WATER RESEARCH COMMISSION

ADAPTATION AND CALIBRATION OF AN URBAN RUNOFF QUALITY MODEL

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

OBJECTIVES

The primary objective of this research was to develop a water quality model, WITQUAL, for application to South African catchments and conditions. The following objectives were set and have been addressed in this research:-

1. To adapt an existing urban runoff model to include simulation of runoff quality, typically for suspended and dissolved solids, phosphorus and nitrogen forms and selected heavy metals. The model will simulate quality changes during runoff events in a continuous manner from rainfall data and a knowledge of catchment parameters.

2. To incorporate into the model "best management practices" such as diversion of the first flush, detention basins and infiltration to reduce peak flows and improve water quality.

3. To use locally collected data to initially develop and improve model concepts and collect new data from suitable catchments to test and validate the model.

The catchments selected were the Shembe and Amanzimnyama catchments in Durban, Natal. The Shembe catchment has as its land-use an informal settlement while the Amanzimnyama catchment has a more commercial and industrial land-use. Due to the difficulties in gauging and the numerous point sources and spills that occurred in the Amanzimnyama catchment, the model was not applied to this catchment only the water quality levels and loads are reported.

The WITQUAL model was to use hydrographs generated using the WITSKM rainfall runoff model (Coleman and Stephenson, 1993) to produce pollutographs of the variation of pollutant concentration with time on an event basis. This will allow for the generation of pollutant loads which can be used for input into receiving water quality models. In addition best management practices (BMP) of diversion and detention/retention structures have been included in the model which will allow for the development of stormwater management plans for urban areas.

The quality of urban stormwater runoff has been shown by a number of monitoring programs (Simpson, 1986 ; Wimberley, 1992 ; Coleman, 1993 ; Wright, 1993) on a variety of urban land use types in South Africa to have a quality that exceeds the general effluent, recreation, and instream water quality standards for a number of pollutants. The pollutants that generally exceed the standards are the nutrients, oxygen demanding organic content, suspended solids, and the bacterial quality. Heavy metals such as lead have also been found on occasions to exceed the drinking water and general effluent standards. The areas that have been found to be responsible for large quantities of pollutants are the informal and squatter type settlements that are expanding rapidly around South African urban centres. Attention will have to be given to the management of both the quality and quantity of urban runoff when designing stormwater drainage systems for urban areas. To be able to achieve this, urban planners and engineers need a tool to assist in the examination of "what if" management scenarios. The WITQUAL and WITSKM package have been developed to provide this tool.

CATCHMENT DESCRIPTION AND DATA ACQUISITION

Data was collected on the flow, rainfall, and quality of the dry weather and storm flows from the Amanzimnyama and Shembe catchments from October 1991 to December 1993. The pollutants tested for were suspended solids, TDS, total phosphorus, dissolved phosphorus, nitrate, ammonia, presumptive and confirmed coliforms, COD, BOD, total and dissolved forms of copper, chrome, lead, zinc, cadmium, and mercury as well as dissolved and particulate forms of Kjeldahl nitrogen. Not all the pollutant concentrations were determined for all the samples collected. For many of the events only composite samples were analysed for the quality parameters.

The Shembe catchment has a catchment area of 5.6 km^2 and is developed largely with informal settlements. The breakdown of the land-use is given in Table A. the population density of the catchment was estimated to range from 96 to 133 p/ha.

Table A : Land use split for Shembe

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

The Shembe catchment's rainfall was measured continuously using a tipping bucket raingauge and data logger. The flow was measured in the concrete channel draining the catchment using a float system and data logger housed in a stilling chamber. The water samples were taken from the channel on a volume basis using a sampler triggered from the logging equipment. The monitoring system only switched on once the water depth in the channel was above 93 mm due to elevation errors in the installation of the stilling well access pipes.

The Amanzimnyama catchment measures 12 km^2 and is developed largely with industrial and commercial development. The industries present in the catchment range from paint manufacture, oil recycling, scrap metal, textile, and a variety of food manufacturers. The rainfall for the catchment was measured using 3 tipping bucket raingauges and data loggers. The flow depth in the concrete channel draining the catchment was measured behind a weir used as an oil trap. The depth was initially measured using a float system. However the encoder on the float system gave trouble during periods of lightening activity, and was later changed to a 10 turn potentiometer.

RESULTS OF MONITORING PROGRAM

A statistical analysis of the concentration data for the storm flow from the Shembe and Amanzimnyama catchments are presented in Tables B and C. The concentrations presented in Tables B and C show that runoff from both catchments contains considerable pollution. The impacts of the runoff could be eutrophication, de-oxygenation of the receiving water, toxicity, and the creation of a health hazard. The pollutant types that exceeded the special effluent standards and the criteria set for aquatic life are suspended solids, metals, ammonia, COD, and the microbiological quality.

MODEL DESCRIPTION

The overall modelling package consists of the WITQUAL, WITSKM, EDITOR, and OUTPUT programs which are linked together by means of databases. The databases are used to store modelling results as well as observed flow, quality, and rainfall time series. The package is written in the BASIC language for use on IBM compatible PCs. The method of modules has been used as a discretization approach as this approach allows for the easy representation of the catchment surfaces, drainage system and storm water management structures. The drainage system can be easily changed to allow for the inclusion of stormwater management structures at any point in the drainage system and the changing of the drainage system of pipes and channels. The modules that can be used to describe the catchment are overland flow, aquifer, pipes, trapezoidal channels, and storage modules. An input module has also been added to allow for the addition of flow and a pollutant concentration into a module. This has been added to enable the modelling of the dry weather flow found in most urban catchments. Diversion structures are modelled using the storage module. This is done by allowing the spillway and bottom outlet flows to be directed to different downstream modules.

An urban catchment is highly dynamic due to the numerous activities of man in the catchment. The quality of runoff can be affected by traffic densities, construction activities, solid waste removal practices, the level and maintenance of services, and the catchment vegetation and gardening practices. For the complete modelling of all the catchment activities, pollutant pathways, processes and reactions, particularly of the non-conservative pollutant types such as the nutrients, would be a difficult task and would result in an overly complex model.

The approach used in WITQUAL is to provide subprograms which can be used to model particulates, particulate associated pollutants and dissolved pollutant forms. The particulate or suspended solids (SS) subprogram is the basis for the model as SS acts as the vehicle for the transport of many pollutants from the catchment surfaces. The second subprogram can be used to model the particulate associated pollutant forms as a fraction of the SS. The third subprogram is used to model the dissolved form of the pollutant based on a fraction of the pollutant mass on the catchment that is considered to be soluble. A simple partition coefficient or linear isotherm is used to describe this process.

The general approach is the buildup of material on the catchment surfaces during the dry periods between storm events followed by the entrainment and transport of pollutants from the catchment surfaces during storm events. The basis of the pollutant transport model is the plug flow simplification of the longitudinal dispersion equation. The SS entrainment from the catchment surfaces uses the approach of Wischmeier and Smith (1978) which compares the available material to the transport capacity of the flow. Material is made available by raindrop impact and flow detachment while the Yalin equation (Yalin, 1963) is used to determine the capacity of the flow. A mixing tank assuming partial mixing of the surface runoff and the soil water is used to describe the entrainment of dissolved pollutants from the soil porewater and the impervious catchment surfaces.

For the channels and pipes, the stream power function of Yang (Yang, 1973) is used to estimate the SS transport capacity to determine which of the particles entering a conduit will be deposited. For the conduits no entrainment of dissolved pollutants has been allowed for from the bed material. The routing of pollutants through a storage structure is undertaken using a completely mixed tank approach. The particle settling velocities and detention time in the dam is used to estimate which of the particles entering the dam will be removed. The particulate form of a pollutant of interest is removed according to the pollutant fraction of the SS. Dissolved pollutant forms are assumed to pass directly through the storage facility.

APPLICATION OF THE MODEL

The model was applied to the data collected for 7 events from the Shembe catchment having an observed pollutograph. The WITSKM model was run for the entire monitored period with unchanged model parameters. The simulation results were used as input to the WITQUAL model. The pollutant types modelled were SS, TDS, and particulate and dissolved phosphorus. The original model runs included the buildup process during the dry periods however this was not used for the final runs as the buildup rate turned into a calibration parameter.

The assumption was made that there was always sufficient material available on the catchment surfaces, that the P content of the material on the surface was the same before every storm, and that the partition coefficient remained constant through out the simulation. The only parameters used in calibration were the rainfall and flow detachment parameters applicable to the SS modelling, the P fraction of the particulate mass, and the partition coefficient. Histograms showing the frequency distribution of the ratio of simulated to observed loads are presented in Figures 1 and 2. Plots comparing the simulated and observed pollutographs are shown in the main body of the report.

The model performed reasonably well considering the simplifications made in representing the catchment dynamics and pollutant processes. The results can be considered adequate to examine "what if" management scenarios for urban storm water drainage systems.

CONCLUSIONS

The analysis of the data collected from the catchments showed that the runoff from urban areas is highly polluted with nutrients, heavy metals, organic material, and bacteria. The impacts of the runoff on the receiving water bodies could be severe depending on the ability of the receiving water to assimilate the pollutant loads. The results indicate that management of the stormwater runoff from the Shembe and Amanzimnyama catchment require management.

Although, where possible physically based entrainment and routing procedures were used in the development of the model, the model will require calibration using measured data for a particular catchment. The biggest stumbling block in applying the model is the determination of pollutant buildup rates, the nature of the pollutants on the catchment surface in terms of the pollutant fractions, and the particle size distributions. Nonetheless with calibration, the model produces pollutographs of sufficient accuracy to enable the analysis of stormwater management methods of diversion and particulate settlement in dams as well as the prediction of loads for use in receiving water models.

RECOMMENDATIONS

The following aspects should be considered for further research if the model is to be further developed:-

1. To improve and verify the model algorithms, studies of the buildup and pollutant changes on the catchment surfaces will have to be undertaken. Preferably buildup should be related to catchment land-use activities such as population and vehicle densities, and the level of services and service maintenance.

2. Consideration should be given to expanding the management options by adding wetland, oxidation pond, and engineering treatment modules to the dams and diversion structures included at this stage.

3. The model should be applied to different land-use catchments to assess the transferability of the model parameters and the hypothesis that there is always sufficient material available on the catchment for entrainment.

4. The trapping mechanisms of SS and the associated pollutants by vegetation and gabion lined channels has not been well researched and should be further investigated.

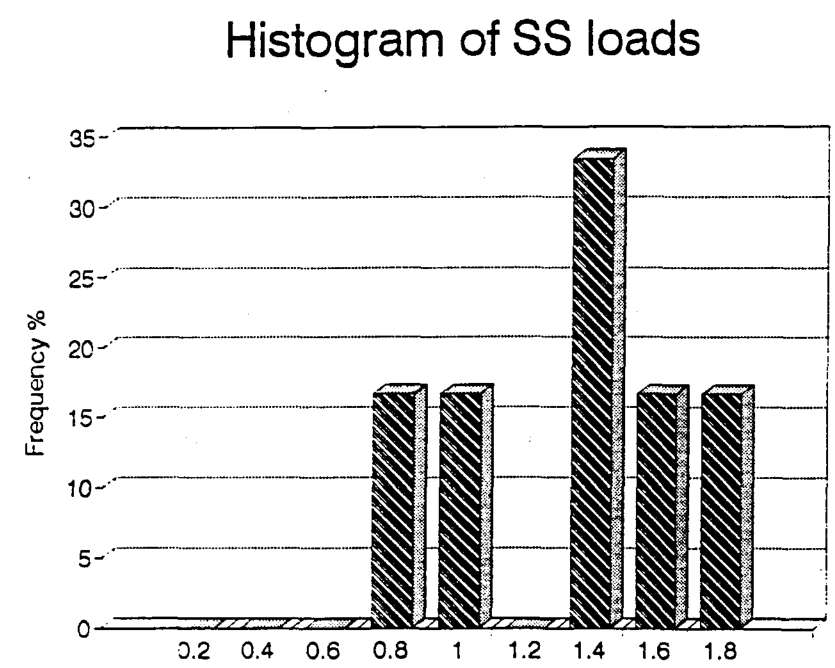
This research, together with the results of other monitoring programs, has shown that urban runoff pollution is at levels that can have impacts on the receiving water bodies such that the original use envisaged for the water bodies are seriously affected. Many water bodies, particularly below informal settlements, are in fact a health hazard. The environmental impact of the runoff from urban developments, both future and existing, should be assessed in a similar fashion to that required of the mining industry. Environmental Management Programs (EMP) should be a legal necessity for urban developments. The WITQUAL and WITSKM programs will be an essential element of formulating EMP documents and providing strategies for the management of urban runoff.

Table B : Statistical analysis of the concentration data for the storm flow for Shembe.

Variable	Mean	Median	Std. Dev	Min	Max	N
pH	7	7.1	0	6	8	25
COND mS/m	59	37.2	81	8	700	225
SS mg/l	1444	922	1586	52	8515	225
SOL P $\mu g/l$	157	124	89	9	456	225
TOT P $\mu g/l$	2073	1480	1910	126	13218	225
NO_3 $\mu g/l$	6851	3473	7404	7	35484	220
NH_3 $\mu g/l$	505	397	604	3	3459	220
SOL KN $\mu g/l$	1451	885	1113	309	3926	51
TOT KN $\mu g/l$	9460	4618	5782	564	24745	51
COD (mg/l O)	217	133	294	10	2889	160
BOD (mg/l O)	18	-	9	6	33	9
Pre E- COLI/100ml	888788	-	1200000	3100	7800000	48
Con E- COLI/100ml	224429	-	160517	11000	560000	14
SOL Cu $\mu g/l$	1	-	2	0	4	8
SOL Cr $\mu g/l$	26	-	38	0	111	8
SOL Pb $\mu g/l$	49	-	26	30	67	2
SOL Zn $\mu g/l$	174	-	248	26	764	8
TOT Cu $\mu g/l$	126	98	137	29	636	59
TOT Cd $\mu g/l$	3	-	7	0	28	29
TOT Cr $\mu g/l$	513	299	952	23	5400	31
TOT PB $\mu g/l$	523	264	1754	7	9921	59
TOT Zn $\mu g/l$	477	285	920	35	4715	30
TOT Hg $\mu g/l$	1	-	0	0	1	1
OIL & GR mg/l	8	-	8	1	24	6
HYDROCARBONS mg/l	7	-	6	1	14	5

Table C : Statistical analysis of the analytical data for the Amanzimnyama canal.

Variable	Mean	Std Dev	Min	Max	N
pH	7.5	0.47	6.5	8.7	73
Cond mS/m	42.6	22.5	8.8	81	148
Susp Sol mg/l	112	226	4	2225	148
Sol P μg/l	145	488	12	5720	148
Tot P μg/l	882	1888	79	19683	148
Nitrate-N μg/l	1647	2548	6	17302	114
Ammonia-N μg/l	256	810	1	8223	106
Sol Kjel-N μg/l	1100	1286	334	8865	39
Tot Kjel-N μg/l	4492	11492	823	74396	39
COD μg/l	129	163	1	995	118
BOD μg/l	29	20	5	72	19
Pre E-Coli/100ml	130000	170000	1000	740000	43
Con E-Coli/100ml	190000	220000	8400	740000	11
Sol cu μg/l	N/D				
Cd μg/l	N/D				
Cr μg/l	12	1	11	13	4
Pb μg/l	41	7	33	51	4
Zn μg/l	96	80	22	326	15
Hg μg/l	N/D				
Tot Cu μg/l	75	111	9	785	72
Cd μg/l	4	4	1	20	50
Cr μg/l	58	145	4	1175	71
Pb μg/l	242	371	7	1803	71
Zn μg/l	375	641	45	5500	72
Hg μg/l	1.5	1.9	.1	7.6	13
Oil/Grease mg/l	14	25	2	98	13
Hydrocarbon mg/l	5	4	1	14	13



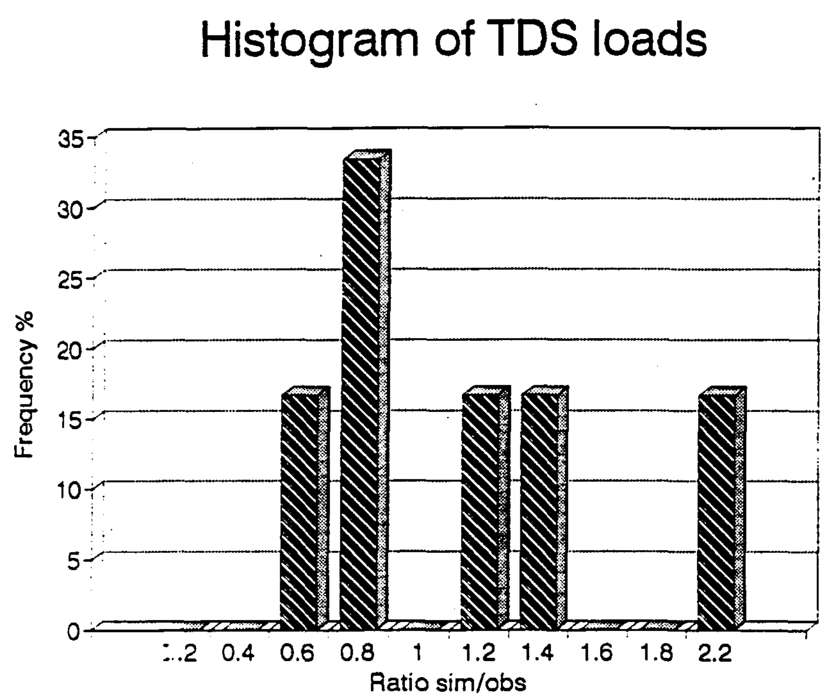
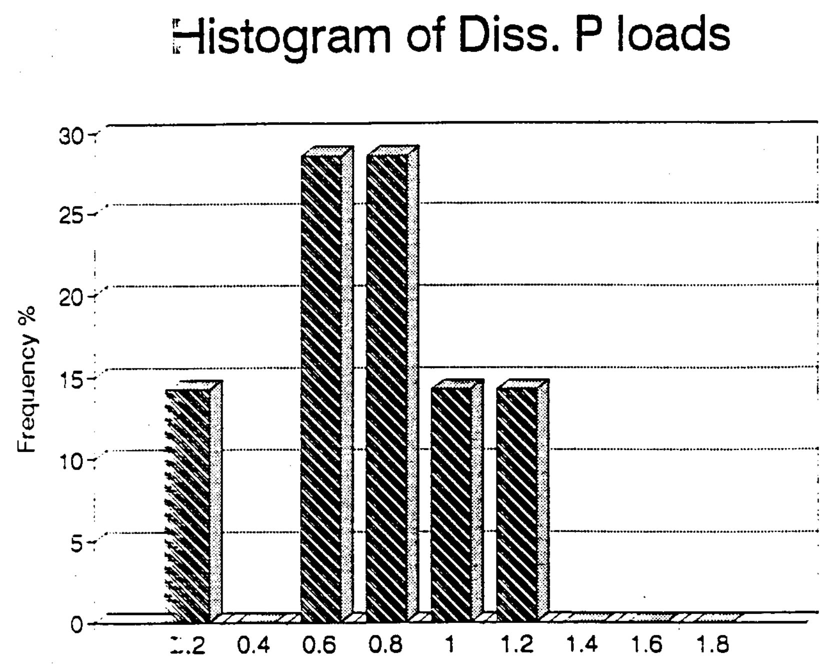


Figure 1 : Histogram of ratio of simulated to observed SS and TDS loads



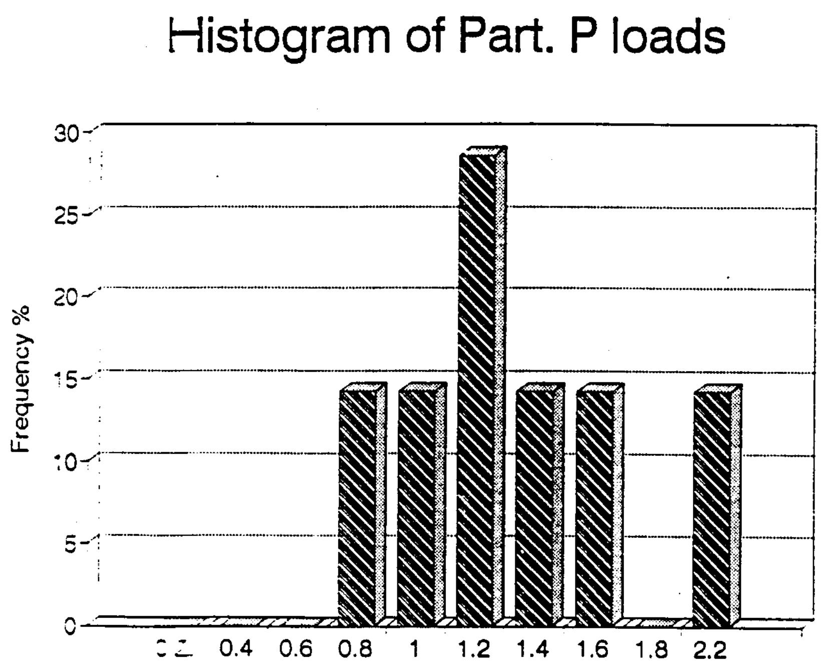


Figure 2 : Histogram of ratio of simulated to observed Dissolved and Part. P loads

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Dr G Tredoux	Watertek, CSIR
Mr J L J van der Westhuizen	Department of Water Affairs and Forestry
Mr P W Weideman	Water Research Commission (Committee Secretary)

The project was planned as a collaborative effort between the CSIR and the Water Systems Research Group of the University of the Witwatersrand with Mr D E Simpson of the CSIR as the project leader. However during the course of the project, staff reductions by the CSIR resulted in the retrenchment of Mr D E Simpson. The responsibility for the completion of the project then reverted to the Water Systems Research Group under the management of Mr J Gordon-Lennox of the CSIR. The continued support of the project by Mr Simpson after his retrenchment is gratefully acknowledged.

