Quantification of Point and Non-point Inputs to Water Pollution From Urban Areas: I – Effluent Discharges and Sediment Loading to Streams

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Abstract
Not knowing the sources (i.e., point and non-point sources) of instream pollutants, water resource managers, city planners and policy makers may be unable to decide whether or not a particular remedial action is appropriate. The degrees of urbanisation, type of industries, types of roads and pavements, its topography, etc. make it quite difficult to separate effluent discharges and sediment loadings into point and non-point components. In view of this, an attempt was made to partition point and non-point components of surface run-offs and sediment loads originating from urban areas. Nine cities located in the lower peninsula of Michigan were selected for this study. ARC/INFO and ERDAS GIS software along with SYSTAT and other statistical software were used in boundary delineation, data analyses and summary extraction. Several limiting assumptions were made. Model-based predictions of point and non-point effluent discharges and sediment loads were projected for nine selected urban areas. Cities varied in respect to the amount of effluent discharged. Highly industrialised cities such as Midland, Battle Creek and Kalamazoo generally provided greater loadings to their rivers and streams than relatively less industrialised cities such as Ann Arbor and Pontiac. The estimated amounts of point and non-point components of effluent discharges and sediment loads for the selected cities were quite reasonable and in the order of expectation. The proposed model is quite robust and is universally applicable for partitioning point from non-point run-offs, effluent discharges and sediment loadings from urban areas.
(Key Word: Prediction, Nutrient modelling, Surface run-off, Urban pollution, Water quality modelling)

X.1 Introduction

Instream water quality problems caused by non-point pollution sources always have been a challenge to water resource managers as well as to water quality modellers. While agriculture, forested lands and barren lands act as non-point sources, urbanised areas act as both non-point and point sources of pollutants. In the past, several problems and irregularities in reports regarding effluent discharges have been noted. Vail (1993) found reporting errors such as monthly averages greater than the maximum for the given months, and blanks in discharge monitoring reports for some parameters. In the recent past, about 14% of the industries located in the Grand River watershed alone reported flow measurements that were unreasonable (Vail, 1993). It is quite possible that the effluent discharge reports from many industries located in other watersheds of Michigan may have similar data reporting errors. Consequently, implementing pollution control remedial action based on such reports may jeopardise the success of pollution control measures. In view of these complexities, a need was felt to find an approach where the contribution of each of the point and non-point source discharge contributions from urbanised areas could be estimated. The theoretical approach conceptualised to solve such difficulties is presented in the following section.

X.2 Theoretical Approach

To know the subsurface flow and overland run-off from urbanised areas, it seems reasonable to measure the stream flow and instream concentration of some important chemicals such as suspended sediments at some upstream and downstream locations at or near a city boundary. Such measurements, made at any point of time, can be

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used as a means of separating, and subsequently estimating the loading caused by non-point as well as point sources of pollution. Flow measurements made at an upstream station (UPSTF) may consist of the following:

1. Surface water run-off from upstream areas reaching streams and water bodies (ROF_u) -- a non-point source, and

2. Subsurface water movement in upstream areas reaching streams and water bodies (BSF_u) -- a non-point source. Hence,

$UPSTF = (ROF_u) + (BSF_u)$ .... (1)

On the other hand, measurements made at a downstream station (DNSTF) may consist of the one or more of the following:

1. Surface water run-off (or flow) from upstream areas, excluding city areas, reaching streams and water bodies (ROF_d) -- a non-point source,

2. Subsurface and underground water movements from upstream areas, excluding city areas, reaching streams and water bodies (BSF_d) -- a non-point source,

3. Surface water run-offs (or flows) solely from city areas reaching streams and water bodies (CAF) -- a non-point source,

4. Subsurface and underground water movements solely from city areas reaching streams and water bodies (CBF)-- a non-point source,

5. Wastewater discharges from Waste Water Treatment facilities (WWTF) located in city -- a point source, and

6. Waste water discharges from industrial plants and facilities (IPF) located in city - a point source.

Hence,

$DNSTF = (ROF_d) + (BSF_d) + (CAF) + (CBF) + (WWTF) + (IPF)$ .... (2)

Since urbanised areas occupy a relatively small portion of the surrounding landscape on a watershed scale, it is reasonable to assume that subsurface and underground water flow (CBF) from such small areas during summer flow or dry seasons (i.e., during July and August in the lower peninsula of Michigan) are quite negligible. Further, it is assumed that the distance between two stations (i.e., location of upstream and downstream stations) for a city is too small to cause any appreciable difference in the base flows (BSF) at two stations particularly during low flow or dry seasons (i.e., during July and August in the lower peninsula of Michigan). Hence, it was assumed that the base flow at upstream station and base flow at downstream station during summer seasons are the same, and that the difference between base flows at two stations is negligible. From the above assumptions,

$CBF = 0$

$ROF_u = ROF_d$, and

$BSF_u = BSF_d$.

