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EVALUATION OF POLLUTION LOADINGS FROM URBAN NONPOINT SOURCES: METHODOLOGY AND APPLICATIONS

J. Marsalek and H. Y. F. Ng
National Water Research Institute
P.O. Box 5050
Burlington, Ontario L7R 4A6

ABSTRACT. In preparation of remedial action plans for the St. Clair, Detroit, and St. Marys rivers, a planning-level methodology for evaluation of pollutant loadings from urban nonpoint sources was developed and applied in three Canadian cities: Sarnia, Sault Ste. Marie, and Windsor. This methodology uses computed annual volumes of runoff and mean constituent concentrations, estimated from field sampling, to produce estimates of annual pollutant loadings. For the constituents studied, the total loadings were predominantly from point sources in about three quarters of all cases. For some of the less common substances, occurring at low levels, the nonpoint sources contributed loadings which were comparable to or even higher than those from point sources. Such findings will be useful in the development of remedial action plans which need to focus on control of pollutant sources.
ADDITIONAL INDEX WORDS: Urban runoff, combined sewer overflows, toxic substances.

INTRODUCTION

Since 1973, the Great Lakes Water Quality Board has identified "areas of concern" along the Great Lakes where various water quality standards, criteria, or guidelines, established to protect water uses, have been exceeded, and remedial measures are needed to restore all beneficial uses. Such areas generally include major municipal and industrial centers on the Great Lakes, and rivers, harbors, and connecting channels. The board also identified the sources of pollution causing such problems, including urban land runoff and combined sewer overflows (Great Lakes Water Quality Board 1982).

In preparation of remedial action plans, the magnitudes of pollutant contributions from point as well as nonpoint sources need to be assessed. Such an assessment was recently completed for three areas of concern; the St. Clair River, the St. Marys River, and the Detroit River (UGLCC Study Workgroup 1988a, 1988b, and 1988c). This paper presents a planning-level methodology developed for estimation of pollutant contributions from urban nonpoint sources and results of application of such methodology to these areas.

METHODS

Computation of Urban Nonpoint Source Loadings

Urban runoff is considered here as a nonpoint source of pollution which is discharged into the receiving waters in two forms, either as stormwater discharges from storm sewers, or overflows from combined sewer systems. Pollutant loadings in urban runoff can be generally estimated by one of several methods depending on the level of analysis and the size of the area.

In detailed analysis of small catchments, the best estimates of runoff loadings are obtained from field measurements (Huber 1986), or from detailed simulations with calibrated mathematical models (Novotny *et al.* 1985). In a planning-level analysis of large areas, the loadings are calculated from empirical load functions, in the form of unit area loading rates or mean concentrations, for various types of land use (Sullivan *et al.* 1978, USEPA 1983). Although the ability of general load functions to estimate loadings from specific areas may be questioned, such functions were derived from large samples of data from many catchments and this contributes to their general applicability (USEPA 1983).

Method for Computation of Loadings

The goals of the loading computation method used in this study are to retain some simplicity of the methods based on general loading rates and, at the same time, to reflect local conditions. The annual loading of pollutant j in runoff from an area with a particular land use can be expressed as

$$L_j = \sum_{i=1}^{N} Q_i C_{ji} \quad (1)$$

where subscript i = 1,. . .N denotes individual events during the year, Q_i is the event runoff volume, and C_{ji} is the event mean concentration. Eq. (1) can be further simplified by recognizing lack of correlation between Q and C, as found for example in the Nationwide Urban Runoff Program (NURP) (USEPA 1983), and introducing a mean concentration C_j. Eq. (1) is then rewritten as

$$L_j = C_j V \quad (2)$$

where $V = \Sigma Q_i$ is the annual runoff volume, and the annual mean concentration C_j is estimated from field data as

$$C_j = \frac{1}{V} \sum_{i=1}^{N} C_{ji} Q_i \sim \frac{1}{n} \sum_{i=1}^{n} C_{ji} \quad (3)$$

where n is the number of events actually sampled. The total loading for an urban area is then obtained by summation of contributions from individual land use types.

