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CONTAMINANTS IN URBAN RUNOFF IN THE UPPER GREAT LAKES CONNECTING CHANNELS AREA

by

J. Marsalek and H.Y.F. Ng

National Water Research Institute
River Research Branch
Canada Centre for Inland Waters
Burlington, Ontario, L7R 4A6

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ABSTRACT

Concentrations and annual loadings of 18 contaminants in urban runoff have been studied in the Upper Great Lakes Connecting Channels area. Towards this end, runoff samples have been collected at 15 sites in Sarnia, Sault Ste. Marie and Windsor, and analyzed for selected nutrients, metals and industrial chemicals. The annual loadings were then produced from the mean observed concentrations and simulated runoff volumes for all 18 parameters. The estimated runoff loading magnitudes for individual cities can be ranked, in the descending order, as follows: chloride (10^6 kg/yr); iron (10^5 kg/yr); oil and grease (10^4 - 10^5 kg/yr); ammonia and phosphorus (10^3 - 10^4 kg/yr); lead and zinc (10^3 kg/yr); copper (10^2 - 10^3 kg/yr); nickel and phenols (10^2 kg/yr); cyanide, PAH's, cadmium and cobalt (10^1 - 10^2 kg/yr); PCB's and mercury (10^0 kg/yr); and HCB and OCS (10^{-2} - 10^{-1} kg/yr).

MANAGEMENT PERSPECTIVE

The Upper Great Lakes Connecting Channels (UGLCC) area has been identified by the International Joint Commission (IJC) as one of the "areas of concern" characterized by persistent water pollution problems. Most of such problems are caused by industrial chemicals, metals and nutrients originating from a number of sources identified by IJC. To develop an effective strategy for control of such sources, their strength and significance need to be evaluated and this task is being completed under the UGLCC study. The report that follows evaluates one of the nonpoint sources in the UGLCC area, urban runoff. Toward this end, the concentrations and annual loadings of 18 industrial chemicals, metals and nutrients in urban runoff are presented.

The reported urban runoff data will be included in the final report on the UGLCC study and compared to those for other non-point and point sources. When writing this report, evaluations of other sources have not been yet available and thus the assessment of the relative significance of urban runoff as a source of contaminants in the UGLCC area will have to be deferred until the other study components have been completed.

The results and methodologies presented here can be used in comparative studies of contaminant sources and in planning-level studies of urban runoff pollution.

INTRODUCTION

The Upper Great Lakes Connecting Channels (UGLCC) area has been identified by the Water Quality Board of the International Joint Commission (IJC) as one of the areas of concern where pollution problems have been repeatedly reported. The causes of such problems have been addressed in the UGLCC Study and included both point and nonpoint (diffuse) sources. Among the nonpoint sources, urban runoff has been selected as one of the sources to be studied. Urban runof conveys various contaminants from urban areas and discharges them into the receiving water body through a large number of outfalls. Such discharges can be either in the form of stormwater discharges, or combined sewer overflows. The former type of discharges applies in the case of separate storm sewers and the latter corresponds to combined sewer systems.

In the report that follows, a methodology for the assessment of urban runoff as a diffuse source of selected contaminants is described and applied to the study area to produce the annual contaminant loadings and their distributions. Because such loadings will be used primarily in comparative evaluation of various sources, loading estimates within one order of magnitude should be adequate.

The report starts with a description of the study area, followed by the methodology used, study results and their discussion, and conclusions.

STUDY AREA

A map of the UGLCC study area is shown in Fig. 1. There are three major sources of urban runoff on the Canadian side of the connecting channels, namely, the cities of Sarnia, Sault Ste. Marie and Windsor. Considering the desired accuracy of contaminant loading estimates, it was acceptable to neglect contaminant loadings from other small municipalities located along the connecting channels.

Besides detailed studies of urban runoff contaminant loadings from the above three urban centres, the estimates of urban runoff loadings for the Lake St. Clair Basin were produced from the literature data and also included in this report.

A brief description of the three urban centres studied follows.

The City of Sarnia

The City of Sarnia has a population of about 50,200 inhabitants and is located at the outflow of the St. Clair River from Lake Huron. The St. Clair River is an important international waterway which is subject to extensive use as a major shipping channel and as a receiving water body for numerous industrial and municipal effluents. Other uses include water supply for drinking and industrial purposes, recreation, and fish habitat.

The water in the St. Clair River is significantly polluted, particularly by various industrial chemicals discharged by numerous chemical industries located along the river. Such pollution has been well documented elsewhere (Department of Environment and Ministry of the Environment 1986).

The drainage in the City of Sarnia is provided by combined and separate sewers, and some less developed parts are drained by open channels. Combined sewers serve the older parts of the city (about 540 ha in area) and discharge into an interceptor running along the river. Along the interceptor, there are four overflow structures which allow combined sewage in excess of the interceptor capacity to escape without any treatment into the river. The intercepted flow is conveyed to the pollution control plant which is described later. Newer parts of the city are served by separate storm sewers all of which except one discharge into the St. Clair River. All principal runoff discharge points, in the form of municipal storm or overflow outfalls, are shown in Fig. 2. In addition, there are some private drainage outfalls in the chemical valley area.

Besides sewer drains, there are some open ditch drains, among which the most important one is the Municipal Drain running through the chemical valley area. Characterization of the flow composition in this drain has been reported earlier (Marsalek 1986).

The City of Sault Ste. Marie

The City of Sault Ste. Marie has a population of about 82,900 inhabitants and is located along the St. Mary's River which represents the principal water body in this urban area. Principal uses of the river include navigation, power generation, water supply, wild life habitat, and transport of stormwater and wastewater effluents.

Water quality in the St. Mary's River has been of some concern, particularly the levels of polyaromatic hydrocarbons (PAH's) and some other industrial chemicals. For that reason, the river has been selected as one of the sites under the MISA program currently conducted by the (Ontario) Ministry of the Environment.

Surface drainage in the City of Sault Ste. Marie is provided by storm sewers which discharge either directly into the St. Mary's River or into one of several creeks draining into the river. Stormwater outfalls are shown in Fig. 3.

The City of Windsor

The City of Windsor has a population of about 192,500 inhabitants and is located along the Detroit River. The principal water resources in this urban area are three water courses, the Detroit River, Little River and Turkey Creek. The water resources in the area are used for potable water supply, recreation, wild life habitat, navigation, agricultural drainage, and transport of runoff and wastewater effluents.

Although water quality in the Detroit River has shown some improvement over the last 10 to 15 years, there is evidence that microbiological quality along the Windsor shoreline is poor with fecal coliform densities exceeding Provincial Water Quality Objectives

(Lafontaine, Cowie, Burato & Associates, Ltd. 1986). Sediment data indicate high concentrations of heavy metals violating dredging criteria for disposal in open water. Major sources of such pollutants are stormwater and combined sewer overflows. Water quality in the Little River and Turkey Creek is also poor, with high bacteria counts and some heavy metal and phenol pollution.

Runoff drainage in the City of Windsor is provided by combined sewers, storm relief sewers, storm sewers, and open drains. As shown in Fig. 4, there are 26 combined sewer overflow structures discharging into the Detroit River. Such discharges occur during wet weather when runoff and sewage flows exceed the interceptor capacity. It was noted that two areas in the city are served by combined sewers, a relatively large district (2100 ha) along the Detroit River and a small area (260 ha) close to the Little River Pollution Control Plant. The rest of the city is served by storm sewers.

Storm sewers generally discharge into municipal drains, including Grand Marais Drain, Lennon Drain, and Cahill Drain, and into the Little River. Stormwater may be polluted by cross-connections with sanitary sewers and overflows from septic tanks.

STUDY APPROACH

Urban runoff, in the form of stormwater discharges or combined sewer overflows, represents a diffuse source of contaminants intermittently discharged into the receiving waters at numerous points. Consequently, it is impossible to monitor all the discharge points and runoff events and other approaches to estimating the contaminant loadings need to be taken. As an alternative to extensive field monitoring, it is suggested to characterize the composition of runoff through field investigations and to use such characteristics in conjunction with estimates of total flow volumes to obtain loadings. Such an approach is feasible, if certain conditions are met. In particular, runoff quality characteristics should represent mean values derived from flow-weighted mean event concentrations for a number of events and such characteristics should be produced for typical land use types within the study area. The higher the number of event samples, the better the accuracy of mean runoff quality characteristics. On the other hand, the cost of sample collection and analysis, or study time constraints, suggest to keep the number of samples to an acceptable minimum. Although it is not possible to specify the minimum number of events to be sampled, or their total rainfall, some guidance can be obtained from an earlier long-term study of urban runoff quality (Marsalek and Ng 1987). In that study, the mean concentrations calculated for the first 13 events in a series of 117 events did not statistically differ from the entire set means for six out of eight constituents. For the remaining two constituents, the differences were about 40%.

Although accurate calculations of instantaneous runoff flows are quite difficult and hard to achieve, the annual runoff volume can be estimated fairly accurately from the known precipitation and the contributing area using the procedures detailed later. Annual loadings of contaminants are then obtained by multiplying the annual flow volumes by mean concentrations. In such calculations, estimates of mean concentrations are the main source of uncertainties.

The description of the study procedures starts with field investigations of runoff quality followed by computations of runoff volumes.

Field Investigations of Runoff Quality

Field investigations of runoff quality represented a major effort in the study of contaminants in urban runoff in the UGLCC area and were conducted from April 1985 to November 1986. The main objective of such investigations was to collect representative samples of urban runoff and combined sewer overflows to be used in calculations of annual loadings. The description of the field program starts with discussion of sources and pathways of urban runoff contaminants followed by details of procedures used.

Sources and pathways of urban runoff contaminants

In order to design an effective sampling program for investigations of urban land runoff contamination, it is necessary first to examine the sources and pathways of runoff contaminants in urban areas. Although such processes are very complex, considerable simplifications are acceptable for the purpose of estimating annual pollutant loadings.

The sources of contaminants in urban runoff are quite numerous and include atmospheric sources as well as sources related to land use activities. The atmospheric sources may be of local or remote origin and contribute to runoff pollution through both dry and wet precipitation.

Dry precipitation results in accumulation of particle deposits on the catchment surface and these deposits are then washed off during the periods of runoff. The composition of such deposits may vary depending on the local sources of contaminants and the direction and intensity of their transport. Contaminants from remote sources are imported to the catchment and their characteristics do not necessarily correlate well with local land use and other conditions. On the other hand, local air pollution also contributes to contaminant accumulation and such a contribution will be related to the distance from local sources and prevailing wind directions.

Another source of contaminants is wet precipitation. It has been noted in the literature that many toxics are transported over large distances and reach the ground in the form of wet precipitation. Thus such substances are imported and do not necessarily relate well to the local land use.

Other sources of contaminants are those related to land use activities. Such sources include applications of agricultural chemicals and deicing materials in urban areas, accumulation of litter and traffic byproducts, illicit discharges of pollutants from industrial operations, spills, sewer cross-connections, etc. Many such activities are particularly pronounced in industrial areas.

During the periods of runoff, the rainwater, which is already contaminated, reaches the catchment surface and washes off and transports substances accumulated on the catchment surface. Such processes are particularly intense on impervious parts of the catchment where practically all the rainwater runs off and the flow velocities and the resulting transport rates are fairly high. On pervious areas, the rainfall rate is smaller than the rate of losses (i.e. infiltration and surface storage) for long segments of the storm, and, consequently, the rate and volume of runoff are rather small. Exceptionally, during rain storms of high intensity, or in the case of poorly drained soils, pervious parts of the catchment may contribute appreciably to the catchment runoff. Thus the monitoring activities should concentrate on impervious areas whose extent is closely related to land use and the population density.

