

Modelling Phosphorus Loads and Pollutographs from an Urban Catchment with an Informal Settlement Land-Use.

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Introduction

The WITQUAL model has been developed to produce time series of pollutant concentrations (pollutographs) for runoff events from urban areas. The model has algorithms for the modelling of suspended solids (SS), particulate associated, and dissolved pollutant forms. The hydrological input required by the model is produced using the WITSKM (Coleman and Stephenson, 1993) rainfall-runoff model. The abilities of the modelling approach used are tested against SS, particulate phosphorus (P), and dissolved P data collected from the Shembe catchment. Plots of pollutographs and histograms of the ratio of simulated to observed event pollutant loads are used to assess the abilities of the model.

Description of Catchment and Data Collection

The Shembe catchment is situated outside Durban in the Kwa-Zulu Natal region of South Africa. The catchment area is 5,6 km² and the breakdown of the catchment land-use and the number of dwelling units as estimated in 1993 are given in Table 1.

Table 1 : Breakdown of land-use for Shembe catchment

Land Use Type	Percentage of catchment	No of units
Formal low cost residential	11	770
Informal settlement	35	7560
Rural settlement	25	965
Commercial, industrial	5	-
Natural catchment	24	-

The population density for the catchment is 96 to 133 p/ha. The highest population densities are at the lowest part of the catchment in the informal and formal low cost residential areas. The lower population densities are situated in the upper reaches of the catchment in the rural settlements. The services provided in the catchment are basic. The sanitation system is pit latrines. Some of the pit latrines are supplied others are self made. The water supply is by means of vendors and the refuse removal is rudimentary with skiffs located at central points. The catchment is drained by well defined natural streams. The last 150 m of the main natural stream draining the catchment has been canalised into a concrete lined channel. The streams drain to the Umhlangana river, a tributary of the Mgeni river. The catchment has numerous

valleys with steep side slopes ranging from 0,07 to 0,15. The channels are well vegetated with reeds, shrubs, and trees.

The rainfall data was collected at two minute intervals by means of a tipping bucket raingauge situated on top of a building at the lower end of the catchment. The water depth was measured in the concrete lined channel. The depth was measured using a float system housed in a stilling well constructed next to the channel. The base of the stilling well was unfortunately built 93 mm above the invert level of the channel. The flow rate first had to reach 1,5 m³/s before any recordings could be made. Water samples were collected for analysis using a sampler triggered by the logging system. The analyses for the different pollutant forms were carried out by the CSIR according to the Standard Methods for the analysis of water and wastewaters (APHA, 1989).

Description of Quality Algorithms

The WITQUAL model consists of a catchment surface entrainment and transport (washoff) module and a conduit transport module. The model is subdivided into three main sub models for the modelling of suspended solids, particulate associated and dissolved pollutant forms. Different algorithms are used to describe the entrainment of suspended solids and dissolved pollutant forms from the impervious and pervious catchment surfaces. The entrainment and deposition of particulates is considered in the conduits but the entrainment of dissolved pollutant and particulate associated forms are not considered.

The routing of pollutants overland and through the conduit system is undertaken using the one dimensional advection equation.

$$\frac{\partial(QC)}{\partial x} + \frac{\partial(AC)}{\partial t} = wLat - KAC$$

where Q (m³/s) is the flow rate, C (g/m³) is the cross sectionally averaged pollutant concentration, A (m²) is the flow cross sectional area, x (m) is the distance, t (s) is time, K (/s) is the decay constant, Lat (g/m²/s) is the lateral entrainment or deposition of pollutant from or onto the catchment surface, and w is the catchment or channel width.

