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Study Proposal for Assessing Potential for Great Lakes Contamination via Groundwater

Great Lakes Science Advisory Board. Groundwater Contamination Task Force

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A Study Proposal for Assessing Potential for Great Lakes Contamination via Groundwater
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Prepared by the Groundwater Contamination Task Force of the Science Advisory Board of the International Joint Commission

October, 1985
Windsor, Ontario
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Preface

Annex 11 1(d) of the 1978 Great Lakes Water Quality Agreement (GLWQA) calls for surveillance and monitoring activities that will identify emerging problems. As of a few years ago, the groundwater pathway was given little consideration as a possible pathway for contaminants to the Great Lakes. Given the Niagara River incident, the subsurface pathway has now emerged as a potential significant route of contaminant transport to the Great Lakes.

The following study proposal provides a strategy that can be used to determine the potential for Great Lakes contamination through the underground pathway. The study when initiated and completed would serve as an initial framework around which a comprehensive groundwater-surface water monitoring strategy for the Great Lakes can be developed in keeping with Annex 11 1(d) of the GLWQA.

The preparation of the study proposal would not have been possible without the special funding appropriation made to the Northeastern Regional Office of the United States Geological Survey (USGS). In this regard, the Task Force acknowledges the efforts of Mr. Marvin Sherrill with the Illinois District Office and staff of the Northeastern Regional Office of the USGS for assistance in bringing together the information for this report and assistance in drafting the report. The Task Force is also indebted to the following Great Lakes Regional Office staff during the review and report preparation process: Dr. Ron Drynan for providing many constructive comments, Ms. Evelyn Sayers for editorial improvements, and Ms. Susan Morgan and Mr. Yvan Gagne for reproduction of the maps.

Any viewpoints contained herein are those of the Groundwater Contamination Task Force and should not necessarily be construed as those of the Great Lakes Science Advisory Board or the International Joint Commission. The Board's summary of the study proposal, conclusions and recommendations can be found in
their 1985 Annual Report. Copies of the Report may be obtained from the International Joint Commission at the Great Lakes Regional Office in Windsor, Ontario, Canada.
1. Introduction

Contamination of the Great Lakes from groundwater transported substances was examined by the Great Lakes Science Advisory Board (SAB) of the International Joint Commission (IJC) in 1983. Numerous controlled and uncontrolled waste disposal sites were identified within the Great Lakes basin and some cases were reported where toxic substances from these sites have contaminated groundwater which in turn was transported into the Great Lakes.

The Board found that major deficiencies exist in the knowledge about the nature and extent of groundwater contamination within the basin. Existing estimates of groundwater flow based upon general geology were also found to be inadequate. Even more importantly, the hydrogeologic regimens that have the greatest potential for contaminating the Great Lakes have not been well defined.

Drawing upon the findings of the SAB, it was decided at the first Groundwater Contamination Task Force (GCTF) meeting that "a detailed study design be prepared for inventorying, assessing and subsequently identifying the major hydrogeologic regimens that have a high potential for contaminating the Great Lakes." It was agreed that the activities should be titled "Hydrogeological Inventory and Assessment of the Great Lakes Basin" and the objective would be to define the major hydrogeologic regimens of the Great Lakes basin and to assess their potential for contaminating the Great Lakes. At their December 11-12, 1984 meeting, the SAB of the IJC, unanimously approved a special appropriations to the U.S. Geological Survey (USGS) to assist the Groundwater Contamination Task Force with the preparation of a study proposal.

This report presents a proposal for a study that will identify the major hydrogeologic regimens of the Great Lakes basin and assess their potential impacts upon Great Lakes water quality.
The study proposal includes:

a) a discussion of the need for such a study including a statement of objectives, scope and limitations;
b) an approach or methodology for defining the hydrogeology and land-use of the Great Lakes basin and determining pollution sources which can contaminate groundwater and ultimately affect the water quality of the Great Lakes;
c) an estimation of the time and costs for the study;
d) a bibliography of relevant references and maps required for this investigation including their sources; and
e) background information on the Great Lakes, and preliminary geologic, hydrologic and land-use maps of a nature similar to those which may be produced in the study phase during the fiscal years of 1986/87 and 1987/88. These maps, which include a preliminary contamination potential map, will be referred to throughout the remainder of this report.

Migration of contaminants to the Great Lakes via groundwater depends partially upon the hydrogeological processes of dispersion, diffusion and adsorption. Physio-chemical properties of the contaminant are also important. Chemicals of most concern would be soluble, nonvolatile and persistent. The characterization of contaminants with respect to these properties will not be a part of this study proposal since under diverse or complex subsurface environments, as is the case for much of the Great Lakes basin, the behaviour of both organic and inorganic substances remains poorly understood. The role of physio-chemical properties in contaminant migration will be considered only in a generic sense in that certain contaminants tend to be associated with certain land-use activities and disposal practices.
Figure 1. Location of Major Cities in the Great Lakes Basin

USA – COUNTIES BY STATES

MINNESOTA
1. COOK  2. LAKE  3. ST. LOUIS  4. TAHOE

WISCONSIN

MICHIGAN

CANADA – ONTARIO COUNTIES, DISTRICTS & REGIONAL & DISTRICT MUNICIPALITIES

USA – COUNTIES BY STATES

MINNESOTA
1. COOK  2. LAKE  3. ST. LOUIS  4. TAHOE

CANADA – ONTARIO COUNTIES, DISTRICTS & REGIONAL & DISTRICT MUNICIPALITIES

USA – COUNTIES BY STATES

MINNESOTA
1. COOK  2. LAKE  3. ST. LOUIS  4. TAHOE

CANADA – ONTARIO COUNTIES, DISTRICTS & REGIONAL & DISTRICT MUNICIPALITIES
## Table 1

### The Physical and Cultural Characteristics of the Great Lakes Basin

<table>
<thead>
<tr>
<th>Physical Characteristics</th>
<th>Superior</th>
<th>Michigan</th>
<th>Huron</th>
<th>Erie</th>
<th>Ontario</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Water Surface Area (km²)</td>
<td>81,103</td>
<td>57,757</td>
<td>59,570</td>
<td>25,667</td>
<td>19,010</td>
</tr>
<tr>
<td>- Land Surface Area (km²)</td>
<td>128,954</td>
<td>118,104</td>
<td>134,162</td>
<td>61,099</td>
<td>64,129</td>
</tr>
<tr>
<td>- Shoreline Length (km)</td>
<td>4,798</td>
<td>2,671</td>
<td>5,116</td>
<td>1,377</td>
<td>1,168</td>
</tr>
<tr>
<td>- Volume of Water (km³)</td>
<td>11,910</td>
<td>4,915</td>
<td>3,536</td>
<td>483</td>
<td>1,637</td>
</tr>
<tr>
<td>- Flow Retention (years)</td>
<td>191.0</td>
<td>99.1</td>
<td>22.6</td>
<td>2.6</td>
<td>6.0</td>
</tr>
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</table>