The rate of pollutant transport during individual storms is not generally constant, but varies depending on the runoff rate, the amount of pollutants remaining on the catchment surface, and some other factors. Some catchments exhibit the so-called first-flush phenomenon characterized by pollutographs which exhibit the highest concentrations during the early parts of the runoff event (more or less coinciding with the rising hydrograph limb) when the greatest quantities of pollutants are available on the catchment surface. Considering the high costs of toxic analyses, it is infeasible to collect sequential samples and to characterize toxics concentrations variations during storms. If the primary interest is the substance loading, it is preferable to collect composite samples for individual events. Ideally, the sample composition should be flow proportional.

Many contaminants in urban runoff are transported in both dissolved and particulate forms. To obtain their total loadings, it is possible to use extractable concentrations reflecting both contaminant forms in unfiltered samples. Alternatively, it is possible to analyze both forms separately and then determine the total loading as the sum of both components.

When urban runoff leaves the catchment surface, it enters either storm or combined sewers, depending on the sewerage system in the area under consideration. In the former case, runoff which is referred to as the stormwater is conveyed by storm drains (sewers or open channels) to a nearby receiving water body. The duration of such transport is relatively short, generally less than an hour, and except for some limited sedimentation and sediment scouring, the runoff composition is virtually unchanged during short transport in storm sewers.

In the case of combined sewers, both runoff and municipal sewage are transported in a single pipe. During wet weather, the pipe capacity may be exceeded, because of high runoff inflows, and to avoid hydraulic overloading of downstream facilities, the excess flow is allowed to escape from the sewer system in the form of combined sewer overflows. Such overflows represent a mixture of surface runoff and municipal sewage. The pollutional strength of this mixture is increased by scouring of sediment (sludge) deposited during dry weather in combined sewers. Thus, the composition of combined sewer overflows differs substantially from that of runoff and should be investigated separately.

Based on the above discussion, the characterization of composition of urban runoff should be obtained by sampling both stormwater and combined sewer overflows in areas with various urban land use. Emphasis should be placed on residential and industrial land use, because the former is the most predominant and the latter may produce the greatest impact on runoff quality. Samples of runoff (with sediment) should be collected as flow-proportional composite samples for a number of runoff events. Whenever feasible, composite samples from successive events may be further composed proportionately to the event runoff volume.

Sampling sites

The selection of sampling sites was governed by the distribution of urban areas in the study area, local contaminant sources, and land use. It was desirable to sample in all the three urban centres, the cities of Sarnia, Sault Ste. Marie and Windsor. On the basis of the earlier discussion of contaminant pathways, 15 sampling sites have been selected in the urban centres studied. The total number of sampling sites was limited by the resources available for the study in terms of analytical support, field equipment and personnel. In general, the sampling sites served for collection of samples of rainwater, stormwater, combined sewer overflows and sediment. A brief listing of sampling sites is given in Table 1. Additional details can be found in Appendix A.1.

It can be inferred from Table 1 that in the cities with combined sewerage both runoff and overflows were sampled and that runoff was sampled for the three most important land use types - residential, commercial and industrial. Wet-weather flows at the treatment plants were also sampled to characterize combined sewage escaping the collection system during wet weather. Sample collection methods are described in the next section.

Sample collection methods

Flow measurement and sampling methods for studies of urban runoff have been established for conventional pollutants. In such studies, the pollutant concentrations are fairly high and the possibility of sample cross-contamination is limited. The methodology for monitoring of toxics in urban runoff is not well established and many procedures and devices used in this study were developed on the basis of general recommendations of the U.S. Environmental Protection Agency (Versar 1980) and the Water Quality Branch of Inland Waters Directorate. It should also be emphasized that the study budget and schedule did not allow acquisition of sophisticated equipment. Descriptions of various sample collection methods which were presented earlier in the Quality Assurance Plan for this study follow.

Table 1. List of Sampling Sites

Site Designation	Site Name	Medium Sampled	Land Use
S[1].1	Charlesworth Drive	Runoff	Residential
S.2	Devine Street Overflow	Overflow	Mixed
S.3	Eastland Plaza	Runoff	Commercial
S.4	Clifford Street Overflow	Overflow	Mixed
S.5	Pollution Control Plant	Wet-Weather Influent	Mixed
S.6	South Vidal Street	Runoff	Industrial
SSM[2].1	Georgina Street	Runoff	Residential
SSM.2	Station Mall	Runoff	Commercial
SSM.3	Hudson Street	Runoff	Industrial
W[3].1	L.R. Pollution Control Plant	Wet-Weather Bypass	Mostly Residential
W.2	Greendale Avenue	Runoff	Residential
W.3	Tecumseh Mall	Runoff	Commercial
W.4	Chilver Road Overflow	Overflow	Mixed
W.5	Albert & Metcalf Streets	Runoff	Industrial
W.6	Grand Marais Drain	Runoff	Industrial

[1]Sarnia
[2]Sault Ste. Marie
[3]Windsor

Sewer Inlet Sampler

The sewer inlet sampler is a simple custom made device which serves for collection of surface runoff samples. Basically, the sampler consists of a large stainless steel funnel, which fits under the inlet grate, and of a sample container. The funnel diverts a small constant fraction of the total inflow via a teflon tube into a glass bottle.

Automatic Wastewater Samplers

Some stormwater or overflow samples were collected by means of automatic wastewater samplers operated in the sequential mode. Two types of samplers were used, ISCO and Sigmamotor. The ISCO sampler, Model 2100, is recommended for monitoring of toxic substances. It is a sequential sampler which collects samples by means of a peristaltic pump. To avoid sample contamination, all the internal plumbing is made of stainless steel or teflon, with the exception of a short piece (0.6 m) of tubing in the peristaltic pump. This tubing must be fairly flexible for good pump operation and, consequently, a medical-grade silicone rubber tubing is used for this purpose.

The other sampler used was the Sigmamotor, Model 6201, sampler which was modified for the monitoring of toxics in a similar way as done in the ISCO sampler. Again a medical-grade silicone rubber tubing was used in the sampler peristaltic pump. The sample distribution system which could contaminate samples was replaced by new parts made of stainless steel and teflon. Samples were stored in glass bottles.

The sampling equipment was cleaned after every event.

Preservation of samples and cleaning of sample containers

All samples were removed from sampling devices as soon as possible after the end of the sampled event and brought to the laboratory in glass bottles or jars. Samples were then transferred into laboratory bottles, preserved and submitted for analysis. Sample preservation was done according to the Protocol developed by the Water Quality National Laboratory in Burlington.

Sample analysis contaminants studied

The selection of contaminants studied was based on the common contaminants list established for general studies under the UGLCC project. Because of various constraints, all samples could not be analyzed for all parameters and, in some cases, the data had to be transposed almong the areas studied. The parameters included in the UGLCC list and studied during various phases of the study are listed in Table 2. For each parameter, the substrate, method reference and detection limit are specified. The details of analytical methods can be found elsewhere (American Public health Association 1980; Ministry of the Environment 1982; Wastewater Treatment Centre 1985; Water Quality Branch 1979).

Table 2. Urban Runoff Contaminants Studied

Parameter	Abbreviation Used	Analytical Method Code[1]	Detection Limit
Ammonia (nitrogen)	NH_3	A063	.001 mg/ℓ
Phosphorus (total)	P	A073	.001 mg/ℓ
Chloride	-	A034	.050 mg/ℓ
Cadmium	Cd	A102	.001 mg/ℓ
Cobalt	Co	A116	.001 mg/ℓ
Copper	Cu	A123	.001 mg/ℓ
Iron	Fe	A129	.020 mg/ℓ
Lead	Pb	A137	.001 mg/ℓ
Mercury	Hg	A151	.00002 mg/ℓ
Nickel	Ni	A165	.001 mg/ℓ
Zinc	Zn	A192	.001 mg/ℓ
Cyanides (total)	-	{ WTC Analytical	10 µg/ℓ
Oil & Grease	-	{ Methods Manual	0.1 mg/ℓ
Phenols (total)	-	MOE Outline of Analytical Methods	1 µg/ℓ
Hexachlorobenzene	HCB	A205	0.4 ng/ℓ
Octachlorostyrene	OCS	-	1 ng/ℓ
Polychlorinated biphenyls (total)	PCBs	A207	9 ng/ℓ
Polyaromatic hydrocarbons	PAHs	PAHW1(A631-A642) PAHW2(A586-A591)	50 ng/ℓ 150 ng/ℓ

[1]All codes starting with A refer to AWQUALABS codes (Water Quality Branch 1979).

Computations of Annual Urban Runoff and Combined Sewer Overflow Volumes

As stated earlier, estimates of annual runoff and overflow volumes are needed to calculate the annual loadings of contaminants using mean observed contaminant concentrations. Accurate determination of runoff and overflow volumes by means of field measurements is impractical. In the three urban centres studied, such measurements would have to be done at more than 100 outfalls for a number of randomly occurring runoff events. Considering the fact that each site could cost as much as $10,000 - $15,000 to instrument and the corresponding manpower requirements, it is obvious that actual flow measurements at numerous sites are infeasible. Furthermore, such measurements are not even warranted in the screening type of analysis, when the relative strength of individual contaminant sources is investigated. Only if such analysis indicates the significance of a particular source and possible need for its control, are further detailed investigations warranted.

As an alternative to runoff and overflow measurements, it is possible to calculate such overflows by relatively simple procedures. Although the calculated instantaneous flows may be highly inaccurate, because of rainfall and runoff variations in time and space, the total flow volume from a catchment, for a long time period, can be determined fairly accurately. In a limiting case, all precipitation falling over the catchment surface would be converted into runoff.

For actual catchment conditions, such a full conversion is impossible because of rainfall abstractions (also called losses). Thus, the problem of annual runoff estimation is reduced to the estimation of such abstractions which typically vary from 30% to 70% of the rainfall.

Similarly, it is possible to estimate the annual volume of combined sewer overflows from the known intercepting sewer capacity, observed dry weather flow and calculated runoff inflow. Flows in excess of the interceptor capacity are considered as overflows. Runoff and overflow volumes were simulated by the STORM model described below.

STORM model description

Urban runoff from and combined sewer overflows in the studied urban centres were estimated by the STORM model which is generally recommended for planning-level runoff calculations (U.S. Army Corps of Engineers 1977). A brief description of the model follows.

As used in this study, the STORM Model calculates hourly runoff depths according to the following equation:

$$R = C(P - f)$$

where
- R = runoff in mm
- C = composite runoff coefficient
- P = rainfall/snowmelt in mm over the area
- f = available depression storage in mm

Average annual runoff coeficients for pervious and impervious areas need to be specified and are used to calculate a single composite runoff coefficient according to the following equation:

$$C = C_p + (C_{imp} - C_p) \sum_{i=1}^{n} X_i F_i$$

where C_p = runoff coefficient for pervious surfaces

C_{imp} = runof coefficient for impervious surfaces

X_i = area, with land use i, expressed as a fraction of the total catchment area

F_i = fraction of land use i which is impervious

n = total number of land use categories

The above composite runoff coefficient is used for all events in the precipitation record regardless of their characteristics. This method should be satisfactory for catchments with relatively high imperviousness. Besides the above described coefficient method, the STORM model offers two other runoff calculation options which require less commonly available input data.

Meteorologic input data for running the STORM model include hourly precipitation and air temperatures. The model calculates snowmelt, using the degree-day method, and adds the snowmelt depth to the precipitation in the above equation.

The physiographic input data include the catchment area, the distribution of land use within the catchment, and imperviousness of the individual land use types. Finally, three hydrologic process parameters, C_{imp}, C_p and d_{max}, also need to be specified. The maximum depression storage d_{max} is used by the model to calculate the time variable available storage f(t), which varies depending on the rates of filling or recovery (the latter is calculated from evaporation data).

