Quantification of Point and Non-point Inputs to Water Pollution From Urban Areas: II – Nitrogen and Phosphorus Loadings to Streams

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Abstract
Complexity of population structure, degrees of urbanisation and industrialisation, errors in effluent discharge reports, etc. make the separation of point and non-point pollution quite difficult. In view of this, a model was developed to partition nitrogen and phosphorus loads into point and non-point sources 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 for data analyses. Model-based estimates of point and non-point portion of Nitrogen and Phosphorus were projected for nine selected urban areas. Monthly and seasonal trends for nitrogen loading generally followed the stream discharge patterns. Monthly loadings for total phosphorus were different than nitrogen. Forms of nutrients (i.e., particulate vs. ortho-phosphorus and organic vs. inorganic nitrogen, etc.) varied from one urbanised area to another. 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 proposed model is robust and it is universally applicable in separating point and non-point nutrient loadings from urban areas.
(Key Word: Prediction, Nutrient modelling, Urban pollution, Water quality modelling)

X.1 Introduction

The presence of toxic substances in the rivers, streams and ground waters is considered as a significant factor causing environmental and health problems. Hence, the demand for understanding the movement and migration of these pollutants to water bodies has increased. There are some good models such as Agricultural Non-Point Source Pollution (AGNPS) of Young, et. al. (1987), GLEAMS (Leorand, et. al., 1987) and SWRRB-WQ (Arnold, et. al., 1990) which address non-point source issues arising from agriculture, forest and barren lands at watershed scale. However, there is none to address nutrient run-off exclusively from urbanised areas, which act both as non-point and point sources of pollution. Due to the lack of such models, water pollution problems caused by urbanised areas always have been a challenge to city planners and water resource managers. In view of this, a need was felt to develop a model in order to quantify the amount of chemicals from each of the point and non-point source resulting from urbanised areas. The proposed model solve this issue appears to be robust and universally applicable.

X.2 Theoretical Approach

To quantify the nutrient run-off from surface of urbanised areas, it seems reasonable to measure the stream flow and instream concentration of some important chemicals such as nitrogen and phosphorus at some upstream and downstream locations at or near a city boundary. Such measurements, made at any point of time, can be 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 (details and definitions provided in part-I paper included in this proceeding):

$$UPSTF = (ROF_u) + (BSF_u) \quad \text{.......................} \quad (1)$$

On the other hand, measurements made at a downstream station (DNSTF) may consist of the

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following (details and definitions provided in part-I paper included in this proceeding):

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

Based on the assumptions (as given in the part – I of the paper included in this proceeding), the total flow due to urbanised areas (TFU) was calculated by subtracting equation (1) from equation (2) as follows:

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

Substituting CBF = 0,

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

For any month, the total flow from urbanised area (TFU) could be expressed as:

$$TFU = [CAF + WWTF + IPF], \quad \text{and}$$
$$CAF = [TFU - WWTF - IPF] \quad .... (4)$$

By substituting CAF = 0 in equation (3) for dry seasons, we get:

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

This leads to:

$$IPF = TFU^* - WWTF \quad .... (5)$$

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. For details regarding theoretical approach, refer to the part-I paper included in this proceeding.

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 chemical 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. The mean monthly data on stream discharges and concentration of nitrogen, phosphorus, carbon and suspended sediments for the period of 1986 to 1991 were procured from STORET. Cities having complete records of both the upstream and downstream stations were only used in this study. Individual city wastewater treatment facilities were contacted for data on effluent discharges as well as chemical analyses for suspended sediments, phosphorus and nitrogen for 1990.

X.4 Nutrient Load Calculation

Loading rates for nitrogen and phosphorus were calculated using the respective flow volumes and the chemical concentrations for a particular substance as follows:

Load (in kg/hr) = (Substance 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)

X.5 Results

Following the proposed procedure, Nitrogen and Phosphorus loadings from point and non-point sources were separated based on the amount of surface and overland run-offs. Results are presented in the following sections.

