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SEEPAGE OF GROUNDWATER INTO THE ST. CLAIR RIVER NEAR SARNIA, ONTARIO, CANADA

BY

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FACULTY OF GRADUATE STUDIES
UNIVERSITY OF WINDSOR
1987

SEEPAGE OF GROUNDWATER INTO THE ST. CLAIR RIVER NEAR SARNIA, ONTARIO, CANADA

by

© Sharon A. Mason

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J Bent

Frank Simpson

ABSTRACT

The main objectives of this research program were to determine the quantity, quality and source(s) of groundwater seepage from the streambed into the St. Clair River in the vicinity of Sarnia, Ontario, Canada.

Seventeen survey lines were installed on the bed of the St. Clair River in a 100 m by 7 km band between Sarnia Bay and the Sarnia Indian Reserve. The survey lines extended 100 m from shore at an angle of approximately 90° to the shore. Soil cores were collected along the survey lines in conjunction with river bottom descriptions to characterize the river bed. On the survey line locations which had at least 100 mm of granular material, seepage meters were installed to measure seepage rates. Moderate seepage was noted on two of the seven survey lines that contained the granular bottom sediments. Minipiezometers were used on these two survey lines to collect streambed groundwater from depths of 1.0 and/or 1.5 m below the river bed. Electrical conductivity, pH and temperature of the streambed groundwater and river water samples were determined in the field. Selected river water and streambed groundwater samples were also analyzed for: chlorinated hydrocarbons, polychlorinated biphenyls, trihalomethanes, EPA Priority Pollutants (extractables), total organic halides (TOX), chloride, and natural isotopes (oxygen-18, deuterium, and tritium).

The average observed seepage rate of 1.4×10^{-8} $m^3/s/m^2$ suggests higher than expected hydraulic conductivity or hydraulic gradients in the streambed, 2 to 4 orders of magnitude greater than those determined in previous studies. Detectable levels of some organic contaminants were found in the streambed

groundwater samples, i.e., <0.0067 ug/L total chlorinated hydrocarbons, <0.026 ug/L PCB, <2.77 ug/L trihalomethanes, and <2.4 ug/L base neutral extractables. The isotopic and electrical conductivity data indicate that:

(1) the streambed groundwater is not simply river water,
(2) groundwater from the freshwater aquifer does not appear to be a significant component of the streambed groundwater,
(3) some of the streambed groundwater may be partially derived from shallow groundwater, and
(4) a yet unidentified source of water contributes to the streambed groundwater.

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

1.1 STRUCTURE OF THESIS

Chapters 1 to 4 are introductory chapters which describe the scope and objectives of the study, the geology, deep well disposal in the study area, and methods of study, respectively. Chapter 5 discusses the results of the field and laboratory studies and Chapter 6 summarizes the conclusions and recommendations. The appendices provide detailed descriptions and tabulations of field observations, field equipment, field and laboratory analyses and a summary of interpretative notes on the use of environmental isotopes as tracers.

1.2 SCOPE AND OBJECTIVES OF STUDY

In an ideal situation, deep-well disposal is a controlled injection of wastewater into the subsurface in such a manner that all hazards to drinking water sources are minimized. In a well designed system, the "disposal unit" is a porous, permeable, geological stratum which is vertically confined by low-permeability rocks. The disposal unit should be deep enough and the groundwater velocities slow enough to isolate the wastes from the biosphere for a long period of time. The disposal unit should also be structurally simple with no natural or man-made conduits through the confining units (Warner and Lehr, 1981).

Between 1958 and 1976, several industries in Lambton County, Ontario, Canada, used on-site "deep well" disposal systems for their liquid waste disposal. They injected over 8 x 10^6 m^3 of liquid industrial waste into 16 wells completed into the Detroit River Group. The Detroit River Group consists of carbonate strata extending from about 167 to 288 m below ground surface. This disposal unit is overlain by approximately 150 m of shale and dense carbonate rock and about 40 to 45 m of overburden. The injected wastes included a wide range of both organic and inorganic substances produced as by-products of the petrochemical industry. However, the exact nature of these wastes is not well-documented (Rathbone, 1983). In addition to the waste compounds injected into the wells, the products of downhole chemical reactions amongst the various injected wastes and between the wastes and the disposal unit rocks are another potential source of contaminants in the disposal unit. There have been several indications that the waste has migrated at least 1 or 2 km from the injection wells and that above-ground head conditions have developed over a considerable area (Rathbone, 1983).

The recognition of failures of the Sarnia area deep well disposal practices are well documented in the literature. These failures have become extremely sensitive public issues because: the area is along an international boundary, the area is highly industrialized and heavily populated, and much of the waste is toxic (Simpson, 1978).

The main water supply aquifer in Lambton County, the "freshwater aquifer", consists of a relatively thin deposit of granular overburden overlying the bedrock surface. Above the aquifer, most of the overburden is low permeability silty clay till (Quigley and Ogunbedjo, 1976; Desaulniers et al., 1981) which varies in thickness from about 15 m in the eastern part of Lambton County to about 45 m near the St. Clair River in the west. Under natural flow conditions, the hydraulic head in the Detroit River Group was reported to be some 60 m below the base of the freshwater aquifer (Rathbone, 1983).

The occurrence of contaminated, shallow, flowing water wells in the Sarnia area of Lambton County in the early 1970s, coincident with the greatest subsurface waste injection activities, strongly indicates that the deep well disposal of wastes pressurized the Detroit River Formation to such an extent that at least localized contamination occurred in the freshwater aquifer. Piezometric data from the Canadian side of the St. Clair River (Vandenberg et al., 1977) suggest that flow in the freshwater aquifer is toward the St. Clair River. Although there is a considerable thickness of low-permeability clayey till between the streambed and the freshwater aquifer, it is known that there are fractures in the till (Quigley and Ogunbedejo, 1976 and Desaulniers et al., 1981) and that there is a sufficient upward hydraulic gradient to move contaminated water from the freshwater aquifer into the river (Vandenberg et al., 1977).

Various other studies conducted in the Sarnia area (Oliver and Kaiser, 1986; Kaiser and Comba, 1986; and Environment Canada and Ontario Ministry of the Environment, 1986) have shown that the sediments and river water in distinct reaches of the St. Clair River contain varying concentrations of numerous contaminants. It is believed these contaminants are the combined result of the industrial operations along the river, drainage from ditches which drain the industrial properties, and a number of waste disposal sites in the Sarnia area (King and Sherbin, 1986).

There are four possible sources of contaminated water which may affect the quality of the water in the streambed (Figure 1): 1) river water, 2) surface drainage into the river, 3) flow through the shallow, fractured clay

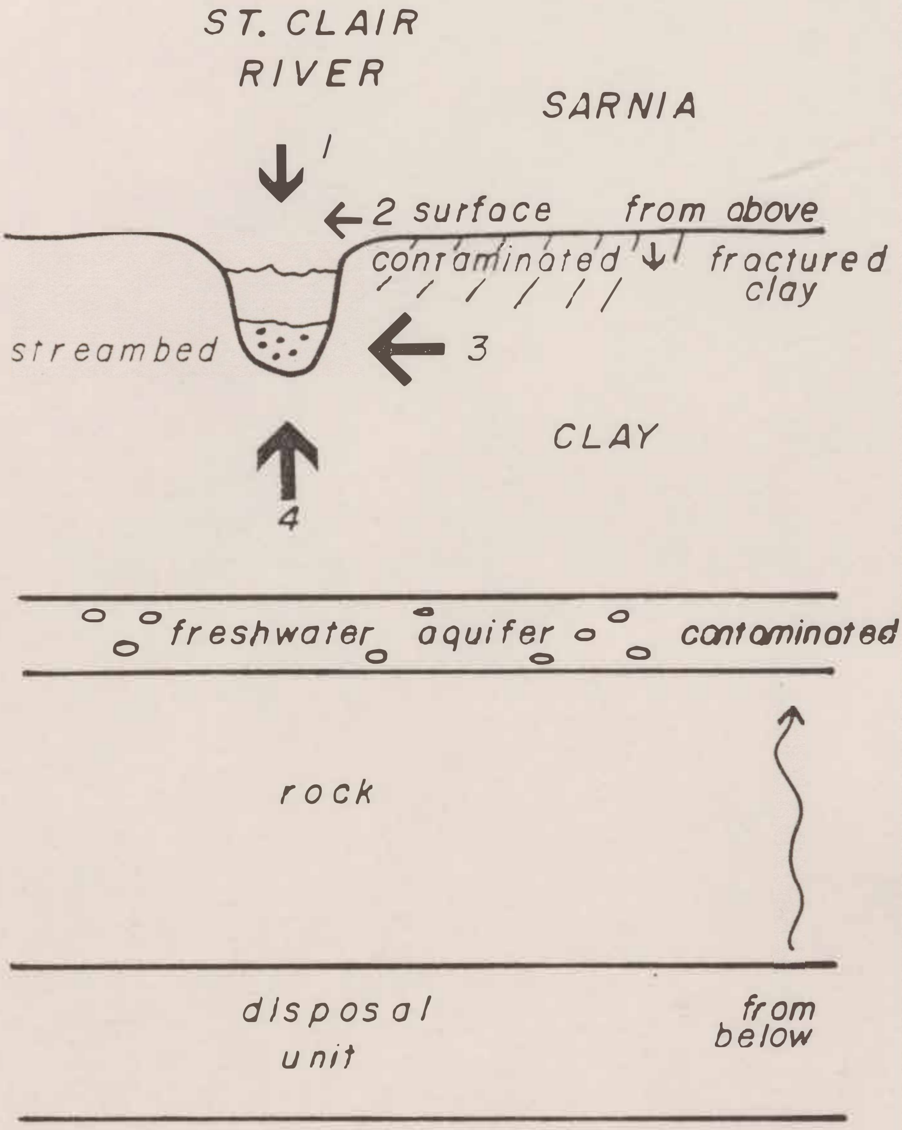


Figure 1. Schematic of problem.

zone, and 4) flow from the freshwater aquifer. Another possible source of contamination to the streambed groundwater would be from contaminants entering the water from the streambed sediments. However, determining the quality of the streambed sediments was beyond the scope of this study.

The main objective of this research program has been to determine if there is any discharge from the streambed sediments into the St. Clair River, and if there is, to determine the quantity, quality and source(s) of the seepage. The problem was approached and studied in several ways which can be grouped into two types of activities:

1. streambed sediment sampling, seepage meters, and minipiezometers were used to map the distribution of groundwater seepage from the St. Clair River streambed and to obtain water samples for organic contaminant analyses, and

2. in order to determine the source(s) of the water in the streambed sediments, field measurements of pH, electrical conductivity (EC), and laboratory analyses of environmental isotopes (oxygen-18, deuterium, and tritium) were used to compare the streambed water to the river water, the shallow groundwater from fractured clayey deposits near ground surface, and the groundwater from the freshwater aquifer.

Monitoring wells drilled into the freshwater aquifer would have greatly aided in this study. However, drilling was beyond funding limitations. The study area was limited in size owing to budget and time constraints. Also, the observation of the characteristics of surface drainage was outside the terms of reference of this study.

2.0 GEOLOGY OF THE STUDY AREA

The study area is located in southwestern Ontario, Canada, along the St. Clair River, adjacent to Lambton County. The primary area consisted of a 7 km by 100 m band of the St. Clair River between Sarnia Bay (located adjacent to the town of Sarnia) and the Sarnia Indian Reserve (southwest of the town of Sarnia) (Figure 2). Numerous survey lines were installed at various locations along the Canadian shoreline within this 7 km reach of the river. Several industrial wells located within close proximity to the river were also sampled during this study.

A review of the geology and hydrogeology in and around the Sarnia area was necessary to put the question of groundwater seepage into the St. Clair River into perspective. This review includes both the Quaternary deposits (and the associated freshwater aquifer) and the Paleozoic bedrock units (including the Detroit River Group, the primary injection interval for deep well disposal in Sarnia).

2.1 QUATERNARY DEPOSITS

2.1.1 GEOLOGY

Although there are areas in southwestern Ontario where bedrock outcrops, the majority of the region is covered by a substantial thickness of till deposits, consisting of silt-clay till and glaciolacustrine materials. Till thicknesses of up to 122 m (400 ft.) have been recorded in bedrock valley areas. Intera (1987) reported a valley in the bedrock surface in Lambton County adjacent to the St. Clair River. In the Intera (1987) study, which delt only with Sarnia, the depth to bedrock was reported to vary from less than 40 m to about 53 m.

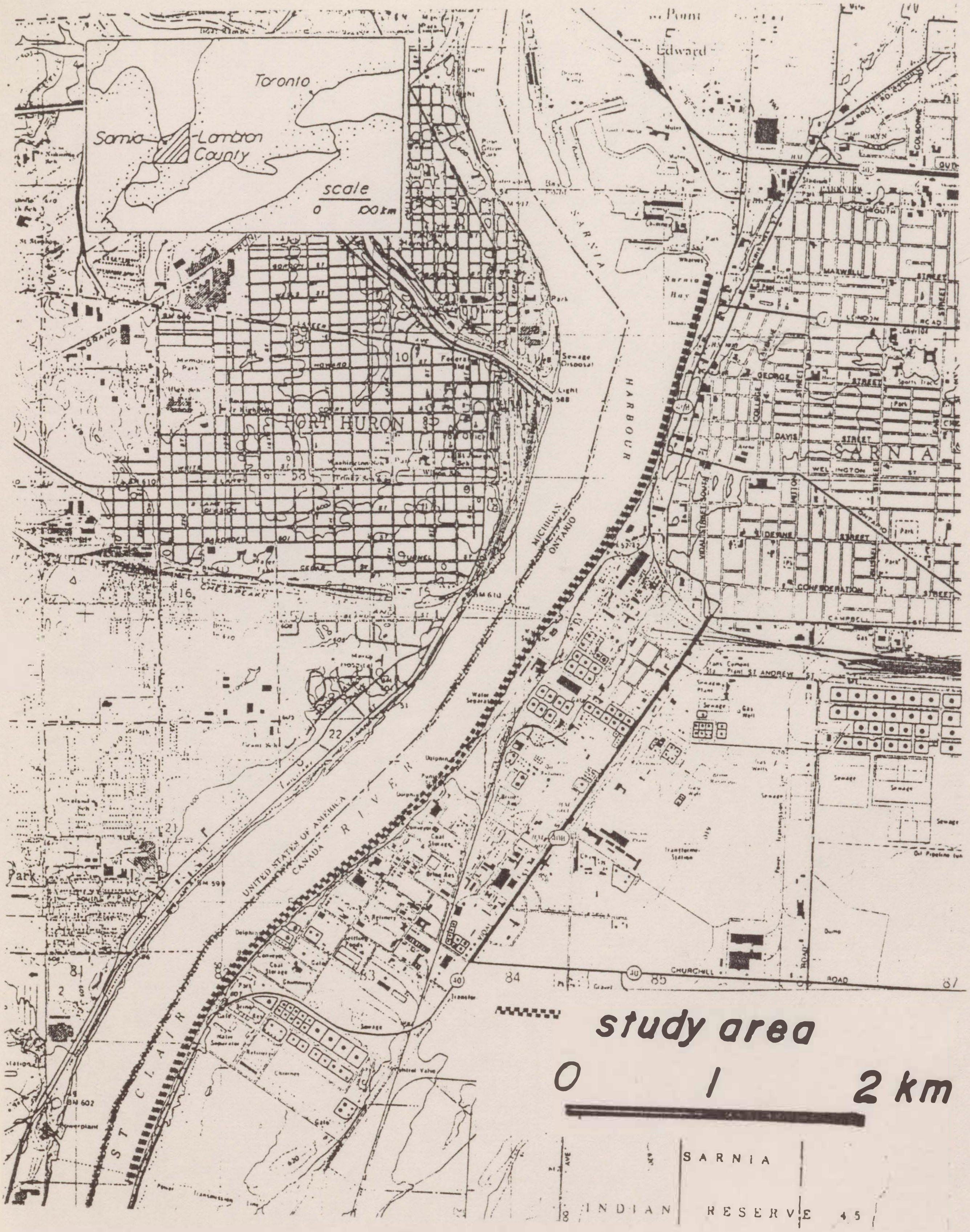


Figure 2. Map of the study area.

In and around Sarnia, there are approximately 45 m of till deposits overlying the Devonian shales and limestones of the Lambton, Hamilton and Detroit River Groups (Figure 3). These deposits vary in thickness from about 15 m in the eastern part of Lambton County to 45 m near the St. Clair River in the west. On the basis of texture, homogeneity and slight over-consolidation, these deposits are considered to be water-laid, glacial tills of late Wisconsin-Age (Quigley and Ogunbadejo, 1976).

Quigley and Ogunbadejo (1976) studied the tills near Sarnia within the boundaries of the municipal landfill site for Sarnia, located on the flat grasslands 7 km southeast of Sarnia. Their study indicated that at least two tills could be distinguished within the upper 27 m (90 ft) of deposits. These till deposits contained 40-50% clay size material and were only slightly over-consolidated (except for the desiccated crust above 7 m). The moisture content of the tills remained constant until a depth of 14 m, below which the moisture content increased with depth. Pockets of silty sand, about 4 m thick, were observed within the clayey soil sequence at a depth of approximately 18 m.

2.1.2 HYDROGEOLOGY

The "freshwater aquifer", the main source of potable groundwater in rural areas of Lambton County, consists of a thin layer of granular overburden directly overlying the bedrock. The term "freshwater aquifer" has been used in order to distinguish it from deeper aquifers containing brackish water and brine (GTC, 1985). The freshwater aquifer is generally less than 3 m thick and is spread out unevenly over the bedrock surface and the upper fractured

PERIOD	ERA	GROUP / FM		LITHOLOGY
		DRIFT		clays, gravels
DEVONIAN	UPPER	PORT LAMBTON		sandstone, shale
		KETTLE POINT		shale
	MIDDLE	HAMILTON		limestone, shaly limestone
		DUNDEE		limestone
		LUCAS DETROIT RIVER AMHERSTBURG		dolomite, cherty limestone
	LOWER	BOIS BLANC		cherty limestone
SILURIAN	UPPER	BASS ISLANDS		dolomite with shaly interbeds
		SALINA	G	shaly dolomite
			F	shaly dolomite, anhydrite salt
			E	dolomite with shaly interbeds
			D	anhydrite, salt
			C	shale, dolomitic shale
			B	anhydrite, salt
			A-2	dolomite, salt, anhydrite
			A-1	limestone, dolomite, anhydrite

Figure 3. Partial stratigraphic column for southwestern Ontario (after Vandenberg *et al.*, 1977).

portion of the bedrock. This freshwater aquifer is confined beneath by both the shale of the Kettle Point Formation and the shale and limestone of the Hamilton Formation, and above by approximately 35 to 40 m of clay and till which forms the bulk of the overburden (URM, 1984).

The intergranular hydraulic conductivity of the clay and till of the overburden ranges from 8×10^{-10} to 9×10^{-10} m/s (Desaulniers et al., 1981). Goodall and Quigley (1977) and Desaulniers et al. (1981) determined that the vertical hydraulic gradient in the clayey deposits is downward with values between 0.01 to 0.18.

Weathering of this upper till has caused close-spaced fissuring apparently brought about by leaching and desiccation. The intensity of the fissuring decreases with depth with reported fissure spacings of about 1 m at a depth of 5 m (Quigley and Ogunbadejo, 1976). Desaulniers et al. (1981), concluded that the hydraulic conductivity of the clay and till was not greatly affected by the fractures.

About 90% of the water wells in Lambton County obtain water from the freshwater aquifer (URM, 1984). When this aquifer is used as a water supply, the wells are drilled into the top of the bedrock and they rely on the fractured nature of the shallow bedrock to draw water from the aquifer.

The topography and piezometric head of the freshwater aquifer apparently follow the westerly trend of both the land surface and the bedrock surface. Figure 4, the piezometric head distribution in the freshwater aquifer, indicates a general westerly direction of groundwater movement. The

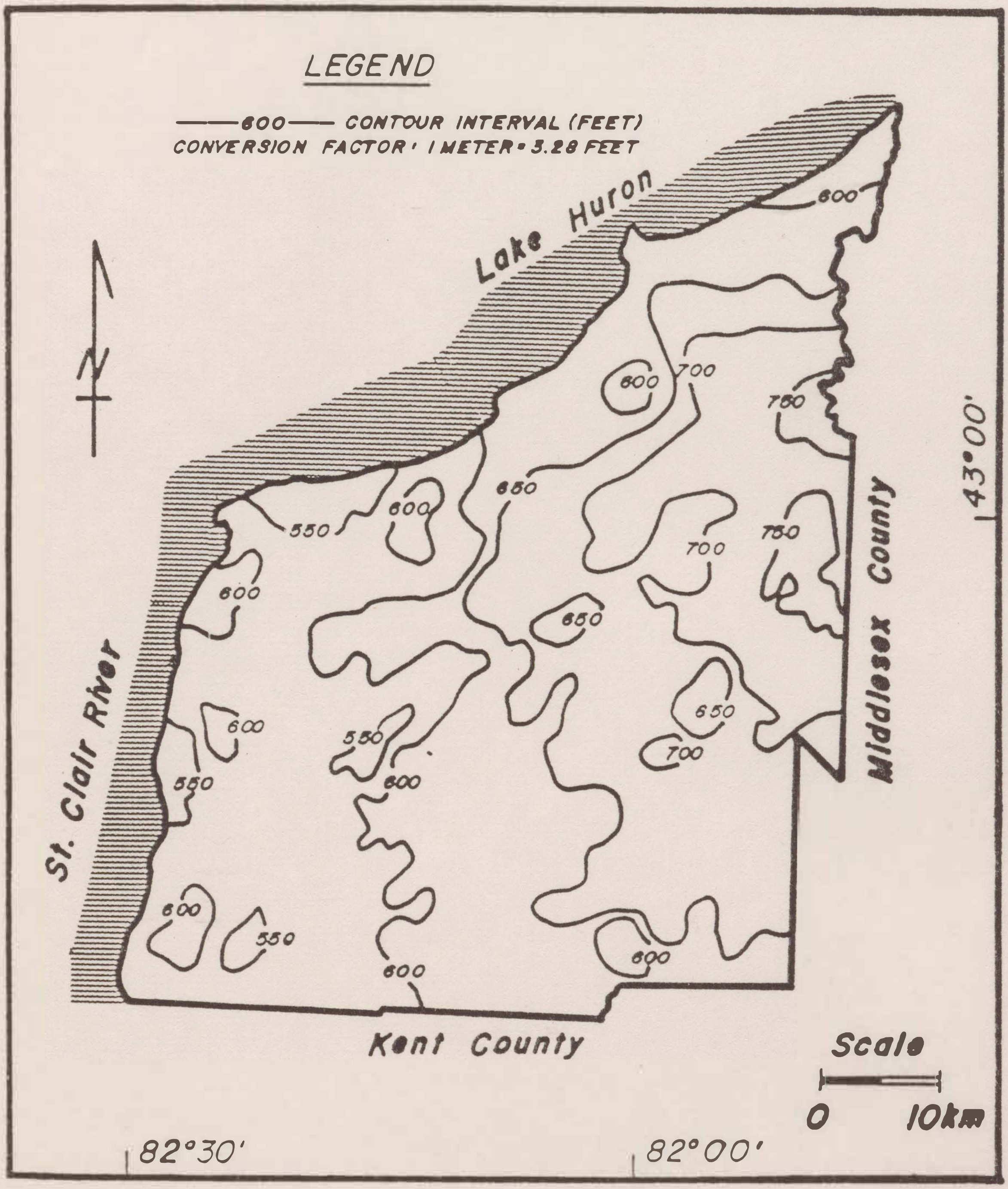


Figure 4. Piezometric head of the freshwater aquifer (after Vandenberg *et al.*, 1977).

piezometric surface in this aquifer is generally within 15 m of ground surface (GTC, 1985).

Vandenberg et al. (1977) have identified regions of similar groundwater chemistry in the freshwater aquifer (Figure 5). Figure 5 shows that chloride (Cl^-) water dominates the freshwater aquifer in the study area. The direction of groundwater movement, as inferred from these water chemistry types, is consistent with the flow directions revealed by the piezometric-head map.

Regional recharge to the freshwater aquifer occurs in the high areas on the eastern border of the county where elevations range from 242 masl (metres above sea level) to 212 masl. Regionally, the aquifer is believed to discharge into the St. Clair River and near shore tributaries of the river, as well as Lake Huron (Vandenberg et al, 1977). Locally, however, the river occasionally recharges the aquifer (GTC, 1985).

Owing to the extremely low permeability of the clayey materials in the overburden, effective vertical recharge of the embedded sand and gravel bodies is probably prohibited throughout most of Lambton County. Isotopic data from Desaulniers et al. (1981) and Scott (1986) suggest that groundwater from some of these deposits is almost as old as the deposits themselves. Therefore, it is difficult to determine the rate of groundwater movement with any certainty. Rather than indicating rapid circulation controlled by precipitation and topography, the slope of the potentiometric surface may instead reflect the fact that pressure heads are similar in each isolated part of the aquifer (URM, 1984). However, Scott's (1986) isotopic data indicate an isotopic

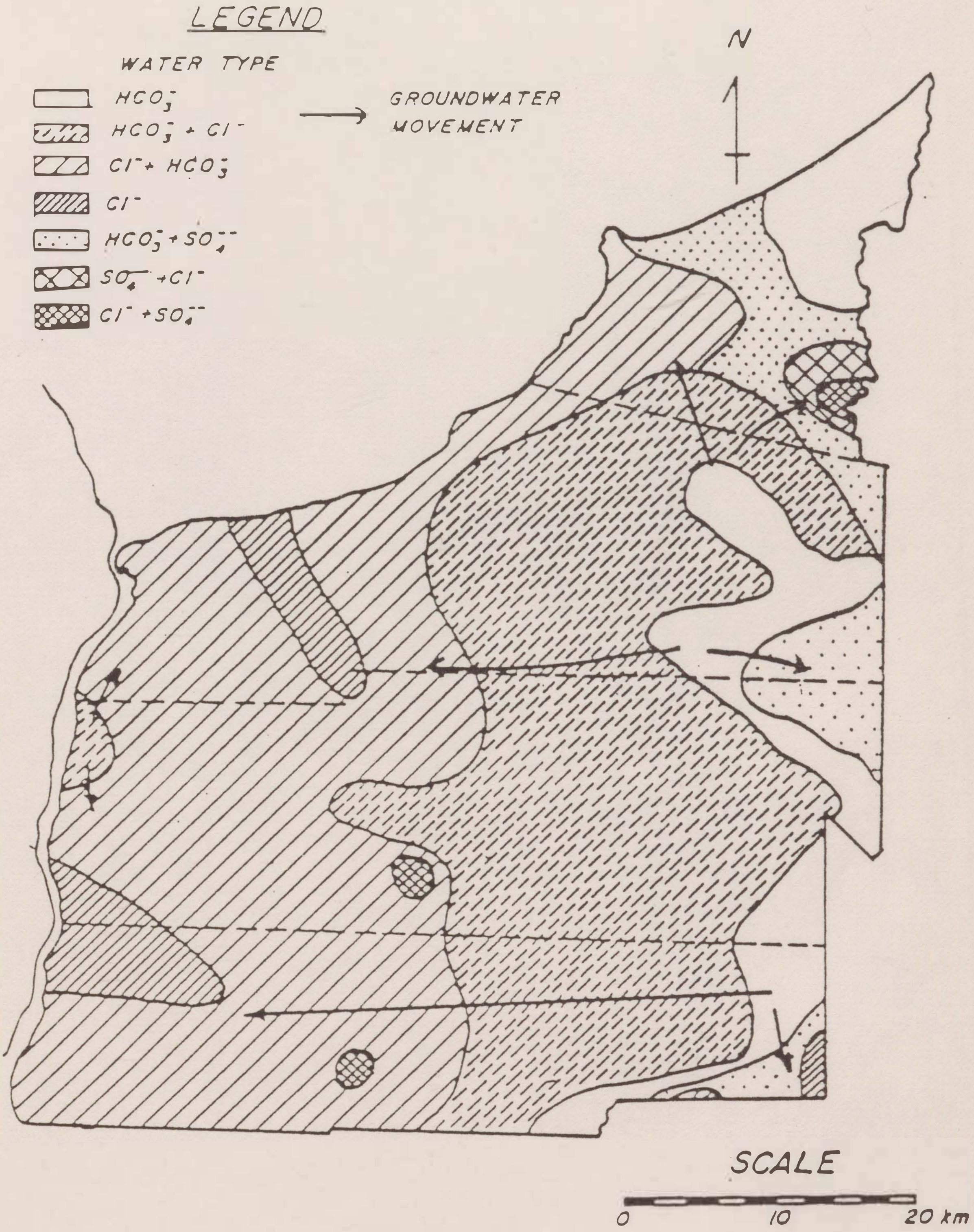


Figure 5. Groundwater chemistry of Lambton County (after Vandenberg *et al.*, 1977).

continuity within the aquifer that does not appear to be controlled by the isolated highs and lows of the potentiometric surface.

GTC (1985) used representative hydrogeologic properties for the aquifer to calculate a groundwater velocity of less that 2 m/yr. Hyde (1987) calculated an average velocity of approximately 3 to 4 m/yr using computer simulations of the freshwater aquifer flow.

2.2 BEDROCK

2.2.1 GEOLOGY

The Sarnia area is located toward the eastern edge of the Michigan Basin. In this area, the dip of the bedrock is to the northwest toward the centre of the Michigan Basin, at a rate of about .00947 m/m (50 ft./mile) (URM, 1984). The structural attitudes of the formations have locally been affected by processes other than tectonic deformation. In some areas, the beds have been affected by collapse as a result of dissolution of salt beds and/or by drape over reefal structures (URM, 1984). The following is a brief description of the bedrock stratigraphy of southwestern Ontario. Most of the detail is devoted to the Devonian Detroit River Group which was used as the primary injection interval during deep-well disposal.

The uppermost bedrock unit throughout most of Lambton County is the Port Lambton Group, of which the Kettle Point Formation is the most prevalent (Figure 3). The Port Lambton Group is composed of shale with minor sandstone and siltstone. The Kettle Point Formation is a black, bituminous shale with an average thickness of 45 m immediately east of the St. Clair River and decreasing in thickness toward the east (GTC, 1985). This formation unconformably overlies the Hamilton Formation and forms much of the bedrock throughout Kent and Lambton Counties.

The Port Lambton Group is underlain by the Hamilton Group, a series of calcareous shales and argillaceous and fossiliferous limestones. The lowermost formation of the Hamilton Group is the Dundee Formation. The Dundee Formation consists of microcrystalline limestone which is about 50 m thick near Sarnia (URM, 1984). A lenticular zone of high porosity dolostone ("lost circulation zone") occurs near the base of the Dundee (URM, 1984). The lower part of the Dundee Formation was often used as the disposal unit for disposal wells in the Sarnia area. The Port Lambton and Hamilton Groups are the confining units for the disposal formation (URM, 1984).

The Dundee Formation overlies the Detroit River Group. The Detroit River Group, which outcrops near Ingersoll approximately 241 km (150 miles) east of Sarnia, dips to the west at an average rate of .001 to .0009 m/m (5 to 10 ft/mile) (Rathbone, 1983). The Detroit River Group continues to dip under the St. Clair River and into Michigan. Another outcrop of this group occurs in southeastern Michigan, in Monroe and Wayne Counties (Dorr and Eschman, 1970). In Monroe County the outcrop consists of a broad band trending northeast-southwest across the northern third of the county. It abruptly narrows in the western part of the county and turns south into Ohio (Mozola, 1970). The outcrop is a prominent east-west band in the southern part of Wayne County (Mozola, 1969).

In southwestern Ontario, the Detroit River Group is divided into two formations: the top is the Lucas Formation and the bottom is the Amherstburg Formation. The Lucas Formation was the most heavily utilized interval for injection of wastes in Lambton County.

The Lucas Formation consists mainly of dolomite and limestone with minor anhydrite and salt beds in the lower part of the formation. In Lambton County, the thickness of the disposal formation ranges from 91 m in the north to 61 m in the south with an apparent increase in thickness toward the northwest or centre of the Michigan Basin. The formation subcrops approximately 105 km (65 miles) east of Sarnia. The top of the formation dips westward from an elevation of 91 masl on the eastern boundary of the county to 30 mbsl (metres below sea level) on its western boundary (Vanderberg et al., 1977). In the Sarnia area, the Detroit River Group is found at depths ranging from 167 to 288 m below ground surface (Rathbone, 1983).

The Lucas Formation was considered to be well suited for high volume injection because of its vuggy and cavernous porosity (GTC, 1985). The caverns were created by the dissolution of halite in the limestone. These caverns, or open zones, are the "lost circulation" zones commonly selected as suitable disposal intervals for injection wells. Although the disposal intervals usually spanned the entire Lucas Formation, these lost circulation zones may have been only several metres thick and were often responsible for 90% of the flow from the interval (GTC, 1985).

The Amherstburg Formation, a limestone and dolomite unit, is found beneath the Lucas Formation. Fossiliferous and biohermal reef structures are known to occur in this formation (URM, 1984). The contact between the underlying cherty carbonates of the Bois Blanc Formation and the Amherstburg Formation appears to be gradational. The thickness of the Amherstburg Formation in the study area ranges from 46 to 76 m (150 to 250 ft.). Most disposal injection was directed into the top of this formation. Zones of high porosity and/or lost circulation have not been reported in this interval (URM, 1984).

The structure of the confining layer, the Hamilton and Port Lambton Groups, has been affected by reefal structures and dissolution of salt beds (GTC, 1985). Pinnacle reefs in the underlying Silurian Guelph Formation caused overlying layers to be draped over reefal mounds. Also the dissolution of deeper salt formations (Salina Formation) has caused localized collapse of the strata resulting in thickening of the formation above.

There is a reported localized thinning of the Dundee Formation and the Detroit River Group along the Dawn Structure in Lambton County. This localized thinning has also been associated with leaching of salt from the underlying Salina Formation. The same process may have caused similar features along the Kimball-Colinville monocline and the unnamed trend east of this monocline. The collapse associated with such leaching may have produced fractures which would cause an increase in vertical as opposed to horizontal permeability within the Detroit River Group and overlying formations in this particular area (Vandenberg et al., 1977). If fracture connection is present, transport of waste will depend on the pressure profile and hydraulic conductivity along the fracture connection.

2.2.2 HYDROGEOLOGY

The regional groundwater flow direction in the bedrock disposal unit is similar to the regional shallow (freshwater aquifer) groundwater movement, which is generally to the west-northwest. It appears that the flow direction is influenced by topography (Vandenberg *et al.*, 1977). The apparent hydraulic gradient is directed away from the highest subcrop near Stratford (approximately 130 km northeast of Sarnia) toward the north, west and south. Areas of possible regional discharge are in the vicinity of Lake Huron and connecting waterways.

Locally, the potentiometric surface of the bedrock is irregular. These irregularities have been attributed to deep-seated geologic structures representing zones of variable permeability or irregular area-wide recharge of the groundwater from the glacial overburden (URM, 1984). Figure 6 shows a piezometric map of the disposal zone from Vandenberg *et al.* (1977) which suggests a hydraulic gradient directed to the west. The piezometric head in the disposal zone (under natural conditions) has been reported to range from 60-90 m (Vandenberg *et al.*, 1977) to 0-60 m (Rathbone, 1983) below the piezometric head in the shallow aquifer.

During the height of deep-well disposal in Lambton County (1967-1971), contaminated groundwater, believed to be from deep-well sources, flowed from abandoned water wells. These flowing wells indicate that static water levels rose to levels above the lower boundary of the freshwater aquifer and to above ground surface (Rathbone, 1983). These outbreaks were thought to be the result of over-pressurization of the disposal formation during waste injection. Any modifications, such as these, to normal subsurface pressures

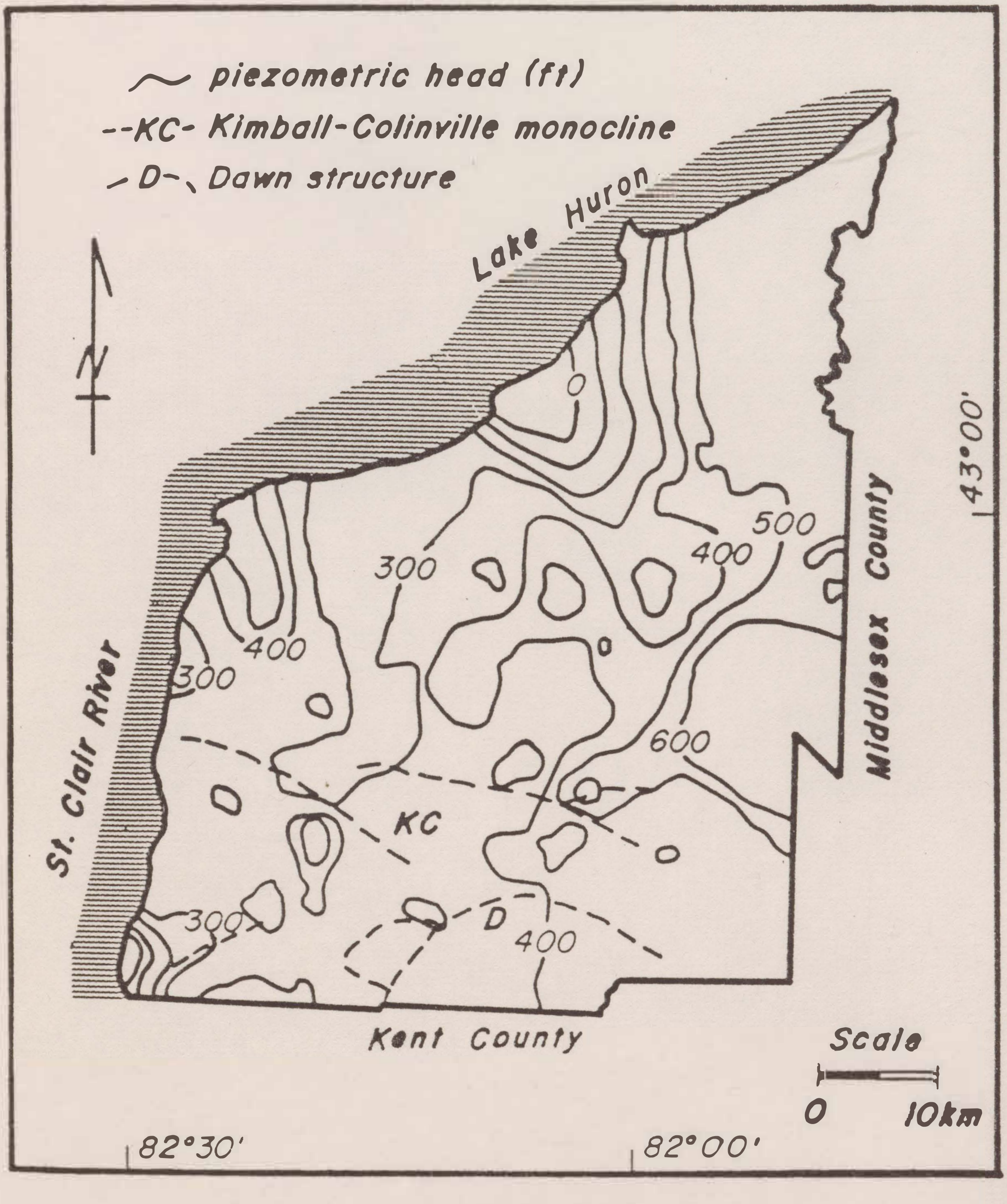


Figure 6. Piezometric map of the disposal zone (after Vandenberg et al., 1977).

can alter water levels from above normal to above surface. As the number of operating wells declined and injection pressures were reduced, static water levels in the Detroit River Group reportedly declined. Information on the rate of decline of pressures or current water levels in the deep disposal unit is not readily available.