The STORM model can also be used to simulate the volume of combined sewer overflows. In such calculations, runoff is calculated as described above and, furthermore, it is required to specify dry weather flow, infiltration into sewers, the number and volume of storage facilities, and the treatment rate. The combined flow including dry weather flow, infiltration and runoff fills storage which is draining, at the treatment flow rate, into the treatment plant. Whenever the storage volume is exceeded, overflows occur and their volume and duration are calculated by the model.

Runoff simulations in the study area

As stated in the previous section, runoff simulation by the STORM model requires meteorological data, hydrologic process parameters and catchment parameters as input data. The meteorological data required included hourly precipitation, hourly air temperatures (for snowmelt calculations), and daily evaporation rates. Both types of hourly data are readily available from the Atmospheric Environment Service (AES), though with some limitations. In particular, the hourly precipitation data are available for the periods from April to October on magnetic tapes and for the remaining period only daily values are reported. To overcome this deficiency, it was required to divide the daily values into 24 equal hourly values and enter those manually into the data base. To reduce this extra labour involved in preparing the input data base, it was decided to run the STORM model for each of the three cities for one year period only. To maintain some representativeness of average conditions in the catchments, such a year was selected from the historical record as the year with annual precipitation approximating the long-term average. Such a condition was met by 1982 data in Sarnia, 1984 data in Sault Ste. Marie, and 1976 data in Windsor.

Evaporation input data were obtained from published climate normals (AES 1982).

The STORM model contains three runoff computation options of various complexity. The simplest of these options, the coefficient method, was selected because only that method could be fully supported by the available data. The coefficient method requires three basic hydrologic parameters - volumetric runoff coefficients for impervious and pervious areas, and surface depression storage on impervious areas. The values of such coefficients were selected from the literature data (Kibler 1982) and further tested in the sensitivity analysis described later. The parameter values used in the study area are listed in Table 3.

Finally, it was required to determine some physiographic data for the three study subareas. The data required included the total runoff contributing area, the division of this area among the principal land use types, the degree of imperviousness for each land use type and, for areas with combined sewers, also the average dry weather flow, infiltration flow, treatment flow rate, and storage volume.

Runoff contributing and land use type areas were determined from the land use maps received from the planning departments of the three cities studied. A summary of such data is given in Table 3. It should be mentioned that the runoff contributing areas listed in Table 3 are generally smaller than the total land within the city limits. This can be explained by the fact that undeveloped land along the city limits was considered as rural land, not producing urban runoff, and as such it was excluded from runoff calculations. Similarly, land areas in individual land use categories in Table 3 may be smaller than those indicated on the land use plans, which include future developments.

For individual land use categories, typical imperviousness was estimated from field inspections. The effects of inaccuracies involved in such estimates on runoff computations were further tested by the sensitivity analysis.

It can be inferred from Table 3 that the selected hydrologic parameter values were almost identical for all three subareas. A somewhat higher value of the runoff coefficient was selected for pervious areas in Sault Ste. Marie to reflect steeper slopes and the resulting higher production of runoff. The values of imperviousness for the three subareas are quite similar, except for somewhat lower values in Sault Ste. Marie reflecting a lower density of development. Dry weather flows and treatment rates are listed only for two subareas with combined sewers - Sarnia and Windsor.

Table 3. Hydrologic and Catchment Input Data for Runoff Simulations in the Study Area

Parameter	Study Subarea		
	Sarnia	Sault Ste. Marie	Windsor
<u>Hydrologic Parameters</u>			
Runoff coefficient for			
(a) Impervious areas	0.9	0.9	0.9
(b) Pervious areas	0.15	0.2	0.15
Surface depression storage (mm)	1.5	1.5	1.5
<u>Catchment Parameters</u>			
Runoff contributing area (ha)	3,200	4,500	9,800
Land use data:			
Area (ha)/Imperviousness (%)			
Residential	1,570[1]/30%	2,340/25%	6,900[1]/30%
Institutional	30/25%	270/25%	160/25%
Commercial	160/85%	360/85%	540/85%
Industrial	1,090/40%	580/35%	1,800/40%
Open Land	350/3%	950/1%	400/3%
Combined sewers area (ha)	540	-	2,360
Daily dry weather flow plus infiltration (m^3/day)	57,000	-	163,000
Treatment rates (m^3/day):			
(a) Full treatment	68,000	-	386,000
(b) Partial treatment (screening and aerated grit removal)			771,000

[1]The total area which includes the combined sewers area listed below

Using the meteorological data described earlier and the input data listed in Table 3, annual runoff and combined sewer overflows were calculated for the subareas studied and listed in Table 4.

Table 4. Simulated Annual Volumes of Runoff and Combined Sewer Overflows for the Study Subareas

Annual Volume	Study Subarea		
	Sarnia	Sault Ste. Marie	Windsor
Surface runoff	6.7×10^6 m^3/yr	13×10^6 m^3/yr	22.3×10^6 m^3/yr
Combined sewer overflows	1.0×10^6 m^3/yr	-	5.2×10^6 m^3/yr
Total volume drained	7.7×10^6 m^3/yr	13×10^6 m^3/yr	27.5×10^6 m^3/yr

Uncertainties in the computed runoff volumes

It was of interest to evaluate uncertainties in the calculated runoff volumes. Such uncertainties are introduced by the computational procedure itself and by uncertainties in the input data. To evaluate uncertainties in the results shown in Table 4, a sensitivity analysis of the modelling results was conducted. Towards this end, the input parameters were varied, one at a time, within a practical range of values and the impact of such variations was evaluated. All the remaining parameters were set equal to the reference values shown in Table 3. The resulting calculated runoff volumes were expressed as percentages of the reference volumes (given in Table 4) and summarized in Table 5.

Table 5. Sensitivity Analysis of Runoff Simulations in Three Study Subareas

Input Parameter Varied		Modelled Runoff Volume (% of the reference volume)		
		Sarnia	Sault Ste. Marie	Windsor
Hydrologic Parameters				
C_{imp} = 0.70		83	86	83
0.95		104	103	104
C_p = 0.10		92	80	92
0.40		142	138	141
d_{imp} = 2.0 mm		96	96	97
0.5 mm		111	109	108
Land Use Imperviousness				
Residential	i = 15%	-	90	-
	20%	91	-	87
	35%	-	109	-
	40%	109	-	113
Institutional	i = 15%	100	-	-
	30%	100	-	-
Commercial	i = 70%	99	-	99
	i = 90%	100	-	101
Industrial	i = 20%	87	96	93
	50%	-	103	-
	60%	113	-	107
Open Land	i = 1%	100	-	-
	5%	100	-	-

It can be inferred from Table 5 that runoff volume simulations are barely sensitive to other input parameters than the runoff coefficients C_{imp} and C_p. For C_{imp}, the deviations from the reference value are about -16% and +4% which are relatively small values. For C_p, average deviations ranged from -12% to +40% for C_p equal to 0.1 and 0.4, respectively. Even though the reference value of C_p = 0.15 (0.2 in Sault Ste. Marie) may lead to underestimation of runoff from pervious areas, it is believed that such an underestimation would not be fully reflected in the calculated loadings, because runoff from pervious parts is much less contaminated than that from impervious parts of the catchment.

Similar approach was adopted to calculation of combined sewer overflows in Sarnia and Windsor. Such calculations were done using the STORM model and the sensitivity of model results was evaluated for variations in input data. The results of the sensitivity analysis are shown in Table 6. Further explanations follow.

In Sarnia, the area served by combined sewers was estimated as 540 ha. Even within this area, some drainage is conveyed by storm sewers and the combined sewers may carry some inflows originating outside of the area. Thus, there is some uncertainty in the above estimated area and in its imperviousness. For loading calculations, the annual volume of $V=0.96x10^6m^3=1x10^6m^3$ was adopted. It corresponds to the combined sewer area measured from the map and the selection of a somewhat lower imperviousness (i=30%) reflects the fact that some runoff within this area is conveyed by separate storm sewers.

Table 6. Sensitivity Analysis of Combined Sewer Overflow Simulations

Study Subarea	Area Served by Combined Sewers	Annual Overflow Volume (10^6 m^3/yr)			
		Area Imperviousness			
		15	30	45	60
Sarnia	270	0.20	0.36	0.52	0.70
	540	0.58	0.96	1.34	1.71
	810	0.96	1.56	2.15	2.71
Windsor (a)	260 high Q_t[1]		0.21	0.35	0.52
	260 low Q_t		0.46	0.66	0.86
(b)	2,100 high Q_t		1.24	2.06	3.11
	2,100 low Q_t		3.02	4.54	6.11
(a)+(b)	2,360 high Q_t		1.45	2.41	3.63
	2,360 low Q_t		3.48	5.20	6.97

[1] Q_t = treatment rate; the high and low values correspond to partial and full treatment, respectively.

In Windsor, there are two areas served by combined sewers. The smaller area of 260 ha is south of the Little River Pollution Control Plant. The second area, 2100 ha, is located along the Detroit River in the central district. Thus both areas are well defined. Uncertainties in overflow calculations arise from the area imperviousness, which affects the volume of surface runoff, and from the treatment rate. Among the imperviousness values, the value of 45% was selected as characteristic for the combined sewer area.

The selection of the treatment rate, Q_t, was based on the information given in the Water Pollution Assessment Plan for the City of Windsor (Lafontaine, Cowie, Buratto & Associates Ltd. 1986). The West Windsor Plant has a treatment capacity of 163,000 m^3/day. The capacity of pumping facilities is 790,000 m^3/day. All flows are directed through coarse and fine screens and through aerated grit removal facilities. Flows up to 386,000 m^3/day are further treated by chemically aided sedimentation. Flows in excess of 386,000 m^3/day bypass the sedimentation process. Treated and untreated effluents are chlorinated prior to discharge into the Detroit River. Thus the level of treatment depends strongly on the plant inflow. Depending on the inflow rate, the influent is treated to a various degree, or it may partly bypass the plant.

For the calculation of overflows, Q_t was selected as 386,000 m^3/day, because higher flows receive minimum treatment deemed ineffective in removal of the contaminants studied. The selection of the above value results in the annual volume of overflows from the central district of 4.54×10^6 m^3/yr. For Q_t equal to the pumping capacity, the volume of overflows would be reduced in almost one half. Using a similar reasoning, the annual volume of overflows from the smaller area of 260 ha was determined as 0.66×10^6 m^3/yr. Thus the total overflow volume was taken as 5.2×10^6 m^3/yr and represents a somewhat conservative estimate.

RESULTS

The results of the study of urban runoff pollution in the UGLCC area are reported in two forms, as mean concentrations and annual loadings of contaminants.

Mean Contaminant Concentrations

The contaminant concentrations presented below were derived from field observations for up to 75 events monitored in the three urban centres studied. Besides stormwater samples, samples of combined sewer overflows and snowmelt were also collected. The observed concentrations were characterized by their mean values listed in Table 7 and plotted in Fig. 5. For some parameters, a significant percentage of the data was below the detection limits. In those cases, the procedures established for the UGLCC project recommend that two estimates, low and high, should be produced. The low estimate is obtained by assuming all concentrations below the detection limit equal to zero. For the high estimate, such concentrations are assumed equal to the detection limit. A somewhat similar procedure was followed in few exceptional cases where the concentrations exhibited large variations generally caused by some high concentrations which could not be further verified at this time. Such data were also described by low and high estimates to reflect such variations. Both estimates were used in loading calculations.

Besides stormwater and overflow data used directly in loading calculations, some data on composition of rainwater and snowmelt were also collected. Such data are listed in the Appendix and referred to in the following discussion of stormwater and overflow composition.

Table 7(a). Mean Concentrations Observed in Stormwater and Combined Sewer Overflows in Sarnia.