The annual runoff volume V can be adequately estimated by approximate methods, including the runoff coefficient method (USEPA 1983), the Soil Conservation Service method (Kibler 1982), and the STORM model (U.S. Army Corps of Engineers 1977). The main difficulty in application of eq. (2) is the estimation of C_j by field sampling recognizing that, in the planning-level of analysis, the target accuracy may be as low as an order of magnitude and can be achieved with a relatively small number of samples.

Field sampling should characterize three sources of variability in C_j—during individual runoff events, between events, and among sites. Variability during events can be accounted for by collecting flow-proportional composite samples.

Variability between events requires a number of events to be sampled at each site. Although the minimum number of events to be sampled cannot be specified *a priori*, it is possible to continue sampling until the uncertainties in the mean concentrations become so low that they do not affect the outcome of relative comparisons of total nonpoint and point source loadings. In the NURP Program, variability due to sampling was described by the coefficient of variation which typically attained values in the range from 0.5 to 1.0. The reported lack of correlation between event runoff volumes and mean concentrations makes it acceptable to sample events of any magnitude, without a particular emphasis on large events (USEPA 1983).

Finally, to characterize variability in C among sites, it is required to sample in areas with various land use and rates of export of pollutants. Representativeness of samples is increased by establishing sampling sites with large contributing areas.

Similar procedures can be applied to combined sewer overflows, where the annual volume of overflows can be estimated from the known intercepting sewer capacity, observed dry weather flow and infiltration, and calculated runoff inflow. The flows in excess of the interceptor capacity are considered as overflows (U.S. Army Corps of Engineers 1977). The composition of overflows is obtained by sampling wet weather flow at overflow structures or in the interceptor.

The assumption of lack of correlation between overflow volumes and mean concentrations may require further field verifications for the specific pollutants studied. Composition of overflows is affected by many factors including sewer flow characteristics, mixing of dry weather flow with surface runoff, scouring of sewer sediment during high flows, deposition of sediment during low flows, the times of overflow occurrence during the day and week, and characteristics of the overflow regulator. The importance of individual factors varies depending on the constituent studied, the climate, characteristics of the sewer system, pollution of surface runoff and dry weather flow, and timing during an overflow event. Consequently, no single source of pollution dominates pollutant loads in overflows (Krejci *et al.* 1987) and the correlations between event runoff volumes and pollutant loads may be relatively weak.

APPLICATIONS

Study Area

The study area comprised three major sources of urban runoff on the Canadian side of the Upper

Great Lakes Connecting Channels. The City of Sarnia, located at the outflow of the St. Clair River from Lake Huron, has a population of about 50,000 inhabitants. The drainage in the city is provided by combined and separate sewers, and open drains. Combined sewers serve some older parts of the city, about 540 ha in area, and discharge into an interceptor with four overflow structures. Private drainage outfalls in the chemical valley area were studied by others as point sources (UGLCC Study Workgroup 1988b). The petrochemical industry is the principal industry in this area.

The City of Sault Ste. Marie, Ontario, has a population of about 83,000 inhabitants and is located along the St. Marys River. Surface drainage in the city is provided by storm sewers. The principal industry in the city is the primary manufacturing of iron and steel.

The City of Windsor, located along the Detroit River, has a population of about 193,000 inhabitants. Drainage in the city is provided by combined sewers, storm sewers, storm relief sewers, and open drains. Two areas in the city, a central district (2,100 ha) along the Detroit River and a small area close to the Little River Pollution Control Plant (260 ha), are served by combined sewers. The rest of the city is served by storm sewers. The principal industry in the city is the automotive industry.