Despite the vast amount of data available on oil and gas wells drilled in Lambton County, the information is not appropriate for the evaluation of the hydrogeology of the disposal zone. Some of the problems in the interpretation of the data are related to the reliability of the data: the data may not reflect conditions throughout the system, considerable time delay may elapse between a change of area-wide head levels and subsequent responses of other strata, and the scarcity or unreliability of head measurements. These problems, coupled with the lack of sufficient information on current pressure gradients and water levels in the deep disposal zone, make interpretation difficult.

3.0 DEEP WELL DISPOSAL

3.1 WASTE INJECTION IN THE SARNIA AREA

Injection of industrial wastes into deep, subsurface aquifers has been widely practiced in Canada as a means of isolating noxious substances from the biosphere (Simpson, 1976). The injected wastes are brines which are produced through the operation of oil fields and the controlled solution of evaporite strata, as well as a variety of organic and inorganic wastes from oil refineries and chemical plants.

This subsurface disposal has frequently been described as an ultimate or final process which can be used to dispose of hazardous wastes. These descriptions carry a connotation of permanent isolation of wastes. However, this is not always the case. As will be discussed, numerous studies conducted in the Sarnia area have reported incidences of contaminated groundwater and flowing wells which have been attributed to past injection of hazardous wastes.

3.1.1 HISTORY

The first industrial disposal wells in Ontario were completed by Imperial Oil Limited at Sarnia, between 1958 and 1960 (URM, 1984). Five disposal wells were drilled on the refinery property to dispose of refinery spent caustics and phenolic water. These disposal wells were completed in the Detroit River Group (Figure 7).

Additional disposal wells were drilled by other industries in the Sarnia area. These wells were also completed in the Detroit River Group and ranged in depth from 182 to 294 m (600 to 970 ft.) (URM, 1984). Dow Chemical also

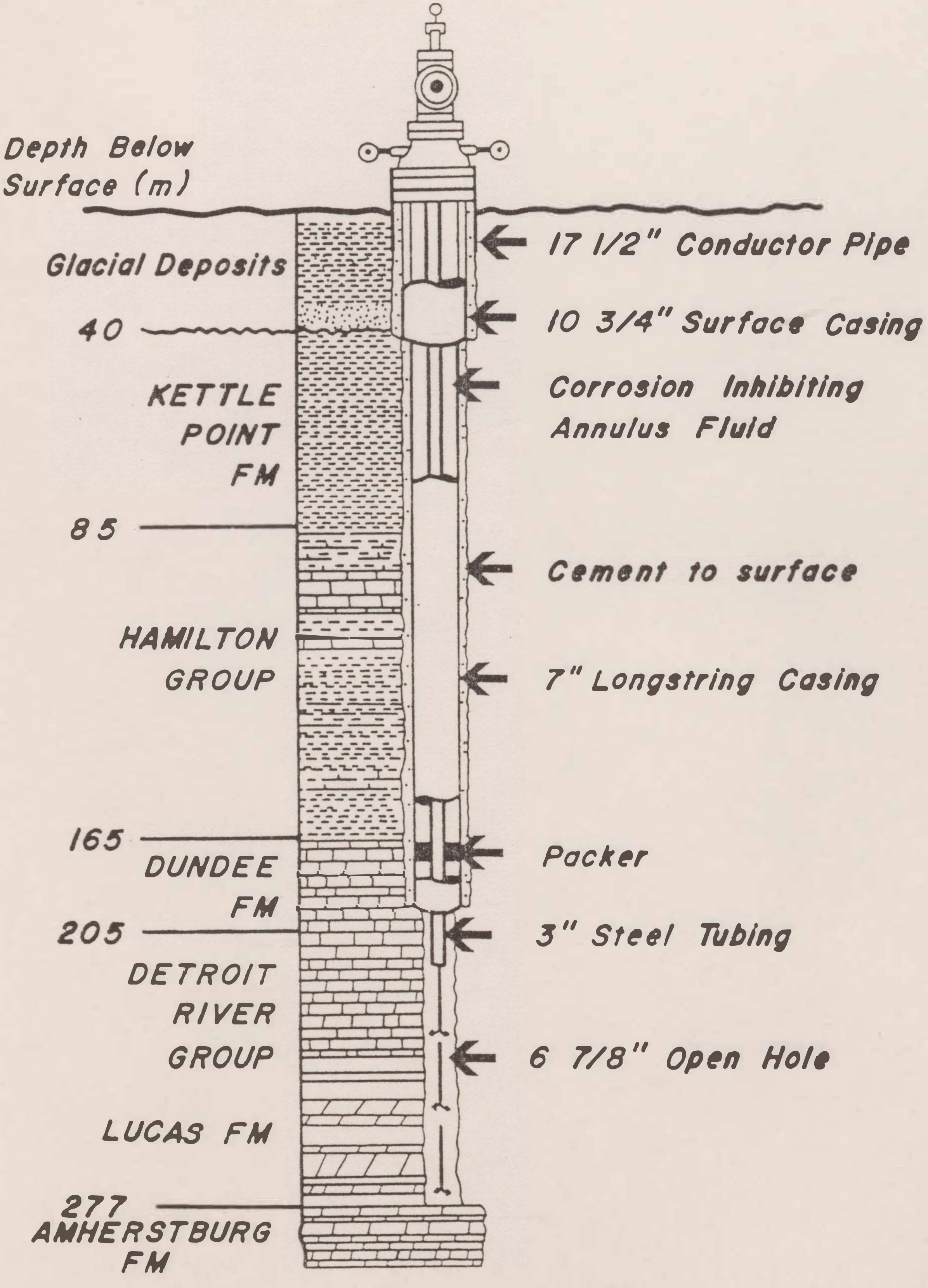


Figure 7. Schematic of a disposal well illustrating the bedrock geology and formation thickness (after URM 1984)

operated disposal wells that were completed in open cavities in the salt beds within the Salina Group (Environment Canada and Ministry of the Environment, 1985). These storage cavities ranged in depth from 579 to 610 m (1900 to 2000 ft.).

A total of 16 deep wells was used in and around the Sarnia area for waste disposal between 1958 to 1976. Table 1 summarizes the disposal wells located in the study area. These deep-well disposal systems were the primary waste management tool for most of the industrial complexes in and around Sarnia during the years the wells were permitted to operate (Rathbone, 1983). The disposal systems were characterized by low injection rates (generally less than 545 m^3/d or 100 gpm), injection pressures from atmospheric pressure to 3100 kPa (450 psig), and work-over acidization pressures (at the well head) of up to 5512 kPa (800 psig) (Simpson, 1978).

A wide range of organic and inorganic compounds, produced as by-products by local industries, required disposal (Rathbone, 1983). The primary wastes injected into the wells were: spent caustics, acids, phenols and hydrocarbons (GTC, 1985). Reportedly, a total volume of approximately 8 x 10^6 m^3 of fluid waste was injected into the subsurface during the 18 years of operations (Rathbone, 1983). By late 1969 or early 1970, the total rate of injection into these wells reached a maximum of approximately 1,893 m^3/d (500,000 gpd).

It was apparent that hydraulic head levels in the Detroit River Group had already risen significantly by 1965. Information on formation pressure build-up and recovery indicates the formation was likely pressurized to levels above ground surface shortly after the start of injection in 1958, and was

Table 1. Summary of disposal wells in study area (after URM, 1984).

COMPANY WELL NAME	COUNTY	TWP	TOTAL DEPTH (M)	INJECTION ZONE INTERVAL (M)
				Detroit River Group
Imperial Oil Limited (6 wells)	Lambton	Sarnia	244	184-244
			250	184-250
			206	192-206
			250	194-250
			250	194-250
			NA	NA
Polysar			274	NA
Dow Chemical (2 wells)			NA	Cavern, Salina Salt
			NA	576
				Detroit River Group
Suncor			294	206-294
Shell Canada Limited (2 wells)	Lambton	Moore	290	183-274
			290	198-290

NA not available

significantly pressurized by 1965 (GTC, 1985). In some cases, the formation was still at pressures that could cause the injection wells in the Detroit River Group to flow to the surface. This was evidenced by a well drilled by Suncor into the Detroit River Group in 1965 which found static water levels to be at land surface (URM, 1984). The original head levels (prior to waste injection) in the Detroit River Group were reported to be between 60 to 90 m (200 to 300 ft.) below the piezometric head in the shallow, freshwater aquifer (Vandenberg et al., 1977).

At this time, other industries were using well head pressures of up to 3,100 kPa (450 psi) to dispose of wastes at a rate of 273 to 545 m^3/d (50 to 100 gpm) (URM, 1984). It was known that at least one deep-well operator, Imperial Oil, practiced well stimulation to improve the receiving volume of their wells (Rathbone, 1983). This practice involved the use of acidization, acid fracturing and sand fracturing. Although the purpose of this procedure was to open up additional space within the injection zone, this stimulation may have caused fracturing in the overlying confining layer (Rathbone, 1983).

High pressures in the Detroit River Group were encountered in a number of boreholes and wells drilled in and around Sarnia during subsurface disposal activities. These high pressures caused several boreholes and wells in the area to flow, thus indicating that the pressurized zone had extended into the confining layers (GTC, 1985). Figure 8 relates the location of the disposal wells in the study area to: the known locations of several flowing wells, the location of the 2 survey lines used for water quality sampling during this study, and the bedrock valley discussed in the previous section.

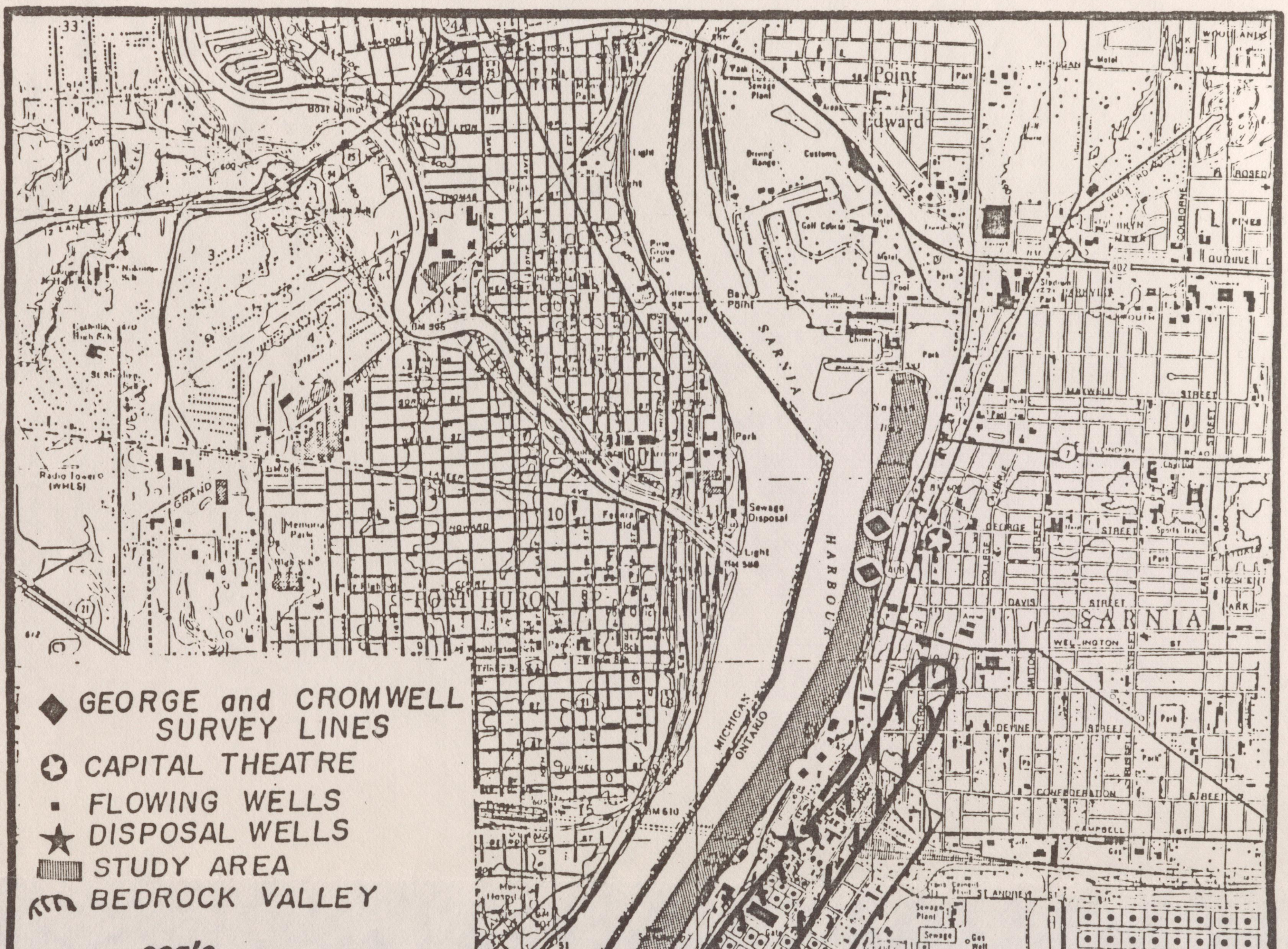


Figure 8. Relationship between disposal wells and study area.

The following is a brief account by URM (1984) of the flowing wells that occurred in the Sarnia area:

1. A well drilled on Imperial Oil property south of Sarnia, for disposal to Cambrian strata, flowed at the surface when the Detroit River Group was penetrated.
2. Shell Oil (located approximately 9 km south of Sarnia) drilled a second disposal well to the Detroit River Group which reportedly flowed to the surface.
3. Imperial Oil also encountered pressurized wastes in the Hamilton Formation at depths of between 76 to 91 m (250 to 300 ft.).
4. In 1966, high-pH phenolic wastes emerged beneath a building on the Imperial Oil property.
5. Two wells, located within 2 km of the Canadian Industries Limited (CIL) operations near Courtright (approximately 10 km south of Sarnia) flowed.
6. In 1972, an abandoned well at the rear of the Capital Theatre in downtown Sarnia discharged a greenish fluid that smelled strongly of hydrogen sulfide.

Simpson (1978) also reported high chloride and sulphate contents of water samples taken from water wells and springs in Lambton County. These high chloride and sulphate levels suggested upward leakage of deeper formation brines (Simpson, 1978). Also, outbreaks of formation fluids (brines and hydrocarbons) during 1965 in Port Huron, were reported by the Michigan Department of Conservation. These outbreaks occurred in shallow wells and there was speculation that the outbreaks were caused by pressurization of subsurface formations related to waste injection (Simpson, 1978).

Coupled with the Port Huron outbreaks, several incidents were reported where industrial waste or brine flowed to land surface through abandoned and inadequately plugged boreholes (URM, 1984). It has been estimated that approximately 10,000 wells and boreholes were drilled in southwestern Ontario and eastern Michigan during oil and gas exploration around the turn of the century, and were never plugged (URM, 1984). More recently, there could be as many as an additional 30,000 oil and gas wells in the numerous oil fields of the region (GTC, 1985). These unplugged or uncased holes may have served as conduits for upward migration of injected wastes from the disposal unit to the shallower strata.

Van Everdingen (1974) discusses some of the problems encountered during pressure build-up in the disposal formation resulting from waste injection. This build-up may cause reactivation of abandoned and inadequately plugged oil, gas and water wells, even if they do not penetrate the confining interval. Pressure build-up will also lead to an increased discharge rate from the disposal formation, whether from outcrops or through leaky confining beds. Salinity of discharge may also gradually increase and eventually waste material will appear in the discharge. This increase can take place even if injection is discontinued. Waste material may even be discharged over a time which is appreciably longer than the period of operation of the injection well. When a constant injection rate is maintained in an injection well, the fluid pressure in the formation increases with time. This pressure may ultimately reach a critical value, at which "hydraulic" fracturing of the formation takes place.

It appears that the injection pressures employed during subsurface disposal may have provided the fundamental cause for vertical movement of fluids. In light of the previous discussions, there are clear indications that hydraulic continuity had been established between the disposal unit and the overlying strata.

As a result of these problems, and under advisement from the Ministry of Mines and Northern Affairs, the industries utilizing subsurface disposal voluntarily agreed to a cutback in disposal rates, in some cases to 50% or less. Close observation of some problem wells was undertaken to see if the pressure would subside with time. An observation well located approximately 3 km (10,000 ft.) east of the industrial district in Sarnia (on Imperial Oil property) was monitored. This well had experienced a 358 kPa (52 psi) increase in bottom hole pressure in the period from 1958 to 1966, after which time the pressure was reportedly relatively stable (URM, 1984).

A study conducted by GTC Geologic Testing Company Ltd. (1985) reported that only a few wells have had detailed pressure monitoring since their closure. Pressure recovery information for a few of the disposal wells is given in Figure 9. Recovery information for the ESSO wells was complicated by the fact that the wells were filled with fuel oil. An equivalent water filled gauge pressure for ESSO NO. 5 was determined. The shape of the curve indicates that the well was not yet at zero gauge pressure and appeared to still be recovering (GTC, 1985). For the CIL wells the formation pressure had recovered to below ground surface but still above the freshwater aquifer by about 1982, or after about 10 years of inactivity (GTC, 1985). The Suncor

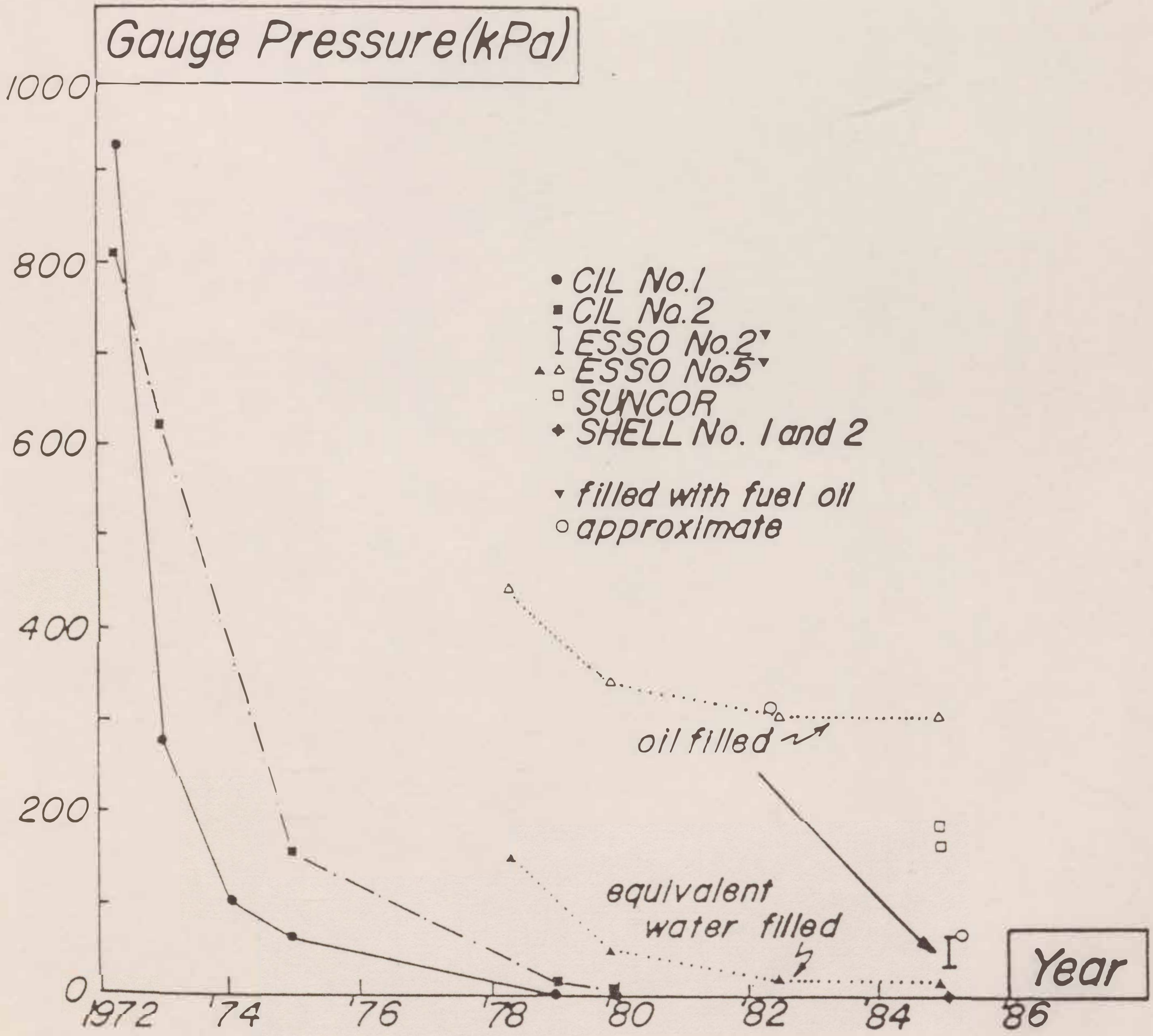


Figure 9. Pressure recovery data for several disposal wells (after GTC, 1985).

well was at about 172 kPa gauge pressure in December, 1984, but no information is available for the recovery prior to this date.

The breakout problems were reviewed by the Ministry of Mines and Northern Affairs in 1970. This review resulted in numerous warnings to industries. One such warning was that wells utilizing the Detroit River Group were to be phased out within two years in the area along the St. Clair River (URM,1984).

After passing numerous deadlines for cessation of injection of industrial wastes, injection finally ceased in 1976 (when the last permit expired). Since December 31, 1976 only brine has been injected into the Detroit River Group. No disposal to this formation is permitted within 8 km (5 mi.) of the St. Clair River. Static or shut-in water pressures are required to be 3 m (10 ft.) below the lowest occurrences of freshwater. Operating well head pressures are limited to zero gauge pressure (gravity drive) (URM, 1984). Between 1970 and 1982, 8 wells in southwestern Ontario were used for disposal of brine from salt caverns (used for storage) and 19 wells were used for reinjection of oil field brines (Pupp, 1985).

3.1.2 SUITABILITY OF INJECTION INTERVAL

The results of the review conducted by URM (1984) indicate that the Detroit River Group and the overlying formations do not meet the generally accepted criteria which have been applied to disposal zones and confining beds. Even though the disposal unit is overlain by about 150 m of shale and dense carbonate rock and 45 m of overburden, it is believed this formation is too shallow to ensure the safe disposal of liquid waste (Simpson, 1978). Locally, trends in the bedrock may be related to fracture-bounded sinks which formed as collapse features due to localized solution of the Silurian evaporite strata. These fracture systems present a hazard to subsurface disposal because they constitute possible conduits for upward movement of fluid wastes to the subsurface or near surface (Simpson, 1976).

4.0 METHODS OF STUDY

The field work for this study began on July 8, 1985 and was, for the most part, completed by September 16, 1985. Figure 10 summarizes the sequence of procedures used in this study. The first phase of the field study involved the installation of streambed survey lines, the characterization of the river bottom, and streambed core sampling. These procedures identified sites for subsequent installation of seepage meters and minipiezometers. Seepage flux rates (quantity of seepage) were determined through the use of the seepage meters and chemical analyses, performed on water samples collected from the minipiezometers, aided in determining the quality and sources of seepage.

4.1 SURVEY LINES

The accurate placement of the survey lines was very important in this project for they were used as a control during the installation of the seepage meters and minipiezometers.

Prior to the installation of the survey lines, a reconnaissance survey of the shoreline and river bed was conducted to determine the areas most suitable for instrumentation. Initially, the survey was to include 40 survey lines with one line every 250 m for 10 km. Industrial outfalls, river traffic and access, bottom conditions, and the strength of the river current were important factors in our site selections. As it turned out, the laying of these survey lines in the strong current of the St. Clair River was a difficult and complex procedure requiring that both the number and location of these lines to be modified. A detailed description of the installation procedures is included in Appendix 1.

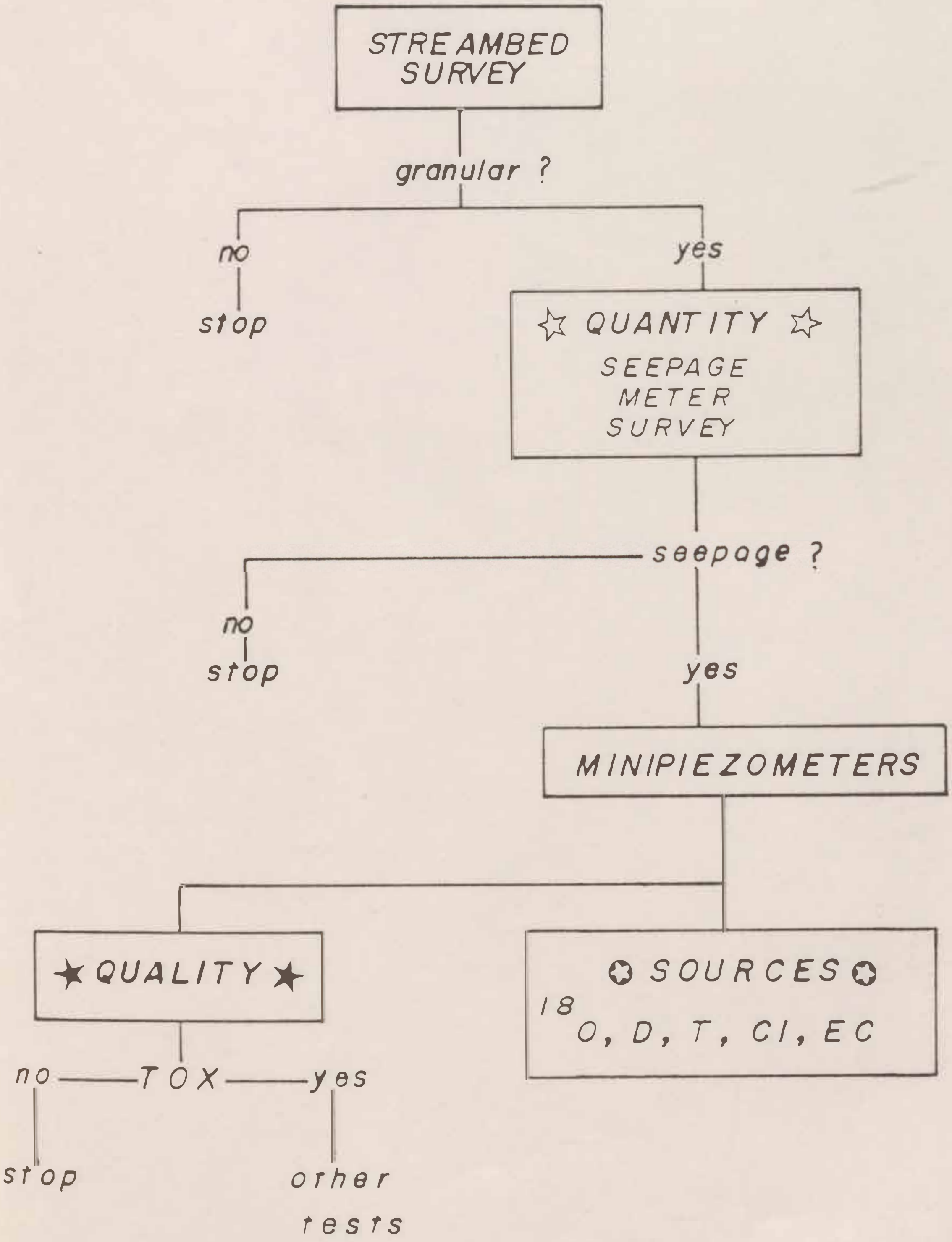


Figure 10. Flow chart of methods.

4.1.1 SURVEY LINE EQUIPMENT

The survey lines consisted of 100 m of 10 mm diameter yellow polypropylene line knotted at 10 m intervals. Plastic labels marked with station numbers (#1 on shore to #11 at 100 m from shore) were affixed at the appropriate positions. A stainless steel stake, driven into the ground at the shoreline, was used to anchor Station #1 of the line. Large, spiral, metal screws (dog ties) were then used to secure the line (at each 10 m station knot) to the stream bed. This was done to prevent the line and station from moving in the strong currents.

4.1.2 SURVEY LINE LOCATIONS

Figure 11 shows the locations of the 16 survey lines installed on the bed of the St. Clair River in the study area, a 100 m by 7 km band between Sarnia Bay and the Sarnia Indian Reserve. An additional survey line was installed in Lake Huron approximately 1 km northeast of the Blue Water Bridge. Detailed maps and location photographs of the survey lines are included in Appendix 1.

4.2 STREAMBED SAMPLING SURVEY

During the survey line installation, the divers recorded descriptions of the river bottom in the area of the survey lines and collected stream bed core samples which aided in the selection of appropriate sites for later seepage meter and minipiezometer installations. The detailed river bottom descriptions are given in Appendix 2.

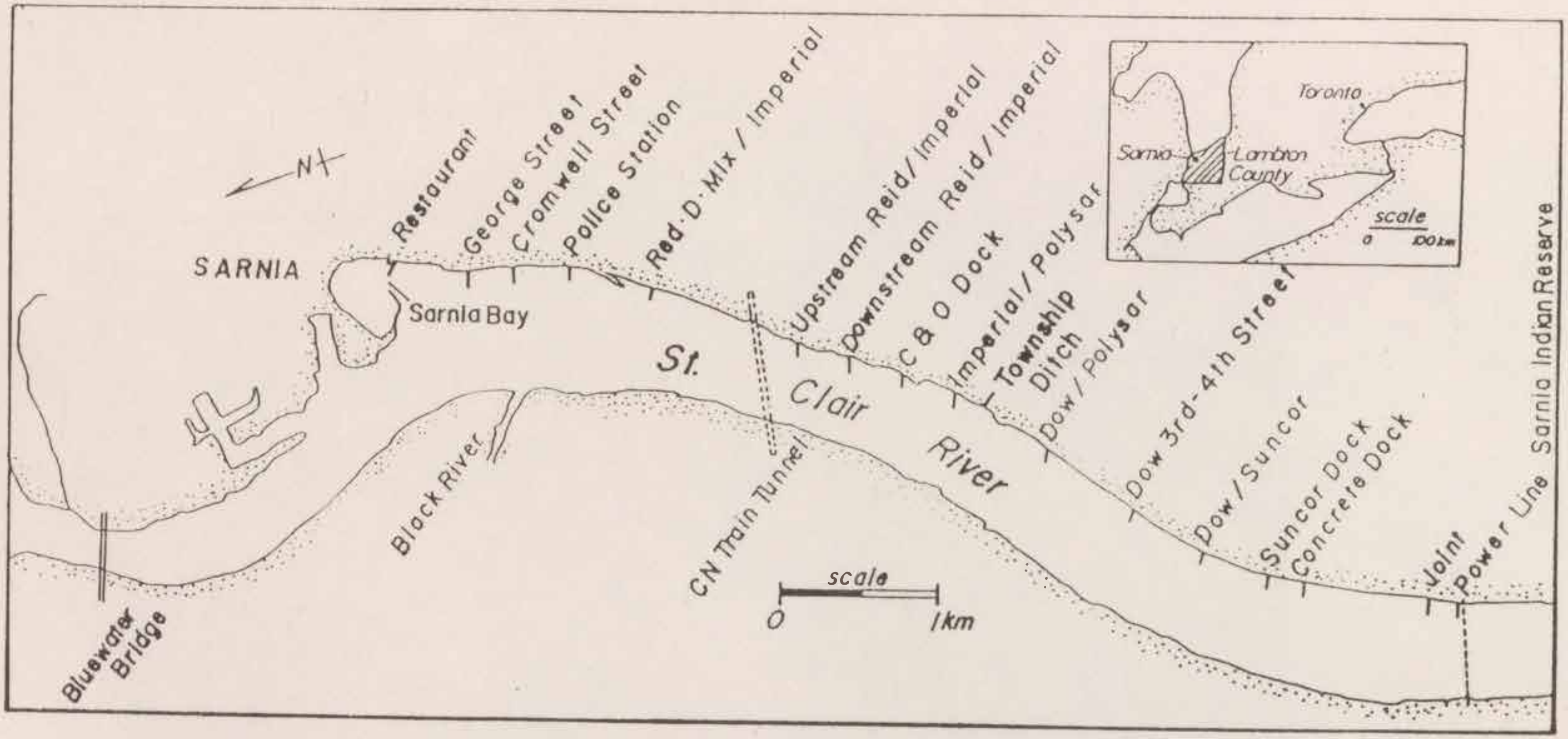


Figure 11. Map of streambed survey lines.

4.2.1 STREAMBED SAMPLING EQUIPMENT

The divers used modified Oakfield Model C Soil Samplers (Figure 12) which they tapped into the river bottom to a depth of 46 cm. Modifications to the sampler included a hole drilled into the handle for a rope loop and welding of the handle to the core barrel.

The divers began their streambed sampling traverse as soon as the survey line was weighted at the last station (Station #11). They collected bottom cores at the midway points between adjacent stations which were located between 5 m and 85 m from shore. After pulling the sampler from the stream bed, the divers slipped the core tube into a PVC plastic tube to bring it to the surface.

Once the divers returned to the boat with the samples, the core tubes were examined for core recovery and core description. Appendix 3 contains the bottom core descriptions and recoveries. It was assumed that zero recovery or missing core sections represented either a plugged corer, or granular material which had been blown out of the core tube by the river current during delivery to the boat.

4.2.2 STREAMBED SAMPLING LOCATIONS

Streambed sampling was conducted on 15 of the 16 survey lines shown on Figure 11 plus the Lake Huron Survey Line. The Restaurant Survey Line was not used as a streambed sampling location due to the excessively silty conditions and strong currents.

Figure 12.   Modified Oakfield Model C Soil Sampler.

4.3 SEEPAGE METER SURVEY

The surface water-groundwater interaction in lake bottoms and stream beds is often controlled at or near the sediment-water interface (Lee, 1977). Depending upon the interaction, groundwater flow in lake bottoms and stream beds can be upward, downward or horizontal. The direction and rate of flow is dependent upon the texture, stratigraphy and physiography of the subsurface materials (Lee and Cherry, 1978). Local flow can vary considerably from one location to another, thus providing a variety of observational conditions within a small study area.

The nature of the hydrologic interactions between the groundwater and the river water in the St. Clair River were studied primarily by using two devices: seepage meters and minipiezometers.

4.3.1 SEEPAGE METER EQUIPMENT

The seepage meters, installed in the sediment on the river bed, were used to quantify groundwater inflow into the river and to determine the spatial and temporal variations in seepage flux through the river bottom sediments. The principle of the seepage meter is that the seepage flux from the groundwater and the overlying surface water can be measured directly by covering a known area of river bottom sediment (by an open-bottomed seepage meter) and measuring the collection time and water volume change in a sample bag attached to the seepage meter. Seepage flux from the surface water to the groundwater can be determined by measuring the loss of water in a sample bag over a given time period.

Seepage meters used in this study were a modified version of Lee's (1977) seepage meter design (Figure 13). Modifications were necessary to adapt these seepage meters for use in the fast flowing and deep water in the St. Clair River, for groundwater of unknown quality, and for a need to reuse the meters several times.

The seepage meters were fabricated in the Central Research Shop at the University of Windsor. The devices were made from 1.6 mm thick, #304 stainless steel, rolled and welded into 50 cm diameter cylinders, 15 cm high. Tops were constructed of the same material and welded to each cylinder. A single 10 mm O.D., 0.035 mm wall, #304 stainless steel tube, located 5 cm from the edge of the top, allowed seepage to escape (Figure 14). This tube was also designed to act as a handle when moving the seepage meter. A brass quick-connect/disconnect mechanism at the end of this tube was attached to the collection bag apparatus. The quick-connect/disconnect mechanism prevented any loss or addition of water during collection and transport of the collection bag.

The collection bag apparatus contained a flexible plastic bag placed inside a rigid plastic container designed to protect the flexible bag from the river current. The brass connect/disconnect was attached to a stainless steel tube that extended through a hole in the plastic bottle cap into a rubber stopper fit into the neck of the bottle. An opening was cut into the bottom of the rigid plastic bottle which allowed examination of the collection bag and aided in keeping the bag at an ambient river-bottom hydraulic head. Photographs of the collection bag apparatus and additional photographs of the seepage meters are contained in Appendix 4.

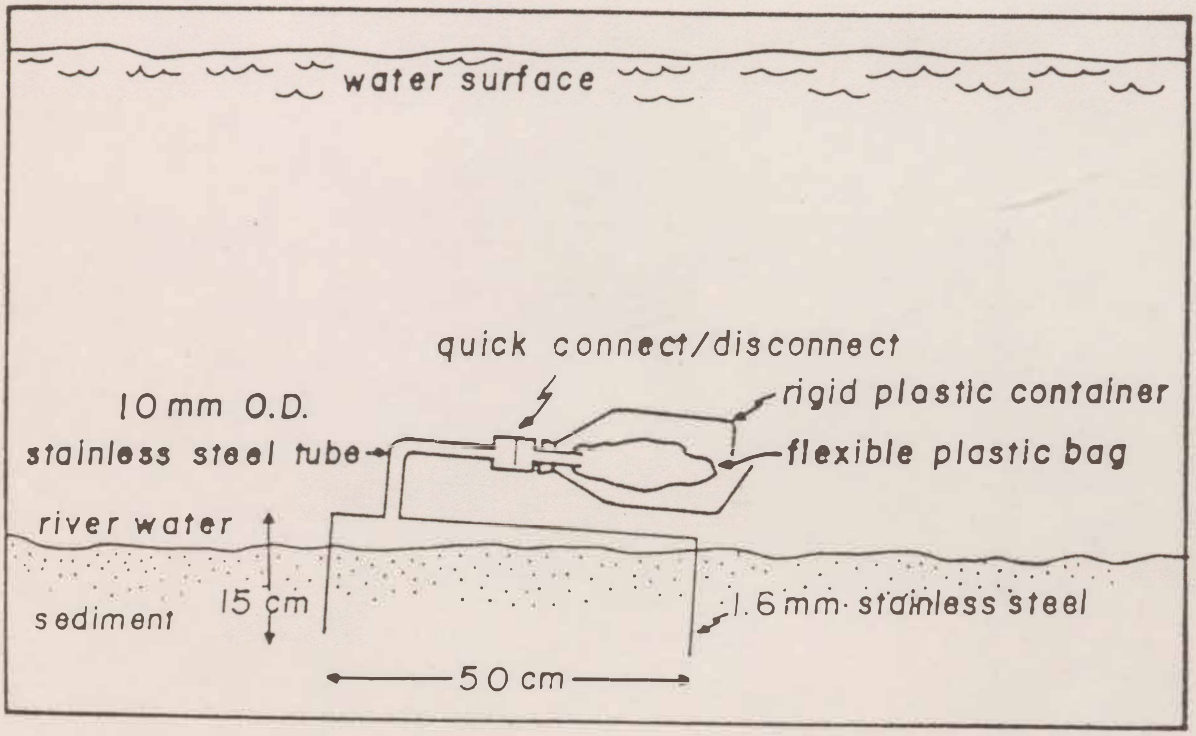


Figure 13. Schematic diagram of modified seepage meter.