Parameter	Units	Stormwater: Residential	Stormwater: Commercial	Stormwater: Industrial	Combined Sewer Overflows
Ammonia (N)	mg/ℓ	0.45	0.27	0.70	3.9
					15.7
Phosphorus (total)	mg/ℓ	0.37	0.16	0.22	0.4
					3.4
Chloride	mg/ℓ		172[1]		32.9
			343[1]		65.3
Cadmium	mg/ℓ	0.00	0.0023	0.0007	0.005
		0.006	0.008	0.009	0.008
			0.006[2]		0.008[2]
Cobalt	mg/ℓ	0.00	0.00	0.00	0.00
		0.02	0.02	0.02	0.02
			0.0035[2]		0.003[2]
Copper	mg/ℓ	0.009	0.051	0.087	0.14
Iron	mg/ℓ	3.1	5.0	9.4	2.5
					8.4
Lead	mg/ℓ	0.066	0.28	0.45	0.29
Mercury	mg/ℓ	0.00006	0.00004	0.00018	0.00005
		0.000063			0.00075
Nickel	mg/ℓ	0.018	0.005	0.030	0.005
		0.026	0.025	0.039	0.023
Zinc	mg/ℓ	0.18	0.33	0.48	0.24
					1.64
Oil & Grease	mg/ℓ	2.1	4.1	10.3	7.5
					34.8
Phenols	mg/ℓ	0.0170	0.0107	0.0188	0.0099
					0.0255
Cyanide	mg/ℓ	0.0035	0.0017	0.0030	0.0030
HCB	ng/ℓ	1.55	4.4	257	12
					43
OCS	ng/ℓ		2		2
PCB's (total)	ng/ℓ	75	146	324	150
17 PAH's	ng/ℓ	8,500	2,800	6,700	5,000
		12,000	3,300	7,000	15,400

[1]Equivalent mean concentration
[2]Mean of concentrations detected in all three subareas

Table 7(b). Mean Concentrations Observed in Stormwater in Sault Ste. Marie.

Parameter	Units	Stormwater		
		Residential	Commercial	Industrial
Ammonia (N)	mg/ℓ	0.87	0.42	0.49
Phosphorus (total)	mg/ℓ	0.36	0.23	0.17
Chloride	mg/ℓ		142[1] 285[1]	
Cadmium	mg/ℓ	0.00 0.009	0.0011 0.008 0.006[2]	0.00 0.009
Cobalt	mg/ℓ	0.00 0.02	0.00 0.02 0.0035[2]	0.00 0.02
Copper	mg/ℓ	0.042	0.063	0.031
Iron	mg/ℓ	5.8	11.4 0.21	8.3 0.16
Lead	mg/ℓ	0.09	0.000013	0.000030
Mercury	mg/ℓ	0.000032	0.000021	0.000033
Nickel	mg/ℓ	0.012 0.027	0.014 0.024	0.003 0.021
Zinc	mg/ℓ	0.29	0.29	0.21
Oil & Grease	mg/ℓ	2.5	2.6	2.6
Phenols	mg/ℓ	0.0165	0.0120	0.0100
Cyanide	mg/ℓ	0.0017	0.0027	0.0030
HCB	ng/ℓ	0.23 0.43	0.15 0.42	0.00 0.40
OCS	ng/ℓ	-	-	-
PCB's (total)	ng/ℓ	26	40	13
17 PAH's	ng/ℓ	11,500 23,900	4,700 5,100	3,000 3,500

[1]Equivalent mean concentration
[2]Mean of concentrations detected in all three subareas

Table 7(c). Mean Concentrations Observed in Stormwater and Combined Sewer Overflows in Windsor.

Parameter	Units	Stormwater Residential	Stormwater Commercial	Stormwater Industrial	Combined Sewer Overflows
Ammonia (N)	mg/ℓ	0.28	0.30	0.43	2.5
Phosphorus (total)	mg/ℓ	0.24	0.17	0.31	0.54 26.0
Chloride	mg/ℓ		120[1] 240[1]		
Cadmium	mg/ℓ	0.00 0.01	0.001 0.009 0.006[2]	0.0006 0.0086	0.001 0.0072 0.008[2]
Cobalt	mg/ℓ	0.00 0.02	0.0014 0.017 0.0035[2]	0.0004 0.017	0.0006 0.017 0.003[2]
Copper	mg/ℓ	0.018	0.03	0.048	0.10
Iron	mg/ℓ	5.8	3.0	6.9	1.2
Lead	mg/ℓ	0.13	0.184	0.21	0.05 0.16
Mercury	mg/ℓ	0.000018 0.00006	0.00003	0.000043 0.000050	0.000043
Nickel	mg/ℓ	0.008 0.021	0.026	0.017 0.028	0.010 0.044
Zinc	mg/ℓ	0.16 0.25	0.23	0.30	0.34 0.50
Oil & Grease	mg/ℓ	1.4	2.3	1.7 5.8	12.3
Phenols	mg/ℓ	0.0025	0.0040	0.0050	0.0080
Cyanide	mg/ℓ	0.003	0.003	0.003	0.003
HCB	ng/ℓ	1.4	0.0 0.4	0.2 0.92	1.09
OCS	ng/ℓ	-	-	-	-
PCB's (total)	ng/ℓ	31.6	25.8	109.0	100
17 PAH's	ng/ℓ	1,100 1,600	2,100 2,600	4,600 5,700	4,000 4,400

[1]Equivalent mean concentration
[2]Mean of concentrations detected in all three subareas

Nutrients

Concentrations of ammonia in stormwater varied from 0.28 mg/ℓ to 0.87 mg/ℓ, with the highest values observed in Sault Ste. Marie. Such a range of values compares quite well with the rainwater data from Windsor (mean = 0.28 mg/ℓ) and Sarnia (mean = 0.61 mg/ℓ) and the long-term runoff data from Burlington (0.46 mg/ℓ; Marsalek and Ng 1987). Total phosphorus concentrations in stormwater varied from 0.16 to 0.37 mg/ℓ which is in the range reported in the literature (Ellis 1986). It was of interest to note that snowmelt composition in Windsor was similar to that of stormwater.

Much higher concentrations of nutrients were found in combined sewer overflows. Ammonia concentrations in overflows in Windsor were characterized by the mean value of 2.5 mg/ℓ. In Sarnia, two estimates were considered. The lower estimate of 3.9 mg/ℓ was observed in overflows upstream of the pollution control plant. Wet weather inflows at the plant were characterized by the value of 15.7 mg/ℓ which was adopted as the higher estimate. It should be noted that this higher value can be substantiated by the literature data (U.S. EPA 1974).

Concentrations of TP in overflows varied from 0.4 mg/ℓ to 3.4 mg/ℓ. Because of this variation, two estimates, 0.4 mg/ℓ and 3.4 mg/ℓ, were adopted for Sarnia. Windsor overflows were characterized by the value of 0.54 mg/ℓ.

Chloride

The major source of chloride in urban runoff is road salting. This is reflected in chloride concentrations in urban runoff and snowmelt which may reach the range from 10^3 to 10^4 mg/ℓ (Waller and Hart 1986). Such concentrations go largely unnoticed because conventional runoff monitoring stations are closed down during freezing weather. Once the chloride accumulations are washed off the catchment surface or removed with snow, chloride concentrations in stormwater drop to relatively low values in the order from 1 to 10 mg/ℓ. For that reason, chloride loadings were estimated directly from road salt usage in the area. After dividing such loadings by the annual runoff volume, estimates of flow-weighted mean concentrations were obtained in the range from 120 mg/ℓ to 340 mg/ℓ. Such values are significantly lower than those reported by Waller and Hart (1986) for Halifax and may be affected by snow removal and disposal.

In combined sewer overflows, chloride concentrations varied from 26 to 65.3 mg/ℓ.

Metals

Seven metals were included on the list of parameters studied, cadmium (Cd), cobalt (Co), copper (Cu), iron (Fe), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn). Their frequencies of detection and concentrations in stormwater and overflows varied widely. In general, metal concentrations in stormwater exceeded those in overflows.

The highest concentrations were observed for iron, up to 11.4 mg/ℓ in stormwater and 8.4 mg/ℓ in overflows. The stormwater values compare quite well against the literature data (Malmqvist 1983). Next in the magnitude of concentrations were three heavy metals Zn, Pb and Cu. All were detected in practically all samples above the detection limit with ranges of mean site concentrations of 0.16-0.48, 0.07-0.45, and 0.01-0.09, respectively. Such values fall within the much wider ranges reported in the literature (Ellis 1986; Malmqvist 1983) and are somewhat higher than the means of extensive runoff data from two urban catchments in Burlington (Marsalek and Ng 1987). The Burlington data from Zn, Pb and Cu were characterized by mean values of 0.21-0.22, 0.08-0.09, and 0.027-0.033, respectively. The higher concentrations in the study area can be explained by industrial sources.

Nickel was detected only in some samples and, consequently, the low and high estimates were produced for all subareas. Cadmium and cobalt typically occurred in concentrations below the commonly used detection limits of 0.01 and 0.02 mg/ℓ, respectively. Occasionally, higher sensitivity analytical procedures were used and those produced some quantitative data. It would appear that the higher estimates of concentrations in Table 7 are primarily controlled by the concentration data set equal to the detection limit. This appears to be true for both stormwater and overflows.

Quantitative data were produced for mercury which was analyzed for using a method with the detection limit of 0.00002 mg/ℓ. Concentrations in stormwater and overflows, about 0.00005 mg/ℓ, were comparable except for some higher readings in Sarnia overflows (0.00075 mg/ℓ).

Industrial Chemicals

This group included six parameters, oil & grease, cyanide, hexachlorobenzene (HCB), octachlorostyrene (OCS), total polychlorinated biphenyls (PCB's) and 17 polyaromatic hydrocarbons (PAH's). Most of these parameters are not commonly studied in urban runoff studies and hardly any verification data were found in the literature. A discussion of individual parameters follows.

Oil & grease concentrations were fairly consistent and typically varied from 1.4 to 10.3 mg/ℓ. The highest values were found in industrial areas and the lowest ones in residential areas. Only one source of similar data was found in the literature, a study of oil & grease in runoff from two urban catchments in Alaska (Barrett et al. 1987). With the exception of several high concentrations (10^2-10^3 mg/ℓ) during an initial period of a minor event with an extended antecedent dry period, the observed concentrations varied from 1 to 19.6 mg/ℓ and generally support the levels reported here for the study area.

All cyanide concentrations were found in a relatively narrow range from 0.0017 to 0.0030 mg/ℓ regardless of the source, location or land use. No verification data were found in the literature.

Among the remaining parameters studied, the highest concentrations were found for PAH's, followed by PCB's, HCB and OCS.

Stormwater and overflow samples were commonly analyzed for 12 PAH's listed in the Appendix A.3. In the second year, additional analytical support was made available and the samples were analyzed for 17 PAH's. In many samples, most of the PAH's were below or close to the detection limit (50 ng/ℓ) and only three common substances, phenanthrene, fluoranthene and pyrene contributed most of the loadings. At some sites, PAH concentrations showed relatively large variations and for that reason two estimates, low and high, are given in Table 7. In Windsor, analytical data were available only for 12 PAH's. The data for the remaining were prorated from the Sarnia data. The observed concentrations of all 17 PAH's varied from 1,100 to 23,900 ng/ℓ. The overflow data were generally at the lower end of this range. Compositions of stormwater and overflow total PAH's loadings differed and indicated different sources of PAH's.

PCB's were found in relatively low concentrations from 13 to 324 ng/ℓ. The concentrations in overflows varied from 100 to 150 ng/ℓ.

HCB concentrations varied from 0.2 to 4.4 ng/ℓ at all sites except surface runoff from the industrial site in Sarnia where the mean concentration was 257 ng/ℓ. Such a relatively high concentration can be explained by strong local industrial sources.

