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Pollutograph Modeling of an Impervious Catchment

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Abstract

The urbanisation of a catchment not only changes the rainfall-runoff processes but also has significant effects on the quality of runoff. Nonpoint source of pollution in the form of stormwater runoff from urban areas has contributed greatly to deterioration of water quality in receiving waters. The transport of nutrients from urban catchments can lead to eutrophication of water bodies and is detrimental to the various users of the water source.

Field investigations of stormwater pollution are tedious and expensive. In this study an investigation is undertaken to relate the factors which have the greatest influence on contaminant transport which are characterised by the washoff coefficients. From the results of this analysis a water quality model has been developed to predict pollutographs for ungauged urban catchments. Field data from impervious plots in a US urban catchment from Denver was used for testing the newly developed method. The predicted pollutographs agree closely with measured values of the selected water quality parameters.

1. Introduction

Urban stormwater quality monitoring of catchments is a difficult, expensive and a time consuming process. Mathematical models, however, are particularly suited for such studies and can also provide the desired information quickly. Estimation of pollutant washoff during any storm event is essential for engineers to design water pollution control structures to reduce pollutant loadings downstream of the urban catchments.

Recently a new semi empirical washoff method was developed (Sivakumar and Boroumand-Nasab,, 1993) to predict pollutant washoff load from urban catchments based on the assumption that transport rate is proportional to the distribution and availability of pollutants. The proposed washoff method has been calibrated and verified for two Australian urban catchments. For urban pollutants such as total phosphorous (TP) and total oxidised nitrogen (NO_x-N) good agreement between measured and predicted washoff loads has been found.

Based on the new washoff equation and analysis of the existing data from 89 storm events from seven US urban catchments, a new water quality model has been developed for estimating the total washoff loads, EMCs, pollutographs and loadographs. In this paper pollutographs have been predicted for two water quality parameters namely Non-Filterable Residue (NFR) and Total Phosphorus (TP).

2. Proposed Pollutograph Model

The amount of pollutant washoff in an urban catchment is directly related to availability of pollutants, and the quantity of runoff volume (Sivakumar and Boroumand-Nasab, 1993) and is described as:

$$P_0 - P = P_0\,(1 - e^{-KV^a}) \qquad (1)$$

where $P_0 - P$ = pollutant washoff, kg
P_0 = initial pollutant load, kg
V = cumulative depth of runoff, mm
K = washoff coefficient
a = exponent

Equation 1 describes the total washoff load of a given pollutant since the beginning of a storm event. By using Equation 1, the pollutant washoff rate can be derived as:

$$\frac{dP}{dt} = -K\,a\,V^{a-1}\,R_t\,P_0\,e^{-KV^a} \tag{2}$$

where dP/dt denotes the rate of pollutant in kg/h and R_t is runoff rate in mm/h. Eq. 2 can simulate urban storm loadographs.

The instantaneous pollutant concentration (C_t) can be calculated as: $= \dfrac{\text{Pollutant load}}{\text{Area} \times \text{Runoff rate}}$

and hence

$$C_t = \frac{dP}{A\,R_t\,dt} \tag{3}$$

wherein A is the catchment area in hectares and C_t is the concentration, mg/L. Substituting "dP/dt" from Eq. 2 into Eq. 3, the following expression was obtained. Hence,

$$C_t = \frac{100\,K\,a\,V^{a-1}\,P_0\,e^{-KV^a}}{A} \tag{4}$$

Equation 4 expresses the instantaneous concentration of pollutant C_t as a function of cumulative runoff volume V, initial pollutant P_0, catchment area A and washoff parameters K and a. The newly proposed instantaneous concentration model has the ability to simulate urban storm pollutographs.

3. Washoff Parameters

It is important to understand the physical meaning of the washoff parameters in the proposed methods. For this purpose, calibration of more than 89 storm events from seven US catchments was carried out using data obtained by Mustard et al (1987a). The imperviousness fraction of the selected catchments ranged between 0.04 and 0.98. Multiple correlation analysis was undertaken to relate washoff parameters with storm and catchment characteristics (Boroumand-Nasab, 1994).