X.5.1 Nitrogen Loading to Receiving Streams From Urbanised Areas

The rates of total loading of ammonia-nitrogen from selected cities were found to be quite variable. The total loading was comprised of the surface run-off transported (non-point source), the WWTF effluent discharge (point source), and the industrial plants and establishments discharge (point sources). Total loading rates (kg/hr) varied from a minimum of 2.4 (Ann Arbor) and 2.7 (Pontiac) to a maximum of 89.9 (Grand Rapids) followed by 54.5 (Saginaw) and 42.2 (Midland). For other urbanised areas it was low and was in the order of 5 to 12 kg/hr. WWTF contributions were generally very low except for Grand Rapids and Ann Arbor. Grand Rapids WWTF contributed to the extent of 91.01 % and Ann Arbor WWTF contributed 49.55 % of the total loading. This indicates that the non-point source contributions were less than 10 % for Grand Rapids and 50% for Ann Arbor since total loading included both the industrial discharges (point sources) and surface run-off and over land flows (non-point sources). It follows that the higher the WWTF contribution, the greater the effort needed to improve processing efficiency of WWTF in order to reduce the amount discharged to the stream. In cases where the major contributions are either from industrial plants and facilities (point sources) or from city surface run-off (non-point sources) or both, remedial efforts should be focused accordingly (Table 1).

Table 1. Net discharges of effluent NH_3-N from selected urbanised areas. This includes WWTF and

IPF discharges as well as surface run-off transported NH_3-N from city areas.

City	Up-Stream NH_3-N (kg/hr) *	Down-Stream NH_3-N (kg/hr)**	Net Input of NH_3-N (kg/hr)	WWTF Effl. NH_3-N (kg/hr)*	WWTF Contribution (%)
Ann Arbor	2.88	5.30	2.42	1.20	49.55
Battle Creek	0.97	10.30	9.33	2.18	23.38
Flint	3.40	15.71	12.31	0.63	5.08
Grand Rapids	25.76	115.71	89.94	81.86	91.01
Kalamazoo	6.89	12.51	5.63	0.66	11.76
Lansi-ng	6.45	11.92	5.47	0.49	8.96
Midla-nd	4.62	46.83	42.22	10.98	26.00
Pontiac	0.38	3.07	2.69	0.68	25.37
Sagin-aw	100.02	154.54	54.52	21.19	38.87

* is mean of four to six years during 1986 to 1991, ** is for only 1990

X.5.1.1 Mean Monthly Surface Run-off Transported Ammonia-nitrogen Loading From Selected Cities (Non-point Source)

The mean monthly instream loading of ammonia-nitrogen results indicate that run-off contributions were negligible during the months of February (cold season) and August (dry season). Highest loadings were during September and October, 0.435 and 0.299 kg/hr., respectively. During the months of March, June and December, the rates were moderate being 0.152, 0.159 and 0.199 kg/hr., respectively (Figure 1). All differences were highly significant ($p < 0.001$). The highest loading rates of ammonia-nitrogen corresponded to September and October, when mineralization rates of soil nitrogen are expected to be generally high due to fertilisation of lawns and golf courses.

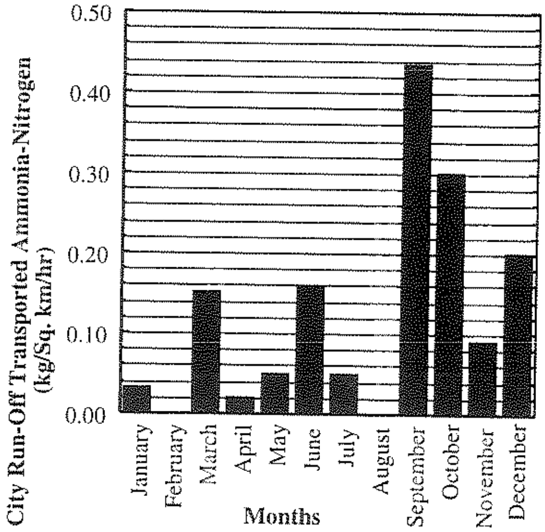

Figure 1. A general trend of monthly mean-loading of ammonia-nitrogen to instreams from surface run-off in urbanised areas.

X.5.1.2 Surface Run-off Transported Ammonia-Nitrogen Loading From Urbanised Areas (Non-point Source)

Different cities varied in transporting ammonia-nitrogen in their surface run-offs. Grand Rapids had a negative contribution of NH_3-N from city surface run-off, which is not correct. If Grand Rapids is excluded from the analysis, then the results indicate that Ann Arbor had the lowest surface run-off transported loading of ammonia-nitrogen (i.e., 0.02 kg/km^2/hr) whereas Saginaw had the highest rate of loading (4.1 Kg/Km^2/hr) followed by Midland (0.91 kg/km^2/hr). For other selected urbanised areas the loading rates (kg/km^2/hr) were relatively quite low, and were in the order of 0.03 (Pontiac), 0.03 (Battle Creek), Lansing (0.05), Kalamazoo (0.06), and Flint (0.11) (Figure 2).