The last substance studied was OCS. Because of difficulties with obtaining analytical services for OCS, only 10 stormwater and overflow samples from Sarnia were analyzed for OCS. Such data were fairly consistent and ranged from less than 1 to 12 ng/ℓ, with the average value of 2 ng/ℓ. This average value was adopted for Sarnia. Since Sarnia appears to be the only city among the three cities studied with industrial use of OCS, the transposition of Sarnia data would lead to overestimation of OCS loadings in both Sault Ste. Marie and Windsor. Such an overestimation would not be particularly important because of very low loadings involved.

Annual Contaminant Loadings

Annual contaminant loading estimates were obtained by multiplying the annual flow volumes by the mean concentrations given in Table 7. In the case of stormwater, the loading calculations were done separately for the land use types studied and the total loading was obtained as the sum of individual components. Because no water quality data were available for relatively small volumes of runoff from institutional and open land, such volumes were added to the volume draining off the residential areas. For combined sewer overflows, only one loading calculation was done, because the composition data represented a mixed flow originating from districts with mixed land use.

A summary of total stormwater and overflow loadings is given in Table 8. Whenever applicable, the low and high estimates are given. With the exception of Cd and Co, both estimates are generally within the same order of magnitude.

Table 8. Summary of Annual Loadings in Urban Runoff from the Study Area

Parameter	Sarnia			Sault Ste. Marie	Windsor		
	Stormwater	Overflows	Total	Total Stormwater	Stormwater	Overflows	Total
Ammonia (N)	3,600	3,700	7,300	9,800	7,200	13,000	20,200
		15,000	18,600				
Phosphorus	1,800	400	2,200	4,100	5,600	2,800	8,400
		3,300	5,100				
Chloride	1,150,000	31,600	1,180,000	1,850,000	2,550,000	135,000	2,685,000
	2,300,000	62,700	2,363,000	3,700,000	5,100,000		5,235,000
Cadmium	3.8	4.8	8.6	2.0	6.5	5.2	11.7
	40.2[1]	8.0[1]	48.2[1]	78.0[1]	133.8[1]	41.6[1]	175.4[1]
Cobalt	0	0	0	0	6	3	9
	131(23)[1]	19(3)[1]	150(26)[1]	263(46)[1]	420(78)[1]	88(16)[1]	508(94)[1]
Copper	326	134	460	572	613	520	1,133
Iron	40,700	2,400	43,100	92,100	127,600	6,200	133,800
		8,100	48,800				
Lead	1,750	280	2,030	1,550	3,530	260	3,790
						830	4,360
Mercury	0.7	0.1	0.8	0.4	0.6	0.2	0.8
	0.8	0.7	1.5		1.1		1.3
Nickel	144	5	149	144	285	52	337
	220	22	242	338	524	229	753
Zinc	2,200	230	2,430	3,660	4,600	1,770	6,370
						2,600	7,200
Oil & Grease	40,000	7,200	47,200	33,300	35,700	64,000	99,700
		33,400	73,400		59,700		123,700
Phenols (total)	112	9	121	196	75	42	117
		24	136				
Cyanide	20	3	23	27	67	16	83
HCB	0.8	0.0	0.8	0.002	0.021	0.006	0.027
				0.006	0.026		0.032
OCS	0.013	0.002	0.015	(0.026)[2]	(0.045)[2]	(0.010)[2]	(0.055)[2]
PCB's (total)	1.3	0.1	1.4	0.4	0.5	0.5	1.0
		0.2	1.5	3.2	1.1		1.6
17 PAH's	47	5	52	122	49	21	70
	59	15	74	238	63	23	86

[1]Loadings calculated from data above the detection limit
[2]Loadings calculated using the Sarnia data

In terms of loading magnitudes, there is a great deal of consistency among all three subareas. In general, the loadings can be ranked in a descending order as follows:

Parameter	Annual Loading Magnitude (kg/yr)
Chloride	10^6
Iron	10^5
Oil & Grease	10^4-10^5
Ammonia, Phosphorus	10^3-10^4
Lead, Zinc	10^3
Copper	10^2-10^3
Nickel, Phenols	10^2
Cyanide, PAH's, Cadmium and Cobalt	10^1-10^2
PCB's, Hg	10^0
HCB	10^{-2}-10^{-1}
OCS	10^{-2}

When comparing the loadings carried by stormwater and combined sewer overflows, it appears that overflows are a predominant source of ammonia and phosphorus. For several other parameters including zinc, oil & grease, and mercury, both source strengths are comparable. For the remaining parameters, stormwater is the dominating source. This is particularly true for industrial chemicals, in which case stormwater contributes about 80% of the total loadings.

Finally, potential loadings of contaminants in urban runoff draining into Lake St. Clair were also estimated assuming no changes during transport. These loading estimates were based on an earlier estimate of the volume of urban runoff in the Lake St. Clair Basin (Marsalek and Schroeter 1984) and mean concentrations of all data from the UGLCC study area. A summary of such urban runoff loadings, which are obviously considerably less accurate than those given for the studied area, is presented in Appendix A.4. It appears that the estimated Lake St. Clair loadings are comparable to the total loadings from the three study subareas.

Distribution of Annual Loadings in Time

In some studies of water quality, it may be required to work with runoff loadings distributed in time and space. Spatial distribution of city-wide loadings can be determined proportionately to the contributing areas of individual outfalls, or more simply, proportionately to the flow capacity of individual outfalls. The determination of temporal distributions, which is more difficult, can be done from continuous simulations of runoff. Although such distributions should be derived from long-term data, some indication of temporal runoff distributions can be obtained from the typical precipitation/runoff records used in this study.

Runoff records simulated by the STORM model were analyzed for monthly runoff and overflow distributions. The results of such analysis are shown in Table 9. Finally, some basic characteristics of the largest runoff and overflow events were also determined and summarized in Table 10.

In spite of limitations of the distribution data in Tables 9 and 10, arising from the short length of the data records and limitations of the precipitation data used, non-uniformity of runoff distribution in the study area is quite obvious. Wet months may produce up to 21% of annual runoff or overflows. In fact, from 6% to 12% of the annual runoff or overflow may be conveyed by a single event lasting from 7 to 42 hours. The largest events, occurring on the average twice a month, convey from 72 to 94% of the annual runoff or overflow. Thus, it may be concluded that the hydraulic loadings to receiving waters are rather nonuniformly distributed and the same or even higher variations can be expected for contaminant loadings in runoff.

DISCUSSION

The estimates of contaminant loadings in urban runoff were prepared for comparison of various sources of selected contaminants in the study area. For such purposes, an accuracy in the order of magnitude is generally sufficient and, for some parameters, even two orders of magnitude may be acceptable, if there are large differences in the strengths of various sources. Only when the sources being compared are all significant and of similar strengths, better accuracies may be required.

Table 9. Monthly Runoff Distributions in the Study Subareas.

Study Subarea	Monthly Runoff and Overflow Volumes (Percent of Annual Volume)											
	J	F	M	A	M	J	J	A	S	O	N	D
Sarnia												
Runoff	1	2	17	4	7	10	3	17	8	1	18	12
Overflows	0	2	17	5	8	10	3	21	9	1	16	8
Sault Ste. Marie												
Runoff	0	8	6	17	2	11	7	9	14	14	6	6
Windsor												
Runoff	0	21	12	10	10	12	7	4	15	7	2	0
Overflows	0	21	11	9	10	13	9	5	16	4	2	0

Table 10. Basic Characteristics of Top-Ranked Runoff and Overflow Events in the Study Subareas.

	Event Volume (Percent of Annual Volume)					
	Sarnia		Sault Ste. Marie	Windsor		
	Runoff	Overflows	Runoff	Runoff	Overflows	
					Low Q_t	High Q_t
Top-ranked event	8	11	10	6	7	12
Total of 12 top-ranked events	50	55	54	52	52	73
Total of 24 top-ranked events	81	73	72	76	80	94
	Average Duration (hr)					
Top-ranked event	7	8	42	24	7	13
12 top-ranked events	26	24	21	15	11	12
24 top-ranked events	20	17	19	11	9	10

Annual pollutant loadings in urban runoff were derived as products of mean concentrations and annual flow volumes. It is evident that the total flow volume is estimated fairly accurately as shown by the sensitivity analysis of runoff simulations. It should be further recognized that there is some variability in the annual precipitation and that the precipitation is not uniformly distributed throughout the year. Some winter months (e.g. January) produce hardly any runoff, because of snow accumulation, and wet months may carry up to 21% of the annual runoff volume. Such nonuniform distribution of runoff combined with variations in pollutant concentrations results in a very nonuniform loading distribution.

In cities with combined sewerage, it is required to estimate the annual volume of sewage overflows which are affected by surface drainage. Overflow volumes are affected by surface runoff rates (controlled by precipitation, the runoff contributing area and its imperviousness), the dry weather flow rate, the sewer infiltration flow rate, the interceptor capacity, and the treatment and storage capacities of the wastewater treatment plant. Using generally available data, the total overflow volumes can be estimated with an acceptable accuracy, as shown by the sensitivity analysis. It should be also noted that for most contaminants overflows in the study area conveyed significantly lower loads than surface runcff and this somewhat reduces the requirements on the accuracy of estimates of overflow loadings.

Recognizing the relative accuracy of runoff volume computations, the main sources of uncertainties in the calculated contaminant loadings appear to be those associated with establishing the mean concentrations for the annual runoff volume. A number of steps have been taken to reduce such uncertainties. The first one is the selection of an appropriate sampling procedure. Recognizing large variations in instantaneous concentrations in urban runoff, it is desirable to concentrate on mean event concentrations which exhibit much less variation. This was done by collecting flow-proportional composite samples during individual events and, whenever feasible, composing such samples from several events in proportion to event runoff volumes. Such procedures increase the proportion of the total runoff sampled without increasing analytical costs.

The selection of catchment segments to be sampled is also very important. Surveys of land use distribution and runoff generation in the study area indicate that the most important areas to be sampled are the residential areas which produce more than two thirds of the total runoff. Next in importance would be industrial and commercial areas.

It follows from the earlier discussion that it is possible to assume that uncertainties in the calculated loadings are controlled by uncertainties in the mean concentrations used in loading calculations. Ideally, such concentrations would be defined as the annual contaminant flux divided by the annual runoff volume and would account for variations in the actual event concentrations caused by storm characteristics and catchment conditions. Such characteristics would include the storm rainfall depth and intensity, and the catchment conditions would include seasonal effects and contaminant accumulations during the antecedent dry period. The differences between the concentration calculated from the annual contaminant flux and that calculated for sampled events will diminish with the increasing number of events sampled. It is therefore of interest to examine the variations in sampled concentration data.

It was noted that mean concentrations for various land use did not vary significantly and, consequently, the stormwater data for individual subareas were aggregated into single data sets. The same was done for combined sewer overflows. For individual subareas and media sampled, the mean concentrations as well as their 95% confidence limits were determined. Subsequently, ratios of U/L were calculated where U and L are the upper and lower limits, respectively. The calculated U/L's were classified into the following three categories:

low variation (L)	$U/L \leq 3.3$
intermediate variation (I)	$3.3 < U/L \leq 6.6$
high variation (H)	$6.6 < U/L \leq 10$

Note that the upper limit value, U/L = 10, corresponds to the variation within an order of magnitude. The results of the above classification are summarized in Table 11.

Table 11. Evaluation of Variations in Estimates of Mean Concentrations.