### Cultural Characteristics

<table>
<thead>
<tr>
<th>Cultural Characteristics</th>
<th>Superior</th>
<th>Michigan</th>
<th>Huron</th>
<th>Erie</th>
<th>Ontario</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Population (000's)</td>
<td>706</td>
<td>13,970</td>
<td>2,259</td>
<td>12,863</td>
<td>6,125</td>
</tr>
<tr>
<td>- Population of Total (%)</td>
<td>2.0</td>
<td>38.9</td>
<td>6.3</td>
<td>35.8</td>
<td>17.0</td>
</tr>
<tr>
<td>- Population Density (people/km²)</td>
<td>5.5</td>
<td>118.3</td>
<td>16.8</td>
<td>210.5</td>
<td>95.5</td>
</tr>
<tr>
<td>- Land-use</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Urban</td>
<td>0.1</td>
<td>3.5</td>
<td>1.8</td>
<td>9.2</td>
<td>4.4</td>
</tr>
<tr>
<td>- Agricultural (%)</td>
<td>1.4</td>
<td>23.4</td>
<td>22.5</td>
<td>59.1</td>
<td>31.6</td>
</tr>
<tr>
<td>- Woodlands or Barren</td>
<td>98.5</td>
<td>73.4</td>
<td>75.7</td>
<td>31.7</td>
<td>64.0</td>
</tr>
</tbody>
</table>

### Major Industries

- Iron, Nickel & Copper Mining; Pulp & Paper; Tourism.
- Steel & Paper Production; Dairy & Agriculture; Tourism; Sand & Gravel.
- Forestry; Chemical & Cement Production; Mining; Tourism.
- Steel & Glass Production; Auto Mfg.; Sand & Gravel Mining; Commercial Fishing; Agriculture.
- Steel Production; Printing & Publishing; Electrical Goods; Transport Equipment; Tourism; Agriculture.

### Major Urban Centres

- Duluth, MN; Marquette, MI; Thunder Bay, ON; Superior, WI.
- Chicago, IL; Green Bay & Milwaukee, WI; Gary & South Bend, IN; Muskegon, Grand Rapids & Lansing, MI.
- Bay City, Saginaw, Port Huron, Midland, Alpena & Cheboygan, MI; Sudbury & Sarnia, ON.
- Detroit, MI; Buffalo, NY; Cleveland & Toledo, OH; Erie, PA; Windsor & London, ON.
- Rochester, Utica-Rome & Syracuse, NY; Hamilton, Toronto & Kingston, ON.

At 701 m. (2,301 ft.), the Lake Superior drainage basin in Minnesota contains the highest headwater elevation. The Great Lakes basin spans across three major and two minor Physiographic provinces that respectively include the Central Lowland, Superior/Laurentian Upland and the Appalachian Plateau; and at the St. Lawrence River the Adirondack and St. Lawrence Valley Provinces.

The basin has been glacially altered by four major glacial episodes and has a glacial till depth to bedrock ranging from zero to over 305 m. (1,000 ft.) (Figure 2). Bedrock in the southern part of the basin consists of sedimentary units of sandstone, shale and carbonate rocks overlying crystalline rocks (Figure 3). In the northern parts of Minnesota, Wisconsin and Michigan; the western part of New York; and in Canada, crystalline rocks are exposed or covered by thin layers of glacial till.

The annual precipitation received by the basin varies substantially from north to south because of temperature differences and west to east either because of lake effects or highlands. Average annual precipitation near Lake Superior is about 71 centimeters (28 inches) while to the south of Lake Michigan it is 96 centimeters (38 inches) (Sanderson, 1982). The largest amount of precipitation occurs in the Adirondack Mountains at greater than 127 centimeters (50 inches). Large amounts of snowfall typically occur on the leeward side or eastern side of the Lakes. Amounts greater than 250 centimeters (100 inches) per year have been recorded.

Average annual stream runoff in the region is 29 cm. (11.6 inches) with ranges from 23 cm. to 97 cm. (9 to 38 inches) (Great Lakes Basin Commission, 1975, p.25). The wide range of runoff is due to differences in precipitation, geology, topography and land-use. Twelve major tributary river basins to the Great Lakes have drainage areas ranging from a few to several hundred square kilometers (Waller and Allen, 1975).

The average annual flow at the outlet of the Great Lakes basin (St. Lawrence River at Cornwall) is 6,825 m.³/sec. (241,000 cfs). Because the lakes are essentially in an equilibrium condition over the long-term, this quantity can be assumed to be the long-term natural recharge for the Great
Figure 2. Drift Thickness in the Great Lakes Basin

Drift Thickness, in metres

- □ > 91
- □ 30-91
- □ < 30

Insufficient Data Generally < 30
Fig. 3 Bedrock Geology of the Great Lakes Basin

Adapted from Hough. 1959

GENERALIZED GEOLOGIC SECTION
NOT TO MAP SCALE

Great Lakes Basin drainage boundaries
Subbasins
1
Subbasin number

Lakes basin. Of this natural runoff total, 3,087 m$^3$/sec. (109,000 cfs) is streamflow to the lakes from the U.S. side of the basin (Sonzogni et al., 1978); 1,146 m$^3$/sec. (50,000 cfs) is net annual precipitation minus evaporation on the Lakes surfaces themselves (Great Lakes Basin Commission, 1976, p. 40); and the remainder of 2,322 m$^3$/sec. (82,000 cfs) is streamflow to the Lakes from the Canadian side of the basin.

Using a conservative estimate by Waller and Allen (1975, p. 8), 37 percent of the U.S. annual runoff or 1,132 m$^3$/sec. (40,000 cfs) is contributed by groundwater as baseflow. This estimate was based upon the 70 percent flow duration. However, according to Waller and Allen (1975, p. 8), "Where reliable flow-duration curves are available and represent ground-water drainage area, values up to 60 percent may be used as the minimum ground-water potential of an area". For example, the 60 percent value for the U.S. Great Lakes basin total is approximately 1,574 m$^3$/sec. (55,590 cfs) or 51 percent of the streamflow being from groundwater inflow.