3.1 Washoff exponent "a"

Correlation analysis of washoff coefficient "a" with storm and catchment characteristics indicated that it is independent of storm size. However, it was found that the exponent "a" correlated well with the percentage of imperviousness of the catchments as shown in Fig. 1. The following equations have been derived to relate "a", i.e the exponent value for different water quality parameters, to the percentage of imperviousness (Imp.) of the catchment.

$$a_{NFR} = -0.006\ \text{Imp.} + 1.290 \tag{5}$$

$$a_{TP} = -0.006\ \text{Imp.} + 1.286 \tag{6}$$

The similarity between the equations for NFR and TP can be attributed to the similar behaviour of these contaminants. From the analysis of the inter-relationship between NFR and nutrients, it was found that the TP values are closely correlated with NFR in the selected urban catchments. This may be attributed to the availability of higher proportion of non-filterable phosphorus in the urban stormwater.

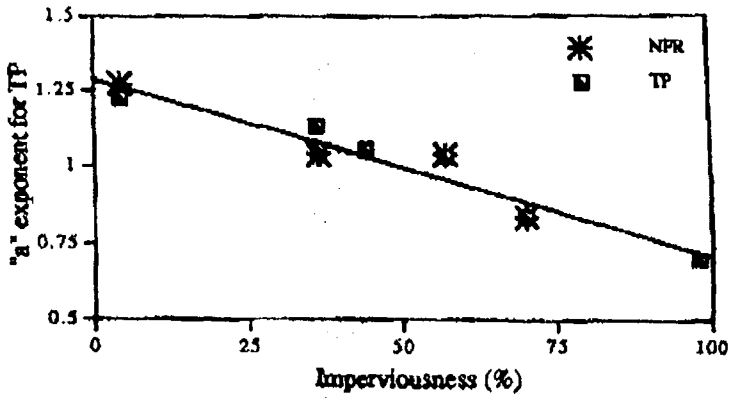

Fig. 1 Relationship Between Imperviousness and Exponent "a" for NFR and TP

3.2 Washoff coefficient "K"

The washoff coefficient "K" however appears to vary with catchment and storm characteristics. From multiple regression analysis, it has been found that "K" is related to areal pollutant loading and total runoff depth. These relationships are shown in Eqs. 7 and 8 for NFR and TP respectively.

$$"K_{NFR}" = 0.298\,(P_a)_{NFR}^{-0.36}\,V^{0.10} \qquad (7)$$

$$"K_{TP}" = 0.015\,(P_a)_{TP}^{-0.51}\,V^{-0.14} \qquad (8)$$

in which Pa refers to areal pollutant loading of the urban catchment. In the case of TP the total runoff depth (V) and P_a are found to be inversely proportional to K. Whereas for NFR, the total runoff depth is directly proportional to K and P_a is inversely proportional to K. The graphical illustration of equations 7 and 8, are shown in Fig. 2. It is seen that K is less sensitive to the variation of total runoff depth, and is highly sensitive to areal pollutant loading for both pollutants.

4. Application to an Impervious Catchment.

The model is applied to an urban catchment located in the Denver metropolitan area, Colorado, USA. The urban area was divided into nine plots of 0.0093 hectare each. The selected study plots were in North Avenue which has four lanes major access road to the Denver Federal Centre. The original study and the data were presented by Mustard et al. (1987b) and information from hydrographs and loadographs are obtained by a digitising process. The data collected characterises the runoff quantity and quality for different simulated rainfall intensities after one, two, three, four, and five dry days. Data collection was carried out on each plot by a rainfall simulator with sprinklers. Runoff rate was measured at the outlet of each plot with a measuring flume. Water quality samples were collected by hand at the outflow of the flume and analysed for NFR and TP. The pollutants buildup were measured with simulated rainfall of about 50 millimetres per hour. The measured runoff volumes were between 9 to 31 mm. The information on the storm runoff volume and initial pollutant load for each plot is given in Table 1.

