
Port Clinton	Portage	66,000		6,100
Toledo	Maumee	1,400,000		766,000
Oswego	Oswego	100,000	141,000	49,000
Rochester	Genesee	590,000	1,100,000	220,600

1. from Sonzogni et al., (1978)

2. from Raphael et al., (1974)



suspension of fine sand to the cultures. They attributed this effect to light attenuation. This lessening of primary productivity may take place even with high nutrient levels, as is evidenced in a lake in the Netherlands (Gulati, 1972) where dredging activities resulted in persistently high turbidities.

Others have documented similar influences of turbidity on primary productivity (Cheng and Tyler, 1976). The adverse effects of light attenuation may be compounded by altered oxygen relationships in surface waters, due both to lessened oxygen production and the high oxygen demand of the sediment influx.

Several examples of turbidity affecting primary productivity are available in the Great Lakes literature. Sullivan (1953) found that phytoplankton standing crops were usually lower at the mouths of Lake Erie tributaries with high suspended sediment loads than at those with clearer waters. However, very high nutrient loading may override the negative effects of turbidity. Sullivan found standing crops of phytoplankton to be higher near the mouth of the Maumee River (which contributes a very high nutrient load) despite the high concentration of suspended solids, a fact which may be attributed to extremely high productivity near the surface. Further into Maumee Bay, the situation reverts to a reduced standing crop of phytoplankton, which may be at least partially due to turbidity and light attenuation (Great Lakes Basin Commission, 1976b). Swenson *et al.* (1976) found that zooplankton densities were higher near the surface in turbid Lake Superior waters. They suggest that this may have reflected higher phytoplankton densities due to nutrient and silica enrichment of the water and the fact that the phytoplankton are forced to move toward the surface due to the light attenuating turbidity.

### Macrophytes

Aquatic macrophytes are found to be strongly affected by turbidity and siltation. Suspended sediment may reduce photosynthesis by either shading the plants or coating leaves with a layer of fine particulates. Excessive siltation may cause direct mortality in macrophytes, as many are unable to quickly re-establish root zones in response to rapid sediment deposition. Documentation of this in the Great Lakes is largely descriptive and based on historical observations. However, several authors do refer to the disappearance of macrophytic vegetation in Lakes Erie and Ontario during the late 19th century. Davis (1969) comments on the decline of aquatic plants in these lakes, observing that one would expect an enrichment of flora given the marked increase in nutrient inputs due to human activities. Several authors (Trautman, 1957; Cole, 1973; White *et al.*, 1975) attribute the disappearance of Lake Erie macrophytes to increased suspended sediment inputs from the Maumee River and other south shore tributaries. Approximately 50 percent of the aquatic floral species present at Put-in-Bay, Ohio, in 1898 are not present there today (Stuckey, 1971). Among the reasons cited for the changes are increased siltation due to agricultural activities and high turbidity from dredging and resuspension of bottom sediments. No estimate of the relative significance of the various factors was made, nor was any specific evidence available to support this reasoning.

It is apparent that suspended sediment influx from Lake Erie tributaries



has increased since 1850. Kemp et al. (1974) estimated that sedimentation rates in Lake Erie have increased threefold since that time, due largely to land clearing and agriculture in the basin, assuming that shoreline erosion inputs are fairly constant. This may not be strictly true, as White et al. (1975) felt that the loss of aquatic vegetation (due to siltation) has resulted in an increased rate of erosion along the shores of Lake Erie.

Other variables may accentuate the effects of increased siltation on aquatic vegetation. King and Hunt (1967) state that the increasing numbers of carp have a large impact on macrophytes, by uprooting plants and by stirring up the bottom to cause high turbidities. The importance of carp relative to increased tributary sediment loading has not been established.

### Benthos

As Lee and Plumb (1974) have pointed out, it is difficult to determine the effect of suspended solids on benthic fauna and flora because very little is known about their response to increased rates of siltation. Some benthic organisms, Tubificiae and Chironomids, for example, may tolerate or even thrive in increased sedimentation.

Rolan and Skoch (1976) present an overview of oligochaete and amphipod distributions in the Great Lakes. In many cases the occurrence of oligochaetes is not strictly determined by substrate, but may be controlled by organic matter from sewage or industrial discharges. Nonetheless, soft substrate is required to support large populations of these benthic organisms.

Large populations of oligochaetes are found throughout the southern portion of Lake Michigan and near the mouth of the Grand River. High organic loading from Chicago, Milwaukee, Gary, and St. Joseph may contribute to the high concentrations in southern Lake Michigan (Mozley and Howmiller, 1977). The high concentration near the mouth of the Grand River may be at least partially a function of organically enriched suspended sediment input from the river.

Oligochaetes in Lake Huron are most numerous near the mouth of the Saginaw River and, to a lesser extent, along the eastern side of Saginaw Bay. This distribution may be indicative of organic pollution from the Saginaw River, although correlation of oligochaete populations with the distribution of river sediments is poor. Substrate requirements for these benthic fauna are met in many areas of Saginaw Bay, and abnormally high densities may be due to a combined substrate/pollutant effect. Hexagenia nymphs are no longer present in Saginaw Bay, possibly due to depletion of dissolved oxygen at the bottom (Rolan and Skoch, 1976). Among suggested causes are high inputs of oxygen-demanding sediments.

A definite west-to-east gradient of oligochaete distribution is present in Lake Erie, with highest densities in the western basin. Large populations of Limnodrilus and Tubifex have been found near the mouths of the Maumee, Raisin and Detroit Rivers. High nonpoint suspended sediment loads are associated with these rivers, and the organic fraction of these loads may be a significant factor



in determining oligochaete occurrences. Brinkhurst (1969) documents the increase in numbers of oligochaetes in the nearshore waters of Lakes Erie and Ontario, a distribution which may be attributable to increased organic enrichment of these waters. Whether this increase is due to increased land drainage of soil particles and thus partially attributable to nonpoint sources, or to organic waste inputs from point sources is not clear. However, Brinkhurst feels that the phenomenon is not due to depth requirements of the organisms, as no such depth-related pattern is established from other parts of the Great Lakes system.

## Fish

Most studies of Great Lakes fish populations have concentrated on Lake Erie fish. Turbidity, siltation, and the loss of macrophytes are common reasons given for the decline of fish populations inhabiting or spawning in Maumee Bay and the shallow areas of Lake Erie. Leach and Nepszy (1976) noted several species declines which can at least be partially attributed to these factors.

Lake trout tend to avoid turbid waters and additionally are sensitive to siltation of hard-bottom spawning areas. Unrestricted commercial exploitation and destruction of summer oxygen regimes have compounded the problem.

Whitefish populations have suffered from the same set of environmental perturbations, and Hartman (1973) noted that, since Lake Erie is at the southern limit for whitefish populations, the fishery is very sensitive to environmental perturbations. Hartman (1973) stated that the increasing silt load in the Maumee River around the turn of the century destroyed whitefish spawning areas in Maumee Bay and the western basin of Lake Erie, leaving only the open lake spawners to support the fishery. Overfishing, water temperature increases, and decreased dissolved oxygen decimated the rest of the population, according to this hypothesis.

The sauger has virtually disappeared from Lake Erie, a fact which Regier et al. (1969) attributed to degradation of spawning areas in the nearshore waters and tributaries of the western basins. Earlier, increased turbidity and fertility in the shallow areas of Lake Erie actually resulted in a peak production of the light-sensitive sauger, but these same factors ultimately led to its demise. Other fish species which were allegedly adversely affected by siltation and turbidity were the walleye (compounded by oxygen depletion and decline of the mayfly) (Beeton, 1966; Parsons, 1970), the silver chub (White et al., 1975), the muskellunge, the mooneye, and the smallmouth black bass. Migratory stream spawning species such as the lake sturgeon, northern pike, and sucker have been negatively affected by the destruction of macrophitic spawning areas and the obstruction of streams by physical or "chemical" dams (White et al., 1975).

Table A4 lists some of the fish species inhabiting western Lake Erie prior to 1957 (Trautman, 1957). It is interesting to note that, of 47 fish species listed, 29 have habitat requirements of either clear waters, aquatic vegetation, or gravel/sand spawning substrate.