Urban Land Runoff Volumes

Estimates of the annual volumes of runoff from the study area were produced by the STORM model (U.S. Army Corps of Engineers 1977). For each urban area, the model was run for 1 year with the annual precipitation approximating the long-term average. Although the model was not calibrated, the selection of model parameters was guided by a sensitivity analysis and the literature data. In the sensitivity analysis, model input data, listed in Table 1, were varied within a practical range of values (Marsalek and Ng 1987). It was noted that among the input data, only the runoff coefficients for impervious and pervious areas had significant impacts on computed volumes. The adopted value of the runoff coefficient for impervious areas was verified against the literature data (Kibler 1982). Therefore, the main source of uncertainty in runoff calculations is the runoff coefficient for pervious areas.

From the point of view of pollution generation, contributions from urban pervious areas, generally represented by grassed areas, are relatively small, because runoff from such areas is much less polluted than runoff from impervious areas (USEPA 1983). Consequently, even significant uncertainties in volumes of runoff from pervious areas may be acceptable, because of their limited impact on pollution loadings.

A similar approach, based on the sensitivity analysis, was adopted in the selection of input parameters for calculations of overflow volumes (Marsalek and Ng 1987). Stormwater discharges in Sarnia, Sault Ste. Marie, and Windsor were determined as 6.7, 13.0, and 22.3 million m^3/yr, respectively, and the volumes of combined sewer overflows in Sarnia and Windsor were calculated as 1.0 and 5.2 million m^3/yr, respectively.

Runoff and Overflows Composition

The list of constituents studied, shown in Table 2, was established by analysis of water quality problems in the study area (UGLCC Study Workgroup 1988a, 1988b, 1988c). All such constituents were deemed important for design of remedial measures.

The study resources, in terms of personnel, field equipment, and analytical support, allowed the establishment of 15 sampling sites; ten for sampling stormwater in all three cities and five for sampling overflows in Sarnia and Windsor (Marsalek and Ng 1987). The stormwater sampling sites were distributed among residential, commercial, and industrial areas. The sites for sampling combined sewage were located either at overflow structures or along the interceptor. Considering the relatively low accuracy required and the observed limited variability of runoff composition among sites, the total number of sampling sites was found adequate.

Stormwater and combined sewer overflow samples were collected by means of automatic samplers and sewer inlet samplers. The automatic samplers collected sequential samples of overflows or stormwater, which were composed into flow-proportional samples. The sewer inlet samplers collect directly flow-proportional samples (Marsalek and Ng 1987). This type of sampling does not reflect temporary variations in water quality caused by storage in catch basins or sewers, which were considered unimportant over extended time periods. However, another limitation of sampling at sewer inlets should be recognized—it cannot detect illicit discharges from point sources into storm sewers (Schmidt and Spencer 1986). Such

TABLE 1. Runoff simulations: input data and results.

	Study Area		
	Sarnia	Sault Ste. Marie	Windsor
INPUTS			
Hydrologic Parameters			
Runoff Coefficient			
Impervious Areas	0.90	0.90	0.90
Pervious Areas	0.15	0.20	0.15
Surface Depression Storage (mm)	1.50	1.50	1.50
Land Use Data			
Area (ha)/Imperviousness (%)			
Residential	1,570/30%	2,340/25%	6,900/30%
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%
Other Data			
Runoff Contributing Area (ha)	3,200	4,500	9,800
Combined Sewerage Area (ha)	540	-	2,360
Daily Dry Weather Flow Plus Infiltration (m^3/day)	57,000	-	163,000
Full Treatment Rate (m^3/day)	68,000	-	386,000
RESULTS			
Annual Runoff and Overflow Volumes			
Surface Runoff (m^3/yr)	6.7×10^6	13.0×10^6	22.3×10^6
Comb. Sewer Overflows (m^3/yr)	1.0×10^6	-	5.2×10^6
Total Volume Drained (m^3/yr)	7.7×10^6	13.0×10^6	27.5×10^6

discharges were not considered important in the nonindustrial parts of the study area, and in industrial parts, storm drains with possible contamination from point sources were considered as point sources (UGLCC Study Workgroup 1988a, 1988b, 1988c).