TERMINOLOGY

Best Management Practices (BMP)

The use of management methods such as detention/retention ponds, diversions and catchment cleaning practices to improve the water quality of the runoff.

Particulate Associated Pollutants

Pollutants such as Phosphorus, nitrogen, and some heavy metals that are adsorbed to the particulates or form part of the particulate compounds such as organic matter.

Dissolved Pollutants

Generally icms or dissolved compounds that pass through a 0,45 μm filter.

Suspended Solids (SS)

The particulate material that remains on the 0,44 μm filter.

COD

Chemical oxygen demand.

BOD

Biochemical oxygen demand.

TDS

Total Dissolved Solids.

TKN

Total Kjeldaml Nitrogen. This test gives the nitrogen in ammonia form and bound up in organic matter.

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Storm water runoff from urban catchments has been found in many areas to be a major source of pollution of their receiving water bodies. Wanielista (1979) reports that in the United States of America, the water quality downstream of approximately 80% of urban areas is determined by the quality of the storm water runoff or diffuse sources rather than point sources of pollution. Similarly Henderson and Moys (1987) report that the quality of some 3700 km of rivers in England and Wales are classified as being poor to bad quality, largely due to the overflow from combined sewer systems. In South Africa urban runoff has been found to contain levels of nutrients, heavy metals, organic material, and E Coli (Simpson, 1986; Coleman, 1993; Wimberley, 1992; Wright, 1993) that would have a significant effect on the water quality of the receiving water body. The Department of Water Affairs (1986) estimate that some 40% of the salt loads that enter the Vaal River at the barrage are generated by storm water runoff from the southern catchments of the Johannesburg metropolitan area.

South Africa is undergoing rapid urbanisation. The Urban Foundation (1990) projected a movement from the rural to the urban areas of some 2,8 million people during the period 1990 to 2000. This coupled with an estimated population growth of 2% will result in an increase in the population in the urban areas by 8,0 million people to give a projected total urban population of 30 million people by the year 2000. The storm water runoff from the resultant expansion and densification of the urban centres, could have a serious effect on their receiving water bodies if not managed correctly. Particular attention will have to be paid to the management of the water quality aspects of the runoff, as much of the urbanisation will take the form of informal or squatter settlements. These settlements are often over crowded and do not have adequate sanitation, refuse removal, water supply, and storm water reticulation systems. A monitoring program undertaken on such a settlement by Wimberley (1992), showed levels of suspended solids, nutrients, micro-organisms, and organic material that had a deleterious effect on the receiving river water.

The quality of storm water runoff is such that its management is becoming essential in South Africa. Attention has been given to the management of runoff quantity (Green, 1984; Coleman and Stephenson, 1993) by using management techniques such as detention/retention ponds, dual drainage, and the use of disconnected impervious areas. This greater attention to the management of storm water quantity has occurred largely as a result of the development of PC based computer programs which allow the modelling of storm water runoff and management methods. The development of a PC based computer program for the modelling of urban runoff quality is essential if the management of the quality of the stormwater runoff from urban areas is to be considered and encouraged.

1.2 OBJECTIVES FOR THE MODEL

The type of algorithms used in an urban drainage model to address an urban water quality problem depends largely on the objectives of the runoff quality analysis. Huber (1985) lists 5 possible objectives of such an analysis
as :-

1) Characterisation of the urban runoff
2) Provide input to receiving water analysis
3) Determine effects, sizes and combinations of control options.
4) Perform frequency analysis on quality parameters
5) Provide input to cost-benefit analysis

The first two objectives characterise the magnitude of the problem whereas the remaining 3 objectives relate to the analysis and solution of the problem. The level of detail of the modelling output varies according to the objective. The estimation of average pollutant concentrations and total loads may satisfy the first two options, while a detailed concentration time series (pollutograph) and hydrograph may be required to satisfy objective 3.

The model required to address the problems facing South Africa should be able to provide the necessary level of detail to investigate and analyse "what if" scenarios as far as the implementation of best management practises is concerned. The results of the analysis will provide input to cost-benefit analyses of management strategies. The model will therefore be required to produce estimates of the loads that could be expected from urban catchments for the analysis of receiving water impacts and detailed pollutographs for management purposes. The model should be suited to South African conditions especially when dealing with the informal settlements which require a different modelling approach from those included in more conventional urban drainage models.

1.3 SOUTH AFRICAN WATER QUALITY MODELS

The models developed and used in South Africa such as the TDS model of Herold (1981), the sulphate management model for coal mines (WMB, 1992), and the phosphorus export model of Weddepohl and Meyer (1992) operate at monthly time steps and are pollutant specific. The TDS model of Herold (1981) and the sulphate model of WMB (1992) are used for the development of water resource management strategies for bulk water supplies. This type of model is not suited for urban catchments where storm events are to be managed and small time step modelling is required. Pollutographs of phosphorus concentrations can be produced using the phosphorus model of Bath (1989). Although phosphorus washoff off catchments is modelled, a rainfall-runoff component and the required storm water management options are not included in the model. The RAFLER model (Paling et al, 1990) models rainfall-runoff and erosion. The model uses monthly rainfall input and is used for water resource planning and statistical analysis of sediment loads. There are at present no South African developed models available which are suited to the modelling of urban drainage runoff quality and management.

1.4 REVIEW OF EXISTING URBAN DRAINAGE MODELS

The modelling of urban runoff quality can be undertaken using statistical or deterministic methods. The statistical approach normally used is to look for relationships between catchment, climate, rainfall, and runoff parameters and pollutant concentrations or loads. These types of relationships have been examined by Jewell and Adrian (1981), Simpson (1986), Coleman (1993), Colwill et al (1984), Whipple et al (1977), Green et al (1986), and Bedient et al (1980) to name a few. The results of this type of analysis have been conflicting. In general the relationships vary from catchment to catchment. This type of approach however has proved useful in providing an estimate of the pollutant loads that can be expected from a catchment when local data is available.

The deterministic approach is more widely used in urban drainage models. In this approach the processes such as transport, erosion, and deposition occurring in the pollutant pathways through an urban catchment are modelled. This approach is more suited to the application of best management practises as the processes, if modelled correctly, can account for the effects on the quality of the runoff due to changes in the catchment characteristics, storm input, and management.

There are a number of deterministic models that have been developed over the years to address various aspects of the quality of urban runoff. The algorithms and approaches used in the models vary from empirical to those having a more physical basis. The algorithms used in the earlier models such as STORM (HEC, 1977), SWMM (Huber et al, 1982), HSPF (Johanson et al, 1984), and ILLUDAS (Kuo et al, 1987) were based on the pioneering work of Sartor and Boyd (1972), the National Urban Drainage Program of the EPA, and the American Public Works Association (APWA) study in Chicago in 1969 (Huber, 1985). These models use the empirical exponential decay washoff function for the generation of pollutants from the catchment surfaces. DR3M-QUAL (Alley et al, 1980) was one of the first urban drainage models to attempt to use sediment transport theory for the entrainment and transport of sediment. More recent models such as MOSQITO (Henderson and Moys, 1987), and MOUSE (DHI, 1993) use algorithms which have a physical basis for the transport and generation of pollutants from urban catchments. The SWMM model has been rewritten (WP Software, 1993) but the original water quality algorithms have been kept.

The main aim of MOUSE and MOSQITO is to address the rehabilitation of combined sewer systems which have become a problem in Europe. A great deal of computational effort is expended on flow and pollutant routing in the sewer system. For South African conditions, particularly for the informal settlements which have no services, the level of detail of input required by these models is unnecessary.

A source area model dealing with the washoff of pollutants from the catchment surfaces, particularly the pervious areas, is more appropriate for dealing with the informal settlement land uses than the models that concentrate on the in stream processes in the conduit network. In addition the pervious areas of these catchment types play a more important role in the runoff and generation of pollutants than in a more formal urban development. Little attention is given in the existing urban drainage models to the entrainment of pollutants, in particular dissolved pollutant forms, from the pervious catchment areas.

1.4 OBJECTIVES OF THIS RESEARCH

The primary objective of this research to develop a water quality model WITQUAL for application to South African catchments and conditions. The following objectives have been set for and are addressed in this research:-

1. To adapt an existing urban runoff model to include simulation of runoff quality, typically for suspended and dissolved solids, phosphorus and nitrogen forms and selected heavy metals. The model will simulate quality changes during runoff events in a continuous manner from rainfall data and a knowledge of catchment parameters.

2. To incorporate into the model "best management practices" such as diversion of the first flush, detention basins and infiltration to reduce peak flows and improve water quality.

3. To use locally collected data to initially develop and improve model concepts and collect new data from suitable catchments to test and validate the model.

The catchments selected were the Shembe and Amanzimnyama catchments in Durban, Natal. The Shembe catchment has as its land-use an informal settlement while the Amanzimnyama catchment has a more commercial and industrial land-use. Due to the difficulties in gauging and the numerous point sources and spills that occurred in the Amanzimnyama catchment, the model was not applied to this catchment only the water quality levels and loads are presented.

CHAPTER 2 POLLUTION TYPES AND PROCESSES

2.1 INTRODUCTION

An urban catchment is a combination of water, air, land, and man made systems. Within each system there are physical, chemical, and biochemical processes taking place that can transport, generate, and change the nature and form of a pollutant. The modelling of the quality of runoff from such an area requires an understanding of the processes within each of the systems and the interaction processes between the systems. To include a detailed representation of each of the systems would be difficult if not impossible and would result in a model that is unusable in terms of input requirements and computational effort. A usable model should only include the processes and systems that are essential to the meeting of the modelling objective. The mathematical algorithms describing these essential physical processes and systems in the model should be at a level of sophistication commensurate with the availability of the input information while still producing results that meet the modelling objective.

By identifying the nature and sources of the pollutants that are found in urban runoff at levels that warrant management or treatment, the essential processes, systems, and management options can be determined for inclusion in the model. The identification of the pollutants and their sources can be made from the results of monitoring programs undertaken on urban areas having different land-uses, climatic conditions, topography, soil types, level of services and service maintenance, demographics, and vegetation cover.

2.2 POLLUTANT PROCESSES

There are numerous processes that can occur in an urban catchment. These processes can be grouped into the broad categories of physical, chemical, and biochemical processes. The processes involved in the transport of pollutants from a

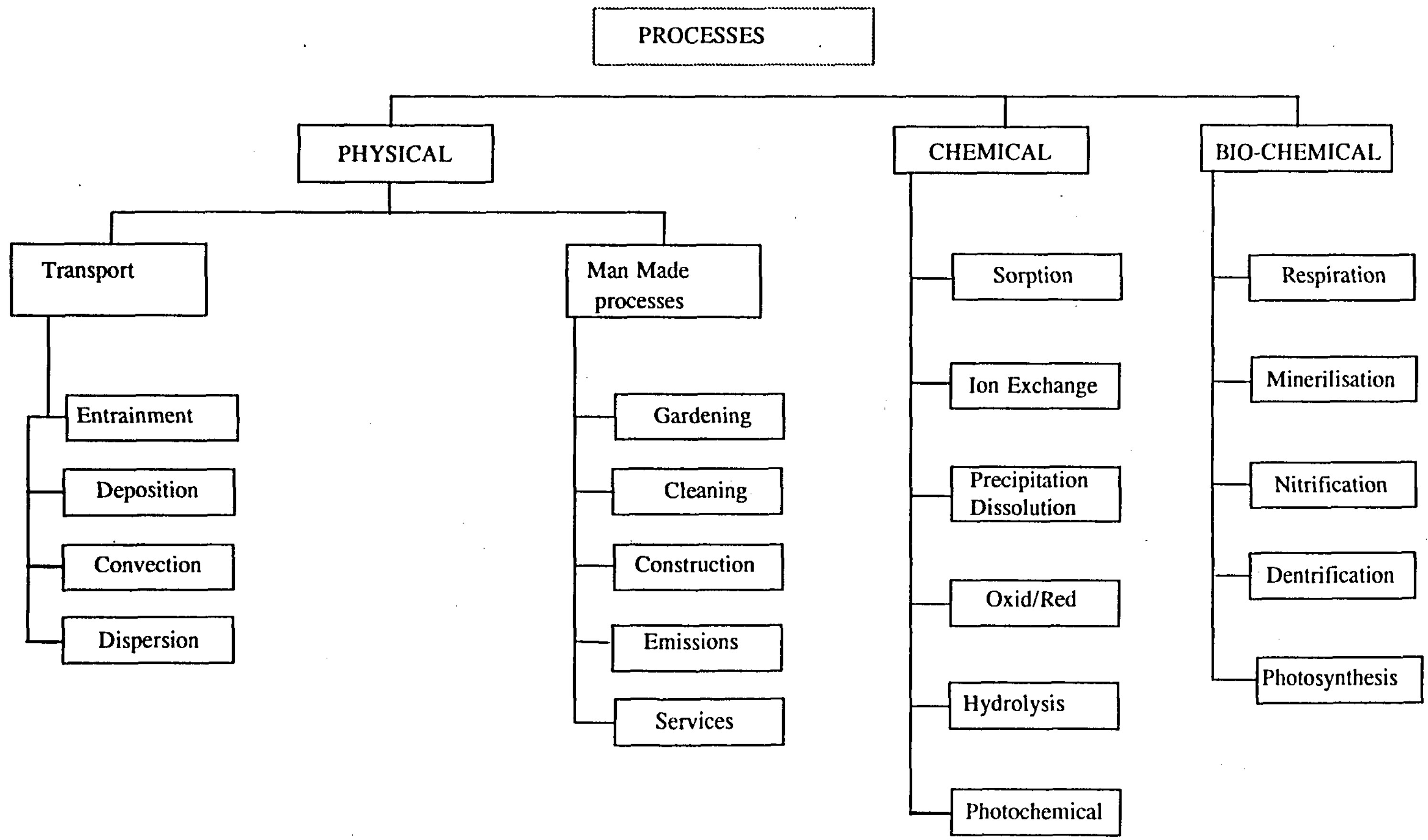


Figure 2.1 Categorisation of pollutant processes

catchment are complex. The processes that fall under the various headings are summarized in figure 2.1 and will be briefly discussed below.

2.2.1 Physical processes

The physical processes include the sub-processes of transport, and the man made processes. The transport processes of convection and dispersion, are for the storm event models, amongst the most important processes and are included in all the urban drainage models in some form. The transport processes generally occur during runoff as a result of rain although there is still transport during the dry periods between events through the soil into the stormwater drainage system. During storm events the effect of raindrops and the interaction of the surface flow with the boundary leads to the formation of a boundary layer which for most flow situations encountered in urban drainage can be modelled as being turbulent. The turbulent eddies and raindrop impact effects result in the entrainment of both particulates and dissolved chemicals into the flow from the surfaces.

In the case of the particulates, depending on the settling velocity and the properties of the flow, they may deposit back onto the catchment surface or settle out during transport through the conduit system. The entrainment and deposition processes play an important role in many stormwater management methods. The man made processes are associated with both the generation and removal of pollutants from the catchment. Industrial and vehicular emissions, gardening activities, lack of services and service maintenance resulting in sewerage spills are all pollutant generating activities. The street sweeping, refuse removal, and the sewerage system are actions for the removal of pollutants from the catchment.

2.2.2 Chemical processes

Adsorption/desorption (sorption) is the process by which ions present in one phase tend to condense and concentrate on the surface of another phase. Although adsorption can be categorised into chemical, exchange or physical adsorption (Sawyer and McCarty, 1978), a distinction between the different types of adsorption processes for a particular pollutant cannot always be made. The physical adsorption is due to the weak van der Waal's forces of attraction between molecules. In physical adsorption the molecule is not fixed to a specific site on the solid surface but is free to move around over the surface (Sawyer and McCarty, 1978). This process is reversible with the molecules desorbed to more or less the same extent that it was originally adsorbed. In the case of chemical adsorption, a much stronger chemical bond is formed at the surface. A monomolecular layer is formed over the surface of the molecule and once the surface is covered the capacity of the surface to further adsorb molecules is exhausted. This form of adsorption is seldom reversible. In exchange adsorption which includes ion exchange, the ions concentrate at the surface of the solid due to electostatic attraction to sites on the solid of opposite charge.

The precipitation and dissolution processes occur depending on the solubility of the solids found on the catchment. The solubility reactions are well defined in terms of solubilities or solubility products for specific compounds in pure water systems but these reactions can deviate widely in dynamic soil-water systems. The concentration levels of the major ions and anions found in urban runoff are generally dilute and would represent a complete dissolution of the readily soluble chemicals on the catchment surface. The precipitation/dissolution reaction can be important in the soil during evaporation when the chemicals in the soil reach concentrations sufficiently high to cause precipitation.

The hydrolysis and oxidation-reduction reactions involve the changes in the nature of the chemical due to a reaction. In the case of hydrolysis with water molecules and for oxidation-reduction reactions the swopping or sharing of electrons between chemical compounds to form new compounds. In the case of photochemical reactions, energy from light promotes the cleavage of chemical bonds causing new compounds to form. The exact compounds that could be present on the catchment surfaces, atmosphere or in the soil water are not known and difficult to determine. The inclusion of these reactions in a model would be difficult and unnecessary for most cases.

The sorption and ion exchange processes involve the interaction of molecules with the surface of solids while the precipitation and dissolution processes deal with the ability of water to breakdown the chemical bonds of a particular pollutant compound into its elements or sub-compounds. The relationship between the dissolved form of the pollutant and the solid or solid associated form are often described by conditions at equilibrium. In the case of sorption by isotherms and dissolution by solubility products and chemical equilibria diagrams. Both the rate of change between equilibrium conditions and the conditions at equilibrium depend on additional factors such as pH, and temperature.

2.2.3 Biochemical processes

Microorganisms can facilitate or their enzymes can act as catalysts for many chemical reactions. The behaviour of microorganisms are responsible for the minerilization of organic matter to CO_2 and water, the nitrification and denitrification processes of the nitrogen cycle, and for the leaching of ions from the soil. An example is the production of SO_4 from iron pyrites. In many of the biochemical reactions, the process represents a coupled system of reactions. The disappearance of organic matter or ammonia can be coupled to the disappearance of oxygen. Photosynthesis is the process by which chlorophyll bearing plants use energy from the sun to convert carbon dioxide and water to sugars with the production of oxygen. Not only are plants photosynthetic but algae and certain bacteria known as cyanobacteria are also photosynthetic. These plants play an important role in maintaining oxygen levels in maturation and oxidation ponds.

2.3 SOURCES AND NATURE OF POLLUTANTS FOUND IN URBAN RUNOFF

A wide range of pollutants have been found in urban stormwater runoff. The pollutant types found include plant nutrients, oxygen demanding organic compounds, heavy metals, hydrocarbons, sediment, pesticides, litter, and microbiological pollutants. The possible impacts of the pollutants on the receiving water body are given in Table 2.1. Although the levels of pollutants found in urban runoff are often compared to drinking water or effluent quality standards, the significance of the pollutant levels need to be evaluated in terms of the environmental criteria set for the receiving waters. These criteria could be based on a variety of considerations, including human health, drinking water standards, and toxicity to aquatic life. From these considerations and the ability of the receiving waters to assimilate pollutants, appropriate water quality criteria can be set for the runoff from a particular catchment.

The studies undertaken in South Africa on Pinetown (Simpson, 1986), Hillbrow (Coleman, 1993 ; Green et al, 1986), Khayelitsha (Wright, 1993), Alexandra (Wimberley, 1992), and Sunninghill Park (Wimberley and Coleman, 1993) and this study of Shembe and Amanzimnyama have found that the pollutant types that are at levels that could cause concern are generally the nutrients, heavy metals, organic material, suspended solids, and the microbiological quality. Based on these types of monitoring programs, the forms of the pollutants found in each of these groups and possible sources and processes are presented below.