TABLE A4

## FISH FOUND INHABITING THE WESTERN BASIN OF LAKE ERIE UP TO 1957

Species	Period found in Maumee Bay	Habitat
1. Lake sturgeon	Before 1916, 1916-1950	Declined because of inability of fish to reach spawning grounds. Spawns in large rivers or in the shallows of the lake.
2. Spotted gar	Before 1901, 1901-1950	Prefers quiet, clear water with large abundance of aquatic vegetation.
3. Longnose gar	Before 1901, 1901-1950	Inhabits same areas as spotted gar, but with less dependence on vegetation.
4. Mooneye	Before 1901, 1901-1950	Prefers clearest waters with swift current; needs large supply of small fish to feed on. Decline since 1935 directly attributed to increased turbidity.
5. Eastern gizzardshad	Local records	Is tolerant of clear and turbid waters if phytoplankton population is high. Winter death rate appears to be high, especially among the young.
6. Whitefish	Local records	Experienced sharp decline in number spawning in Maumee Bay early in 1900's due to increased smothering of spawning grounds by siltation.
7. Northern pike	Before 1910, 1910-1950	Inhabits clear water with abundant aquatic vegetation. Large catches recorded in Maumee Bay from 1900-1910. Decline since 1910 due to inability to reach spawning grounds.
8. Great Lakes muskellunge	Before 1900, after 1920	Was one of first species to become commercially important; declined in Maumee Bay after 1905. Spawns in clear, shallow waters with abundant aquatic vegetation.
9. Bigmouth buffalofish	Local records	Maintained large population in Maumee River in 1942. Occupies shallow and turbid waters, and is in competition with the carp.
10. Silver redhorse	1885-1900	Inhabits areas where siltation and industrial pollutants are at a minimum.
11. Northern shorthead redhorse	Local records	Inhabits shallow and clear waters with clean and silt-free bottom of sand, gravel, or bed-rock. More abundant before 1925. Declined with increased turbidity.

SOURCE: Adapted from Trautman, 1957.



TABLE A4 (cont'd.)

## FISH FOUND INHABITING THE WESTERN BASIN OF LAKE ERIE UP TO 1957

Species	Period found in Maumee Bay	Habitat
12. Greater redhorse	Before 1900	Prefers clear water with clean sand, gravel, or boulders. High degree of intolerance to turbidity and chemical pollutants. Before 1890-1920, species was numerous in Maumee River.
13. Common white sucker	Local records	Appears tolerant to increased turbidity, siltation, organic and inorganic pollutants, and low oxygen. Favors dense aquatic vegetation rich in nutrients.
14. Carp	After 1880	Inhabits warm stream with abundant organic matter (either contributed by sewage or by biologic conversion of inorganic fertilizers from fields, rooted aquatic vegetation, or byproducts). Inhabits either clear or turbid waters.
15. Goldfish	Local records	Is possible carp-goldfish hybrid. Occupies same habitat as carp, but is less tolerant to cool waters, turbidity, rapid siltation, and domestic and industrial pollutants.
16. Goldenshiner	Local records	Inhabits quiet and clear waters with bottom composed of organic debris and/or sand with abundant aquatic vegetation.
17. Silver chub	Before and after 1900	Is usually found in clear water 1-20 m deep with a gravel bottom.
18. Common emerald shiner	Local records	Inhabits clear waters with the bottom unimportant.
19. Northern redbfin shiner	Local records	Needs clear water with sandy or gravel bottom and some aquatic vegetation.
20. Spottail shiner	Before 1926, 1926-1952	Inhabits clear water with depth ranging from 1-20 m with bottom composed of sand or gravel. Has decreased in Maumee Bay due to increased silting and turbidity.
21. Spottfin shiner	Local records	Appears tolerant to many environments, such as increased turbidity, siltation, and domestic or industrial pollutants. Deposits eggs on underside of objects.



TABLE A4 (cont'd.)

## FISH FOUND INHABITING THE WESTERN BASIN OF LAKE ERIE UP TO 1957

Species	Period found in Maumee Bay	Habitat
22. Northeastern sand shiner	Local records	Experienced a drastic decrease in numbers from 1920-1950 in the Maumee River. Inhabits bottom composed of sand and gravel with a current. Needs clear water with rooted vegetation.
23. Bluntnose minnow	Local records	Inhabits waters with depth ranging from 0-30 m. Appears tolerant to turbidity, inorganic and organic pollutants.
24. Channel catfish	Local records	Inhabits fairly clean bottoms, usually composed of sand, gravel, boulders, or silt-dense. Aquatic vegetation unnecessary.
25. Brown bullhead	Local records	Prefers clear, cool water with moderate amounts of aquatic vegetation. Bottom composed of sand or gravel. Appears more tolerant to turbid waters than black bullhead.
26. Black bullhead	Before 1901, 1901-1950	Occurs in turbid, warm waters and is tolerant to industrial and domestic pollutants and silting.
27. Stonecat madtom	1901-1950	Inhabits bottom composed of gravel, boulder, or bedrock. Appears in large streams free of silt and other pollutants with an abundance of insects, crayfish, and forage fish.
28. American eel	Before and after 1910	Adjusts to turbid waters by finding food by scent.
29. Eastern burbot	Local records	Comes into shallow waters in winter.
30. Troutperch	Local records	Inhabits bottom composed of clean sand or gravel. Appears numerous in water less than 1.5 m deep.
31. Brook silversides	Before 1901, 1901-1950	Inhabits clean water with sand or organic muck bottoms. Does not like turbid waters.
32. White bass	Local records	Inhabits clear waters with firm bottom. Occurs in depths less than 9 m. Needs abundance of small fish.
33. White crappie	Local records	Is one of the most sought after panfishes. Tolerant to many conditions, especially to turbidity and siltation.



TABLE A4 (cont'd.)

## FISH FOUND INHABITING THE WESTERN BASIN OF LAKE ERIE UP TO 1957

Species	Period found in Maumee Bay	Habitat
34. Black crappie	Local records	Appears to decrease in numbers in turbid waters. Needs clear waters with abundance of submerged aquatic vegetation and a sandy bottom.
35. Northern smallmouth blackbass	Local records	Decreased in last 25 yrs due to increased turbidity. Inhabits bottoms composed of clean gravel or boulder. Requires a maximum depth greater than 1 m.
36. Northern largemouth blackbass	Local records	Inhabits essentially nonflowing waters with bottoms composed of soft muck and organic debris, gravel, hard sand, or nonflocculent clays.
37. Green sunfish	Local records	Exhibits no preference to type of bottom. Appears more tolerant to turbidity and siltation than other sunfish.
38. Northern bluegill sunfish	Local records	Has decreased from 1920-50 despite repeated planting of fry and adults. Inhabits waters which are clear or which contain little suspended clay or silts, with bottoms composed of sand, gravel, or muck containing organic debris. Needs an abundance of aquatic vegetation.
39. Pumpkinseed sunfish	Before 1926, 1926-1950	Inhabits clear non-flowing waters which do contain clayey silt in suspension. Needs bottom composed of muck or sand partly covered with organic debris with a dense aquatic vegetation.
40. Sauger	Local records	Inhabits shallow, more turbid waters with silty bottoms.
41. Yellow walleye	Local records	Inhabits shallow water with bottoms composed of gravel and bedrock. Has declined in Maumee Bay due to increased turbidity.
42. Yellow perch	Local records	Inhabits clear, shallow water with an abundance of rooted aquatic vegetation. Bottom composition usually muck, organic debris, sand, or gravel. Has declined in turbid and siltating waters.



TABLE A4 (cont'd.)

## FISH FOUND INHABITING THE WESTERN BASIN OF LAKE ERIE UP TO 1957

Species	Period found in Maumee Bay	Habitat
43. Channel darter	Before 1924, 1924-1952	Inhabits bottoms composed of coarse sand with fine gravel beaches. Occurs in clear water 1 m deep in the day and in shallow water at night.
44. Northern logperch darter	Local records	Inhabits area with bottom composed of sandy and/or fine gravel beaches. Needs moderately dense beds of submerged aquatic vegetation, especially for the young.
45. Central johnny darter	Local records	Appears tolerant to many organic and inorganic pollutants and increased turbidity. Eggs are deposited on the underside of stones. Inhabits bottom composed of sand or gravel. Appears less tolerant of submerged aquatic vegetation than the scaly johnny darter.
46. Scaly johnny darter	Local records	Inhabits non-flowing water with silty bottoms in bays and protected beach areas.
47. Freshwater drum	Local records	Inhabits waters ranging from 1.5-18 m deep. In warmer months, inhabits waters less than 1.5 m deep. Appears to tolerate turbid water, but likes clear water with clean bottoms.



Swenson et al. (1976) have investigated the effects of red-clay turbidity on the aquatic environment of Lake Superior and have concluded that definite differences in fish community structure are evident between clear and turbid waters. However, they do not document any changes which have occurred over time due to increased suspended sediment loads. In essence, their studies describe ecologic differences which exist in response to natural nonpoint source suspended sediment loadings.

Larval herring are similarly most abundant near the surface in turbid waters where zooplankton densities are also high. This situation has historically aided the survival of herring larvae by ensuring an ample food supply (zooplankton) and limiting predation by turbidity-sensitive lake trout. The rise in populations of immigrant rainbow smelt in the early '50s has largely negated this advantageous position. Smelt also tend to congregate in the near-surface waters and are thought to prey on larval herring (Swenson, 1977). Thus, although turbidity appears to result in greater herring survival in the absence of smelt, turbidity indirectly may cause lower survival of larval herring and population decline through its influence on smelt distribution and food habits (Swenson et al., 1976).