Figure 14. Seepage meter.

4.3.2 SEEPAGE METER LOCATIONS AND INSTALLATION PROCEDURE

The seepage meters were installed on 8 survey lines where bottom cores indicated the existence of considerable granular material. The divers installed the seepage meters starting at the shoreline end of the survey line. During installation, the seepage meters were twisted and tapped (with a small mallet) into the bottom sediments in such a manner to insure that the vent hole was elevated slightly to allow any gas from the sediment to migrate into the collection bad. Once the meter was installed, it was then secured to a dog tie at that position to prevent the loss of the meter in the strong currents. In spite of the extra effort of securing the seepage meters to dog ties at each station, the strong currents blew several meters away, and overturned others. A number of collection assembly bags was also blown off the seepage meters by the currents.

Prior to the installation of the collection bag apparatus, the apparatus was labelled by position. The assemblies were then carried down and attached to the seepage meters by the divers. The collection assemblies were replaced by the divers every one to three days with assemblies being left on some seepage meters for up to nine days in order to determine any temporal variations in seepage rates. Once the collection assembly was replaced by the divers and brought to the surface, the accumulated seepage in the collection bag was measured in a plastic graduated cylinder and noted after every recovery. Samples of seepage water were retained for field measurements of pH, electrical conductivity (EC) and temperature. No further chemical testing was done on these samples due to the generally low seepage rates which resulted in the incomplete displacement of river water by seepage water in the meter, and because of the possible contamination from surface sediments. Appendix 4 contains the seepage meter field data which includes: pH, EC, temperature, seepage volume, sampling duration, and seepage rates, for each station monitored.

4.4 MINIPIEZOMETER SURVEY

"Minipiezometers" were used to determine the quality and source(s) of seepage water from the bed of the St. Clair River. Minipiezometers were installed at sites where significant seepage was measured. The minipiezometers designed for this study had to address several potential problems including: the difficulty of installing any tall or wide instruments in the strong river current, unknown streambed material below a depth of about 50 cm, ease of installation by the divers, ease of attachment to the pumping equipment, and potentially contaminated surface sediments.

4.4.1 MINIPIEZOMETER EQUIPMENT AND INSTALLATION PROCEDURE

The minipiezometers were fabricated in the Central Research Shop at the University of Windsor. The devices were constructed of 10 mm O.D., 0.89 mm wall thickness #304 stainless steel tubing, 1.0 and 1.5 m in length (Figure 15). The bottom of each minipiezometer contained a #304 stainless steel screen (0.15 mm diameter holes, 0.64 mm spacing between hole centres) which permitted the entry of pore water from the river bed sediments. This screen was kept in place by a stainless steel spring which allowed removal for cleaning (Figure 15). Drive heads were welded to the minipiezometer and the casing to aid in installation.

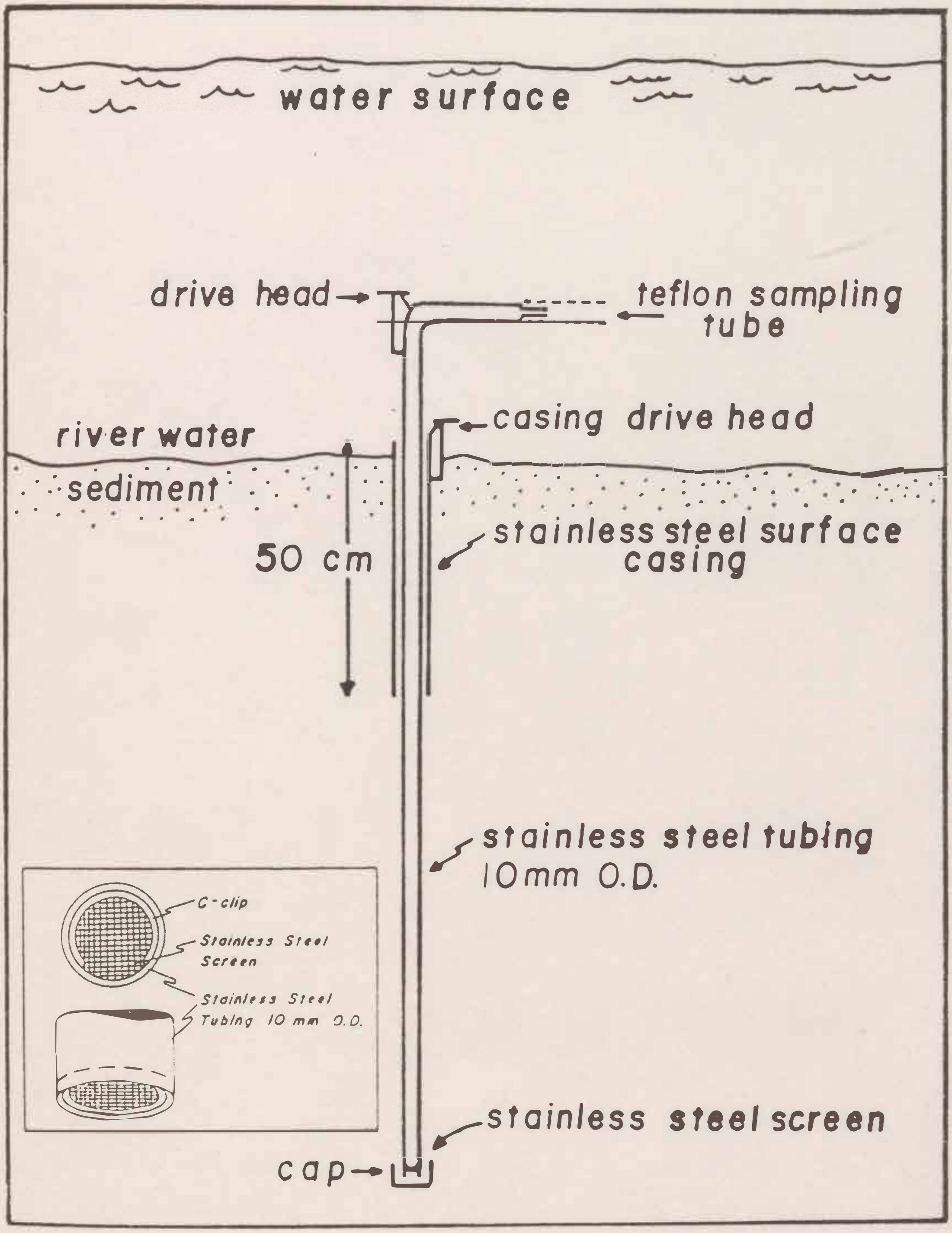


Figure 15. Schematic diagram of a minipiezometer.

The minipiezometers were thoroughly cleaned and sterilized in the laboratory prior to their use by the divers. The procedures for cleaning the minipiezometers were as follows: the minipiezometers were washed with a lab-grade detergent and rinsed with organic free distilled water, this was followed by a solvent rinse (i.e., pesticide-grade acetone) and another organic-free distilled water rinse. After drying, the ends of the minipiezometers were covered with similarly cleaned aluminum foil to keep them clean during transport and handling.

Prior to the installation of the minipiezometers, the divers drove stainless steel stakes into the stream bed near the sampling site. Marker buoys were attached to these stakes and the boat was moored to the buoys.

Figure 16 shows the small diameter outlet end which accepted the small diameter teflon tube that was used during sampling. A teflon tube (0.476 cm I.D., 0.051 cm wall thickness), secured by a nylon rope, was attached to the minipiezometer outlet. Distilled water was pumped through the teflon tube for 5 minutes to wash the minipiezometers prior to sampling. The tubing was kept attached to the pump (Masterflex Model 7570 peristaltic pump) so that the tubing would not drain as the minipiezometer was carried to the river bed by the divers.

The divers entered the water with the minipiezometers attached to the teflon tubing. They placed a metal plate on the river bottom through which they drove a 50 cm stainless steel casing with a loose fitting end cap. This casing was driven through the upper sediments to ensure that the minipiezometer tip did not come into contact with the upper sediments

Figure 16. Minipiezometer and casing.

(especially those which may have been contaminated). The metal plate prevented the casing from being buried in the river bottom.

On signal from technicians in the boat, the divers began to insert the minipiezometer into the casing as more distilled water was pumped through the minipiezometer (this was done to keep the screen clean). The minipiezometer picked up the end cap from the casing as it was driven to its full length. After being driven to its full length, the minipiezometer was pulled back about 2 cm to free the end cap from the screen. Once this procedure was completed, the minipiezometer was ready for sampling.

The minipiezometers provided a means of sampling the water at and beneath the river bed to depths ranging from 1.0 m to 1.5 m below the river bottom. There is no information on the thickness distribution of streambed sediment. Minipiezometer lengths of 1.0 and 1.5 m were selected to sample the streambed water near the surface water interface, but deep enough to ensure that river water would not be pumped in during sampling. Prior to sample collection, water was drawn through the minipiezometer and sample tubing for a minimum of 10 minutes and until the EC stabilized, to ensure that adequate purging of the pre-pumped distilled water had taken place. Samples were then collected and the pH, EC and temperature were recorded. A detailed description of the minipiezometer sampling procedures, field parameter data (pH, EC and temperature), and photographs showing details of the minipiezometers, are included in Appendix 5.

The minipiezometers were also intended to be used to determine the hydraulic gradient in the streambed sediments. However, owing to excessive gas bubble formation in the teflon tubing, accurate measurement of hydraulic head in the minipiezometers was not possible.

4.4.2 MINIPIEZOMETER LOCATIONS

The minipiezometers were originally to be installed at all sites where significant seepage was found during the seepage meter survey. However, due to time limitations on the field study, minipiezometers were installed on only 2 of the 17 survey lines, George Street and Cromwell Street (Figure 11). These two lines were selected partially because of the substantial granular layer on the streambed and the measurable quantity of seepage encountered during the seepage meter survey. They were also selected because of the contaminated groundwater that had been observed to be flowing from an abandoned well a few blocks inland from where the lines were located.

4.5 ENVIRONMENTAL ISOTOPE TRACER SURVEY

Environmental isotopes are naturally occurring isotopes which can be used as tracers in investigations of groundwater and surface water systems. The environmental isotopes were very important in this study for their concentrations and distributions provided information on the age and origin of the waters collected from both the minipiezometers and the river. Appendix 6 outlines some of the background on the use of environmental isotopes as tracers.

4.5.1 USE OF ENVIRONMENTAL ISOTOPES AS WATER TRACERS

Oxygen-18 (^{18}O), tritium (^{3}H or T) and deuterium (^{2}H or D), are commonly used environmental isotopes in hydrogeological studies. All three isotopes were used in this study. These isotopes are commonly used largely because they are constituent parts of some water molecules.

Tritium is normally used as a guide to the age of groundwater while ^{18}O and D are used mainly to provide information on the type, origin and movement (transit time) of groundwater and surface water. Generally, if the isotopic content of water in a flow system does not change within the system, the isotopic content of the water will reflect the origin of the water. If the isotopic content changes along the flow path, the changes reflect the history of the water. The origin deals with the location, period and process of recharge, while the history encompasses the mixing, movement and discharge processes (Fontes, 1980).

In shallow groundwater flow regimes with normal groundwater temperatures, ^{18}O and D are non-reactive tracers. Their concentrations, under these conditions, are altered only by physical processes such as: mixing, diffusion, dispersion, and radioactive decay. Their concentrations arise from the isotopic composition of the precipitation that falls on the ground surface and by the amount of evaporation that occurs before the water penetrates below the upper part of the soil zone. Once this water moves below the upper part of the soil zone, the ^{18}O and D concentrations become a characteristic property of the subsurface water mass. These characteristics enable the source areas and mixing patterns to be determined by sampling and analysis for these isotopes (Freeze and Cherry, 1979).

Dansgaard (1964) and others have demonstrated that isotopic variations in precipitation around the globe are linearly related to mean annual temperature (Figure 17). This relationship has been used by Fritz et al. (1974), Desaulniers et al. (1981), MacGregor (1985), Scott (1986) and others to estimate the age of groundwater. Fritz et al. (1974) used the oxygen-18 content of fossil shells and glacial ice to demonstrate that the climatic conditions in southern Canada have remained much the same for about the last 10,000 years and that much colder temperatures prevailed prior to that time (Figure 18). On the basis of this argument, Desaulniers et al. (1981) have suggested that: (1) the $\delta^{18}O$ values of shallow groundwater in southwestern Ontario which are similar to the current rain $\delta^{18}O$ values (approximately -10 ‰), represent recent recharge (<10,000 years) compared to (2) the $\delta^{18}O$ values of deep groundwater in southwestern Ontario (-15 to -17 ‰) which are very depleted in oxygen-18 relative to current precipitation and represent recharge which occurred more than about 10,000 years ago, and (3) intermediate ^{18}O values which represent mixtures of older and younger waters.

Tritium is a radiogenic isotope of hydrogen whose half-life is approximately 12.35 years. Natural tritium is produced in the upper atmosphere by cosmic neutron bombardment of nitrogen-14. The natural background concentration of tritium has been marked by enormous amounts of man-made tritium since 1952. This loading was the result of the production of tritium in the stratosphere during thermonuclear tests. Tritium concentrations in precipitation before 1952 have been estimated to range from 4 to 25 TU, however, post 1952 concentrations of up to three orders of magnitude greater than the natural levels have been reported (Figure 19) (Gat, 1980).

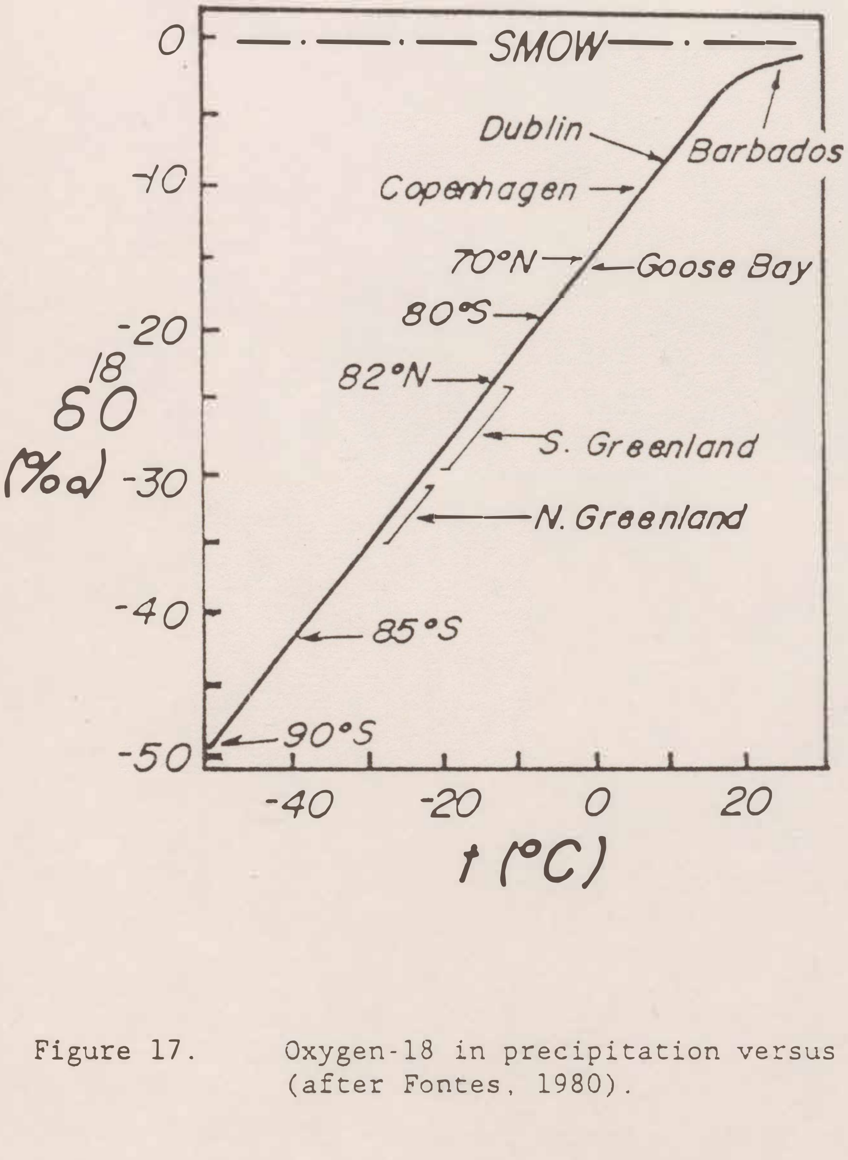


Figure 17. Oxygen-18 in precipitation versus temperature (after Fontes, 1980).

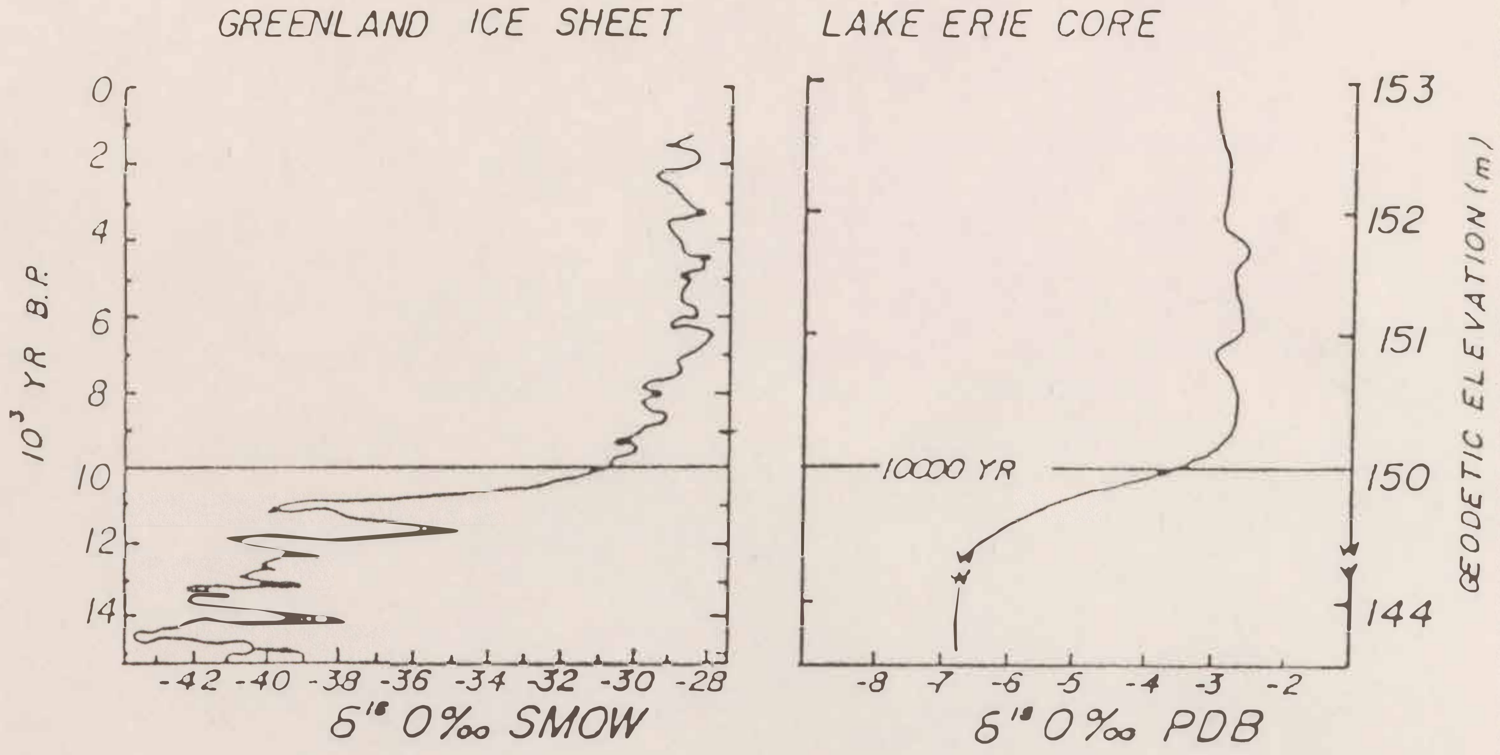


Figure 18. $\delta^{18}O$ in meteoric water over the past several thousand years (after Fritz et al., 1974).

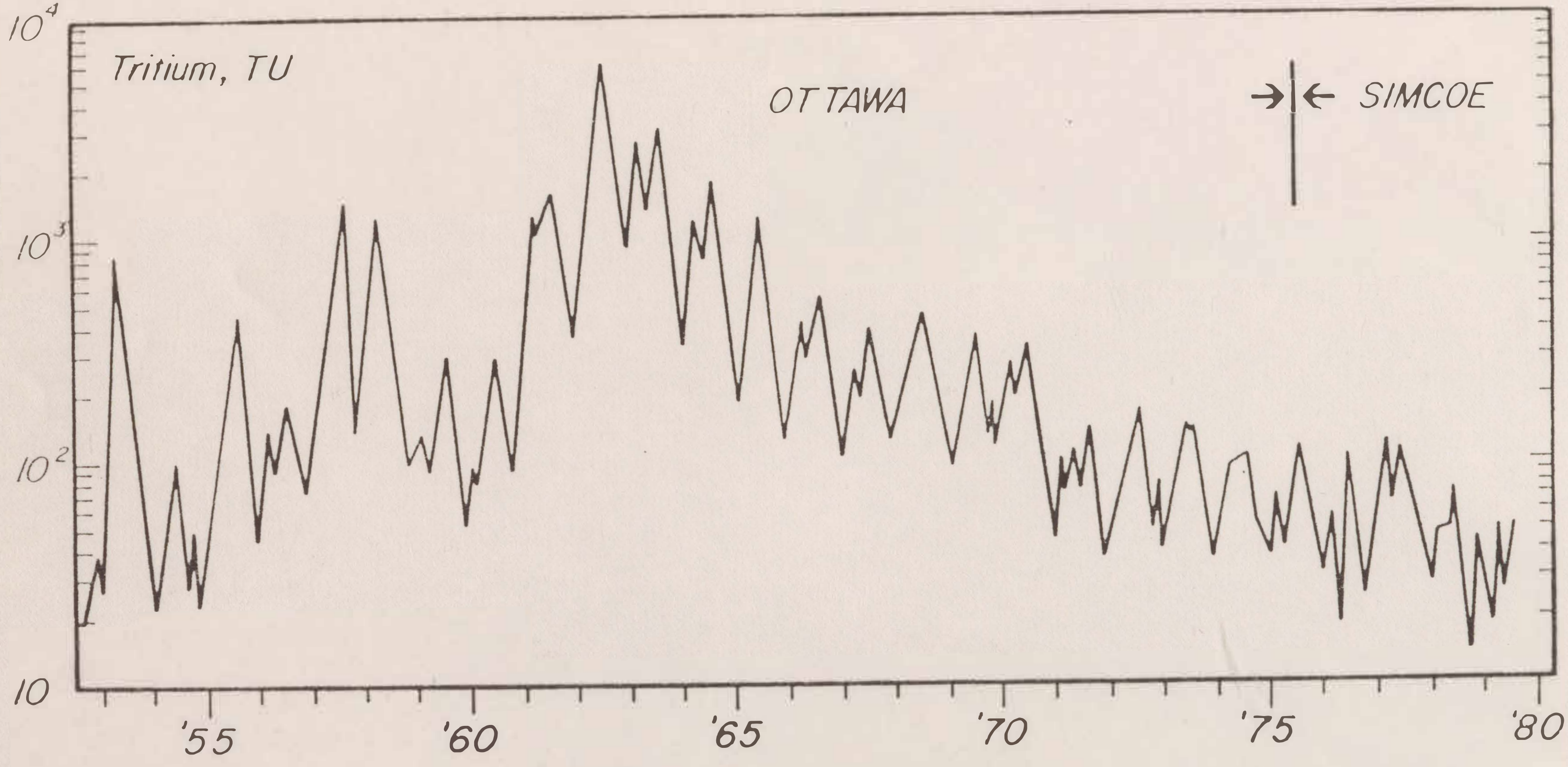


Figure 19. Tritium in precipitation versus time (after I.A.E.A., 1979).

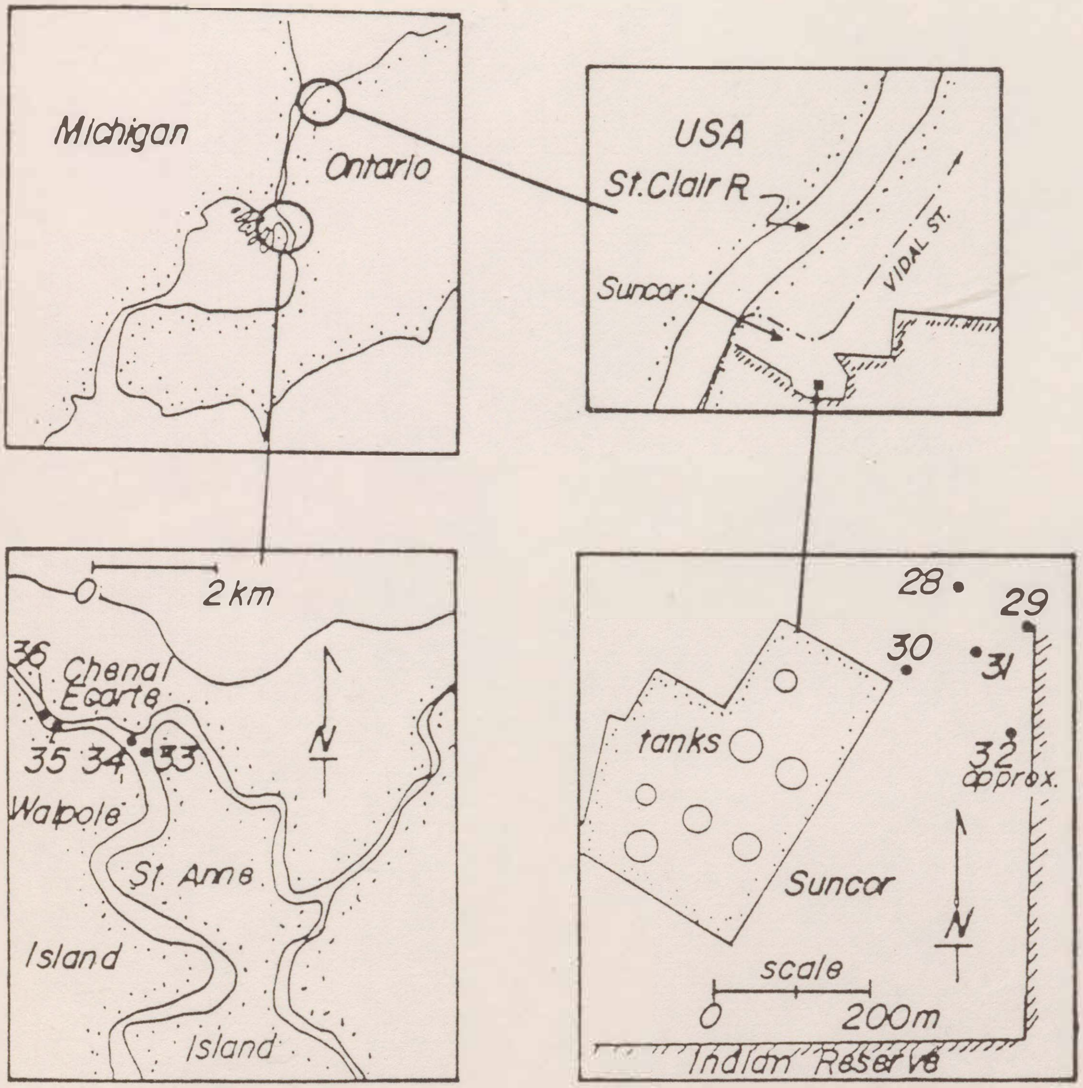
Both natural and bomb produced tritium appear in the form of tritiated water and can be used to distinguish different age zones within the modern (post-1952) water part of a groundwater flow system or to distinguish zones of mixing between two adjacent flow zones. Two attributes that make tritium an excellent indicator of young groundwaters are: the conservative nature of tritium and the temporal variations in the tritium concentrations in precipitation over the past 40 years. Since the half-life of tritium is 12.35 years, any water recharged before 1952 would have tritium concentrations less than about 5 TU; conversely, waters recharged after 1952 would have more than about 5 to 10 TU (Fontes, 1980).

4.5.2 ENVIRONMENTAL ISOTOPE SAMPLING AND ANALYSIS

Samples for environmental isotope analysis were collected during the minipiezometer and river water sampling. A 250 mL nalgene plastic bottle, filled with no head space, was used to contain each sample.

A total of 29 samples of river water and streambed groundwater were collected for isotopic analysis. In addition, samples for isotopic analysis were collected from shallow observation wells in the till on Suncor's property (in Sarnia), and river water samples were taken from the Chenal Ecarte in the St. Clair River delta (Figure 20).

The isotopic analyses were performed under contract by the Isotope Laboratory, Department of Earth Sciences, University of Waterloo. They used standard isotopic analysis procedures and water standards recommended by the IAEA (International Atomic Energy Agency). A detailed description of the



Chenal Ecarte samples

Suncor samples

Figure 20. Chenal Ecarte and Suncor sample locations.

analytical procedures and quality control used during analyses are described in Appendix 6.

4.6 CHEMICAL ANALYSES

Selected river water and streambed groundwater samples collected during the minipiezometer survey were analyzed for the following parameters: chlorinated hydrocarbons, polychlorinated biphenyls, trihalomethanes, EPA Priority Pollutants (extractables), TOX (total organic halogens), chloride and environmental isotopes (oxygen-18, deuterium and tritium). Owing to a limitation in funding, a phased approach was used to determine exactly how many parameters would be run on each sample.

4.6.1 SIGNIFICANCE AND APPROACH FOR ANALYSES

All river water and streambed groundwater samples were analyzed in the field for pH and electrical conductivity. A total of 29 samples of river water, streambed groundwater, blanks, spikes and duplicates were analyzed for TOX by Zenon Environmental Inc. of Burlington, Ontario. Zenon Environmental Inc. was recommended for analysis by Environment Canada (Hallett, personal communication). Owing to time and budget constraints, the selection of additional samples for analysis was limited to samples showing elevated TOX levels. Eleven samples showing elevated TOX levels were also analyzed for chlorinated hydrocarbons, including polychlorinated biphenyls and trihalomethanes. Five of these eleven samples were then analyzed for the EPA Priority Pollutant Extractables.

As previously mentioned, isotope analyses were performed on all 29 of the river water and streambed groundwater samples in addition to samples collected from wells on Suncor's property (Sarnia) and river water samples taken from the Chenal Ecarte in the St. Clair River delta.

The overlap in test methods used during the water analysis, i.e., PCB was analyzed using two different methods, permitted qualitative and quantitative confirmation of results from the other tests, as well as improving upon parameter detection limits from parts per million (ppm) to parts per trillion (ppt).

4.6.2 ANALYTICAL METHODS

Table 2 contains a summary of the parameters, number of samples for each parameter, and the analytical methods used during analysis of the samples. Mason *et al.* (1986) give brief summaries of the analytical methods and the complete Work/QA Project Plan, which includes detailed sampling procedures and detailed descriptions of analytical methods.

Table 2. Parameter table.

Sample Matrix = all Streambed groundwater
and river water

Parameter	Number of Samples	Analytical Method	Detection Limit	Precision Protocol
Total Organic Halides (TOX)	29	EPA Standard Method 9020	1-5 ug/L depending on compound	1 Blank 1 Duplicate and 1 spike /20 samples
Volatile Halogenated Organics (Trihalomethanes)	11	Modified ASTM Method D3973 (GC/ECD Pentane extraction Method)		1 Blank 1 Duplicate and 1 Standard /20 samples
Organo Chlorines Chlorinated Hydrocarbons/PCB	11	EPA Federal Register Method 608 (Dichloromethane extraction, silica cleanup, GC/EC)		1 Blank 1 Duplicate 1 Standard /20 samples
Semivolatile Organics (Base/Neutral and Acid Extractables)	5	EPA Federal Register Method 625 (with capillary column)		
Isotopic Analyses Oxygen, Deuterium and Tritium	29 oxygen-18 29 tritium 29 deuterium	Mass Spectrometry		1 Duplicate /15 samples
pH	22	Corning Combination Electrode and Model 103 Digital pH Meter		measurements on duplicate samples
Electrical Conductivity	22	YSI Conductivity Probe and Model 32 meter		measurements on duplicate samples
Phenols	5	Method 510, Standard Methods (4AAP and solvent extraction)		
Chloride	25	Specific Ion electrode		

5.0 RESULTS AND DISCUSSIONS

5.1 RIVER BOTTOM CHARACTERIZATION

The types and distribution of sediments on the riverbed were examined using both divers' descriptions and sediment samples. The divers collected 71 core samples from various locations along 16 of the 17 survey lines installed for use during this study. Appendix 2 contains river bottom descriptions and Appendix 3 contains bottom core descriptions.

Interpretation of the physical character of the river bottom was aided by a study conducted by Environment Canada and the Ontario Ministry of the Environment in the St. Clair River (Environment Canada and Ontario Ministry of the Environment, 1986) which describes the bottom profile of distinct reaches of the river in the area of several of our survey lines. The first section of the river is the steep upper reach between Lake Huron and the mouth of the Black River (Figure 21) where the channel is approximately 450 m wide and 9 m deep, with a mean surface current of 1.5 m/s. The second section has been defined as the middle reach which extends downstream to the St. Clair River delta. It has a variable width (600-900 m) and depth (8-15 m), and a mean surface current of 1 m/s.

The reach of the St. Clair River along Sarnia's industrial shoreline is described as a stable channel which is 500-800 m wide and 9-15 m deep (Environment Canada and Ontario Ministry of the Environment, 1986). The adjacent, highly altered, shoreline is low-lying with a maximum height of less than 10 m above mean water level. Considerable artificial smoothing of the industrial shoreline by landfilling occurred between 1955 and 1973 (Environment Canada and Ontario Ministry of the Environment, 1986).

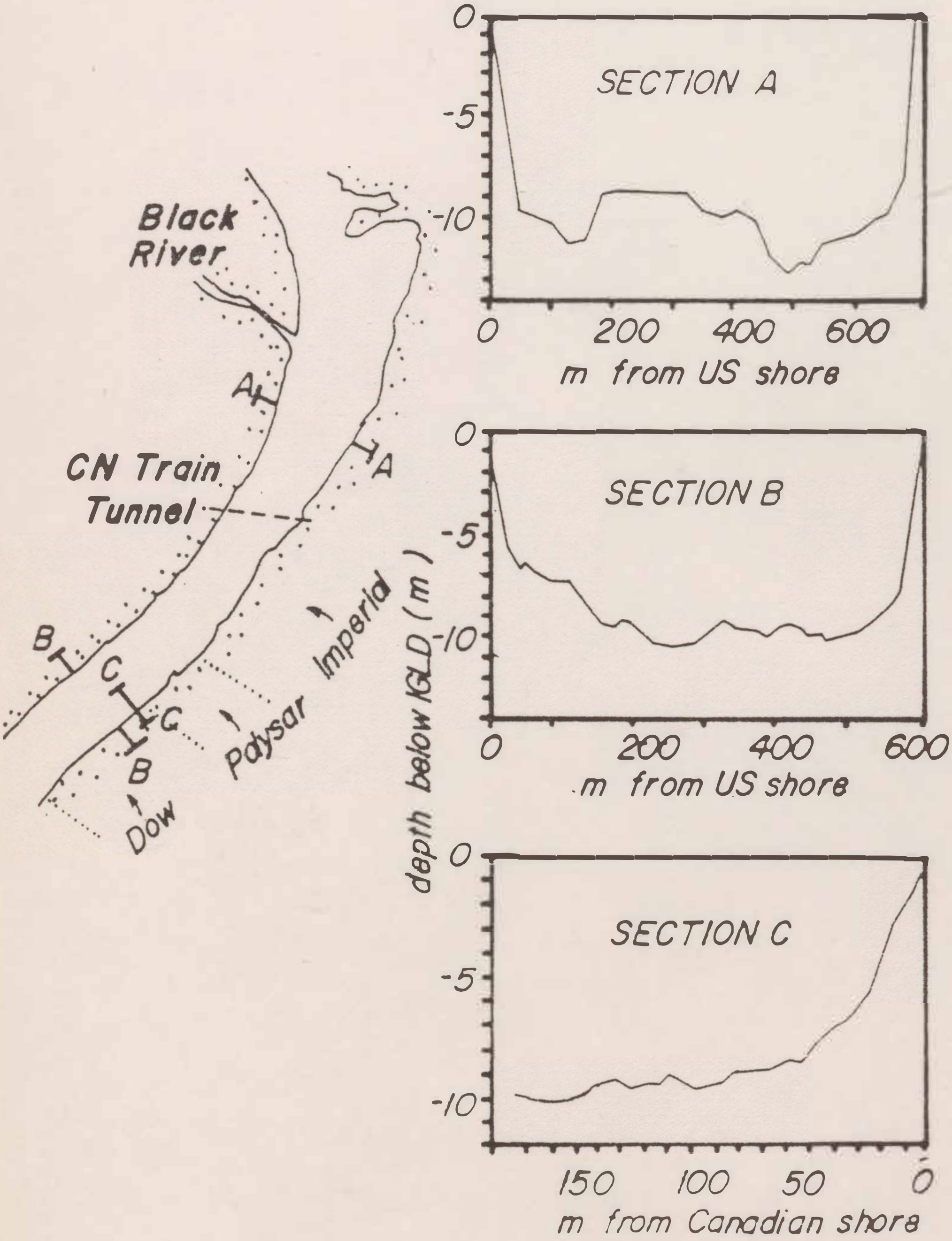


Figure 21. Profiles of the St. Clair River bottom and cross-section locations (after Environment Canada and Ontario Ministry of the Environment, 1986).