The modelling approach used in the entrainment of suspended solids from the catchment surfaces is based on the approach of Meyer and Wischmeier (1969). In this approach the entrainment and transport of suspended solids from the catchment surfaces is considered to consist of detachment and transport subprocesses. The detachment processes consist of that due to rainfall impact on the catchment surface and the movement of water over the surface. The transport of the detached sediment is by raindrop splash and flow. The mass of material that is entrained or deposited is determined by comparing the transport capacity of the flow to the detached mass of material. In the model, the Yalin equation (Yalin, 1977) equation is used to determine the transport capacity of the flow. The detachment of mass by raindrops is determined using the following formulation (Li, 1979)

$$D_r = a_e i^2 \left(1 - \frac{y}{y_p}\right) (1 - c_v)$$

where D_r (g/m²/hr) is the detachment rate, a_e is a parameter to account for the soil erodibility, c_v is the vegetation cover factor, y_p is the depth of penetration of raindrops, and y is the water depth on the surface. The penetration depth y is taken as 3 times the median raindrop diameter (mm) given by $2,32i^{182}$ where i is the rainfall intensity (mm/hr). The vegetation cover factor has a value between 0 and 1 while the soil erodibility factor can be estimated using $0,0138K_e$ (g/m²/hr) (Foster, 1982) where K_e is the universal soil loss equation soil erodibility factor. The detachment of soil by flow is given by a fraction of the difference between the available mass on the catchment surface and the mass required to meet the flow capacity requirements. For the pervious areas, the detached material is assumed to have the same particle size distribution as the in situ material of the catchment. This material is added to the available mass in the store from which the particulates are removed based on the transport capacity of the flow. In the case of the impervious surfaces, the material is deposited from the atmosphere, by previous rain events, or by the activities of man. The detachment functions are still used on these areas but they become more of an entrainment function (Price and Mance, 1978).

The modelling of particulate associated pollutants is undertaken using a potency factor. The fraction of the suspended solids that is the pollutant of interest is input to the model. The concentration of suspended solids, as output by the suspended solids model, are used together with the potency factor to give the concentrations of the particulate associated pollutant of interest.

The entrainment of dissolved pollutant forms from the pervious catchment surfaces is undertaken assuming that there is a soil layer of depth Z (m) from which the dissolved pollutants are removed. The entrainment rate is taken as an entrainment coefficient E (m/s) times the porewater concentration C_{sd} (g/m³). A mass balance around the surface layer yields the following relationship

$$Z\theta \frac{dC_{sd}}{dt} = -EC_{sd} - fC_{sd}$$

where the moisture content θ is taken as the porosity of the upper soil layer, and f (m/s) is the infiltration rate. The entrainment coefficient E is taken as being directly proportional to the shear velocity u^* (m/s) as the shear velocity can be considered to be an indication of the flow turbulence or the rate at which pollutants can be mixed into the flow from the surface. The entrainment rate of dissolved pollutants from the impervious catchment surfaces is undertaken using the methodology suggested by Akan (1987) where the rate at which mass is entrained is proportional to the mass present on the catchment at any time t and the shear stress acting on the surface. The following equation results

$$D_{pd} = k \tau_0 P$$

where k is a constant, τ_0 is the shear stress (N/m^2), P is the pollutant mass (g/m^2) on the impervious surfaces at any time t and D_{pd} ($g/m^2/s$) is the dissolved pollutant entrainment rate. The shear stress is given by

$$\tau_0 = \gamma y S_0$$

where γ is the unit weight of water (N/m^3), y (m) is the flow depth, and S_0 is the slope of the surface.

Application of Model

The WITQUAL and WITSKM programs were applied to the data collected from the Shembe catchment. Although information was collected on a number of runoff events from the catchment, only water depths in excess of 93 mm were logged due to the errors in the installation of the stilling well. This resulted in only one or two points being collected on the hydrographs for many of the smaller events. There were 7 complete events which were selected to test the capabilities of the model. The dates, peak rainfall intensities, and the storm durations are given in Table 2.

Table 2 : Details of storm events used in the comparison of the observed and simulated pollutographs

Date	Peak rain intensity (mm/hr)	Storm duration (mins)
92-01-01	68	300
92-02-18	75	220
92-03-01	92	190
92-04-11	37	218
92-10-08	28	1800
93-01-09	52	448
93-07-29	75	60

The storms cover a variety of storm types from high intensity short duration to low intensity long duration storms. The catchment was discretised into 4 subcatchments and 8 channels as shown in figure 1. The WITSKM model was run first and the results of the WITSKM runs were used as input to the WITQUAL model.

