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EVALUATION OF POLLUTANT LOADS
FROM URBAN NONPOINT SOURCES

by

J. Marsalek

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

June 1989
NWRI Contribution #89-118

MANAGEMENT PERSPECTIVE

In spite of recent improvements in control of point source pollution, the water quality goals and designated uses are unattainable in many waters without some control of nonpoint source pollution. Consequently, the abatement of nonpoint source pollution is attracting more attention as one of major control options in water quality management. In the report that follows, urban runoff is evaluated as a nonpoint source of pollution and compared to urban point sources. The evaluation of runoff loads is based on simulated runoff volumes and fitted probability distributions of pollutant concentrations. The results and methodologies presented are applicable in comparative evaluations of pollutant sources and planning-level studies of urban nonpoint source pollution.

PERSPECTIVE GESTION

Malgré les progrès accomplis récemment dans la lutte contre la pollution à partir de sources ponctuelles, en beaucoup d'endroits, on ne peut atteindre les objectifs liés à la qualité de l'eau et se servir de l'eau aux fins désignées sans maîtriser dans une certaine mesure la pollution originaire de sources étendues. C'est pourquoi la lutte contre cette dernière forme de pollution se distingue comme une des principales options de gestion de la qualité des eaux. Dans le rapport qui suit, l'écoulement urbain est évalué, comme source étendue de pollution, et comparé à des sources urbaines ponctuelles. Les valeurs estimées des charges d'écoulement sont basées sur des volumes d'écoulement obtenus par simulation et sur des distributions de probabilité ajustées de concentrations de polluants. Les résultats et les méthodes présentés peuvent servir à des évaluations comparatives de sources de polluants et à des études, au stade de la planification, de la pollution urbaine étendue.

RÉSUMÉ

Pour l'élaboration de plans d'intervention dans les zones caractérisées par des problèmes environnementaux dans le bassin des Grands Lacs, il importe de déterminer l'ampleur des apports de polluants à partir de sources ponctuelles et de sources étendues. Une méthode statistique a été utilisée dans une de ces zones pour l'évaluation préliminaire de la pollution à partir de sources urbaines étendues. La méthode en question permet de calculer la charge polluante annuelle en tant que produit de l'écoulement annuel et de la concentration moyenne des polluants dérivée d'une distribution lognormale des concentrations. On peut établir des intervalles de confiance approximatifs pour la concentration moyenne, intervalles qui servent à déterminer les intervalles de confiance propres aux charges de polluants. En ce qui touche les conditions étudiées, la méthode probabiliste a produit des estimations des charges suffisamment exactes pour autoriser des comparaisons entre les sources de pollution et l'élaboration de la stratégie d'intervention.

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J. Marsalek*

*National Water Research Institute
Burlington, Ontario L7R 4A6, Canada

ABSTRACT

In preparation of remedial action plans for areas of environmental concern in the Great Lakes Basin, the magnitude of pollutant contributions from point as well as nonpoint sources need to be assessed. For screening evaluations of urban nonpoint source pollution, a statistically-based method was applied in one of the areas of concern. This method computes the annual pollutant load as a product of the annual runoff and the mean pollutant concentration derived from a lognormal distribution of concentrations. Approximate confidence intervals can be determined for the mean concentration and used to compute confidence intervals of the loads. For the conditions studied, the probabilistic method produced load estimates which were sufficiently accurate for comparisons of pollution sources and formulation of the remedial strategy.

KEYWORDS

Urban runoff pollution; nonpoint sources of pollution; runoff pollutant loads; probabilistic modelling; the Great Lakes Basin.

INTRODUCTION

In spite of recent improvements in control of point sources of pollution, the water quality goals and designated uses are unattainable in many waters without some control of nonpoint source pollution (Humenik *et al.*, 1987). Consequently, the development of remedial action plans has to consider all pollutant contributions from point as well as nonpoint sources. While the evaluation of point source contributions is relatively straightforward, the evaluation of nonpoint sources is much more intricate. This follows from the fact that nonpoint source pollution originates over broad areas, pollutant fluxes are intermittent, and the mode of their conveyance is often not amenable to analysis by conventional hydraulic techniques (Vigon, 1985).