2.3.1 Total Solids

The total solids refers to the solids which are in dissolved and particulate form. The particulate form is referred to as suspended solids (SS) and the dissolved solids as the total dissolved solids (TDS). The division of the solids between the dissolved and particulate forms is generally made using the 0,45 micron filter (APHA, 1985). The other pollutants of interest all form part of the total solids. Both the TDS and SS can be divided into organic and inorganic fractions. The categorization of the total solids and the other pollutant forms associated with the solids fractions is presented in figure 2.2.

2.3.1.1 Suspended Solids

As is shown in figure 2.2, the SS found in urban runoff is one of the more important pollutants for inclusion in the model. Not only do the particulates themselves have an impact on a receiving water body in terms of aesthetics, many other pollutant types are associated with the particulate fraction. These could be either as an organic or inorganic particulate compound or be associated with the SS due to adsorption. Analysis of the results of monitoring programs have shown strong regression relations between the SS and total phosphorus (TP), total COD, total nitrogen, and the heavy metals particularly Fe and Pb (Simpson, 1986 ; Coleman, 1993). The relationships between the COD and the nutrients is not surprising as a fraction of the SS is in fact organic and would therefore contain organically bound forms of phosphorus and nitrogen as part of the SS. The size of the organic fraction would vary depending on the nature of the catchment.

The results of some of the monitoring programs as regards the different fractions of the solids are presented in Table 2.2. The percentages presented in Table 2.2 are averages taken over the monitoring period. The values did vary from event to event and with season. The percentage split of the SS between the organic and inorganic fractions are presented where determined in the monitoring program. The study of Ahern et al (1981) found that the organic content of the SS was higher in the autumn and depended on leaf cleaning programs. The organic component of the SS (volatile SS) of the total SS are shown in Table 2.2 to be

Table 2.1 : Receiving water impacts and associated pollutant types.

IMPACT	POLLUTANT
Oxygen Depletion	Organic content - Normally determined by COD or BOD tests. Ammonia NH_4
Toxicity	Heavy metals such as Pb, Cd, Cu, Fe, Cr, Mn and Hg Hydrocarbons such as PAH'S, PCB's, pesticides and oils and greases
Disease Potential	Microbiological quality - bacteria and viruses. Diseases such as polio, cholera, typhoid, dysentery, skin and eye irritations. Test for presumptive E-Coli and faecal coliforms normally undertaken
Aesthetics	Litter - cans, wrappers plastic containers Colour - dissolved organics, suspended solids
Eutrophication	Nutrients - Forms of Nitrogen and phosphorus - from PO_4, NO_3, NO_2, NH_4 organically bound - tested for by using Total P, TKN.
Dissolved Salts/Salinity	Anions and cations such as SO_4, Cl, CO_3, HCO_3, Na, Ca, K, Mg

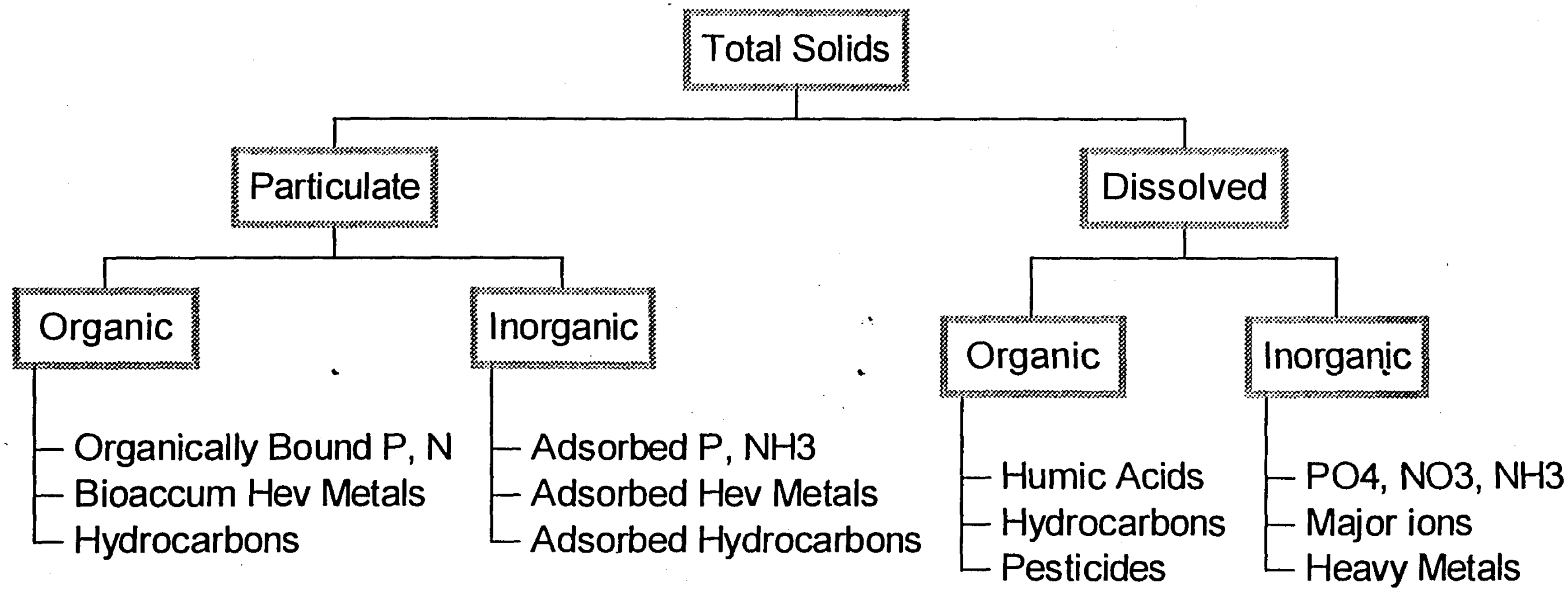


Figure 2.2 Categorization of pollutant forms

Table 2.2 Percentages of the total solids found in some urban runoff studies

		Dissolved			Suspended Solids		
Reference	Catchment Type	Organic	Inorganic	Total	Organic	Inorganic	Total
Waller & Hart (1985)	Residential Ontario, Canada	37	63	14,2	26	74	85,8
Simpson (1986)	Pinetown Residential commercial	(35)		22	(65)		78
Coleman (1993)	Hillbrow high density residential	24	76	26	-	-	74
Wimberley (1992)	Alexandra high density informal	-	-	14	-	-	86
Chui et al (1982)	Seattle highway runoff	-	-	-	18	82	-
Ahern et al (1981)	Madison residential commercial	-	-	-	21	79	-
Wimberley & Coleman (1993)	Sunninghill Park low density residential	-	-	60	-	-	40
Shembe	high density informal	-	-	22	-	-	78
Amanzimnyama	industrial commercial	-	-	54	-	-	46

( ) % spilt for total organics

typically of the order of 20% as compared to typical values for raw sewage of 87%. The particle size distributions of the SS have been determined in some studies. The sizes have been found to be fine. Simpson (1986) found that on average 80% of the SS was finer than 20 micron. The grading of the transported sediment did vary from event to event. The analyses carried out on the samples collected at Shembe showed that on average 86% was finer than 20 micron. Similar fine gradings were found by Ellis et al (1981) where the particle sizes ranged from 1.6 to 48 micron for a catchment in London, England. Pratt and Adams (1981) trapped washed off sediments in gulley pots which gave gradings with 62% of the particles less than 600 micron.

The major sources of the SS have been cited as vegetation, catchment soils, faeces, litter, exhaust emissions, and atmospheric dust. Simpson (1986) found for Pinetown that on average 15% of the SS is contributed from the atmosphere either as dry or wet fallout. Other sources could be the wear of tyres, brakes, pavement, and clutch linings. Chui et al (1982) found a strong correlation between total SS and the traffic density indicating both emissions and particulates transported onto the roads with the vehicles as possible sources of SS. In the case of catchments having a high standard of services, the predominant sources of the organic SS content will be vegetation, litter, and atmospheric dust.

Hydrocarbons and pesticides associated with the particulate fraction have been observed in urban runoff (Fam et al, 1987 ; Marsalek, 1985). The sources of these hydrocarbons have been associated with fuels and oils and greases. In catchments developed with informal settlements such as Shembe and Alexandra, the buildup of faeces and refuse on the catchment surfaces due to the lack of adequate services would also be a major source of organic material for entrainment and transport from the catchment. In the case of Alexandra (Wimberley, 1992), there is minimal erosion protection due to the lack of vegetation cover which results in high SS loads. The major source of the inorganic fraction of the SS would be the catchment soils and soils deposited on the impervious areas either by atmospheric fallout, the activities of man, or deposited there from earlier rainfall events.

SS are not necessarily conservative as the organic content is subject to biochemical reactions of mineralization due to the actions of microorganisms. The rate at which the organic matter is broken down depends on the availability of oxygen, pH, temperature, presence of chemicals that may be toxic for the microorganisms, and the nature of the organic material. If vegetation is the main source of organic matter, the time scale for the degradation of the vegetation is of the order of days to weeks and need not be considered during the transport of SS from the catchment during storm events whose duration is of the order of hours. For the processes that take place on the catchment between storms however, the organic material that is deposited on the catchment can decay with time to produce micro-organisms, nutrients, CO_2 and water. The extent to which the organic material is biodegradable can be tested with the BOD test. The average BOD value from Shembe was found to be 18% of the COD value for the storm runoff and 48% for the dry weather flow. In sewage plant design typical values of the readily biodegradable fraction of the influent which is normally considered to be in fine or dissolved form is given as 20% (Ekama et al, 1984).

2.3.1.2 Dissolved solids

The inorganic fraction of the dissolved solids consists of the major cations and anions such as SO_4, Cl, CO_3, PO_4, NO_3, Na, K, Ca, and Mg. Coleman (1993) found Ca, Na, K, CO_3, and SO_4 to be the predominant ions in the runoff from Hillbrow. Traces of dissolved heavy metals such as Pb, Cd, Cr, Zn, and Cu are also found in the runoff as well as dissolved organics such as hydrocarbons (Fam et al, 1987). The dissolved form of any of the pollutants are generally considered to be more reactive than the particulate or SS associated forms.

The sources of the dissolved solids given in Table 2.2 are atmospheric due to washout during rainstorms, exhaust emissions, spills, the products of decay processes on the catchment or in the stormwater drainage system, and the dissolution of any compounds that may be present on the catchment surface. Simpson (1986) gives 28% of the TDS as atmospheric. A mass balance on Sunninghill Park (Wimberley & Coleman, 1993) showed that there is a net import of pollutants onto the catchment from the atmosphere.

At the concentrations found in urban runoff there is no net removal of dissolved pollutants from the runoff water by biochemical and chemical reactions. The total dissolved solids (TDS) are normally considered to be conservative as a balance of charges has to be maintained in solution. Some specific ions found in dissolved form such as PO_4, ammonia, and heavy metals can be subject to adsorption and disappear from the dissolved state to be associated with the solids. The dissolved nutrients are also readily available for uptake by microorganisms and plants.

2.3.2 Nutrients

The nutrients are made up of the various forms of nitrogen (N) and phosphorus (P) found in urban runoff.

2.3.2.1 Phosphorus

There are numerous forms of P compounds found in urban runoff requiring different testing procedures to determine these forms or compounds. The basic distinction is normally made between the soluble and particulate forms of P. The solid forms consist of inorganic compounds, adsorbed P, and organic P in plant and animal matter while the soluble P forms include inorganic orthophosphate, hydrolyzable polyphosphate, and some organic forms (Lee et al, 1989). The predominant species of phosphorus in dissolved form are the orthophosphates (Ahern et al, 1981 ;

Waller and Hart, 1985). Most of the P found in urban runoff is in particulate form. The fraction of the total P in particulate form varies with the catchment. Simpson (1986) found an average fraction of 80%, Ahern et al (1981) 65%, Weeks (1981) 60%-80%, and Waller and Hart (1985) 90%. The results of the Shembe and Amanzimnyama catchment monitoring programs gave average percentages of 7% and 23% respectively of the total phosphorus in dissolved form. In the case of Shembe, the dry weather flow had dissolved to total phosphorus ratio of 0,5 showing the mobilization of particulates during stormwater runoff. Strong linear regression relationships between total P and SS concentrations have been found by Coleman (1993), Simpson (1986), and Chui (1982) which reinforces the contention that much of the phosphorus is associated with the particulates.

Another reason for the association of P with the particulates is the tendency of P to adsorb to particulates. This has been investigated by Sharpley et al (1981), Bonzongo et al (1992), and Chien and Clayton (1980). The adsorption of P is considered in models such as the removal of P in grass buffer strips (Lee et al, 1989) and in the modelling of P in HSPF. The enrichment of P in the runoff has also been noted by Ghadiri and Rose (1991). This has been investigated and found to be due to the breakdown of conglomerates and the preferential transport of the finer sediments to which most of the P adsorbs. Simpson (1986) carried out P analysis on different particle fractions and found that between 60% and 90% of the particulate P was associated with the <20 micron size fraction. The particulate nature of the P in urban runoff can be connected to the source.

The major source of P is generally considered to be vegetation or decaying plant material (Waller and Hart, 1985). In South Africa detergents, leaking sewage pipes, and illegal connections to the stormwater system (Wimberley, 1992; Wright, 1993; Coleman, 1993) have been cited as sources of P particularly in the informal settlements. The atmosphere is a source of particulate phosphorus. This would be wind blown pollen and vegetation. The dissolved forms are not found in any great quantities from the atmosphere. The contribution of P from the atmosphere is generally considered small of the order of 8% (Simpson, 1986).

2.3.2.2 Nitrogen

Nitrogen can assume many oxidation states and as a result many compounds can be formed. The oxidation state can even be positive or negative depending on whether aerobic or anaerobic conditions prevail. The predominant forms found in nature are NH_3 , NO_2, and NO_3. The NH_3 form is found in organic compounds in proteins or amino acids.

In urban runoff nitrogen like P can be in solid or dissolved form. The solid form can be organically bound or as adsorbed species such as ammonia. The dissolved form of nitrogen is normally as NO_2, NO_3, free and saline ammonia, or bound up in dissolved organic compounds. The organically bound nitrogen as determined by the Kjeldahl method has been found by Ahern et al (1981) to be 63% for a residential area, Wimberley (1992) to be 75% for Alexandra, and Coleman (1993) to be 77% for Hillbrow. For Shembe the organically bound fraction was found on average to be 53% of the total nitrogen forms for the storm flow and 24% for the dry weather flow. For Shembe the organically bound nitrogen was found to be predominantly in the solid form for the stormwater runoff with 84%. The dry weather flow only 23% of the organically bound nitrogen was in the solid form. This shows the mobilization of particulate nitrogen forms during the runoff process.

With 60% of the atmospheric gases being nitrogen the atmosphere serves as a reservoir from which nitrogen is constantly removed by the action of electrical discharge and the nitrogen-fixing bacteria and algae. Rainfall samples collected at Hillbrow, Alexandra, and Pinetown showed relatively high levels of ammonia and nitrate-nitrite. For Pinetown (Simpson, 1986) an average of 49% of the soluble nitrogen forms were contributed from the atmosphere. The nitrate-nitrite system is not subject to adsorption but is taken up by plants and involved in redox reactions as an oxidant in the breakdown of organic matter as part of the nitrification process. This reaction normally takes place under anoxic conditions in the absence of oxygen. The ammonia form can, in the presence of oxygen, be changed to nitrate and nitrite as part of the denitrification process. The forms of nitrogen that are predominant in urban runoff are the nitrate-nitrites in dissolved form and the particulates as given by the TKN test which includes the ammonia. The major sources of these pollutants are vegetation, sewage, products of decay processes, and the atmosphere.

2.3.3 Heavy Metals

The heavy metals normally found in urban runoff are Cu, Pb, Zn, Cd, and Cr. These heavy metals have been found in numerous monitoring programs (Palmgren and Bennerstedt, 1984 ; Ellis et al, 1990 ; Murakami and Nakamura, 1990 ; Xanthopoulus and Hahn, 1993). More recently Morrison and Wei (1993) have found platinum in the runoff in Sweden due to the use of platinum as a catalyst in vehicle exhaust systems. The heavy metals found in urban runoff come in many forms. The broad definition is to distinguish between the heavy metals in the dissolved and particulate forms.

Regression analyses have been carried out between the suspended solids and the heavy metal concentrations. Strong correlations have generally been found between Pb, and Fe concentrations and the suspended solids concentrations (Coleman (1993) ; Simpson (1986) ; Palmgren and Bennerstedt (1984)). Weaker relationships are generally reported for Cd, Cr, Cu, and Zn. Schemes and testing methods have been presented to further breakdown the forms of the heavy metals found in urban runoff. The speciation of the heavy metals in the runoff have been investigated by (Morrison et al, 1984 ; Rodriguez et al, 1990).

The heavy metals are divided into 2 broad categories viz the dissolved and particulate fractions. The dissolved fraction is further subdivided into free ions or bioavailable metals, weakly complexed metals, and the strongly bound fraction. The particulate or suspended solid phase metals are divided into the exchangeable fraction, carbonate and hydrous metal oxide fractions, and the organic fraction. The exchangeable fraction are particulate associated heavy metals which exchange or complex with anions and can be released into the soluble phase under normal pH conditions found in urban runoff. The carbonate and hydrous metal oxide fractions are more strongly bound and occur as surface associated metals. They accumulate in the soils and sediments of rivers and estuaries and can be released due to a drop in pH. The organically bound fraction is unlikely to be bioavailable. This fraction may act as an important transportation mechanism and sink for metals in particular lead and copper.

Simpson (1986) and Irvine et al (1987) carried out an analysis on the different size fractions of the suspended particles and found that between 70 and 80% of the particulate heavy metals are associated with the particle sizes less than 20 micron in size. On average some 75% to 90% of the total Pb, Zn, Cu, and Fe are associated with the particulate phase while only 25% for Cd. The ratio of mass of heavy metals to TSS varies with average daily traffic (ADT) (Chui et al, 1982). They found that a linear expression between the ratio and ADT gave good correlations. The ratio varied from .55 mg/g to 4.58 mg/g for Pb to .26 mg/g to 5.71 mg/g for Zn and .08 mg/g to .3 mg/g Cu. The sources of heavy metals are atmospheric deposition of particulates from exhaust and industrial emissions, corrosion of roofing and plumbing metals in the catchment and brake lining wear.

2.3.4 Microbiological quality

The microbiological quality component is one of the major pollutants found in urban runoff. The indicator tests on runoff from urban catchments in South Africa have shown high levels of E-Coli and Faecal-Coliforms. The poor microbiological quality of urban runoff has rendered recreational water bodies such as Centurion Lake (Barnard, 1992) and beaches in the Western Cape (Wright et al, 1993) unsafe for recreational use. The sources are largely dependent on the catchment and are generally human or animal faeces either deposited directly on the catchment surface or from sewage spills or leaks.

The indicator organisms are generally from the gut of a mammal and once subject to the change in environment found in the receiving water die off (Wimberley, 1992). The microorganisms in urban runoff are involved in the minerilization of organic matter, nitrification, and denitrification. They themselves are organic and are subject to the decay processes.

2.4 STORMWATER MANAGEMENT METHODS

The management of stormwater involves the management of both the quantity and quality of the runoff. Many of the techniques that can be used for the management of runoff peaks and volumes have a beneficial effect on the quality of the runoff. The use of stormwater attenuation ponds results in the removal of particulates by settling. The use of vegetated channels, infiltration trenches, and disconnecting impervious areas can lead to a reduction in the level of pollutants found in the runoff from urban areas.

The management of urban runoff quality can be both non-structural and structural. In South Africa educating the urban dweller to realise that he is part of the pollution problem is important. By managing the man made processes of pollutant generation in reducing population densities, improving the standard and maintenance of services, controlling illegal connections to the stormwater system, and vehicle emissions will go a long way to improving the quality of the runoff in many urban areas. The best management practises (BMP) generally referred to are grit traps, screens, retention/detention dams, diversion structures, maturation ponds, grass swales, and wetlands which have been used to control and reduce the impacts of urban runoff on the receiving water body. The processes involved in BMP are deposition, entrainment, and biochemical processes of assimilation, minerilization, photosynthesis, sorption, and the processes of the nitrogen, sulphur, and phosphorus cycles.

2.5 SUMMARY OF POLLUTANT TYPES AND PROCESSES

From the discussion in the previous sections, a summary of the predominant pollutant types and their processes is presented in Table 2.3. The important groups of processes that apply to all the pollutant types are the transport and man made processes. These groups should be included in an urban drainage model and in fact are included in most models.

Table 2.3 : Pollutant types and processes

Pollutant types		Processes				
		Pr/dis	Sorp	Bioch	Trans	Man
Solids	Org SS	Y	Y	Y	Y	Y
	Ino SS	Y	Y	N	Y	Y
	TDS	Y	N	N	Y	Y
Nutrients	NH_3	Y	Y	Y	Y	Y
	NO_3	Y	N	Y	Y	Y
	PO_4	Y	Y	Y	Y	Y
	Org Nut	N	N	Y	Y	Y
Heavy metals	Pb, Zn, Cd, Cr, Cu, Hg, Fe	Y	Y	Y	Y	Y
microbio	E-Coli F-Coli	N	N	Y	Y	Y

Y=yes
N=No

In some models such as HSPF and that of Lee et al (1989) include the biochemical and sorption processes in the modelling of nutrients. The modelling of the reaction rates is normally undertaken using first order kinetics. The resulting models are complex and require numerous input parameters for their operation.