VIEW OF THE BIRD LIFE IN GREAT BRITAIN AND IRELAND 1978

Burnham et al. (1978) have investigated the effects of red-clay fertility on the aquatic environment of Lake Superior and have concluded that definite differences in fish community structure are evident between clear and turbid waters. However, they do not discuss any changes which have occurred over time due to increased nutrient loading. In contrast, their analysis describes ecological differences which exist in response to natural non-point source suspended nutrient loading.

Further bearing on the effects of nutrient loading on the surface in turbid waters where zooplankton densities are also high. This situation has been particularly noted in the context of pelagic larvae by operating an ample food supply (zooplankton) and this is a condition which is usually associated with high rates in production of zooplankton. This also tends to concentrate in the near-surface waters and as a result of high nutrient loading (Sweeney, 1977). Thus, although turbid waters appear to result in greater pelagic survival in the absence of smelt, turbid waters may cause lower survival of larval herring and population density through the influence on smelt distribution and food habits (Sweeney et al., 1978).

Year	Species	Abundance
1978	Herring	High
1978	Smelt	Low



## DISSOLVED SOLIDS

Dissolved solids naturally enter the Great Lakes through weathering and decomposition of rocks, soils, dead plant material, etc. The runoff cycle is a major factor in the rate of chloride influx (Spain and Andrews, 1970). In the Colorado River basin, for example, it is estimated that natural diffuse sources of salt contribute some 60 percent of the daily salt load exported by the river (Blackman *et al.*, 1973). Certain agricultural, forestry, industrial and mining practices, and transportation activities (road salt application) significantly add to such natural background levels of dissolved solids. Sorenson *et al.* (1977) provide a good, comprehensive review of potential sources and biological effects of dissolved solids. Two important constituents which contribute to total dissolved solids, chloride and silica, will be discussed below.

### CHLORIDE

#### General Impact

Chloride is a conservative constituent of freshwater environments, meaning that it does not combine with other aqueous or solid phases and is not removed from the system by common chemical, physical and biological processes such as precipitation, sorption, chelation and biological uptake. Because of its conservative nature, chloride has been used as an index of pollution in the Great Lakes (Rainey, 1967; Tiffany and Winchester, 1969). In the last decade many investigations have been undertaken concerning chloride transport (Richardson, 1974; Lam and Simmons, 1976) and estimates of future chloride levels in the Great Lakes have been made (Meredith *et al.*, 1974; Rumer *et al.*, 1974; Ownbey and Kee, 1967; Dobson, 1967). Sonzogni *et al.* (1978) have also estimated chloride tributary loads for the Great Lakes, including the diffuse component.

This review found no studies that conclusively relate increasing levels of dissolved solids in the Great Lakes with biological effects. As aptly summed up by Sorenson *et al.* (1977), "Effects of this water quality parameter are usually subtle, seldom serving to completely eliminate or to completely stimulate biological systems." A few investigations have made some interesting inferences, however.

Stoermer *et al.* (1974) asserted that some less desirable phytoplankton species that have adapted to physical conditions in the Great Lakes come primarily from saline waters and that increases in conservative ion levels may selectively favor them, resulting in an increase in abundance. This conjecture is based in part on observations of phytoplankton abundance and species assemblages in Lake Ontario. Stoermer (1977) has further hypothesized that a



biological breakpoint exists between 7.5 and 10.0 mg/L chloride, which may cause a shift in phytoplankton towards nuisance, taste- and odor-causing blue-green algae.

Until recently, information in the literature has generally supported the conclusion that osmotic problems, resulting when salt concentrations are increased, are responsible for observed changes in productivity (Schmidbauer and Ried, 1967). It has been suggested, however, that sodium stress rather than osmotic stress may be responsible for biological changes previously associated with increasing chloride concentrations (Batterton and vanBaalen, 1978; Hellebust, 1978). Brownell and Nicholas (1967) found that the blue-green alga, Anabaena cylindrica, underwent reduced nitrogen fixation as a result of sodium deficiency. Blue-green algae have an absolute need for sodium and potassium, a characteristic not shared by other fresh-water algal groups, and it has been proposed that monovalent ions, as well as other factors, may be responsible in favoring blue-green algae (Pravasoli, 1969).

Robertson and Powers (1967) found that total organic matter and total dissolved organic matter in the Great Lakes increased in this order: Superior, Huron, Michigan, Erie, and Ontario. Many investigators have noted that primary productivity and/or standing crop increase with total dissolved solids (Rawson, 1951, 1960; Northcote and Larkin, 1956; Kerekes and Nursall, 1966; Seenayya, 1973). It has been hypothesized by Kerekes and Nursall (1966) that as total dissolved solids increase more nutrients become available, resulting in an increase in productivity to a certain point. Total dissolved solids beyond a certain concentration were found to be osmotically limiting to standing crop in some lakes of British Columbia (Topping, 1975).

Virtually no literature exists concerning the effects of chloride concentrations prevalent in the Great Lakes on benthic organisms and zooplankton. Several studies have investigated the effects of very high salinities on fresh-water benthic organisms (Shirgur and Kewalrammi, 1973; Wichard and Komnick, 1974). Recently, Crowther and Hynes (1977) investigated the effects of common road salts on the drift of benthic invertebrates in a southern Ontario stream. Though results did not indicate any clear evidence of deleterious effects in this instance, the authors believe that soon this may no longer be true. High winter/spring peak loads of chloride are approaching levels that may have effects. For example, Bubeck et al. (1971) found average winter chloride levels in Irondequoit Creek (tributary to Lake Erie) of 320 mg/L with pulses of between 700 and 4,000 mg/L. This input is thought to emanate largely from urban drainage.

Even less information exists with respect to chloride effects on zooplankton. Investigations attempting to relate total dissolved solids to crustacean zooplankton abundance have not been successful in separating the effects of increased nutrient input from total dissolved solids (Patalas, 1973; Patalas and Salki, 1973). Studies have shown that salt-tolerant zooplankton species are able to occupy a wide variety of freshwater habitats (Anderson, 1974; Whittaker and Fairbanks, 1958).

In the last two decades the presence of salt-tolerant zooplankton species



has been noted in all of the Great Lakes with the exception of Lake Superior (Engel, 1962; Robertson, 1966; Evans and Stewart, 1977). Specific occurrences of these species will be discussed subsequently with respect to chloride loading in each of the Great Lakes.

### Lake Superior

Because its basin lies mostly outside the Paleozoic carbonate belt that underlies the remainder of the Great Lakes basin (International Joint Commission, 1977c), Lake Superior naturally exhibits considerably lower levels of dissolved solids and alkalinity than the other lakes. Chloride levels are extremely low with the exception of localized areas where brine from mining operations are released (Spain *et al.*, 1969; Spain and Andrews, 1970; Sonzogni *et al.*, 1978). If these mine discharges are considered point sources, the diffuse inputs of chloride are not currently likely to have a measurable effect on the lake. In contrast to the other Great Lakes, Lake Superior has actually undergone a slight decrease in total dissolved solids concentration (Kramer, 1964; Weiler and Chawla, 1969), according to the long-term data available.

### Lake Michigan

Attempts have been made to differentiate the sources of chloride loads in Lake Michigan. Ownbey and Willeke (1965) estimate that 43 percent of the total annual chloride load to Lake Michigan is due to land runoff. Upchurch (1972) attributed only 27 percent of the chloride load to natural loading. The discrepancy is probably partially due to the fact that the former authors include deicing salt runoff in their land-runoff calculations, whereas Upchurch does not.

Localized effects from deicing salt runoff have been observed in areas of Lake Michigan. Industrial Bio-Test, Inc. (1972) sampled the Kenosha water treatment plant intake on a monthly basis for over a year (1970-71). Increases in sodium and chloride concentrations in the winter were attributed to deicing salt in the nearby city of Kenosha. Similar winter increases in chloride concentration have been observed at inshore areas along the western shore (U.S. Geological Survey, 1973, 1974a).

Ownbey and Willeke (1965) concluded that increasing levels of chloride, sulfate, and other dissolved materials in Lake Michigan do not seriously threaten water quality. Nutrient input was considered a more serious and imminent problem. In contrast, recent work (Stoermer, 1977) indicates the build-up of dissolved solids in Lake Michigan may be a very serious problem with more permanent and potentially irreversible effects, due to the conservative nature of chloride.