Suspended Solids modelling

For the modelling of suspended solids, the particle size distribution and densities, and the rain and flow detachment parameters for the impervious and pervious areas are required. The grading of the soil was estimated from the USDA soil texture diagram to be 60% sand, 30% silt, and 10% clay. A fine and a coarse particle size class of 0,064 mm and 1 mm were used to describe the soils on the impervious catchment surfaces. The split between the two size classes was 0,4 in the fine class and 0,6 in the coarse class. Three size classes of 0,064, 0,1, and 2,0 mm with fractions of 0,3, 0,3, and 0,4 were used to describe the soils on the pervious catchment surfaces. The specific gravity of the particulates was taken to be 2,65. The rainfall detachment parameter for the pervious areas was estimated using the Universal Soil Loss Equation (USLE) soil erodibility parameter as suggested by Foster (1982) to be 0,2. However this value was found to be too high and was adjusted to 0,1. The same value was used for the rainfall detachment or entrainment parameter for the impervious surfaces. The flow detachment parameter was not used for the impervious surfaces, and a value of 0,6 was used for the pervious surfaces. The vegetation cover factors of 0,1 and 0,8 were used for the impervious and pervious areas respectively.

A comparison of the simulated and observed pollutographs for some of the events modelled are shown in figure 2. In figure 5 a histogram of the ratio of the simulated to observed loads is presented.

Phosphorus Modelling

Both the particulate and dissolved forms of P were modelled. The particulate P was modelled using a potency factor approach where the fraction of the particulates on the catchment surfaces and the modelled suspended solids concentrations are used to produce particulate P pollutographs. The ortho-phosphate pollutographs were modelled using the modelling approach for dissolved pollutant types. The potency factor used for the particulate P on the catchment surfaces was 0,0015 (g/g). An initial mass of 5 g/m² of P and a value of 0,1 for k was used for the entrainment of dissolved P from the impervious surfaces. A value of 0,0001 m/s was used for the entrainment coefficient E. The initial dissolved P concentration in the soil layer was computed using the potency factor of 0,0015, the mass of soil in the surface store of depth 0,01 m, and a partition coefficient of a linear isotherm of 3 (Bonzongo et al, 1992).

A comparison of the simulated and observed pollutographs for some of the events modelled are shown in figure 3 and 4. In figure 5 a histogram of the ratio of the simulated to observed loads is presented.

Conclusions

Based on the application of the model to the data collected on the Shembe catchment, the following conclusions can be drawn :-

- i) The model generally over predicted the SS and particulate P loads due to the peaky shapes of the SS pollutographs

- ii)The model predicted the rising concentrations of the dissolved P on the recession limbs of the hydrographs.
- iii)The model generally under predicted the dissolved P loads.

Despite these shortcomings, the model is able to predict pollutographs with reasonable accuracy using the same set of model parameters. Considering the dynamic nature of the catchment and the complexities of the pollutant pathways and processes, the WITQUAL model was able to produce results that can be used by engineers and urban planners to analyse stormwater management systems for the runoff from urban areas and to assess receiving water impacts.

References

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Figure 1 : Discretization of Shembe catchment