The depth and shape of the channel is reported to vary with distance downriver. North of the CN railway tunnel, the channel has steep, smooth sides and a central ridge, 2 to 4 m high, separating Canadian and American sub-channels (Figure 21, cross-section A). The shape of the cross-section gradually changes further south as the slope of the American shore decreases and the sub-channels become less prominent (Figure 21, cross-section B). Profiles A and B fall within close proximity to several of the survey lines for this study. Cross-section A is close to the Red-D-Mix /Imperial Survey Line, and cross-section B is adjacent to the Dow-3rd-4th Street Survey Line (Figure 11).

In addition, Environment Canada and the Ontario Ministry of the Environment (1986) conducted a detailed survey of the morphology of the slope of the shore in the vicinity of the 1985 spill at Dow's property. The inshore slope is smooth and very steep with grades as high as 1 in 3 (18^{o}). The bottom contours are generally parallel to the shore. The slope gradually decreases offshore for approximately 5 m then a pronounced break in the slope occurs. There is also an increase in bottom roughness between 50 and 100 m off shore at a depth of between 7 and 9 m. The local relief on the lower slope and in the adjacent channel floor ranges from 0.1 to 0.5 m.

Rukavina (1986) described the river channel as generally having a complex erosional midsection cut into glacial deposits and consisting of a steep inshore slope with a veneer of modern sediments. According to Fitzgerald *et al.* (1979) the river bed is cut in a hard, stoney glacial clay known as the Black Shale Till. The tills and their erosional products form much of the bed material. The bed material is described as a pavement of well-rounded cobbles and boulders with sand or till in the interstices (Rukavina, 1986).

The divers' observations and core samples from this study are consistent with the preceding descriptions. The bed of the St. Clair River in the study area can be broadly described as a clayey till overlain in areas by sand and gravel. The divers reported distinct benches up to tens of centimetres in height cut into the clayey till of the river bottom in numerous locations. Data on the observed sand and clay thicknesses from cores taken along the 16 survey lines are presented in Figure 22. The river bed within 30 m of the shore is covered with varying thicknesses of sand-size sediments and gravel. Further from shore, the vegetation becomes less dense and coarser sands and gravels predominate. Clay is exposed or lightly covered by gravel in several areas along the survey lines. There does not appear to be any correlation between distance from shore and lithology.

A zero recovery was reported at numerous locations throughout the survey. This could have been due to conditions such as rock and coarse gravel unable to fit in the core barrel or silt or fine sand being blown out of the corer by the river current during transport to the boat.

Some of the survey lines were completely mantled by fine-grained sand which ranged in thickness from 1 to 46 cm (total length of core sampler). The Restaurant Survey Line contained so much loose silt that core samples could not be taken as the material was blown out of the sampler by the river current. Various amounts of debris (rubble, piles, logs, boats, etc.),

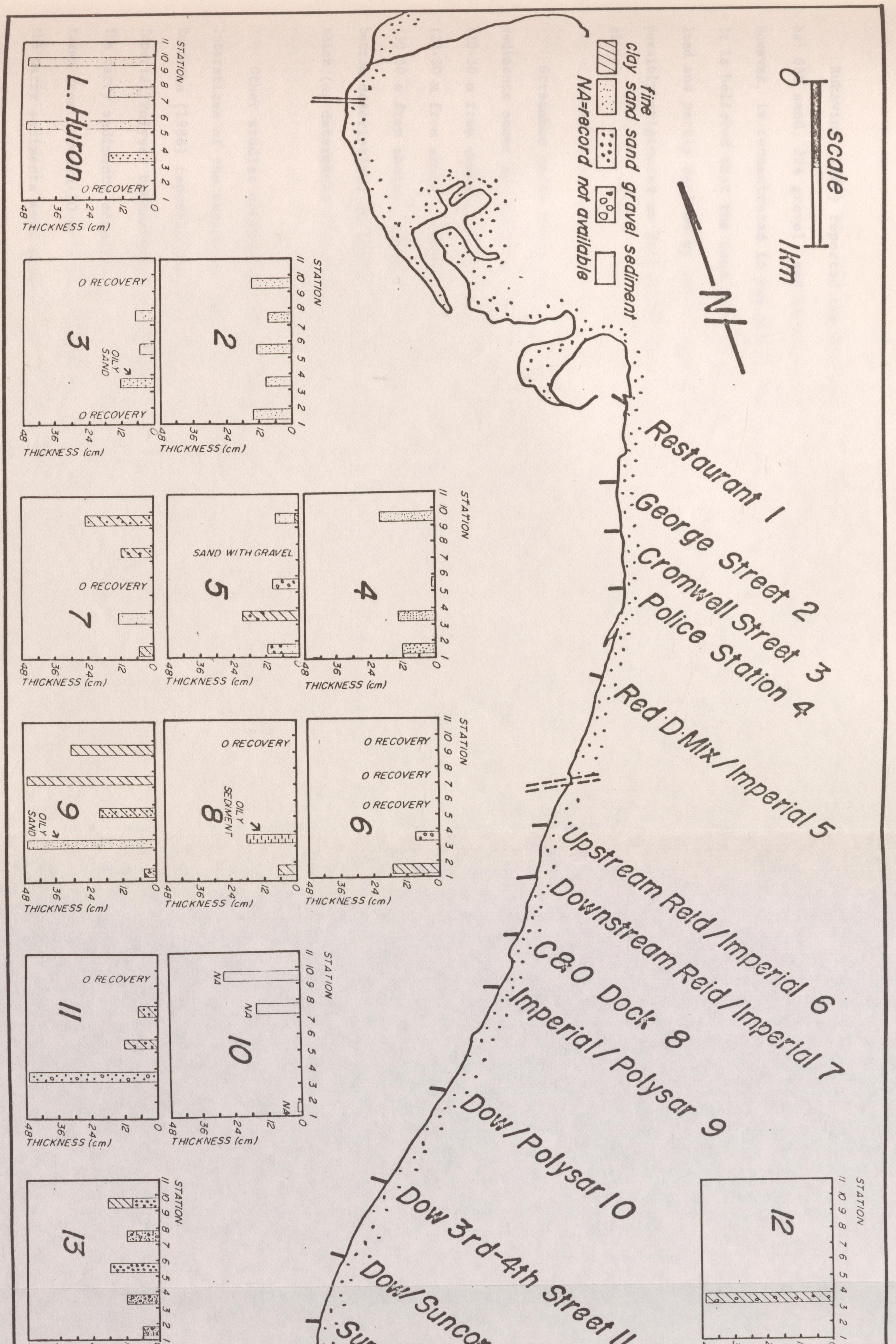


Figure 22. Distribution of sediment thickness along the survey lines.

scattered over the entire length and width of the survey area, were noted by the divers.

Rukavina (1986) reported the average texture of the river sediments to be: 63% sand, 32% gravel, and 5% silty-clay. Most of the sediment size, however, is concentrated in two modes: fine gravel and fine to medium sand. It is believed that the sand mode is partly transported by the river as bed load and partly derived by local erosion of the glacial clay. The gravel mode possibly originated as fill which was used to extend or stabilize the shore slope.

Streambed cores taken during this study reveal that black oily sand and sediments occur at several stations along five of the survey lines: C & O Dock (20-30 m from shore), Imperial-Polysar (20-30 m from shore), Cromwell Street (20-30 m from shore), Dow-Polysar (50 m from shore), and Dow 3rd-4th Street (30-50 m from shore). These were described either in the sample cores and/or bottom descriptions as black oily sand, varying in thickness from 5 to 46 cm thick (as determined from core samples).

Other studies confirm the presence of a black "tar-like" substance in the interstices of the sediments in several areas along the industrial shoreline. Rukavina (1986) reported the occurrence of tarry sediments just north of the Imperial/Polysar boundary and extending just south of the Suncor property. The tarry sediments occurred at the surface or just below the surface in cores taken from between 10 m to 25 m offshore. South of the Dow/Suncor boundary, the tarry sediments were present only in the inshore cores. A sharp contrast (rather than gradational) was reported between the clean and contaminated sediments.

Oliver and Pugsley (1986) also reported sediment cores containing variable amounts of this black tar-like material. As was the case during this sediment survey, the top layer of some cores appeared relatively clean but the bottom layers were apparently saturated with this material.

In a study conducted by Nagy et al. (1986), the highest concentration of alkanes and polyaromatic hydrocarbons were reported in the bottom sediments in the vicinity of the petrochemical industrial area (from Polysar to just past Suncor) on the Canadian side of the St. Clair River. The presence of these contaminants can account for the black tar-like sediments.

5.2 RATES AND DISTRIBUTION OF SEEPAGE

As previously discussed, the divers installed seepage meters along eight survey lines which contained enough granular material to adequately seat the seepage meters. Once installed, the water collection assemblies on the seepage meters were replaced every one to three days, with several assemblies left on longer to determine any temporal variation in the seepage rate.

From the seepage meter survey, field values were determined for pH, electrical conductivity and temperature of water collected from the seepage meters. The seepage rates for a number of stations along the survey lines were calculated by measuring volumes of seepage and dividing by the collection time. Appendix 4 contains the field data from the seepage study. Table 3 shows the average seepage rates for the seven survey lines where seepage meters could be installed. The data in Table 3 represent the re-calculated means of the seepage values at each station after seepage rates differing from the mean by more than two standard deviations were removed.

The seepage rates varied both temporally and areally. The largest variation over a 24 hour period for seepage fluctuations was reported for a seepage meter on the Concrete Dock Survey Line where seepage varied from 63 to 464 mL/h/m^2 (an increase of 401 mL/h/m^2 within 24 hours). A seepage meter on the Suncor Dock Survey Line also showed a large variation within a 24 hour period ranging from 7 to 398 mL/h/m^2. The highest rate of seepage on the Concrete Dock Survey Line was reported at the seepage meter 50 m from shore, where as the highest seepage rate of the Suncor Dock Survey Line was reported at a seepage meter located 60 m from shore.

Overall, the average seepage rates for individual sites ranged from 1 to 176 mL/h/m^2. The lowest average seepage rates (1 to 23 mL/h/m^2) were reported on the George Street Survey Line which had a mean seepage rate of 10 mL/h/m^2 and a standard deviation of 8 mL/h/m^2. The Concrete Dock Survey Line had a mean seepage rate of 72 mL/h/m^2 and a standard deviation of 67 mL/h/m^2. The highest seepage rates recorded during this survey occurred at several stations along this line. There appears to be no simple relationship between the observed thickness of the granular sediment and the seepage rates (Figure 23), nor is there an obvious relationship between seepage rate and distance from shore (Figure 24).

Table 3. Groundwater seepage into the St. Clair River.

	SEEPAGE RATE (mL/h/m^2) STATION NUMBER									
LINE	1	2	3	4	5	6	7	9	11	$\bar{x}$	s
L. Huron	#59	134	136	-	9	-	3	30	5	58	56
George	1	-	5	-	9	-	10	13	23	10	8
Cromwell	29	-	6	-	32	-	20	132	46	44	45
Police	7	-	21	-	61	-	34	14	49	31	21
Red-D-Mix	2	-	39	-	4	-	135	67	112	60	55
Suncor	-	-	19	-	19	-	61	-	176	69	74
Concrete	-	8	8	25	99	131	161	-	-	72	67

* distance from shore = (Station No. - 1) x 10 m

$1\ mL/h/m^2 = 2.8 \times 10^{-10}\ m^3/s/m^2$

$\bar{x}$= mean s= standard deviation

values represent averages for each seepage meter location

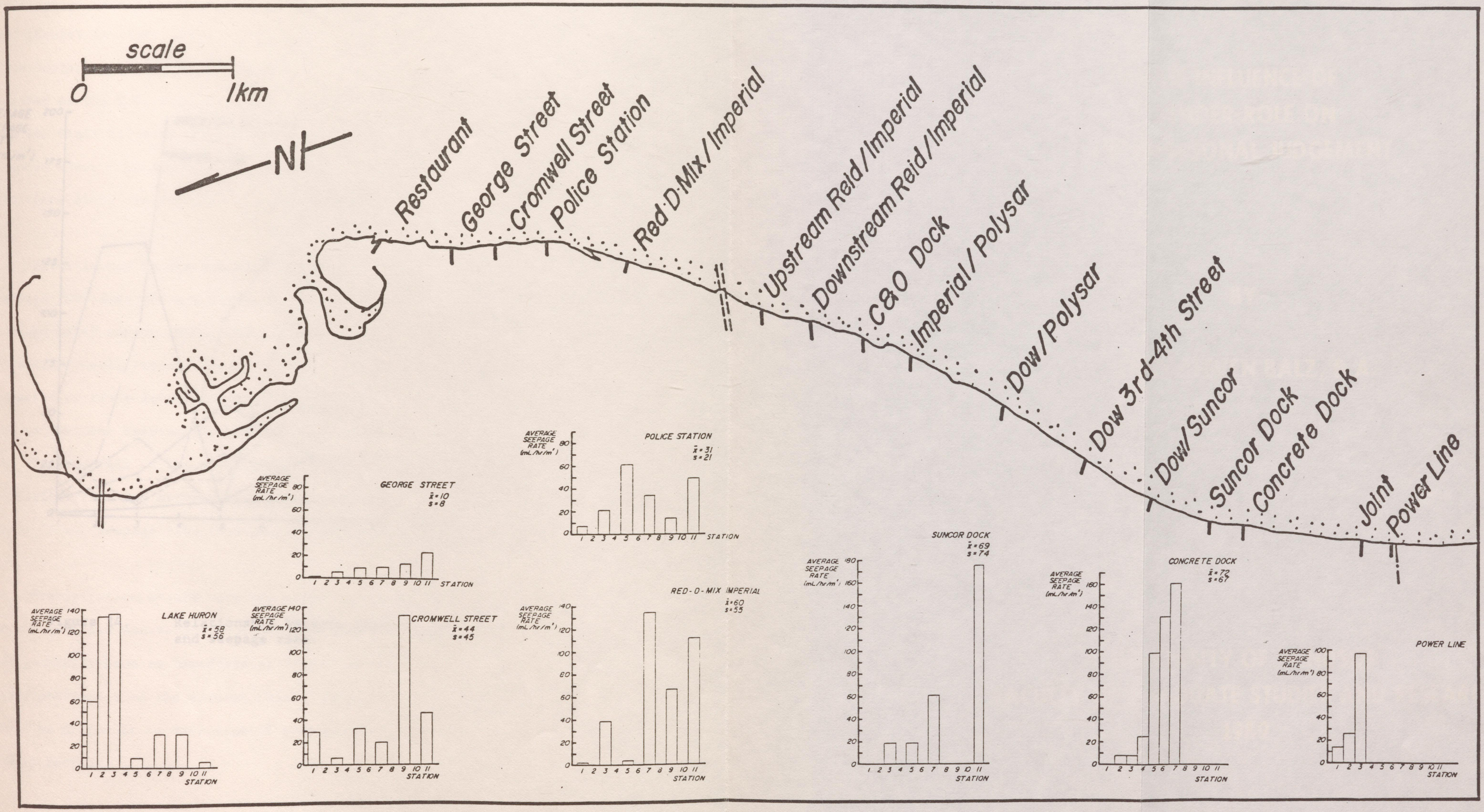


Figure 23. Seepage distribution along survey lines.

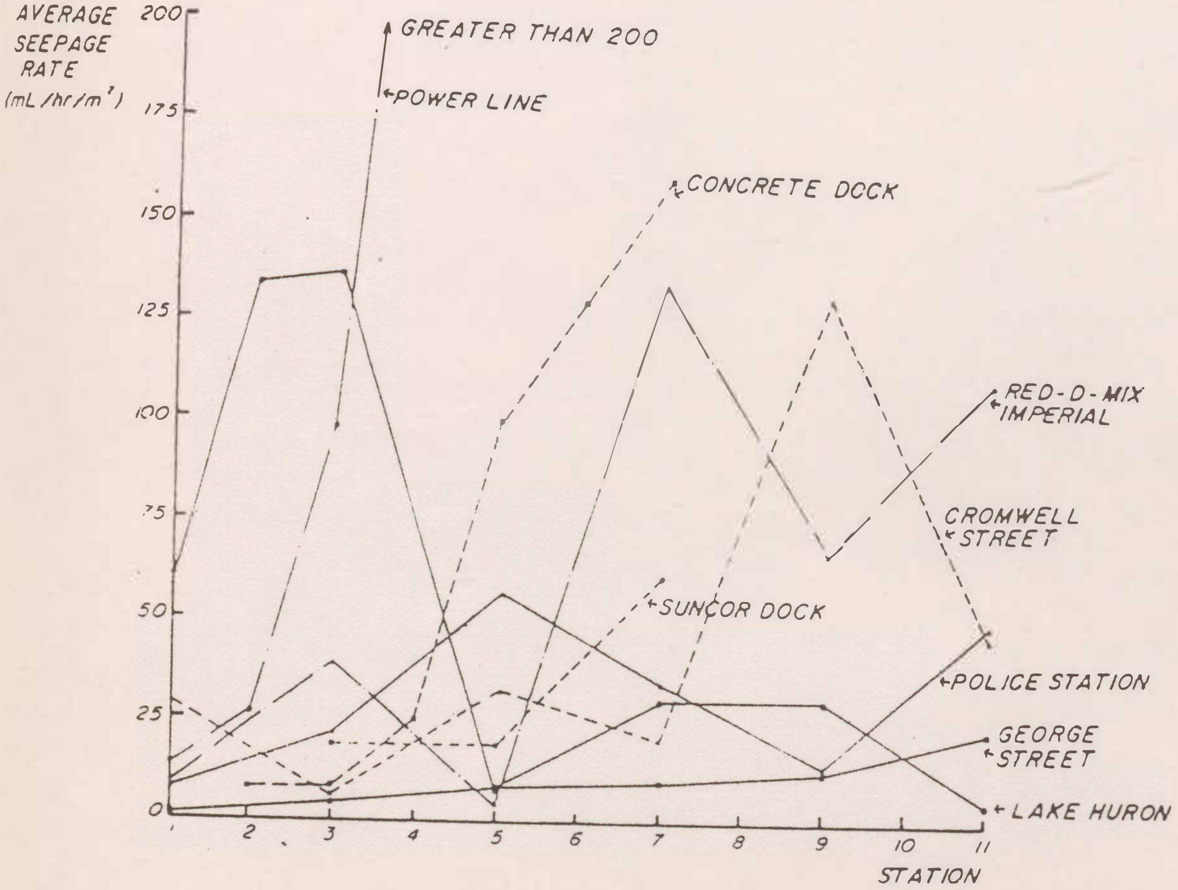


Figure 24. Relationship between distance from shore and seepage rate.

River level data were obtained from several St. Clair River gauging stations to determine if any correlation existed between average seepage rates and changes in river stage. Two gauging stations, the MBR Gauge and the Dry Dock Gauge, located close to several of the seepage meter survey lines, are located on the U.S. side of the St. Clair River. The MBR Gauge is located on the St. Clair River at the mouth of the Black River and the Dry Dock Gauge is located about 4 km south of the MBR Gauge (Appendix 4 contains a map of gauge locations along the St. Clair River).

River levels in the area of the survey lines generally only fluctuated between .031 and .003 m (.1 and .01 ft.) per day (except for waves) during the seepage meter survey (NOAA, 1985). Daily seepage rates along the George Street, Cromwell Street, Suncor Dock and Concrete Dock Survey Lines were compared to river levels during the same time period. An obvious relationship was not evident between the times of the highest and lowest seepage rates and the rise and fall of the river levels. Nor did there appear to be any consistent time lag between high or low water levels and high or low seepage rates (i.e., seepage rate increases 24-48 hours after a higher river stage).

Precipitation events were not considered during this comparison. Owing to the confined nature of the freshwater aquifer, precipitation events would not generally have an immediate or direct impact on the aquifer and/or an immediate impact on the seepage rates. Response times would be slow and it would be difficult to determine if seepage rates varied owing to precipitation.

More data are required to determine if correlations exist between the seepage rates, the fluctuations in river levels, and precipitation events. Owing to the relatively short duration the seepage meters were left in place, the intermittent placement of the seepage meters, and the lack of river level data in the immediate area of the survey lines, no attempt was made to draw any quantitative conclusions concerning correlations.

Lee (1977), Lee and Cherry (1978), and Woessner and Sullivan (1984) have reported variations in seepage rates with distance from shore, river stage fluctuations, and season. Lee (1977) attributed the large variations in seepage rates to currents being too great to get reproducible seepage measurements and to streambed heterogeneity. Also, heterogeneous streambed material can vary widely in hydraulic conductivity due to the shifting, sorting and downstream migration of sediments in fluvial systems.

Woessner and Sullivan (1984), who studied the reservoir behind the Hoover Dam, also found variations in seepage distributions when conducting a study on the effects of reservoir stage variations on shoreline groundwater systems. Seepage meter data indicated large variations in seepage rates from nearshore to offshore locations. The highest seepage rates were recorded at seepage meters located farthest from shore and in the deepest water. Observed seepage rates showed large seasonal variations. The only recharge to groundwater occurred during a large lake stage rise of 2 m, with no other period of recharge to the groundwater system identified within their monthly sampling scheme.

Lee (1977) found the opposite relationship between distance form shore and seepage rates. In his study, seepage measurements along the shoreline showed that near shore discharge was greatest and that rates declined approximately exponentially with distance from shore.

The variations in seepage rates encountered during this study and the lack of obvious correlation with distance from shore and river levels, may be attributed to: the strong currents in the St. Clair River, the variations in bottom materials, and the limited time the seepage meters were installed. Perhaps, if the seepage meters were left in place for 3 to 6 months, a relationship between the average seepage rates and changes in river elevations or seasons would become evident.

The pH and electrical conductivity (EC) values of the water collected from the seepage meters are similar to those of the river water. The means and standard deviations of the river water pH values (n=7) were 7.47 and 0.34, respectively. The seepage meter waters (n=159) had pH values between 5.9 and 8.7 with a mean of 7.29 and a standard deviations of 0.46. The mean and standard deviation of the river water EC (n=7) were 204 uS/cm and 50 uS/cm. The EC values for seepage meter waters (n=159) ranged between 104 and 495 uS/cm, with a mean of 237 uS/cm and a standard deviation of 70.6 uS/cm. Owing to a malfunction of the temperature probe on the conductivity meter during field work, none of the EC values are temperature corrected to 25 ^{0}C. However, since all of the samples collected were about the same temperature throughout the study, relative errors in the EC values should be small.

Lee (1987) found similar variations in the EC of the water at the river-sediment interface in the St. Clair River. Lee surveyed 25 line-kilometres of the riverbed adjacent to Sarnia using an underwater probe, towed behind a boat, to record variations in both the temperature and EC of the sediments. Lee's (1987) results showed that the river-sediment interface contained areas of anomalously high and low electrical conductance. He found that normal riverbed EC values were approximately 195 uS/cm. The anomalous EC values were either less than 100 uS/cm or greater than 450 uS/cm. Lee's normal EC values correlate closely to the mean of the river water EC values from this study (204 uS/cm). The seepage meter waters from this study also showed similar low and high variations ranging from 104 to 495 uS/cm.

Lee (1987) offers two possible explanations for the anomalous EC values: (1) areas of high conductance usually are areas of elevated dissolved solids and may be associated with zones of groundwater entry, and (2) areas of low EC may be locations of organic liquid (heavier than water) possibly mixed with sediments and situated in pockets which are unaffected by river currents. It should be noted that high dissolved solids may exist near industrial discharge pipes and could also cause high EC values.

Three possible explanations for the similarities in EC and pH of the streambed groundwater and the river water are: (1) river water leaked into the seepage meters, (2) the seepage rate was so slow that little displacement of the river water trapped during installation of the seepage meter had occurred, and (3) the streambed groundwater had the same EC and pH as the river water. In situations where the granular deposits are thin and poor seals between the seepage meter and the clay could be expected, the leaking hypotheses (1) is likely to be correct. The hypothesis that the EC and pH values of the streambed groundwater and the river water are the same is disproved by the minipiezometer data which will be discussed in the next section. The low seepage rate appears to be the most likely explanation.

Assuming the optimum seepage conditions (8 cm of the seepage meter buried and the maximum recorded seepage rate of 565 $mL/h/m^2$), the minimum time required to displace the river water trapped in the seepage meter during installation would be over 5 days. Taking into consideration that the average seepage rate was an order of magnitude lower, complete displacement would require an average of more than 50 days. Since the divers sampled the seepage meters every few days, and since no seepage meters were left in place for more than a few weeks, most of the water collected in the collection assemblies was likely to be displaced river water with some streambed groundwater.

Darcy's Law can be used to estimate complementary sets of hydraulic conductivity and hydraulic gradient values necessary to satisfy the observed seepage rates. Table 4 lists the calculated hydraulic gradients for given hydraulic conductivities, assuming that the average of the survey line seepage rates (approximately 1.4×10^{-8} $m^3/s/m^2$ or 49 $mL/h/m^2$) represents the seepage rate from the streambed into the river.

Desaulniers _et al._ (1981) report that the hydraulic conductivities of the upper 20 m of till are in the order of 10^{-10} m/s. From Table 4, this magnitude of hydraulic conductivity suggests that either there is an extremely high hydraulic gradient in the streambed or that the hydraulic conductivities in the streambed are 2 to 4 orders of magnitude greater than the 10^{-10} m/s

Table 4. Calculated hydraulic gradients in the streambed

HYDRAULIC CONDUCTIVITY (-log K in m/s)	HYDRAULIC GRADIENT
10	140
9	14
8	1.4
7	0.14
6	0.014
5	0.0014

estimate. Isotopic and EC data (to be discussed later) for some streambed groundwater samples are consistent with water moving through the near-surface fractured clay which could have intergranular hydraulic conductivities of from 2 to 4 orders of magnitude greater than 10^{-10} m/s.

Assuming that the values of hydraulic conductivity determined by Desaulniers _et al._ (1981) do apply to the streambed and that hydraulic gradients are between 0.01 and 1, then it would take between 162 days and 44 years to completely displace the river water from the seepage meter. Since several of the seepage meters collected water with noticeably higher EC values than the river (perhaps a mixture of river water and groundwater) after only a few days, it is unlikely that the low hydraulic conductivities suggested by Desaulniers _et al._ (1981) can apply to all of the streambed.

5.3 SEEPAGE WATER QUALITY

It has been shown through numerous studies, many conducted concurrent with, or after the field work for this study, that the sediments and river water in distinct reaches of the St. Clair River contain various concentrations of numerous contaminants. It is believed these contaminants are the combined result of the industrial operations along the river and drainage from the Township Ditch (Figure 11) which drains both industrial properties and a number of waste disposal sites in the Sarnia area (King and Sherbin, 1986). In an attempt to determine the quality of the streambed groundwater in the study area, both river water and streambed groundwater samples were analyzed for the following parameters: chloride, TOX, chlorinated hydrocarbons, polychlorinated biphenyls, trihalomethanes, and EPA Priority Pollutant Extractables (acid and base/neutral).

Water quality samples from the streambed were collected through minipiezometers. Owing to time limitations on the field study, minipiezometers were installed on only 2 of the 17 survey lines, George Street and Cromwell Street. The minipiezometers were installed to depths of 1.0 and 1.5 m below the streambed at 4 stations on the George Street Survey Line and at 2 stations on the Cromwell Street Survey Line.

Twenty-three river water and streambed groundwater samples were analyzed by Zenon Environmental Inc. for chloride (Cl^-). Appendix 7 contains the complete analytical results. The Cl^- levels in the river water ranged from 5.2 to 5.5 mg/L, with a mean of 5.34 mg/L and a standard deviation of 0.13 mg/L (n=5). In contrast, the Cl^- levels in the streambed groundwater ranged from 7.8 to 111 mg/L, with a mean of 33.9 mg/L and standard deviation of 37.9

mg/L (n=18). The mean Cl^- concentrations of the river and streambed groundwater are therefore statistically different at the 5% level of significance. Of the 18 streambed groundwater and river water samples analyzed, 5 contained Cl^- levels in excess of 80 mg/L. All 5 samples were obtained from the George Street Survey Line (Station #5), with 4 of the 5 samples being from the 1.0 m depth. Table 5 is a summary table of the water quality at the various minipiezometer sampling locations.

Zenon Environmental Inc., analyzed a total of 29 samples of river water, streambed groundwater, blanks, spikes and duplicates for TOX (Total Organic Halogens). It should be noted that one of the two lab blanks supplied by Zenon for use during field sampling, showed noticeable TOX values of 3.0 ug/L and 9.95 ug/L (9.95 ug/L is an average of a duplicate run on one of the blanks with reported values of 11.5 ug/L and 8.4 ug/L). These elevated values indicate possible lab interference introduced through sample bottles, blank water, or analytical procedures. The blank values were taken into consideration during the interpretation of the analytical results, however, the values reported here are not corrected values. Owing to time and budgetary limitations, additional sampling and/or additional analyses were not performed to confirm or refute these results.

The uncorrected TOX values for the 29 samples ranged from <1 to 18.3 ug/L, with a detection limit of between 1 and 5 ug/L depending upon the compound (Foster, personal communication). When considering the blank values, elevated but not excessive TOX levels were detected. The highest TOX values were reported at George Street Station #11 (river water), and Station #5 (streambed groundwater), with values of 18.3 and 16.0 ug/L, respectively.

TABLE 5. SUMMARY TABLE OF WATER QUALITY FOR RIVER WATER AND STREAMBED GROUNDWATER

Stations	G_5	G_6	G_7	G_{11}	C_6	C_{11}
Cl^- (mg/L)	76	23	15	15	9	8
TOX (ug/L)	6	8	7	14	4	3
Chlorinated Hydrocarbons (ug/L)	.0012	.0024	.0027	.0033	.0047	.0020
PCB* (ug/L)	.026	.019	ND	ND	.015	-
Trihalomethanes (ug/L)	6	6	1	5	1	1
Base/Neutral* (ug/L)	.8	-	.1	1	7	4
Acid (ug/L)	ND	ND	ND	ND	ND	ND

ND	not detected
-	not analyzed
*	actual values, all other values represent means

G 5,6,7 and 11 - George Street Stations
C 6 and 11 - Cromwell Street Stations

Samples with elevated TOX levels were selected for the following additional analyses: chlorinated hydrocarbons, including polychlorinated biphenyls and trihalomethanes (11 samples), and EPA Priority Pollutant Extractables (5 samples).

The 11 samples analyzed for chlorinated hydrocarbons and polychlorinated biphenyls (PCB) showed detectable levels of chlorinated hydrocarbons (<0.0027 ug/L) in particular: hexachlorobenzene (HCB) (<0.0027 ug/L), a-benzenehexachloride (<.00022 ug/L), g-benzenehexachloride (<0.0019 ug/L), and p,p'-DDE (<0.0014 ug/L). The total chlorinated hydrocarbons were <0.0067 ug/L, with the value of the lab blank reported at <0.0009 ug/L.

It should be noted, that the chlorinated hydrocarbons and PCBs detected in this study are not regulated under the Primary or Secondary Drinking Water Standards. However, several of these compounds are on the Priority Pollutant List. Maximum permissible concentration levels for the compounds listed as Priority Pollutants are based on the specific compound and the toxicity of that compound.

Some interference was encountered during the analysis for PCBs resulting in the reduction of the number of PCB results to 8. Of these 8 samples, PCB was detected at Stations #5 and #6 on the George Street Survey Line and Station #6 on the Cromwell Street Survey Line. A duplicate run of the Cromwell Street Station #6 sample, however, showed PCB to be non-detected. Values for this study ranged up to 0.0026 ug/L.

Various trihalomethanes were evident in all the samples with values ranging from 0.04 to 2.77 ug/L. A field blank, also analyzed for trihalomethanes, showed levels from 0.04 to 1.18 ug/L for the various parameters. Carbon tetrachloride (CTC) (<0.29 to 1.76 ug/L), tetrachloroethylene (<0.08 to 1.18 ug/L) and chloroform (<0.47 to 2.77 ug/L) were detected in all the samples.

An EPA Priority Pollutant (base/neutral and acid extractable) analysis was performed on 5 samples. No acid extractables (including phenols) were detected in any samples (detection limits between 1 and 5 ug/L). Base/neutral extractables were run on samples taken from 3 stations along the George Street Survey Line (Station #5, #7 and #11) and two stations along the Cromwell Street Survey Line (Station #6 and #11). Base/neutral extractables were detected in each of the samples from these locations. Of the base/neutral extractables detected, benzo(ghi)perylene (<2.4 ug/L), dibenzo(a,h,)anthracene (<0.4 ug/L), and indeno(1,2,3,-cd)pyrene (<2.4 ug/L) were the most prevalent, at detection limits of 0.05 to 1.0 ug/L. PCBs were not detected on this scan because of the higher detection limit of 2 ug/L.

Several other studies have reported similar water quality results for the St. Clair River water in the study area.

The Cl^- levels in this study (5 to 111 mg/L) are not excessively high when compared to the Cl^- levels of the shallow groundwater reported by Vandenberg et al. (1977) (332 to 2180 mg/L) and Desaulniers et al. (1981) (0 to 350 mg/L).

Hexachlorobenzene (HCB) was the most prominent and consistent chlorinated hydrocarbon detected in the water samples in this study. Several other studies conducted in the St. Clair River have reported elevated levels of HCB and also detectable levels of PCB. The St. Clair River Pollution Investigation (Environment Canada and Ontario Ministry of the Environment, 1986) reported appreciable concentrations of HCB in river water downstream of our survey lines (Figure 25) in the vicinity of Dow's property, with elevated levels persisting for at least 25 km downstream. HCB concentrations ranged from 1.0 ng/L (ppt) (0.001 ug/L) at the mouth of the St. Clair River, to 15 ng/L (0.015 ug/L) just below Suncor. A reported value of 1.0 ng/L (0.001 ug/L) HCB was detected at a sample location in the area of the George Street and Cromwell Street Survey Lines. The highest concentrations of HCB were detected at sampling locations downstream from Polysar to Suncor. Figure 26 shows both the maximum (dashed line) and average (solid line) concentration levels of HCB detected in this reach of the St. Clair River.

Oliver and Kaiser (1986) also reported varying concentrations of chlorinated hydrocarbons in near shore waters and tributaries of the St. Clair River. HCB was one of the most commonly detected contaminants, with concentrations that increased downriver. PCBs were detected in varying quantities throughout the study area. The reported PCB levels ranged from non-detected to 7.7 ng/L (0.0077 ug/L), exhibiting levels higher than the PCB levels in this study of 0 to 0.0026 ug/L.

The three trihalomethanes that were evident in water samples analyzed in various other studies were: carbon tetrachloride (CTC), tetrachloroethylene, and chloroform. The Environment Canada and Ministry of the Environment Study

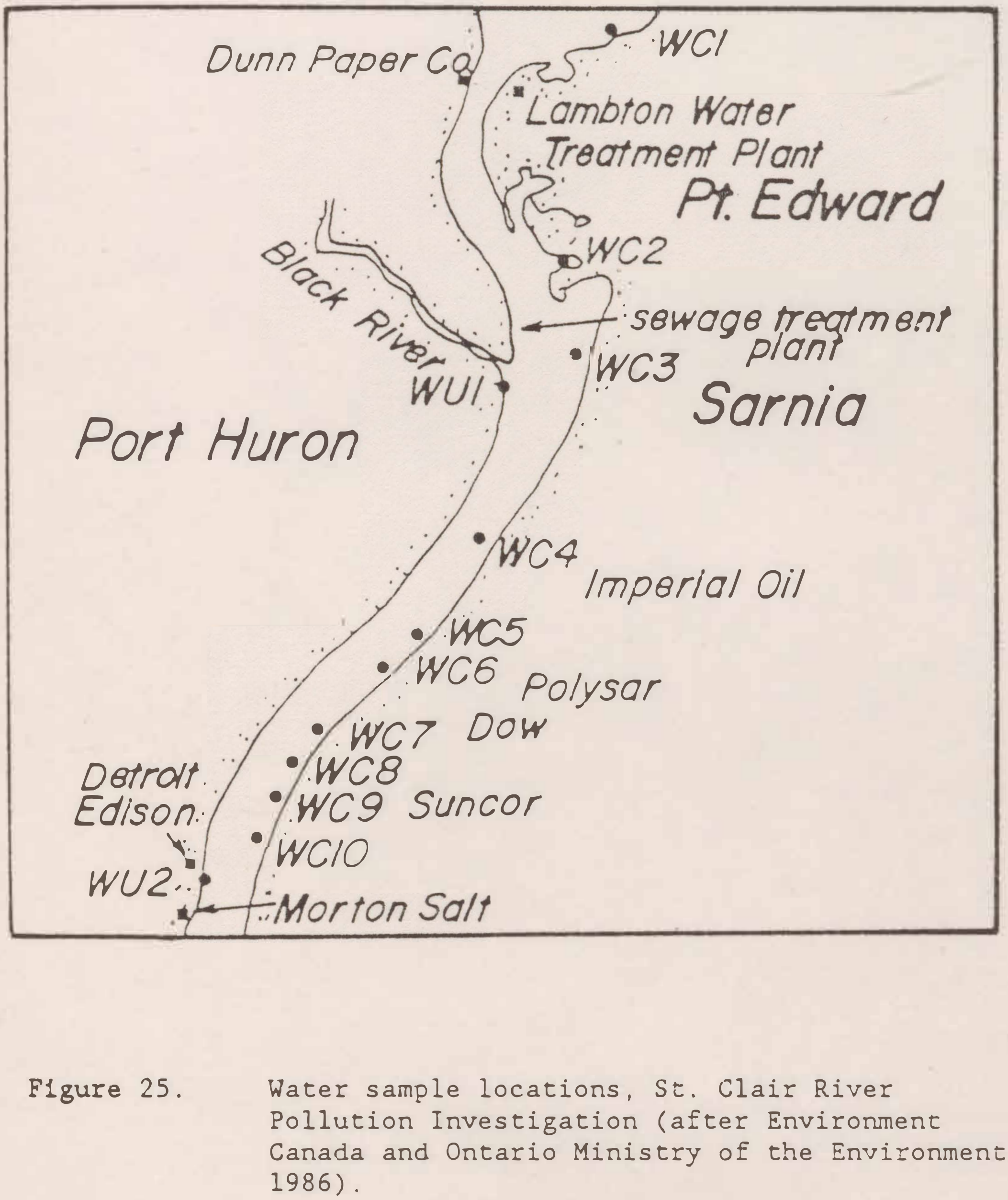


Figure 25. Water sample locations, St. Clair River Pollution Investigation (after Environment Canada and Ontario Ministry of the Environment, 1986).