For example, the filamentous, blue-green alga, Stephanodiscus, which may cause filter clogging at water intakes as well as taste and odor problems, has been observed to be more prevalent in extreme southern portions of Lake Michigan in the vicinity of industrial chloride discharge. Stoermer (1977) believes that chloride concentration may be a crucial factor in evoking a shift in



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plankton composition toward salt-tolerant species such as Stephanodiscus.

The rapid spread of the marine alga, Bangia atropurpurea, has been related to high levels of halogens and trace metals which are present in runoff waters and contaminated harbors of Lake Michigan (Lin and Blum, 1977). Bangia was first found on the southwestern shore of Lake Michigan and presently covers suitable substrates on the southern two-thirds of the lakeshore. It is interesting to note that Kann (1959) found that Bangia only occurred in portions of a freshwater lake in Germany where chloride concentration was a relatively high 30-40 mg/L.

Similarly, Evans and Stewart (1977) noted the presence of salt-tolerant benthic and epibenthic microfauna in nearshore areas of southeastern Lake Michigan. For example, Eurytemora affinis, a brackish water calanoid, was found in samples. The organism was first detected in Lake Erie in 1961 (Engel, 1962) and is now also found in Lakes Michigan, Huron and Ontario. Three other zooplankters observed by Evans and Stewart (1977) exhibit salinity tolerances which range from slightly to moderately saline (Whittaker and Fairbanks, 1958).

#### Lake Huron

Weiler and Chawla (1969) observed that chloride and sulphate have increased similarly in Lake Michigan and Lake Huron. It was thus suggested that Lake Michigan is the primary source of dissolved ions in Lake Huron. Tiffany and Winchester (1969) indicate that the Saginaw River basin is the prime contributor of halogens to Lake Huron which otherwise derives its halogens from relatively unpolluted areas. This is in accord with Sonzogni et al. (1978), who indicate that approximately 80 percent of the chloride tributary load to Lake Huron arises from the Saginaw River. Approximately 60 percent of the Saginaw River's chloride level is attributable to nonpoint sources.

The only documentation of biological effects of chloride loading in Saginaw Bay notes that abundances of the diatom, Asterionella subcylindrica, at stations in and adjacent to Saginaw Bay were highly correlated to chloride concentrations greater than 5 mg/L (Schelske et al., 1974).

#### Lake Erie

Chloride concentrations have increased greatly in Lake Erie since 1910 (Beeton, 1965; Ownbey and Kee, 1967), and it is forecast that these increasing levels may threaten the use of Lake Erie water for some purposes (Rumer et al., 1974). The U.S. Environmental Protection Agency has found that chloride levels have increased significantly in the last ten years (Rockwell, personal communication, 1978). There is very little in the literature regarding the effects of chloride on Lake Erie biota.

Based on the recent estimates of Sonzogni et al. (1978), as much as 90 percent of the tributary chloride load is derived from diffuse sources. Direct discharges from municipal sewage treatment plants (e.g., Detroit and Cleveland plants) and industrial operations around Detroit/Windsor also contribute



considerable amounts of chloride.

Ownbey and Kee (1967) consider industries on the Detroit and Grand (Ohio) Rivers to be the principal contributors of chloride to Lake Erie. Weiler and Chawla (1969) attribute high chloride concentrations in offshore waters near Toledo and Cleveland, Ohio, and Erie, Pennsylvania, to the industrial development in and around these cities. Ownbey and Kee (1967) attribute approximately 11 percent of the total chloride input into Lake Erie in 1964 to deicing salt runoff, based on amounts of salt applied to U.S. roads within the basin. Though use of deicing salt is increasing with population growth, industry is and will continue to be the primary contributor of chlorides to Lake Erie (Ownbey and Kee, 1967).

It appears that management and restriction of deicing salt runoff would be most effective in localities where such runoff constitutes the prime contributing source of chloride. For example, Rumer et al. (1974) estimated that 36 percent of the total chloride load discharged by Buffalo, New York, was attributable to sodium chloride applied to city streets. It is interesting to note that approximately 90 percent of the total weight of chlorides applied to city streets eventually reached the lake via the combined sewer system. Runoff of deicing salt within the Lake Erie basin was considered to be an important source of chloride and presented very serious water quality problems in small embayments with low flushing rates (Rumer et al., 1974). No impacts on the biota due solely to the high chloride levels were obvious.

As a follow-up to their case study in Buffalo, Meredith and Rumer (1976) developed a simulation model for evaluating the effects of road salt runoff. It was concluded that the amount of deicing salt used in the Buffalo area is greater than can be justified economically, but no clear rationale for reducing levels to protect the Great Lakes was given.

Upchurch (1972) stated that chloride concentrations in the Maumee River were probably due to street salt runoff, based on a high positive correlation between sodium and chloride concentrations in Maumee River water. Those systems dominated by cultural wastes will supposedly show significant correlations between components added by man, and reduced correlation significance between cultural and natural components. This correlation has not been verified, and it appears street runoff may not be as significant a contributor to the Maumee chloride load as suggested by Upchurch.

Sonzogni et al. (1978) found high diffuse loads of chloride, estimated at 251,100 metric tons per year, emanating from the Maumee River. This value comprises over 90 percent of the total chloride load. It is difficult to ascertain what proportion of this load is due to natural background levels (as opposed to road salt runoff), but it is probably a large percentage.

Documentation of the possible effects of chloride levels on Lake Erie biota seem to be restricted to scattered observations concerning the recent occurrences of euryhaline taxa. For example, Young (1975) observed an unusually dense bloom of the brackish water diatom, Skiletonema subsalum, in



Sandusky Bay during April of 1974. This diatom had not previously been reported in the western hemisphere. Chloride loading data (Sonzogni *et al.*, 1978) indicate that the Sandusky River carries about 50,000 metric tons of chloride per year into the bay, with over 90 percent of this load originating from diffuse sources. At this point, however, it is a matter of conjecture whether chloride inputs are related to observed algal blooms. Investigations concerning direct and indirect effects of a range of chloride concentrations on algal species composition and productivity are necessary. It would be interesting to look at blooms off of the Maumee River, which has a chloride loading five times as great as that of the Sandusky.

### Lake Ontario

Lake Ontario is also receiving large amounts of chloride. According to Dobson (1967), chloride and sodium levels in Lake Ontario are changing more rapidly than any other constituents and, at their present rate of increase, concentrations will double in the next fifty years. The Oswego River is responsible for 85 percent of the U.S. tributary load. Fifty percent of the Oswego input comes from identified point sources (Sonzogni *et al.*, 1978).

As in Lake Erie, localized water problems in embayments adjacent to highly urbanized areas can be directly related to deicing salt runoff. Bubeck *et al.* (1971) found that local chloride build-up in Irondequoit Bay had increased five times in the last 20 years, exceeding limiting values set for drinking water. Chloride levels were largely due to runoff of deicing salt. During the winter of 1969-70, runoff was high enough to prevent complete vertical mixing in spring. It was determined that the period of summer stratification had been prolonged by a month based on comparisons with 1939 conditions. This is a good example of a nonpoint source impact.

Stoermer *et al.* (1974) noted that many dominant and subdominant taxa of phytoplankton in Lake Ontario occur most abundantly in brackish and saline inland waters. Phytoplankton compositional changes have previously been attributed to eutrophication in general, but Stoermer *et al.* (1974) emphasized the importance of considering the interaction of both physical and chemical factors when regarding such changes. Beeton (1966) similarly suggests that changes in benthic communities, bacterial abundances and fish growth rates may be due to environmental conditions not related to eutrophication. He also stressed the importance of looking at total dissolved solids and major ions.

### SILICA

Silica is an absolute necessity in diatom cell wall formation and cell division (Lewin, 1962). Diatoms are able to increase in biomass only until all available silica has been utilized in cell wall formation. The silica depletion that results from high phosphorus loading thus causes qualitative and quantitative changes in algal populations. When phosphorus is added to a system in excess, depleting silica, a species shift will occur towards predominately nonsiliceous algal forms, such as the undesirable blue-greens.



Recent experiments (Schelske and Stoermer, 1971, 1972) have shown that silica is indeed limiting diatom growth in southwestern Lake Michigan. Approximately ten to twenty times more phosphorus is being added than can be utilized by diatoms at available silica levels. In 1969, lowest concentrations of silica were found in southernmost surface samples within Lake Michigan (Schelske and Callender, 1970). Chicago water intake records also show decreasing silica concentrations with time (Powers and Ayers, 1967). Diffuse source loads of phosphorus in Lake Michigan are contributing to phosphorus overloads with respect to silica concentrations.