RESULTS

Sampling results were used to estimate mean pollutant concentrations for residential, commercial, and industrial land. Using such mean concentrations and the corresponding annual runoff volumes, the pollutant subloadings were computed for individual land use types and then summed up to yield the total loadings for all individual constituents except chloride (Marsalek and Ng 1987). Chloride originates from winter road salting and its concentrations in urban runoff vary so much during the year that it was not feasible to characterize them by limited sampling. Consequently, the chloride loadings were estimated from road salt usage records assuming, somewhat conservatively, that all salt is washed off by runoff.

The mean concentrations of pollutants in stormwater from individual cities can be determined by division of the total loadings by the total annual runoff volume. Such concentrations are shown in Table 3 together with some literature data (Marsalek and Schroeter 1984, USEPA 1983) and the hypothetical equivalent point source concentrations, which were defined as the annual point source loadings divided by the annual volume of stormwater. The data in Table 3 can serve for comparisons of runoff characteristics among the three areas studied, verification of such data against the literature data, and a quick evaluation of stormwater pollutant levels. The stormwater loadings are comparable to the point source loadings if the pollutant levels in runoff are comparable to the equivalent point source levels shown in Table 3.

Finally, the stormwater and overflow loadings

TABLE 2. Urban runoff constituents studied.

Parameter	Detection Limit (mg/L)	Parameter	Detection Limit (ng/L)
Ammonia (nitrogen)	.001	Polynuclear Aromatic Hydrocarbons (PAHs)	
Phosphorus (total)	.001		
Chloride	.050		
Cadmium	.001	Indene	50
Cobalt	.001	1,2,3,4-Tetrahydro-naphthalene	50
Copper	.001		
Iron	.020	2-Methylnaphthalene	50
Lead	.001	Quinoline	50
Mercury	.00002	1-Methylnaphthalene	50
Nickel	.001	2-Chloronaphthalene	50
Zinc	.001	Acenaphthylene	50
Cyanides (total)	.010	Acenaphthene	50
Oil & Grease	.1	Fluorene	50
Phenols (total)	.001	Phenanthrene	50
		Fluoranthene	50
	Detection Limit (ng/L)	Pyrene	50
		Benzo(b)fluoranthene	100
Hexachlorobenzene (HCB)	0.4	Benzo(k)fluoranthene	100
Octachlorostyrene (OCS)	1	Benzo(a)pyrene	100
Polychlorinated Biphenyls (total PCBs)	9	Indeno(1,2,3-cd)pyrene	100
		Benzo(ghi)perylene	100

were added to the point source loadings determined by the UGLCC Study Workgroup (1988a, 1988b, 1988c), to obtain the total loadings from all sources and the relative contributions of various nonpoint and point sources. Annual loadings for individual sources, overflows, stormwater, municipal and industrial point sources, are shown in Figure 1. Numerical results can be found elsewhere (Marsalek and Ng 1987; UGLCC Study Workgroup 1988a, 1988b, 1988c). The distributions of total loadings among individual sources are presented in Figure 2.

DISCUSSION OF RESULTS

Discussion of results focuses on uncertainties in loading estimates, verification of stormwater and overflow composition data, comparison of sources, and a general evaluation of the methodology used. Uncertainties in the nonpoint source loadings should be considered in the context of the primary use of such data for comparisons of relative contributions of pollutant sources and development of cost effective remedial measures. For the majority of constituents studied, the total loadings are clearly dominated by point sources and even considerable uncertainties in nonpoint loadings may be acceptable as long as they do not affect water management decisions.