In WITQUAL, many of the pollutant stores and pathways have been lumped together. In the soil pollutant store a linear isotherm relationship has been included relating the dissolved and particulate pollutant forms. During transport overland and through the conduit system, a first order decay function has been included to enable the modelling of biochemical reactions. The physical transport processes of entrainment and deposition have been included as they are important processes within the time frame (normally hours) of a storm runoff event. Three models have been developed to model SS, particulate associated forms of a pollutant, and the dissolved forms. The SS movement is the mechanism for the transport of the particulate associated pollutants. A potency factor method (Appendix A) has been used to model these pollutant forms. Although simple this approach has support from statistical analyses where well correlated linear regression relationships have been found between SS and the particulate forms of pollutants.

CHAPTER 3 GENERAL DESCRIPTION OF MODEL

3.1 INTRODUCTION

The catchment conceptualization and the representation of this conceptualization within a modelling and programming framework are discussed and presented in this chapter. The topics covered are the method of discretization, sliding time scale, and the structure of the program. A brief description of the WITSKM program and the evaporation model used is also presented in this chapter. The detailed description of the algorithms used in the water quality model are presented in Appendix A.

3.2 CATCHMENT CONCEPTUALIZATION

From the results of the monitoring programs, an urban catchment can be considered to be made up of a number of pollutant stores (Figure 3.1). These stores are the atmosphere, impervious and pervious catchment surfaces, sub-soil, the drainage system, and the catchment activities. The catchment activities include both pollutant generating and removal activities. The pollutant generating activities include leaf falls, and the activities of man such as traffic, gardening, construction, the disposal of garbage and faeces on the catchment surfaces, and spills due to the failure of services. The removal activities include street cleaning, garbage removal, and the sewerage system. The pervious catchment areas are considered to consist of a surface and a soil store. It is difficult to distinguish between these two stores. The surface store is the accumulation of pollutants deposited on the surfaces such as leaves, faeces, and atmospheric fallout. This results in a readily available layer of pollutants on the surface of the catchment soils. A similar layer is formed on the impervious surfaces. The drainage system functions more as a means of transporting pollutants to the catchment outlet. However particulates can deposit out in the drainage system for entrainment during future runoff events. The movement of pollutants between the stores is by means of water, air, and man.

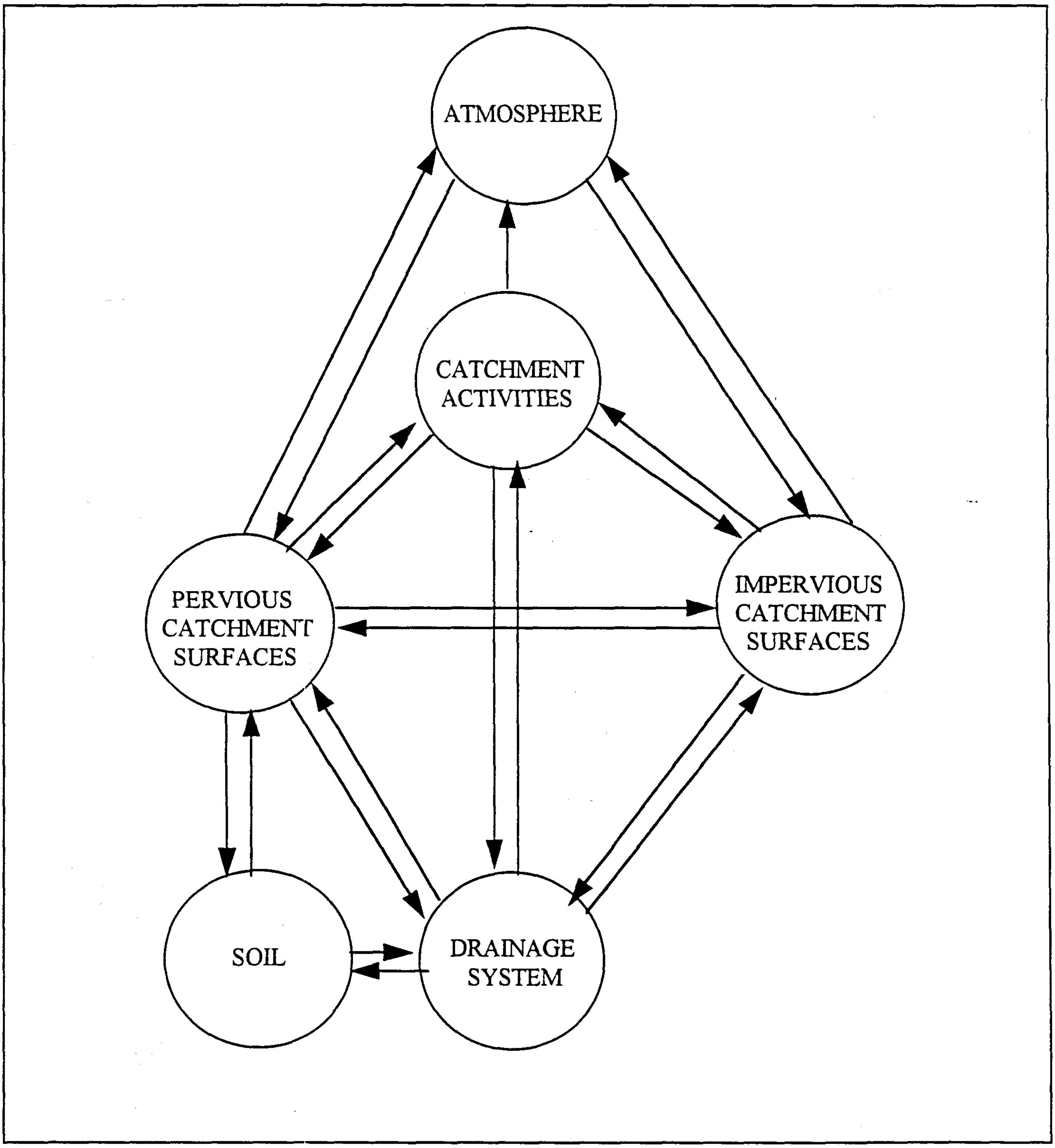


Figure 3.1 : Conceptualization of an urban catchment

The main medium that is considered in the model is water. The air movements moving pollutants to and from the atmospheric store are not considered in the model. This would require information on the wind velocities and directions, as well as sources of pollutants beyond the boundaries of the catchments. This information is not always available and difficult to obtain. The pollutant removal from the atmosphere is purely by fallout during dry weather. During runoff events a temporary store is created on the catchment surfaces and in the drainage system by the runoff water. In this store are pollutants that have been entrained from the catchment surfaces and washed from the atmosphere.

The monitoring programs found that the pollutants can be in particulate or dissolved form. The procedure adopted in WITQUAL is to assume that the dissolution and sorption reactions occur during the saturation of the catchment surfaces at the onset of the rain and not during the transport in the temporary store on the catchment surfaces during runoff. The entrainment processes are developed for the removal of pollutants in the dissolved and particulate forms depending on their presence in the surface stores during the event.

3.3 METHOD OF DISCRETIZATION

An urban catchment can be seen as flow and pollutant generating surfaces which feed their runoff into a stormwater drainage system of pipes and channels before discharging to the receiving water body. The runoff can be intercepted at any stage during its passage off the catchment and the quality or quantity characteristics of the runoff altered by means of stormwater management systems. The discretization methodology employed should be able to account for these elements of an urban catchment as well as the variation of catchment parameters such as land-use, soil and vegetation types, pollutant sources, and topography. The discretization methods should also be at a level of detail commensurate with the available information and the objective set for the model. As the analysis of stormwater management systems is an iterative process, the program structure and the discretization method should be sufficiently flexible to allow for changes in the layout and connectivity of the drainage system.

3.3.1 Catchment discretization methods

The discretization methods commonly found in the literature that are used in models can be grouped into

1. Grid methods
2. Element methods
3. Sub-catchment methods
4. and module methods

3.3.1.1 Grid methods

In the grid method, a uniform grid is superimposed over the catchment surface regardless of internal catchment boundaries or drainage systems (Figure 3.2). The grid method has been used in SHE (Abbott et al, 1986) and KINE2 (Constantinides, 1982). The method lends itself to two dimensional runoff modelling with the grid doubling as the finite difference grid for the solution of the overland flow equations. However unless the grid is very fine, the topography and rivers can be poorly detailed. An element of the grid can fall in a position with the crest of a hill in the middle of the element. The grid approach is also rigid in its structure and not easily adapted to include man made stormwater drainage systems of pipes, channels and management structures. The system is not easily changed to accomodate the iterative examination of stormwater management options. This methodology is more suited to the modelling of rural watersheds.

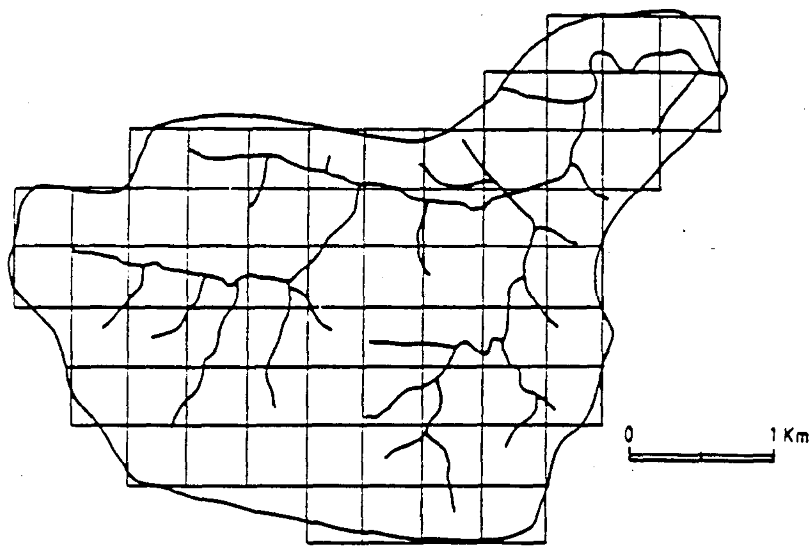


Figure 3.2 : Example of the grid method of discretization

3.3.1.2 Element method

The element method involves the subdivision of a catchment into sub catchments or segments with the boundaries chosen along convenient flow lines and water divides (figure 3.3). These segments are further divided into elements parallel to the topographical contours and to the stream at the bottom of the hillslope. This approach has been used in VSAS2 (Bernier, 1985), RUNOFF1 (Jayawardena and White, 1979), and by Holden (1993). By being able to position the elements parallel to contours, the method is more amenable to the treatment of the subsurface and overland flows as one dimensional. The level of discretization can be tailored to a level to optimize accuracy in terms of the distribution of catchment parameters and computational effort. This system however requires effort and a great deal of data in setting up the elements. Like the grid method, the element method is not suited to easy changes in the drainage system for the examination of management options and is too detailed for the planning objective for the model and the level of information required.

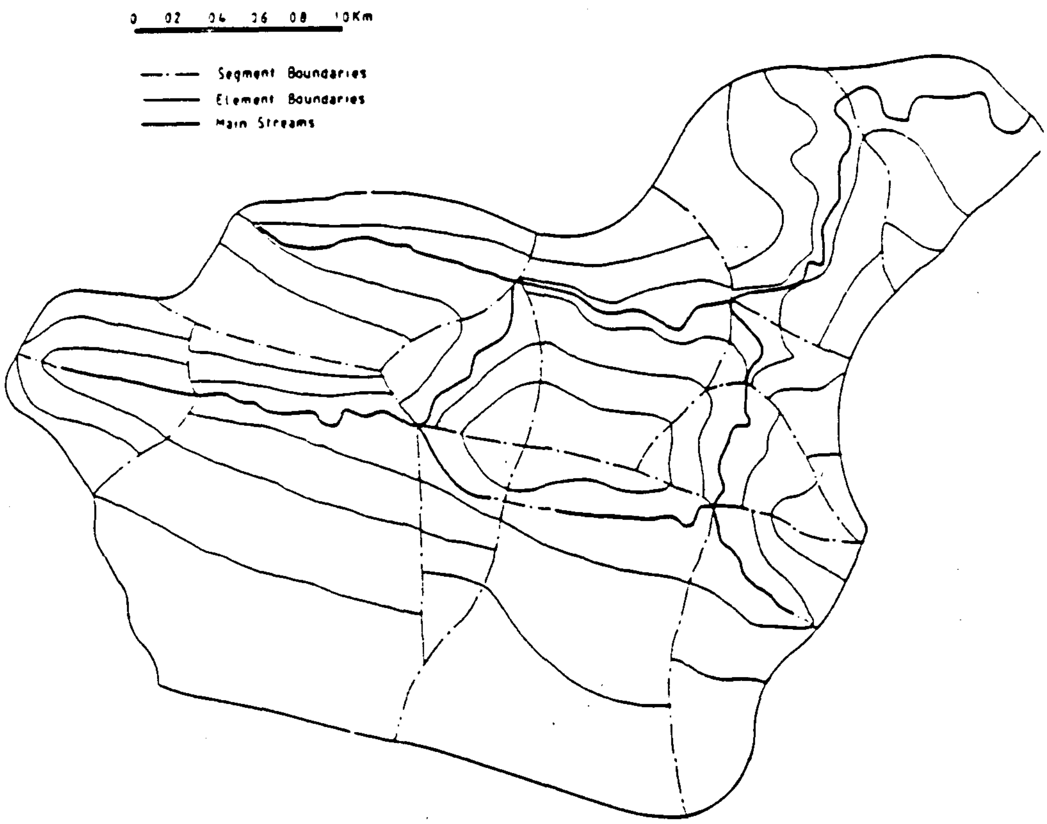


Figure 3.3 : Example of the elemental method of discretization

3.3.1.3 Sub-catchment methods

The sub-catchment approach is one of the more common methods of discretization used in urban drainage models. The methodology is used in SWMM (Huber at al, 1982) and WITWAT (Green, 1984). In this approach the catchment is divided into sub-catchments based on topography, vegetation, soils, and land-use. Each catchment is considered as homogeneous and is given a single set of parameters. Thus unless an extremely fine level of discretization into sub-catchments is undertaken and provision is made for the routing of runoff and subsurface flows through cascades of sub-catchments, the sub-catchment method may not accurately represent the variation in catchment parameters. In routing the flows off a sub-catchment using a technique such as kinematic routing, a flow length has to be specified. By doing this the subcatchment is represented as a rectangular plane with the length and width chosen such that the one dimensional sheet flow off the plane will produce the same runoff as the actual sub-catchment. The overland flow length tends to lose its physical meaning and becomes a calibration parameter. The other shortcoming often raised (Holden, 1993) in the use of sub-catchment method is that the runoff from the catchment is assumed to enter the drainage system at a point rather than laterally along the length of the drainage system. This could be seen as a problem in the modelling of rural water sheds, but is not as big a problem in urban catchments where the runoff off a particular sub-catchment often enters the drainage system via a kerb inlet or is channelled off the catchment at a point due to the stormwater drainage system within the sub-catchment.

Despite these shortcomings, the sub-catchment approach offers the flexibility necessary for modelling urban stormwater drainage systems with a level of data input suitable for a planning model. The method has been found to work successfully in the application of SWMM and WITWAT to urban drainage problems.

3.3.1.4 Modular method

The modular approach (Stephenson, 1989) is an extension of the sub-catchment method described above. The sub-catchment approach is used for the overall discretization of the catchment. However the method considers an urban catchment to be made up of a number of modules which can be linked together in such a way so as to represent the catchment and the stormwater drainage system. The approach also allows for the modelling of stormwater management methods and provides a sufficiently flexible framework for the iterative examination of stormwater management options. This approach has been used in the development of the urban drainage programs.

3.4 MODEL STRUCTURE

The modules provided are overland flow modules, pipes, trapezoidal channels, soil layer, dams, diversion structures, a pollutant generation module, and a module used to input a flow and pollutant concentration into a specified module. This has been included in the model to allow for the input of the dry weather flow which is an important source of pollutants. Rather than a global buildup of pollutants for the entire catchment, a pollutant buildup module has been included which will allow for the modelling of the spatial variation of the pollutant buildup over the catchment depending on factors such as population and traffic densities.

Each module is given an unique number and the connectivity between the modules is achieved by specifying at least a downstream module number to which runoff has to be routed. In the case of pipes, and channels an overflow number has to be specified allowing for the routing of surcharges. In the case of a dam with a bottom outlet, the flow through the outlet can be directed to a different module from the spill from the dam. This feature is used to model diversion structures.

The overland flow planes, which represent the catchments, require a downstream module number and the module number of the underlying aquifer. A cascade of up to 4 sub-soil layers can be created under any overland flow module to represent the underlying soil profile. For a pollutant buildup module, the number of the module in which the pollutant buildup is required must be specified. The pollutant buildup module is only active in the dry periods between the storms. If data from more than one raingauge is available for a catchment, the raingauges are numbered from 1 upwards and the number of a particular raingauge is entered with the overland flow module data. The program uses the raingauge number to search and extract the correct information from the database for use for that particular overland flow module.

3.5 OVERALL PROGRAM STRUCTURE

The urban stormwater drainage package presented in this report consists of 2 stand alone programs which have been linked together to provide both stormwater runoff quantity and quality information for the management of urban stormwater runoff. The two programs are the WITSKM and WITQUAL programs. WITSKM (Coleman and Stephenson, 1993) provides the quantity information which is used as input by the quality program WITQUAL. Both models have been developed for use on IBM compatible PCs. The programming language used is Microsoft BASIC 7.1. The link between the two programs is achieved by means of databases (Figure 3.4). There are two databases which have been developed using the ISAM database system of BASIC 7.1.

The first database system stores the simulation results from runs by WITSKM and WITQUAL. The second database contains the observed rainfall, flow, and quality data used either as input to the models as in the case of rainfall, or for use for calibration and verification of the models. The comparison of the results is by means of OUTPUT programs which produce plots comparing observed and simulated results. The OUTPUT programs also have the capability of dumping the data to an ASCII file for import to spread sheet programs for further analysis or the production of hard copies. The input data required by the WITSKM and WITQUAL programs are kept in ASCII files which can be edited using an editor. The movement between the different programs and applications is by means of a menu system.

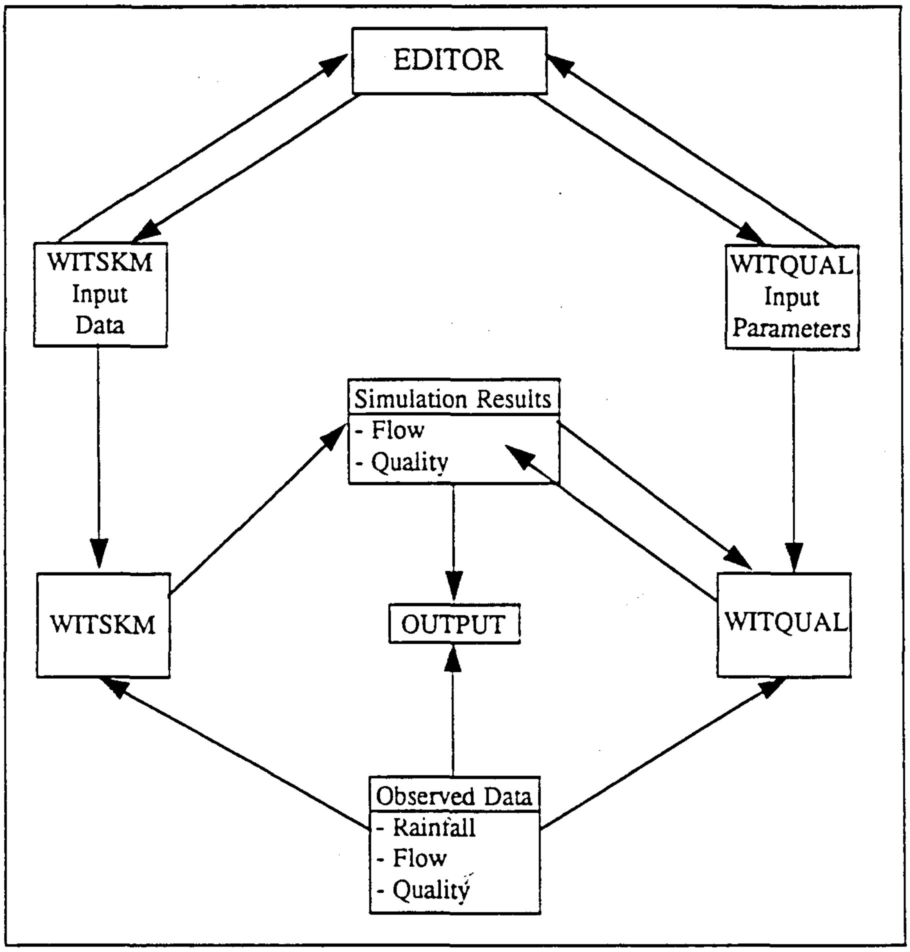


Figure 3.4 Description of Program structure

3.6 VARIABLE TIME STEP

The modelling of storm events is undertaken at a small time step of the order of minutes, typically 5 minutes. For long simulation periods, this would mean excessively long run times if during dry periods the simulation continued at the small time step. To overcome this a variable time step was incorporated into the model. During dry periods once the storm flow had been routed from the catchment surface and through the drainage system, the time step is increased to a day. However if the time period to the next storm was less than a day, the simulation was continued at an hour time step or part thereof until the next storm event was reached. In this way the run times for long runs could be reduced. The decision process is summarized in figure 3.5.