While some have suggested that diatom production is dependent on watershed input of silica (Lund, 1972; Upchurch, 1972), the majority of investigators have emphasized the importance of contributions of reactive soluble silica via dissolution and recycling processes (Duthie and Sreenwasa, 1971; Frey, 1974; Parker and Edgington 1975, 1977a; Conway *et al.*, 1977; Nriagu, 1978). For example, silica budget calculations (Nriagu, 1978) have shown that regeneration of silica from Lake Ontario and Erie sediments far exceeds annual inputs from external sources. About 90 percent of the silica taken up by diatoms is reconverted to soluble silica at the mud-water interface following die-off and settling of diatom blooms (Nriagu, 1978).

Table A5 shows that, while the storage pool of silica in the lakes is large, some silica is lost permanently each year. Thus, inflow of silica from tributaries is necessary to maintain silica levels. The impact that control of nonpoint sources might have on silica inputs to the Great Lakes is not known, but should be considered in the future. Possibly a reduced silica load would encourage growth of less desirable blue-green algae over diatoms.



TABLE A5

BUDGET FOR DISSOLVED SILICA  
IN LAKES ONTARIO, ERIE AND SUPERIOR

Source/Sink	Annual Input/Output (10 <sup>7</sup> kg)
<u>LAKE ONTARIO</u>	
Inflow, Niagara River <sup>1</sup>	4.72
Inflow, other sources <sup>2</sup>	7.60
Outflow, St. Lawrence River <sup>3</sup>	5.83
Storage pool, lake water <sup>3</sup>	62.9
<u>LAKE ERIE</u>	
Inflow, Detroit River <sup>2</sup>	17.5
Inflow, other sources <sup>1</sup>	11.0
Outflow, Niagara River <sup>1</sup>	4.72
Storage pool, lake water <sup>3</sup>	12.6
<u>LAKE SUPERIOR</u>	
Inflow, all sources <sup>4</sup>	28.0
Outflow, St. Marys River <sup>4</sup>	16.0
Storage pool, lake water <sup>3</sup>	2,800

1. Including the Welland Canal.
2. Data from Upchurch, 1972.
3. N.D. Warry, personal communication. Data do not include about  $2.5 \times 10^{10}$  kg of SiO<sub>2</sub> loaded annually into the lake as taconite tailings. See Nriagu, 1978.
4. Calculated from the monitor cruise data bank at Canada Centre for Inland Water, Burlington, Ontario.

SOURCE: Nriagu, 1978.



## TOXIC MATERIALS

A major concern identified by the Pollution from Land Use Activities Reference Group (PLUARG) is the impact of toxic materials entering the Great Lakes from both point and nonpoint sources (PLUARG, 1978a). Although a great deal of information has been collected on the toxicological effects of contaminants in the environment (see for example, the extensive literature review of Leland *et al.*, 1978), relatively little is known about the significance of nonpoint sources. This section summarizes available information on three important classes of toxic contaminants known to arise from land drainage: heavy metals and trace toxic elements; industrial organics; and pesticides. Many gaps in understanding the impact of trace contaminants on the Great Lakes ecosystem still need to be filled.

### HEAVY METALS AND TOXIC ELEMENTS

Problems caused by heavy metals entering the Great Lakes ecosystem were brought to the attention of both scientists and the public at large in the late 1960s when mercury contamination closed the Lake St. Clair fishery. While steps have been taken to alleviate this problem, there is still concern about the potential for future problems associated with mercury and other toxic elements.

In an extensive study, Fitchko and Hutchinson (1975) correlated heavy metal concentrations in sediment at 116 river mouth locations with general levels of development in the watershed. Generally, undeveloped watersheds showed low concentrations while those with significant urban-industrial activities showed higher levels. A number of significant correlations were also reported between metal concentration (especially lead, copper, nickel, zinc, manganese, and mercury) and clay and organic matter content, (measured by loss on ignition). It is difficult to separate out point and nonpoint source effects, but it is probably safe to conclude that nonpoint sources are not a significant source of metals, since past studies (Sonzogni *et al.*, 1978) indicate inputs from undeveloped areas are derived mostly from nonpoint sources. This conclusion is consistent with the results of the land runoff monitoring program conducted by PLUARG (1978b).

As with phosphorus, the availability of metals and toxic elements is a factor in determining effects. Limited studies on suspended solids from Great Lakes tributaries (Armstrong *et al.*, 1978) indicate that 20 to 70 percent of the total concentration of metals such as copper, zinc and lead were in an available form. The variation in the percent available depends on the river system, size fraction and specific metal. In most cases it would appear that less than 50 percent of the metal is available.



Two criteria have been suggested (PLUARG, 1978a) for evaluating the problem potential of a given heavy metal or trace element:

1. Potential for methylation to a more toxic, bioactive form.
2. Increased levels in the Great Lakes system, indicating loadings above natural background (Thomas, 1977).

Using the above criteria, the following prioritized list was suggested for further study:

1. mercury, lead
2. arsenic, cadmium, selenium
3. copper, zinc, chromium, and vanadium

Of these, only lead is strongly linked to nonpoint sources. The discussion which follows is thus limited to lead.

### Lead

Most of the lead entering the Great Lakes is from diffuse sources. In general, lead levels do not significantly limit the use of the Great Lakes. Lead concentrations in the open waters of the lakes fall well below limits recommended by the Water Quality Objectives Workgroup of the International Joint Commission. Levels of lead in Great Lakes fish also fall well within the established guideline of 10 mg/kg (PLUARG, 1978a). Concern has been expressed, however, that lead may undergo chemical and biological methylation in the lakes, magnifying its potential toxicological effects. Lead has been found to inhibit photosynthesis and to bioaccumulate in both vertebrates and invertebrates, where it may produce lethal and sublethal effects.

Sources. It is estimated (PLUARG, 1978a) that approximately 90 percent of the 6,700 metric tonnes of lead entering the Great Lakes are from diffuse sources. About 3,600 metric tonnes, or 60 percent of the diffuse load, is from atmospheric deposition. Another 800 tonnes per year is from shoreline erosion. This leaves approximately 1,600 tonnes contributed each year by land drainage.

The greatest nonpoint source contributors of lead on a unit area basis are urban areas, where automobile exhaust gases and industrial processing emissions are the major sources. Unit load estimates found by PLUARG range from 0.06 kg/ha-yr in residential areas to a high of 7.0 kg/ha-yr in industrial areas. Average loading values for urban areas in general range from 0.14 to 0.5 kg/ha-yr.

Observed unit area loads of lead from agricultural areas are an order of magnitude less than those from urban areas, with estimated values ranging from .002 to .08 kg/ha-yr. Sources include native lead in the soil and atmospheric deposition on the land surface.

Unit area loads from forested and other lands are generally lower than those from agricultural areas. Unit area loads of 0.01 to 0.02 kg/ha-yr have been reported. Sources are similar to those on agricultural lands.

Effects on the Great Lakes. As mentioned, a principal concern about lead



in the lakes is its potential ability to undergo chemical and biological methylation, forming highly toxic tetramethyl lead. There is some question about how extensive methylation is in the Great Lakes. An alternative view holds that most of the lead inputs are lost to the bottom sediments. Data clearly shows that significant quantities of lead are reaching the sediment (International Joint Commission, 1975 ; PLUARG, 1978a). Little information is available regarding the potential for its subsequent re-release to the water column.

There is evidence, however, of release mechanisms other than direct release from the sediments. Studies of angiosperms in English lakes indicated that lead content of root and shoot tissue varied more closely with sediment lead concentrations than with concentrations in the water (Welsh and Denny, 1976). Other studies on a small English estuary have shown a pattern between lead concentrations in filter feeders (clams) and concentrations in sediments (Brynan and Hummerstone, 1977). Lead levels in algae, on the other hand, have been correlated with concentrations of lead in the water (Payer et al., 1976).

Although lead is widely recognized as an environmental toxicant, information concerning its effects on the biota is far from complete. Experimental results have shown that concentrations needed to inhibit growth and metabolic processes in aquatic flora vary considerably, depending on such factors as the degree of chelation, concentration of cells and nutrients, physiological state of cells, and temperature (Leland et al., 1978). Toxicity is generally greater in waters of low hardness. This is significant as Great Lakes waters are of low to medium hardness (Great Lakes Basin Commission, 1976a). Concentrations of  $PbCl_2$  as low as 0.085 mg/L Pb have been found to reduce photosynthesis of P. tricorutum by 25 to 50 percent, while at 8.5 mg/L Pb concentrations photosynthesis was completely suppressed (Wollery and Lewin, 1976). Inhibition of growth has also been reported by Silverberg et al. (1977). Gaechter (1976) found that lead inhibited photosynthesis less than did mercury, copper, calcium, and zinc. Evidence of synergistic and seasonal variation in organism sensitivity was also discovered.