Hence, the total flow due to urbanised areas (TFU) can be calculated by subtracting equation (1) from equation (2) resulting in the following:

$TFU = (DNSTF) - (UPSTF) = [ROF_d + BSF_d + CAF + CBF + WWTF + IPF] - [ROF_u + BSF_u]$

$= [CAF + CBF + WWTF + IPF]$

Substituting $CBF = 0$,

$TFU = [CAF + WWTF + IPF]$ .... (3)

By substituting the values generated by the above three sources, the volume of run-off from urbanised areas, the volume discharged from waste water treatment facility, and the volume discharged from the industrial plant(s), it is possible to calculate the amount of total water released to nearby streams and other water bodies from a particular urban area at any time or a season.

Among these three factors, the value of CAF is not automatically known and it is very hard to physically calculate. Regarding IPF, industrial facilities maintain records of effluent discharges and releases, but because of the private nature of the records, and relaxed regulatory compliance due to being small in size of operations, etc., it is difficult to obtain access to their records. Where records are available, they may not be very reliable. Therefore, some other means of estimating IPF is the only option. On the other hand, access to reports and data from WWTF is easy and the reliability of data records is generally high. Additionally, it was assumed that the number of residents in an urban area was relatively constant year around. Therefore, per capita use of water resources in such areas also stays very much the same. Consequently, the statistics on per capita wastewater discharge of one urbanised area can be used for computing and estimating per capita wastewater discharges by the residents of other cities with little limitations. For any month, then, the total flow from city or urbanised area (TFU) may be presented as:

$TFU = [CAF + WWTF + IPF]$, and

$CAF = [TFU - WWTF - IPF]$ .... (4)

Based on both the long-term precipitation trend and the available precipitation data for the sixteen Lower Michigan watersheds studied, it was assumed that precipitation was nil or negligible during summer (i.e., dry) seasons. Hence, surface run-off from urbanised areas (CAF) was assumed to be negligible. Substituting CAF = 0 in equation (3) for dry seasons,

TFU* = [0 + WWTF + IPF] = [WWTF + IPF]

Therefore,

IPF = TFU* - WWTF .... (5)

TFU is known from upstream and downstream measurements for each month, and WWTF is known from city records. TFU* is assumed to be equal to TFU during dry months when CAF is negligible. By considering the discharges from industrial plants and facilities to be constant throughout the year (assumed to be equal to IPF as calculated from equation (5), above, during dry months), it is possible to estimate the value of IPF. Further, run-off values for each month for a city area (CAF) can be calculated by substituting the corresponding IPF value in equation (4) above.

X.3 Methods of Study

To separate point source and non-point source contributions of nutrients from urbanised areas, measurements of flow and chemical concentrations at stations upstream and downstream of cities are necessary. The Surface Water Quality Section of the Michigan Department of Natural Resources (MDNR) measures the flow and sediment concentration at upstream and downstream stations for major urban centres in Michigan. These data are maintained in STORET by US-EPA Region-5 office in Chicago, Illinois. Data on mean monthly stream discharges and concentration of suspended sediments for the period of 1986 to 1991 were procured from STORET. The selected cities were Ann Arbor (Huron Watershed), Flint (Flint Watershed), Lansing and Grand Rapids (Grand Watershed), Midland (Titabawassee Watershed), Pontiac (Clinton Watershed), Kalamazoo and Battle Creeck (Kalamazoo Watershed) and Saginaw (Saginaw Watershed). Cities having complete records of both the upstream and downstream stations were only used in this study (Table 1).

Individual wastewater treatment facilities were contacted for data on effluent discharges as well as chemical analyses for suspended sediments for the year 1990 (Table 2).

Table 1. Basic information for selected urbanised area of Michigan (Slater and Hall, 1992).

City	Area (km^2)	Popul.*	Density ($persons/km^2$)
Ann Arbor	67.1	109592	1633
Battle Creek	110.9	53540	483
Flint	87.6	140761	1607
Grand Rapids	114.6	189126	1650
Kalamazoo	63.6	80277	1262
Lansing	87.8	127321	1450
Midland	71.5	38053	532
Pontiac	51.8	71166	1374
Saginaw	45.2	69512	1538

* based on 1990 census

Table 2. Basic information from wastewater treatment facilities (WWTF) discharges for selected urbanised areas during 1990.