The overall uncertainty in nonpoint loadings calculated from eq. (2) is a resultant of uncertainties in the estimated annual runoff volumes and mean concentrations. Uncertainties in stormwater runoff volumes were estimated from sensitivity analysis of runoff simulations and described by a coefficient of variation $C_{vV} = 0.15$. Uncertainty in mean concentrations results from several sources, among which the most important seems to be variabilities at the site and among sites.

Variability in concentrations among sites was described by $C_{vAS} = 0.17$, which was obtained by evaluating deviations of mean concentrations among the sites sampled. Variabilities at sites were evaluated for individual constituents from event data. The resulting C_v's ranged from 0.17 to 0.71 and represented the main source of uncertainties in loadings. Using the above component C_v's for stormwater, the composite coefficients of variation in concentrations were calculated as $C_{vC} = (C_{vAS}^2 + C_{vS}^2)^{0.5}$ in the range from 0.23 to 0.73 and, for loadings, C_{vL} ranged from 0.28 to 0.75. For over-

TABLE 3. Constituent concentrations.

	Mean Stormwater Concentrations (mg/L)					Point Source Equivalent Concentrations (mg/L)[1]		
Constituent	Sarnia	Sault Ste. Marie	Windsor	NWRI Data Base[2]	NURP Data Base[3]	Sarnia	Sault Ste. Marie	Windsor
Ammonia	.522	.744	.296	-	-	75.4	181.5	27.7
Phosphorus	.299	.309	.231	-	.330	4.0	3.4	3.7
Chloride	343	285	229	-	-	19,600	623	17,850
Cadmium	.0068	.0060	.0054	.0015	-	.0075	.002	.0151
Cobalt	.0035	.00035	.0023	.0040	-	.046	.0	.133
Copper	.0472	.0434	.0440	.0270	.034	.587	.0228	.424
Iron	5.71	6.96	5.71	-	-	28.2	50.6	5.47
Lead	.233	.0966	.154	.146	.144	1.6	.174	.491
Nickel	.0385	.0313	.0278	.022	-	.212	.0512	.278
Zinc	.307	.274	.234	.490	.160	2.2	1.0	2.8
Cyanides	.0029	.0020	.0030	-	-	.047	2.0	.038
Oil & Grease	5.37	2.52	2.14	-	-	135	282	30.0
Phenols	.017	.0151	.0033	-	-	.627	.286	.776
	Mean Stormwater Concentrations (μg/L)					Point Source Equivalent Concentrations (μg/L)		
Mercury	.104	.029	.043	-	-	2.3	.16	.10
Hexachlorobenzene	.0985	.00046	.0017	.0089	-	1.343	.0	.0
Octachlorostyrene	.0019	-	-	-	-	.254	.0561	.0
PCBs	.179	.0269	.0888	.131	-	.179	.0	.641
PAHs	9.1	9.0	2.1[4]	-	-	18.0[5]	19.4[5]	13.6[5]

[1]Concentrations calculated from point source loadings (Upper Great Lakes Connecting Channels Workgroup 1988a, 1988b, 1988c) which were divided by the annual volume of stormwater runoff
[2]Data from Marsalek and Schroeter (1984)
[3]Data from U.S. Environmental Protection Agency (1983)
[4]Only the first 12 PAHs listed in Table 1 were studied
[5]The selection of PAH substances analyzed for point sources somewhat differed from those listed in Table 2

flow loadings, the uncertainties were somewhat higher, with C_{vV} estimated at 0.25 and C_{vC}'s ranging from 0.24 to 0.99. The resulting uncertainties would range from 0.35 to 1.02.

Variations in mean concentrations in stormwater from individual cities are small for relatively common pollutants whose levels can be, therefore, verified by comparisons among the study subareas. Consequently, a limited number of sampling sites is sufficient to obtain runoff characterization for these pollutants. Larger differences become apparent for less common substances, such as HCB, PAHs, and PCBs, which originate from local industrial sources. Consequently, more extensive sampling may be required for such substances.