Parameter	Stormwater			Combined Sewer Overflows	
	Sarnia	Sault Ste. Marie	Windsor	Sarnia	Windsor
Ammonia (N)	L[1]	L	L	L	H
Total P	L	L	L	H	H
Copper	L	L	L	L	I
Iron	L	L	H	L	-
Lead	L	L	L	L	I
Mercury	L	L	L	H	-
Nickel	L	L	L	L	I
Zinc	L	L	L	I	L
Oil & Grease	I[2]	L	-[4]	H	-
Total Phenols	L	L	L	I	I
Cyanide	I	L	-	I	-
HCB	I	L	L	H	L
PCB's(total)	L	L	L	I	I
17 PAH's	L	H[3]	L	I	I

[1]Low variation, $U/L \leq 3.3$.
[2]Intermediate variation, $3.3 < U/L \leq 6.6$.
[3]High variation, $6.6 < U/L \leq 10$
[4]- Data not available

It appears from Table 11 that no data exceed the limit of the order of magnitude. For stormwater, the variations are particularly low with the exception of Fe in Windsor and PAH's in Sault Ste. Marie. In both cases, higher variations were caused by a particular site giving consistently high values. It can be expected that all calculated loadings are well within the targetted accuracy. For combined sewer overflows, higher variations were noticed. Relatively high variations were noticed for NH_3, P, Hg, Oil & Grease and HCB at either subarea, or in one case (P) at both subareas. These higher variations are generally less significant for calculations of total loadings which are mostly controlled by stormwater.

Among the parameters studied, chloride, OCS, Cd and Co are not listed in Table 11 and require further discussion.

Chloride concentrations in stormwater exhibit extreme seasonal variations and unless the snowmelt period is fully sampled, observed concentrations are not suitable for calculation of annual loadings. For that reason, chloride loadings were calculated from road salt usage records. Road salt is applied over impervious surfaces and later removed with snowmelt. Eventual losses caused by snow removal or splashing are considered to be small (Waller and Hart 1986). Consequently, two estimates of chloride loadings were proposed. The high estimate is based on an assumption that there are no losses and all chloride applied reaches the receiving waters. In the low estimate, the losses were somewhat arbitrarily estimated at one half and the remaining half would reach the receiving waters.

Octachlorostyrene was not routinely studied because of limited analytical support. The only OCS data available were collected in Sarnia during a special survey. Such data showed a relatively low mean concentration (2 ng/ℓ) which reflects the relatively limited use of OCS in the production of specialty polymers. Among the subareas studied, Sarnia is the only one with reported direct use of OCS. Consequently, OCS loadings were calculated only for Sarnia. It should be noted that transposition of Sarnia data to the other subareas, which cannot be fully justified, would produce minimal loadings (10^{-2} kg/yr) for these areas.

For Cd and Co, the commonly used analytical methods had detection limits of 0.01 and 0.02 mg/ℓ, respectively. For these limits, practically all the data were below the detection level. Consequently, more sensitive methods were applied to about 10% of all samples and produced quantitative data. Such data from all three subareas were grouped together and used to estimate mean concentrations which were then used in loading calculations. The numbers of such samples were insufficient to judge the uncertainties in the calculated loadings. It should be noted that the estimated loadings for Cd and Co represent about one half and one sixth, respectively, of the loadings corresponding to the conventional detection limits.

The study objective was to estimate contaminant loadings within an order of magnitude which would indicate the lower and upper bounds as about 30% and 300% of the mean estimates given, respectively. The general consistency of runoff quality data and good accuracy of runoff volume calculations indicate that the loadings produced meet such criteria. For most parameters, the accuracy of loadings is much better than the above criterion. The only total loadings which may contain uncertainties as high as an order of magnitude are those of PAH's in Sault Ste. Marie and mercury in Windsor.

CONCLUSIONS

A methodology for evaluation of urban runoff as a diffuse source of contaminants has been developed and applied to the Cities of Sarnia, Sault Ste. Marie and Windsor. This methodology is based on calculation of source loadings from representative mean concentrations and calculated runoff volumes in the form of stormwater or combined sewer overflows. Runoff calculations were accomplished by the STORM model which is a simple continuous model. This model was applied to each study subarea using hourly precipitation data from years with average annual precipitation. For each application, a sensitivity analysis of runoff modelling was done and its results were helpful in the selection of final model parameters. It was noted that the annual runoff volume represented about one third of the annual precipitation and the volume of overflows represented from 4 to 8% of the annual wastewater treatment plant flow. Annual runoff and overflow were nonuniformly distributed during the year, with the largest event conveying from 6 to 10% of the annual volume and the wet months contributing up to 21% of the annual volume.

The characteristic runoff quality data were determined by sampling runoff quality at a number of sites in each study subarea. Such sites were located in principal land use sectors, including residential, industrial and commercial land. At each site, runoff or overflow samples were collected in the form of composite flow-proportional samples and when feasible such samples from two or more events were further composed according to the event runoff. By this approach, it was possible to increase the number of events sampled and analyzed with a given limited analytical support.

Contaminant loadings were obtained as products of mean characteristic contaminant concentrations and flow volumes. In terms of loading magnitudes, the contaminants are ranked below and the loading magnitudes are given in the brackets: Chloride (10^6 kg/yr), iron (10^5 kg/yr), oil and grease (10^4-10^5 kg/yr), ammonia and phosphorus (10^4 kg/yr), lead and zinc (10^3 kg/yr), copper (10^2-10^3 kg/yr), nickel and phenols (10^2 kg/yr), cyanide, PAH's, cadmium and cobalt (10^1-10^2 kg/yr), PCB's and mercury (10^0 kg/yr), HCB (10^{-2}-10^{-1} kg/yr), and OCS (10^{-2} kg/yr). Such loadings will be further evaluated by the UGLCC study team in relation to those from other sources.

The consistency of runoff quality data and relative accuracy of volume calculations indicate that the loading accuracy requirement of an order of magnitude is met by the calculated loadings. The annual loadings are nonuniformly distributed during the year with single events carrying up to 11% of the annual hydraulic loading.

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APPENDIX

Appendix A.1

Sampling Sites in Sarnia

S.1 - Charlesworth Drive - flow-proportional samples of runoff from a residential areas were collected by an inlet sampler.

S.-2 - Devine Street Overflow Chamber - flow-proportional samples of combined sewer overflows were collected. An automatic wastewater sampler was actuated by the rising water level and sequentially collected samples were composed, after the event, according to the flow record.

S.3 - Eastland Mall - flow-proportional samples of runoff from a commercial area were collected by an inlet sampler.

S.4 - Clifford Street Overflow Chamber - flow-proportional samples of combined sewer overflows were collected. An automatic wastewater sampler was acuated by the rising flow level and sequentially collected samples were composed, after the event, according to the flow record.

S.5 - Pollution Control Plant - influent to the plant was sampled during wet weather. The composition of influent would be comparable to that of combined sewere overflows. Samples were collected by an automatic wastewater sampler actuated by the flow level increase beyond the normal daily/weekly variation.

S.6 - South Vidal Street - flow-proportional samples of runoff from an industrial area were collected by an inlet sampler.

Sampling Sites in Sault Ste. Marie

SSM.1 - Georgina Street - flow-proportional samples of runoff from a residential area were collected by an inlet sampler.

SSM.2 - Station Mall - flow-proportional samples of runoff from a commercial area were collected by an inlet sampler.

SSM.3 - Hudson Street - flow-proportional samples of runoff from an industrial area were collected by an inlet sampler.

Sampling Sites in Windsor

W.1 - Little River Pollution Control Plant - plant bypasses during wet weather were sampled. The composition of such bypasses should be comparable to that of combined sewage overflows. Samples were collected by an automatic wastewater sampler actuated by the rising flow level. Sequentially collected samples were composed, after the event, according to the flow record.

W.2 - Greendale Avenue - flow-proportional samples of runoff from a residential area were collected by an inlet sampler.

W.3 - Tecumseh Mall - flow-proportional samples of runoff from a commercial area were collected by an inlet sampler.

W.4 - Chilver Road Overflow Chamber - flow-proportional samples of combined sewer overflows were collected. An automatic wastewater sampler was actuated by the rising flow level and sequentially collected samples were composed, after the event, according to the flow record.

W.5 - Albert and Metcalf Streets - flow-proportional samples of runoff from an industrial area were collected.

W.6 - Grand Marais Drain - sequential samples of runoff from industrial areas were collected by an automatic wastewater sampler actuated by the rising water level. Sequential samples were flow-proportionately composed after the event.

Appendix A.2. Characterization of Rainwater and Snowmelt Composition in the Study Area.

Parameter	Units	Rainwater		Snowmelt in Windsor		
		Sarnia	Windsor	Residential	Commercial	Industrial
NH_3	mg/ℓ	0.61	0.28	0.41	0.16	0.58
TP	mg/ℓ	0.015	0.017	0.24	0.14	0.19
Chloride	mg/ℓ	0.63	-	-	-	-
Cd	mg/ℓ	L0.005	L0.005	L0.01	L0.01	L0.01
Co	mg/ℓ	L0.02	L0.02	L0.02	L0.02	L0.02
Cu	mg/ℓ	L0.01	L0.01	0.083	0.037	0.033
		0.021	0.01			
Fe	mg/ℓ	0.25	-	-	-	-
Pb	mg/ℓ	0.022	0.008	0.09	0.11	0.25
		L0.05	L0.02			
Hg	µg/ℓ	0.043	0.02	0.033	0.06	0.053
			L0.02			
Ni	mg/ℓ	L0.02	0.004	L0.02	L0.02	L0.02
		0.032	L0.02		0.06	0.03
Zn	mg/ℓ	0.085	0.063	0.17	0.25	0.66
HCB	ng/ℓ	3.6	L0.4	1.6	2.2	1.6
PCB's	ng/ℓ	27.6	L9	115	126	209
			10			
12 PAH's	ng/ℓ	715	0	1665	6769	4673
		1175	600	2067	7086	4940

Explanations:

L = less than (detection limit). All single entries are mean values. For parameters with data below the detection limit, a range of values is given. For PAH's concentrations, the lower and upper estimates are given. In the former one, all values below the detection limit are taken as zeroes. In the upper estimate, the values below the detection level are set equal to the detection limit.

Appendix A.3. List of 17 PAH's Studied.

Substance	AWQUA LABS CODE
Indene	A631
1,2,3,4-Tetrahydronaptha	A632
2-methylnapthalene	A633
Quinoline	A634
1-methylnapthalene	A635
b-chloronapthalene	A636
Acenapthalene	A637
Acenapthene	A638
Fluorene	A639
Phenanthrene	A640
Fluoranthene	A641
Pyrene	A642
Fluoranthene	A586
Benzo-b-fluoranthene	A587
Benzo-k-fluoranthene	A588
Benzo-a-pyrene	A589
Indenopyrene	A590
Benzopyrene	A591

Appendix A.4. Potential Contaminant Loadings in Urban Runoff in the Lake St. Clair Basin.