Among nonpoint sources, urban runoff was reported as the second most frequent cause of pollution of surface waters, after agriculture (Anon., 1986), and the incidence of such pollution impacts is particularly common in urban rivers and lakes. Consequently, urban runoff pollution and its control received much attention during the last 20 years and many procedures for determination of urban runoff pollution loads have been developed and reported in the literature (U.S. EPA, 1983; Johansen *et al.*, 1984; Hemain, 1986; Huber, 1986; Harremoës, 1988; Tasker and Driver, 1988; Marsalek and Schroeter, 1989). Such procedures were typically applied in isolation from investigations of urban point sources. In the following, a probabilistic method for evaluation of annual runoff pollution loads is presented and advantages of its application in conjunction with known point source loads are demonstrated.

Level of Analysis

In a top-down approach, the selection of a procedure for assessing pollutant sources should reflect the needs of water management planners and decision makers. Ideally, the main selection criteria should be the effects of computed results on decision making and the costs of procedure application (Reckhow *et al.*, 1985). According to the study objectives, three distinct types of analysis are recognized in urban runoff studies; planning, design/analysis and operation. The discussion that follows focusses on the planning-level analysis which is used for evaluations of broad policy measures, such as appraising urban nonpoint source loads relative to other sources, or the targeting of problem subareas. The corresponding tools should be simple, inexpensive to apply, and should use input data which are mostly available from the existing data bases (Barnwell and Krenkel, 1982).

Characterization of Urban Runoff Pollution

Screening analyses employ various types of runoff quality data depending on the pollutants of concern and their impact on the receiving waters. For urban runoff, the types of impact were classified by Harremoes (1988) as acute and cumulative effects. Acute effects are short-term effects which typically result from a single event of duration measured in hours. Examples of such effects include bacteriological contamination (Harremoes, 1988) or dissolved oxygen depletion (Hvitved-Jacobsen, 1982) caused by combined sewer overflows. These effects can be evaluated by extreme event statistics and their full evaluation is beyond the scope of those screening procedures which use integrated or temporarily-averaged outputs inappropriate for non-conservative constituents. Cumulative effects are characterized by a gradual build-up of pollutant mass and concentrations in the receiving water leading to environmental damages after some threshold levels have been exceeded. Typical examples of such effects are those associated with transport of nutrients or toxic substances in stormwater discharges (Harremoes, 1988). In this case, the main interest focusses on the loads accumulated over extended time periods and the use of screening methods producing integrated or temporarily-averaged outputs is justified.

Screening Procedures

Urban runoff loads can be estimated by field measurements, detailed computer modelling, and statistically-based screening procedures. Even though the best estimates of runoff loads would be obtained from extensive field measurements, this approach is impractical because of the associated costs, time requirements, and the lack of prediction capability for future catchment conditions. Similarly, the utility of detailed computer modelling in screening evaluations is limited by the need of model calibrations (Huber, 1986). Consequently, the emphasis is placed on screening procedures which typically use a statistical approach in estimation of runoff loads. Four types of such procedures are discussed below.

Data bases. Difficulties with refinement of deterministic descriptions of urban runoff quality led to a statistically-based analysis of runoff quality and its impact on receiving waters (U.S. EPA, 1983; Di Torro, 1984; Hemain, 1986; van der Heijden *et al.*, 1986; Harremoes, 1988). To facilitate this approach, data bases were established with such objectives as to characterize urban runoff, evaluate its potential as a significant contributor to water quality deterioration, and assess selected runoff control measures (U.S. EPA, 1983). Runoff quality characteristics were determined for median and percentile urban sites and these data were recommended for screening evaluations of runoff quality in areas similar to those studied (U.S. EPA, 1983).

Unit area pollutant loads. Numerous urban unit area pollutant loads, defined as the pollutant mass exported from a unit area of certain characteristics over the period of one year, were proposed and their selection can be aided by the watershed matching process (Reckhow *et al.*, 1985). The unit loads represent a workable concept, particularly in the hands of experienced users. Limitations of this procedure arise from its applicability only to the pollutants exerting cumulative impacts on the receiving waters (Harremoes, 1988), difficulties to assess errors in computed loads, and limited availability of unit loads for basic parameters only.