Combined sewer overflow concentrations were compared for Sarnia and Windsor. Significant differences were observed for ammonia, phosphorus, zinc, iron, and HCB. It appears that overflows reflect the local composition of point sources, municipal and industrial sewage, and generalizations of results should be avoided.

For nine constituents listed in Table 2, the concentration data from the study area were compared to similar data, based on event mean concentrations, representing a wide range of urban areas (Marsalek and Schroeter 1984, USEPA 1983). A good agreement was found for five fairly common constituents: total phosphorus, copper, lead, zinc, and nickel. For these constituents, the use of the literature data would have produced loadings fully comparable to those obtained from field sampling. For the remaining four constituents, the agreement for cobalt, PCBs, and cadmium was good to fair, and rather poor for HCB. It appears from these comparisons that the general data bases provide fairly reliable results for substances commonly occurring in urban areas, but their usefulness is

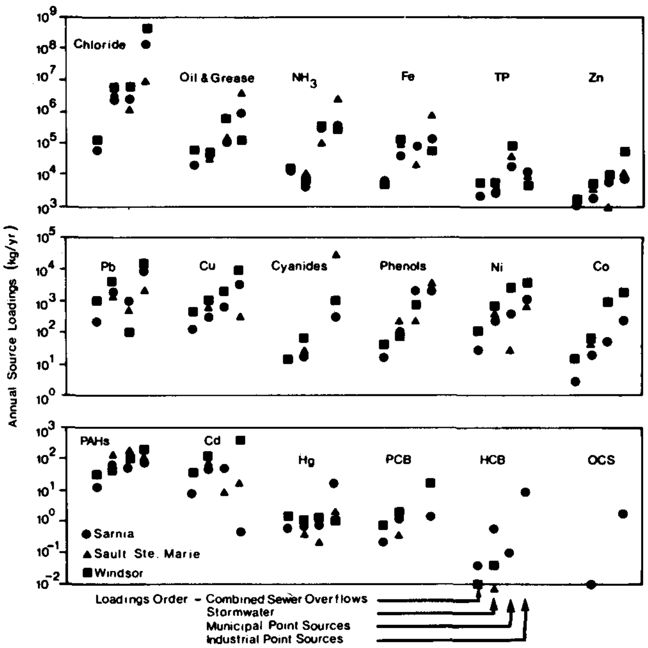

FIG. 1. Annual source loadings in the study area.

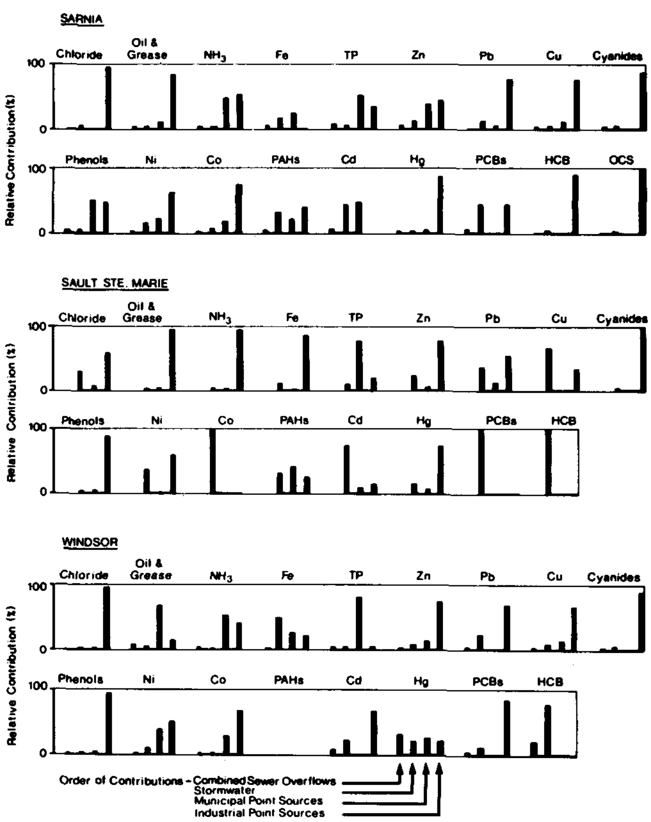

FIG. 2. Relative source contributions.

reduced for less common substances occurring at very low levels and originating from local industrial sources.