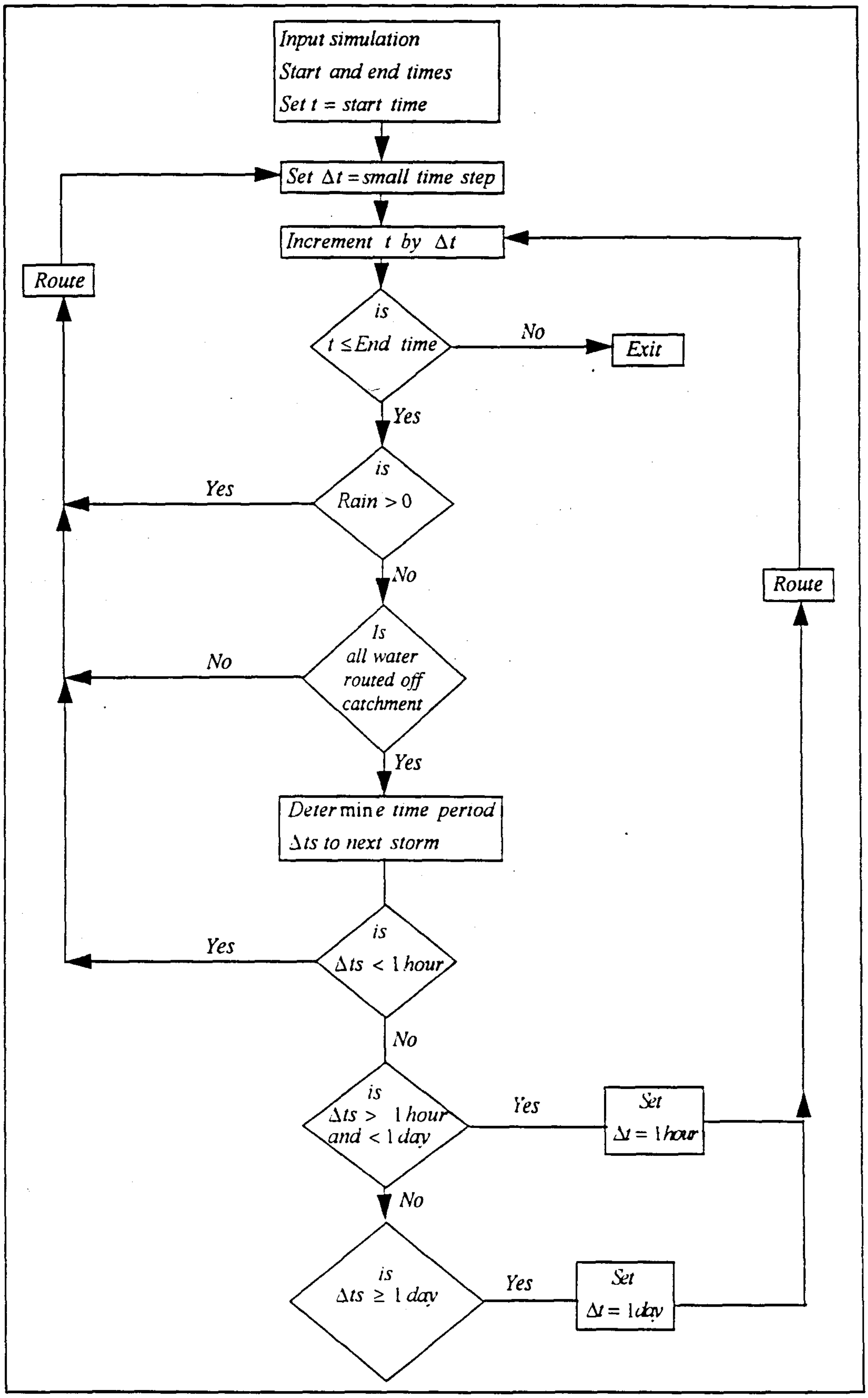


Figure 3.5 : Decision making process for the sliding time scale

3.7 GENERAL DESCRIPTION OF WITSKM

The WITSKM model is described in Coleman and Stephenson (1993) and certain elements of the model will be summarized in this section as background. The model was adapted from a single event model by including an evaporation component which enabled the continuous simulation of runoff (Coleman and Simpson, 1991). This was undertaken to allow for the modelling of the pollutant buildup processes during dry periods between storm events.

3.7.1 Flow Routing and Infiltration

Kinematic flow routing is used for all the modules in the WITSKM model. The numerical scheme used in the model matches the numerical diffusion caused by the finite difference approximations of the derivatives in the continuity equation to the physical diffusion (Holden, 1993 ; Koussis, 1983 ; Cunge, 1969). The numerical scheme used has been shown to be robust and unconditionally stable. By matching the diffusivities, the method can for a wide range of flow conditions produce answers comparable to the full solution of the dynamic and continuity equations without requiring downstream boundary conditions and complex numerical schemes.

The Green and Ampt infiltration model is used. This model is preferred to the Horton equation as the parameters of the Green and Ampt equation do have some physical significance and guidelines are given on parameter values based on soil texture information (Rawls et al, 1983). Routing in the soil layers allows for both vertical and horizontal movement of water. In this way interflow, if important, and the effect of perched aquifers on runoff can be modelled in a simple way.

3.7.2 Evaporation Model

The evaporation model included in WITSKM is a simple model based on the model of Holden (1993) using monthly Symons pan evaporation figures as estimates of the evaporation potential Ep (mm/month). The monthly pan evaporation figures can be obtained from water resource manuals (HRU 9/81) or nearby weather stations.

The evaporation model used in WITSKM covers the evaporation processes of transpiration from vegetation and the evaporation from the soil in more detail than the empirical approaches such as that used in SWMM (Huber et al, 1982) which simulates the evaporation process as the recovery of infiltration capacity. This is achieved with a function similar to the Horton equation. The model of Holden (1993) splits the potential evaporation Ep between the soil and the vegetation using the leafy area index (LAI) which is the ratio of the shaded catchment surface area to the exposed area. A LAI of 0 would imply no vegetation and a LAI of the order of 6 represents dense vegetation. The functions used to determine the potential evaporation rate for the soil Esp and for transpiration Tp are

$$T_p = 1.06\ E_p\ (1-e^{-k\ Lai})$$
$$E_{sp} = E_p\ e^{-\ LaI}$$

where k is a constant which has been taken as unity in the model.

3.7.2.1 Transpiration

The reduction of the tranpiration rate from the potential rate as the vegetation becomes stressed with the reduction in the moisture content is modelled using a relationship due to Doorenbos and Kassam (1979) which gives the actual transpiration Ta as a function of Tp and plant available moisture (PAM) (Figure 3.6). The PAM is given by $(\theta-\theta_r/(\theta_s-\theta_r)$ where θ_s is the saturated moisture content or porosity, θ_r is the residual moisture content, and θ is the moisture content in the soil at the current time step.

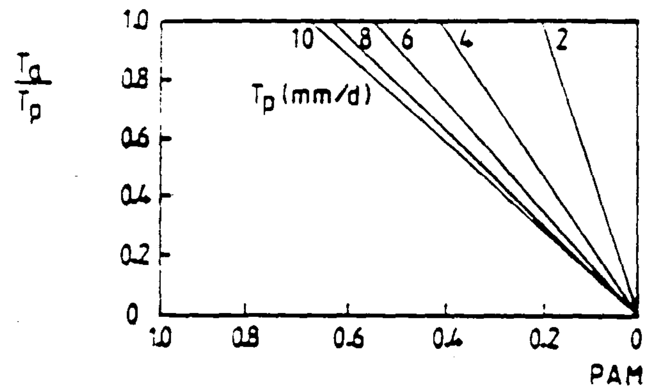


Figure 3.6 : Effect of soil moisture stress on transpiration rate (after Doorenbos and Kassam, 1979)

The relationship shown in figure 3.6 has been built into the model. Holden (1993) divided Ta between the different soil layers using a root density factor. In WITSKM only transpiration from the surface soil layer is modelled. A factor is included in the model which can reduce the transpiration rate to account for different root depths.

3.7.2.2 Evaporation

To model the reduction in the evaporation rate from the soil as the moisture content drops, the relationship shown in figure 3.7 is used where Esa is the actual soil evaporation and θ_f is the field moisture content.

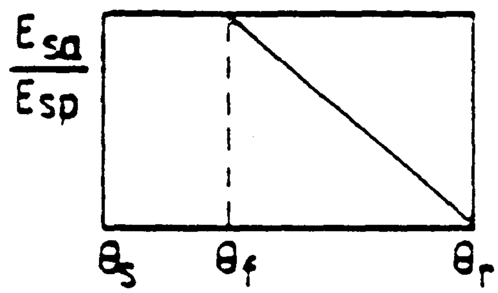


Figure 3.7 : Effects of soil moisture changes on the soil evaporation rate.

Typical values of porosity, field and residual moisture contents are given in Schulze (1995) for different soil types.

CHAPTER 4 DESCRIPTION OF CATCHMENTS AND MONITORING

4.1 INTRODUCTION

Two catchments having different land uses were instrumented to collect data on the rainfall and the water quality and quantity of their runoff. These catchments were Shembe and Amanzimnyama. Both catchments are situated in the Durban area (Fig 4.1). The data was collected on a continuous basis using data loggers while samplers were used to collect water samples for analysis for water quality parameters. On the Shembe catchment grab samples were taken to get an indication of the quality of the low flow. The monitoring period was from October 1991 to December 1993.

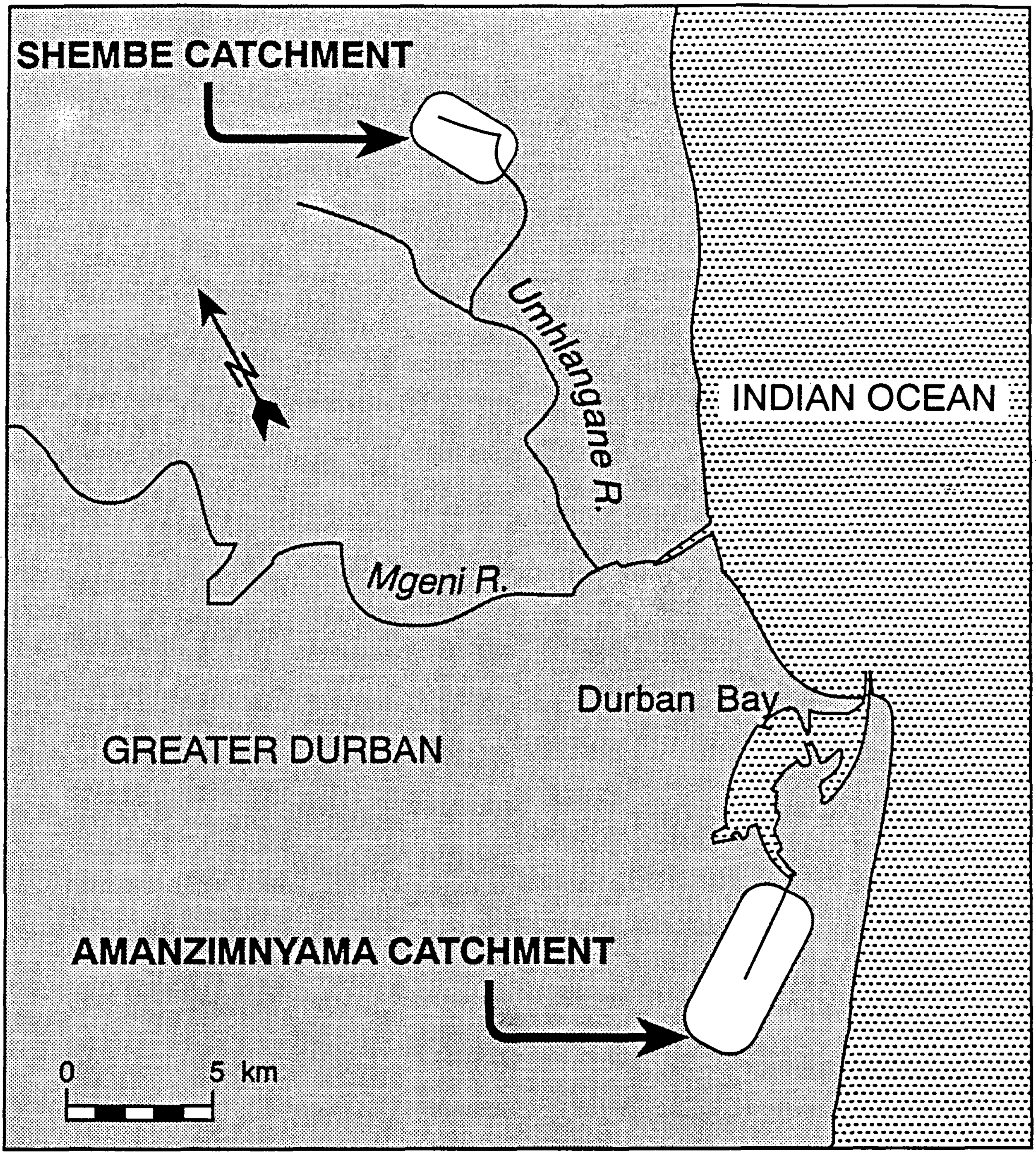


Fig 4.1   Catchment locality plan.

4.2 CATCHMENT DESCRIPTIONS

4.2.1 Shembe

Shembe catchment has an area of 5.6 km^2 and is located on the edge of the Phoenix industrial township to the north of Durban. The catchment has low cost housing and informal settlements as the predominant land uses. Inspection of the aerial photography gave the following land use split and number of units per category (Table 4.1).

Table 4.1 Land use split for Shembe

Land Use Type	Percentage of Area	No of Units
Formal low cost residential	11	770
Informal settlement	35	7560
Rural settlement	25	965
Commercial, industrial	5	-
Unsettled area	24	-

Estimates of the number of people per unit living in the informal settlements range from 5.8 up to 8/unit (Mtembu, 1993). This gives for the catchment a range of 54000 to 74000 people or a density of 96 to 133 p/ha. The formal low cost residential area is situated at the lower end of the catchment and has a tarred road network. The informal settlements have developed on the catchment slopes and are shack houses as compared to the mud huts of the more traditional rural settlements.

The services provided in the catchment are basic. The sanitation system is pit latrines. Some of the pit latrines are supplied and others are self made. The water supply is by means of vendors where water can be purchased at 5c/25l at 1992 prices. The refuse removal is rudimentary with skiffs located at central points.

The catchment is drained by well defined natural streams. The streams drain to the main drainage channel viz the Umhlangane 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 densely vegetated with reeds, shrubs, and trees. The average slope of the longest water course was estimated as 0.05.

The soils of the catchment are a sandy loam to a silt loam with the depths on the steep slopes estimated to be of the order of 300 to 500mm. The catchment vegetation cover is generally dense especially in the region of the stream channels. The vegetation has been stripped off the areas surrounding the shacks. Low level bridges (drifts) have been constructed across many of the streams.

The main drainage channel from the catchment has been canalized into a concrete lined rectangular channel having a width of 5.0m and a slope of 0.008. The monitoring station was established on this channel.

4.2.2 Amanzimnyama

The Amanzimnyama catchment has an area of 12 km^2. The catchment is situated to the South of Durban and is highly developed. The land use is about 70% industrial and commercial and 25% formal residential and 5% open and natural. The industries present in the catchment range from paint manufacture, oil recycling, scrap metal and processing, textile and a variety of food manufacturers.

The topography is generally flat in the centre of the catchment. The flat central area is bounded by the ridges of the Bluff on the Eastern side and Montclair on the West. Drainage is via a number of stormwater culverts that enter a central concrete canal which varies in width from 10 to 24m and has a depth of up to 5.0m.

The monitoring site is located at a broad crested weir which acts as a surface oil trap. The trap is serviced 2 to 3 times weekly. The canal enters the Durban harbour in an area referred to as the "silt canal".

4.3. INSTRUMENTATION

4.3.1 Rainfall and Flow depth instrumentation

Four tipping bucket raingauges each with a customized CSIR data logger have been installed on the catchments. One was installed on the Shembe catchment and three on the Amanzimnyama catchment. The rainfall tips were totalled and recorded every 2 minutes. The raingauges are sited on top of buildings for security reasons. In the case of the Shembe catchment, the only secure site was on a building at the lower end of the catchment. The location of the raingauges and flow gauging sites are shown in figure 4.2 and 4.3.