Regression load equations. Regression load equations were initially developed to explore the observed data (Hemain, 1986) and later recommended for transposition to other areas for predictions. In a recent example of this approach, Tasker and Driver (1988) derived linear

regression models for estimating storm runoff event volumes, event pollutant loads, event mean pollutant concentrations, and mean seasonal or annual pollutant loads. For the ten pollutants studied, the average prediction errors ranged from 56 to 334 percent. For predictions within the same catchment with limited data, Hemain (1987) estimated the errors in annual loads as ± 50 percent. Even though such prediction errors are appreciable, they may be acceptable in comparisons of sources or for designing a field sampling program.

Methods using statistically described runoff volumes and quality. In these methods, pollutant loads are computed as products of runoff volumes and some characteristic concentrations, described by statistical measures or probability distributions. Marsalek and Schroeter (1989) evaluated annual loads of selected toxic substances in urban runoff from mean annual runoff volumes, computed for various land uses, and the corresponding mean concentrations which were obtained from a data base. Johansen et al. (1984) computed the annual loads in combined sewer overflows from computed annual overflow volumes and mean concentrations obtained by weighted averaging of observed pollutant concentrations in overflows and stormwater. Harremoes (1988) used probability distributions of storm rainfalls and chemical oxygen demand (COD) concentrations to derive the probability distribution of COD event fluxes in both combined and storm sewers. In general, these methods are flexible in meeting various user objectives and are suitable for screening evaluations of pollutant loads. Error estimates, which are important for comparisons of sources, were not reported for any of the above methods. A probabilistic method yielding such information is presented in the next section.

PROBABILISTIC SCREENING METHOD FOR URBAN RUNOFF LOADS

Background Information

Concerns about the impairment of water uses in the Upper Great Lakes Connecting Channels (UGLCC) area (Water Quality Board, 1987) led to a comprehensive study of pollution sources in this area and development of a remedial action plan. Such sources included point sources, in the form of treated municipal and industrial effluents, and nonpoint urban sources in the form of urban runoff discharged either as stormwater or combined sewer overflows. Although the studies were done in three cities (Marsalek and Ng, 1987), only the results obtained in the City of Sault Ste. Marie are presented here.

The City of Sault Ste. Marie has a population of about 85,000 inhabitants and is located along the St. Mary's River. The principal industry in this city is the primary manufacturing of steel and iron. All pollution sources, including surface drainage conveyed by storm sewers, discharge into the St. Mary's River, which serves as an outfall of Lake Superior. The mean discharge of the river, $2,100 \text{ m}^3/\text{s}$, shows very little variation. Water uses of the St. Mary's River include navigation, power generation, water supply, wildlife habitat, and transport of stormwater and wastewater effluents. Water quality in this river has been of some concern, particularly the levels of industrial chemicals and polynuclear aromatic hydrocarbons (PAHs). Besides the concerns about the ambient water quality in the river itself, it is recognized that some pollutants travel through this connecting channel to the downstream lakes.

Source Load Evaluations

Actual evaluations of individual sources should progress from point sources to nonpoint sources, because point sources can be evaluated fairly easily and the data obtained are helpful in evaluations of nonpoint sources. For general studies of water quality in the UGLCC area, a common list of constituents of interest was established and the relevant parameters are shown in Table 1.

Point source loads. Point source loads were established in the study area by field surveys and sampling of all effluents. For this purpose, continuous discharge data were available and mean effluent concentrations were established by collecting 24-hour flow-proportional samples for seven days during each of several sampling campaigns. Estimates of load uncertainties were not available, but in view of the extensive sampling, they should not be excessive. The annual point source loads are listed in Table 1 (King, 1988).

Nonpoint source evaluation. The only significant nonpoint sources existing in the study area were urban sources and, in particular, discharges of stormwater. Consequently, it was required to evaluate stormwater annual loads for the parameters listed in Table 1. Considering the fact that the constituents of interest exhibit cumulative rather than acute impacts, the use of annual loads is acceptable.