Parameter	Mean Concentration		Annual Loading (kg/yr)
Ammonia	0.45	mg/ℓ	24,000
TP	0.23	mg/ℓ	12,000
Chloride	100	mg/ℓ	5,330,000
	200	mg/ℓ	10,660,000
Cadmium			320
Cobalt			187
Copper	0.05	mg/ℓ	2,700
Iron	7.1	mg/ℓ	378,400
Lead	0.20	mg/ℓ	10,700
Mercury	0.061	mg/ℓ	3.3
Nickel	0.033	mg/ℓ	1,800
Zinc	0.29	mg/ℓ	15,500
Oil & Grease	4.1	mg/ℓ	219,000
Total Phenols	0.013	mg/ℓ	693
Cyanide	0.0026	mg/ℓ	139
HCB	1.04[1]	ng/ℓ	0.06
OCS	2	ng/ℓ	0.11
PCB's	121	ng/ℓ	6.4
17 PAH's	5300	ng/ℓ	282

[1]High values from Sarnia excluded

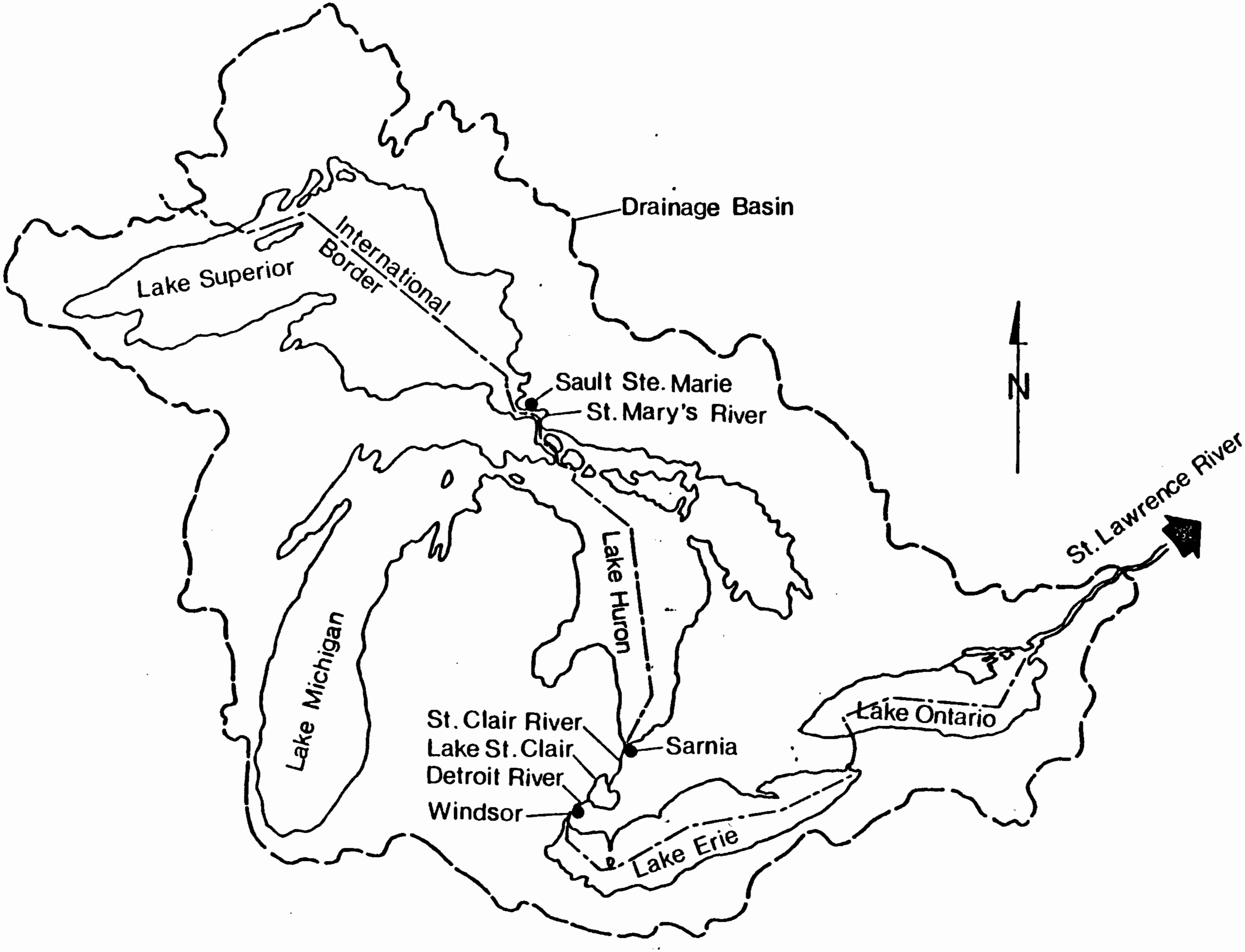

Fig. 1. Great Lakes System and Connecting Channels

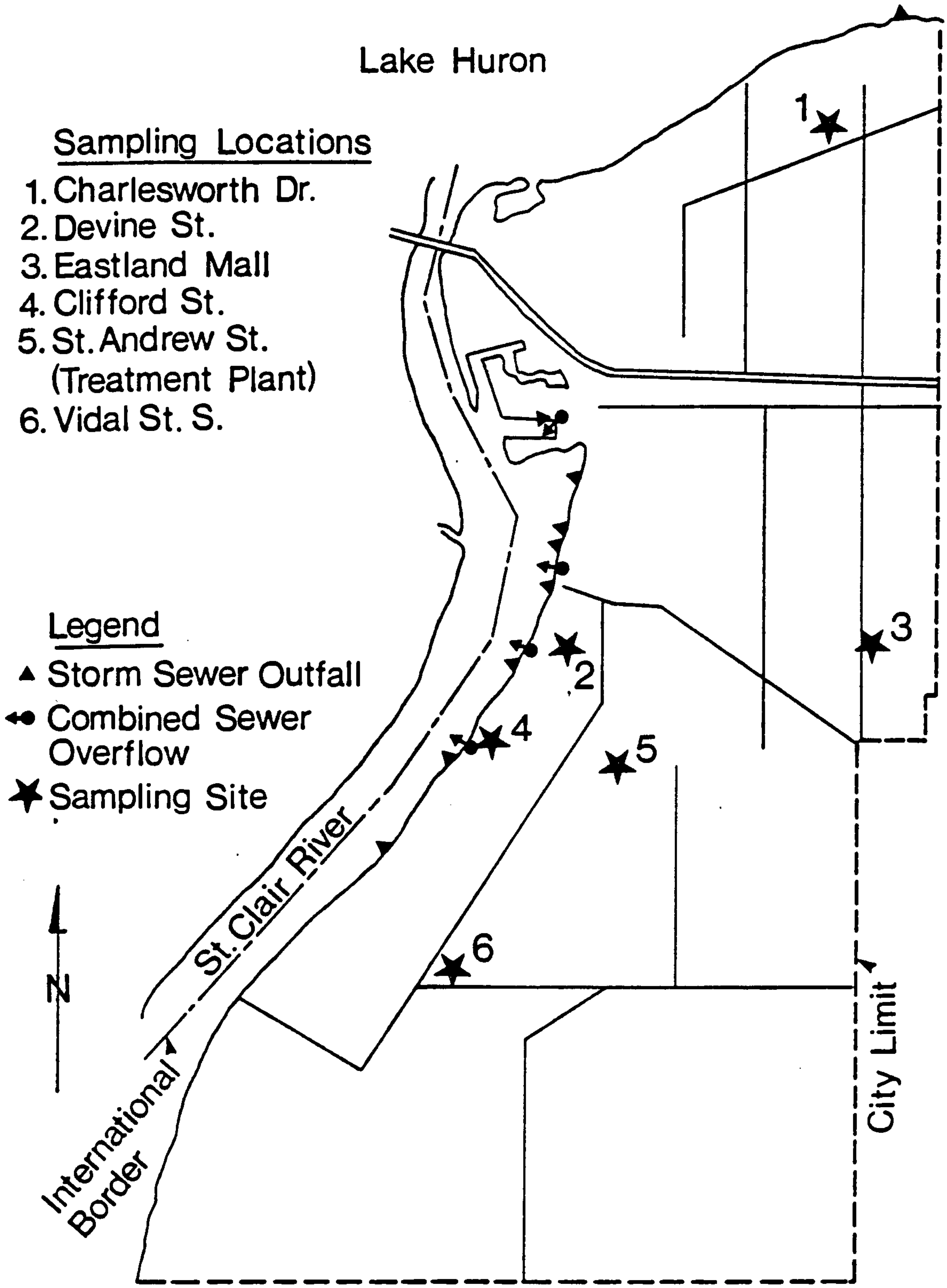

Fig. 2. Runoff Outfalls and Sampling Sites in Sarnia.

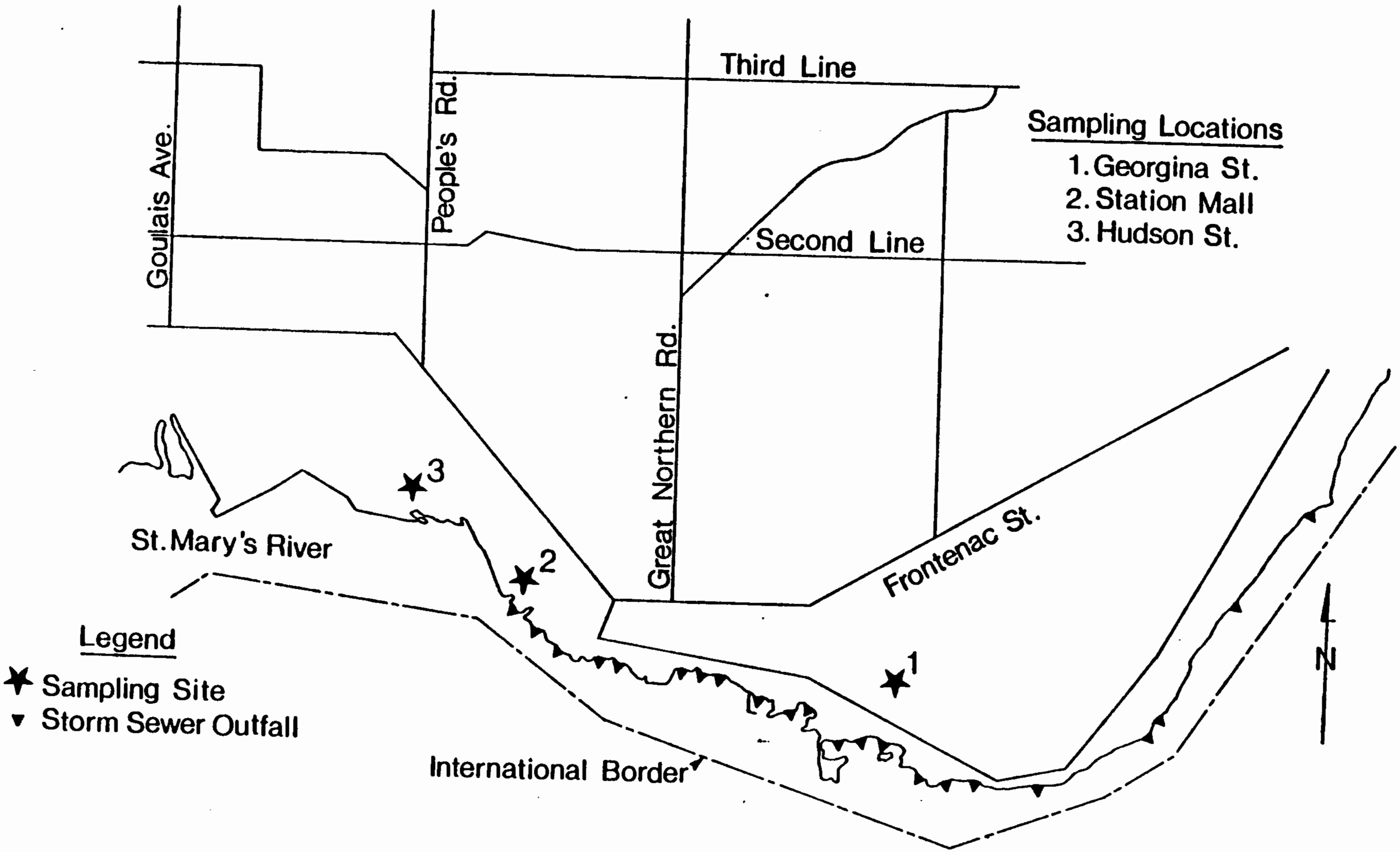

Fig. 3. Storm Sewer Outfalls and Sampling Sites in Sault Ste. Marie.