The average annual contribution of groundwater to streamflow on the Canadian side of the Great Lakes basin is estimated to be less than 20 percent (Ontario Ministry of Natural Resources, 1984, p. 46). This is attributed to a predominance of low permeability deposits such as clay and silt and/or poorly fractured bedrock at the ground surface. Areas characterized by sand and gravel deposits, however, could have a groundwater contribution to streamflow as high as 60 percent.

Investigations undertaken within the Canadian Great Lakes basin during storm runoff events suggest that the groundwater contribution to streamflow is much higher. In the Harp Lake watershed near Huntsville, Ontario groundwater was found to comprise between 40-90 percent of the storm runoff depending upon rainfall amount and intensity, antecedent soil-moisture conditions and water-table depth (Bottomley et al., 1984). Working on another inlet within the same watershed, Sklash (1983) using several isotopic tracers also found a high groundwater contribution (80%) to peak discharge during a storm event. In the sandy Hillman Creek basin near Leamington, Ontario groundwater was estimated to contribute up to 80 percent of the peak discharge during a major storm event (Sklash and Farvolden, 1979). Investigations by Sklash et al.
in Big and Big Otter Creeks near Tillsonburg, Ontario and Sklash (1978) in the Canagagigue Creek near Elmira, Ontario also revealed groundwater contributions during rain events ranging between 52—88 percent of the peak discharge. Similar findings have been reported across the world.

Waller and Allen (1975) describe groundwater conditions for the U.S. side of the basin in some detail. Large supplies of groundwater are contained within the basin; however, productive aquifers are unevenly distributed. Hydrogeologic inconsistencies, such as variable thicknesses and permeabilities of aquifer units (Figures 4 and 5), and water quality variability combined with large localized use demands, cause some areas to have water availability problems.

Shallow groundwater divides generally coincide with surface water divides (Figure 6). Generally, the lakes and their surface water and shallow groundwater divides are never more than 200 km. (125 miles) apart and at one point the divide lies within 3.2 km (2 miles) of the Lakes. The exception to this general rule is the Chicago and Milwaukee areas. The surface water divide extends only a few kilometers from Lake Michigan, while the groundwater divide in the bedrock aquifer extends several kilometers beyond. The cause of this anomaly is heavy pumpage in the Chicago area which has created extensive drawdown cones and caused groundwater to flow into the area from Lake Michigan and from the Mississippi River basin beyond the surface water divide and outside the Great Lakes region. Because of the depths of these cones of depression and the interception of this water by wells, the water recharged from outside the surface water basin should not be a contributing factor to the pollution of the Great Lakes from groundwater.

2.2 CULTURAL CHARACTER

Besides containing the world's largest contiguous body of freshwater, the Great Lakes basin is also one of the more populated areas of North America. It is estimated that between 30-40 million people live and work in the basin. This area accounts for almost 15 percent of the United States and 1/3 of Canada's total population.
Figure 4. Relative Permeability of Unconsolidated Deposits in the Great Lakes Basin

Relative Permeability
- High
- Medium
- Low

Insufficient Data
Figure 5. Near-Surface Aquifer Units in the Great Lake Basin

<table>
<thead>
<tr>
<th>Near-Surface Aquifer Units</th>
<th>Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand and gravel aquifer</td>
<td>Moderate to high</td>
</tr>
<tr>
<td>Fractured rock aquifers</td>
<td>Moderate to high</td>
</tr>
<tr>
<td>Carbonates</td>
<td>Generally low</td>
</tr>
<tr>
<td>Pre-Cambrian rocks</td>
<td>Generally low</td>
</tr>
<tr>
<td>Low permeability aquifers (mainly shales)</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>Sandstone</td>
<td></td>
</tr>
</tbody>
</table>

Yields:
- Moderate to high: Moderate to high production potential.
- Generally low: Generally low production potential.
- Low to moderate: Low to moderate production potential.
Figure 6. Generalized Water Table and Groundwater Flow Directions in the Great Lakes Basin.

Explanation
- Line of equal water table level dashed where approximated Elevations in metres above NGVD
- Contour interval is 61m
- Flow direction

Legend:
- Insufficient Data
- Line of equal water table level
The population is not evenly distributed throughout the Great Lakes basin. Approximately 75 percent of the people are clustered in the Lake Michigan and Erie basins (Table 1). At 12 percent, the Lake Ontario basin is third in terms of population. This is followed by the Lakes Huron and Superior basins which have only about eight percent of the total Great Lakes population. The Lake Ontario basin is unique since it is the only area where the Canadian population exceeds its U.S. counterpart. The major urban centers located in each of the Great Lakes basins are given in Table 1.

About 73 percent of the Great Lakes basin remains in a natural state. Because of the huge tracts of forested land, pulp and paper is a major industrial activity (Figure 7). It is estimated that about 25 percent of the United States' total paper production is manufactured in the Great Lakes region.

The Lake Erie basin is the only Great Lake basin in which forested or barren lands are not the dominant land-use (Table 1). About 95 percent of the land area is devoted to agriculture. The major agricultural commodities produced include soybeans, vegetables, wheat, grapes and orchard fruits. This basin is also the most urbanized and most densely populated of the Great Lakes (Table 1). The land-uses in the Great Lakes basin are given in Figure 7.

The Great Lakes region is the manufacturing heartland of North America. Approximately 1/5 of the U.S. and 1/2 of the Canadian manufacturing is carried out in the Great Lakes region. Steel manufacturing is particularly significant; about 70 percent of the United States and 62 percent of Canada's steel is produced in the region (Great Lakes Basin Commission, 1979). Other major industries are chemical production (25 percent of the U.S. total production), car manufacturing (65 percent of U.S. cars are manufactured in the Lake Erie basin) and, as previously mentioned, paper production.

A major use of the Great Lakes, in terms of economic returns, is shipping. The major commodities shipped include iron ore and coal for steel production, other metal ores such as nickel and copper, wheat for overseas export, lumber
**Figure 7. Major Land-Uses of the Great Lakes Basin**

- **Urban, commercial, industrial**
- **Forest, wetland**
- **Agriculture**
and petroleum. Water-based recreation and tourism generate approximately $8—12 billion for the region's economy, of which $1.5 billion worth of business is accounted for by the sports fishery (Great Lakes Governors Task Force, 1985).