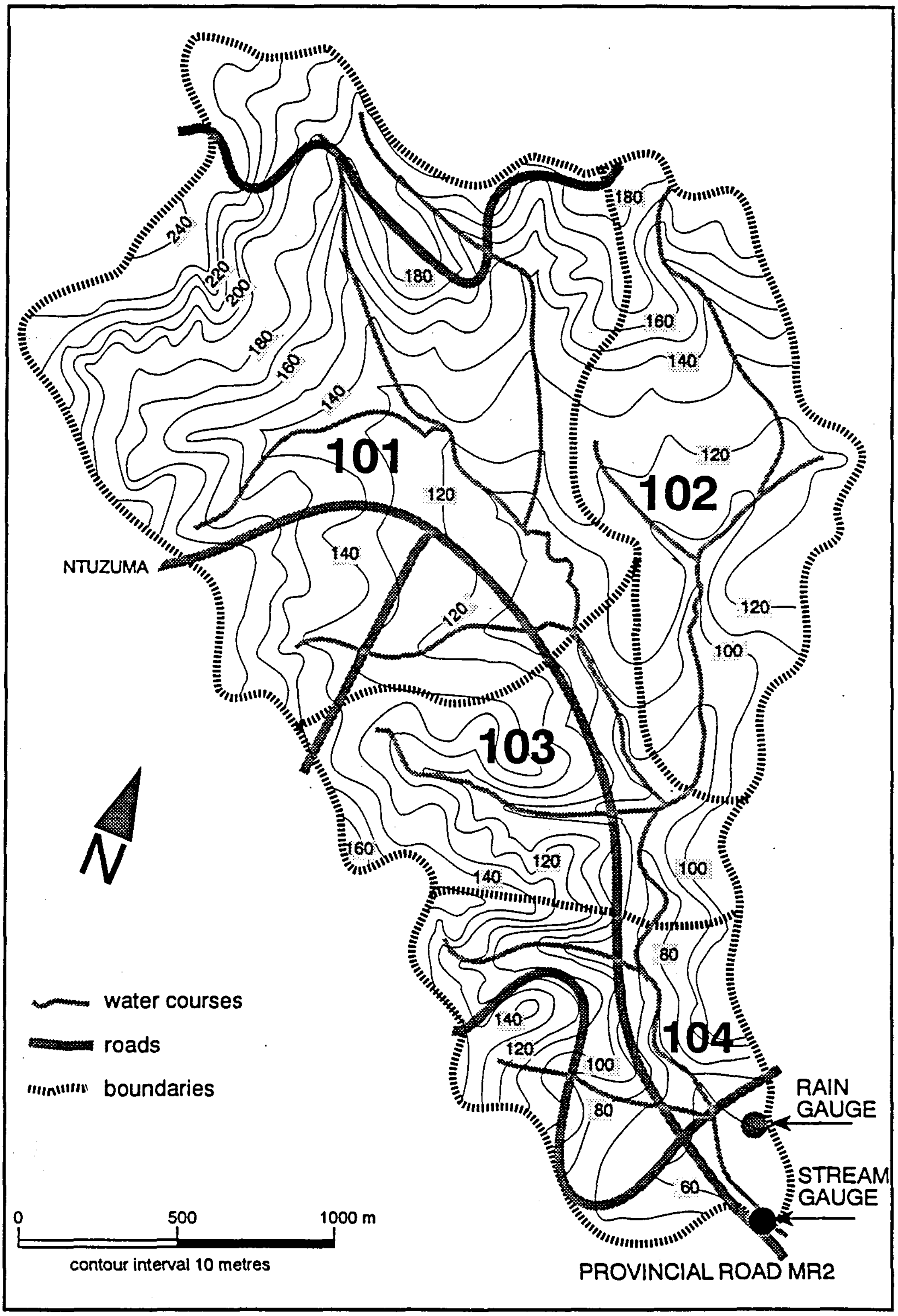


Fig 4.2 Location of instruments for Shembe

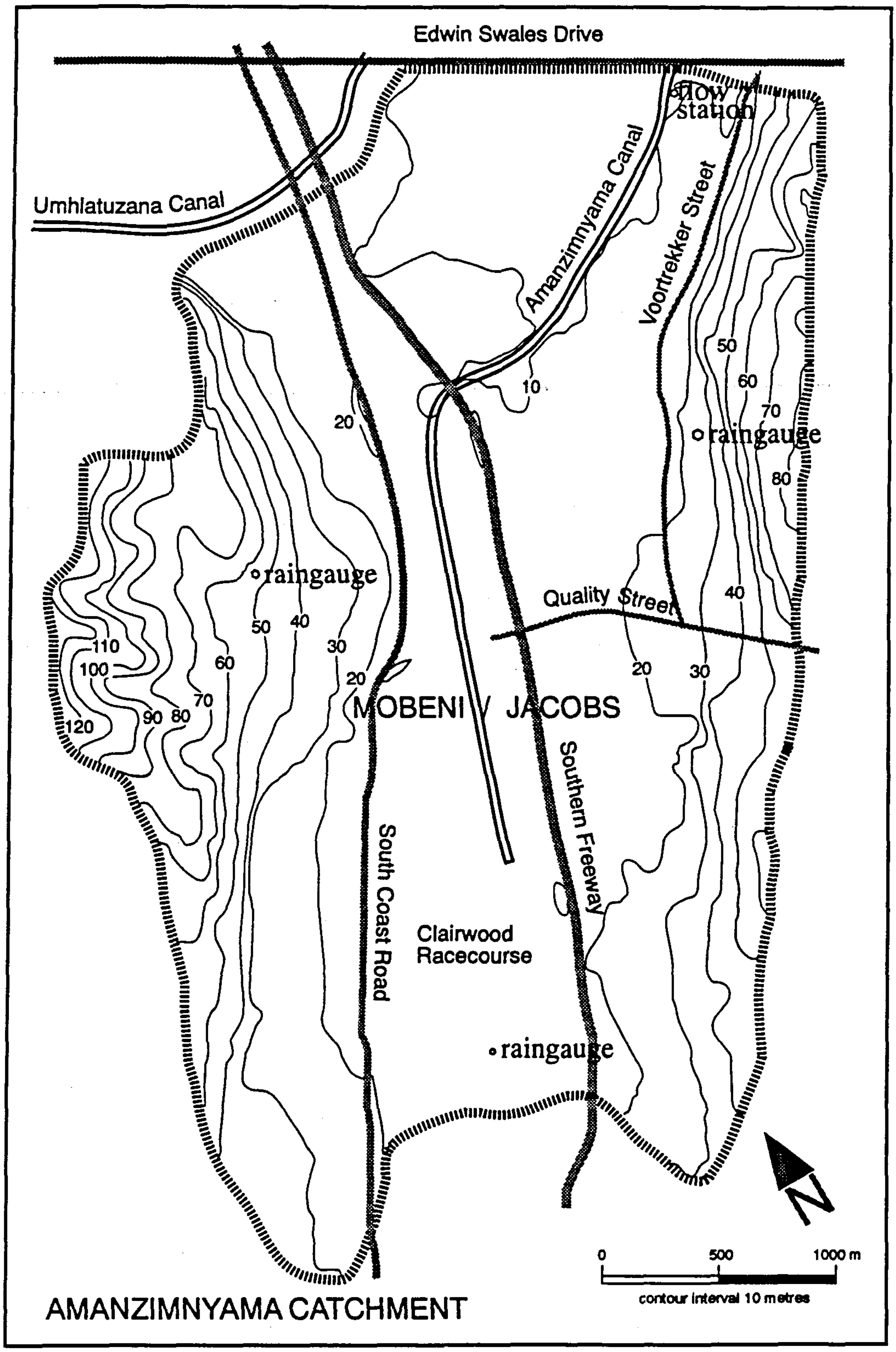


Fig 4.3 Location of instruments for Amanzimnyama

The flow stations were established on the canal sections draining the catchments. The Physical Environment Service Unit of the Durban Corporation constructed stilling wells on the banks of the canals out of 1.0m diameter pipes. The wells were connected to the channels with 150mm diameter pipes. Unfortunately the base level of the stilling well at the Shembe site was constructed 93mm above the invert level of the canal. The flow rate first had to reach 1.5m^3/s before any recordings could be made. At the Amanzimnyama catchment the depth behind the oil trap weir was sufficient to maintain a water depth in the stilling well. The MC data logging system was used to record the times and flow depths. The loggers were housed in steel boxes on top of the stilling wells. A float system was used to measure the flow depths at Shembe. At Amanzimnyama the MC logging system kept jumping out of its program during lightning activity which resulted in periods of data loss. The logging system was ultimately modified by replacing the encoder on the float system with a 10 turn potentiometer not as prone to interference by electrical discharges.

4.3.2 Water Sampling

The MC data logger cannot control a water sampler and equipment had to be custom built to perform this function. By negotiation with MC systems staff, an IC (integrated circuit) was added to their loggers to give a serial output of data via a plug whenever their logger recorded data (every 10 minutes for Amanzimnyama and 5 minutes for Shembe). This information is received by a Sharp PC1600 micro-computer. Before transmitting the information, a signal (change in polarity on a pin) is sent to the Sharp to turn it on in order to receive the data. Thereafter the microcomputer selects the relevant information (level measurement) from the data string and through a programme in Sharp basic language performs a number of functions which are briefly described below:

1. The level measurement data is selected and a test is then made to see if it is above a preset threshold value (in the

case of Shembe canal the water level has to rise above the invert of the connecting pipe to register flow and therefore flow below this cannot be measured, i.e: threshold of 0.093m). The sampling at Amanzimnyama was undertaken at the preset volume interval on a continuous basis as there was always flow in the canal.

2. If there is no flow then no record is taken. There is however provision for 2 records to be taken daily for equipment checking purposes.

3. If above the threshold, the level is converted to flow by accessing a rating table. A check is made to see if the threshold has just been exceeded, if yes then the sampler is activated immediately and a record stored in file consisting of date, time, flow and sample number.

4. If in the flow mode, subsequent level measurement signals are used to calculate flow volume since the previous reading, accumulate it and activate the sampler when preset volumes are exceeded.

5. In between such tests and calculations the Sharp switches off automatically in order to conserve power.

The micro-computers were replaced after samples had been collected but are able to last in the field for at least 3 weeks. Back at the laboratory the recorded data was downloaded to a PC using an inter computer communication programme (Procomm).

A purpose built interface to the microcomputer activates the sampler when required and also provides power to the microcomputer from an external battery. Two Manning water samplers were used. Field tests have shown that they can cope with the required water lift (3,2 and 4.8m for the Amanzimnyama and Shembe canals respectively).

A sample intake system, consisting of 6mm plastic tubing contained within copper tubing for protection was initially installed in the Shembe canal. The tubing and plastic strainer intake were fixed onto the floor of the canal. Within a short time, however, all of the material was removed by vandals. The sampler intake was replaced with "less desirable material" (no metal) and survived the remainder of the project.

4.4 WATER QUALITY PARAMETERS

The samples collected were tested for pH, suspended and dissolved solids. Conductivity was used as a measure of the dissolved solids. The nutrients tested for were the soluble and particulate phosphorus forms, ammonia, nitrate, and the soluble and particulate forms of Kjeldahl nitrogen. The Kjeldahl nitrogen test included the ammonia form of nitrogen. The organic content was tested for by using the COD and BOD tests on unfiltered samples. The dissolved and total concentration of the metals lead, copper, cadmium, chromium, zinc and mercury were determined. The level of hydrocarbons and oils and greases were also determined as Amanzimnyama, having an industrial land-use, was considered to be a source of these pollutant types. The microbiological quality was determined using presumptive and confirmed E-Coli testing.

Not all the tests were carried out on all the samples for a particular storm event. Some of the tests were carried out on composite samples to reduce the costs. Not all of the tests were carried out for the full duration of the monitoring period, for example the tests for the dissolved forms of the metals were dropped early on in the monitoring period.

CHAPTER 5 ANALYSIS OF MONITORING RESULTS

5.1 INTRODUCTION

In this chapter, the water quality and quantity data collected from the monitoring programs on Shembe and Amanzimnyama are analysed. The purpose of the analysis is to compare the runoff concentrations to aquatic and effluent quality standards. Using the flow data, pollutant loads per unit catchment area for the different pollutant types are determined as these could prove useful in broad water resource planning for areas having similar land-use.

5.2 SHEMBE

For the Shembe catchment up to 26 grab samples were taken of the dry weather flow and 225 samples of the storm flow. The 225 storm flow samples covered some 27 storm events from the catchment from 8 October 1991 to 7 October 1993. Not all the pollutant types were analysed for in every sample taken. The arithmetic average, the number of samples N, the minimum and maximum concentrations, and the median concentration from the catchment for the dry weather and storm flows are presented in Table 5.1 and Table 5.2.

Table 5.1 : Statistical analysis of the concentration data for the storm flow for Shembe.

Variable	Mean	Median	Std. Dev	Min	Max	N
pH	7	7.1	0	6	8	25
COND mS/m	59	37.2	81	8	700	225
SS mg/l	1444	922	1586	52	8515	225
SOL P µg/l	157	124	89	9	456	225
TOT P µg/l	2073	1480	1910	126	13218	225
NO_3 µg/l	6851	3473	7404	7	35484	220
NH_3 µg/l	505	397	604	3	3459	220
SOL KN µg/l	1451	885	1113	309	3926	51
TOT KN µg/l	9460	4618	5782	564	24745	51
COD (mg/l O)	217	133	294	10	2889	160
BOD (mg/l O)	18	-	9	6	33	9
Pre E- COLI/100ml	888788	-	1200000	3100	7800000	48
Con E- COLI/100ml	224429	-	160517	11000	560000	14
SOL Cu µg/l	1	-	2	0	4	8
SOL Cr µg/l	26	-	38	0	111	8
SOL Pb µg/l	49	-	26	30	67	2
SOL Zn µg/l	174	-	248	26	764	8
TOT Cu µg/l	126	98	137	29	636	59
TOT Cd µg/l	3	-	7	0	28	29
TOT Cr µg/l	513	299	952	23	5400	31
TOT PB µg/l	523	264	1754	7	9921	59
TOT Zn µg/l	477	285	920	35	4715	30
TOT Hg µg/l	1	-	0	0	1	1
OIL & GR mg/l	8	-	8	1	24	6
HYDROCARBONS mg/l	7	-	6	1	14	5

The concentrations given in Table 5.1 and Table 5.2 result from a statistical analysis of all the samples taken. In Table 5.3 are shown event mean concentrations (EMC) which were determined for each event and are calculated by dividing the total load for a particular event by the runoff volume for that event. The load and runoff volumes for an event were calculated for the time period from the first sample to the last sample taken for the event. The average and the range of EMC are presented in Table 5.3 for each pollutant type.

Table 5.2 : Statistical analysis of the concentration data for the dry weather flow for Shembe

VARIABLE	MEAN	MEDIAN	SD	MIN	MAX	N
pH	7.9	8.0	0.5	6.6	9.0	28
COND mS/m	68.1	66.6	9.8	50	92	28
SS mg/l	47	36	46	2	208	28
SOL P μg/L	120	88	102	7	331	28
TOT P μg/L	217	168	132	44	453	28
NO3-N μg/l	3246	2223	3716	558	9772	5
NH3-N μg/l	206	74	276	4	670	5
SOL KJEL-N μg/l	846	629	612	418	1899	5
TOT KJEL-N μg/l	1143	1091	550	593	2038	5
COD mg/l	56	39	55	7	174	12
BOD mg/l	27	26	21	1	80	21
Pre E-COLI/ 100ml	34085	13900	51900	20	178000	12

The dry weather flow concentrations given in Table 5.2 are generally lower than the stormwater concentrations. This is particularly true of the solids related pollutants such as the particulate P, COD, Tot KN, and the bacteria. This is due to the washoff or mobilization of particulate forms of the pollutants from the catchment surfaces during storm events.

The monitoring period more or less covered the 91/92, 92/93 rainy period. Only the beginning of the 93/94 rainy period was monitored. The pollutant loads for the storm flows (kg/ha) for each of the years are given in Table 5.4. The rainfall and storm runoff depths for each of the years and for the total monitoring period are also presented. The loads given in Table 5.4 will be lower than the actual loads as the logger only recorded once the flow depth exceeded 93 mm. The loads were calculated from the first sample to the last sample taken for each event. The total load for the storm flow could then be determined. There were some runoff events whose depths of runoff did not exceed the 93 mm depth and were therefore not recorded. The dry weather flow loads from the Shembe catchment were estimated using the grab sample concentrations and an average dry weather flow rate of 0,015 m^3/s.

Table 5.3 : Average and range of Event Mean Concentrations for Shembe

Pollutant	Averages	Minimum	Maximum	Number
SS (mg/l)	1214.11	182.64	3568.53	27.00
Sol P (μg/l)	134.85	32.00	237.67	27.00
Tot P (μg/l)	1804.87	261.05	4533.60	27.00
NO_3(N) μg/l	5615.58	167.00	26329.46	26.00
NH_3(N) μg/l	374.41	10.00	1382.60	26.00
COD mg/l	186.05	45.85	400.00	23.00
Total Cu (μg/l)	187.52	46.00	541.33	11.00
Total Cr (μg/l)	175.90	60.00	390.00	10.00
Total Pb (μg/l)	329.57	63.00	1084.97	10.00
Total Zn (μg/l)	602.60	267.00	1367.49	6.00
Sol KN (μg/l)	1645.56	926.23	2550.00	4.00
Tot KN (μg/l)	9511.51	3805.00	17620.00	4.00
BOD mg/l	16.83	6.20	27.30	4.00
PCOLI/100 ml	206541.45	81420.10	347507.35	3.00

Table 5.4 : Pollutant loads (kg/ha) for runoff from Shembe.

Pollutant	1991			1992			1993		
	Storm flow kg/ha	Low flow kg/ha	Total kg/ha	Storm flow kg/ha	Low flow kg/ha	Total kg/ha	Storm flow kg/ha	Low flow kg/ha	Total kg/ha
SS	1067.443	26.468	1093.911	643.797	26.468	670.265	1139.536	26.468	1166.003
Sol P	0.079	0.066	0.146	0.095	0.066	0.161	0.201	0.066	0.268
Tot P	1.370	0.121	1.491	0.992	0.121	1.113	0.713	0.121	1.835
NO_3 (N)	5.255	1.827	7.082	1.890	1.827	3.716	14.924	1.827	16.750
NH_3 (N)	0.313	0.114	0.427	0.316	0.114	0.430	0.454	0.114	0.568
COD	122.495	31.536	154.031	75.691	31.536	107.226	154.786	31.536	186.322
BOD		15.204	15.204		15.204			15.204	15.204
Tot Cu	0.060		0.060	0.080		0.080	0.074		0.074
Tot Cr	0.066		0.066	0.002		0.002	0.076		0.076
Tot Pb	0.083		0.083	0.005		0.005	0.100		0.100
Tot Zinc	0.198		0.198	0.008		0.008	0.025		0.025
Sol Kjel-N		0.475	0.475		0.475	0.475	0.885	0.475	1.360
Tot Kjel-N		0.643	0.643		0.643	0.643	3.429	0.643	4.071
Volume (mm)	75	84	159	71	84	155	177	84	201
Rainfall (mm)	45.5			344			265		

Period of Rainfall Record: From 20.12.91 To 10.12.93

The volumes and loads for 1991 are calculated from 8 October 1991 to end of December 1991.

5.3 AMANZIMNYAMA

The instrumentation on the Amanzimnyama catchment gave a number of problems which resulted in data loss both in terms of flow and sampling. The flow data was infilled as best as possible. The Amanzimnyama catchment has a very strong base or dry weather flow. This flow was estimated to be of the order of 0,5 m^3/s. The baseflow runoff volume was twice as much as the storm runoff over the monitoring period. However 1992 was a particularly low rainfall year which resulted in low storm runoff volumes. The sources of the dry weather flow are due to groundwater seepage and springs (Pitts, 1990 ; Burgess, 1992) and many of the industries discharging water illegally into the canal. The industrial discharges are of water that has been imported into the catchment in the water supply.

The results of the statistical analysis on the samples taken for Amanzimnyama are presented in Table 5.5.

Table 5.5 : Statistical analysis of the analytical data for the Amanzimnyama canal.

Variable	Mean	Std Dev	Min	Max	N
pH	7.5	0.47	6.5	8.7	73
Cond mS/m	42.6	22.5	8.8	81	148
Susp Sol mg/l	112	226	4	2225	148
Sol P µg/l	145	488	12	5720	148
Tot P µg/l	882	1888	79	19683	148
Nitrate-N µg/l	1647	2548	6	17302	114
Ammonia-N µg/l	256	810	1	8223	106
Sol Kjel-N µg/l	1100	1286	334	8865	39
Tot Kjel-N µg/l	4492	11492	823	74396	39
COD µg/l	129	163	1	995	118
BOD µg/l	29	20	5	72	19
Pre E-Coli/100ml	130000	170000	1000	740000	43
Con E-Coli/100ml	190000	220000	8400	740000	11
Sol cu µg/l	N/D				
Cd µg/l	N/D				
Cr µg/l	12	1	11	13	4
Pb µg/l	41	7	33	51	4
Zn µg/l	96	80	22	326	15
Hg µg/l	N/D				
Tot Cu µg/l	75	111	9	785	72
Cd µg/l	4	4	1	20	50
Cr µg/l	58	145	4	1175	71
Pb µg/l	242	371	7	1803	71
Zn µg/l	375	641	45	5500	72
Hg µg/l	1.5	1.9	.1	7.6	13
Oil/Grease mg/l	14	25	2	98	13
Hydrocarbon mg/l	5	4	1	14	13

Using the 0,5 m^3/s as a baseflow, the runoff data was analysed to give EMC concentrations for the dry weather and storm flow for Amanzimnyama. These are presented in Table 5.6

Table 5.6 : EMC for dry weather and storm runoff from Amanzimnyama.

VARIABLE	DRY WEATHER FLOW	N	STORM FLOW	N
COND mS/m	66.1	71	27.6	102
SUSP SOL mg/l	36	71	148	102
SOL P $\mu g/l$	107	71	226	102
PART P $\mu g/l$	365	77	805	102
NO_3-N $\mu g/l$	1888	55	1093	62
NH_3-N $\mu g/l$	282	53	118	56
COD mg/l	77	53	153	75
E COLI/100 ml	473776	20	161229	22
TOT Cu $\mu g/l$	33	43	120	24
TOT Cr $\mu g/l$	29	39	56	24
TOT Pb $\mu g/l$	53	35	460	29
TOT Zn $\mu g/l$	198	42	493	24

The export coefficients for the dry weather and storm runoff for Amanzimnyama are given in Table 5.7.

Table 5.7 : Export coefficients (kg/ha/a) for the dry weather and storm flow and the total runoff from Amanzimnyama

VARIABLE	LOW FLOW kg/a	HIGH FLOW kg/a	TOTAL kg/ha/a
TDS FROM CONDUCTIVITY	2780762	464151	2704
SUSPENDED SOLIDS	226897	373152	500
SOLUBLE P	674	570	1.04
TOTAL P	2975	2599	4.65
NITRATE-N	11899	2756	12.2
AMMONIA-N	1777	298	1.73
COD	485308	385759	725
BOD	132357	148757	234
TOTAL COPPER	208	303	0.43
TOTAL CHROMIUM	183	141	0.27
TOTAL LEAD	334	1160	1.25
TOTAL ZINC	1248	1243	2.08

5.4 COMPARISON OF WATER QUALITY TO WATER QUALITY CRITERIA

The runoff from both the catchments contains considerable pollution. The impacts the runoff from the catchments could have are eutrophication, de-oxygenation of the receiving water stream, toxicity and pose a health hazard. This point is illustrated in figure 5.1 where the percentage of sample results for the low flow and the storm flow data sets which exceed the criteria for the protection of aquatic life as given by Kempster et al, (1980) are plotted.