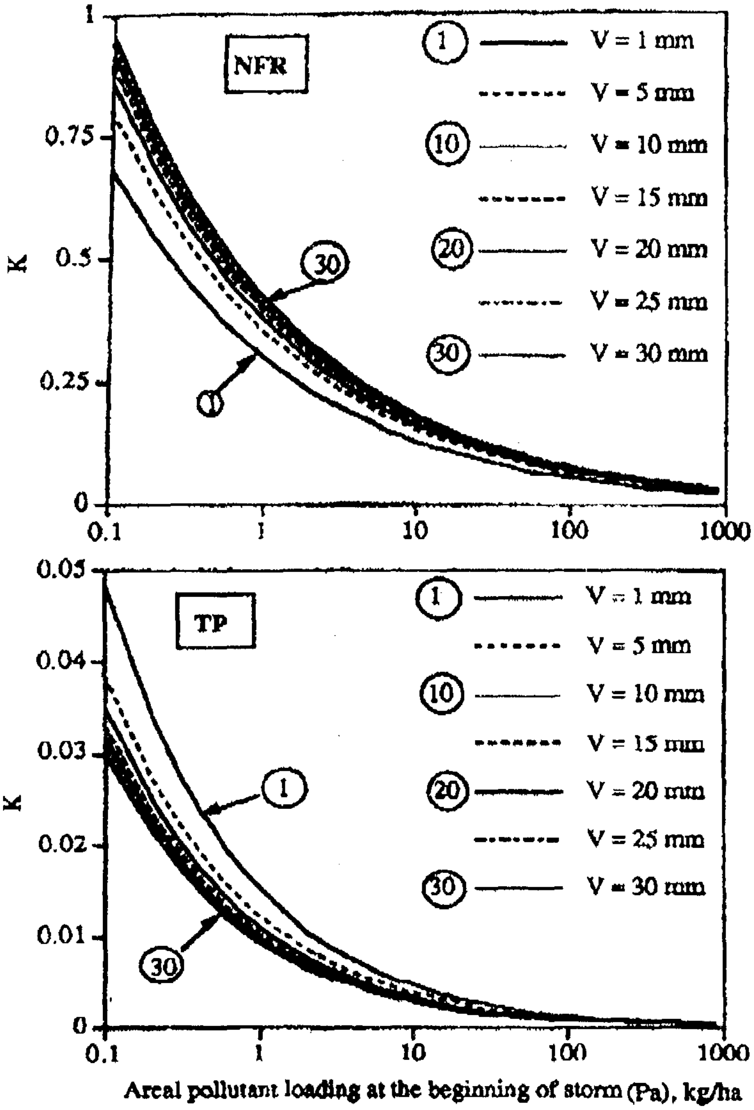

Fig. 2 Variation of K with areal pollutant loading for NFR and TP

Table 1 Summary of Runoff Information and Initial Pollutant Load

Plot No.	Meas. runoff volume (mm)	Initial load NFR (kg)	Initial load TP (kg)
1	9.55	0.112	0.000194
2	26.56	0.112	0.000194
3	9.52	0.186	0.000259
4	27.28	0.186	0.000259
5	9.05	0.27	0.000319
6	28.95	0.27	0.000319
7	10.67	0.45	0.00041
8	31.02	0.45	0.00041
9	10.79	0.57	0.000527

The washoff parameters "K" and "a" for each water quality parameter in the proposed model are obtained by the following methods. The "K" parameter has been derived based on the total runoff volume and areal pollutant loading at the beginning of storm used in the Eqs. 7 and 8 for NFR and TP respectively. The "a" exponent is derived based on the impervious fraction by using derived Eqs. 5 and 6 for NFR and TP, respectively. These coefficients for the events analysed are shown in Table 2 for NFR and TP. The values of "K" for TP in the parentheses are obtained by using the new values of initial pollutant loads (5 P_0). This is because the measured initial pollutant for some events is less than the measured washoff load. This also shows the complexities of pollutant buildup phenomenon in urban areas.

Table 2 Derived Coefficients for the Analysed Storm Events

Plot No.	NFR		TP	
	K	a	K	a
1	0.152	0.680	0.079 (0.035)	0.676
2	0.169	0.680	0.068 (0.030)	0.676
3	0.127	0.680	0.068 (0.030)	0.676
4	0.141	0.680	0.059 (0.026)	0.676
5	0.110	0.680	0.062 (0.027)	0.676
6	0.124	0.680	0.052 (0.023)	0.676
7	0.093	0.680	0.053 (0.023)	0.676
8	0.104	0.680	0.046 (0.020)	0.676
9	0.086	0.680	0.046 (0.020)	0.676

(Calculated values of K for TP, using 5^*P_0 are shown within parentheses)

5. Results of pollutograph simulation

The newly developed model has the capacity to simulate pollutographs in urban catchments during storm events. It has been tested in terms of its ability to reproduce the overall shape of the observed pollutographs of various water quality parameters.