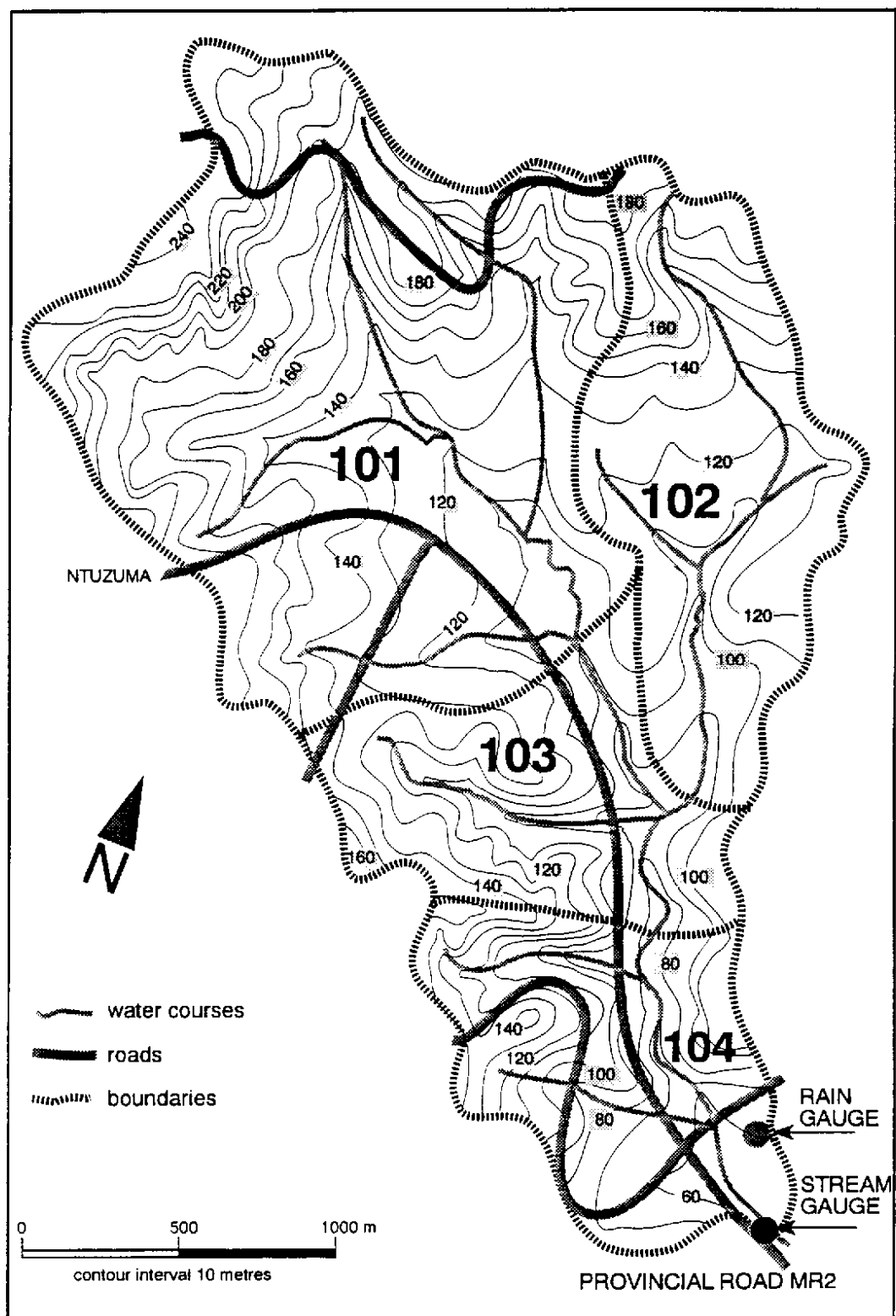


Figure 2 : Comparison of simulated and observed SS pollutographs