The commercial fishery is also substantial. Although it has been negatively affected by polluted water and contaminated fish, about $24—25 million is produced from this activity each year (United States Environmental Protection Agency, 1982b; Ontario Ministry of the Environment, 1982).

2.3 WATER USE

Economic development in the Great Lakes can be attributed to the availability of water, transportation and other resources. Heaviest water use is in the urbanized/industrial areas. In Canada, the Lake Ontario basin and in the United States the Lake Michigan and Erie basins are the most urbanized and industrialized. Only small amounts of water are used in the forested areas of the basin.

Steel production, petroleum refining, manufacturing of chemicals and paper and food products account for about 80 percent of the water used in the basin and many of the water quality problems (Great Lakes Basin Commission, 1976). With the generally large quantities of water available and with most of the major urban areas located on their shores, large quantities of water are withdrawn from the Great Lakes. The National Water Summary of 1983 (U.S. Geological Survey, 1983) indicated a renewable water supply of 281 billion litres per day (74.2 billion U.S. gallons) for the United States portion of the basin with only six billion litres per day (1.6 billion U.S. gallons) of consumptive use. In Ontario, approximately two billion litres (0.5 billion U.S. gallons) of water per day is consumed (Ontario Ministry of Natural Resources, 1984). Concern about the adequacy of supplies occurs where higher use areas are remote from the lakes and are dependent on groundwater from poorly productive aquifers or where restrictions exist concerning use of lake water, e.g. the Chicago area. Water use in the United States portion of the basin is summarized by Solley et al. (1983) and in Canada by the Ontario Ministry of Natural Resources (1984).
3. Problem and Need

3.1 SOURCES OF CONTAMINATION

Contamination of the Great Lakes from groundwater sources is an emerging concern to both the United States and Canadian governments. In 1982 the SAB of the IJC recommended that "groundwater resources of the Great Lakes System be studied to determine potential contamination routes via this source and to establish mitigative measures". Reports written by Swain (1985) and Gillham (1985) for the IJC, described the potential for Great Lakes contamination by groundwater sources from the United States and the Canadian portions of the Great Lakes basin, respectively. These reports pointed out that the necessary conditions for contamination of the lakes to occur via groundwater are all present within the basin. The conditions are:

(1) there must be a source of contaminants;

(2) the hydrogeology must be such that the contaminants can be transported into and thru the groundwater system over a short enough time and flow path that dilution or decomposition of the contaminants will be minor; and

(3) the direction of the flow should be toward the lakes or their tributaries.

Swain (1985) based on 1983 data, reported that 1,930 hazardous waste disposal sites, or about 20 percent of the U.S. total identified under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), are found in the Great Lakes basin. Of the National Priority Sites (Superfund Sites), about 18 percent are within the Great Lakes drainage basin. Based upon the December 1984 U.S. Environmental Protection Agency (USEPA) list, the number of U.S. Superfund sites within the basin increased from 74 to 112.
This accounts for about 14 percent of the 786 sites nationwide. The greatest concentrations of hazardous waste sites are in areas adjacent to the Great Lakes, especially the Chicago, Illinois; Cleveland, Ohio; and the Niagara River area. Figure 8 shows the distribution of waste disposal sites by county for both the United States and Canada.

Groundwater can be contaminated by both diffuse (non-point) and point sources. Diffuse sources include, among others urban runoff; spreading fertilizers and pesticides over agricultural fields or forested lands; spreading of road salt on highways; and atmospheric fallout and acid rain which might leach contaminants into the groundwater system. The high density of non-sewered residential areas in the basin (40 or more septic systems per square mile) is considered to have a high potential for non-point source contamination (Miller, 1980). The degree of severity of groundwater contamination from diffuse contaminant sources depends on the amount, type and toxicity of the contaminants, and the proximity of water-producing or water-transmitting aquifer units.

Diffuse sources of pollution are a concern in southwest Michigan where extensive agricultural lands may be a major contributor to excessive nitrate concentrations in groundwater. In one county, water from 23 percent of the wells drilled for domestic supplies contained nitrate-nitrogen concentrations exceeding the U.S. Environmental Protection Agency's (1976) drinking-water standard of 10 milligrams per liter (Cummings et al., 1984).

Point sources contribute relatively small quantities of contaminants to groundwater but with concentrations normally much higher than diffuse sources. Point sources of contaminants in the basin are many and varied. These include waste disposal sites, salt storage sites, individual and clustered septic systems, cesspools, industrial and municipal waste discharges, ponds, pits, waste lagoons, and mine wastes and tailings. Also included in this point source category of groundwater contamination would be industrial waste dumping, accidental spills (either on site or as contaminants that are being transported), and leakage from storage containers or faulty deep well injection systems.
Figure 8. Distribution of Waste Disposal Sites in the Great Lakes Basin by County

USA - Hazardous CERCLA Sites (as of Dec 1984)
Canada - Known, Solid, Liquid and Hazardous Sites (as of Jan 1974)

Sites per county:
- Over 100
- 51 - 100
- 21 - 50
- 5 - 20
- Less than 5
Some specific examples and locations of point source contamination are summarized below:

a. Hazardous, industrial and municipal wastes disposal sites (Figure 8)——

The more densely populated and thus industrialized areas of the basin tend to be characterized by a high number of waste disposal sites. The municipal and industrial areas of the basin are shown in Figures 1 and 7. Major producers of industrial wastes includes such areas as Chicago, Illinois; Cleveland, Ohio; Gary, Indiana; Detroit, Michigan; and the Niagara River frontier.

The potential magnitude of the problem, if not properly controlled, can be assumed to be greater on the United States side of the basin because of a greater concentration of population centers and more intense economic activity. For example, in New York there are 12 sites in the Lake Ontario basin where industrial wastes have been disposed (Pishdadazar and Moghissi, 1980). In Pennsylvania, "considerable amounts of industrial wastes are created each year, much of which is hazardous" (Pennsylvania Department of Environmental Sciences, 1981). In Gary, Indiana (Lake County), groundwater became polluted with volatile organic compounds because disposal sites overlie lake dune sand deposits (U.S. Environmental Protection Agency, 1982a).