TABLE 1 Annual Pollutant Loads From Urban Sources in Sault Ste. Marie
(point source data after King, 1988)

Constituent ¹	Point Source Load (kg/yr)	Nonpoint (Runoff) Load (kg/yr)			
		Mean	95% Confidence Interval		
Ammonia (as N)	2,360,000	7,570	5,860	-	9,780
Total phosphorus	44,000	3,200	2,480	-	4,130
Cadmium	25	54	41	-	71
Copper	296	530	420	-	680
Iron	658,000	113,000	80,000	-	161,000
Lead	2,260	2,020	1,120	-	3,670
Mercury	2.1	0.37	0.34	-	0.44
Nickel	666	350	290	-	430
Zinc	13,300	3,420	2,850	-	4,110
Cyanides	26,600	33	21	-	51
Oil and Grease	3,663,000	33,300	28,600	-	38,700
Total phenols	3,722	178	139	-	229
Hexachlorobenzene (HCB)	0 ³	0.0059	0.0054	-	0.0064
PCBs	0 ³	0.39	0.27	-	0.57
PAHs ²	252	90	33	-	245

¹ All concentrations are extractable readings.

² A complete list of 17 PAHs (EPA Priority Pollutants) was reported by King (1988).

³ Zero loads were assigned to undetected constituents.

Evaluations of runoff pollution loads is analogous to river load calculations for which several methods with varying degrees of sophistication have been developed. In a typical case, it is required to estimate the annual load from flow records available for the whole period and constituent concentrations available for a limited number of days or events. Reviews and evaluations of suitable computational methods were presented by Dolan *et al.* (1981), El-Shaarawi *et al.* (1986) and Brown (1987). These methods included the direct average method, the flow-weighted-concentration method, and the regression method.

In the direct average method, the average load is obtained by multiplication of the mean measured daily flow by the mean of observed concentrations. In the flow-weighted-concentration (FWC) method, the average load is multiplied by the ratio of mean-sample and mean-population flows to adjust for potential differences in flow distributions of the sample and flow data. This method is sometimes further modified by including a variance constant, proposed by Beale (Dolan *et al.*, 1981), to account for potential bias associated with covariance between the load and flow. The regression method follows the FWC method and an exponent factor is added to account for potential bias associated with the correlation between concentration and flow, and in its modified version, a variance constant similar to that described for the FWC method is also added (Brown, 1987). Furthermore, all these methods can be applied to stratified or unstratified data sets.

Although the advantages or acceptability of individual methods can be demonstrated for specific data sets, such findings are not general. For example, Brown (1987) obtained the best results with the simple flow-weighted-concentration method, but Dolan *et al.* (1981) obtained the best results by including the Beale's estimator. Considering the scarcity of data in urban runoff studies and the widely reported statistical independence of event volumes and event mean concentrations (U.S. EPA, 1983; Harremoes, 1988), the load computations based on the direct-average methods are of particular interest. It was demonstrated by El-Shaarawi *et al.* (1986) that the direct-average method produces an unbiased estimate of the mean load if there is no correlation between the flow and concentration.

The annual runoff load can be estimated as

$$L_1 = N \sum_{i=1}^n V_i C_i / n \quad (1)$$

or

$$L_2 = N \bar{V} \bar{C} = R \bar{C} \quad (2)$$

where L is the annual load of a particular constituent, V is the event runoff volume, C is the event mean concentration (EMC), subscript i = 1,2,...,N denotes individual events during the

year, n is the number of events sampled, $\bar{V} = \sum V_i / N$, $\bar{C} = \sum C_i / n$, and $R = \sum V_i$ is the total annual runoff. Note that for V_i 's the mean is calculated from N events, but C is estimated from samples of n events ($n < N$). Although eq. (2) is a better estimator of the mean load than eq. (1) (El-Shaarawi *et al.*, 1986), in the absence of correlation between V and C , both equations produce identical results.

Considering the fact that the annual runoff R can be determined fairly accurately, either by measurements or by computer simulations, the main task in applying eq. (2) is the determination of the mean concentration C . It is generally recognized that urban runoff EMCs are not normally distributed and some values may be below the detection limit (censored data). Under such circumstances, it is advantageous to approximate EMCs by a distribution model which can be used to draw inferences about the sample mean and, if required, to treat censored data. For urban runoff EMCs, the use of lognormal distribution has been widely reported (U.S. EPA, 1983; Di Torro, 1984; Harremoës, 1988) and the applicability of this distribution to particular data sets can be verified by standard statistical tests.