City	Total Population Served*	Density Served (Persons/ km^2)	Av. Monthly Discharge to Stream* (m^3/hr)
Ann Arbor	109592	1633	2875.6
Battle Creek	100000	902	2183.9
Flint	160000	1826	6094.9
Grand Rapids	189126	1650	9349.5
Kalamazoo	150000	2359	4927.2
Lansing	150000	1708	3828.0
Midland	38053	532	1254.3
Pontiac	71166	1374	2631.2
Saginaw	69512	1538	4576.2

* based on the data for discharge and population served by WWTF for the year 1992, and/or 1990 census (Slater and Hall, 1992).

X.3 Sediment Load Calculation

Loading rates of sediment was calculated using the respective flow volumes and the sediment concentrations as follows:

Load (in kg/hr) = (Sediment Conc., mg/litre)* 0.001)*(Flow Volume, m^3/hr)

Load (in $kg/km^2/hr$) = (Load in kg/hr) ÷ (Total area of city in km^2) .... (6)

Surface run-off from city areas, effluent discharges from industrial plants/facilities were estimated using equations 1 through 5.

X.4 Results

Following the proposed procedure, the point and non-point volumes of water and sediment loads draining to the stream were apportioned. Results are presented in the following sections.

X.4.1 Water Flows and Run-Off

Results indicated that surface run-off from the city areas and industrial plants and facilities constituted the major share of effluent discharge to streams, which in most cases exceeded 80 % during the 1986

- 1992 data period. Ann Arbor had the lowest while Midland had the highest average net input of effluent discharge to their respective streams (i.e., 5713.0 m^3/hr and 116011.17 m^3/hr, respectively). Ann Arbor WWTF contributed 50.33 %, while Midland WWTF contributed only 1.08 % to their respective net effluent discharge volumes (Table 3). Therefore, effluent discharge from the surface area plus the industrial establishments in Ann Arbor and Midland were 49.7 % and 98.9 %, respectively. The higher the discharge of effluent (i.e., processed water) from WWTF to the streams, the lower should be the sediment loading in streams, and consequently, the higher the instream water quality.

Table 3. Discharges of effluent waters from selected urbanised areas. These include WWTF and IPF discharges as well as surface run-offs from city areas.

City	UPSTF (m^3/hr)	DNSTF (m^3/hr)	TFU (m^3/hr)	WWTF (m^3/hr)	WWTF Contribution (%)
Ann Arbor	47917	53630	5713	2876	50.3
Battle Creek	18769	108410	89641	2184	2.4
Flint	53063	86738	33675	6095	18.1
Grand Rapids	433214	485599	52385	9350	17.9
Kalamazoo	110604	137152	26549	4927	18.6
Lansing	63318	96356	33037	3828	11.6
Midland	81565	197576	116011	1254	1.1
Pontiac	4836	26434	21598	2631	12.2
Saginaw	550193	568021	17827	4576	25.7

X.4.2 Monthly Mean Surface Run-Off From Urbanised Areas

The average CAF (i.e., surface run-off from the city areas) were lowest during summer months (i.e., 22.0 and 19.1 m^3/km^2/hr during July and August, respectively). The highest CAF values (708.0 and 768.3 m^3/km^2/hr) were noted during the early spring season (i.e., March and April, respectively, Figure 1). The results indicated that on an annual mean basis, the estimated surface run-off volumes from selected urbanised areas were in the range of 304.3 to 178.8 m^3/km^2/hr except for Ann Arbor and Midland. It was lowest for Ann Arbor (i.e., 38.8 m^3/km^2/hr, standard error of estimate = 11.0 m^3/km^2/hr), and highest for Midland (1029.0 m^3/km^2/hr, standard error of estimate = 325.1 m^3/km^2/hr) (Figure 2).

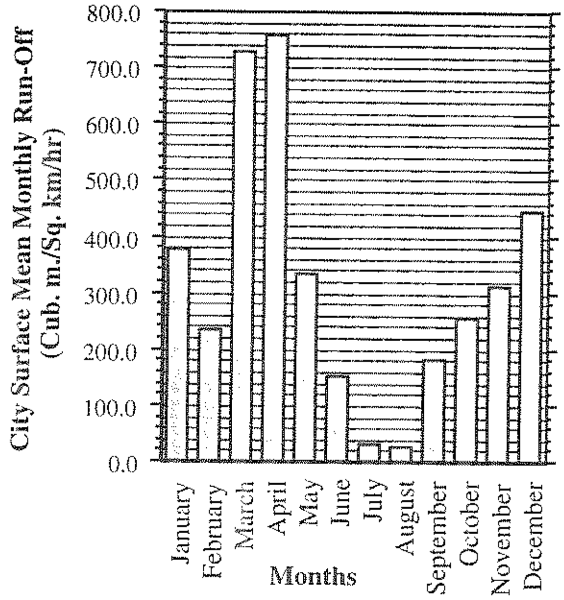

Figure 1. Model estimation of CAF (i.e., city surface mean monthly run-off) in m^3/km^2/hr for the selected cities.