Waste disposal sites in Canada also pose a potential widespread cause of groundwater contamination. The potential magnitude of the problem, however, is not likely to be as great as the United States because of fewer disposal sites. Nevertheless, in the past, there were areas where large volumes of liquid wastes, such as halogenated hydrocarbons, and agricultural chemicals and defoliants were disposed. One such site was at Elmira in the Regional Municipality of Waterloo. Presently, only one site in
Lambton County is allowed to receive and dispose of hazardous wastes after some degree of treatment.

b. Septic systems.—-

In some areas, particularly along the lakeshores, septic systems and cesspools may be sources of contaminants such as nitrogen, phosphorous, dissolved organic carbons and pathogenic bacteria.

c. Ponds, pits, and lagoons.—-

Data on numbers of these sites have been summarized by Kammerer (1984) and Western Michigan University (1981a) respectively for Wisconsin and Michigan. These potential contaminant sources need to be located and mapped elsewhere in the Great Lakes basin.

d. Mine wastes and tailings.—-

As of the mid-1970's, the total number of active and closed mine tailing disposal sites in the Canadian portion of the Great Lakes basin was 149 (International Reference Group on Great Lakes Pollution from Land Use Activities, 1977). The greatest concentration of sites was in the Sudbury, Ontario area. The tailing disposal sites associated with uranium mining around Elliot Lake, Ontario are of particular concern. In the United States, areas near Duluth, Minnesota are a potential source of contamination.

e. Accidental spills and leakage from storage tanks.—-

Normally little hydrogeologic consideration is given to the siting of storage tanks and often there is leakage from old or ruptured tanks. Gasoline from storage tanks should be viewed as a serious threat to local groundwater quality because of its great solubility (mobility) and toxicity. In New York, underground contamination by petroleum products was reported at
187 wells across 49 counties. In Elkhart, Indiana (Elkhart County) contamination of the municipal groundwater supply is threatened by trichloroethylene.

f. Deep well disposal, abandoned test wells and brine contamination.—

The escape of wastes or displaced liquids from disposal wells through unplugged or inadequately plugged test wells or from the receiving formations can cause pollution of ground or surface waters (International Lake Erie and Lake Ontario Reports to IJC, 1972). Near Sarnia, Ontario (Lambton County) deep well injection has caused high chloride concentrations in some shallow groundwater wells (Gillham, 1985). Two crude oil seeps and one natural gas seep started from three abandoned wells in Port Huron, Michigan (International Lake Erie and Lake Ontario reports, 1972). In Ohio, one of the greatest problems is from brine contamination from oil and gas wells, both from surface land sources and from illegal dumping.

3.2 SITE SPECIFIC STUDIES

Numerous site specific studies completed since the 1983 IJC Reports have given further support to the concerns that groundwater can be a major flow path for contaminants to the Great Lakes.

In the Traverse City, Michigan area, along the northern end of Lake Michigan, a plume of contaminated groundwater has recently been investigated by the USGS. The plume which is believed to originate from accidental spills, extends approximately a mile from the shoreline at the east arm of Grand Traverse Bay. Samples of the plume from groundwater test wells indicate a maximum benzene concentration within the plume of 3900 μg/l. Samples of lake water taken 90 meters (300 feet) offshore in the Bay have been reported to contain 20 μg/l of benzene (Twenter et al., 1985).
At an industrial site in the Oswego, New York area near Lake Ontario, a recently completed study by Anderson and Miller (1984) determined that leaking barrels of chemical wastes have contaminated the groundwater in the area as evidenced by higher concentrations of nine "USEPA priority pollutant" organic compounds at wells inside the site as opposed to those upgrade or beyond the streams. The study concluded that the pollutants are moving through the unconsolidated glacial deposits at a rate of 12 cm. (0.4 ft.) per day, discharging into White and Wine Creeks and then into Lake Ontario.

In the Report of the Niagara River Toxics Committee (p. 8-5, Oct. 1984), the summary of findings section stated the following:

1. "Over 215 hazardous waste disposal sites have been identified in Erie and Niagara counties (New York). One hundred and sixty-four of these are within 3 mi. of the Niagara River and include sites used by major industries along the river for disposal of large quantities and a wide variety of hazardous wastes. Based on specified U.S. criteria, sixty-one of these one hundred and sixty-four sites have been determined to have significant potential to impact the Niagara River...

2. Seventeen landfill sites have been identified in the Niagara and Welland River drainage basins in Ontario. Of these, based on specified Canadian criteria, five have been identified as having a significant potential to impact the Niagara River...

3. General overall groundwater contamination with metals and synthetic organic chemicals covers a large areal extent in the three mile band along the U.S. side of the river...

4. (not cited)

5. The horizontal movement of groundwater in the unconsolidated deposits in this three mile band on the U.S. side is generally toward major surface water bodies including Lake Erie, the Niagara River and its
tributaries. Contamination has also been detected in the bedrock in the Niagara Falls, New York sub-area and this is believed to be an avenue of chemical migration to the Niagara River.

6. It was not possible during the present project to quantify loading contributions from these non-point sources to the river."

The criteria for determining significance were different between Canada and the U.S. agencies. The U.S. sites were selected on the basis of site specific investigations. On the Canadian side, any site known or suspected to contain or have received any industrial wastes was designated as significant. Thus, the two groups of sites are not directly comparable.

The science concerning groundwater quality evaluations is relatively new and imprecise and the migration of contaminants is one of the least understood and least documented of the sciences. Once contaminants enter the groundwater system, their movement can be very slow. A few weeks to tens of thousands of years could elapse before contaminants are discharged into a surface water body. Contaminants that do not readily mix with water tend to travel slowly as well-defined slugs or plumes. Concentrations generally decrease over time and distance; the rate of attenuation depending mostly on the type of contaminant and the hydrogeology of an area. The potential for contamination of the reservoir (Great Lakes) by the groundwater or groundwater/surface-water migration path depends upon several factors including the volume of discharge from the contamination source, the concentration of the contaminants in the discharge, the distance from the source to the discharge point, the hydraulic gradient (slope) of the travel path, the time involved in travelling that path and the types of materials travelled through (permeability).

3.3 HYDROGEOLOGY

Having established that potential sources exist in the basin from which contaminants could be transported to the groundwater system, the next concern is whether hydrogeologic conditions will allow the contaminants to be transported into and through the groundwater system and at what rate. This
aspect of the potential contamination is almost wholly dependent upon the type of material into which the water and solutes must move.