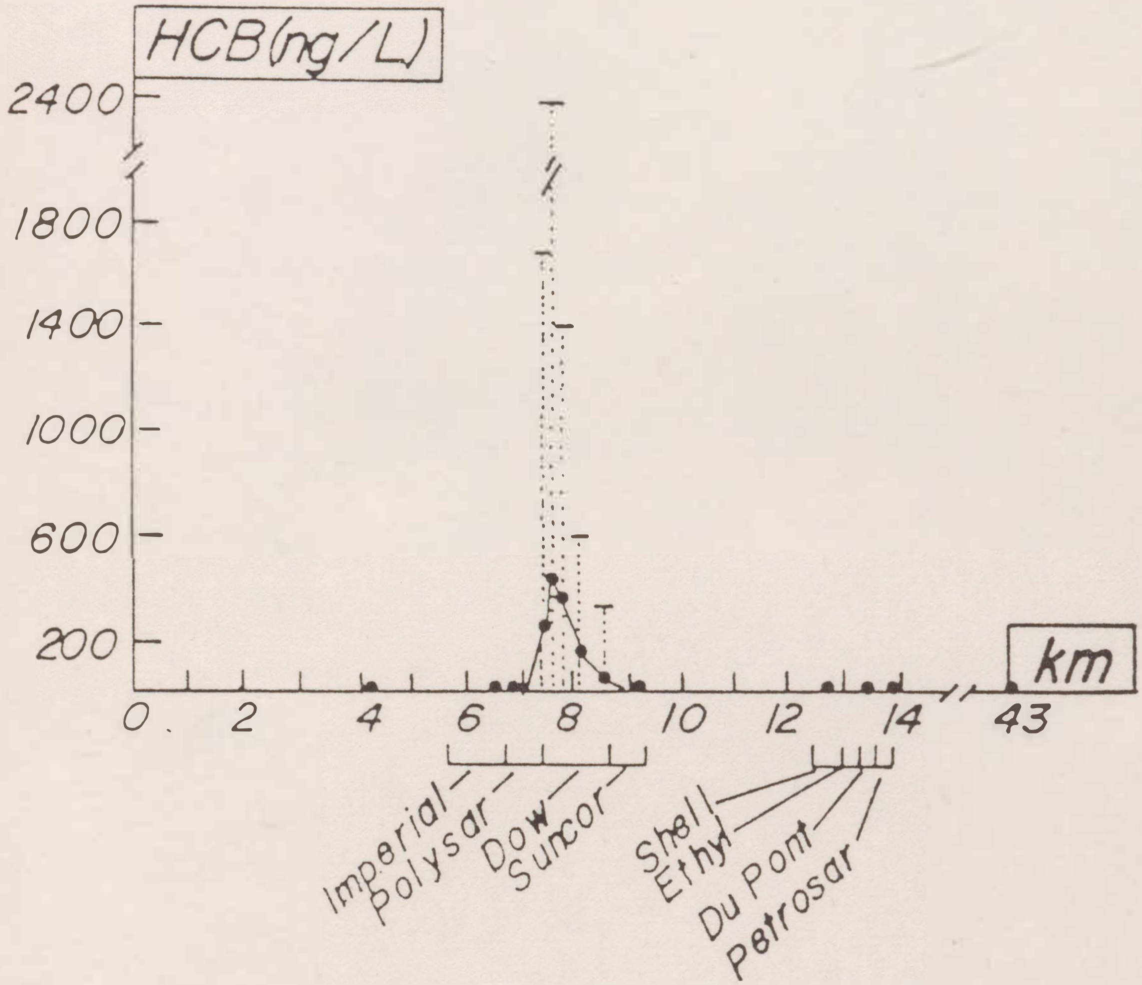


Figure 26. Hexachlorobenzene in river water, St. Clair River Pollution Investigation (after Environment Canada and Ontario Ministry of the Environment, 1986).

(1986) reported CTC levels in the range of 1 to 10 ng/L (0.001 to 0.01 ug/L). These levels were detected in the river water at most stations along the western shore of the St. Clair River and upstream stations on the eastern shore. A CTC concentration of over 2000 ng/L (2.0 ug/L) was found at a station just upstream from the CN railway tunnel (downstream of the George Street and Cromwell Street Survey Lines). These CTC levels appear to be consistent with CTC levels that were reported in this study. A CTC concentration of 1.76 ug/L was reported in this study at George Street Station #6, located just upstream of the CN railway tunnel. Elevated levels at downstream locations primarily in the near shore zone were also reported by Environment Canada and Ministry of the Environment (1986).

In a study conducted of the St. Clair River in the Sarnia area, by Kaiser and Comba (1986), over 30 river bottom water samples were analyzed for volatile halocarbon contaminants at stations located 10 m, 25 m, and 100 m off shore. Considerable inputs of CTC and perchloroethylene were evident in these near shore zones. A maximum CTC concentration of 2411 ng/L (2.41 ug/L) was reported at a station located 25 m from shore, upstream of the Township Ditch. Smaller loadings of a variety of other volatile compounds were also noted.

Another parameter included in the Kaiser and Comba study was chloroform, with levels of between 10 to 20 ng/L (0.01 to 0.02 ug/L) observed in the river water on both sides of the river. As noted in the report, chloroform is primarily a by-product of raw and waste water chlorination and the observed concentrations are expected from the large volume of cooling water discharged along the St. Clair River.

As evidenced from the chemical analysis of the streambed groundwater and river water samples taken along the George Street and Cromwell Street Survey Lines, low to moderate concentrations of contaminants appeared in these water samples. These may be indicative of contaminants entering the river via streambed seepage. The quality of the streambed sediments in the area of the minipiezometer survey is currently unknown. Contaminants contained within the sediments could also have an impact on the quality of the streambed groundwater. Further investigation is warranted to determine the sources of the observed contaminants. Additional sampling events would be necessary before any conclusions can be made regarding the water quality of the streambed groundwater.

5.4 SOURCES OF SEEPAGE

To determine the sources of the streambed groundwater ^{18}O, T, and D concentrations in the river water and streambed groundwater were investigated. In addition, field measurements of EC and pH were conducted on the river water and streambed groundwater samples taken from the minipiezometers.

A hydraulic gradient from the streambed sediments to the river must exist for groundwater to flow from the bed into the river. It should be noted that hydraulic heads in the minipiezometers were not measured because of generally slow response times, time constraints on the field work, and gas bubbles in the sampling line. However, there was some evidence that hydraulic heads in the streambed can be above river level. At Cromwell Street Station #11 (100 m from shore, 1.5 m depth), water flowed from the minipiezometer through the teflon tube to a height of approximately 70 cm above river level after the sampling tube was removed from the pump.

The EC values of the streambed groundwater and the river water are statistically different at the 5% level of significance. The mean and standard deviation of 19 streambed groundwater samples were 996 uS/cm and 328 uS/cm, respectively, and the mean and standard deviation of 7 river water samples were 204 uS/cm and 50 uS/cm, respectively (Appendix 6 contains the complete minipiezometer field data).

The EC values of the streambed groundwater are less than the EC values (>2000 uS/cm) reported in a study of the freshwater aquifer near Sarnia (Scott, 1986). The freshwater aquifer survey included samples from four wells installed by the Ontario Ministry of the Environment, and 34 domestic wells in Lambton County sampled by Scott (1986).

The ranges of pH for the streambed groundwater and river water were not as noticeably different. For 19 streambed groundwater samples the pH ranged form 6.7 to 7.8, with a mean of 6.99 and a standard deviation of 0.32. The pH values of the river water were 7.0 to 7.8, with a mean of 7.47 and a standard deviation of 0.34 (n=7).

The pH values of the freshwater aquifer near Sarnia are generally between 7.0 and 8.0 (Scott, 1986). Since the pH values of water from the river, streambed, and freshwater aquifer are all similar, pH is not a good tracer for determining the source(s) of water in the streambed.

Twenty-nine river water and streambed groundwater samples, as well as samples collected from shallow observation wells on Suncors' property and river water samples collected from the Chenal Ecarte, were analyzed for ^{18}O and T. Nine of these samples were also analyzed for D.

The ^{18}O and T data for these water sources are summarized in Table 6. Appendix 6 contains the complete isotopic results. Values of $\delta^{18}O$ for the river water ranged from -7.14 to -7.40‰, while T values ranged from 74 to 124 TU. The streambed groundwater $\delta^{18}O$ and T values ranged from -7.26 to -8.01‰ and 6 to 87 TU, respectively. Water samples collected from Suncor wells had ^{18}O concentrations ranging from -8.61 to -9.68‰ and T concentrations from 6 to 29 TU.

Several isotopic studies conducted in southwestern Ontario and Michigan, particularly in the Sarnia area, (Brown, 1970; Desaulniers *et al.*, 1981; Scott, 1986; MacGregor, 1985; Erdmann, 1987), have generated isotopic data for the freshwater aquifer, shallow groundwater, and river water in the study area. From these data and data collected during this investigation, interrelationships between St. Clair River water and groundwater (streambed groundwater, groundwater in the shallow, fractured till, and groundwater in the freshwater aquifer) can be examined.

Figure 27 is a contour map of the ^{18}O concentrations in the freshwater aquifer in Lambton County (Scott, 1986). Scott (1986) found that the ^{18}O concentrations in the freshwater aquifer follow a trend from recent precipitation values ($\delta^{18}O$ of approximately -8 to -10‰) in the recharge area in the eastern part of Lambton County to depleted values (about -16‰) near the

Table 6. Summary of oxygen-18 and tritium data.

SOURCE	Oxygen-18 (‰)			Tritium (TU)		
	n	$\bar{x}$	s	n	$\bar{x}$	s
minipiezometer 1.0 m	11	-7.53	0.34	11	53.4	18.6
minipiezometer 1.5 m	6	-7.51	0.26	6	23.2	12.9
Suncor wells $<$10 m	5	-9.37	0.43	5	14.0	10.2
St. Clair River	8	-7.25	0.08	8	89.1	17.4
Chenal Ecarte	4	-7.25	0.13	4	108	11.8

n = number of samples, $\bar{x}$ = mean, s = standard deviation

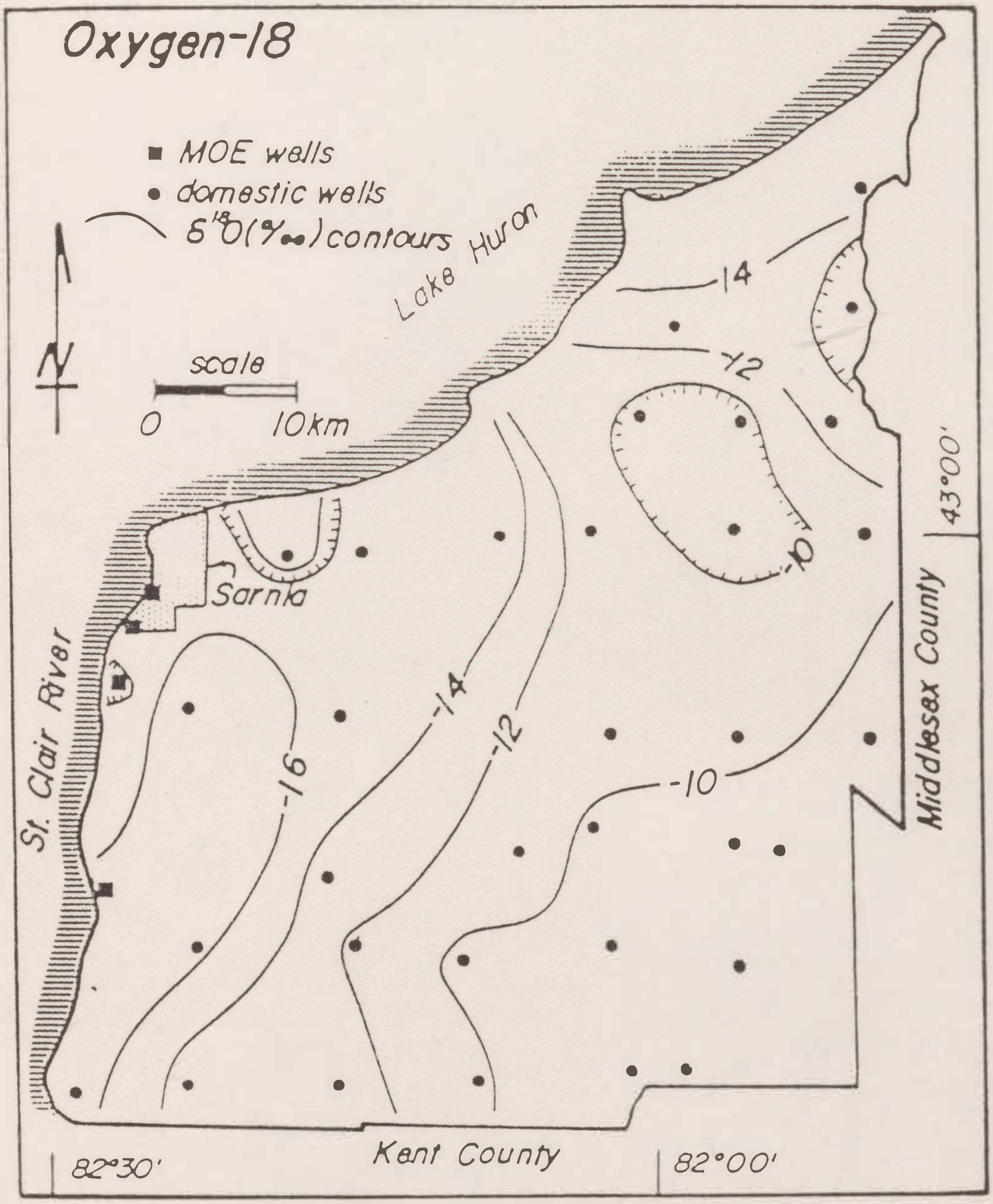


Figure 27. Contour map of oxygen-18 in the freshwater aquifer in Lambton County (after Scott, 1986).

St. Clair River in the west. Similar ^{18}O concentrations were reported by Erdmann (1987) for the freshwater aquifer in St. Clair County, Michigan, where the $\delta^{18}O$ values ranged from -9‰ in the western part of the county to -16‰ along the St. Clair River in the east. These depleted $\delta^{18}O$ values near the St. Clair River, according to the reasoning of Desaulniers et al. (1981), represent groundwater which is in the order of 10,000 years old. Erdmann (1987) has concluded that the freshwater aquifer discharges into the St. Clair River since the $\delta^{18}O$ contours are "mirror-images" on opposite sides of the river.

Scott (1986) concluded on the basis of her T data from the freshwater aquifer (Figure 28) that, in general, very young waters (<35 years old) occur in part of the recharge area in the eastern portion of the county and that most of the remaining freshwater aquifer, including the portion along the St. Clair River, contains non-tritiated water.

The relatively enriched ^{18}O and D values (due to evaporation in the upper Great Lakes) and the characteristic T values (ranging from about 80 to 130 TU) observed for the river water in this study, are consistent with the isotopic values of the water at the outlet of Lake Huron (Brown, 1970). Brown noted T concentrations of 179 and 200 TU in 1966 and 1969, respectively. Considering the half-life of T and the effects of long residence times in the upper Great Lakes, the T values which were obtained in this study for the river, are reasonable.

Figure 29 is a plot of the ^{18}O and T data for samples of streambed groundwater, the river water at the George and Cromwell Street Survey Lines,

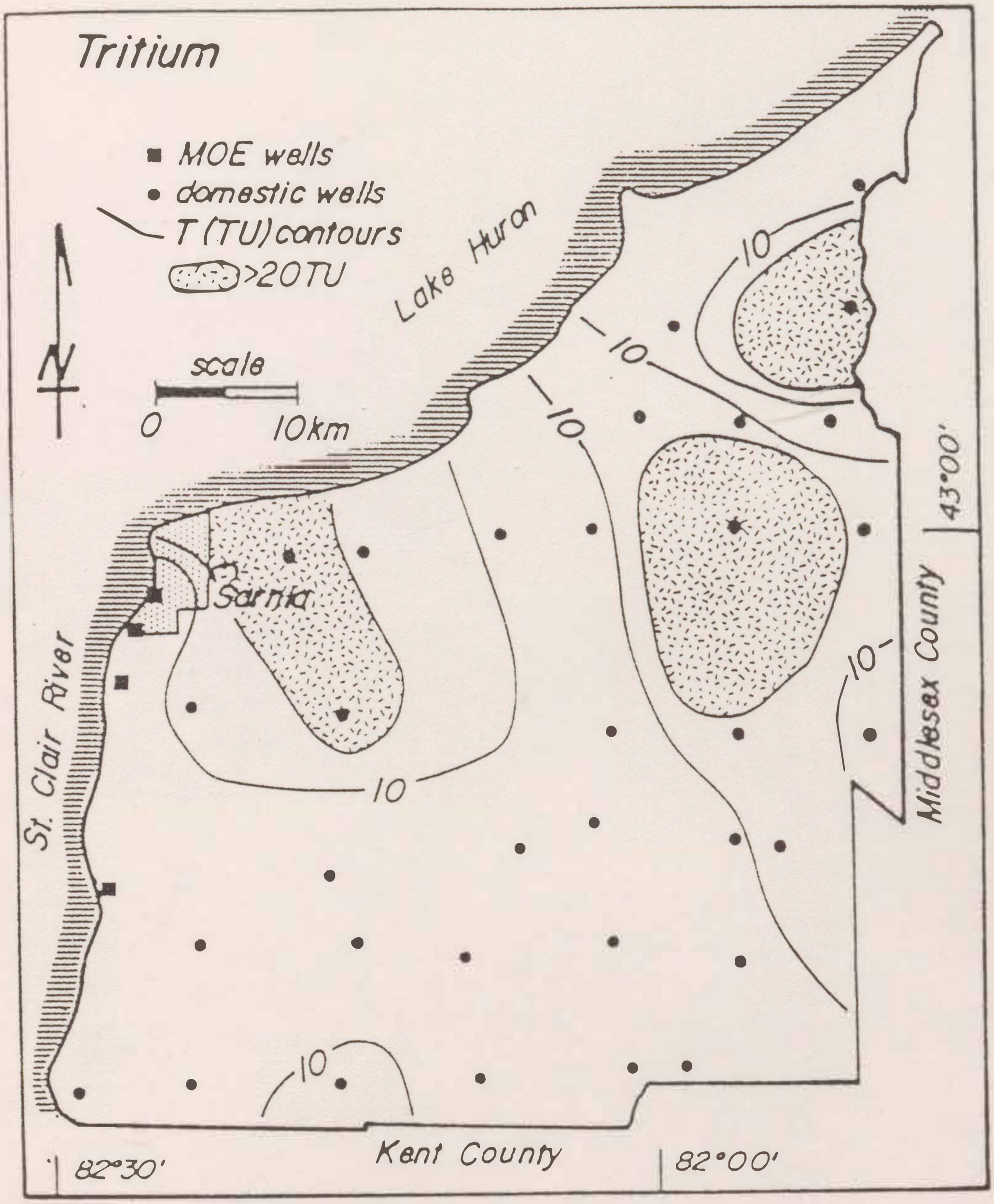


Figure 28. Contour map of tritium in the freshwater aquifer in Lambton County (after Scott, 1986).

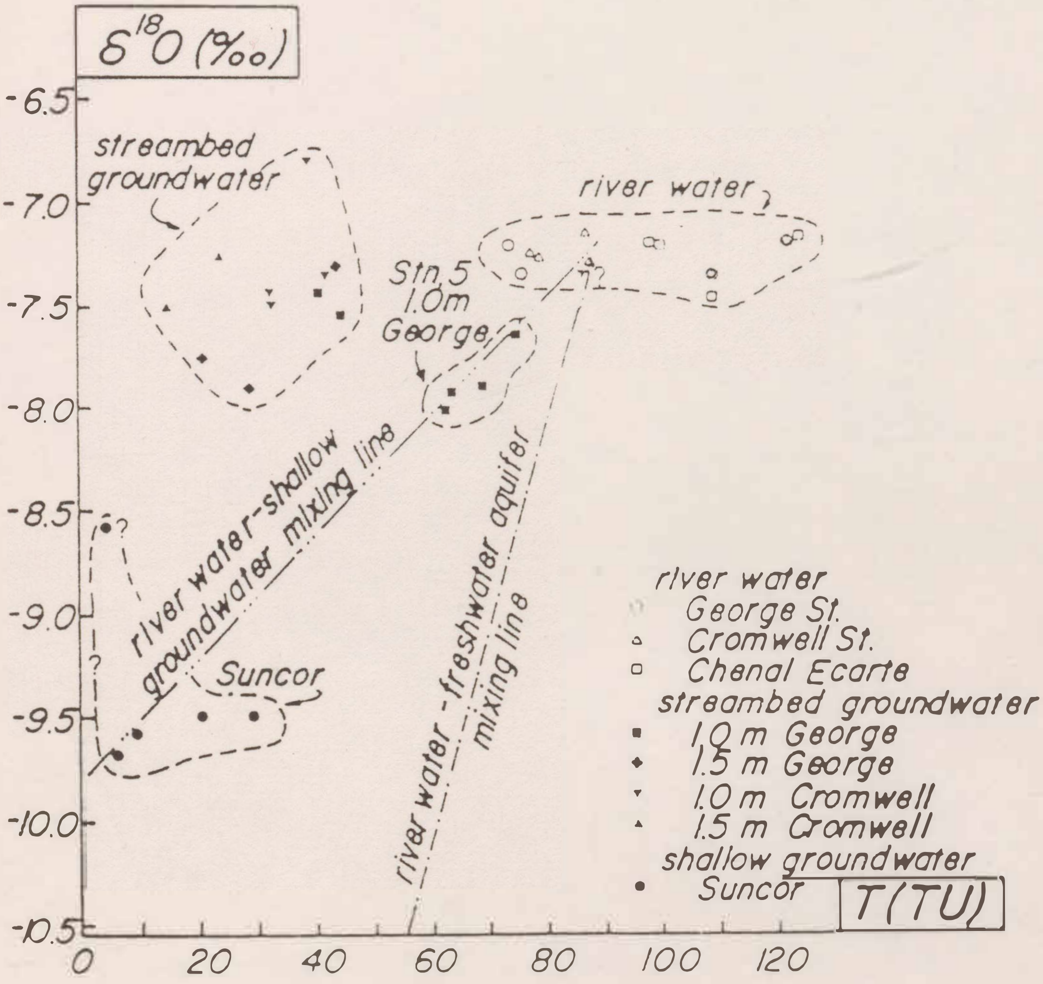


Figure 29. Plot of oxygen-18 versus tritium.

river water from the Chenal Ecarte (in the delta of the St. Clair River), and the shallow groundwater from the upper 10 m of clayey till at the Suncor landfarming site near the southern boundary of the study area.

There are several obvious groupings of the ^{18}O versus T data in Figure 29. The shallow groundwater samples from the Suncor wells are more depleted in δ^{18}O and much lower in T than the river samples which plot in the opposite corner of the figure. The ^{18}O concentrations of the Suncor samples are typical of the current mean annual rainfall ^{18}O concentrations for southwestern Ontario (Desaulniers *et al.*, 1981). The low T values in the shallow groundwater can be expected when considering the low matrix permeability of the clayey till, with higher values suggesting the influence of fractures. Both the ^{18}O and T concentrations (-8.61 to -9.68‰ δ^{18}O and 6 to 29 TU) from the Suncor site are consistent with the values for shallow groundwater in the Sarnia area reported by Desaulniers *et al.* (1981).

The samples from the minipiezometers fall into two distinct groups in Figure 29. The 1.0 m samples from Station #5 on the George Street Survey Line fall on a mixing line between the shallow groundwater from the Suncor wells and the river water. The other streambed groundwater samples fall into a group which is slightly more depleted in ^{18}O than the river water and which has less than one-half of the T of the river water samples. These samples do not fall along the river water-shallow groundwater mixing line nor along the river water freshwater aquifer mixing line. The source(s) of this streambed groundwater is currently unknown.

Figure 30 is a plot of ^{18}O versus D for the various water samples. The meteoric water line based on a cross-section of freshwater aquifer samples and the shallow groundwater samples from Suncor is:

$$\delta D = 7.6\,\delta^{18}O + 7.35$$

Since this line is parallel to the meteoric water line for southwestern Ontario (Desaulniers et al., 1981), it can be assumed that groundwater samples used for this line are unevaporated meteoric water.

Also plotted on Figure 30 are the streambed groundwater samples and the average of two river water samples which were analyzed for both ^{18}O and D. Since the river water samples fall below the meteoric water line, they represent evaporated water. These data are consistent with data from Brown (1970) who reported D values of about -67‰ for the outlet of Lake Huron. The streambed groundwater samples also fall below the meteoric water line (between the river samples and the line) indicating either some evaporation of the streambed groundwater prior to recharge or that the streambed groundwater is mixed with evaporated water. Since the isotopic data for both the shallow groundwater at Suncor (except for one sample) and the freshwater aquifer near the St. Clair River indicate that the groundwater is not evaporated, the mixture hypothesis is most likely to be true.

Cluster analyses were performed on the streambed groundwater and the river water isotopic data. The cluster analysis for T (Figure 31) highlights two distinct groups of water. One group consists of streambed groundwater taken from the minipiezometers at depths of 1.0 and 1.5 m, the second group consists of predominately river water. Four samples taken from the 1.0 m depth (at Station #5) on the George Street Survey Line, are similar in T

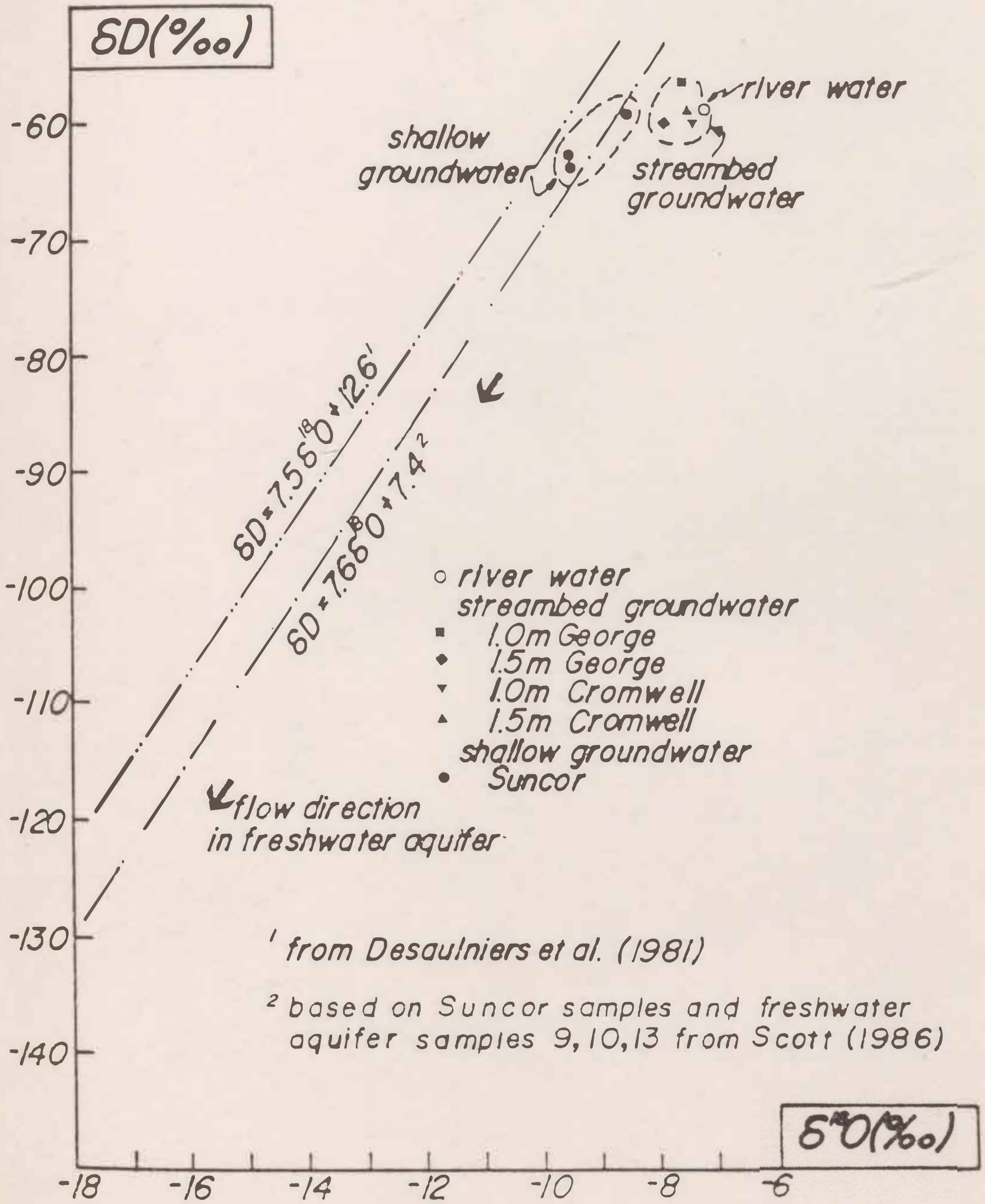


Figure 30. Plot of $\delta^{18}O$ versus D for river water and groundwaters.

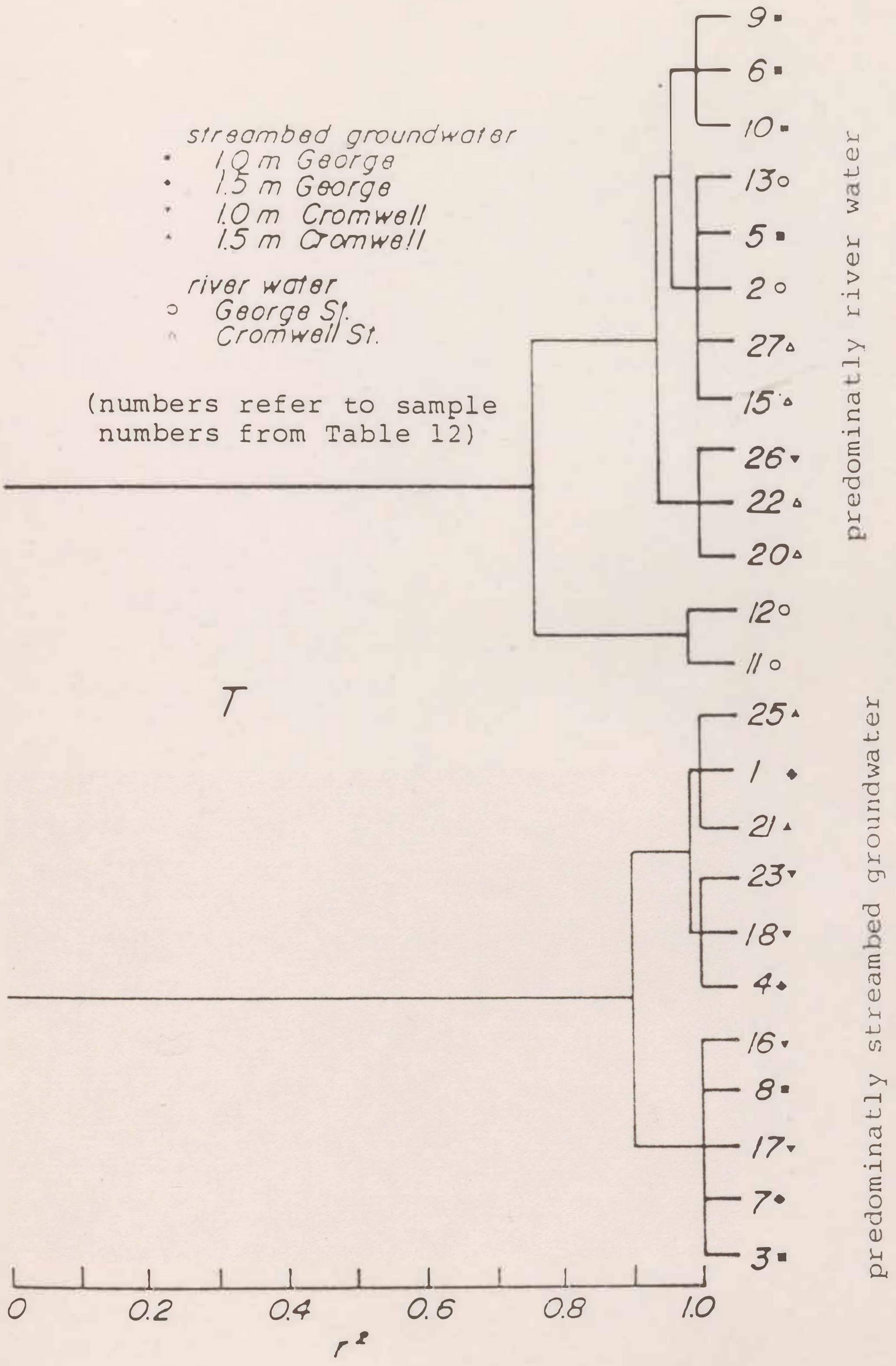


Figure 31. Cluster analysis for tritium data.

content to the river water. These samples belong to the same group of samples that appeared as a river water-shallow groundwater mixture on the ^{18}O versus T plot.

The ^{18}O cluster analysis also results in two main groupings: streambed groundwater, and a river water/streambed groundwater mixture (Figure 32). The cluster analyses, as well as the ^{18}O versus T plot, confirm the presence of several distinct groups of water. These distinct groups appear on the plots as river water, streambed groundwater, and a mixture of river water and streambed groundwater.

Figures 33 and 34 are plots of ^{18}O and T versus EC for the various types of water examined in this study. Estimated mixing lines between the river water and the shallow (Suncor) and deep (freshwater aquifer) groundwater are drawn on the figures. Figure 33 indicates that there is a high EC source of water which has not yet been accounted for, contributing to the streambed groundwater. Although the streambed groundwater T and EC can be accounted for by a mixture of river water and the freshwater aquifer (Figure 34), this mixture cannot explain the ^{18}O results.

The chloride values are plotted against T and ^{18}O in Figures 35 and 36. Low chloride levels for the river water and the majority of streambed groundwater samples are evident on both plots, however, the George Street Station #5, (1.0 and 1.5 m depth samples) show elevated chloride levels when compared with the other samples. From the T versus chloride plot (Figure 35) of the river water and streambed groundwater samples, three groupings are evident: river water with high T and low chloride, streambed groundwater with

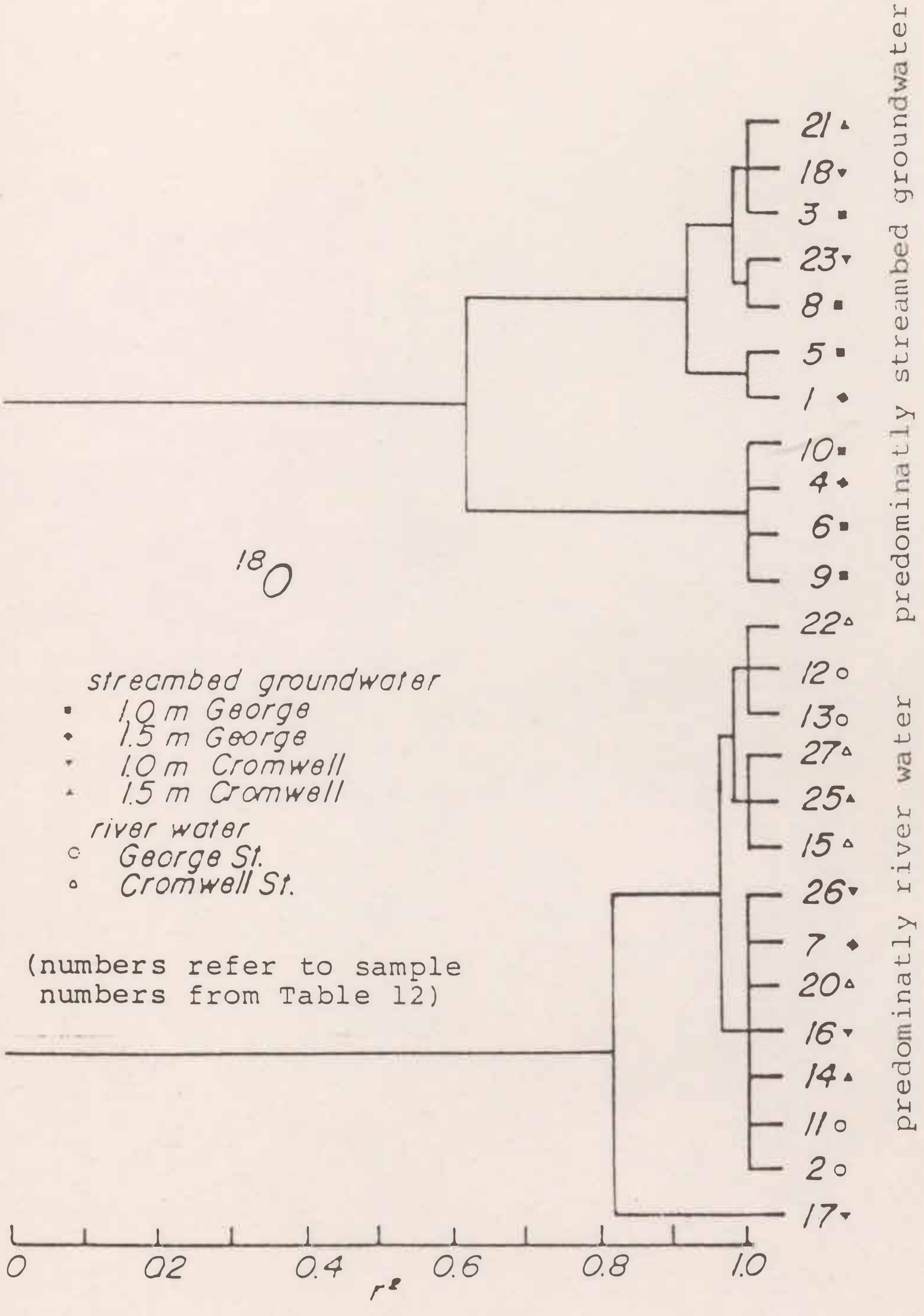


Figure 32. Cluster analysis for oxygen-18 data.