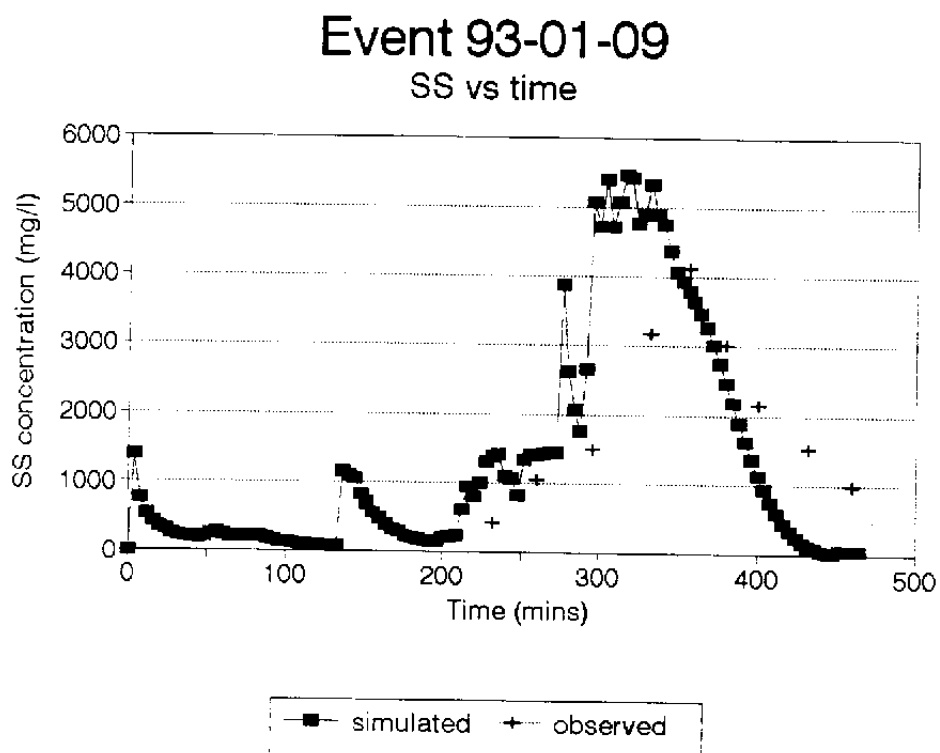
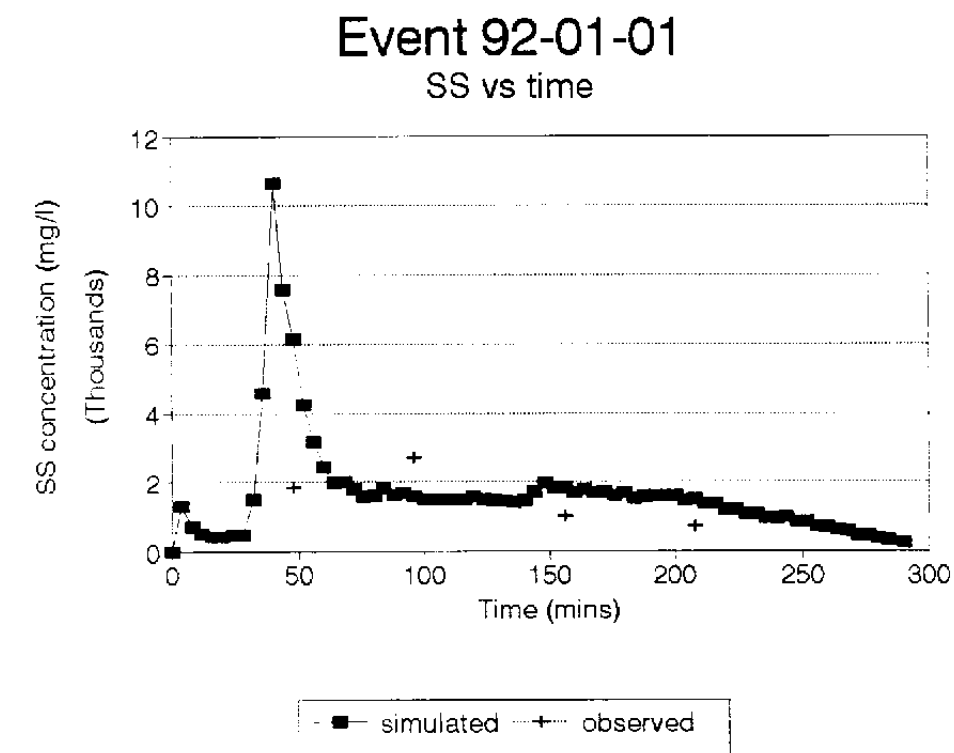