X.4.3 Estimation of Industrial Effluent Discharge (IPF) From Urbanised Areas

Effluent discharges from IPF (i.e., point sources) were separated based on the concept presented earlier. Results indicated that Saginaw and Ann Arbor had negligible amounts of IPF discharges (30.2 m^3/hr and 236.0 m^3/hr, respectively). The two top IPF dischargers were Battle Creek and Midland (53707.8 and 41181.8 m^3/hr). The IPF discharges from Lansing, Pontiac, Flint, Kalamazoo and Grand Rapids were 4295.8, 5902.1, 7989.5, 10247.4 and 12381.6 m^3/hr, respectively (Figure 3).

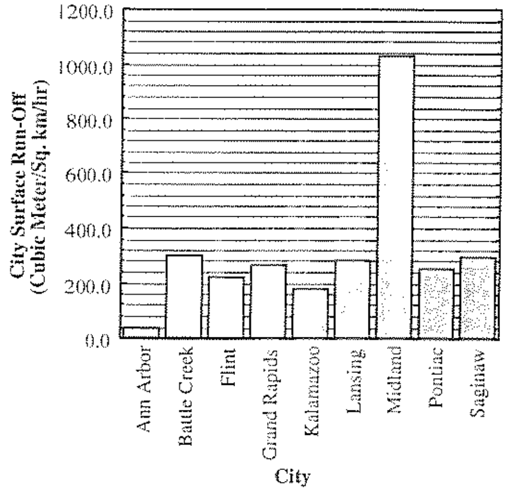

Figure 2. Estimated run-off ($m^3/km^2/hr$) indicative of non-point source inputs to streams from the city surface of the selected cities.

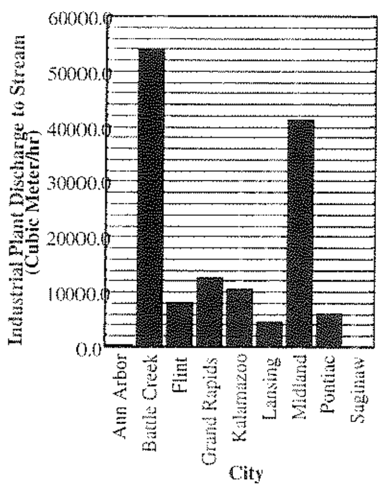

Figure 3. Estimated IPF (m^3/hr) indicative of point source inputs to streams from the selected cities.

X.4.4 Estimation of Instream Suspended Sediment Loading

Results indicate that the net loading of sediment from Ann Arbor (i.e., 3873.2 kg/hr) was lowest where as it was highest from Midland (71873.4 kg/hr). The loading of sediments from the WWTF was generally less than 0.5 %. This indicates that the sediment loading to down-stream from WWTF as a point source was quite negligible and had no significant impact on instream water quality. From this it follows that the industrial plants/facilities (as point sources) as well as the surface run-off from city areas (as non-point sources) were the main causes of instream sediment loading.

X.4.4.1 Estimation of Mean-Monthly Loading Rates of Sediment From City Surface Run-Off (Non-point Source)

The results of mean monthly sediment loading rates, averaged for all selected cities, indicated that dry or summer months (i.e., July and August) had the least sediment loading rates (16.9, 9.5 kg/hr, respectively) where as early spring months (i.e., March and April) had the highest loading rates (343.8 and 344.6 kg/hr). Mean loading rates for the early spring months were about 26 times those of summer or dry months (Figure 4). During winter, particularly December and January, loading rates were relatively higher than other months falling in late spring and fall seasons.

X.4.4.2 City Surface Run-Off Loading From Selected Cities (Non-point Source)

Midland had the highest mean loading rate (481.5 $kg/km^2/hr$) of sediments where as Ann Arbor had the lowest (35.5 $kg/km^2/hr$). The mean loading rates ($kg/km^2/hr$) of sediments for other urbanised areas were in the order of 98.8 (Saginaw), 99.396 (Kalamazoo), 103.9 (Battle Creek), 120.3 (Pontiac), 124.7 (Flint), and 153.8 (Lansing) (Figure 5). In general, the loading rates of sediment correspond directly to the surface water run-off rates.