Hydrogeologic units in the basin can be classified into two broad categories: unconsolidated surficial deposits (glacial deposits) and consolidated bedrock deposits. The near-surface aquifer (hydrogeologic) units are shown in Figure 5.

a) Unconsolidated Surficial Deposits

Most of the basin has been glaciated and deposits range in thickness from near zero to over 185 m. (600 ft.) (Figure 2). Glacial deposits consist of unsorted clay till, lake deposits, and outwash sand and gravel. Areas of low permeability (Figure 4) produce and transmit only small amounts of water and are generally characterized by glacial till and lake clay surficial deposits. Contaminants could be totally contained within these units or move very slowly. As noted by Swain (1985), however, some areas previously mapped as silt, clay or till have several high-yield wells so texture based upon surface mapping alone can not be taken as positive proof of low permeability. Low-permeability materials could also provide relatively rapid pathways of contamination if they contain fracture networks (Gillham, 1985). Additionally, a short circuit in the groundwater flow can occur when groundwater is discharged into a surface stream. A more rapid time of travel from the contamination source to one of the Great Lakes results.

Outwash sands and gravels generally are very permeable allowing for rapid infiltration and water movement resulting in large yields of water. This also allows for rapid transport of contaminants to the Great Lakes.

Unconsolidated deposits generally tend to be more significant in terms of groundwater contamination than bedrock units because of shorter flow paths, steeper gradients and are normally the depository for contaminants.
b) **Consolidated Bedrock Deposits**

Bedrock units in the basin consist of sedimentary carbonates (dolomite and limestone), sandstones and shales, and Pre-Cambrian crystalline rocks. Water movement in carbonate rocks and Pre-Cambrian crystalline rocks is normally through fractures and is characterized by relatively rapid movement with little filtration. Carbonate rock units in particular offer considerable opportunity for rapid contaminant transport since they contain both steeply dipping fractures and fractures along bedding planes. These fractures are often solutionally enlarged. Sherrill (1975) indicated travel times of several meters per minute (under pumping conditions) in dolomitic bedrock of Door County, Wisconsin.

Crystalline rocks normally have less developed fracture systems. Most water-bearing openings are of the steeply dipping variety and in most cases tend to be tighter with depth, except where large shear zones exist. Crystalline rocks do, however, still offer rapid contaminant transport with little decrease in concentration. Sandstones and shales tend to be characterized by interpore permeability rather than fracture permeability.

Sandstones, which locally may be highly permeable compared to non-fractured crystalline rocks, do offer some retardation and decrease of contaminant concentration as the water passes through them. Shales, like glacial till and lake clays, generally yield and transmit only small volumes of water and are generally less of a threat for contaminant movement. Near-surface aquifer units are shown on Figure 5 and a preliminary evaluation of their contamination potential is shown on Figure 9.
Figure 9. Groundwater Contamination Potential in the Great Lakes Basin (Preliminary)

Contamination Potential

- High: Insufficient Data for Canada north of Parry Sound
- Moderate to variable
- Low
c) **Groundwater Discharge**

There have been several studies in the basin over the years but few dealt with groundwater movement and contamination to the Great Lakes. Most are site-specific studies or cover only a few counties at best, lacking unifying aspects to allow transfer of information from one area to another within the basin. Little is known about groundwater flow systems and direction of flow. In some areas it is not even known if groundwater flow is toward or from the Great Lakes. Figure 6 presents a generalized water table map in those parts of the basin with some data.

Cartwright et al. (1979, p. 77) estimated the total groundwater discharge to Lake Michigan through the lake bottom to be $6.0 \times 10^9$ m$^3$/yr. (6700 ft$^3$/s.). Because this quantity is not part of the $3.4 \times 10^{10}$ m$^3$/yr. (37,580 ft$^3$/s.) estimated annual recharge to Lake Michigan from tributary flow (Sonzogni et al., 1978, p. 74), it represents an additional 18 percent of unmeasured recharge to the lake.

Recent work by Anderson et al. (1984) in the Wisconsin area, indicated that the unmeasured volume of recharge through the nearshore bottom sediments was equal to about four percent of the amount recharged by the streams.

Along western Lake Erie and other areas of the Great Lakes basin, shallow aquifers contain high concentrations of brine. If the quantity of recharge through the lake bottoms is as great in the areas where these brines exist, then a large portion of the dissolved solids concentration of the Lakes could be attributable to these saline aquifers.
3.4 NEED FOR THE STUDY

With approximately 30-40 million Americans and Canadians living and working in the Great Lakes basin and dependent on its water; with approximately 2000 abandoned hazardous waste sites in the basin; and with multiple sources of industrial, agricultural and municipal contaminants, it is imperative that much more be known about the hydrologic system and groundwater flow characteristics. The State of Michigan alone has identified 441 sites where groundwater is known to be contaminated and 456 sites where it is suspected (Michigan Department of Natural Resources, 1982). Sources of contamination are widespread in the Great Lakes basin and the hydrogeology is favorable for transport of contaminants by groundwater into the Great Lakes. A better definition and quantification of specific contaminant sites and sources is needed as well as a better definition and delineation of the hydrogeologic system.

At least four studies have recently been completed or are underway where susceptibility to contamination has been defined areally on maps based upon surficial deposit texture and rock types.

The Ontario Ministry of the Environment has published a map (map S100, no date) at 1:1,000,000 scale that shows areas where groundwater is susceptible (high to low) to contamination based upon permeability of near surface materials, direction of groundwater movement, presence of a shallow aquifer and use of groundwater in the area.

The Illinois State Geological Survey (Berg, Kempton and Cartwright, 1984) has developed potential for groundwater contamination maps based on the combination of hydrologic properties and stratigraphic sequences of geologic materials between the surface and 15.2 m. (50 ft.) depth.

The National Water Well Association (Aller et al., 1985) under funding from the USEPA has devised a methodology to evaluate the groundwater pollution potential using hydrogeologic settings. Thru a weighting and rating of the hydrologic factors of Depth to water table, net Recharge Aquifer media, Soil
media, Topography, Impact of the Vadose zone, and hydraulic Conductivity, a DRASTIC INDEX was developed to identify those areas where the groundwater is most susceptible to contamination.

In a fourth study being undertaken cooperatively by the Wisconsin Department of Natural Resources and the Wisconsin District of the U.S. Geological Survey, five resource maps showing depth to water, bedrock geology, depth to bedrock, soil permeability and near-surface bedrock permeability are being developed. By using these maps as overlays, an interpretive contamination potential map will be developed.