Figure 3 : Comparison of simulated and observed Part. P pollutographs

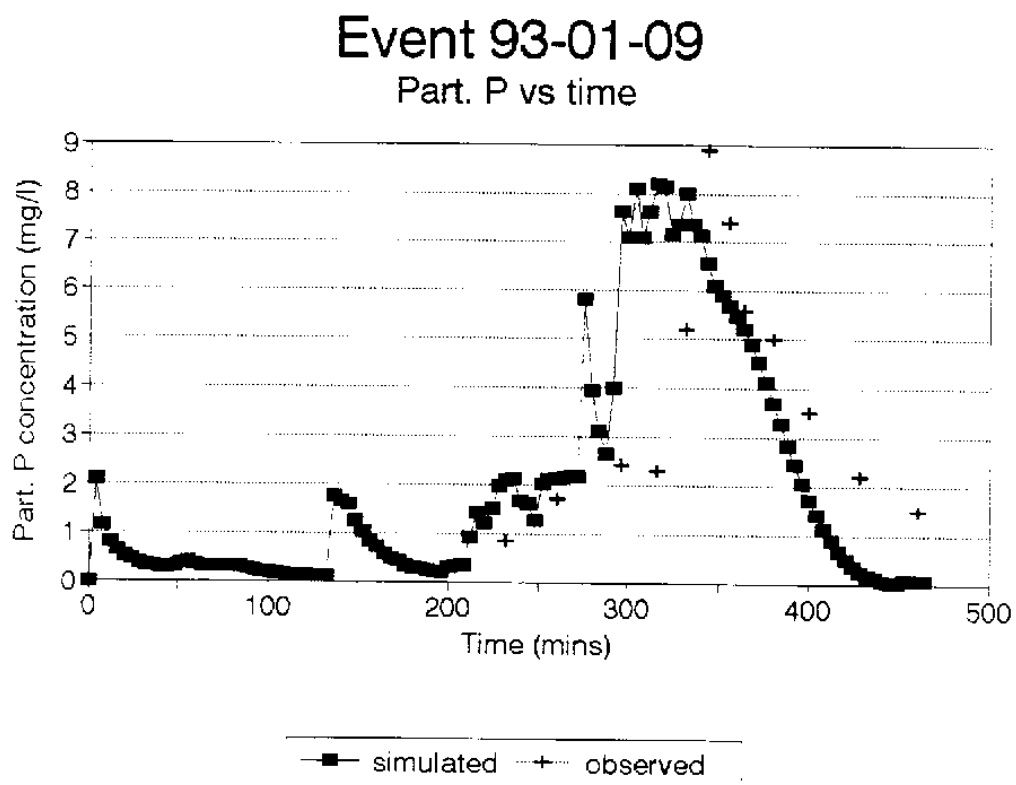
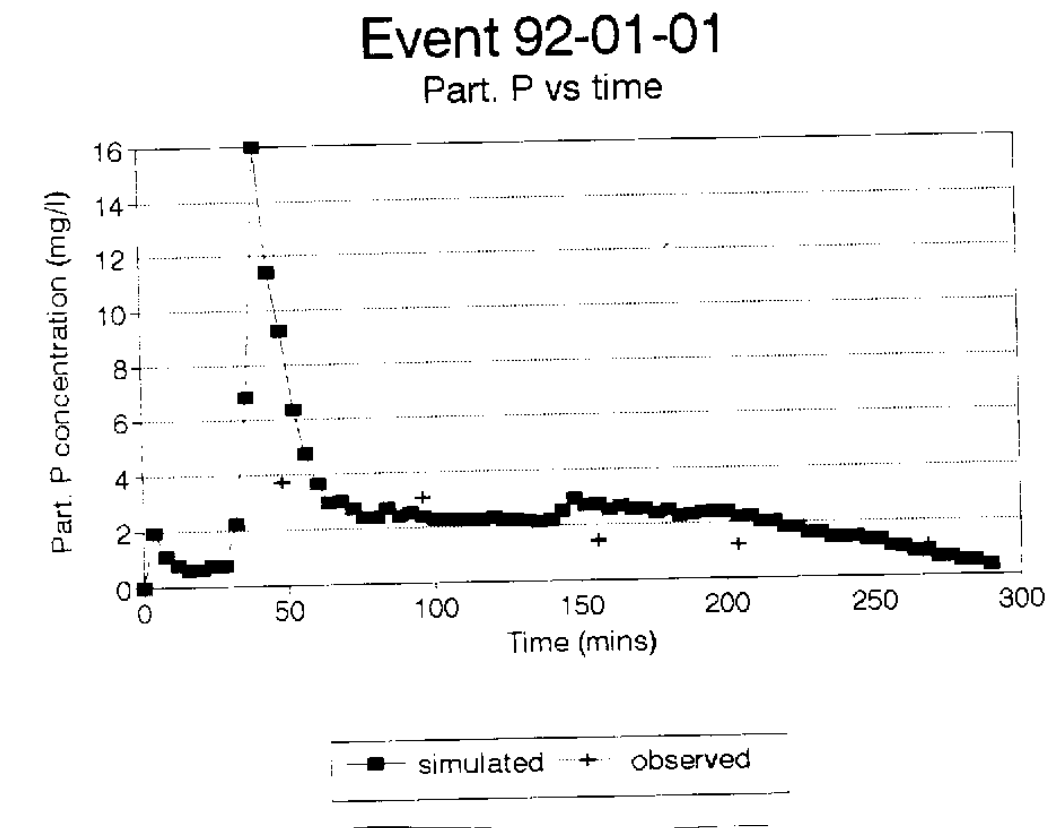