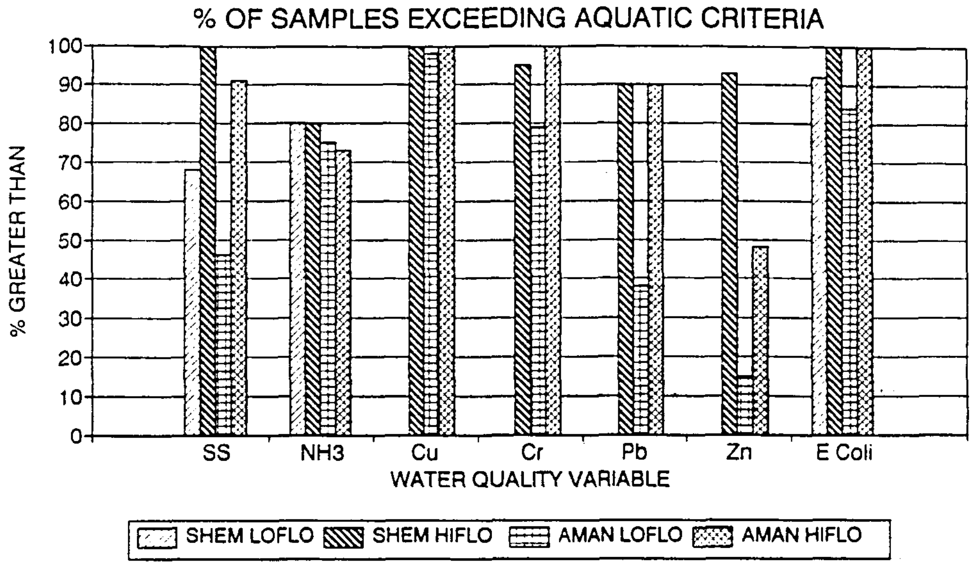


Figure 5.1 : Percentage of samples exceeding the aquatic criteria

The exceedances of the recommended levels are mostly high, particularly for the high flow results which are between 90 and 100% for suspended solids and the metals and above 70% for ammonia. The criteria used for comparison of the microbiological quality is the contact recreation criterion using the 99th percentile of 2000/100 ml (Lusher, 1984). Figure 5.1 shows the poor quality of the runoff for both the low and high flow situations for both catchments.

Similarly the results are shown compared to the special standards for the discharge of effluents (Government Gazette, 1984) in figure 5.2. The percentages of the samples exceeding the standards are also high especially for the suspended solids, COD, and the metal concentrations for high flow.

The results shown in figures 5.1 and 5.2 highlight the high levels of pollution from the catchments. The extent to which such runoff will impact on the receiving streams will depend on the capacity of the streams to dilute the runoff to acceptable levels.

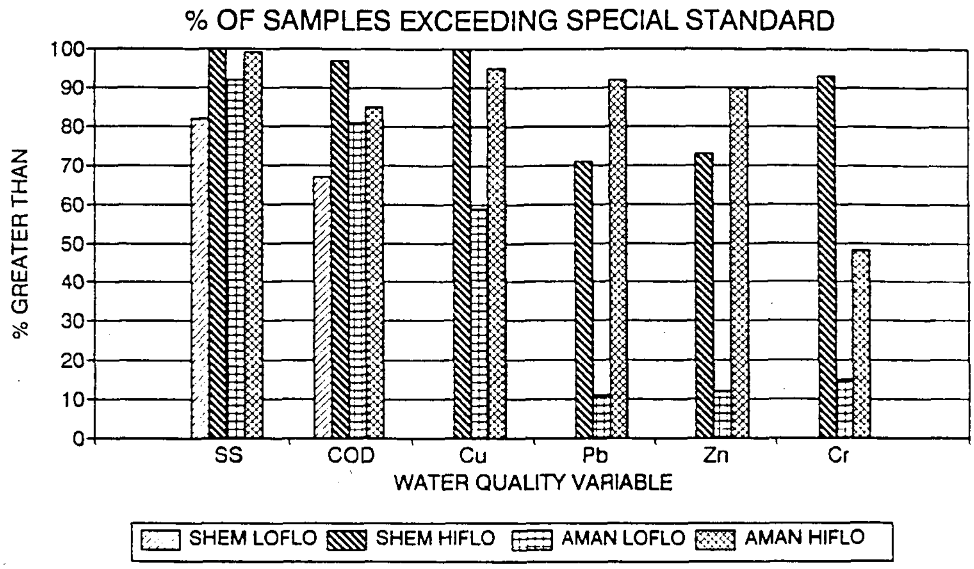


Figure 5.2 : Percentage of samples exceeding the special effluent discharge standards

CHAPTER 6 APPLICATION OF THE MODEL

6.1 INTRODUCTION

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. To test the capabilities of the quality model, the simulated pollutographs of the concentration variations over the complete hydrograph should be compared to the observed values. For many of the events composite samples were taken of the entire event or of sections of the events, only allowing for the comparison of total pollutant loads. Of the 27 events, 7 complete events were selected for comparison of the simulated and observed pollutographs. The dates, peak rainfall intensities, and the storm durations are given in Table 6.1

Table 6.1 : Details of storm events used in the comparison of 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 selected cover a variety of storm types from high intensity short duration to low intensity long duration storms.

The pollutant types tested for (for most of the events) were SS, TDS (conductivity), and filtered and unfiltered phosphorus(P). For some of the events total COD, nitrate, ammonia, and some of the total heavy metal concentrations, E-coli were determined. To test the model's ability, simulated and observed pollutographs of the SS, particulate and dissolved P, and the TDS concentrations were made. These pollutant types were selected as these were available for all 7 of the events and would test the dissolved, SS, and the particulate pollutant form models.

The approach used in applying the model was to simulate the runoff using the WITSKM model. This was done on a continuous basis using a single set of model parameters describing the catchment. Once the simulated flow results had been obtained, these were used as input to the quality model to determine the pollutographs. Values for the buildup of particulates were used in the initial water quality model runs for the catchment. However after a number of trial runs, the pollutant buildup rates were found to have to be continually increased for the impervious areas until the values become purely calibration parameters. To reduce the number of input parameters, the buildup functions were not used and the assumption, similar to that of Henderson and Moys (1987) in the MOSQITO model, was made that there is always sufficient particulate material on the catchment surfaces for entrainment. Similarly the fractions of the particulate material that represent the particulate and dissolved forms of a pollutant were assumed the same at the start of each storm event. As the pollutant buildup was not used in the model, the quality model was not run on a continuous basis but for each of the events individually. However the model parameters were not changed from event to event. Plots of the hydrographs and the pollutographs and comparisons of pollutant loads for the events were used to represent the modelling results.

6.2 CATCHMENT DISCRETISATION

The catchment was discretised into 4 overland flow modules and

8 channels as shown in figure 6.1. The pertinent details for each of the overland flow modules are given in Table 6.2.

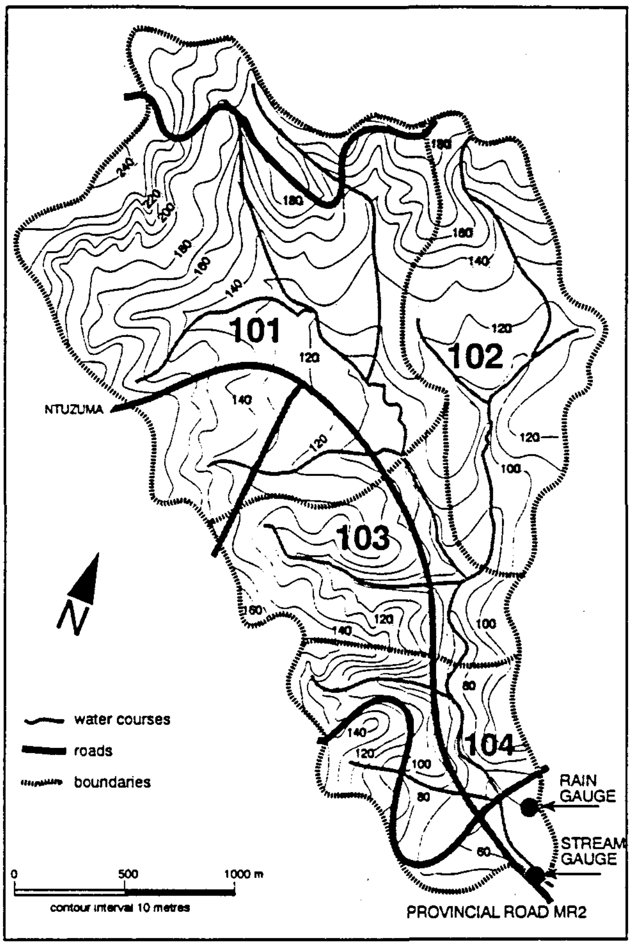


Figure 6.1 : Catchment discretization

Table 6.2 Details of the overland flow modules

Mod No	Area (ha)	Length(m)	% imperv	Slope
101	210	850	5	0,14
102	196	850	5	0,05
103	90	400	40	0,10
104	64	300	50	0,10

The impervious areas on the Shembe catchment are generally disconnected. In the upper reaches of the catchment the shacks are not served by a "tarred" road network and associated stormwater drainage system. The huts are scattered over the hillsides with access by means of at most a dirt road or track. Although the actual percentage impervious area is probably of the order of 20% to 30%, the model requires the directly connected area thus the lower percentage of 5% was used for this area. In the more heavily populated lower end of the catchment, a more formal "tarred" road network and stormwater drainage network has been installed thus the higher percentages directly connected impervious area were used for these regions.

6.3 MODELLING STORMWATER RUNOFF QUANTITY

To model the stormwater runoff quantity, the Green and Ampt infiltration parameters, catchment slopes and areas, Mannings roughnesses, leafy area index, and the thicknesses of the soil layers are required.

The soil was taken to be a silt loam with Green and Ampt infiltration parameters as given in Coleman and Stephenson (1993). These parameters and the soil characteristics are given in Table 6.3. Two soil layers were used to describe the soil profile. The top layer amd lower layer were taken to have depths of 0,15 m and 1,0 m respectively. As has been found by Constantinides (1982) and Holden (1993), the saturated hydraulic conductivity can be reduced by up to 3 times to allow for the partial saturation of the soil during infiltration and a value of 4 mm/hr was found to give reasonable results. The Manning roughness coefficients of 0,018, and 0,25 were used for the impervious, and pervious catchment areas while a value of 0,18 was used for the heavily vegetated channels.

Table 6.3 Infiltration parameters and soil characteristics

Parameter	Sat Con (mm/hr)	Suc Hd (m)	Porosity	Wilt Pt	Field Cap
Value	6,5	0,1	0,42	0,12	0,27

The monthly potential evaporation depths were taken from the

Surface Water Resources of South Africa manuals (HRU 8/91). The values used are given in Table 6.4. A leafy area index of 1.5 was used to represent medium dense vegetation cover. As the vegetation cover is largely grass and bushes, 70% of the roots were assumed to be in the top soil layer.

Table 6.4 : Monthly Symons pan evaporation depths (mm)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evap depth	140	100	90	80	70	60	80	94	100	110	140	140

6.3.1 Results of WITSKM runs

The results of the WITSKM runs are shown plotted together with the rainfall hyetograph for the 7 events in figures 6.2 to 6.8. The extent of the agreement varied from good to poor. The model tended to under estimate the runoff volumes particularly for the low intensity long duration event of the 92-10-08 shown in figure 6.6. The fit was so poor that this event was excluded from the quality modelling runs.