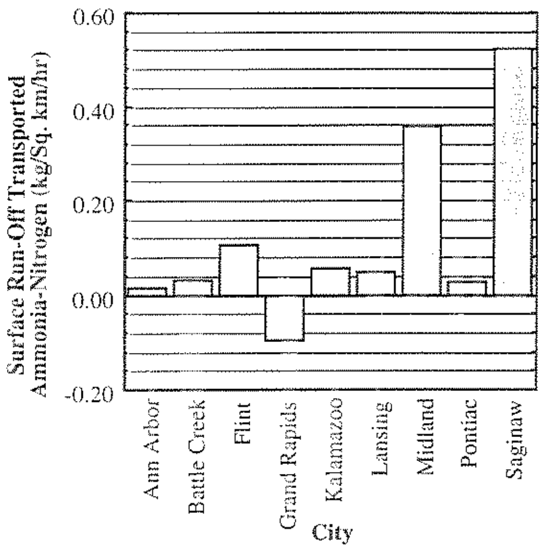

Figure 2. Relative Estimates of Ammonia-Nitrogen Transported by City Surface Run-Off in the Selected Cities.

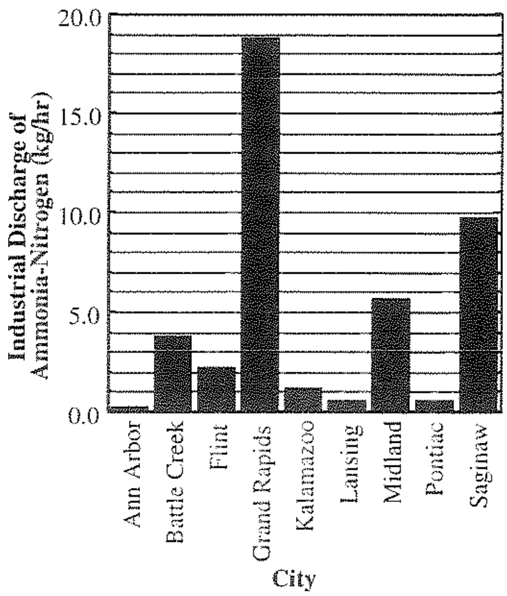

Figure 3. Relative estimates of Ammonia-Nitrogen discharge from the industrial sources in the selected cities.

X.5.1.3 Ammonia-nitrogen Loading To Streams From Industrial Plants and Facilities Located in Urbanised Areas (Point Source)

The results indicate that Grand Rapids industrial effluent discharges loaded the receiving stream with ammonia-nitrogen at a rate of 18.72 Kg/hr followed by Saginaw (9.66 kg/hr), which was nearly double of Saginaw. The lowest dischargers were Ann Arbor, Pontiac and Lansing, (0.16 and 0.47 and 0.53 kg/hr, respectively). The industrial effluent discharges from Midland also caused ammonia-nitrogen enrichment in the receiving stream at a high rate (5.64 kg/hr). The other urbanised areas which caused moderate loadings were Kalamazoo, Flint and Battle Creek in the order of 1.19, 2.20 and 3.71 kg/hr, respectively (Figure 3).

X.5.2 Phosphorus Loading To Receiving Streams From Urbanised Areas

The net input of total phosphorus laden effluents to receiving streams from surface run-off, industrial sources and waste water plants and facilities of urbanised areas was significant. The estimated net-loading of total phosphorus was highest from Midland (16.776 kg/hr) followed by Kalamazoo, Battle Creek and Grand Rapids, the rates being 10.918, 10.461 and 9.795 kg/hr, respectively. Ann Arbor had the lowest rate of loading at 2.167 Kg/hr (Table 6). Flint and Saginaw had about the same loading rates, 7.273 and 7.322 kg/hr, respectively. WWTF effluent discharges contributed 77.11% at Flint and 72.51% at Grand Rapids to their corresponding phosphorus loadings. Ann Arbor WWTF appears to have contributed more than 100% probably due to the presence of three artificial impoundments between the upstream and downstream gauging stations. High rates of WWTF loading suggest that the plant may be operating at a level higher than its designed capacity, or that operation and processing efficiencies are lower, and consequently need improvement (Table 2). The lowest input of WWTF from the city of Midland (i.e., 1.94%) clearly suggested that the effluent discharges are either from industrial facilities (i.e., point sources) or from surface run-off discharges from the city area (i.e., non-point sources), or ungauged tributaries. The separation of an estimated loading from either of these sources has been carried out in the following sections.