The results of pollutograph simulation for each of the nine plots are given in the Figs. 3 and 4 for two pollutants namely NFR and TP, respectively. The parameters used in the simulation were not calibrated to fit pollutographs. However, the results indicated that the proposed simulation gave a good reproduction of pollutographs.

The graphs of measured pollutographs from Plot No. 6 show a peak in concentration at the middle of the pollutographs (22 mins) for NFR and TP, whereas the simulated pollutographs for these two water quality parameters do not predict this peak concentration. Mustard, et al. (1987b) stated that during data collection for Plot No. 6, the flume which was used to measure the flow, was slightly misaligned, resulting in a back water effect and ponding upstream of the flume, where deposition was observed. The small pond was agitated towards the end of the simulation, and the deposited materials were transported through the weir, where samples were collected. The peak of washoff loads depicted at the middle of the pollutograph in Plot No. 6 is not indicative of the washoff mechanism from the plots but resulted from deposition and agitation of the washoff loads.

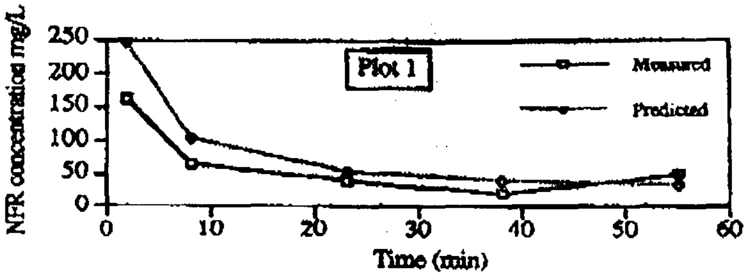

Fig. 3 Results of Pollutograph Simulation for NFR (For Plot 1)