Of the four mapping methodologies outlined above, only groundwater susceptibility to contamination was mapped. Consideration was not given to comparing areas of abundant pollution sources with areas of high susceptibility. Because these methodologies are primarily concerned with the potential to contaminate the groundwater resource itself, they do not include analysis of shallow rapid horizontal flow paths to surface channels as a result of consolidated bedrock very near the surface. Clearly there does not appear to be one specific study technique which would lead itself directly to the specific analysis of the susceptibility of the Great Lakes to contamination from groundwater.

Various jurisdictions, including counties, states/province and two federal governments, are involved with studying the Great Lakes. To avoid replication, it is imperative that close coordination be encouraged. Several Regional Planners have mentioned the need for a central clearing house for geologic and hydrologic data. Not all planners are fully aware of the studies that have been done in their own area. Available data can also be in a form that is not easily usable. Such a central clearing house could also be useful in identifying where data are insufficient for detailed planning purposes.
4. Objectives

The objectives of the study, as proposed herein, are to define the major hydrogeologic regimens of the Great Lakes basin and to assess the potential for groundwater in those regimens to carry contaminants into the Great Lakes. Specifically, the study will attempt to:

1) define regionally the hydrogeologic units within the Great Lakes basin;

2) locate the areas with potentially major sources of groundwater contamination; and

3) evaluate the potential for and significance of accompanying contaminants to move through the hydrogeologic units and into the Great Lakes.

The foremost objective of this work is to identify areas to the IJC where contamination potential is the greatest such that IJC can, in turn, recommend to the various governments those areas of major concern which should be further investigated or where mitigation of the contamination should be carried out.
media. Improved irrigation, the transport of soils and hydraulic conductivity, a
DRASIC INDEX was determined to identify those areas where the groundwater is
most subject to contamination.

Decision-making on the seriousness and impact of the potential contamination
problems to the community concerns the potential impact to the community, the
potential to harm the community's health and well-being. However, it should be
noted that this decision-making process is highly dependent on the local context and
the specific situation. The decision-making process should include a comprehensive
assessment of the risks and benefits, considering the potential impacts on the
community, the environment, and the economy. Several
Regional Planning has established a regional clearing house for
geological information, which includes a digital database of the studies
that are available for the area. These databases also contain
data on the potential impacts on the
identified areas for detailed planning purposes.
5. Approach

The proposed study plan is divided in three phases to be carried out over a period of two years.

Phase I, to be concluded within the first four months of the study's inception, will include examining and subsequently selecting a contamination potential mapping methodology. The contractor, as a minimum, will review the four methods and procedures identified earlier in this proposal and based on that review develop a legend to be used in the interpretative maps. The prepared analysis will include a discussion of where and how the data gathered will be used within the context of the proposed legend; provide specific examples using actual Great Lakes basin data for differing hydrogeologic regimens; and provide conclusions and recommendations on the various methods so that a selection of the preferred method can be made by the Groundwater Contamination Task Force.

Phase II will involve collection of existing information and maps available in public files, for defining the natural hydrogeologic regimens of the Great Lakes basin. The level of mapping detail should be as good as the data allow. The information will be collated and interpretations made on base maps covering the entire basin at a scale of 1:1,000,000. This scale represents a best compromise as many of the existing study maps are at some fraction of the 1:1,000,000 scale. In the mapping efforts, wherever possible, the gathered data should be mapped according to the 15 major U.S. river basins as identified by Waller and Allen (1975) and the 11 major Canadian sub-basins identified by the International Reference Group on Great Lakes Pollution from Land-Use Activities (PLUARG) report (1977). The prepared maps, which will be similar in format to some examples presented with this proposal, will include but not necessarily be limited to the following:
2. Bedrock geology—

The bedrock geology map, such as in Figure 3 which shows rock types, can be developed from existing USGS, state and provincial maps of the basin. Mapping has also been done by some of the universities in the basin. The work done by Waller and Allen (1975) includes important information and citations of sources.

3. Permeability of surficial materials—

A subjective approach was used to develop the example map (Figure 4) on permeability of unconsolidated materials. Three categories of permeability were chosen (high, medium and low) based upon existing information. These data were derived from publications such as USGS Hydrologic Atlases in which permeabilities were derived from Soil Conservation Service (USDA) soil maps. Areas which were not covered by existing publications were assigned "K" values based upon type of surficial material. More definitive information is available in recent publications of state agencies and from university theses; however, this map will require considerable time to develop more completely.

4. Groundwater flow characteristics and directions—

The example map "Generalized Water Table and Groundwater Flow Directions" (Figure 6) was developed from very limited data using USGS reports. This map would be very difficult to develop due to the limited information available. Topographic maps could be used as surrogate information where depth to water table data are lacking.

5. Aquifer utilization—

The example map "Near Surface Aquifer Units" (Figure 5) delineates the upper most water yielding hydrologic unit in a given area. In much of the basin, water supplies are derived from glacial drift, so the aquifer is shown as sand and gravel. In other areas where the drift is thin or nonproductive, water supplies are derived
from bedrock units, e.g. fractured rock (carbonate and crystalline) or sandstone. Nonproductive aquifers or those yielding only small supplies, e.g. shale, are listed as low permeability aquifers.

6. A land-use map including population centers, industrial bases, plus non-point sources of contamination such as those from agricultural, forestry and urban runoff sources and sewered versus non-sewered areas—

The basic foundation for this map (Figure 7) is available in an extensive set of reports by the IJC which inventoried land-use and land practices in the basin by watershed area. More current information is available from the Great Lakes states and provincial agencies. The land-use map should indicate areas by Standard Industrial Code (SIC) wherever clusters of industries—such as chemical, petro-chemical, petroleum pipelines, pumping stations, tank farms, oil and gas wells and mining—that cause groundwater pollution are located.

7. Point sources of contamination, with known types of waste, ponds, lagoons, disposal sites, leaks, spills, mine wastes and leaking disposal wells—

Some state agencies (such as Wisconsin) have conducted recent inventories to locate these sites. The USEPA has several data bases on computer tape available which includes information on hazardous waste generation, storage, treatment and disposal sites on RCRA licensed companies. In addition, the USEPA has listings and locations of approximately 18,000 abandoned CERCLA waste sites within the United States.