Figure 4 : Comparison of simulated and observed Dissolved P pollutographs

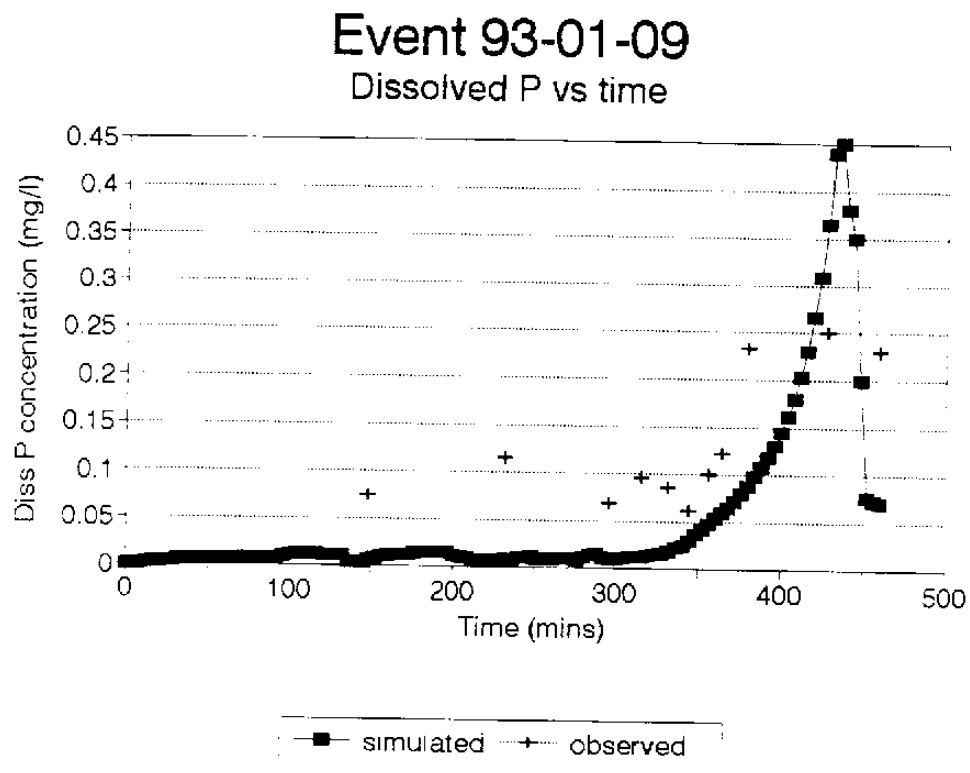
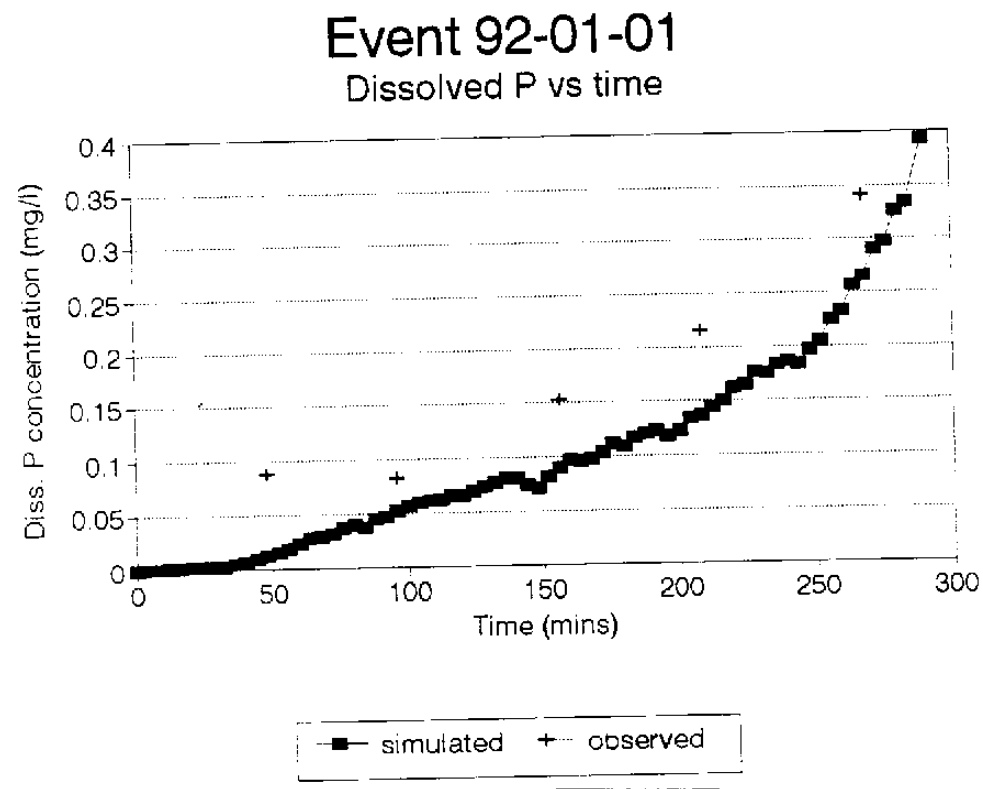
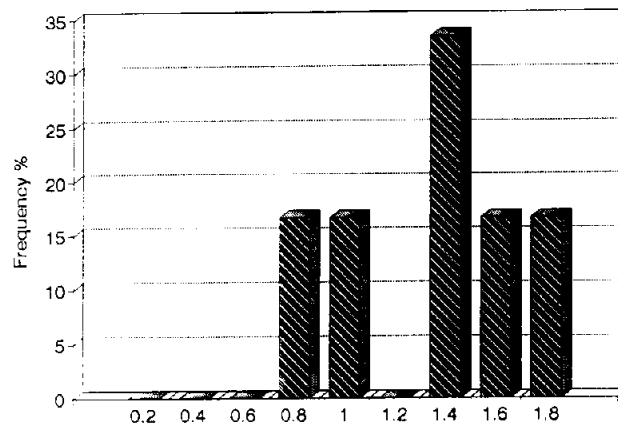
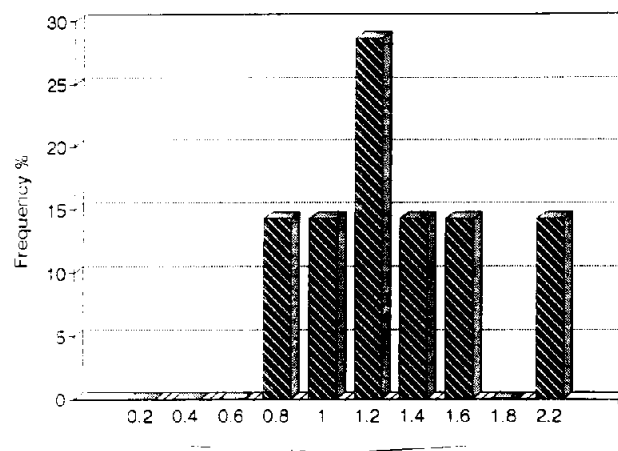


Figure 5 : Histograms of the ratio of simulated to observed loads

Histogram of SS loads



Histogram of Part. P loads



Histogram of Diss. P loads