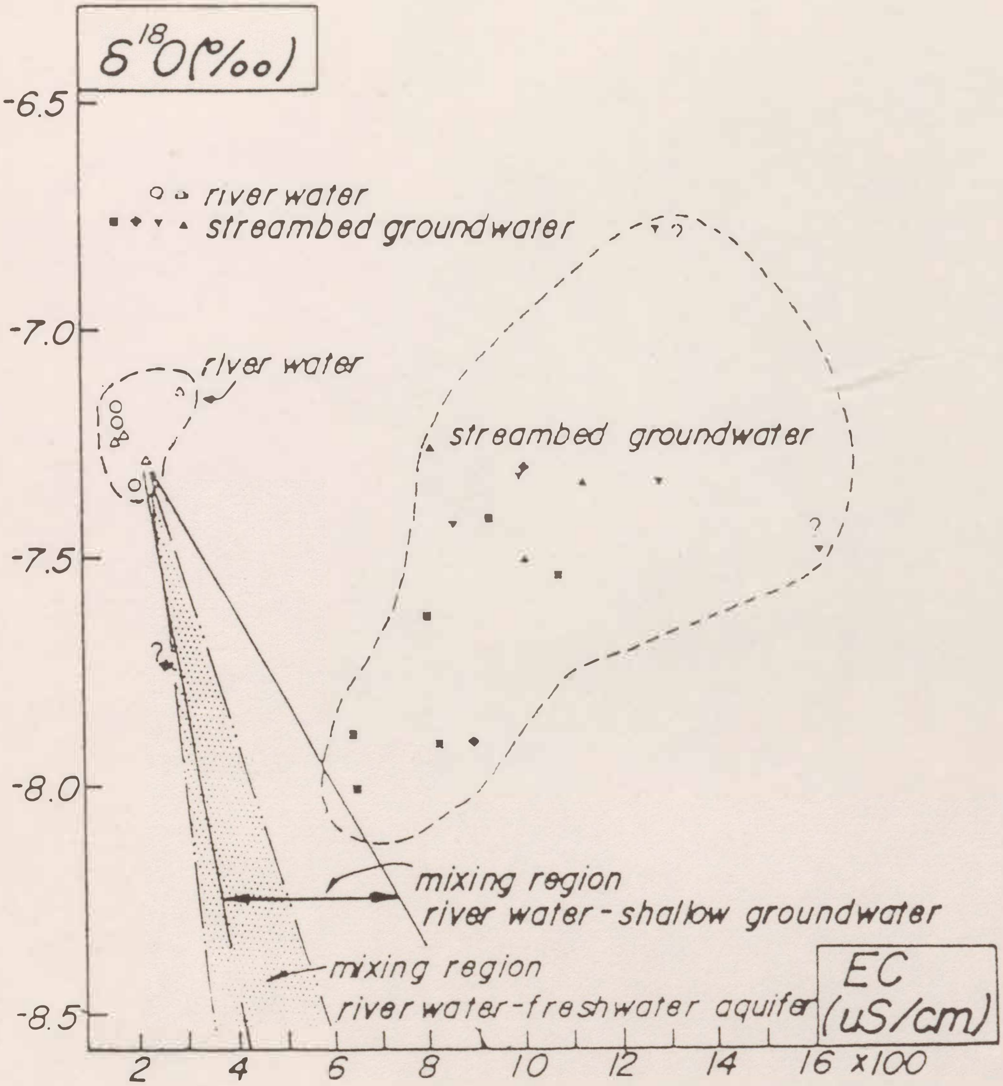


Figure 33. Plot of $\delta^{18}O$ versus EC.

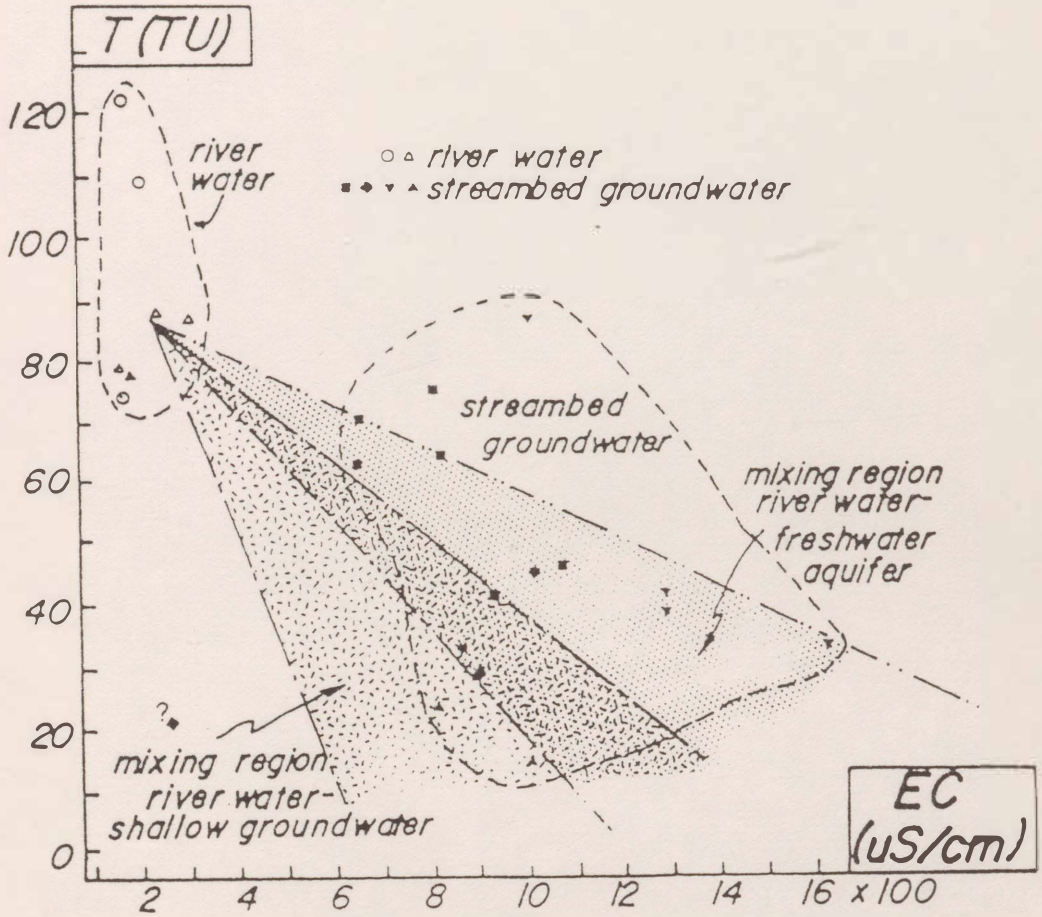


Figure 34. Plot of tritium versus EC.

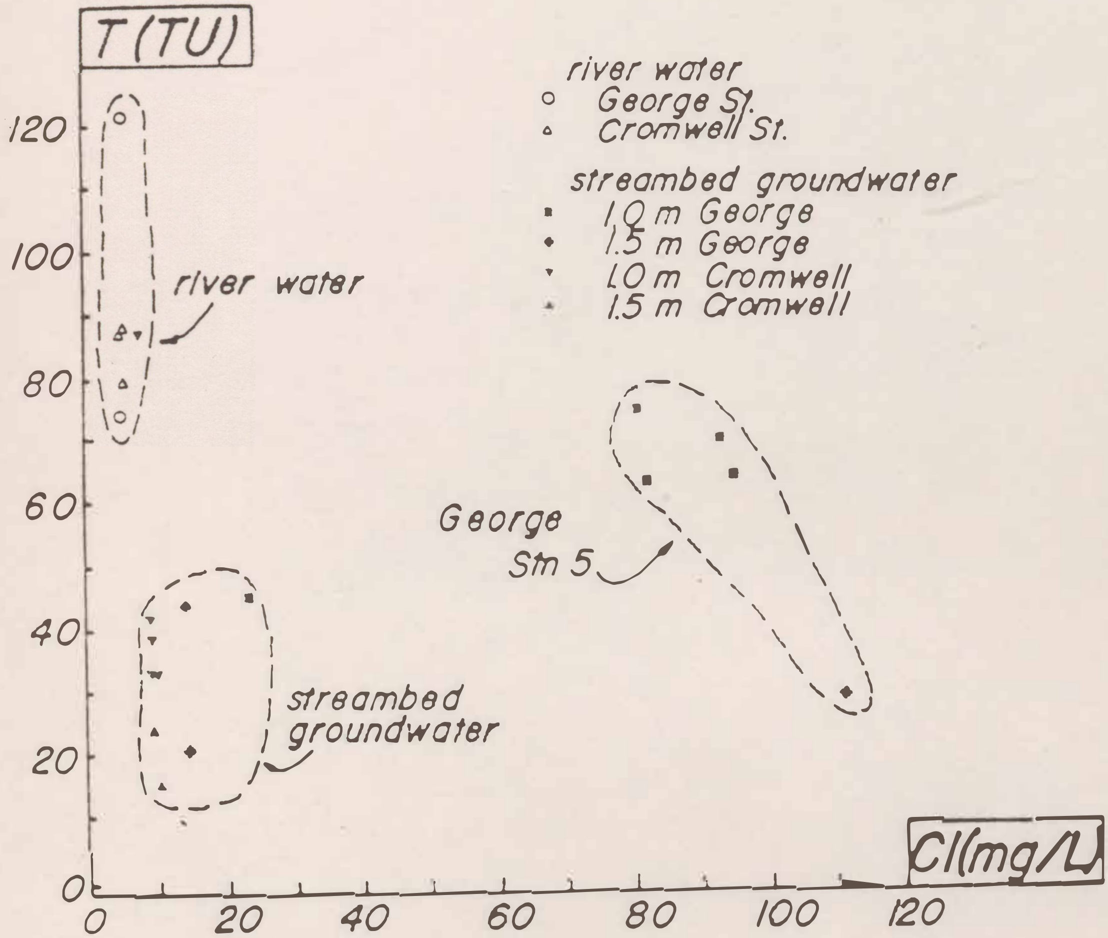


Figure 35. Plot of tritium versus chloride.

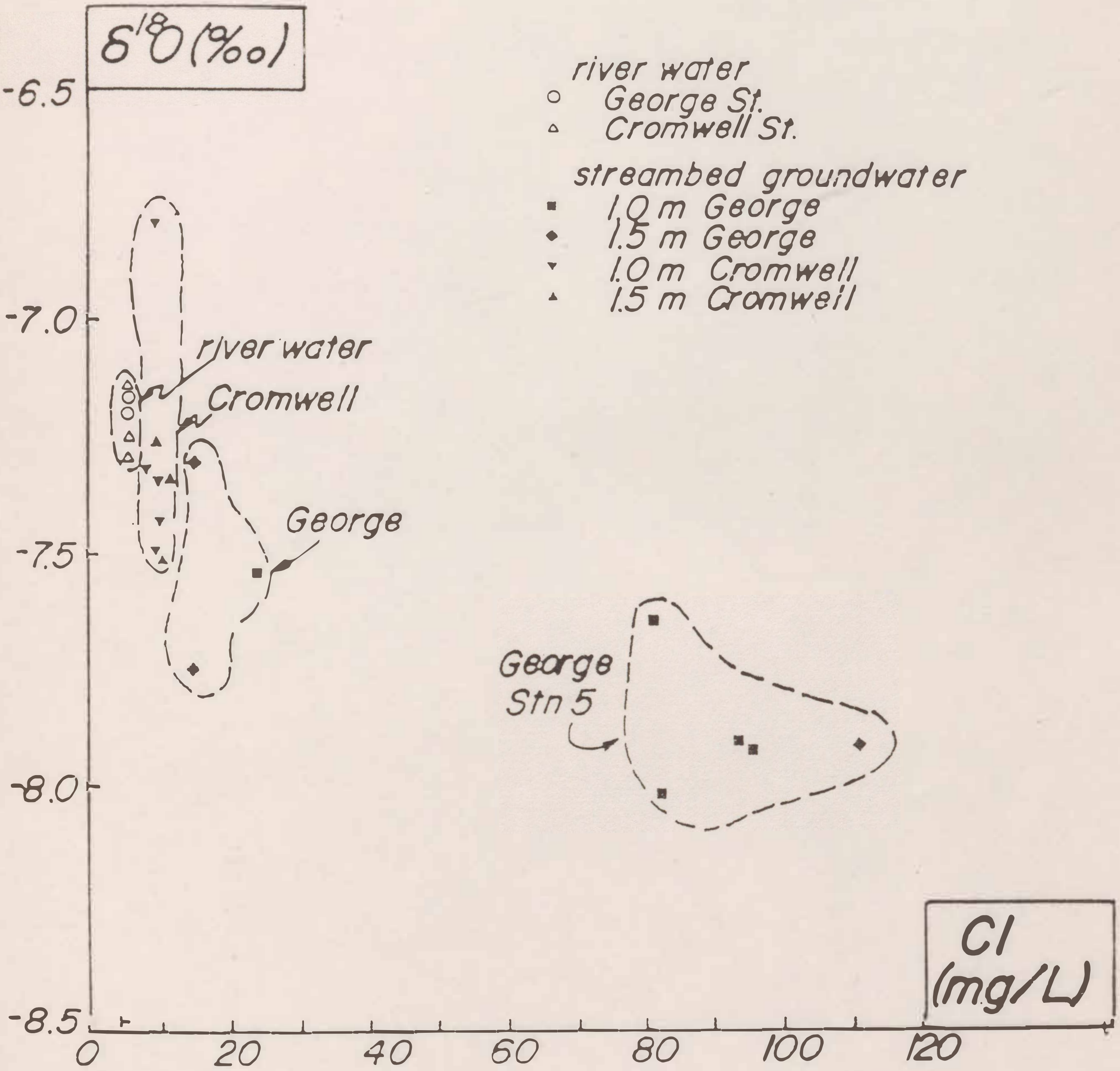


Figure 36. Plot of oxygen-18 versus chloride.

low T and low chloride, and the George Street Station #5 group with T levels between river water and streambed groundwater and high chloride levels. Figure 36 suggests that there is a source of higher chloride water contributing to the streambed groundwater at the George Street station. As shown in a previous plot (Figure 29), the $\delta^{18}O$ values for this group appears to be more depleted than the other streambed groundwater. It is evident that the George Street Station #5 samples appear as an anomalous area.

When Cl^- is plotted against EC, the George Street Station #5 samples again show an anomalous relationship (Figure 37). There is the possibility that seepage of contaminants near George Street Station #5 could be affected by concentrated groundwater flow through fractures in the till in the river bed. The obviously higher chloride and relatively low EC compared to the other streambed groundwater samples, suggest that the 1 m samples from George Street Station #5 are derived from a different source or sources than the other streambed groundwater samples.

One of the remaining unknowns is the low T source of water which causes the streambed groundwater from the Cromwell Street and George Street 1.5 m samples to plot with a similar $\delta^{18}O$ value to the river water but much smaller T concentration than the river water in Figure 29.

Figure 38 is a summary diagram showing the various sources of water investigated during this study, and their associated parameter values.

The $\delta^{18}O$ and δD of the river water and streambed groundwater are similar which suggests evaporation and downward diffusion of river water into the

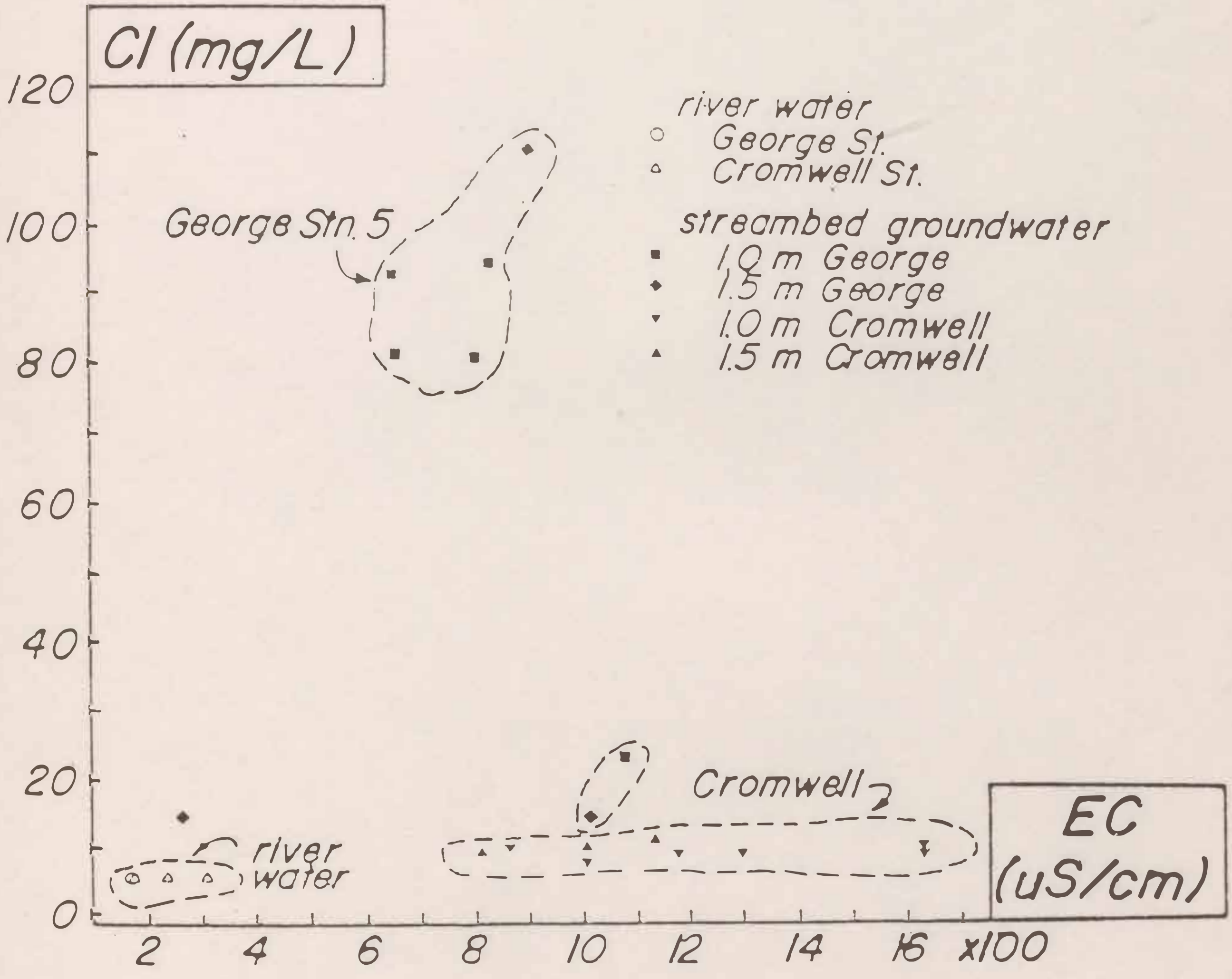


Figure 37. Plot of chloride versus EC.

Figure 38. SUMMARY DIAGRAM OF WATER SOURCES

	EC uS/cm	pH	Cl$^-$ mg/L	^{18}O ‰	T TU	D ‰
0 river water	204	7.47	5.34	-7.25	89.1	-58.7
-1.0 m	944	7.03	33.9	-7.53	53.4	-57.8
-1.5 m	719	7.07	28.5	-7.51	23.2	-59.6
-10.0 m Suncor shallow wells	NA	7.6*	88*	-9.37	14.0	-62.7
-35 to 40 m freshwater aquifer (Esso Wells)	2540	7.5*	700*	-15	<6	-105#

* approximations from Desaulniers et al.(1981)
NA data not available
\# estimate based on meteoric water line and δ^{18}O from this study
Values used are either means, or typical values.

streambed. Another possibility is that the $\delta^{18}O$ and δD values for the streambed groundwater can be indicative of discharge of injected fluids. If these injected fluids were pre-treated or mixed with river water prior to injection, the $\delta^{18}O$ and δD values would be representative of evaporated water.

There is an obvious decrease in T values (89 to <6 TU) from river water to the freshwater aquifer. Unless injected fluids or shallow fracture flow in the till is discharging into the river, this represents either downward diffusion or downward advection. It is possible that this T decrease is the result of a mixture of the pre-treated injected wastes and river water. If these mixtures were injected early in the history of deep well disposal they could contain very low levels of T. These low levels could be explained by the residence time of the water in the upper Great Lakes.

The Cl^- concentrations increased considerably with depth from the river water to the freshwater aquifer suggesting a higher source of Cl^- with depth.

The EC of the various waters appear to be increasing with depth, however, the EC of the shallow groundwater is not known. Several possible sources of high EC include: fluids displaced from formations between the disposal unit and the freshwater aquifer, and groundwater from the freshwater aquifer which was contaminated from deep well disposal activities.

As previously discussed, George Street Station #5, showed anomalous results for EC, T, ^{18}O and Cl^-, and also contains a number of the highest TOX values reported. This water appears to be different from the water of other stations along the George Street Survey Line and from the water encountered on the Cromwell Street Survey Line at the same depth. Further investigation is necessary to determine if these anomalies are caused by upward migration of contaminated fluids through fractures in the till.

6.0 CONCLUSIONS AND RECOMMENDATIONS

It is evident that there is seepage from the streambed into the St. Clair River. The average observed seepage rate of groundwater into the St. Clair River near Sarnia was approximately 1.4×10^{-8} $m^3/s/m^2$, however, seepage varied both temporally and areally. This rate of seepage suggests that either the till in the bottom of the St. Clair River has a hydraulic conductivity which is 2 to 4 orders of magnitude greater than the values determined by Desaulniers et al. (1981) for the till in Sarnia or that the hydraulic gradient in the streambed is very large (>1.4).

Detectable but not excessive (relative to other studies of streambed sediment and river water) levels of organic contaminants were found in the streambed groundwater and the river water. For example: <0.0067 ug/L total chlorinated hydrocarbons, <0.026 ug/L PCB, <2.77 ug/L trihalomethanes, and <2.4 ug/L base neutral extractables were observed.

The isotopic and EC data indicate that:

1) the streambed groundwater is lower in T than the river water but higher in T than the shallow groundwater and the freshwater aquifer.
2) the streambed groundwater, on the basis of ^{18}O and D concentrations, is evaporated or mixed with evaporated water. River water and shallow groundwater in the clay are evaporated. If waste injected through the disposal wells was pretreated with river water prior to injection, it would appear as evaporated water in terms of ^{18}O and D concentrations.
3) the streambed groundwater has Cl^- concentrations which are at least 5 times the river water concentrations. The Cl^- concentrations in

the shallow groundwater and the freshwater aquifer are much higher than the streambed groundwater.

4) the EC pattern is similar to the Cl^- pattern.

Some of the streambed groundwater (George Street Station #5) appears to be mixed with shallow groundwater from the upper part of the till. The other streambed groundwater samples are either mixed with evaporated water which comes from the river or perhaps from the shallow groundwater in the fractured till or, it comes from another source of evaporated water which has not yet been identified (possibly injected waste pretreated with riverwater). The streambed groundwater is influenced by water which has a high EC value (possibly surface water, near surface water or pretreated waste).

It is well documented that deep-well disposal activities have contributed to flowing wells containing contaminated water. These waters contained high levels of Cl^- and high EC among other constituents. It is possible that the high ECs and Cl^- encountered in this study may be the result of these past activities.

Even though EC, ^{18}O, T, and D have been useful in distinguishing between the various possible sources of the streambed groundwater, the exact source(s) of the streambed groundwater are still unknown. The major remaining problem is a lack of information on the freshwater aquifer below the St. Clair River. It is conceivable that the unknown water mentioned above could be contaminated groundwater in the freshwater aquifer below the river.

In summary: river water would affect the streambed groundwater only by diffusion because upward seepage was observed, surface sources would likely affect the streambed groundwater by downward diffusion since there is upward advection, the shallow groundwater could impact the streambed groundwater by both advection and diffusion, and the freshwater aquifer could affect the streambed groundwater by both advection and diffusion only if the clay is fractured.

On the basis of observations and interpretations the following studies are recommended:

(1) Determine the isotopic character of the freshwater aquifer under the St. Clair River in order to use isotopic data to identify the source of seepage into the streambed of the St. Clair River.

(2) Obtain water samples from the bedrock and clayey till below the streambed for isotopic analysis to determine the possible contributions of these waters to the streambed groundwater.

(3) Obtain water samples from the bedrock and till at greater depths below the streambed for chemical analysis to determine the quality of the water at depth below the streambed.

(4) Obtain current information on pressure head levels and water levels in the disposal wells in order to determine if the over-pressurized conditions in the disposal zone still exist.

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8.0 APPENDICES

APPENDIX 1

SURVEY LINES

Survey Line Installation Procedures

Detailed Maps and Photographs of Survey Line Locations

APPENDIX 1

SURVEY LINES

SURVEY LINE INSTALLATION PROCEDURES

The following is a detailed description of the survey line installation procedures and the problems encountered during these installations.

All of the field work was carried out from the "Lab III" research boat, a 6.4 m shallow draught work boat (Figure 39). The survey lines were assembled on the boat. Each of the survey lines consisted of 100 m of 10 mm yellow polypropylene line knotted at 10 m intervals. Plastic labels marked with station numbers were affixed in their appropriate positions. There were 2 m of extra rope left at Position #1 to allow the rope to be tied to the permanent end stake.

The knotted line was coiled onto a large spool with Position #11 on the inside of the spool and Position #1 on the outside. One person placed the spool on an axle mounted on the boat so that the rope would easily uncoil into the water. The diver drove a stainless steel stake into the shoreline and attached Position #1 to the stake (thus becoming Station #1). In some places, the survey line was attached to a permanent and convenient onshore anchoring site (e.g., sheet pile, fence, etc.).

With the divers positioned on shore, the boat crew (3 people minimum) played out the survey line as they headed away from the shore at an angle of 5-10° upstream of 90° to shore. This upstream correction was used to compensate for the downstream drift of our anchoring weights. Just before

Figure 39. Lab III Research Boat.

reaching Position #6 (50 m off shore), we prepared to drop a bouy. These preparations consisted of: releasing considerable slack in the survey line, attaching two 50-lb scale weights to the Position #6 knot of the survey line, and attaching a 21 m bouy line and large marker bouy to the Position #6 knot. The bouy line (the same 10 mm yellow line that was used for the survey lines), was used so that the weights could be winched up at a later time.

The weights, bouy line, and bouy were placed on the side of the boat while the boat was brought into its proper position. The bouy was thrown downstream, clear of the propellers as the boat was maneuvered just upstream of Position #6. The survey line was pulled tight, and the weights were pushed overboard.

The survey line was played out to Position #11 and weights and a bouy line were attached. With an extra 2 m of line, the weights were attached to the side of the boat. The survey line was stretched out by moving the boat over Position #11 (100 m from shore) and releasing the bouy. As the weights were released from the boat, they became suspended above the water. Once the survey line was taught, the 2 m line which held the weights to the boat was cut. The boat surged ahead as it was released from the survey line.

For some of the survey lines (those where seepage meters were installed) we attached permanent bouys at Station #11. These bouys were attached to stainless steel stakes driven into the river bed. The azimuth of the line from the marker bouy at Station #11 to the shore marker (Station #1) was measured.

As previously mentioned, there were several problems encountered during the laying of the survey lines such as: maneuvering the boat upstream (against the strong currents) during the actual installation, the strong currents which the divers had to fight during the installations, and the divers' general lack of visibility due to the silt laden water.

Figure 40. Detailed maps of survey line locations.

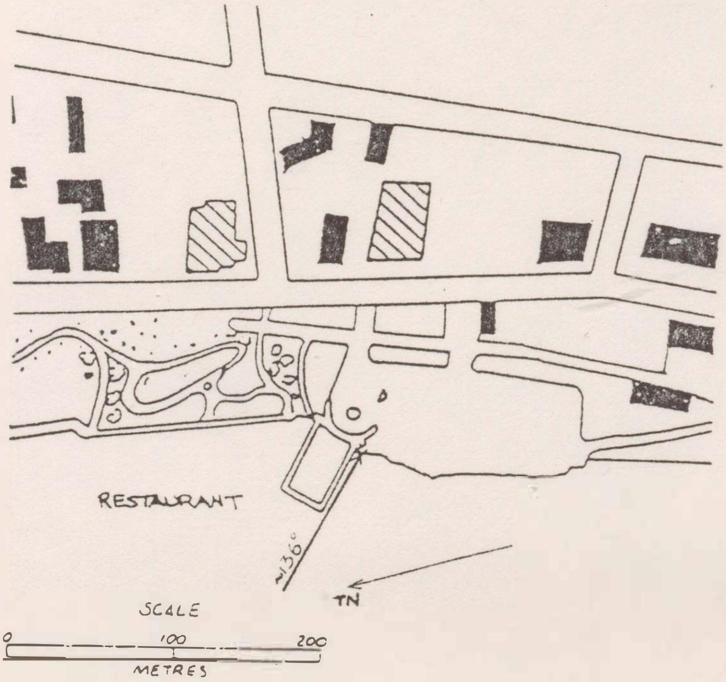

Figure 40a. Restaurant Survey Line.

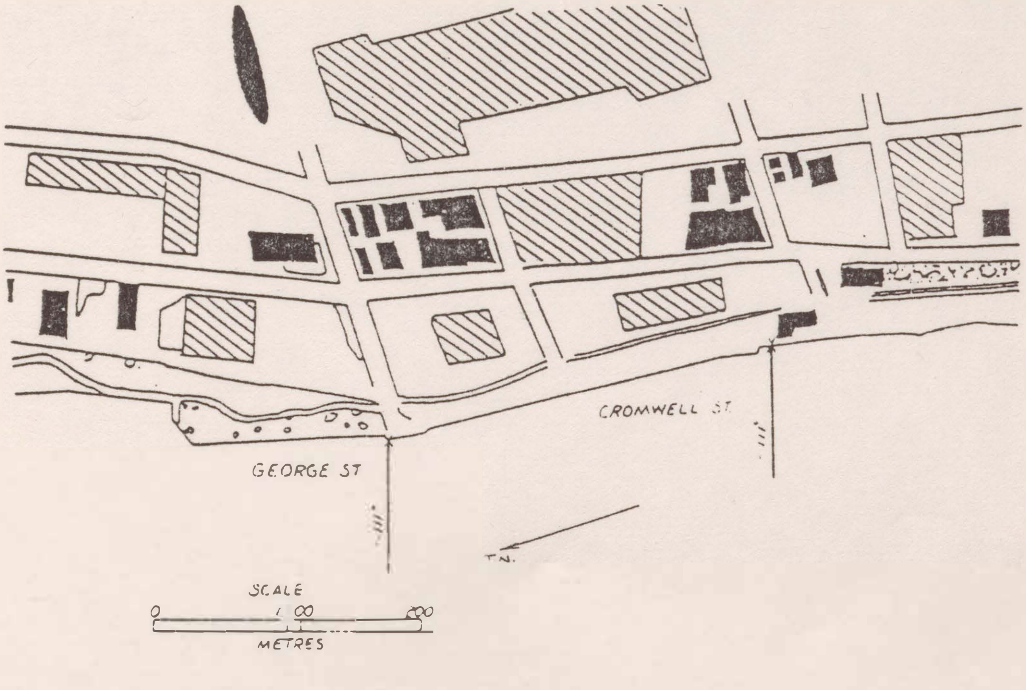

Figure 40b. George Street and Cromwell Street Survey Lines.

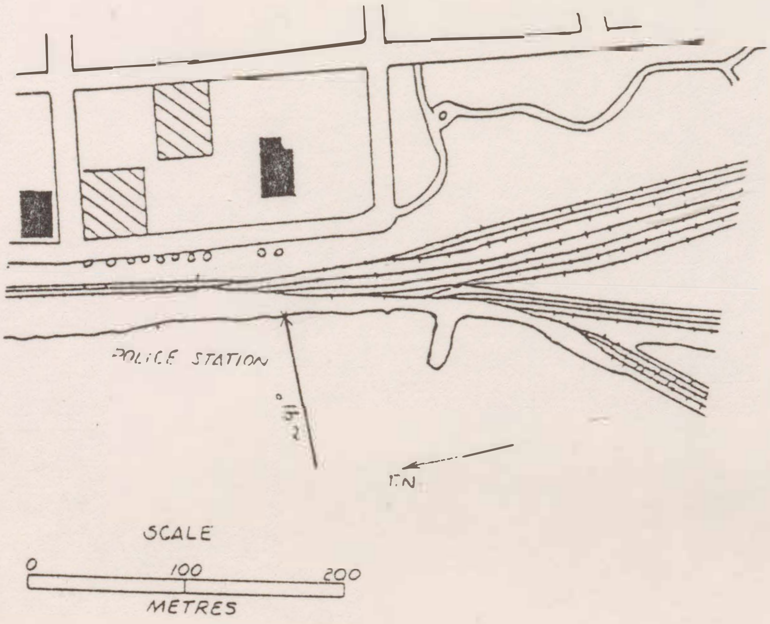

Figure 40c. Police Station Survey Line.

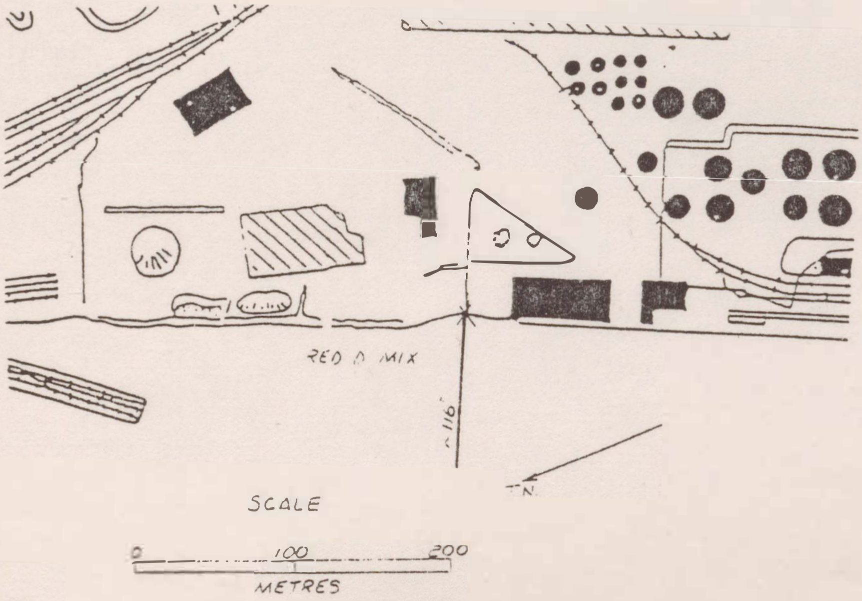

Figure 40d. Red-D-Mix Survey Line.

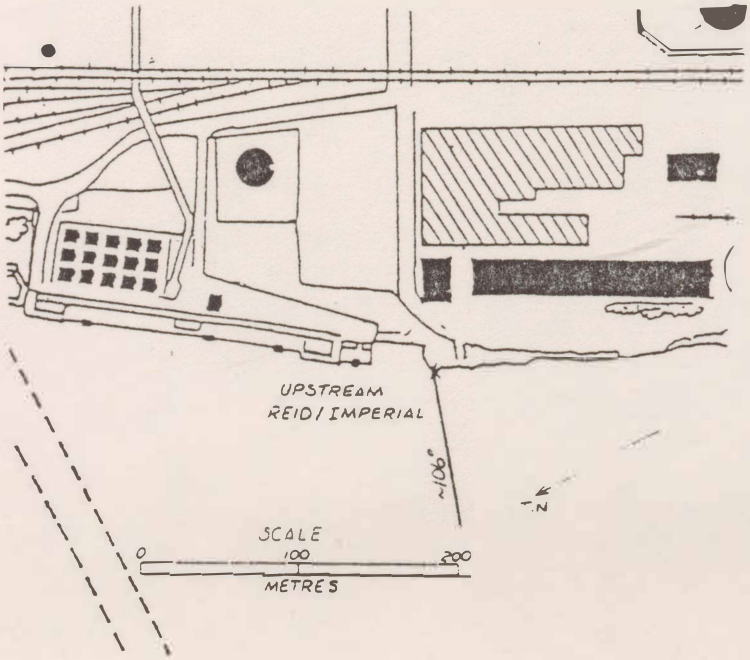

Figure 40e. Upstream Reid/Imperial Survey Line.

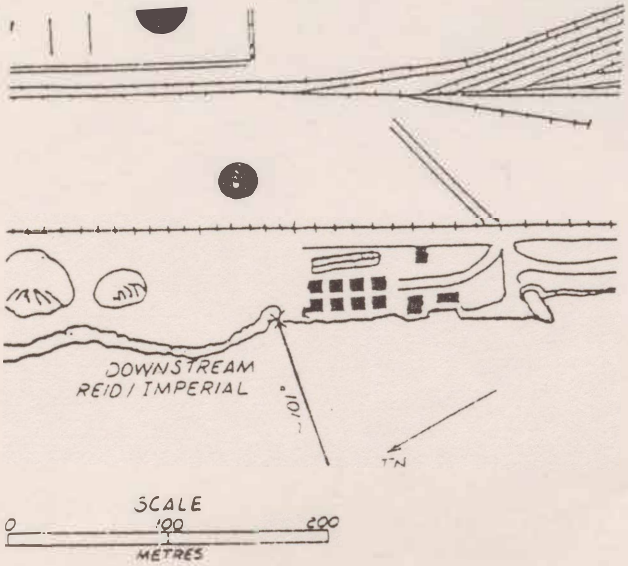

Figure 40f. Downstream Reid/Imperial Survey Line.

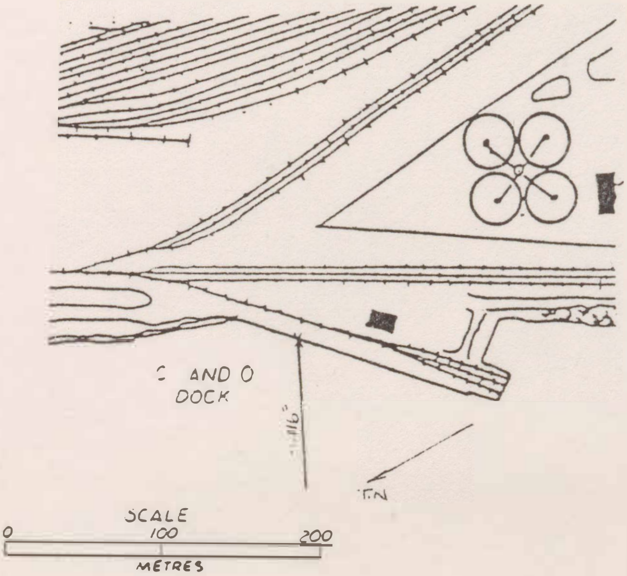

Figure 40g. C and O Dock Survey Line.

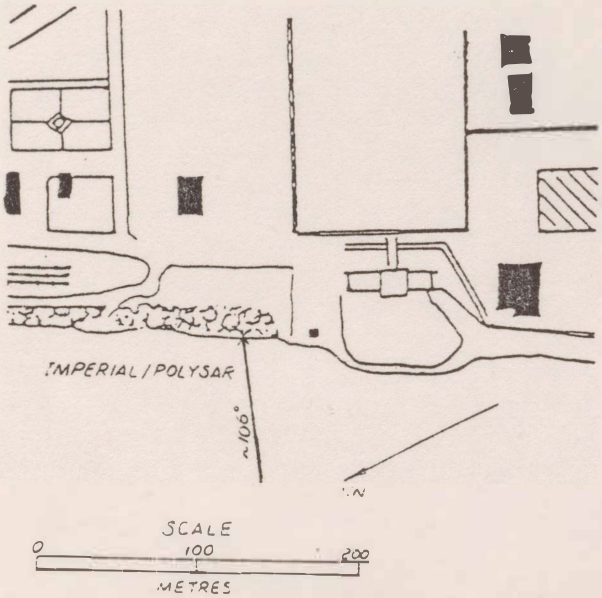

Figure 40h. Imperial/Polysar Survey Line.