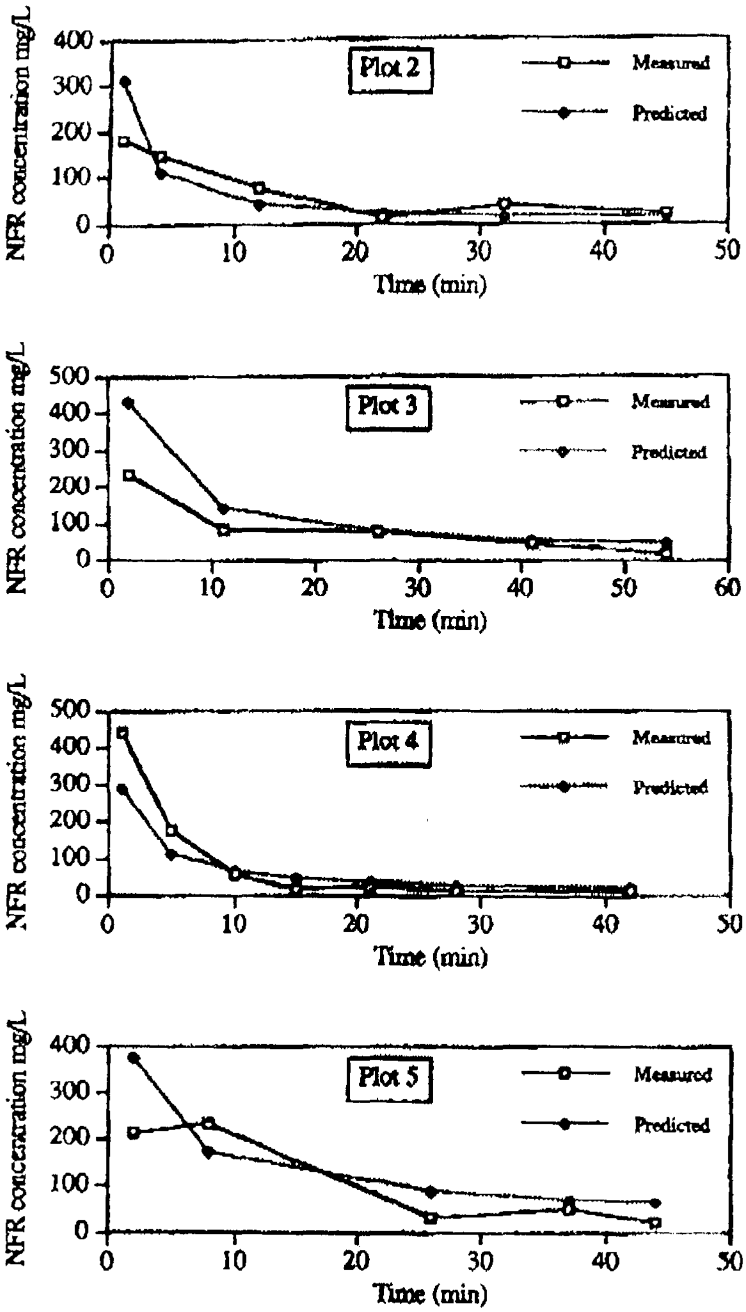

Fig. 3 Results of Pollutograph Simulation for NFR (For Plots 2-5)

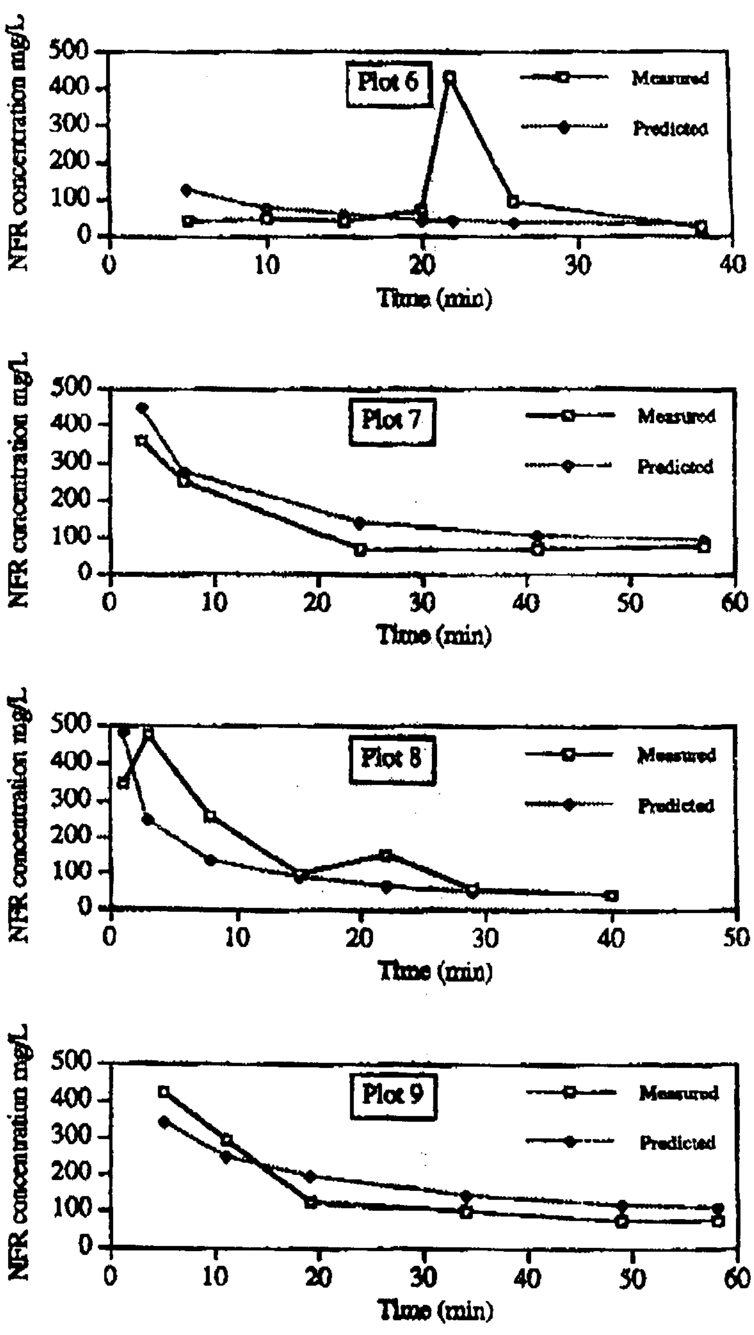

Fig. 3 Results of Pollutograph Simulation for NFR (For Plots 6-9)