Studies of marine and freshwater invertebrates have revealed lead bioaccumulation. Concentrations of lead observed in selected freshwater invertebrates range from 10 to 48 mg/g dry weight (Anderson, 1977; Manly and George, 1977). The latter study also showed a positive correlation between increased body weight and lead concentration in the tissues in contaminated portions of the Thames River; no correlation was found in uncontaminated portions of the river. Recently, Borgmann et al. (1978) found that Lymnaea palustris, a freshwater snail, suffered a significant increase in mortality rate and a 20 percent reduction in biomass production when exposed to low levels of lead in Lake Ontario. Importantly, the level used in these tests was below the limit for lead proposed by the International Joint Commission (1976).

Information regarding lethal and sublethal concentrations of lead for aquatic invertebrates is scarce. Lead concentrations of 0.5 mg/L Pb were found to inhibit unadapted populations of Vorticella convallaria (Sartory and Lloyd, 1976). Relationships have been found between size and metal concentration in many fish species. Unlike pesticides and other organic contaminants, which



concentrate in the fat tissue, lead and other metals tend to accumulate in the organs and muscle (Somero *et al.*, 1977). Other experiments have indicated that the rate of lead uptake increases at lower pH levels, possibly due to higher concentrations of free  $Pb^{2+}$  at lower pH (Merlini and Pozzi, 1977).

Recent literature on the toxicity of metals to fishes has stressed the importance of sublethal effects of exposure: changes in growth, fecundity or brood survival; physiological and biochemical alterations; and immune response suppression. Tests of the chronic toxicity of lead to brook trout showed toxic symptoms at 84 mg/L Pb but not at 39 mg/L Pb (Holcombe *et al.*, 1976). The same experiments showed that lead accumulated during the egg, alevin, and juvenile life stages. In another series of experiments to measure the toxicity of lead to brook trout, Davies (1975) demonstrated that results may vary widely, depending on whether total or dissolved lead concentration is measured. Experimental results in hard water showed a 96-hour lethal concentration to 50 percent of fish (LC50) of from 1.32 mg/L to 1.47 mg/L dissolved lead, compared to 471 mg/L to 542 mg/L total lead. Results in soft water showed a 96-hour LC50 of 1.17 mg/L dissolved lead. Similar patterns were observed when evaluating sublethal effects. Substantial additional data on lethal and sublethal effects on fish can be found in USEPA, 1976. Little or no information is available on Great Lakes fish, however.

Information on accumulation of lead in higher order vertebrates and its effects *vis a vis* water quality use is scarce. A survey of herons on Lake Erie showed no significant lead accumulation (Hoffman and Curnow, 1973). Waterfowl tested in New York State, however, showed lead levels upward to 14.0 mg/kg (Baker *et al.*, 1976). Effects of lead on humans are well documented and have been summarized elsewhere (e.g., U.S. Environmental Protection Agency, 1976).

In summary, it is apparent that excessive levels of lead entering the aquatic environment could adversely affect the biota. Currently, however, lead does not appear to be causing any significant impairment of the Great Lakes resource. Restrictions on the use of leaded gasolines should reduce future inputs. Research should be conducted, however, to determine long-term trends of lead accumulation in the environment and the extent to which methylation occurs.

#### INDUSTRIAL ORGANICS

Industrial organics are of the most recent concern among toxic pollutants in the Great Lakes. Due to the extreme toxicity at very low levels, many of these substances present perhaps the most serious threat to the Great Lakes of all toxic substances. Since industrial organics are derived principally from manufacturing and other industrial processes, land runoff is not usually a major source of these substances. Industrial organics include benzene, hexachlorobenzene, phthalate esters, toluene, dioxins and polychlorinated biphenyls (PCBs). PCBs are perhaps the most well known, at least with respect to the Great Lakes.



## Polychlorinated Biphenyls (PCBs)

Since their introduction 50 years ago, PCBs have spread throughout the environment, primarily by atmospheric transport. Perhaps because of the Great Lakes position at the center of a highly industrialized region and their unique ecological status, they have been particularly susceptible to PCB inputs from all sources: point, land runoff, and atmospheric. Atmospheric deposition on the land and subsequent runoff appears to be the major nonpoint source of PCBs in the lakes. PCBs bioaccumulate in both invertebrates and vertebrates, with lethal and sublethal effects.

Sources. The tributary load of PCBs to the Great Lakes was recently estimated by PLUARG (1978a) to be 700 kg/yr, 40 percent (310 kg/yr) of which comes from urban areas. This estimate may be conservative. Armstrong and Weininger (1978) estimated that, for Lake Michigan alone, streams and municipal wastewaters contribute about 750 kg of PCBs annually. A complete mass balance of PCBs for Lake Michigan, developed by Armstrong and Weininger from information derived from Murphy and Rzeszutko (1977) is given in Table A6.

Estimation of PCB loads is complicated because concentrations are generally low and several isomers are in use. Significant inputs may be entering the lakes undetected.

Results from the PLUARG pilot watershed studies showed PCB unit area loads ranging from 0.003 to 0.26 g/ha-yr from urban areas. Unit area loads from agricultural areas were essentially identical, ranging from 0.08 to 0.22 g/ha-yr (PLUARG, 1978a). This suggests that the major source of PCBs derived from land drainage is atmospheric deposition and subsequent wash-off.

Limited data concerning PCB concentrations in precipitation (International Joint Commission, 1977a) indicate a range from 0.01 to 0.10 mg/L. Assuming that average annual precipitation is 76 cm/yr (30 inches/year), the annual unit area load to the land and water surface would be 0.08 to 0.76 g/ha-yr. An unpublished paper prepared by several PLUARG investigators (Andren et al., 1977) presents a "best estimate" range of 0.2 to 2.0 g/ha-yr for PCB atmospheric loads to the lakes. Studies of atmospheric deposition over the Lake Michigan basin (Kleinert, 1976) have estimated loadings to be 0.50 g/ha-yr. Finally, work done by Murphy and Rzeszutko (1977) showed PCB concentrations in precipitation of 0.119 mg/L, which is 0.88 g/ha-yr in unit area terms. Applying these figures (0.08 to 2.0 g/ha-yr) yields an estimated direct atmospheric contribution to the lakes of 2.0 to 50 tonnes/yr. Based on the data reported above, the "most probable" unit area load is 0.5 to 1.0 g/ha-yr, which narrows the range of loads to 12 to 25 tonnes per year.

Effects on the Great Lakes. Concern over high levels of PCBs in the environment has prompted extensive research into its toxicological effects. The recent literature contains many reports on levels of PCBs in the Great Lakes and its effects on the biota. There still is not a system-wide understanding of how PCBs act in the environment, however.



TABLE A6

## ESTIMATED INPUT, OUTPUT AND CONTENT OF PCBs IN LAKE MICHIGAN

MASS OF PCBs IN WATER (kg)

Dissolved (12 mg/L)	61,000 kg
Suspended (19 mg/L)	91,000 kg
Total	<u>152,000 kg</u>

MASS OF PCBs IN SEDIMENT (kg)

Upper 2 cm (0.4 $\mu\text{g/g}$ )	128,000 kg
2-5 cm (0.02 $\mu\text{g/g}$ )	9,600 kg
Total	<u>137,000 kg</u>

INPUTS (kg/yr)<sup>1</sup>

Streams and wastewaters	750 kg/yr
Precipitation	4,800
Dry fallout	2,800
Sub-total	<u>8,350 kg/yr</u>
Industrial discharges <sup>2</sup>	8,000
Total	<u>16,350 kg/yr</u>

OUTPUTS (kg/yr)

Biodegradation, volatilization, harvesting	0
Surface water discharge	1,520 kg/yr
Sedimentation	6,900
Total	<u>8,420 kg/yr</u>

1. Inputs based mainly on Murphy and Rzeszutko (1977).
2. Loss from the industrial facility at Waukegan, Illinois was about  $0.5 \times 10^6$  kg. One-third was assumed to reach Lake Michigan and the loss was assumed to be distributed over a 20-year period.

SOURCE: Armstrong and Weininger, 1978.



PCB in the Great Lakes sediment have been estimated (PLUARG, 1978a) to total 76.6 tonnes. Of that, more than 45 percent (35.6 tonnes) is in Lake Erie. PCB concentrations in the sediment range from 9 ppb in parts of Lake Huron to 252 ppb in limited portions of Lake Erie. Other studies have reported sediment PCB levels up to 13,000 ppb (Dennis, 1975). The high levels of PCBs observed in bottom sediments indicate that sediment acts as a sink for much of the input to the lakes. Studies on Escambia Bay, Florida, indicate that PCB-laden sediments are a continuing source for the aquatic biota (Duke, 1974).