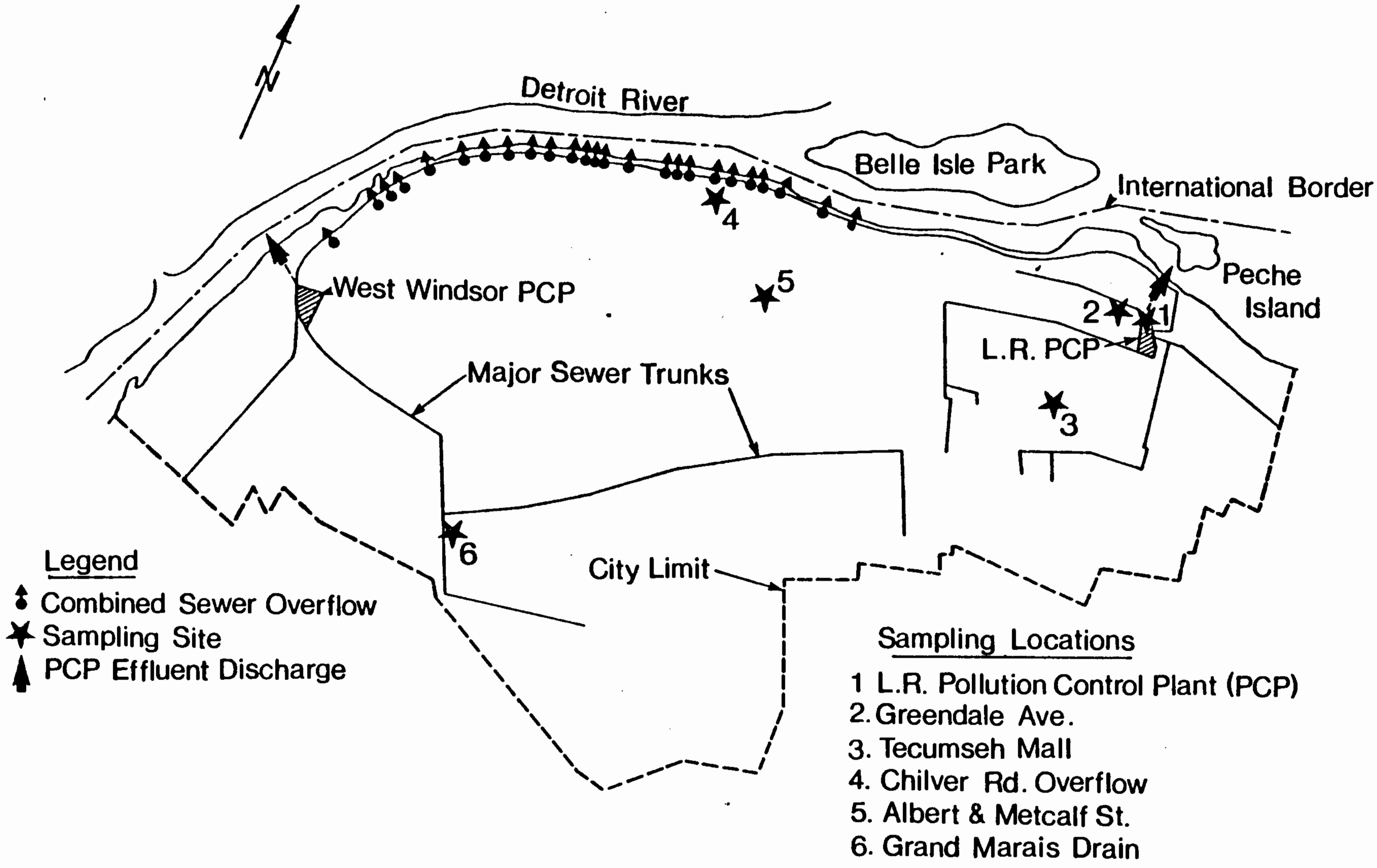

Fig. 4. Combined Sewer Overflow Outfalls and Sampling Sites in Windsor.

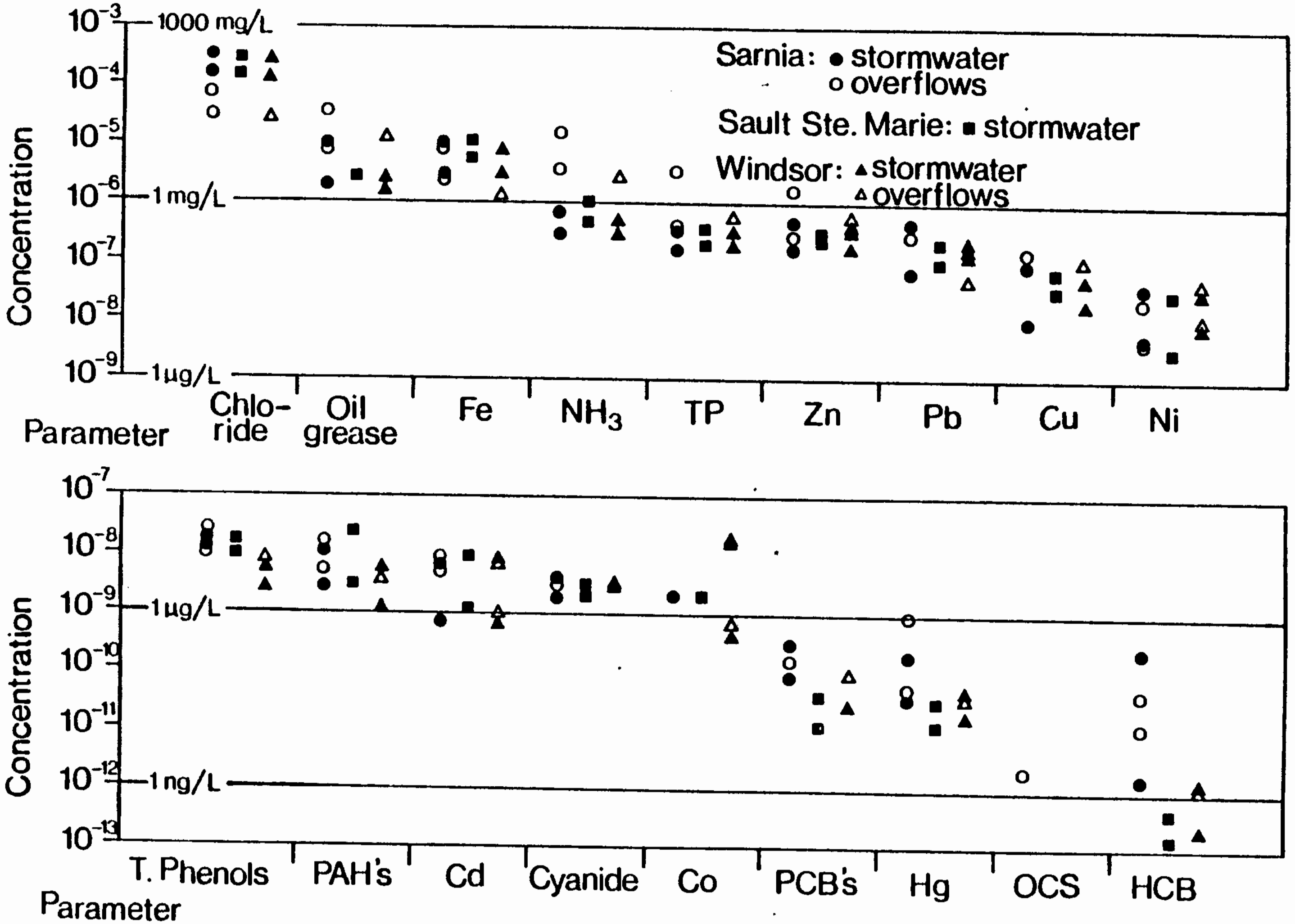

Fig. 5 Ranges of Contaminant Concentrations in Runoff From the Study Area.

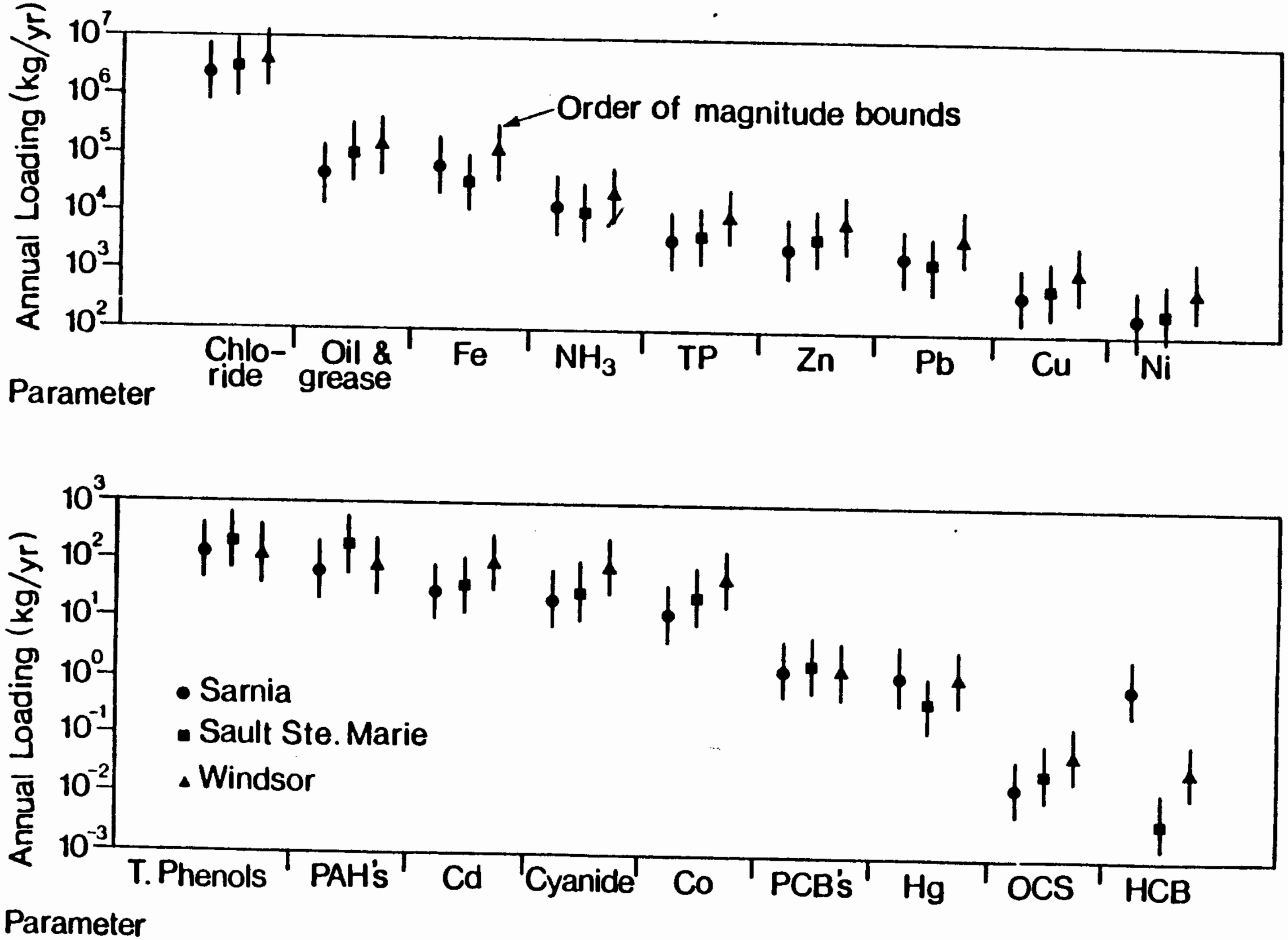

Fig. 6 Annual Contaminant Loadings in Urban Runoff From the Study Area.