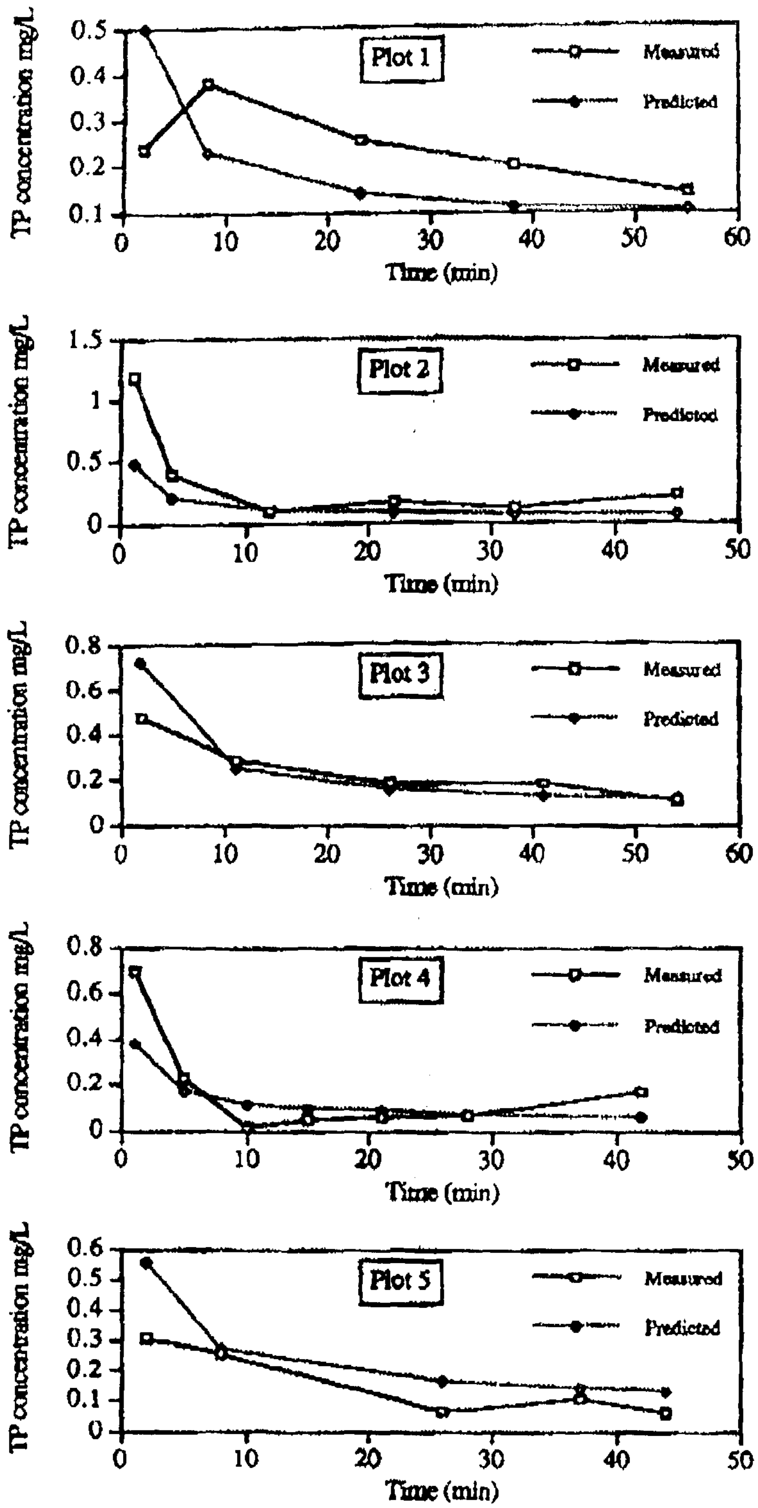

Fig. 4 Results of Pollutograph Simulation for TP (For Plots 1-5)