No information was found on levels of PCB in aquatic flora of the Great Lakes. Information concerning toxic effects on aquatic invertebrates in the Great Lakes is also scarce. Experimental results have shown that small insects and crustaceans with short life cycles are most sensitive to PCBs, although the degree of toxicity is related to the PCB isomer tested (Nebeker, 1975). For example, a 50 percent reduction in midge reproduction was observed at Aroclor 1254 concentrations of 0.45 mg/L. Similar results in *Daphnia* were found at concentrations of 1.3 mg/L (Nebeker, 1975). In the latter case, 2.1 mg/L of Aroclor 1248 were required to produce a similar reduction in reproduction.

In addition to direct toxic effects, PCBs tend to bioaccumulate in insects and other invertebrates. Studies summarized by Nebeker showed bioconcentration factors up to 50,000 for Aroclor 1248 by *Gammarus pseudolimmaeus*. The rapidity with which some organisms accumulate PCB was also demonstrated. *Daphnia magna*, exposed to 1.1 mg/L concentrations of Aroclor 1254, accumulated total body concentrations 48,000 times greater than the water concentration in 96 hours. In another experiment, mosquito larvae (*Culex tarsalis*) accumulated 19 mg/g of Aroclor 1254 in 24 hours, a 12,600-fold magnification of the water concentration of 1.5 mg/L. Although these are results of laboratory experiments, there is evidence that similar bioconcentration factors occur in natural waters. Specific effects of PCBs derived from land runoff on Great Lakes insects are not known, however.

Most of the work reported on PCBs concerns their uptake, accumulation, and effect on fish and higher vertebrates. Ingestion (consumptive uptake) of PCB-concentrating invertebrates is probably a significant source of PCBs in fish. However, direct uptake of PCBs from the water (primarily via the gills), even when concentrations are very low, has been generally thought to be the most important source. Experiments reported by Nebeker (1975) indicated a bioconcentration factor of 30,000 to 270,000 in fathead minnows for a range of Aroclors. Compounds with a higher proportion of chlorine tended to have the highest bioconcentration factors. Other studies (U.S. Environmental Protection Agency, 1976) showed similar results. Studies by Veith and Lee (1971a and 1971b) on the Lower Milwaukee River showed bioconcentration factors for Aroclor 1248 in goldfish ranging from 70,000 to 200,000. Bluegill sunfish exposed to Aroclors 1248 and 1254 showed a bioconcentration factor of 71,000 (Stalling and Mayer, 1972).

Despite dramatic bioconcentration through direct uptake, Weininger (1978) reasoned that it alone does not account for the PCB levels in the Great Lakes fish. Based on a bioenergetics model, he concluded that most of PCBs found in many Great Lakes fish is the result of consumption of PCB-laden foods. The



predominant pathway for these fish was concluded to be the following: water--> phytoplankton and suspended particulates-->zooplankton-->macroinvertebrates-->forage fish (e.g., alewives)-->piscivorous fish (such as lake trout and salmon).

Studies have also been conducted to determine the lethal and sublethal effects of PCB exposure to fish. Ninety-six hour LC50 (Lethal Concentration to 50 percent of the population) values of 15 mg/L and 7.7 mg/L for Aroclors 1242 and 1254, respectively, were determined for fathead minnows. Concentrations of 8.8 mg/L and 4.6 mg/L for the same two Aroclors were fatal to 50 percent of the fathead minnows in a 60-day continuous flow experiment (Nebeker et al., 1974). In contrast, 96-hour LC50 values for cutthroat trout ranged from 1,170 to 50,000 mg/L. Because of its low solubility in water, PCB toxicity to fish tends to increase with longer exposure times.

Tests using fathead minnows (Nebeker et al., 1974) showed that significant reductions in spawning occurred at concentrations of PCB of 1.8 mg/L, although egg hatchability and fry survival were good. Growth of young was affected above 2.2 mg/L Aroclor 1248, however, and none survived at concentrations greater than 5.1 mg/L.

Studies using lake trout Schoettger et al., 1970) showed retardation of growth by exposure to Aroclor 1248 in the diet for three months. Concentrations in the diet of 1.2, 3.8, and 12 mg/g reduced growth by 6, 10, and 28 percent, respectively. Growth of the group fed 12 mg/g was about half that of the control group after six months.

In addition to controlled studies to determine the effects of PCBs on specific fish species, work has been done to determine levels of PCBs in Great Lakes fish populations (Kleinert, 1976; Brezina and Arnold, 1976; International Joint Commission, 1976a; Foster, 1977; Spagnoli and Skinner, 1977). In general, these studies have found measurable amounts of PCBs in fish samples taken throughout the Great Lakes basin, in some cases in excess of the present U.S. standard of 5.0 ppm. Areas with problems include Lake Michigan (Kleinert, 1976; Illinois Institute for Environmental Quality, 1976; Foster, 1977) and Lake Ontario (Spagnoli and Skinner, 1977). Fish species with a high fat content, such as chubs, alewives and salmonids, generally showed the highest levels of contamination. Fish samples collected in western Lake Erie (Brezina and Arnold, 1976; Spagnoli and Skinner, 1977) and Lake Superior (International Joint Commission, 1976) did not exceed U.S. standards. It should be noted, however, that many samples collected in the latter study approached or exceeded the Canadian guideline of 2.0 ppm.

It is not possible to relate the concentrations of PCBs in fish to any particular source. Rather, the effect of PCB inputs from all sources, point, land runoff and atmospheric, are cumulative.

Since fish are major accumulators of PCBs (and other toxics) in the Great Lakes food chain, it might be expected that, if those fish which frequent river mouth areas are accumulating large amounts of PCBs, then land runoff could be identified as a major contributor of PCBs and specific rivers which are major



sources could be identified. This has not been found to be the case, according to the information available.

The anadromous behavior of many of the fish which readily accumulate PCBs increases the difficulty in relating land-derived PCB sources to specific effects on fish in the lakes. The collection of a PCB-laden salmon (which may range great distances in a short period) from a certain area does not necessarily imply that the fish accumulated the PCBs from that area. More probably, the accumulation results from inputs distributed throughout the lake system from all sources.

In a PLUARG study (Jerger *et al.*, 1978) PCB accumulation in benthic organisms off four river mouth areas were sampled. PCBs were found to be a potential problem in only one of the four rivers sampled. This river, the Menomonee, drains an urban complex within the Milwaukee metropolitan area. Furthermore, the stations sampled were predominantly in the estuarine zone rather than in the open lake. Whether the source was urban drainage, atmospheric inputs or discharges from industrial operations could not be ascertained.

One study (Baker *et al.*, 1976) examined levels of PCBs in several species of waterfowl collected in New York State. Levels of PCBs in tissue samples of two species in the Lake Ontario region, the greater scaup and white-winged scoter, were found to exceed U.S. Food and Drug Administration poultry standards of 5.0 ppm.

The effects of PCB contamination of mammals, including humans, have been studied and are well documented (Illinois Institute for Environmental Quality, 1976). Work at the University of Wisconsin (Allen *et al.*, 1974; Barsotti *et al.*, 1976; Norback and Allen, 1976) on nonhuman primates is particularly illuminating with regard to the potential devastating human impacts small levels of ingested PCBs may have. Reference should also be made to studies of the Yusho incident (Karatsure, Masuda and Nagayama, 1975) for an update and review of findings.

Further study is needed to complete the picture of how PCBs affect the Great Lakes system. Now that PCB manufacture and use has been (or will soon be) curtailed, studies need to be initiated to determine long-term trends in PCB levels, especially in fish.

#### PESTICIDES

Identifying the specific impacts of pesticide inputs to the Great Lakes is greatly complicated by the range of compounds and formulations used or manufactured in the basin. Of the approximately 225 million kilograms (490 million pounds) of pesticides used by U.S. farmers in the Great Lakes basin during 1971 (Doneth, 1975), 46 percent were herbicides and 34 percent were insecticides, with the remainder fungicides and other miscellaneous pest control substances. Application of insecticides are projected to remain stable or even decline, while herbicide use will increase by up to 25 percent. This is significant in terms of water quality impacts because herbicides are generally less toxic and persistent than insecticides.



There has also been a significant change in the types of pesticides used, especially insecticides, over the past 10 years. Many of the highly toxic persistent chlorinated hydrocarbon compounds, such as DDT, aldrin-dieldrin, and chlordane, have been banned or have had severe restrictions placed on their use. The organophosphate and carbamate compounds, such as carbaryl (Sevin), malathion and guthion, that have replaced them, are much less persistent and do not bioaccumulate as readily. They may be as toxic to nontarget organisms as the chlorinated hydrocarbons, however. Importantly, the organochlorine pesticides provide an excellent example of how pollutants derived from land runoff have had an obvious and serious effect on the Great Lakes.

Except for waste discharges from manufacturing plants, pesticide inputs to the lakes are from diffuse sources, both atmospheric and land runoff. PLUARG studies detected a range of pesticides in tributary drainage waters, including atrazine, DDT and metabolites, dieldrin, lindane, endrin, heptachlor and endosulfan (PLUARG, 1978c). Levels were generally too low to permit calculation of pesticide loads. Only atrazine, a herbicide used widely in corn production, was found frequently in stream samples (PLUARG, 1978b; Chesters *et al.*, 1978). Because it degrades rapidly and its use appears to be declining, it was determined not to be a significant problem.