X.4.4.3 Estimation of Sediment Loading From Industrial Plants/Facilities (IPF, the Point Source)

Two cities with high loading rates were Midland and Battle Creek with 37435.8 and 23643.5 kg/hr, respectively. For other selected cities, the rates (kg/hr) varied from city to city, and were in the order of 1484.3 (Ann Arbor), 2623.6 (Saginaw), 3614.4(Lansing), 5390.0 (Flint), 5926.1 (Pontiac), and 8421.2 (Kalamazoo).

X.5 Discussion

The primary purpose of the analyses described in this paper was to obtain estimates of the proportion of urban effluents coming from point and non-point sources. Based on the data from upstream and downstream monitoring stations, an attempt has been made to partition the net changes among the several sources in the urban areas studied. It was not possible to verify this partitioning within the scope of this study. In making these analyses, several limiting assumptions were made as outlined in the previous sections. These assumptions proved very useful in developing a first approximation of the partitioning of effluent materials between the several possible sources.

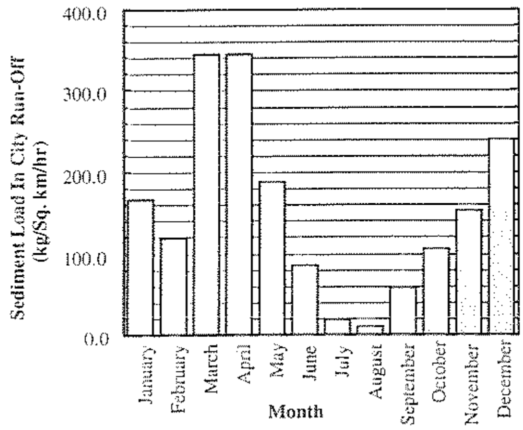

Figure 4. Monthly mean sediment loading in receiving streams from city surface run-off.

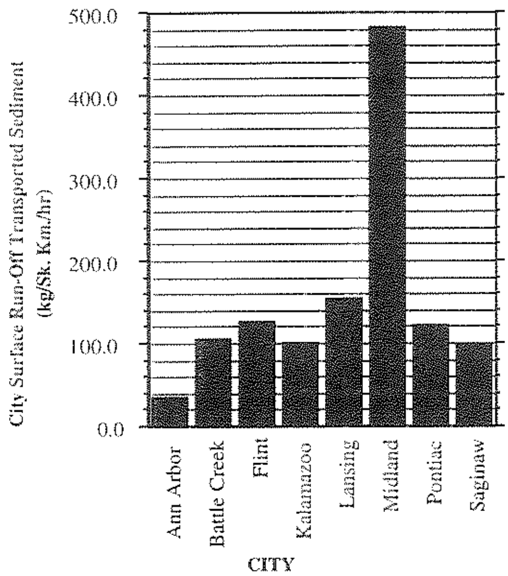

Figure 5. Sediment loading in receiving streams from city surface run-off.

X.5.1 Surface Run-Off

Surface run-off from city surfaces followed a trend similar to seasonal stream discharge patterns. Run-off amounts varied from one city to another and appear unrelated to population density or the area of the city. Model-estimated total effluent discharge, including surface run-off and point source inputs, from Battle Creek was about 28% higher than from Midland in spite of a lower population density (483 vs. 532 persons/km^2, respectively) at Battle Creek. The Battle Creek wastewater treatment facility serves an area larger than the city itself. Model-predicted effluent discharges from industrial sources located in Ann Arbor and Saginaw were negligible. This indicates that non-point sources, essentially surface run-off that does not pass through the wastewater treatment facility, may be the prime cause of instream water pollution in these cities.

X.5.2 Suspended Sediments

The general trend of sediment loading to streams at their outlets followed the seasonal stream discharges with different amounts of sediments from different cities. The contribution of the wastewater treatment facility to instream sediment loads was less than one-half of one percent for all nine cities considered. This left industrial sources and non-point source run-off as the primary contributors to sediment loads. Model estimate of sediment loading from industrial sources was more than ten times of surface run-off from all nine cities considered. Based on these estimates, industrial sediment loadings are substantially greater at Midland and Battle Creek than at any of the other cities. The model-estimates also indicate that sediment loading from surface run-off was noticeably greater at Midland than at any other city considered.

X.6 Acknowledgements

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X.7 References

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