The Ontario Ministry of the Environment is currently developing maps at a scale of 1:50,000 showing active landfills and closed sites. In 1979 an inventory of landfills identified approximately 1500 landfills across the Province of Ontario which had no approvals prior to enactment of the Environmental Protection Act in 1971. Presently, there is no organized mapped information on sewage
lagoons, storage ponds or generator site ponds beyond the list of industries which are licensed for landfilling.

It is estimated that about 80 percent of the region has some type of groundwater reports available, but many of these are reconnaissance in nature and will only furnish part of the desired information. The maps produced may therefore have several blank areas with insufficient data for interpretive purposes.

Phase III will involve synthesis of the existing information and preparation of an interpretive map describing the hydrogeologic regimens in the Great Lakes basin per the methodology selected in Phase I of the study. This work will involve classification of the hydrogeologic regimens as to their hydraulic properties, proximity to and severity of contamination sources, and proximity to the Great Lakes. For example, carbonate bedrock aquifers, which in some areas are hydraulically connected to the Lakes, would potentially be of much more concern than shale bedrock or lake clays adjacent to the Lakes.

The example "Contamination Potential" map (Figure 9) was developed using overlays of the previously developed maps of drift permeability, drift thickness, land-use and potential sources maps, and near-surface aquifer units. The resulting map was heavily weighted by the permeability as sand and gravel aquifers and near-surface carbonate rock aquifer areas are generally shown as areas having high potential for contamination. Low permeability, near-surface aquifer units, are shown as low potential. Mixed till areas and sandstone bedrock areas are depicted as moderate contamination potential. In this example map, the number of sources was given a small weighting as evidenced by the Detroit area.

Figure 9 is one of the many ways the final map may be shown. The interpretive map would indentify the hydrogeologic regimens with a high potential for contamination of the Great Lakes via groundwater. Areas of concern would be evaluated and recommendations made to the IJC for further study.
6. Work Schedule and Resource Requirements

The report would consist of a series of geologic, hydrologic and cultural maps, and at least one interpretive summary map with accompanying text as described in the Approach Section. Intermediate products will include preliminary maps from Phase II.

TABLE 2
TIMING OF MAJOR WORK ELEMENTS OF THE HYDROGEOLOGICAL INVENTORY AND ASSESSMENT OF CONTAMINATION POTENTIAL TO THE GREAT LAKES BASIN

<table>
<thead>
<tr>
<th>Major Work Elements</th>
<th>FIRST YEAR</th>
<th>SECOND YEAR</th>
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<tbody>
<tr>
<td></td>
<td>MONTH 1</td>
<td>MONTH 2</td>
</tr>
<tr>
<td>A. Phase I</td>
<td>123456789</td>
<td>123456789</td>
</tr>
<tr>
<td>1. Review of</td>
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<td>123456789</td>
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<td>contamination</td>
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<td>X=X</td>
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<tr>
<td>potential mapping</td>
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<tr>
<td>methods.</td>
<td>X=X</td>
<td>X=X</td>
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<tr>
<td>2. Development of</td>
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<tr>
<td>example application</td>
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<td></td>
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<tr>
<td>methods.</td>
<td>X=</td>
<td>X=</td>
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<tr>
<td>3. Presentation to</td>
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<tr>
<td>Task Force of</td>
<td></td>
<td></td>
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<tr>
<td>recommendations.</td>
<td>X</td>
<td>X</td>
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<tr>
<td>B. Phase II</td>
<td></td>
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<tr>
<td>1. Literature search</td>
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<td>and collecting</td>
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<tr>
<td>existing informa-</td>
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<tr>
<td>tion and maps.</td>
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<td>X=X</td>
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<tr>
<td>2. Synthesizing and</td>
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<td>X=X</td>
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<tr>
<td>evaluating data.</td>
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<td></td>
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<tr>
<td>3. Preparation of</td>
<td>X=X</td>
<td>X=X</td>
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<tr>
<td>interpretive</td>
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<tr>
<td>parameter maps.</td>
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<tr>
<td>Major Work Elements</td>
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<td>1 2 3 4 5 6 7 8 9 10 11 12</td>
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<tr>
<td>C. Phase III</td>
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<tr>
<td>1. Preparation of summary maps.</td>
<td>X=-------X</td>
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<tr>
<td>2. Report preparation and review.</td>
<td>X=--X X=-----------------X</td>
<td></td>
</tr>
<tr>
<td>3. Printing of colour map (Approximately 4 months after presentation).</td>
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**ESTIMATED FUNDING (U.S.$):**

<table>
<thead>
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<th>Study Year</th>
<th>First</th>
<th>Second</th>
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<tr>
<td>A. Phase I</td>
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<td></td>
</tr>
<tr>
<td>1. Review of mapping methods and presentation to the Task Force.</td>
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<tr>
<td>B. Phase II</td>
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<td></td>
</tr>
<tr>
<td>1. Literature search and data collection.</td>
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<td>2. Synthesis of existing data.</td>
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<td>10,000</td>
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<tr>
<td>3. Map preparation.</td>
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<tr>
<td>C. Phase III</td>
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<tr>
<td>1. Preparation of summary maps.</td>
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<tr>
<td>2. Report preparation and review.</td>
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<tr>
<td>3. Printing of reports (colour maps).</td>
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<tr>
<td>D. Travel and Computer Services.</td>
<td>5,000</td>
<td>5,000</td>
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<td>$95,000</td>
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</table>
7. Recommendations

The Groundwater Contamination Task Force requests that the Great Lakes Science Advisory Board:

1. commission a study to prepare a hydrogeology inventory of the Great Lakes basin as the basis for assessing the potential for Great Lakes contamination via groundwater;

2. the commissioned study be based upon the proposal outlined in this report; and

3. the Water Resources Division, United States Geological Survey be contracted to perform the work.
Phase II
1. Preparation of letter to the Director of the Geological Board.
2. Survey of the area to determine the geologic and topographic conditions of the area.
3. Letter to the nearest laboratory for assaying the borehole for their services.

- First
- Second

Phase III
1. Literature search and data collection: 45,000
2. Synthesis of existing data: 30,000
3. Map preparation: 50,000

Phase IV
1. Preparation of summary report: 20,000
2. Report preparation and review: 10,000
3. Printing of reports (colored maps): 20,000

Transit and Computor Services: 80,000
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GROUNDWATER CONTAMINATION TASK FORCE

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