The initial experimental design of the sampling network was based on assumed significance of land use effects on runoff quality. Such a concept had been first proposed in the early studies of stormwater composition and later adopted in many urban runoff models (Huber 1986). Recent findings indicate that land use, described by general categories, does not offer a reliable basis for explaining differences in runoff composition at various sites (USEPA 1983). This follows from the fact that even though land use affects fluxes of pollutants produced at the site, it has a minimal impact on imports of pollutants from other areas. Furthermore, general land use categories do not adequately describe the frequency and intensity of activities leading to production of pollutants.

In planning-level analysis, it was of interest to test the feasibility of combining runoff quality data for various land uses into a single data set and using the mean in loading computations. This simplified method produced loadings which were only 1.05 times larger (standard deviation = 0.17) than those obtained by summation of loadings for individual land use types and presented in Table 3. A perfect agreement would be obtained by defining the city-wide mean concentrations as weighted means of land-use concentrations, where the weighting factor would be the relative contributions of areas with specific land use to the total volume of runoff.

When comparing loadings in the stormwater to those in combined sewer overflows, overflows exceeded stormwater in loadings of ammonia and total phosphorus in both Sarnia and Windsor. The loadings from both sources were comparable for oil and grease in Windsor, and mercury in both Sarnia and Windsor. For the remaining constituents, the loadings in stormwater were greater than those in overflows.

The comparisons of point and nonpoint source loadings indicate that for majority of parameters, the point source loadings predominate the total loadings. Considering the distribution plots in Figure 2, out of 51 cases, the point sources predominated in 73%, the nonpoint sources in 10%, and the remaining 17% were comparable. The predominance of point sources was particularly strong, in all three areas, for ammonia, phosphorus, zinc, phenols, cyanide, oil and grease, and chloride. For other constituents, the point sources may still be predominant, but not in all areas. This was the case of cobalt, copper, lead, and nickel in Sarnia and Windsor; mercury and iron in Sarnia and Sault Ste. Marie; HCB in Sarnia; and PCBs in Windsor. The nonpoint sources predominated the relatively low loadings of copper, cadmium, PCBs, and HCB in Sault Ste. Marie, and HCB loadings in Windsor. The results of these comparisons were not affected by uncertainties in nonpoint loadings which were discussed earlier.

The source loading comparisons and the equivalent point source concentrations in particular (Table 3) further suggest that the evaluation of point sources, which is straight forward, should be done before nonpoint sources. Examination of point loadings and their equivalent concentrations would reduce the list of constituents that need to be evaluated for nonpoint sources. For example, the point source equivalent concentrations of ammonia, phosphorus, chloride, zinc, and oil and grease in Table 3 are so high that no field sampling would be required to reach conclusions that the loadings of these constituents are predominated by point sources.

If the planning-level analysis of nonpoint sources yields loadings comparable to those from point sources, further more detailed investigations of nonpoint sources may be warranted. Such investigations should be limited to critical pollutants with comparable loadings and their main purpose would be to reduce uncertainties in estimates of nonpoint loadings.

SUMMARY

Planning-level estimates of pollutant loadings from urban nonpoint sources can be obtained by a simple methodology based on computation of annual volumes of runoff and overflows and estimates of their mean composition from field sampling. This methodology yields results consistent with those obtained from general load functions. Applications of this procedure in three Canadian industrial cities in the Upper Great Lakes Connecting Channels area indicated that in 73% of all cases studied, the point sources produced the predominant loadings.

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