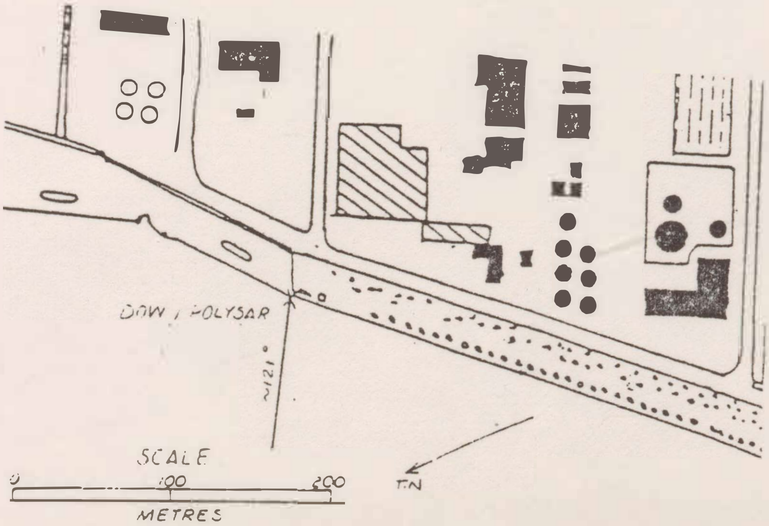

Figure 40i. Dow/Polysar Survey Line.

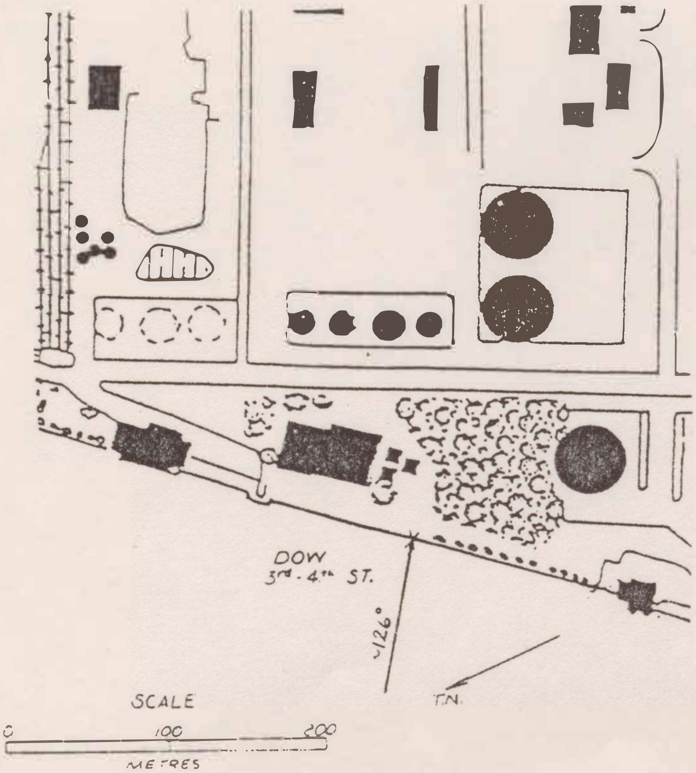

Figure 40j. Dow 3rd-4th Street Survey Line.

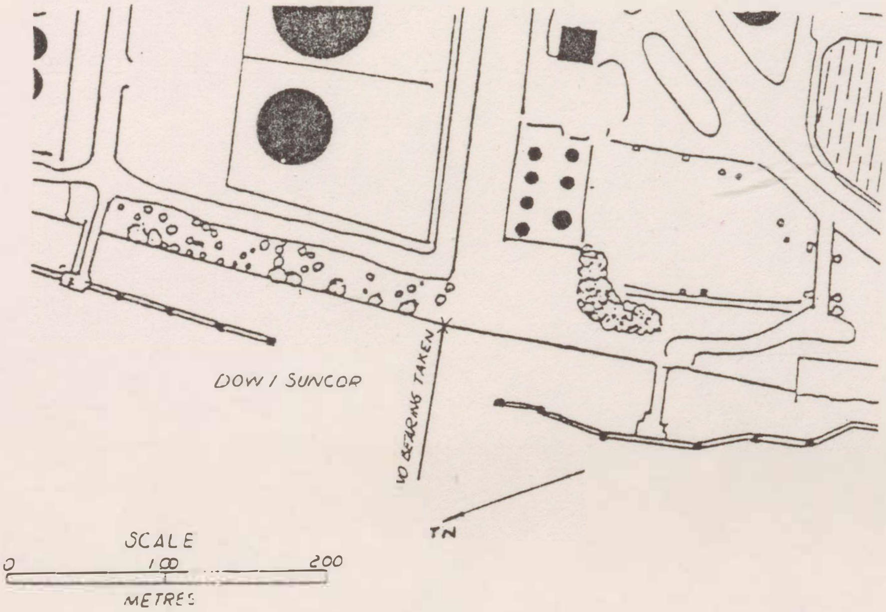

Figure 40k. Dow/Suncor Survey Line.

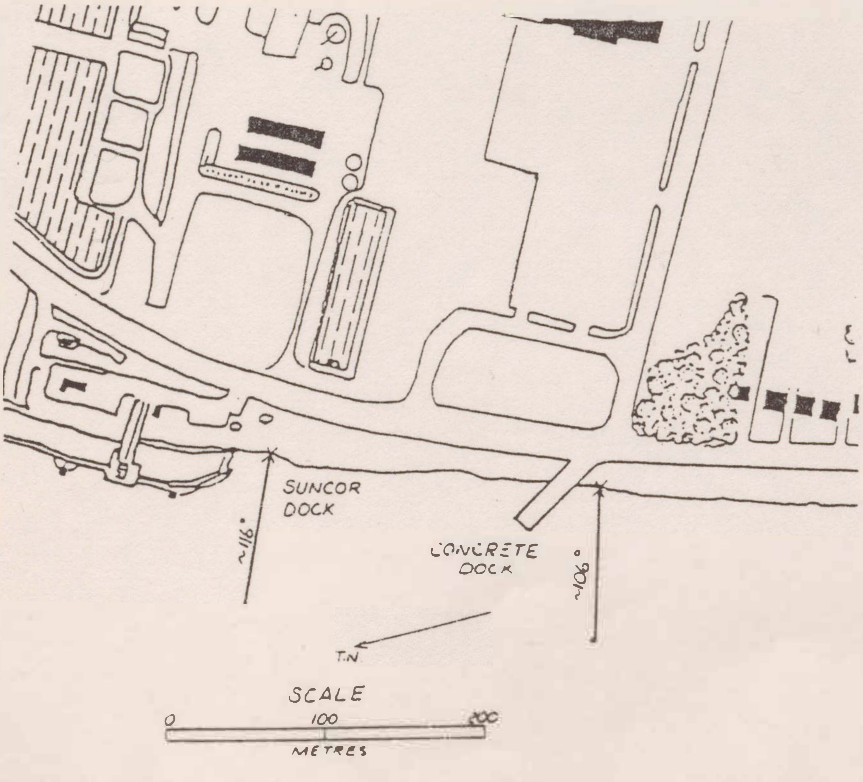

Figure 40l. Suncor Dock and Concrete Dock Survey Lines.

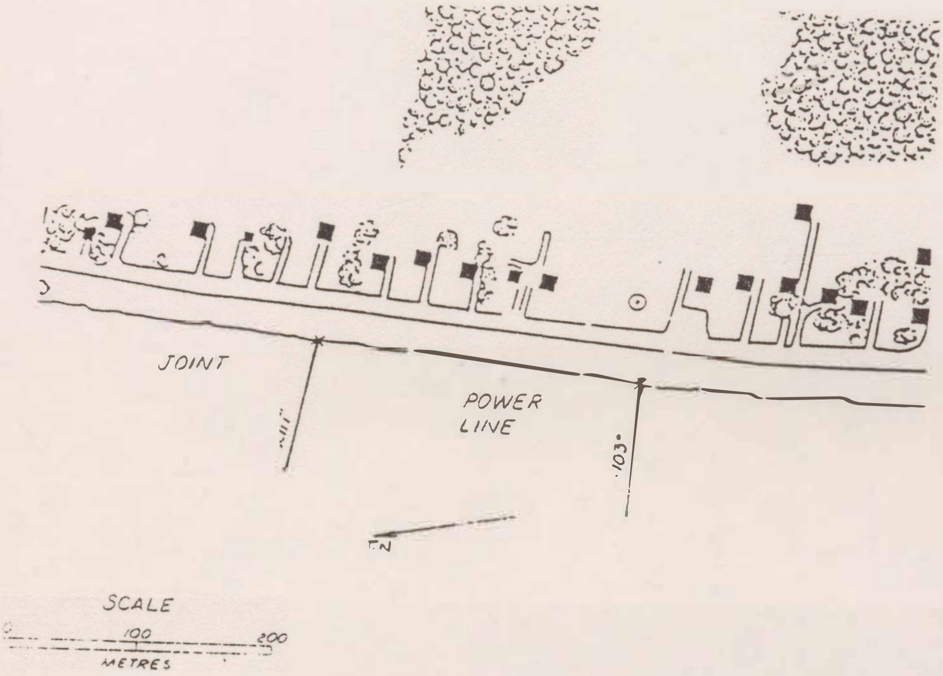

Figure 40m. Joint and Power Line Survey Lines.

Figure 41a. George Street Survey Line location.

Figure 41b. Restaurant Survey Line location.

Figure 41c. Cromwell Street Survey Line location.

Figure 41d. Police Station Survey Line location.

Figure 41e. Red-D-Mix/Imperial Survey Line location.

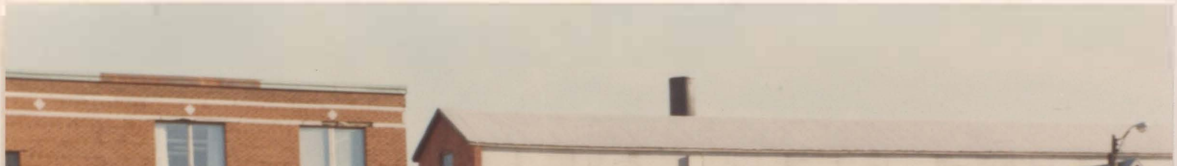

Figure 41f. Upstream Reid/Imperial Survey Line location.

Figure 41g. Downstream Reid/Imperial Survey Line location.

Figure 41h. C and O Dock Survey Line location.

Figure 41i. Imperial/Polysar Survey Line location.

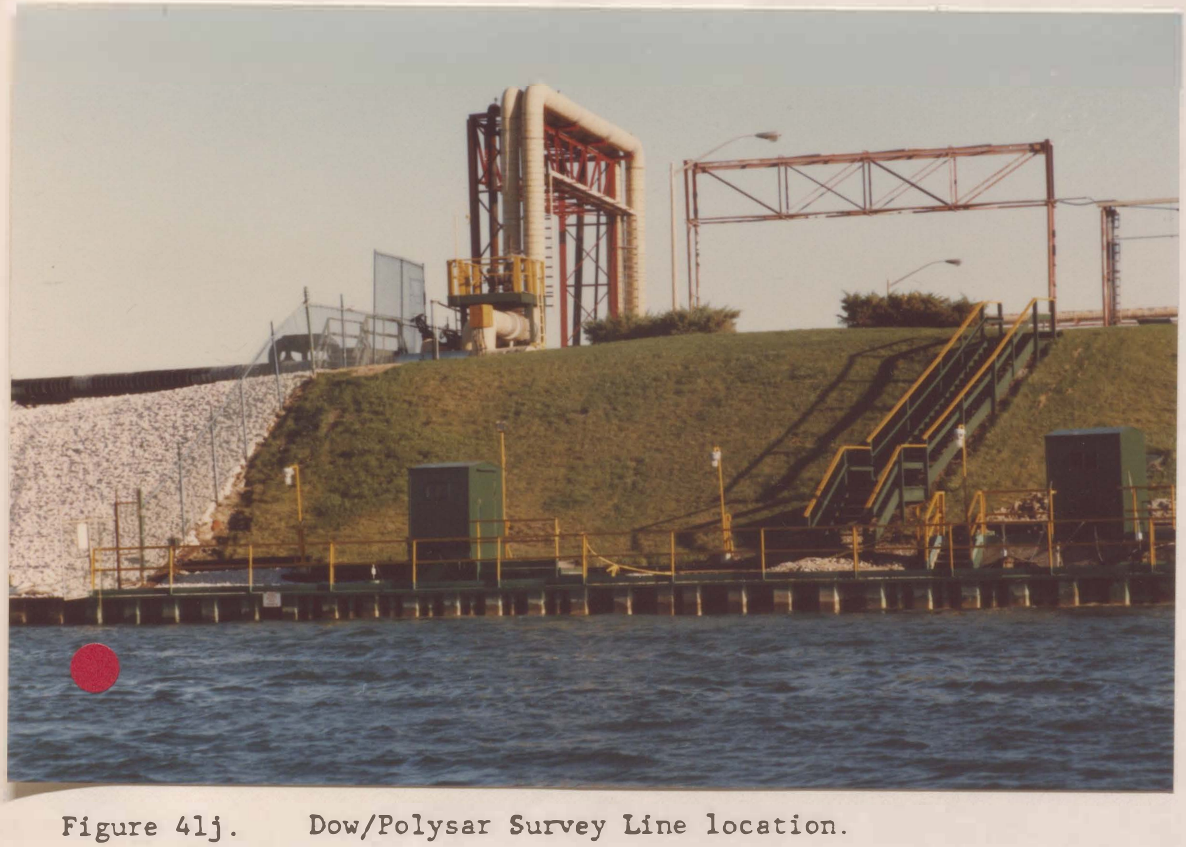

Figure 41j. Dow/Polysar Survey Line location.

Figure 41k. Dow 3rd-4th Street Survey Line location.

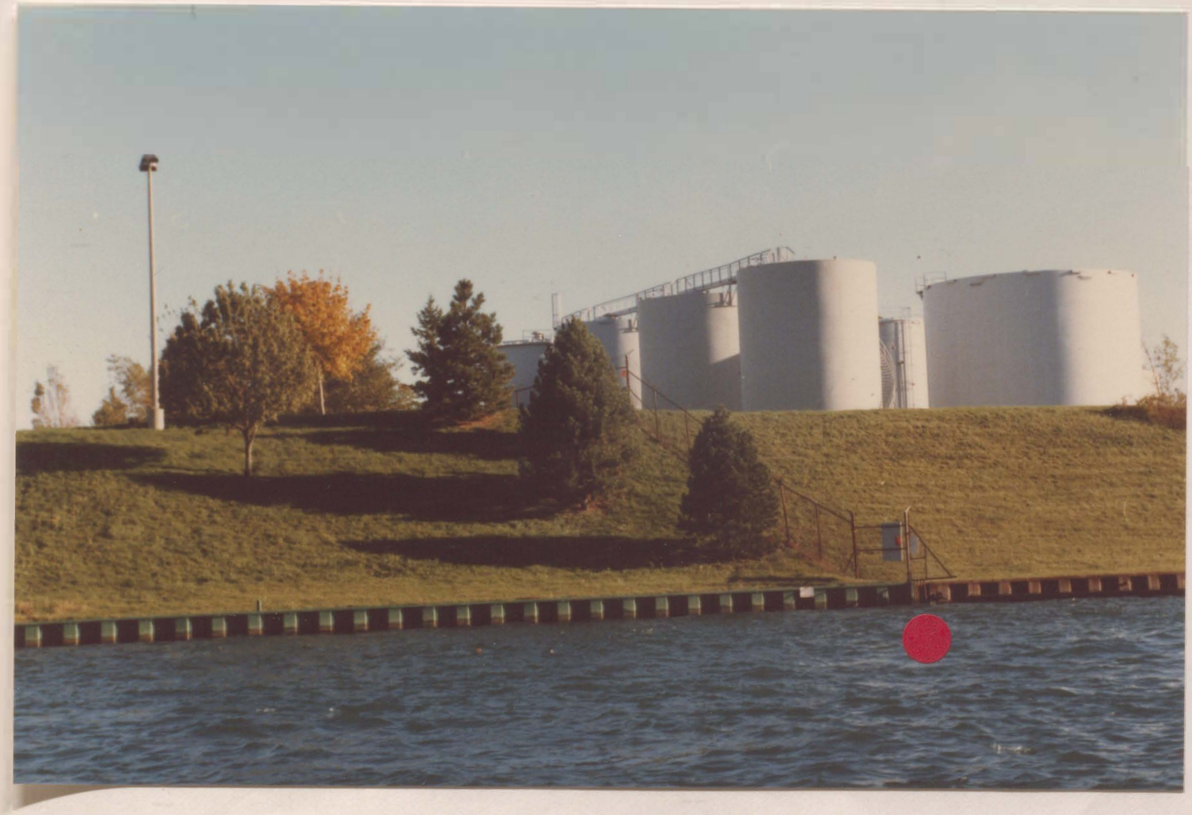

Figure 41l. Dow/Suncor Survey Line location.

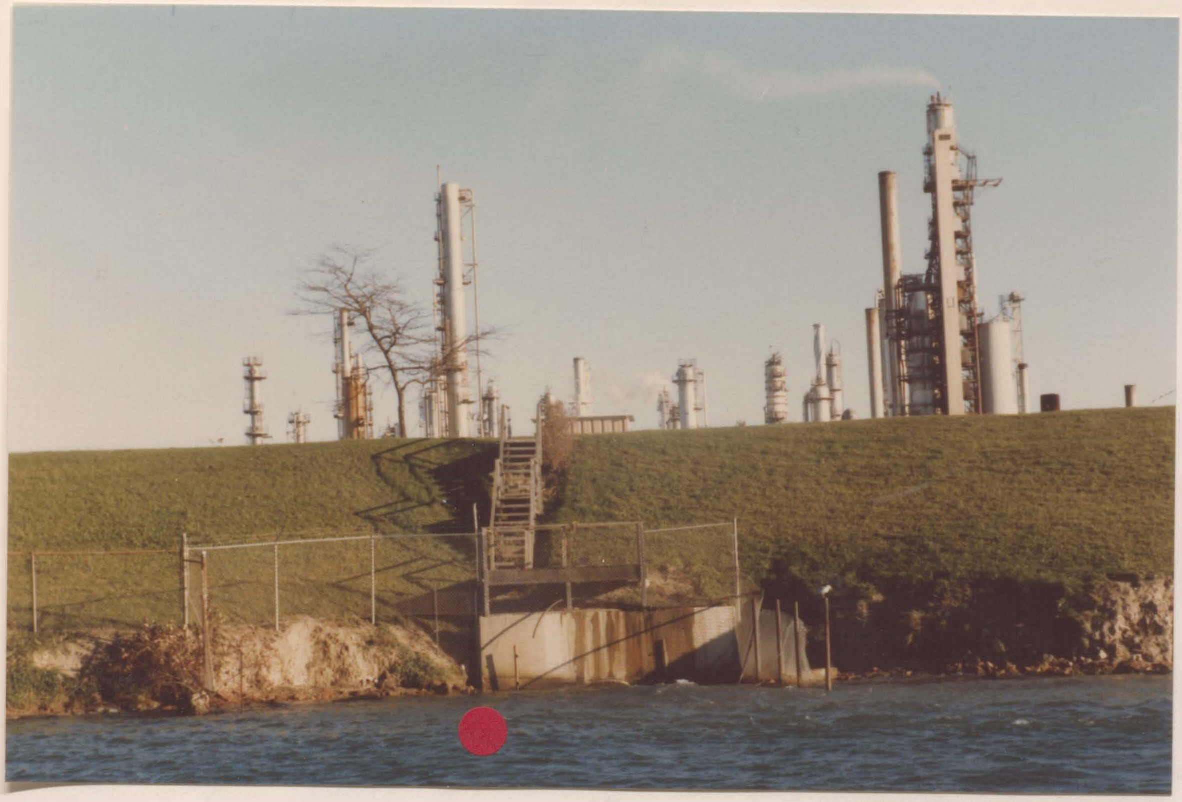

Figure 41m. Suncor Dock Survey Line location.

Figure 41n. Concrete Dock Survey Line location.

Figure 41o.   Joint Survey Line location.

Figure 41p.   Power Line Survey Line location.

APPENDIX 2

RIVER BOTTOM DESCRIPTIONS

Table 7. River bottom descriptions.

Survey Line	Location on Line	Description
Joint (7-18-85)	Near shore	Sandy, much vegetation
	0-30 m (from shore)	Vegetation, coarse sand, gravel, debris
	30-60 m (from shore)	Less vegetation, coarse sand, debris, logs, boulders, steeper slope
	50-100 m (from shore)	Gravel bottom, boulders, debris
Power Line (7-19-85)	Station	
	1-5 (0-40 m from shore)	Sand over clay, vegetation Stn. 1: 17 cm coarse gravely sand Stn. 2: Clay with less than 2 cm sand Stn. 3: Clay with 5 cm sand Stn. 4: Coarse sand and gravel
	5-7 (40-60 m from shore)	Fine sand
	7-9 (60-80 m from shore)	Stn. 7: Sand bar, 10 cm sand over clay
	9-11 (80-100 m from shore)	Sand (less than 5 cm), clay, debris
Reid-Imperial (8-1-85)	Near shore	Sand, gravel underlain by clay, exposed clay in areas
Dow-Polysar (8-1-85)	Station	
	1-4 (0-30 m from shore)	Sand, vegetation
	4-5 (30-40 m from shore)	Sand (5 cm thick), clay
	6 (50 m from shore)	Oily sediments
Dow 3-4th St. (S-10) (8-2-85)	Station	
	1-4 (0-30 m from shore)	Sand, clay, vegetation
	4-6 (30-50 m from shore)	Black sediments
	7-10 (60-90 m from shore)	Clay, gravel
Red-D-Mix Imperial (8-9-85)	Station	
	1-2 (0-10 m from shore)	Fine to coarse sand, vegetation
	3-4 (20-30 m from shore)	Coarse sand
	5-6 (40-50 m from shore	Boulders, gravel, clay
Imperial-Reid (8-14-85)		Clay, rubble
Restaurant (8-14-85)		Very silty

APPENDIX 3

BOTTOM CORE DESCRIPTIONS

Table 8. Bottom core descriptions.

Survey Line	Sample Location	Distance from shore (m)	Recovery* (cm)	Description
Power Line (07-18-85)	Between Stn.		20	Sand and gravel
	6-7	55	5	Clay with sand and gravel
Joint (07-30-85)	Between Stn.			
	1-2	5	10	Clay with gravel
	3-4	25	7	Clay with gravel
	5-6	45	1	Clay
	9-10	85	15	Clay
Police (S-3) (07-30-85)	Between Stn.			
	1-2	5	12	Sand (coarser sand at top of core)
	3-4	25	14	Sand, fine-grained
	5-6	45	1	Sand, fine-grained
	9-10	85	20	Sand, fine-grained
Suncor Dock (07-31-85)	Between Stn.			
	1-2	5	7	Sand with gravel
	3-4	25	12	Sand with gravel
	5-6	45	18	Gravel
	7-8	65	12	Sand with gravel
	9-10	85	19	10 cm gravel 9 cm clay (at bottom of core)
George Street (07-31-85)	Between Stn.			
	1-2	5	14	Sand, fine-grained
	3-4	25	8	Sand, fine-grained (with small chunks of wood)
	5-6	45	13	Sand, fine-grained
	7-8	65	8	Sand, fine-grained
	9-10	85	14	Sand, fine-grained
Downstream Reid Imperial (08-1-85)	Between Stn.			
	1-2	5	12	Sandy clay
	3-4	25	13	Sand, fine-grained
	5-6	45	0	-
	7-8	65	11	Clay with gravel
	9-10	85	25	Sandy clay

* Total length of core barrel - 46 cm

NA - not available

Survey Line	Sample Location	Distance from shore (m)	Recovery* (cm)	Description
Dow-Polysar	Between Stn.			
(08-1-85)	1-2	5	1	NA
	7-8	65	16	NA
	9-10	85	28	NA
	6	50	NA	NA
C and O Dock				
(S-4)	Between Stn.			
(08-2-85)	1-2	5	7	Clay
	3-4	25	17	Oily sediment
Dow 3-4th St.				
(S-10)	Between Stn.			
(08-2-85)	1-2	5	NA	Sediment (with wood at top of corer)
	3-4	25	46	Sand with gravel
	5-6	45	12	Clay with gravel
	7-8	65	7	Clay with gravel
	9-10	85	0	-
Red-D-Mix	Between Stn.			
Imperial	1-2	5	11	Sand with gravel (at bottom of corer)
(08-9-85)	3-4	25	20	Clay with gravel (at bottom of corer)
	5-6	45	10	Gravel (at bottom of corer)
	7-8	65	NA	Sand with gravel
	9-10	85	8	1 cm clay (at top of corer) 7 cm sand (at bottom of corer)
Restaurant (08-14-85)				Very silty (line not used current too strong)
Upstream Reid-Imperial	Between Stn.			
(08-14-85)	1-2	5	17	Clay (at bottom of corer)
	3-4	25	8	Gravel (at bottom of corer)
	5-6	45	0	
	7-8	65	0	
	9-10	85	0	

Survey Line		Distance from shore (m)	Recovery* (cm)	Description
Concrete Dock (08-16-85)	Between Stn.			
	1-2	5	6	Sand, fine-grained (at top of corer)
	3-4	25	9	Sand, fine-grained (at top of corer) clay at bottom
	5-6	45	46	Clay with gravel
	7-8	65	3	Clay (at bottom of corer)
	9-10	85	17	Clay with gravel
Imperial-Polysar (08-19-85)	Between Stn.			
	1-2	5	4	Clay with gravel (at bottom of corer)
	3-4	25	46	Oily sand, fine-grained
	4	30	NA	Clay
	5-6	45	21	Sandy clay (at bottom of corer
	7-8	65	46	Clay
	9-10	85	31	Clay (at bottom of corer)
Cromwell Street (8-19-85)	Between Stn.			
	1-2	5	0	
	3-4	25	12	Oily sand, black (at bottom of corer)
	5-6	45	5	Sand, fine-grained (at bottom of corer)
	7-8	65	7	Sand, fine-grained (at bottom of corer)
	9-10	85	0	
Dow-Suncor (8-21-85)	Between Stn.			
	3-4	25	46	Clay with gravel

Survey Line	Sample Location	Distance from shore (m)	Recovery* (cm)	Description
Lake Huron (8-22-85)	Between Stn.			
	1-2	5	0	All rock
	3-4	25	16	Sand, medium-grained
	5-6	45	46	Sand, fine-grained
	7-8	65	17	Sand, fine-grained
	9-10	85	46	Sand, fine-grained
Lake Huron #1 (8-27-85)	2 cores from 1.5 m radius around site	NA	17 19	Clay with sand Clay with sand

APPENDIX 4

SEEPAGE METERS

Seepage Meter/Collection Assembly Photographs

Seepage Meter Data

St. Clair River Gauging Stations

Figure 42. Seepage meter - inside view.

Figure 43. Seepage meter - top view.

Figure 44. Collection bag apparatus.

Figure 45. Collection bag apparatus - close view.

Table 9. Seepage meter data.

Survey Line	Station # (m from shore)	Date (1985)	pH	EC (μS/cm)	Temp. (C°)	Vol. (ml)	Duration (hrs)	Seepage Rates (ml/hr/m^2)
Lake Huron	Position #1 1/km	08-26	7.40	177	19.6	1450	72.07	102.650
		08-27	7.70	185	19.9	55	19.5	14.390
		09-06	7.44	188	28.2	1745	NA	NA
	2/10	08-23	8.29	200	24.0	1205	23.57	260.838
		08-29	NA	NA	NA	95	66.67	7.270
	3/20	08-23	7.31	192	22.5	1240	23.57	268.415
		08-29	NA	NA	NA	110	66.67	8.418
	5/40	08-23	7.17	197	23.8	65	23.57	14.070
		08-29	NA	NA	NA	50	66.67	3.826
	7/60	08-23	7.65	188	21.9	260	23.57	56.281
		08-26	7.36	184	19.5	1190	72.55	83.686
		08-29	NA	NA	NA	45	66.67	3.444
	9/80	08-23	7.10	186	21.5	370	23.57	80.091
		08-26	-	-	-	NR	-	-
		08-29	NA	NA	NA	125	66.67	9.566
	11/100	08-23	7.01	133	21.3	25	23.57	5.412
		08-26	7.87	184	19.6	55	72.55	3.868
		08-29	NA	NA	NA	275	66.67	21.045

NR - no recovery (dry)
NA - not available
EC - Electrical conductivity

Seepage Meter Data

Survey Line	Station # (m from shore)	Date (1985)	pH	EC (μS/cm)	Temp. (C°)	Vol. (ml)	Duration (hrs)	Seepage Rates (ml/hr/m^2)
George Street	1/shore	08-08	-	-	-	NR	-	-
		08-09	-	-	-	NR	-	-
		08-12	6.87	135	22.8	20	69.4	1.469
		08-13	-	-	-	NR	-	-
		08-16	6.90	271	22.7	55	78.38	3.582
		08-20	7.00	241	19.3	40	92.12	2.214
		08-21	-	-	-	NR	-	-
		08-22	-	-	-	NR	-	-
		08-23	7.81	125	22.0	15	24.63	3.107
		09-14	7.35	268	20.7	105	222.07	2.412
	3/20	08-08	-	-	-	NR	-	-
		08-09	6.45	140	26.6	25	27.66	4.612
		08-12	7.40	245	22.0	90	69.4	6.617
		08-13	7.28	162	26.6	20	28.72	3.551
		08-16	7.12	262	21.9	70	78.38	4.556
		08-20	6.99	161	19.3	35	92.12	1.939
		08-21	-	-	-	NR	-	-
		08-22	7.78	285	22.4	95	19.7	24.602
		08-23	7.83	154	22.4	45	24.63	9.321
		08-30	7.28	125	22.0	180	146.25	6.281
		09-05	7.71	322	23.4	90	140.10	3.278
		09-14	7.51	235	19.3	625	222.07	14.360
	5/40	08-08	7.20	225	25.6	262.5	25.92	51.668
		08-09	6.92	210	26.0	55	27.66	10.143
		08-12	7.14	124	22.8	50	69.4	3.679
		08-13	7.04	268	26.4	60	28.72	10.658
		08-16	6.65	265	21.7	120	78.38	7.811
		08-20	7.18	257	19.3	230	92.12	12.740

EC - Electrical conductivity
NR - No recovery (dry)

Survey Line	Station # (m from shore)	Date (1985)	pH	EC (µS/cm)	Temp. (C°)	Vol. (ml)	Duration (hrs)	Seepage Rates (ml/hr/m^2)
George Street (cont'd)	5/40	08-21	-	-	-	-	-	-
		08-22	7.40	289	22.6	65	19.7	16.837
		08-23	7.48	202	22.6	170	24.63	35.214
		08-30	7.45	253	22.4	240	146.25	8.372
		09-05	8.05	328	23.5	205	140.10	7.466
		09-14	7.52	308	20.1	65	222.07	1.493
	7/60	08-08	6.85	206	25.8	315	25.92	62.005
		08-09	6.93	257	25.0	345	27.66	63.638
		08-12	7.12	272	22.2	195	69.4	14.337
		08-13	7.49	322	26.3	75	28.72	13.321
		08-16	7.04	172	21.9	45	78.38	2.929
		08-20	7.05	335	18.9	92.5	92.12	5.123
		08-21	7.60	353	20.1	125	29.13	21.893
		08-22	7.33	386	22.6	245	19.7	63.454
		08-23	7.64	405	23.4	70	24.63	14.500
		08-30	7.23	225	22.1	280	146.25	9.770
		09-05	7.54	449	23.1	1395	140.10	50.802
		09-14	7.70	204	21.3	40	222.07	0.919
	9/80	08-08	7.06	214	28.0	340	25.92	66.924
		08-09	6.94	244	26.5	50	27.66	9.225
		08-12	7.12	281	22.1	140	69.4	10.291
		08-13	7.32	340	26.0	82.5	28.72	14.658
		08-16	7.21	293	21.8	292.5	78.38	19.041
		08-20	7.09	359	19.1	290	92.12	16.061
		08-21	7.34	382	19.8	60	29.13	10.510
		08-22	7.58	432	22.8	80	19.7	20.719
		08-23	7.34	463	23.9	60	24.63	12.429
		08-30	7.23	279	22.3	180	146.25	6.281
		09-05	7.86	495	23.5	430	140.10	15.659
		09-14	7.73	438	20.6	110	222.07	2.527

Survey Line	Station # (m from shore)	Date (1985)	pH	EC (µS/cm)	Temp. (C°)	Vol. (ml)	Duration (hrs)	Seepage Rates (ml/hr/m^2)
George Street (cont'd)	11/100	08-08	6.97	199	25.7	1370	25.92	269.668
		08-09	7.05	212	24.1	295	27.66	54.413
		08-12	7.40	235	22.0	575	69.4	42.270
		08-13	7.10	289	25.4	425	28.72	75.500
		08-16	7.12	286	21.5	210	78.38	13.668
		08-20	6.91	298	19.2	290	92.12	16.061
		08-21	7.29	305	20.2	105	29.13	18.393
		08-22	7.30	176	22.8	40	19.7	10.357
		08-23	7.52	195	24.8	20	24.63	4.143
		08-30	7.49	172	22.4	80	146.25	2.791
		09-05	7.78	426	24.0	130	140.10	4.734
		09-14	8.04	402	19.8	210	222.07	4.825

Seepage Meter Data

Survey Line	Station # (m from shore)	Date (1985)	pH	EC (µS/cm)	Temp. (C°)	Vol. (ml)	Duration (hrs)	Seepage Rates (ml/hr/m^2)
Cromwell Street	1/shore	08-21	7.95	191	19.6	935	30.63	155.743
		08-22	7.02	229	22.1	110	19.72	28.460
		08-23	7.36	273	26.1	220	24.30	46.191
		08-26	7.29	248	19.7	360	75.40	24.360
		08-28	7.15	325	24.5	160	45.17	18.072
	3/20	08-21	7.06	179	19.3	65	30.63	10.827
		08-22	1.17	203	22.6	75	19.72	19.404
		08-23	7.30	208	25.3	30	24.30	6.300
		08-26	7.15	114	19.4	50	75.40	3.383
		08-28	7.87	180	25.4	20	45.17	2.259
	5/40	08-21	7.00	180	19.5	1050	30.63	174.899
		08-22	7.12	235	22.8	170	19.72	43.983
		08-23	8.10	253	24.7	305	24.30	64.038
		08-26	7.23	227	19.5	140	75.40	9.473
		08-28	8.04	276	25.9	90	45.17	10.166
	7/60	08-21	6.88	186	19.7	275	30.63	45.807
		08-22	6.95	230	23.6	30	19.72	7.762
		08-23	8.01	331	25.5	495	24.30	103.930
		08-26	7.66	289	19.7	330	75.40	22.330
		08-28	8.63	242	27.2	25	45.17	2.824
	9/80	08-21	6.93	181	19.8	1955	30.63	325.645
		08-22	7.25	232	22.5	965	19.72	249.669
		08-23	8.22	252	24.3	1620	24.30	340.136
		08-26	7.98	245	19.7	1430	75.40	96.763
		08-28	7.48	323	25.2	430	45.17	48.569
	11/100	08-21	7.36	180	19.4	590	30.63	98.276
		08-22	7.15	211	22.7	730	19.72	188.869
		08-23	7.68	269	25.4	165	24.30	34.644
		08-26	7.82	241	19.6	475	75.40	32.142
		08-28	7.87	314	26.7	165	45.17	18.637

EC - Electrical Conductivity

Seepage Meter Data

Survey Line	Station # (m from shore)	Date (1985)	pH	EC (µS/cm)	Temp. (C°)	Vol. (ml)	Duration (hrs)	Seepage Rates (ml/hr/m^2)
Police Station (S-3)	1/shore	08-13	6.67	130	26.7	42.5	22.75	9.531
		08-15	6.80	211	19.8	200	48.98	20.855
		08-19	6.95	223	19.1	77.5	97.23	4.067
	3/20	08-13	7.02	226	26.5	107.5	22.75	24.109
		08-15	6.81	209	20.3	525	48.93	54.743
		08-19	6.86	228	19.4	330	97.23	17.316
	5/40	08-13	6.51	217	26.3	1330	22.75	298.273
		08-15	6.74	211	20.3	885	48.93	92.281
		08-19	7.02	252	19.3	550	97.23	28.861
	7/60	08-13	7.20	217	25.1	797.5	22.75	178.854
		08-15	6.65	245	20.0	365	48.93	38.059
		08-19	6.98	273	19.1	560	97.23	29.385
	9/80	08-13	6.90	216	26.1	730	22.75	163.714
		08-15	6.91	206	19.4	155	48.93	16.162
		08-19	7.11	240	18.8	220	97.23	11.544
	11/100	08-13	6.87	220	26.0	1145	22.75	256.284
		08-15	6.76	211	19.5	355	48.93	37.017
		08-19	7.16	229	19.5	1150	97.23	60.345

EC - Electrical conductivity

Seepage Meter Data

Survey Line	Station # (m from shore)	Date (1985)	pH	EC (µS/cm)	Temp. (C°)	Vol. (ml)	Duration (hrs)	Seepage Rates (ml/hr/m^2)
Red-D-Mix Imperial	1/shore	08-13	5.94	212	27.7	12.5	20.05	3.181
		08-15	6.81	183	19.2	215	51.93	21.123
		08-20	-	-	-	NR	-	-
		08-21	7.09	104	20.4	20	29.12	3.504
	3/20	08-13	7.36	130	29.0	40	20.05	10.179
		08-15	6.74	241	19.6	135	51.93	13.264
		08-20	6.97	192	19.0	2145	115.92	94.409
		08-21	7.06	182	19.6	1810	29.12	317.126
	5/40	08-13	-	-	-	NR	-	-
		08-15	6.81	203	19.2	120	51.93	11.790
		08-20	-	-	-	NR	-	-
		08-21	6.98	181	19.6	1155	29.12	202.365
	7/60	08-13	6.87	220	27.7	230	20.05	58.527
		08-15	6.70	187	19.5	2545	51.93	250.042
		08-20	6.60	187	19.0	2180	115.92	95.949
		08-21	6.90	179	19.6	2085	29.12	365.308
	9/80	08-13	6.72	222	26.6	260	20.05	66.161
		08-15	6.64	190	19.1	175	51.93	17.194
		08-20	6.65	205	19.1	2655	115.92	116.856
		08-21	7.07	179	19.6	2080	29.12	364.432
	11/100	08-13	6.47	13	28.2	30	20.05	7.634
		08-15	6.84	186	19.3	2220	51.93	218.112
		08-20	6.47	186	19.1	2475	115.92	108.933
		08-21	7.04	180	19.5	1620	29.12	283.836