X.5.2.1 Monthly Mean Loading of Total Phosphorus From City Surface Run-Off (Non-point Source)

The surface run-off transported total phosphorus inputs were negligible during the months of January, February and July, at -0.016* (note the negative value), 0.002, 0.002 kg/km^2/hr, respectively. The early spring season (i.e. March and April) had the largest loading rates of 0.122 and 0.129 kg/km^2/hr. Also, during October and May the input loads were relatively high at the 0.104 and

0.086 kg/km^2/hr, respectively. Other months have input loads less than 0.024 kg/km^2/hr (Figure 4).

Table 2. Net discharges of effluent total phosphorus loads from selected urbanised areas. This includes the WWTF and IPF discharges as well as surface run-off transported total phosphorus from city areas.

City	Up-Stream Total-P (kg/hr) *	Down-Stream Total-P (kg/hr)*	Net Input of Total-P (kg/hr)*	WWTF Effl. Total-P (kg/hr)**	WWTF Discharge of P (%)
Ann Arbor	1.238	3.405	2.167	2.260	104.29
Battle Creek	1.301	11.762	10.461	0.477	4.56
Flint	3.080	10.353	7.273	5.608	77.11
Grand Rapids	39.575	49.371	9.795	7.102	72.51
Kalamazoo	6.645	17.563	10.918	3.228	29.57
Lansi-ng	4.577	10.348	5.771	1.507	26.11
Midla-nd	3.167	19.942	16.776	0.326	1.94
Pontiac	0.087	4.395	4.308	1.393	32.34
Sagin-aw	77.745	85.067	7.322	2.569	35.09

* is mean of six years data from 1986 to 1991, ** is for only 1990, *** Note that the output is more than input.

X.5.2.2 City Surface Run-off Transported Loading of Total Phosphorus (Non-point Source)

The phosphorus data for Ann Arbor and Saginaw were suspect, and were omitted from all analyses of phosphorus loading. The surface run-off transported total phosphorus was maximum for Midland followed by Battle Creek at of 0.18 and 0.05 kg/km^2/hr. For other urbanised areas, the loading rates were less than 0.03 kg/km^2/hr, for Lansing, Kalamazoo, Pontiac, Flint and Grand Rapids on the order of 0.03, 0.02, 0.02, 0.01 and 0.01 kg/km^2/hr, respectively (Figure 5).

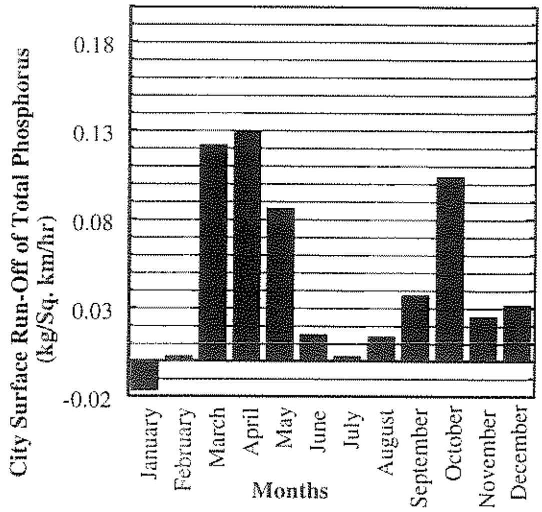

Figure 4. A general trend of monthly mean-loading of total phosphorus to streams from surface run-off in selected urbanised areas.

X.5.2.3 Estimation of Total Phosphorus Loading to Stream From Industrial Effluent Discharges (IPF, the Point Source)

Kalamazoo effluent discharge from industrial sources enriched the stream with total phosphorus at the highest rate of 6.322 kg/hr followed by Battle Creek and Midland (4.786 and 3.256 kg/hr, respectively). Pontiac, Lansing and Grand Rapids also had relatively high inputs at 2.1, 1.7 and 1.7 kg/hr., respectively. Among the selected cities examined, Flint had the lowest input rate of 0.7 kg/hr (Figure 6).