Assuming that $(\ln C_i)$ is normally distributed with mean u and variance s^2 , then $C_i = \exp(\ln C_i)$ is lognormally distributed with mean a and variance b^2 defined as

$$a = \exp(u + s^2/2) \quad (3)$$

$$b^2 = a^2 (\exp s^2 - 1) \quad (4)$$

For the estimate of the lognormal mean a , an approximate confidence interval can be written as (El-Shaarawi, 1989)

$$\hat{a} \exp \{-Z_{1-\alpha/2} [\hat{s}^2/n + 2 \hat{s}^4/(n-1)]^{0.5}\} \leq a \leq \hat{a} \exp \{Z_{1-\alpha/2} [\hat{s}^2/n + 2 \hat{s}^4/(n-1)]^{0.5}\} \quad (5)$$

where $Z_{1-\alpha/2}$ is the tail value for the normal distribution corresponding to the $(1-\alpha)$ confidence limits and \hat{s} is an estimate of s . The main advantage of the above confidence interval is the fact that it always yields positive values.

For independent flow and concentration data and the 95 percent confidence interval, the load confidence interval is estimated as

$$R \hat{a}_{\text{lower 95\% C.L.}} \leq L \leq R \hat{a}_{\text{upper 95\% C.L.}} \quad (6)$$

where subscripts refer to the lower and upper confidence limits of a .

The procedure described above was applied in the study area where urban runoff was studied at a number of sites with various land use. Such data were originally used to estimate loads for individual land use areas and, by summation of such sub-loads, the total load was obtained (Marsalek and Ng, 1987). It was noted that differences among the data sets from areas with various land use were not statistically significant and this is consistent with recent findings from other studies (U.S. EPA, 1983). Consequently, all data were aggregated into a single set and used to produce estimates of mean concentrations and their confidence limits which are shown in Table 2. Using these concentration data, runoff loads were also calculated and presented in Table 1 with point source loads.

The spread of confidence intervals varied for various constituents. For some, such as phosphorus, they were fairly narrow and represented about 1.3 and 1/1.3 times the mean. For others, such as PAHs, they are fairly wide and represented 2.7 and 1/2.7 times the mean. If such uncertainties are unacceptable, further investigations may be required and in fact this was done for PAHs.

Expected annual loads may be affected by the annual runoff and correlations between the annual runoff concentration and volume. Further research is required before a reliable procedure for expected loads can be recommended.

Source Load Comparisons

Following the evaluation of nonpoint sources, the loads from all sources were added and shown in the form of relative contributions in Fig. 1. The relative contributions of pollutant sources in Fig. 1 indicate that among the 15 constituents studied, eight loads are predominated by point sources, four are comparable and three are predominated by stormwater.

TABLE 2 Pollutant Concentrations in Urban Runoff

Constituent	Unit	Concentrations in Urban Runoff					Ambient Water Quality Criteria ³	
		Study Area			Data Bases			
		Mean	95% Confidence Interval		NURP ¹	NWRI ²		
Ammonia (N)	(mg/L)	0.582	0.451	-	0.752	-	-	-
Total P	(mg/L)	0.246	0.191	-	0.318	0.42	-	-
Cadmium	(µg/L)	4.1	3.1	-	5.5	-	1.5	0.2
Copper	(µg/L)	40.9	32	-	52	43	27	5
Iron	(mg/L)	8.72	6.1	-	12.4	-	-	0.3
Lead	(mg/L)	0.155	0.086	-	0.282	0.182	0.146	0.02
Mercury	(µg/L)	0.0283	0.023	-	0.034	-	0.05	0.2
Nickel	(µg/L)	27.1	22	-	33	-	22	25
Zinc	(mg/L)	0.263	0.219	-	0.316	0.202	0.490	0.03
Cyanides	(µg/L)	2.5	1.6	-	4.0	-	-	100
Oil and Grease	(mg/L)	2.56	2.20	-	3.0	-	-	-
Total phenols	(µg/L)	13.7	10.7	-	17.6	-	-	1
HCB	(ng/L)	0.452	0.417	-	0.491	-	8.9	6.5
PCBs	(ng/L)	30.2	21.0	-	43.5	-	13.1	10
PAHs ⁴	(µg/L)	6.95	2.6	-	18.9	-	-	-