NR - no recovery (dry)
EC - Electrical conductivity

Seepage Meter Data

Survey Line	Station # (m from shore)	Date (1985)	pH	EC (µS/cm)	Temp. (C°)	Vol. (ml)	Duration (hrs)	Seepage Rates (ml/hr/m^2)
Suncor Dock	3/20	08-08	6.84	395	26.8	330	30.58	55.058
		08-09	6.80	383	26.8	75	27.70	13.814
		08-12	7.15	213	24.9	45	69.5	3.304
		08-13	-	-	-	NR	-	-
		08-14	7.08	343	24.0	135	30.05	22.921
		08-16	7.00	344	21.3	742.5	43.35	87.388
	5/40	08-08	7.02	193	31.0	25	30.58	4.171
		08-09	-	-	-	NR	-	-
		08-12	7.10	363	22.9	1190	69.5	87.359
		08-13	6.26	22	29.2	20	23.53	4.337
		08-14	-	-	-	NR	-	-
		08-16	6.82	322	21.9	1240	43.35	145.941
	7/60	08-08	6.70	311	31.2	57.5	30.58	9.593
		08-09	7.23	274	26.2	1055	27.70	194.320
		08-12	7.53	263	23.7	1235	69.5	90.662
		08-13	6.07	11	29.2	30	23.53	6.505
		08-14	6.88	270	23.9	2345	30.05	398.146
		08-16	6.70	146	22.8	42.5	43.35	5.002
	9/80	08-13	6.89	250	29.3	2522	23.53	546.849
		08-14	7.01	215	23.8	2312.5	30.05	392.628
	11/100	08-12	7.64	213	23.7	2400	69.5	176.186
		08-13	6.53	231	28.0	2605	23.53	564.846
		08-14	6.90	209	23.9	2375	30.05	403.240

EC - Electrical conductivity
NR - No recovery (dry)

Seepage Meter Data

Survey Line	Station # (m from shore)	Date (1985)	pH	EC (µS/cm)	Temp. (C°)	Vol. (ml)	Duration (hrs)	Seepage Rates (ml/hr/m^2)
Concrete Dock	2/10	08-20	6.94	317	18.0	180	96.17	9.55
		08-21	7.37	335	20.8	50	20.42	2.65
		08-22	-	-	-	-	22.55	-
		08-23	7.59	427	21.4	70	24.85	14.37
		08-26	7.68	459	20.0	385	75.35	4.74
		08-28	8.01	580	25.9	250	45.12	28.27
	3/10	08-20	6.64	301	17.5	160	96.17	8.49
		08-21	7.02	191	21.5	20	20.42	1.06
		08-22	-	-	-	-	22.55	-
		08-23	7.20	193	21.8	20	24.85	20.95
		08-26	7.46	356	19.9	65	75.35	1.35
		08-28	8.20	440	27.1	315	45.12	35.62
	4/30	08-20	7.03	273	18.1	380	96.17	20.16
		08-21	6.85	145	22.8	30	20.42	1.59
		08-22	7.93	118	20.4	15	22.55	3.39
		08-23	7.27	325	22.3	365	24.85	74.94
		08-26	7.95	305	20.3	1595	75.35	24.69
		08-28	7.68	355	25.1	1300	45.12	147.01
	5/40	08-20	6.54	220	18.6	1915	96.17	101.597
		08-21	6.82	143	22.7	35	20.42	1.857
		08-22	7.17	221	20.3	1665	22.55	376.71
		08-23	7.39	228	21.8	1535	24.85	315.15
		08-26	7.40	218	20.4	1210	75.35	103.94
		08-28	8.40	245	24.2	1660	45.12	187.72

EC - Electrical conductivity
NR - No recovery (dry)

Survey Line	Station # (m from shore)	Date (1985)	pH	EC (μS/cm)	Temp. (C°)	Vol. (ml)	Duration (hrs)	Seepage Rates (ml/hr/m^2)
Concrete Dock	6/50	08-20	6.28	128	18.5	2195	96.17	116.45
		08-21	6.88	241	21.8	1185	20.42	62.87
		08-22	7.18	227	20.9	2050	22.55	463.82
		08-23	8.14	217	22.3	2040	24.85	418.84
		08-26	7.54	210	20.0	385	75.35	138.13
		08-28	8.44	240	24.8	1830	45.12	206.95
	7/60	08-20	6.86	217	18.6	1850	96.17	98.15
		08-21	7.01	236	21.9	1535	20.42	81.43
		08-22	7.16	237	21.5	2050	22.55	463.82
		08-23	7.30	215	22.8	1480	24.85	303.86
		08-26	7.51	199	20.0	1215	75.35	100.21
		08-28	8.33	226	25.0	1945	45.12	219.95

Seepage Meter Data

Survey Line	Station # (m from shore)	Date (1985)	pH	EC (µS/cm)	Temp. (C°)	Vol. (ml)	Duration (hrs)	Seepage Rates (ml/hr/m^2)
Power Line	1/shore	07-16	6.99	269	22.5	230	94.03	12.480
		07-17	8.04	304	23.0	75	27.45	13.939
		07-19	7.47	266	22.0	62.5	22.12	14.418
	RW	07-19	7.90	211	20.0	-	-	-
	2/10	07-16	7.65	334	21.0	1210	94.03	65.653
		07-17	7.89	399	21.5	65	27.45	12.082
		07-19	-	-	-	NR	-	-
	RW	07-19	8.33	200	20.5	-	-	-
	3/20	07-16	7.48	138	27.0	1012	94.03	54.913
		07-17	7.64	315	21.0	1075	27.12	202.240
		07-19	7.84	334	21.5	600	22.12	138.393
	RW	07-19	8.46	194	20.5	-	-	-
	4/30	07-16	7.79	240	21.0	1985	94.03	107.709
		07-17	7.75	258	22.0	2010	27.12	378.138
		07-19	8.02	254	21.0	1930	22.12	445.158
	RW	07-19	8.48	230	20.5	-	-	-
	5/40	07-16	7.66	209	20.5	2170	94.03	117.745
		07-17	7.82	230	21.0	1670	27.12	314.174
		07-19	7.92	199	21.0	1105	22.12	254.873
	RW	07-19	7.96	176	20.5	-	-	-
	6/50	07-19	8.16	198	21.0	1655	22.68	372.306
	7/60	07-19	8.02	143	21.0	1525	23.0	338.286

EC - Electrical conductivity
NR - No recovery (dry)
RW - River Water

Survey Line	Station # (m from shore)	Date (1985)	pH	EC (μS/cm)	Temp. (C°)	Vol. (ml)	Duration (hrs)	Seepage Rates (ml/hr/m^2)
Power Line (cont'd)	8/70	07-19	8.45	186	21.0	2270	23.0	503.551
	9/80	07-19	8.55	187	22.0	2340	23.0	519.077
	10/90	07-19	8.66	187	21.0	2380	23.0	527.949
	11/100	07-19	8.63	188	21.5	2195	23.0	486.912
	RW	07-19	8.35	188	21.5	-	-	-

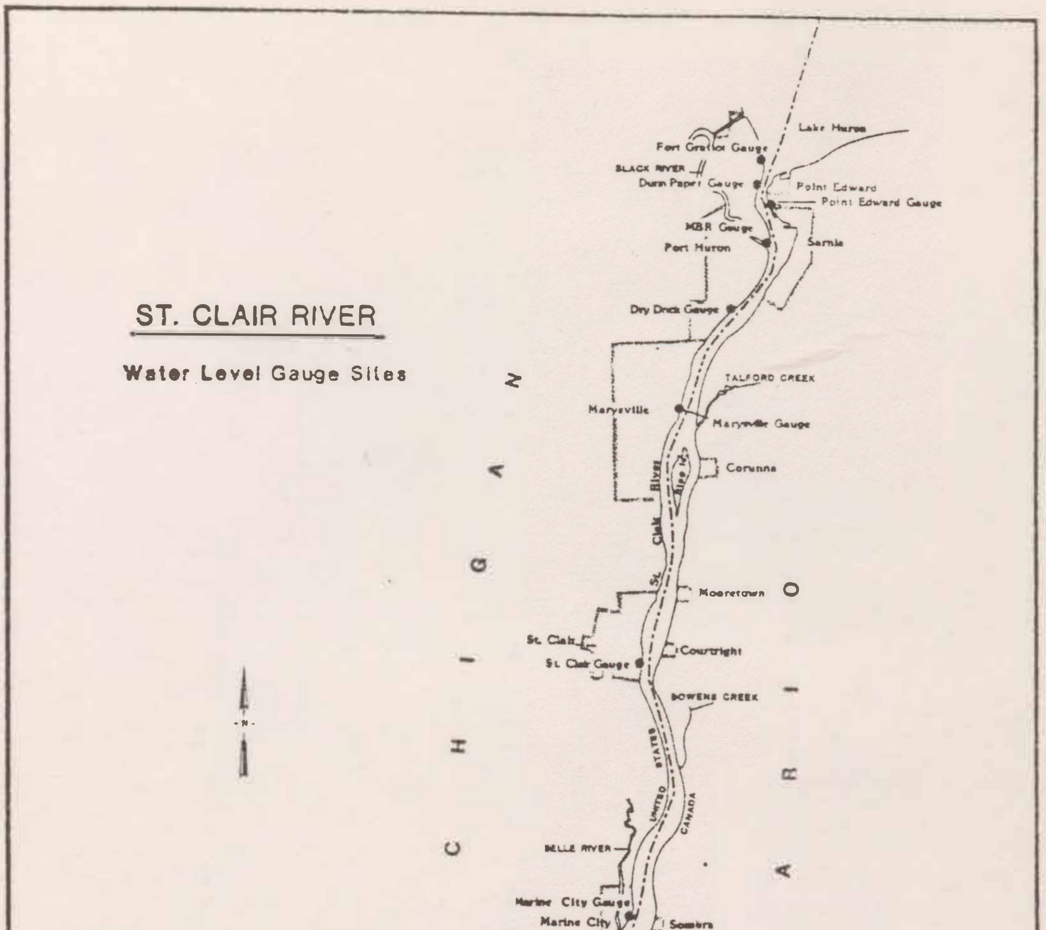

Figure 46. St. Clair River water level gauge stations (after NOAA, 1985).

APPENDIX 5

MINIPIEZOMETERS

Minipiezometer Sampling Procedures

Photographs of Minipiezometers

Minipiezometer Data

APPENDIX 5

MINIPIEZOMETERS

MINIPIEZOMETER SAMPLING PROCEDURES

Prior to and during installation, the minipiezometers were washed by pumping distilled water through the teflon tube. This pre-pumping also aided in keeping the screen clean during installation. Upon installation and prior to sample collection, water was drawn through the teflon tube from the minipiezometer by a Masterflex Model 7570 peristaltic pump. Water was drawn for a minimum of 10 minutes and until the electrical conductivity stabilized before samples were collected and the pH, EC and temperature were recorded. Waiting for the stabilization of the EC was necessary to ensure that adequate purging of the pre-pumped distilled water had taken place before sample collection.

The temperature measurements were not considered representative of the bottom-sediment environment since the extracted water had to pass through at least 10 m of teflon tubing before reaching the surface for collection. The pH was measured in a closed flow cell to prevent exposure of the water to the air.

During sample collection three samples of water were collected at each location: a 1L amber bottle (no head space) with metal lined cap was used to collect water for TOX and GC/MS analysis, a 40 mL amber glass vial (no head space) with a teflon coated septum lined cap was used to collect water for chlorinated hydrocarbons and volatiles, and a 250 mL nalgene plastic bottle (no head space) was used to collect water for isotopic analysis. For the samples for volatile analyses, the pump was stopped prior to sampling and the minipiezometer was allowed to recover in order to reduce the formation of gas bubbles in the teflon tubing and to minimize the potential for loss of volatiles.

Once the streambed groundwater samples at depths of 1.5 m and 1.0 m were collected, the teflon tube was disconnected from the minipiezometer and river water was pumped until a constant EC was attained, at which time samples of river bottom river water were collected. Temperature, pH and electrical conductivity were measured on river water and streambed groundwater samples at the time of collection. Selected samples of river water and streambed groundwater were analyzed for: chlorinated hydrocarbons, polychlorinated biphenyls, trihalomethanes, EPA Priority Pollutants (extractables), total organic halides, chloride, and natural isotopes (oxygen-18, tritium and deuterium).

After collection, the samples were stored on the boat in a cooler with cold packs until they could be refrigerated on shore. They were sent by courier as soon as possible to Zenon Environmental Inc., of Burlington, Ontario for organic analysis. Samples for isotopic analysis were sent to the Isotope Laboratory, Department of Earth Sciences, University of Waterloo, Waterloo, Ontario.

Figure 47. Drive head on minipiezometer.

Figure 48. Drive head on casing.

Table 10. Minipiezometer data.

Survey Line	Station # (m from shore)	Time of Sample	Depth of Piezometer (m)	pH	EC (µS/cm)	Temp. (C°)	Sample #	Remarks/ Appearance
George St. 08-30-85	11*/100	11:00 am	1.5	7.03	532	18.6		- Clear
			1.0	6.80	585	19.9		- Silty
			1.0	7.61	508	18.0		- Slightly yellow
			0.5	7.00	367	19.6		- Silty
			RW	7.79	183	19.3		- Slightly silty
			RW	8.26	172	19.2		- Clear
			RW	8.33	172	19.3		- Clear
			RW	8.25	173	19.0		- Clear
	11/100	3:45 pm	1.5	7.85	259	18.9	(1345)	
			1.5	7.36	373	18.8	(1346)	
			1.5	6.96	449	18.9	(1347)	
		4:30 pm	RW	NA	NA	NA	(1348,1349, 1350)	
George St. 09-03-85	6/50	pm	1.0	7.20	1075	26.6	(1351,1352, 1353)	- Groundwater had strong odor
			RW	7.90	185	21.4	(1354)	
George St. 09-04-85	5/40	am	1.5	7.20	898	20.9	(1355,1356, 1357)	- Clear with slight odor
			RW	7.42	204	22.7	(1358)	- Many gas bubbles
			1.0	7.25	801	22.3	(1359, 1360, 1361)	- Cloudy
George St. 09-05-85	5/40	am	1.0	7.55	824	24.8	(1363,1364, 1365)	
			RW	7.72	182	20.9	(1373)	

* Preliminary samples taken to test equipment
RW - River water
NA - Data not available
EC - Electrical conductivity

Survey Line	Station # (m from shore)	Time of Sample	Depth of Piezometer (m)	pH	EC (µS/cm)	Temp. (C°)	Sample #	Remarks/ Appearance
George St. 09-05-85	7/60	am	1.5	7.11	1012	22.7	(1367,1368, 1369)	
			RW	7.61	181	21.6	(1366)	
		am	1.0	7.18	935	20.5	(1370,1371, 1372)	
George St. 09-14-85	5/40	am	1.0	6.99	650	19.8	(1394,1395, 1396,1397, 1398,1399)	
			RW	7.80	171	18.7	(1400,1401, 1402,1403, 1404,1405)	
Cromwell St. 09-05-85	6/50	pm	1.5	6.76	1130	26.0	(1374,1375, 1376)	- rusty oily and hydrogen-sulfide odor
			RW	7.13	179	18.8	(1377)	
			1.0	6.73	1290	23.5	(1379,1380, 1381,1382, 1383,1384)	
			RW	-	-	-	(1378)	- gas
Cromwell St. 09-06-85	6/50	pm	1.0	6.70	1627	31.4	(1385,1386, 1387,1388, 1388,1390)	
			RW	7.30	233	26.9	(1391,1392, 1393)	

Survey Line	Station # (m from shore)	Time of Sample	Depth of Piezometer (m)	pH	EC (µS/cm)	Temp. (C°)	Sample #	Remarks/ Appearance
Cromwell St.	6/50	10:11 am	1.5	6.80	1005	18.9	(1406,1407, 1408)	- Scum floating on top of water
09-15-85		10:50 am	RW	7.00	303	20.0	(1409,1410, 1411)	
Lab Samples		11:45 am	1.0	6.83	860	26.2	(1412,1413, 1414)	- Strong odor
		1:45 pm	1.0	6.78	1173	19.9	(1415,1416, 1417)	- Hydrogen sulfide
	11/100	3:15 pm	1.5*	6.80	814	18.8	(1424,1425, 1426)	
		3:00 pm	1.0	6.71	1002	19.1	(1427,1428, 1429)	
		3:15 pm	RW	7.81	165	18.8	(1430,1431, 1432)	

*Flowing

Note: Sample 1418-1423 - blanks -(organic free water)

APPENDIX 6

ENVIRONMENTAL ISOTOPES

Distribution in the Hydrologic Cycle

Analytical Techniques

Environmental Isotope Results

APPENDIX 6

ENVIRONMENTAL ISOTOPES

DISTRIBUTION IN THE HYDROLOGIC CYCLE

The stable isotopes ^{18}O and D in water, are normally measured with reference to the commonly accepted international standard SMOW (Standard Mean Ocean Water). The isotopic ratios (ratios of heavy to light isotopes) are expressed in delta units (δ) as per mil differences (parts per thousand or ‰), relative to SMOW (Craig, 1961a):

$$\delta^{18}O \text{ or } \delta D = [(R_x - R_{\text{standard}}) / R_{\text{standard}}] \times 1000 \ (‰)$$

where: R_x and R_{standard} are isotope ratios of $^2H/^1H$ or $^{18}O/^{16}O$ of the sample and the standard, respectively. Analytical precisions for ^{18}O and D analyses by mass spectrometry are better than 0.2‰ and 2.0‰, respectively.

$\delta^{18}O$ and δD values are expressed as either negative (depleted) values or positive (enriched) values relative to SMOW. For example: a sample with a $^{18}O=+10‰$ is enriched in ^{18}O by 10‰ relative to SMOW, and a value of $\delta^{18}O=-5‰$ signifies that the sample has 5‰ less than the standard and is therefore depleted (Fritz and Fontes, 1980). When water evaporates from the oceans, the water vapour produced is depleted in ^{18}O and D relative to ocean water, by about 12-15‰ in ^{18}O and 80-120‰ in D (Fritz and Fontes, 1980). When water vapour condenses, the rain or snow that forms has higher ^{18}O and D concentrations than the remaining water vapour.

The various isotopic forms of water have slightly different vapour pressures and freezing points. These two properties give rise to differences in ^{18}O and D concentrations in the water in the various parts of the hydrologic cycle (Fritz and Fontes, 1980). The process by which these differences occur is known as "isotope fractionation" which results from: evaporation, condensation, freezing, melting, chemical reactions, or biological processes (Fritz and Fontes, 1980).

Craig (1961b) found that the concentrations of ^{18}O and D in unevaporated meteoric waters (waters that were recently involved in atmospheric circulation) are linearly related according to:

$$\delta D = 8\delta^{18}O + 10$$

Waters which have been evaporated plot below the meteoric water line on straight lines with slopes of between 2 and 5 (Fontes, 1980).

Stable isotope concentrations in waters are basically controlled by the number of condensation stages resulting in precipitations and by ambient conditions of any subsequent evaporation (Fontes, 1980). The fractionation of these stable isotopes are different during evaporation and condensation. When water evaporates from soil or surface-water bodies under natural conditions, it becomes enriched in ^{18}O and D. The relative degree of enrichment is different from the enrichment that occurs during condensation. The ratio of $^{18}O/D$ for precipitation that has partially evaporated is greater than the ratio for normal precipitation (Fritz and Fontes, 1980). It is the variation in this ratio that causes a departure of ^{18}O and D concentrations from the meteoric water line.

For a given atmospheric vapour, the more pronounced the cooling process, the more depleted in ^{18}O and D is the vapour phase. Multi-stage cooling gives a condensed phase (liquid or solid) progressively depleted in heavy isotopes. The evaporation process tends to increase the heavy isotope content of the remaining liquid phase. This enrichment is inversely correlated with relative humidity, i.e. with the density of water vapour molecules depleted in heavy isotopes whose condensation at the liquid surface counteracts the enrichment due to evaporation. Evaporated water can be distinguished by the fact that it contains relatively more ^{18}O than prescribed by the meteoric water line, thus plotting below this line (Fontes, 1980). Unevaporated meteoric water is depleted in heavy isotopes relative to SMOW (δ values are negative). Thus, it is possible to determine whether groundwater has undergone appreciable open-surface evaporation prior to infiltration. It appears that waters falling close to the meteoric water line indicate that they are isotopically unaltered meteoric waters.

Tritium is a radiogenic isotope of hydrogen whose half-life is approximately 12.35 years. Natural tritium is produced in the upper atmosphere by cosmic neutron bombardment of nitrogen-14 resulting in steady-state concentrations of less than about 20 TU in precipitation (Fontes, 1980). Since 1952, the natural background has been loaded by enormous amounts of man-made tritium which were injected into the stratosphere during thermonuclear tests and have since been the dominant source of tritium in precipitation.

Tritium behaves similar to D in its fractionation patterns. Because of the relative mass difference between D and common hydrogen, this fractionation is large. However, variations due to isotopic fractionation are still of minor importance if compared to the fluctuations related to meteorological factors (Fontes, 1980).

Tritium contents are determined as concentrations and not as per mil or percent variations from a standard. A tritium unit (1 TU) corresponds to a concentration of one atom of T in 10^{18} atoms of ^{1}H.

ANALYTICAL TECHNIQUES

The isotopic analyses were performed under contract by the Isotope Laboratory, Department of Earth Sciences, University of Waterloo. Oxygen-18, D, and T were analyzed by standard methods used in isotopic analyses of water. A Micromass Model 903 mass spectrometer was used for ^{18}O analysis, a modified Micromass 602 mass spectrometer was used for D analysis, and Intertechnique or Beckman Model 7500 scintillation counters were used for T analysis. Analytical precisions for ^{18}O and D analyses by mass spectrometry are better than +0.2 and +2.0%, respectively.

One in every 15 samples sent for analysis was split in order to evaluate the isotopic results. Internally, the University of Waterloo has a quality assurance program which includes a lab standard SWAT (Standard Waterloo Tap Water). This lab standard is run for each five ^{18}O samples, each six D samples, and each ten T samples. SWAT has been related to three international standards: SMOW (Standard Mean Ocean Water), SLAP (Standard Light Arctic Precipitation), and GISP (Greenland Ice Sheet Precipitation). For each sample analysis, the results are an average of at least 5 sample-standard comparisons for ^{18}O and D and 500 to 660 minutes of T counting. Since there are no international standards for T, sample analyses are periodically compared with results from the Alberta Research Council and the Weizmann Institute in Israel.

Table 11. Sample conversion numbers.

Field Sample Number for O-18 and T *		Report Sample Number**
1346	George Street	1
1353		3
1357		4
1361		5
1365		6
1369		7
1372		8
1396		9
1399		10
1408	Cromwell Street	21
1376		14
1381		16
1384		17
1387		18
1414		23
1426		25
1429		26
1349	George Street	2
1358		11
1402		12
1405		13
1377	Cromwell Street	15
1391		20
1411		22
1432		27
1A	Suncor Wells	28
2A		29
4A		30
5A		31
6A		32
NA	Chenal Ecarte	33
NA		34
NA		35
NA		36

* from Table 10

** from Table 12

Table 12. Isotope results.

Sample No.	Location	Station	Depth	O-18 (‰)	T (TU)	D(‰)
1	George Street	11	1.5m	-7.75	21+7	
3		6	1.0	-7.54	45+8	
4		5	1.5	-7.91	29+7	-59.9
5		5	1.0	-7.64	75+8	-56.0
6		5	1.0	-7.92	64+8	
7		7	1.5	-7.31	44+8	
8		7	1.0	-7.42	41+8	
9		5	1.0	-8.01	63+8	
10		5	1.0	-7.90	70+8	
21	Cromwell Street	6	1.5	-7.51	15+7	-59.2
14		6	1.5	-7.34	6+7	
16		6	1.0	-7.34	42+8	
17		6	1.0	-6.79	39+8	
18		6	1.0	-7.49	33+8	-59.6
23		6	1.0	-7.43	33+8	
25		11	1.5	-7.26	24+8	
26		11	1.0	-7.32	87+8	
2	George Street	11	rw	-7.34	76+8	
11		5	rw	-7.34	109+8	-58.7
12		5	rw	-7.17	122+8	
13		5	rw	-7.20	74+8	
15	Cromwell Street	6	rw	-7.23	78+8	
20		6	rw	-7.29	88+8	-58.6
22		6	rw	-7.14	87+8	
27		11	rw	-7.25	79+8	
28	Suncor Well No.	1A	6.1m	-8.61	6+9	-59.1
29		2A	6.1	-9.50	29+6	-68.3
30		4A	6.1	-9.50	20+7	
31		5A	9.9	-9.58	9+6	-65.1
32		6A	NA	-9.68	6+6	
33	Chenal Ecarte		rw	-7.4	109+9	
34	(near Walpole Island)		rw	-7.20	98+9	
35			rw	-7.19	100+9	
36			rw	-7.15	124+9	

rw river water
NA not available

Table 13.

Oxygen-18, Tritium, and EC Results for the Freshwater Aquifer Samples from the MOE and Esso Wells

WELL NAME	$\delta^{18}O$ (‰)	T (TU)	EC * (uS/cm)
Esso AQ2	-16.3	<6	1672
Esso AQ3	-15.4	<6	1507
Esso AQ6	-15.0	<6	1213
Esso AQ8	-15.4	<6	1233
MOE 1 (Esso)	-14.9	<6	2494
MOE 3 (Dow)	-15.0	<6	2192
MOE 4 (Moore 1)	-13.9	<6	4648
MOE 6 (CIL 1)	-16.1	<6	5355

* data supplied by MOE office in Sarnia

APPENDIX 7

LABORATORY ANALYSES

Laboratory Results

Table 14. Chloride results (mg/L).*

	CHLORIDE
1345	14.5
1348	-
1351	23.4
1355	111
1359	81
1363	95
1367	14.6
1374	11.3
1379	9.4
1382	9.2
1385	9.2
1388	10.3
1392	5.4
1394	82
1397	93
1400	5.5
1403	5.2
1406	10.1
1409	5.2
1412	9.6/9.9
1415	9.0
1424	9.2
1427	7.8
1430	5.4
1619	7.0

- indicates broken sample

* analyses conducted by Zenon Environmental Inc., Burlington, Ontario.

Table 15. TOX results.*

SAMPLE I.D.						TOX CONCENTRATION (ug/l)
83085		George St.	11	1.5 m	1345	10.0
83085	4115	George St.	11	RB	1348	18.3
9385		George St.	6		1351	7.1
9485	1124	George St.	5		1355	16.0, 11.5
9485		George St.	5	1 m	1359	<1, <1
9585	1000	George St.	5	1 m	1363	5.7
9585	1002	George St.	7	1.5 m	1367	6.4
9585	1254	George St.	7	1 m	1370	9.2
9685	1530	Cromwell	6	1 m	1388	4.2
9685	1534	Cromwell	6	1 m	1385	7.5
9685	1559	Cromwell	6	RB	1392	3.4
95	1823	Cromwell	6	1 m	1382	2.3
95	1809	Cromwell	6	1 m	1379	5.7
95	1718	Cromwell	6	1.5 m	1374	4.7
91585		Blank			1421	3.0
915	1515	Cromwell	11	1 m	1424	5.7
915		Cromwell	6	1.5 m	1406	<1
915	1225	George St.	5	RB	1403	<1
		Cromwell	6	1 m	1412	7.3
91585		Blank ZENON			1418	11.5, 8.4
915	1700	Cromwell	11	1 m	1427	<1
914	1219	George St.	5	RB	1400	10.4
914	1156	George St.	5	1 m	1397	<1
		RB			1430	<1
914	1135	George St.	5	1 m	1394	5.8
91585	1345	Cromwell	6	1 m	1415	<1
915		Cromwell	6	RB	1409	3.1
		River Water			1619	2.0
928		80' hole		20 m	1625	2.3

* analyses conducted by Zenon Environmental Inc., Burlington, Ontario.

Table 16. Chlorinated hydrocarbon and PCB results (ug/L).*

	1345	1348	1351	1355	1367	1370
HEXACHLOROBENZENE	0.0000	0.0012	0.0003	0.0003	0.0004	0.0011
a-BENZENEHEXACHLORIDE	0.0002	0.0022	0.0006	0.0000	0.0002	0.0005
g-BENZENEHEXACHLORIDE	0.0005	0.0007	0.0015	0.0000	0.0006	0.0017
HEPTACHLOR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ALDRIN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
OXYCHLORDANE	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
HEPTACHLOR EPOXIDE	0.0000	0.0000	0.0000	0.0009	0.0000	0.0000
a-CHLORDANE	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
g-CHLORDANE	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
a-ENDOSULFAN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
p,p'-DDE	0.0004	0.0014	0.0000	0.0000	0.0000	0.0000
DIELDRIN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ENDRIN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
p,p'-DDD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
o,p'-DDT	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
p,p'-DDT	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PHOTOMIREX	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
MIREX	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
METHOXYCHLOR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOTAL PCB	0.000	0.000	0.019	0.026	0.000	*int

	1385	1388	1412	1421	1424
HEXACHLOROBENZENE	0.0010	0.0012	0.0027	0.0003	0.0014
a-BENZENEHEXACHLORIDE	0.0000	0.0003	0.0013	0.0002	0.0006
g-BENZENEHEXACHLORIDE	0.0019	0.0012	0.0013	0.0004	0.0000
HEPTACHLOR	0.0000	0.0000	0.0000	0.0000	0.0000
ALDRIN	0.0000	0.0000	0.0000	0.0000	0.0000
OXYCHLORDANE	0.0000	0.0000	0.0000	0.0000	0.0000
HEPTACHLOR EPOXIDE	0.0000	0.0000	0.0006	0.0000	0.0000
a-CHLORDANE	0.0000	0.0003	0.0000	0.0000	0.0000
g-CHLORDANE	0.0000	0.0003	0.0000	0.0000	0.0000
a-ENDOSULFAN	0.0000	0.0000	0.0000	0.0000	0.0000
p,p'-DDE	0.0000	0.0003	0.0000	0.0000	0.0000
DIELDRIN	0.0000	0.0000	0.0000	0.0000	0.0000
ENDRIN	0.0000	0.0000	0.0017	0.0000	0.0000
p,p'-DDD	0.0000	0.0000	0.0000	0.0000	0.0000
o,p'-DDT	0.0000	0.0000	0.0000	0.0000	0.0000
p,p'-DDT	0.0000	0.0000	0.0000	0.0000	0.0000
PHOTOMIREX	0.0000	0.0000	0.0000	0.0000	0.0000
MIREX	0.0000	0.0000	0.0000	0.0000	0.0000
METHOXYCHLOR	0.0000	0.0000	0.0000	0.0000	0.0000
TOTAL PCB	0.015	0.000	*int	0.000	*int

*int indicates interference

* analyses conducted by Zenon Environmental Inc., Burlington, Ontario.

Table 17. Trihalomethane and Acid Extractable results (ug/L).*

	1347	1352	1356	1368	1371
CHLOROFORM	1.89	2.77	1.09	0.62	0.56
CARBON TETRACHLORIDE	0.78	1.76	0.91	0.30	0.30
TRICHLOROETHYLENE + BROMODICHLOROMETHANE	1.57	ND@0.01	1.76	0.15	0.16
DIBROMOCHLOROMETHANE	0.15	0.23	0.62	ND@0.01	ND@0.01
TETRACHLOROETHYLENE	0.16	0.98	1.18	0.09	0.09
BROMOFORM	ND@0.01	ND@0.01	ND@0.01	ND@0.01	ND@0.01

	1386	1389	1413	1419	1425
CHLOROFORM	0.85	0.67	0.61	1.18	0.47
CARBON TETRACHLORIDE	0.40	0.34	0.39	0.40	0.29
TRICHLOROETHYLENE + BROMODICHLOROMETHANE	ND@0.01	0.43	0.14	0.41	0.15
DIBROMOCHLOROMETHANE	ND@0.01	ND@0.01	ND@0.01	0.04	ND@0.01
TETRACHLOROETHYLENE	0.16	0.13	0.24	0.17	0.08
BROMOFORM	ND@0.01	ND@0.01	ND@0.01	ND@0.01	ND@0.01

ACID EXTRACTABLES	DETECTION LIMIT	1348	1355	1370	1412	1424
4-Chloro-3-methylphenol	1	ND	ND	ND	ND	ND
2-Chlorophenol	1	ND	ND	ND	ND	ND
2,4-Dichlorophenol	1	ND	ND	ND	ND	ND
2,4-Dimethylphenol	1	ND	ND	ND	ND	ND
2,4-Dinitrophenol	5	ND	ND	ND	ND	ND
2-Methyl-4,6-dinitrophenol	5	ND	ND	ND	ND	ND
2-Nitrophenol	1	ND	ND	ND	ND	ND
4-Nitrophenol	5	ND	ND	ND	ND	ND
Pentachlorophenol	1	ND	ND	ND	ND	ND
Phenol	1	ND	ND	ND	ND	ND
2,4,6-Trichlorophenol	1	ND	ND	ND	ND	ND

* analyses conducted by Zenon Environmental Inc., Burlington, Ontario.

Table 18. Base/Neutral Extractable results (ug/L).*

BASE NEUTRALS	DETECTION LIMIT	1348	1355	1370	1412	1424
Acenaphthene	0.1	ND	ND	ND	ND	ND
Acenaphthylene	0.1	ND	ND	ND	ND	ND
Anthracene	0.1	ND	ND	ND	ND	ND
Aldrin	0.1	ND	ND	ND	ND	ND
Benzidine	0.1	ND	ND	ND	ND	ND
Benzo(a)anthracene	0.1	ND	ND	ND	0.4	0.2
Benzo(b)fluoranthene	0.1	ND	ND	ND	0.6	0.7
Benzo(k)fluoranthene	0.1	ND	ND	ND	ND	ND
Benzo(a)pyrene	0.1	ND	ND	ND	0.4	0.3
Benzo(ghi)perylene	0.1	0.8	0.8	ND	2.4	1.3
Benzylbutylphthalate	1	ND	ND	ND	ND	ND
a-BHC	0.1	ND	ND	ND	ND	ND
b-BHC	0.1	ND	ND	ND	ND	ND
c-BHC	0.1	ND	ND	ND	ND	ND
Bis(2-chloroethyl)ether	0.1	ND	ND	ND	ND	ND
Bis(2-chloroethyloxy)methane	0.1	ND	ND	ND	ND	ND
Bis(2-ethylhexyl)phthalate	1	ND	ND	ND	ND	ND
Bis(2-chloroisopropyl)ether	1	ND	ND	ND	ND	ND
4-Bromodiphenylether	0.1	ND	ND	ND	ND	ND
Chlordane	0.1	ND	ND	ND	ND	ND
2-Chloronaphthalene	0.1	ND	ND	ND	ND	ND
4-Chlorodiphenylether	0.1	ND	ND	ND	ND	ND
Chrysene	0.1	ND	ND	ND	ND	ND
4,4'-DDD	0.1	ND	ND	ND	ND	ND
4,4'-DDE	0.1	ND	ND	ND	ND	ND
4,4'-DDT	0.1	ND	ND	ND	ND	ND
Dibenzo(a,h)anthracene	0.1	0.1	ND	ND	0.4	0.2
Di-n-butylphthalate	1	ND	ND	ND	ND	ND
Di-n-octylphthalate	1	ND	ND	ND	ND	ND
1,2-Dichlorobenzene	1	ND	ND	ND	ND	ND
1,3-Dichlorobenzene	1	ND	ND	ND	ND	ND
1,4-Dichlorobenzene	1	ND	ND	ND	ND	ND
3,3'-Dichlorobenzidine	1	ND	ND	ND	ND	ND
Dieldrin	1	ND	ND	ND	ND	ND
Diethylphthalate	1	ND	ND	ND	ND	ND
Dimethylphthalate	1	ND	ND	ND	ND	ND
2,4-Dinitrotoluene	0.1	ND	ND	ND	ND	ND

* analyses conducted by Zenon Environmental Inc., Burlington, Ontario.

BASE NEUTRALS (CONT.)	DETECTION LIMIT	1348	1355	1370	1412	1424
2,6-Dinitrotoluene	0.1	ND	ND	ND	ND	ND
Endosulfan I	0.1	ND	ND	ND	ND	ND
Endosulfan II	0.1	ND	ND	ND	ND	ND
Endosulfan Sulfate	1	ND	ND	ND	ND	ND
Endrin	0.1	ND	ND	ND	ND	ND
Endrin Aldehyde	0.1	ND	ND	ND	ND	ND
Fluoranthene	0.1	ND	ND	ND	ND	ND
Fluorene	0.1	ND	ND	ND	ND	ND
Heptachlor	0.1	ND	ND	ND	ND	ND
Heptachlorepoxide	0.1	ND	ND	ND	ND	ND
Hexachlorobenzene	0.1	ND	ND	ND	ND	ND
Hexachlorobutadiene	0.1	ND	ND	ND	ND	ND
Hexachlorocyclopentadiene	0.1	ND	ND	ND	ND	ND
Hexachloroethane	0.05	ND	ND	ND	ND	ND
Indeno(1,2,3-cd)pyrene	0.1	0.2	ND	0.1	2.4	1.3
Isophorone	0.1	ND	ND	ND	ND	ND
Naphthalene	0.1	ND	ND	ND	ND	ND
Nitrobenzene	0.1	ND	ND	ND	ND	ND
N-Nitrosodi-n-propylamine	0.1	ND	ND	ND	ND	ND
N-Nitrosodimethylamine	0.1	ND	ND	ND	ND	ND
N-Nitrosodiphenylamine	0.1	ND	ND	ND	ND	ND
PCB-1016	2	ND	ND	ND	ND	ND
PCB-1221	2	ND	ND	ND	ND	ND
PCB-1232	2	ND	ND	ND	ND	ND
PCB-1242	2	ND	ND	ND	ND	ND
PCB-1248	2	ND	ND	ND	ND	ND
PCB-1254	2	ND	ND	ND	ND	ND
PCB-1260	2	ND	ND	ND	ND	ND
Phenanthrene	0.1	ND	ND	ND	ND	ND
Pyrene	0.1	ND	ND	ND	ND	ND
Toxaphene	1	ND	ND	ND	ND	ND
2,3,7,8-TCDD	0.01	ND	ND	ND	ND	ND
1,2,4-Trichlorobenzene	0.1	ND	ND	ND	ND	ND
d-10 ANTHRACENE % REC.		39	10	70	44	37

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