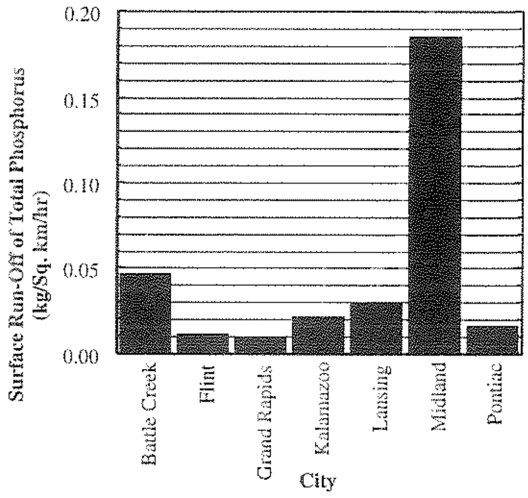

Figure 5. A general trend of loading of total phosphorus to streams from surface run-off in selected urbanised areas.

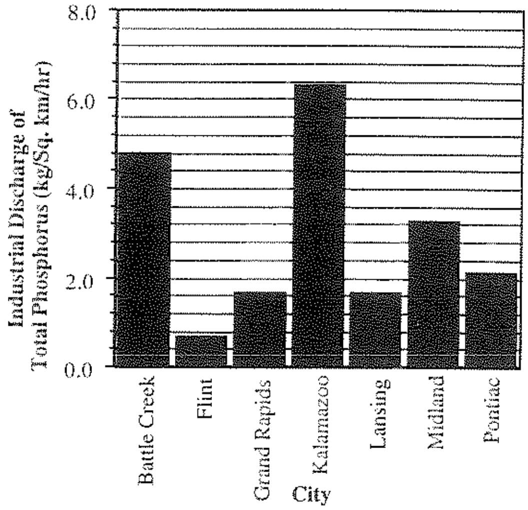

Figure 6. Relative trend of total phosphorus discharge in receiving streams from industrial sources in the selected cities.

X.6 Discussion

The purpose of this study was to estimate the amount of nitrogen and phosphorus arising from point and non-point sources of urban areas. Several assumptions were made as described previously in part – I paper included in this proceeding. These assumptions were very useful in partitioning of effluent materials originating from point and non-point sources in nature.

X.6.1 Nitrogen Loadings to Rivers/Streams

Net input of nitrogen was significantly higher at Grand Rapids, Saginaw, and Kalamazoo followed by Flint and Battle Creeck, which were at lower rates yet quite higher compared to the other four cities. Out of these five cities, it was only the Grand Rapids where the loading of nutrients from its WWTF accounted more than half of its total load. Model-predicted estimates of surface run-off transported ammonia loads were highest in September and October followed by intermediate values in March, June and December. June, September and October coincide with periods of heavy fertiliser applications on lawns and golf courses, and October is a period of leaf fall from deciduous trees. Ammonia-nitrogen loadings from surface run-off were highest at Saginaw and Midland, and it was at least three times of the other cities studied. Surprisingly, the loading was negative (i.e., output < input) for Grand Rapids (Figure 8) which might have been due to retention in lakes/ponds situated between the upstream and downstream gauging stations. Industrial loading was highest at Grand Rapids and it was about two times of Saginaw and 3.5 times of Midland.

X.6.2 Phosphorus Loads to Rivers/Streams

In contrast to nitrogen, the WWTF contributed significant portion of the phosphorus load. It was more than 70 % both at Flint and Grand Rapids. Model-estimated phosphate transport by surface run-off at Midland was quite high, and it may have been due to fertilisation of lawns, golf courses and gardens. The model indicated that other cities had low amounts of phosphorus loads from surface run-offs, making control of non-point source pollution relatively less important for them. Model predicted that the industrial plants in Kalamazoo, Battle Creek and Midland were the major causing point source pollution. In such cases, controlling point source pollution is important if these cities are to reduce phosphorus enrichment of their rivers and streams in order to improve its water quality.

Generally, cities had higher particulate phosphate than ortho-phosphate in their effluent discharges except Lansing and Pontiac. The higher enrichment by ortho-phosphate as compared to particulate phosphate in Lansing and Pontiac hints to their differences in terms of complexity of urbanisation, type of industry and the volume of industrial operations.

X.7 Acknowledgements

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X.8 References

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