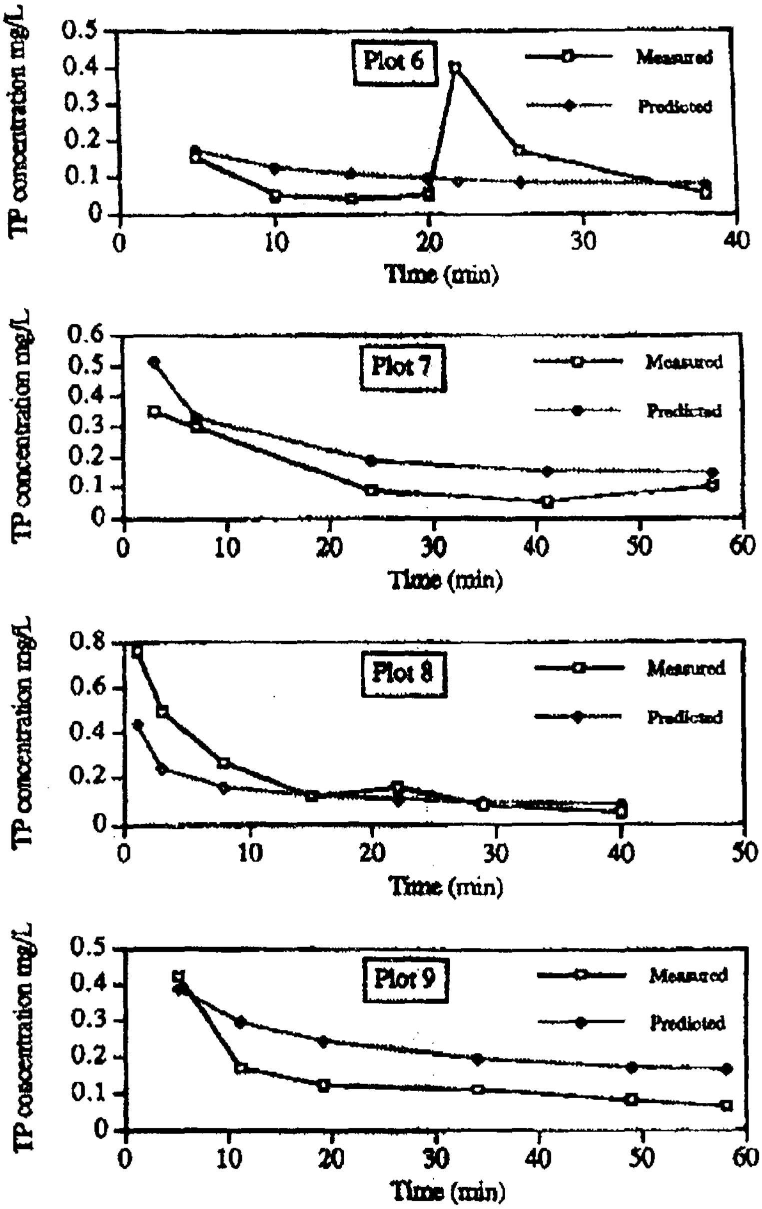

Fig. 4 Results of Pollutograph Simulation for TP (For Plots 6-9)

In water quality studies of urban catchment, regulatory bodies require stormwater to be discharged below certain accepted concentration to minimise impacts on ecosystem downstream. This is particularly so in urbanising catchments where appropriate stormwater treatment measures for worst conditions need to be designed. This model could be used to simulate worst conditions of stormwater pollutographs which could be discharged from urban catchments.

6. Summary

A new equation is proposed to predict pollutographs from an urban catchment. The model was tested against a set of experimental data from impervious plots in Lakewood, Denver, Colorado in USA, where measured initial pollutant loads (P_0) were available. The model coefficients were calibrated independently for data obtained from 89 storm events from seven urban catchments. The results for two pollutants NFR and TP gave satisfactory predictions for a number of storm events.

The proposed model may find application in urban water quality planning and studies relating to design of stormwater treatment facilities. The model's prediction will depend on the accuracy of the washoff parameters selected and a good understanding of the physical significance of these parameters warrants further research.

7. Acknowledgment

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8. References

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