Continuing inputs of chlorinated hydrocarbon compounds, such as DDT and dieldrin, the use of which has been banned or restricted, arise mostly from residues in the soil. The carry-over of persistent pesticides has been demonstrated in studies of agricultural areas where DDT and dieldrin residues in the soil were found to be equal to or greater than the average annual rates of application.

### Insecticides

The three principal characteristics of concern in evaluating the environmental impacts of insecticides are persistence, potential for bioaccumulation, and toxicity. It was the first and second characteristics that raised concern over the use of organochlorine compounds, such as DDT. As mentioned, these compounds are persistent in the soil, causing a significant buildup in fields on which they are applied. The newer organophosphate and carbamate pesticides, on the other hand, have half-lives ranging from several days to three or four months. Thus, they are less likely to be transported to streams and the lakes.

Although the chlorinated hydrocarbons are persistent, degradation mechanisms in the soil reduce their half-life. These include chemical reaction, microbial enrichment and co-metabolism (Goring *et al.*, 1975). While it is not possible to precisely evaluate the activity of these mechanisms on a large scale (i.e., the Great Lakes), it should be noted that their levels in Great Lakes waters and fish samples have declined rapidly since their use was banned or restricted (International Joint Commission, 1976a; PLUARG, 1978a).

Sediments act as a sink for pesticides in the aquatic environment. Release from the sediments to the water is dependent on the solubility of the compound in water, its concentration in the sediment, sediment composition, and the degree of adsorption (Hamelink *et al.*, 1971). Potential for release is probably



minimized, however, due to the input of "clean sediment" (PLUARG, 1978b).

The distribution of these insecticides in Great Lakes sediments varies. Samples from Lake Superior showed trace levels (1.0 mg/kg or less) of DDT, DDD, and DDE. No other pesticide residues were reported. Lake Huron sediment samples showed a range from 3.0 to 30.7 mg/kg for DDT and its metabolites (International Joint Commission, 1977c). Some areas showed contamination with dieldrin. Total DDT residues were found in 90 percent of sediment samples collected on Lakes St. Clair, Erie and Ontario in 1975 (International Joint Commission, 1975), with values ranging from 2 to 88 mg/kg. Some samples also showed contamination with dieldrin and chlordane as well.

Levels of total DDT observed in the upper Great Lakes open waters generally fall within the guidelines for water supply and protection of fish and wildlife (U.S. Environmental Protection Agency, 1976; International Joint Commission, 1976a), although detectable levels (0.001 to 0.004 mg/L) were found in some parts of Lake Huron in 1975 (International Joint Commission, 1977c). Data collected on Lake Ontario showed mean total DDT and dieldrin levels of 0.028 mg/L and 0.005 mg/L, respectively (International Joint Commission, 1977a). It is expected that these relatively high levels will decline as in-place residues are depleted. Data were not available for Lakes Erie and Michigan.

The most obvious impact of organochlorine insecticides in the lakes is their bioaccumulation in the food chain, especially in the higher order fishes. Data collected on fish from all of the lakes except Erie show levels of DDT in excess of recommended FDA and/or IJC levels. (Hesse, 1975; International Joint Commission, 1976a, 1977a, 1977c). In general, however, there is a significant downward trend in concentrations in fish. One exception to this is fish from Lake Superior, where no discernible trend has been found (International Joint Commission, 1977b). The suspected causes are the oligotrophic state of the lake and/or continued sources of DDT. The former is supported by research findings (U.S. Environmental Protection Agency, undated) which indicate that pesticides may be less available to the water in highly fertile systems where the higher organic matter content offers a greater capacity to bind the pesticide residues and make them unavailable.

The PLUARG U.S. Task D sponsored a study (Jerger *et al.*, 1978) of benthos samples collected at the mouth of tributaries known to have high nonpoint source loads. Benzene hexachloride levels were elevated in Vermillion and Menomonee River samples, low levels existed in Maumee River samples, and none were detected in the Grand River samples. The widespread use of this material as an insecticide could explain its presence in biological tissue.

Dieldrin and endrin levels in the benthos were relatively low except for a number of stations in the Menomonee River. The Menomonee River also exhibited higher levels of DDD, and one station on the river provided the only sample to show a detectable level of heptachlor. Elevated levels of methoxychlor were found in the Menomonee and Grand Rivers and elevated levels of chlordane were observed in the Menomonee and Maumee Rivers. Heptachlor epoxide and DDT were essentially undetectable in all samples.



In addition to the bioaccumulative capacity of the chlorinated hydrocarbon compounds, the direct toxicity, both acute and chronic, of all types of insecticides should be considered. Although large scale problems from land-derived insecticides are unlikely, local problems could occur. In this respect, there may be very little difference between the persistent organochlorines and the organophosphates and carbamates: LC50 concentrations for many compounds in each class fall within the same orders of magnitude for a wide range of freshwater organisms (see summary in Appendix 2 of U.S. Environmental Protection Agency, undated).

Table A7 was compiled to show comparative values for a number of organisms. As the figures show, 96-hour LC50 concentrations for invertebrates are similar. Fishes, however, seem to be somewhat less susceptible to the less persistent compounds. This pattern can also be seen in larger data sets (U.S. Environmental Protection Agency, undated). It must be remembered that in a total ecosystem, effects at one level of the food chain will have repercussions throughout the system. Thus, lethal effects on the invertebrates may result in reduced fish populations.

Sublethal and chronic effects are also associated with pesticide inputs. These effects vary from species to species as well as from compound to compound (U.S. Environmental Protection Agency, 1976 and undated).

#### HERBICIDES

In general, herbicides are less toxic and less subject to bioaccumulation than insecticides (U.S. Environmental Protection Agency, 1974). Herbicides such as silvex, pichloram, 2,4-D, and dichlobenil do not appear to bioaccumulate more than tenfold, if at all, in aquatic organisms; this is compared to accumulation factors of one million or more for DDT (U.S. Environmental Protection Agency, 1974).

Many herbicides are water soluble, so they do not partition as greatly in favor of fat tissues as do the organochlorine pesticides. As a result, herbicides and their metabolites are not passed as readily through the food chain, and cumulative effects are not commonly seen.

In actual toxicity tests, a wide range of susceptibilities has been found in freshwater invertebrates. Dichlone was found to be the most toxic compound out of 16 tested, with 48-hour LC50 values of 0.025 mg/L for Daphnia magna and 3.2 mg/L for crayfish (U.S. Environmental Protection Agency, 1974). In comparison, the 48-hour LC50 for D. magna for atrazine, a herbicide found in Great Lakes tributaries, was found to be 3.6 mg/L, a concentration of almost 150 times that of dichlone to produce the same lethal effect. This is more than 1,000 times higher than the mean concentration of atrazine found in PLUARG agricultural watershed monitoring studies (PLUARG, 1978c).

As with other toxic materials, herbicides may also produce sublethal and chronic effects in aquatic organisms. Little information on this is available for Great Lakes waters, however.



TABLE A7

ACCUTE TOXICITY (96-hour LC50) DATA FOR FRESHWATER ORGANISMS (in mg/L)

ORGANISM	Organochlorine			Organophosphate			Carbamate
	DDT	Chlordane	Methoxychlor	Guthion	Diazinon	Malathion	Sevin
Crustacean							
<u>Gamarus lacustris</u>	1.0	26	0.8	0.15	200	1.0	16.0
<u>Daphnia pulux</u>	0.36 <sup>a</sup>	29	0.78		0.9	1.8	6.4
Insects							
-161- <u>Pteronareella badio</u>	1.9					1.1	1.7
<u>Pteronarcy Californica</u>	7.0	15	1.4	1.5	25	10	4.8
Fishes							
<u>Pimephales promelas</u>	19	52	7.5	93		9000	9000
<u>Lepomis macrochirus</u>	8	22	62	5.2		110	6760
<u>Oncorhynchus kisutch</u>	4	56	66.2	17		101	764

a. 48-hour LC50

SOURCE: U.S. Environmental Protection Agency, undated.



In summary, pesticide inputs from past use of chlorinated hydrocarbon compounds continue to be a problem in many parts of the basin. Levels of pesticides are declining, however, indicating that soil residuals are being depleted through erosion and degradation. To date, no severe problems have been found related to the use of organophosphate and carbamate compounds, which have replaced the more persistent organochlorine compounds. Increased use of herbicides is also not expected to cause significant problems. Thus, the overall impact of pesticides on the Great Lakes is expected to diminish in the future.



## APPENDIX A

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