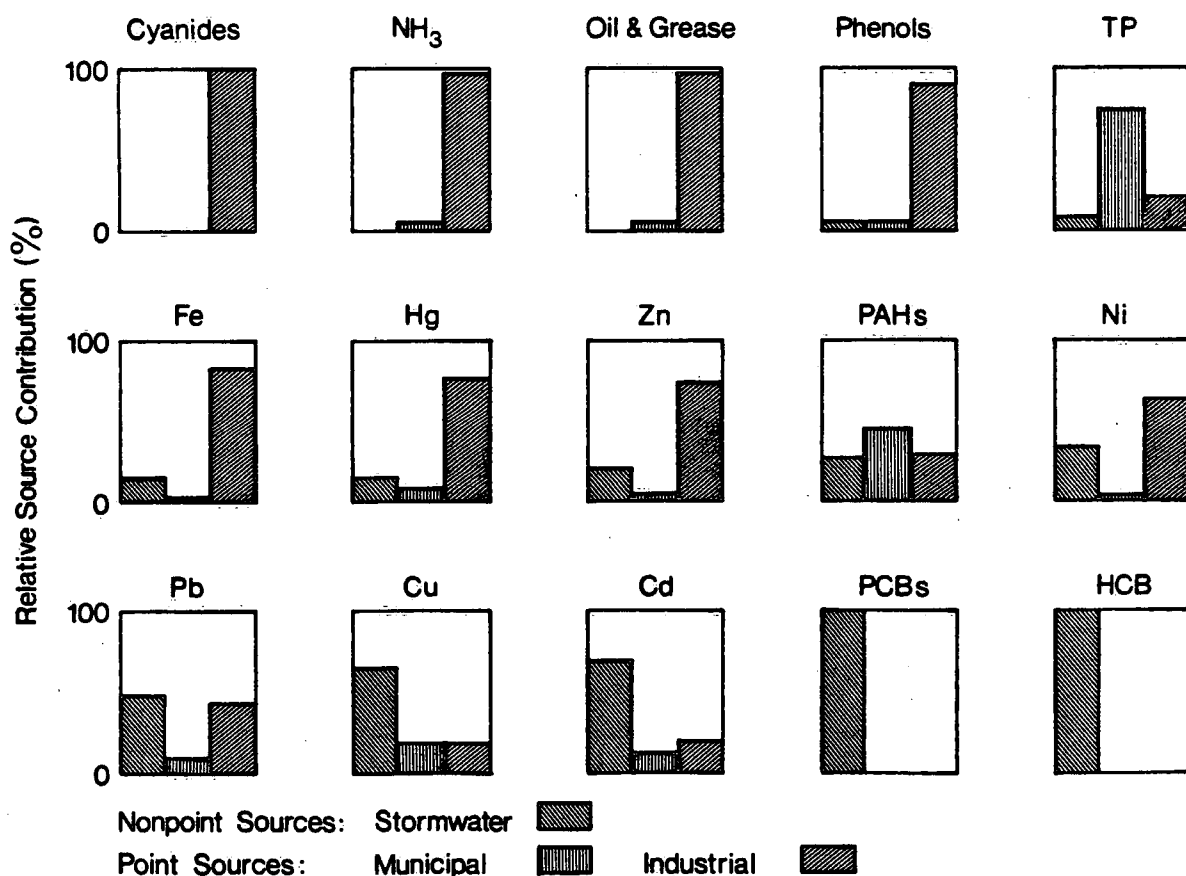
¹ After U.S. EPA (1983).² After Marsalek and Schroeter (1989).³ International Joint Commission and the Province of Ontario criteria for whole water samples (except Hg - dissolved only).⁴ A complete list of 17 PAHs (EPA Priority Pollutants) reported by King (1988).

Fig. 1. Relative pollutant source contributions.

Discussion of Results

The screening-level load estimates for stormwater indicate that even appreciable uncertainties in such estimates may be acceptable in water management studies. It was of interest to compare the load estimates given in Table 1 with those produced by other comparable methods such as more detailed calculations for individual land uses, and the methods based on general data bases (U.S. EPA, 1983; Marsalek and Schroeter, 1989).

The load estimates calculated from eq. (6) agreed well, on the average within several percents, with those computed by considering the individual land uses (Marsalek and Ng, 1987). This was largely expected because both methods used the same data set and somewhat similar methods of analysis. The probabilistic method leads to a better evaluation of uncertainties in the load estimates arising from variations in the concentration data and simpler data processing. In comparison to other screening methods, both these methods are flexible in the selection of constituents studied, but the need for field sampling leads to increased costs. The application of these methods can be simplified if the point source loads are known - they are helpful in establishing the acceptable uncertainties and the extent of field sampling in terms of number of samples and parameters studied.

Another possibility in evaluation of runoff loads is to use runoff characteristic data from general data bases and calculate loads as products of the local annual runoff and general characteristic concentrations, which are available for four common parameters from the U.S. EPA (1983) data base and for eight parameters from other studies (Marsalek and Schroeter, 1989). A comparison of runoff characteristics in the study area with those from the general data bases is shown in Table 2. Because the loads would be obtained by multiplying the concentrations in Table 2 by a constant, it follows that the use of the data bases would produce loads comparable to those obtained from field sampling for total phosphorus, the seven metals studied, and PCBs. Only in the case of HCB, there would be a significant disagreement.

It appears that for common parameters, various screening methods based on local data or general stormwater quality data would produce comparable results, certainly for water management purposes. It should be emphasized that the general data were collected in urban areas with characteristics similar to those of the study area. For less common parameters, the utility of general data bases somewhat diminished. Concentrations of these parameters are strongly affected by local sources and some local sampling is needed to document such influences.

The development of pollution abatement strategy requires consideration of all sources and feasibility of their mitigation to achieve the desired effects in the receiving waters. In most cases, the abatement of point sources is technically more feasible and economical, because of concentration of point source flows at a single point, higher concentrations of pollutants more amenable to effective treatment, and availability of treatment processes. In the study area, the point sources clearly predominate loadings of ammonia, oil and grease, Fe, TP, Zn, cyanides, phenols, and Hg. With the exception of Hg, occurring at very low levels, pollution control orders were issued by the regulatory agency for discharges of all these constituents (King, 1988).

Among the remaining seven constituents, point and nonpoint sources produced comparable loads of Pb, Cu, Ni, and PAHs, and the relatively low loads of Cd, PCBs and HCB were predominated by stormwater. Probabilistic approaches to evaluation of the impact of urban runoff on the receiving waters were developed in recent years (Di Torro, 1984; van der Heijden et al., 1986). It was felt that these approaches were not warranted in this study, because of high discharges and dilutions in the receiving stream, good quality of water in the outfall of Lake Superior, the nature of the water quality criteria used, and the ongoing control of point sources. Considering the high dilutions of runoff in the receiving stream, in excess of 100 times even for peak runoff flows, it appears that the ambient water quality criteria listed in Table 2 would be met under most circumstances. The only exception may be two PAHs, benzo[k]-fluoranthene and benzo[a]pyrene, which may require dilutions of 200 times to meet the general guidelines from another jurisdiction (King, 1988). Such dilutions may not be always available and further studies of PAHs in the receiving water may be required.

CONCLUSIONS

Planning-level estimates of pollutant loadings from urban nonpoint sources can be obtained by using a simple methodology based on simulated annual runoff volumes and probabilistic distributions of constituent concentrations derived from limited field data. For common

constituents, this methodology yields results consistent with those obtained from general stormwater quality data bases. For uncommon constituents (e.g., toxic trace substances), the utility of general data bases diminishes, as strong local sources may control the loads. Application of this screening procedure in the Upper Great Lakes Connecting Channels area showed that, for most constituents, the point sources controlled the overall loads discharged to the receiving waters. The attainment of water quality objectives in the receiving waters required pollution control orders for seven constituents. For most constituents with significant runoff loads, stormwater may require dilutions up to 50 times to meet the ambient water quality objectives and such dilutions are generally available.

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