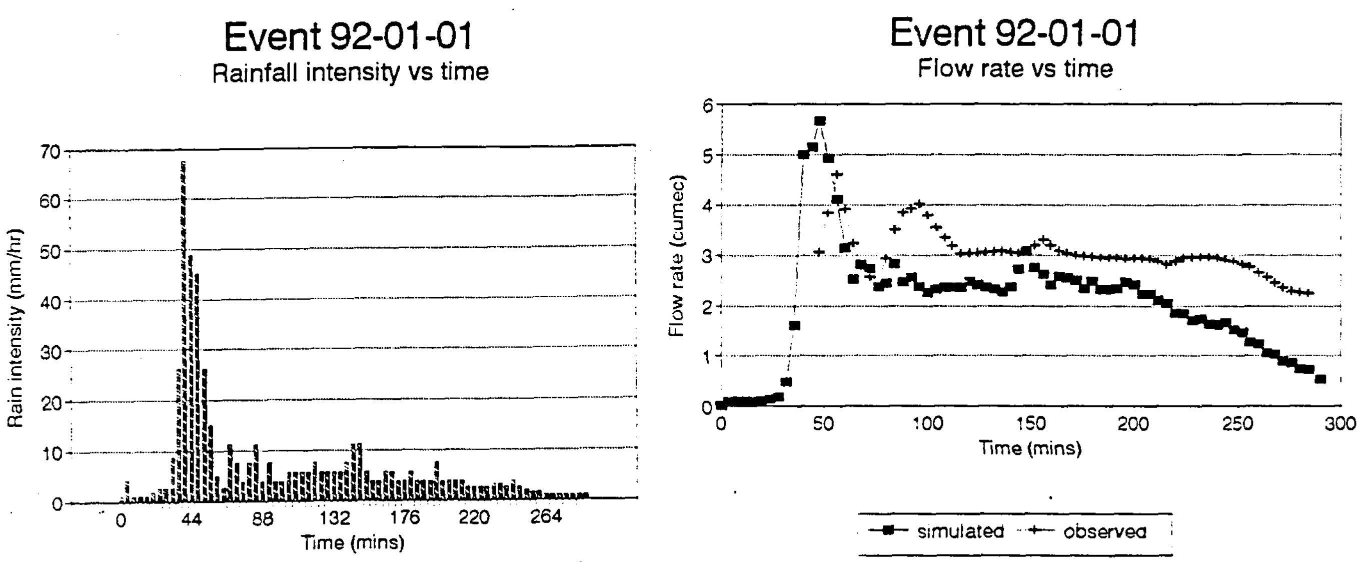


Figure 6.2 : Comparison of observed and simulated hydrographs for event 92-01-01

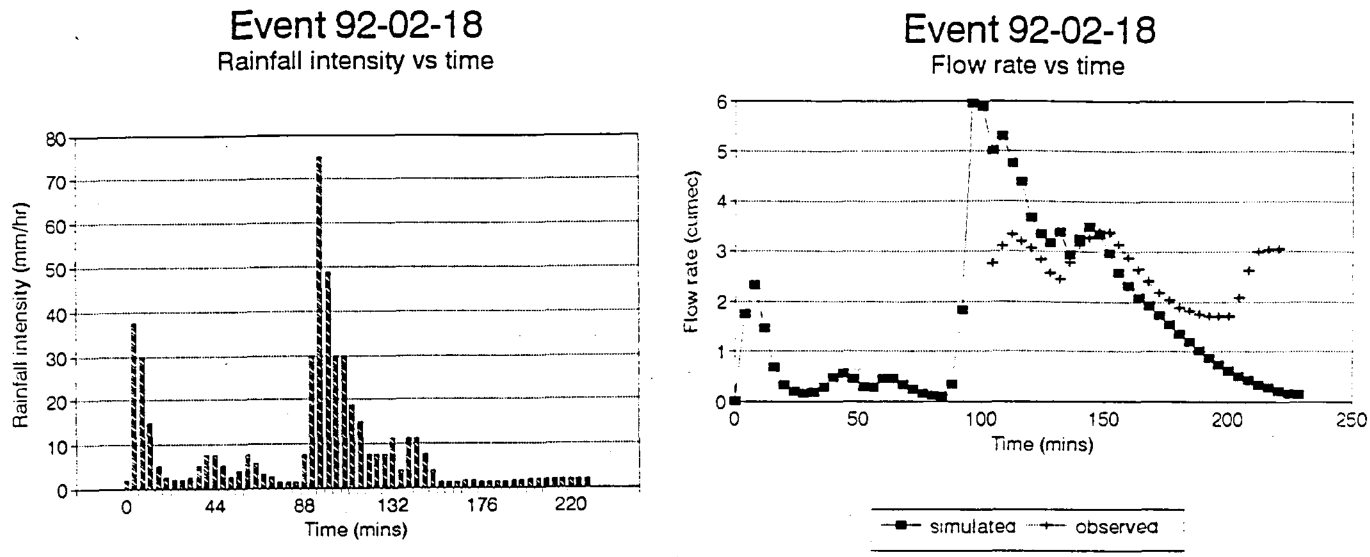


Figure 6.3 : Comparison of observed and simulated hydrographs for event 92-02-18

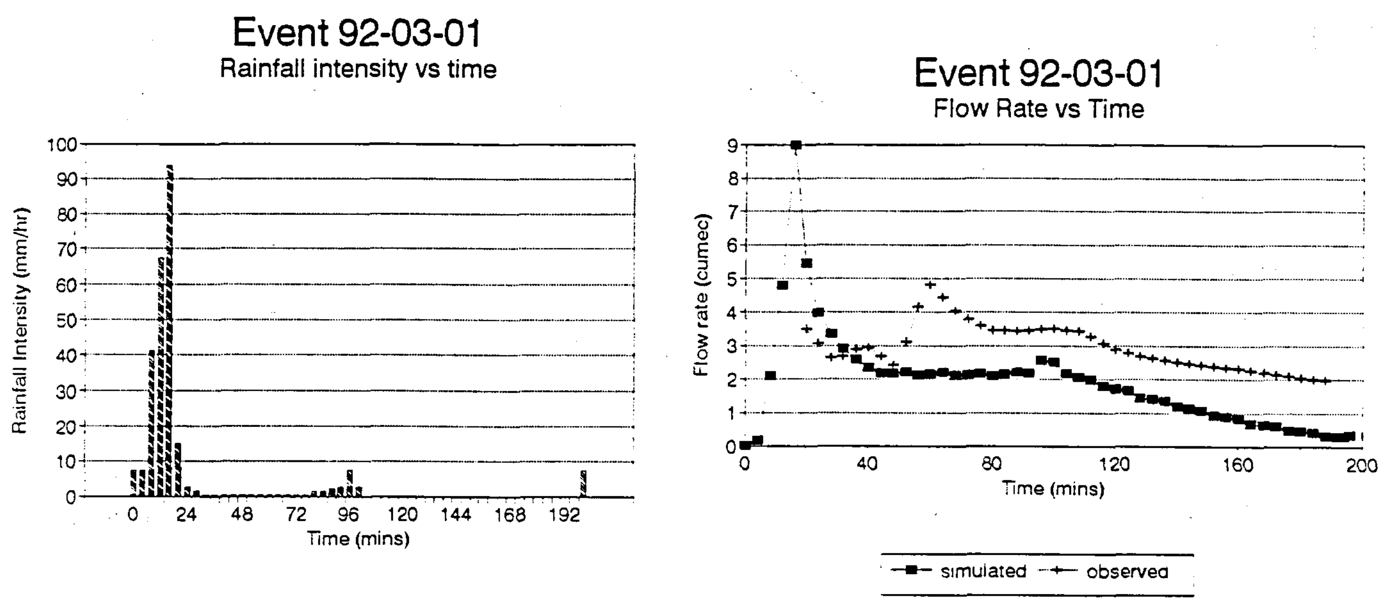


Figure 6.4 : Comparison of observed and simulated hydrographs for event 92-03-01

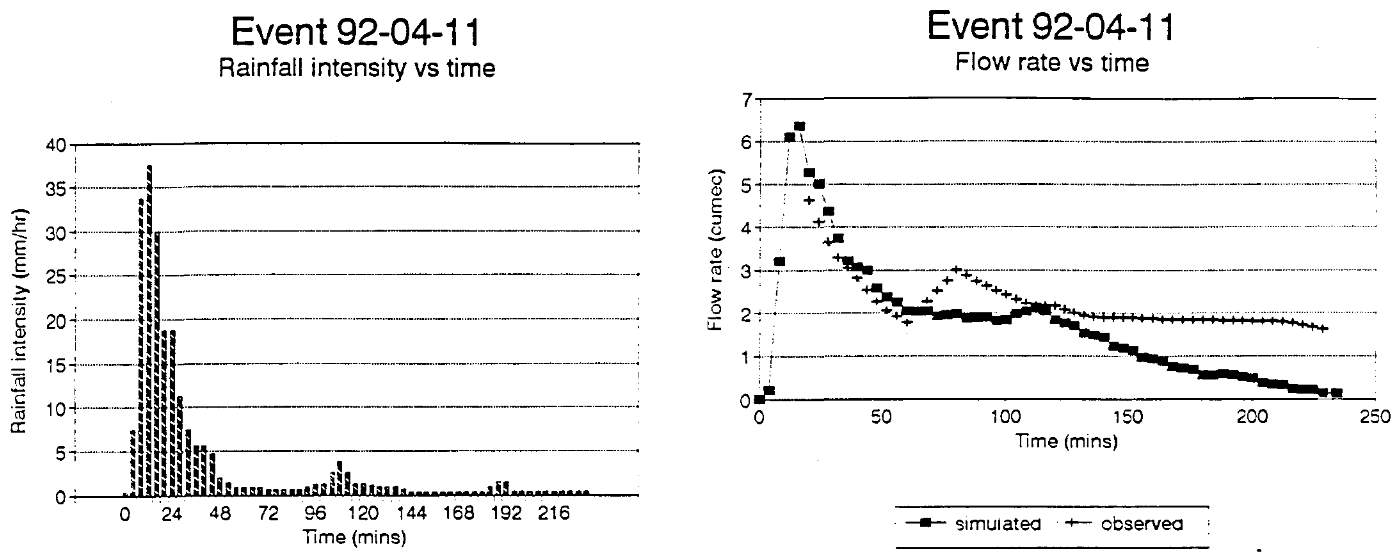


Figure 6.5 : Comparison of observed and simulated hydrographs for event 92-04-11

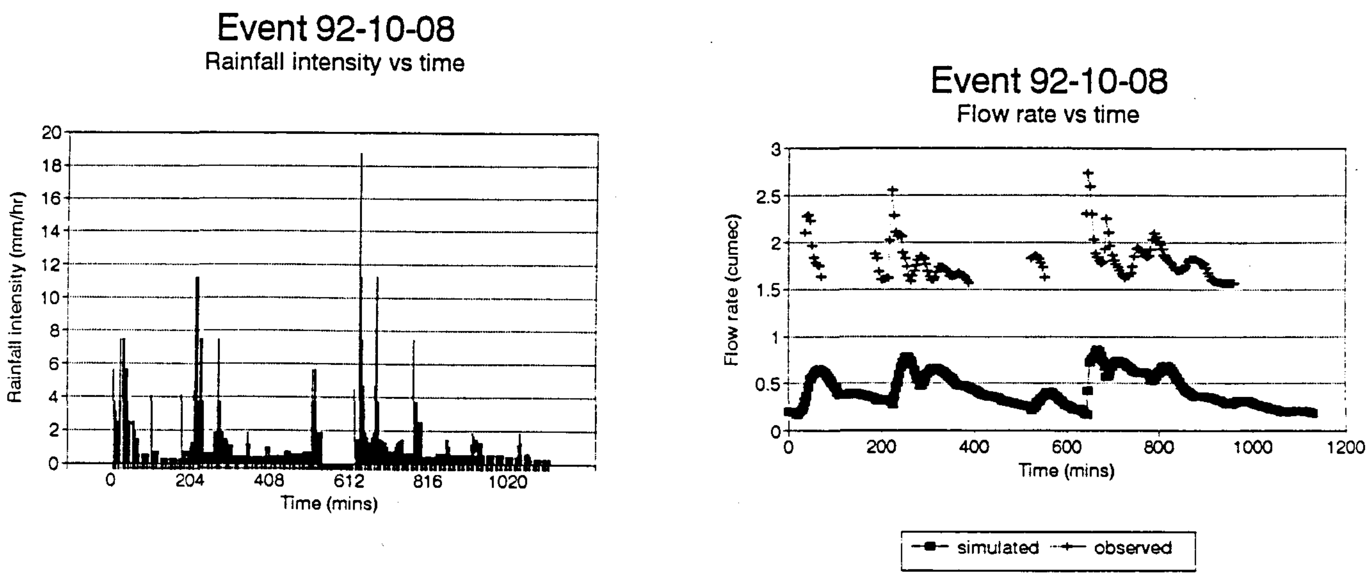
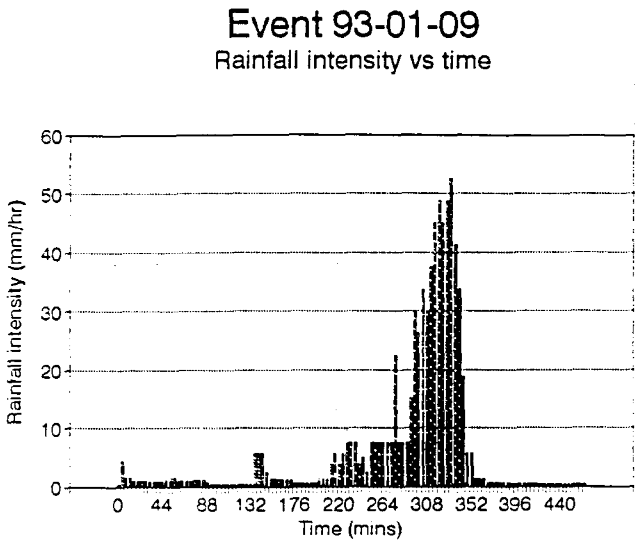


Figure 6.6 : Comparison of observed and simulated hydrographs for event 92-10-08



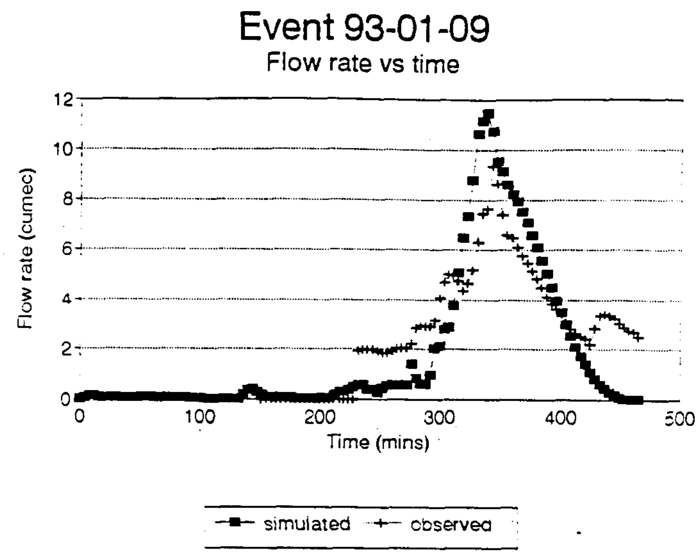
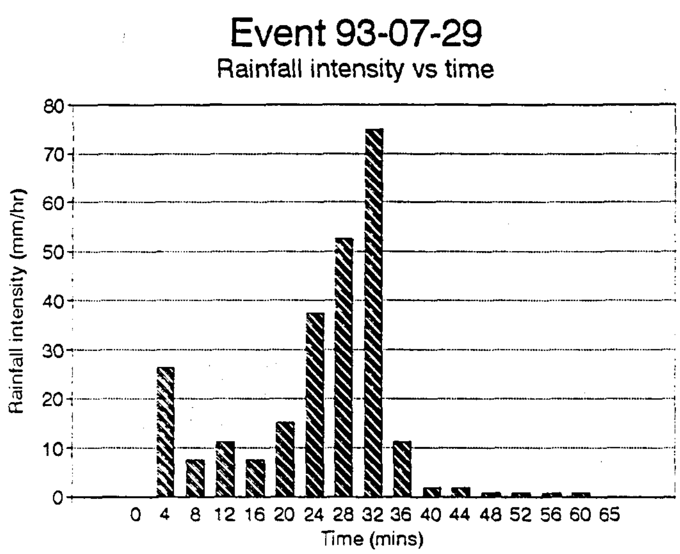


Figure 6.7 : Comparison of observed and simulated hydrographs for event 93-01-09



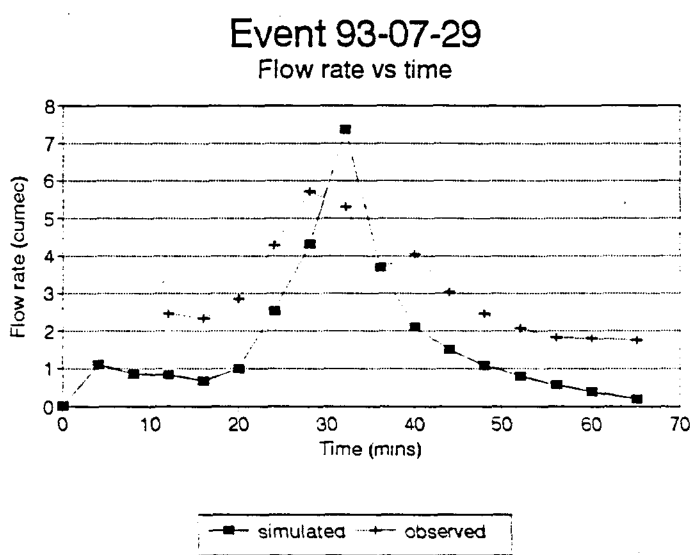


Figure 6.8 : Comparison of observed and simulated hydrographs for event 93-07-29

For the other events for which reasonable hydrographs had been recorded, the simulated and observed runoff volumes are compared in figure 6.9 by means of the histogram of the ratio of the simulated to observed runoff volumes.

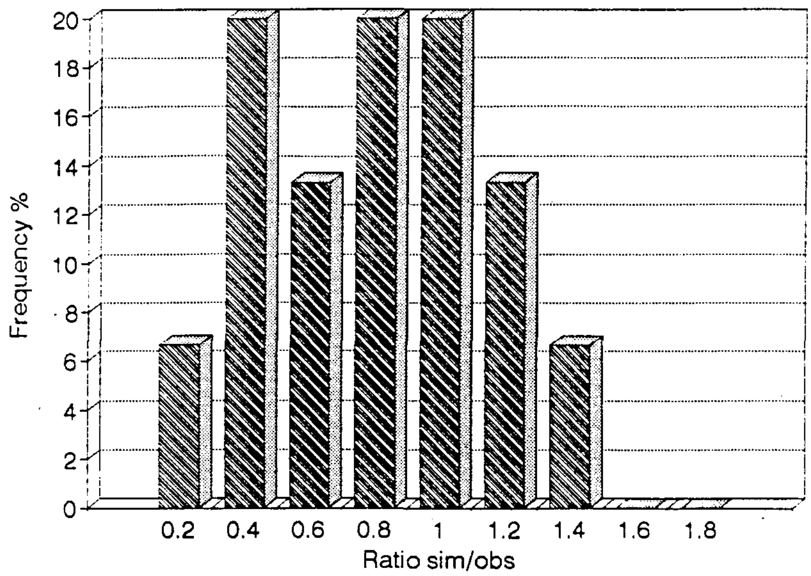


Figure 6.9 : Histogram of ratio of simulated to observed volume

The histogram shows clearly that the model tends to under predict the runoff volumes. Recalibration was attempted but the resulting parameters were well out of the expected range of values. The under prediction could quite easily be due to the spatial distribution of the rainfall over the catchment. A single raingauge located at the lower end of the catchment was used as input to the model. The model does not include cyclical changes in vegetation growth nor was the possible increase in impervious area due to the continued urbanization of the catchment considered during the modelling exercise.

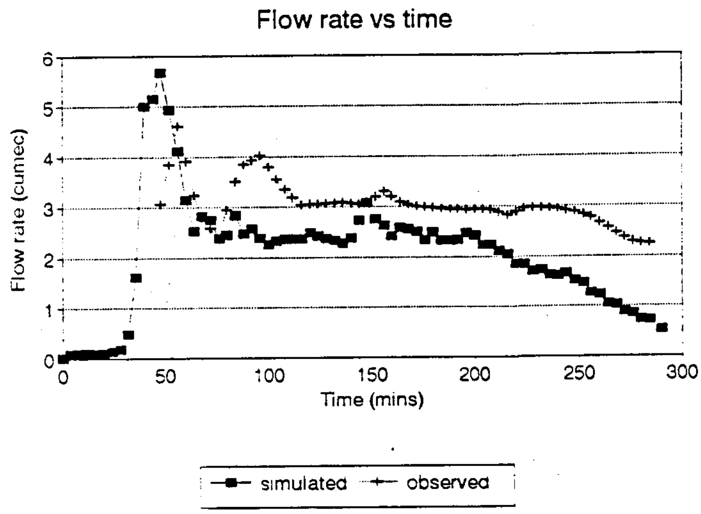
6.4 SUSPENDED SOLIDS MODELLING

For the quality model, 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 silt loam soil was estimated from the USDA soil texture diagram

(Holden, 1993) to be 60% sand, 30% silt, and 10% clay. A fine and a coarse particle size class of 0,064 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 respectively 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 0,001 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.

The simulated pollutographs resulting from the application of the SS model to the 6 events are compared to the observed pollutographs in figures 6.10 to 6.15. The hydrograph has been included for comparison purposes.



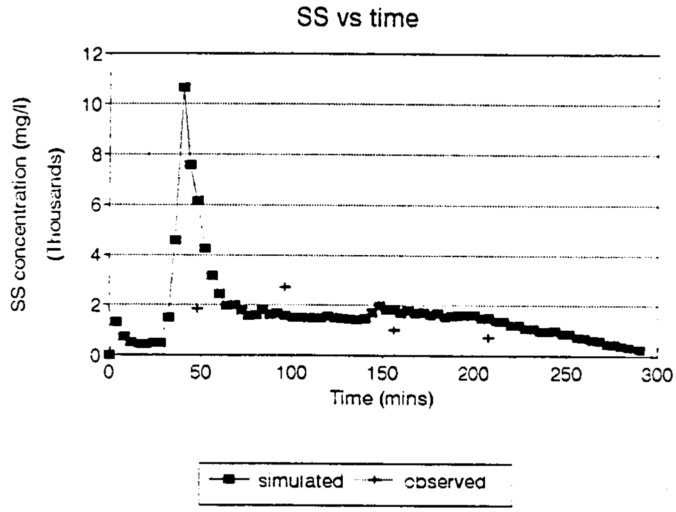


Figure 6.10 : Comparison of simulated and observed SS pollutographs for event 92-01-01

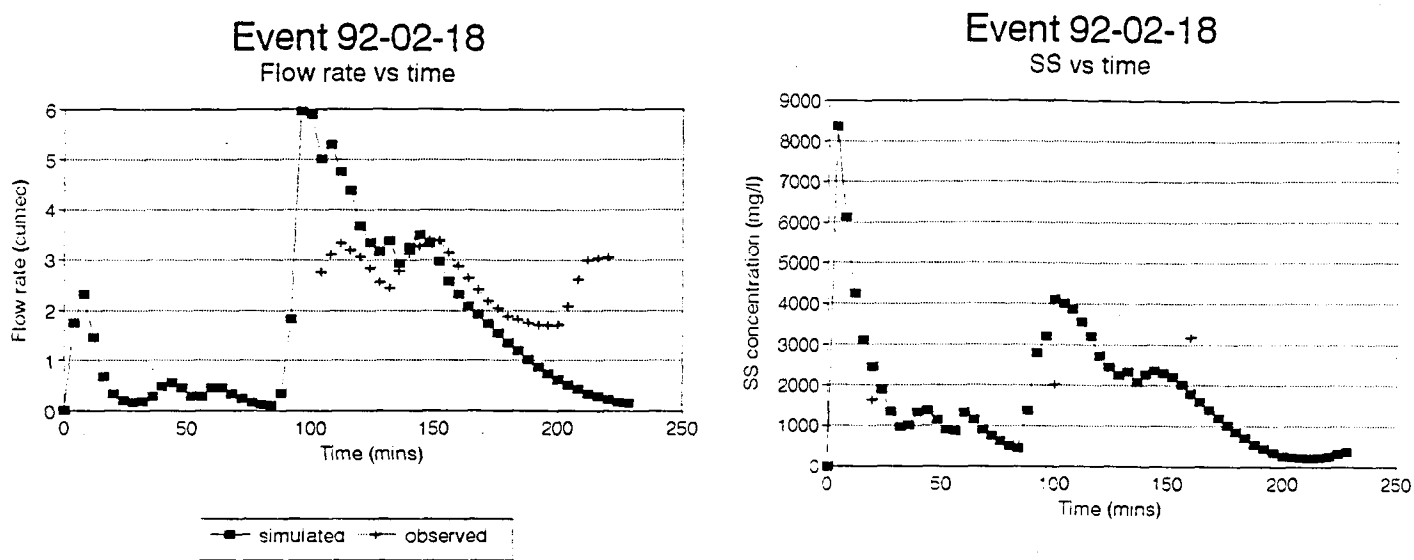


Figure 6.11 : Comparison of simulated and observed SS pollutographs for event 92-02-18

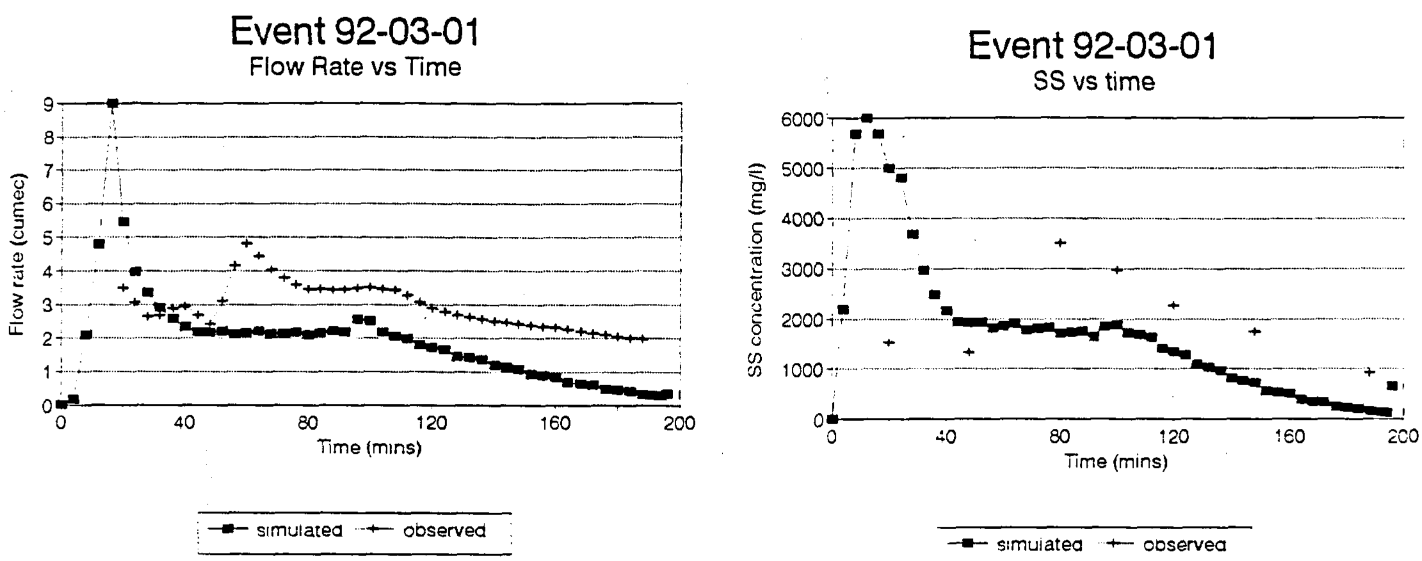


Figure 6.12 : Comparison of simulated and observed SS pollutographs for event 92-03-01

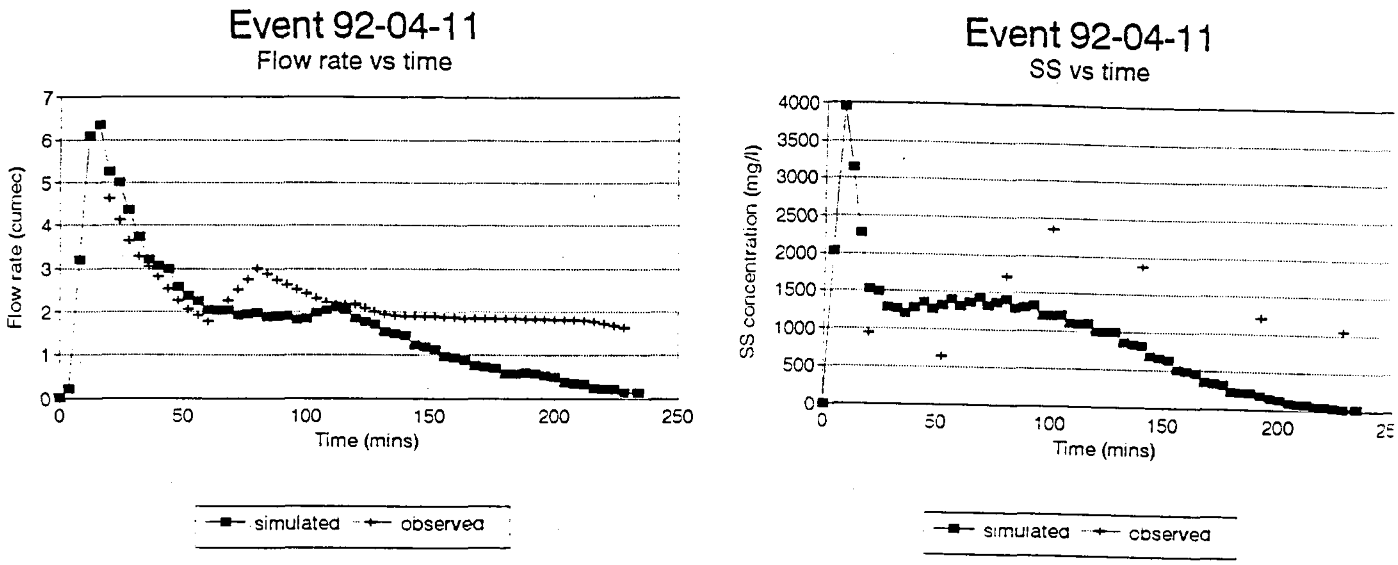


Figure 6.13 : Comparison of simulated and observed SS pollutographs for event 92-04-11

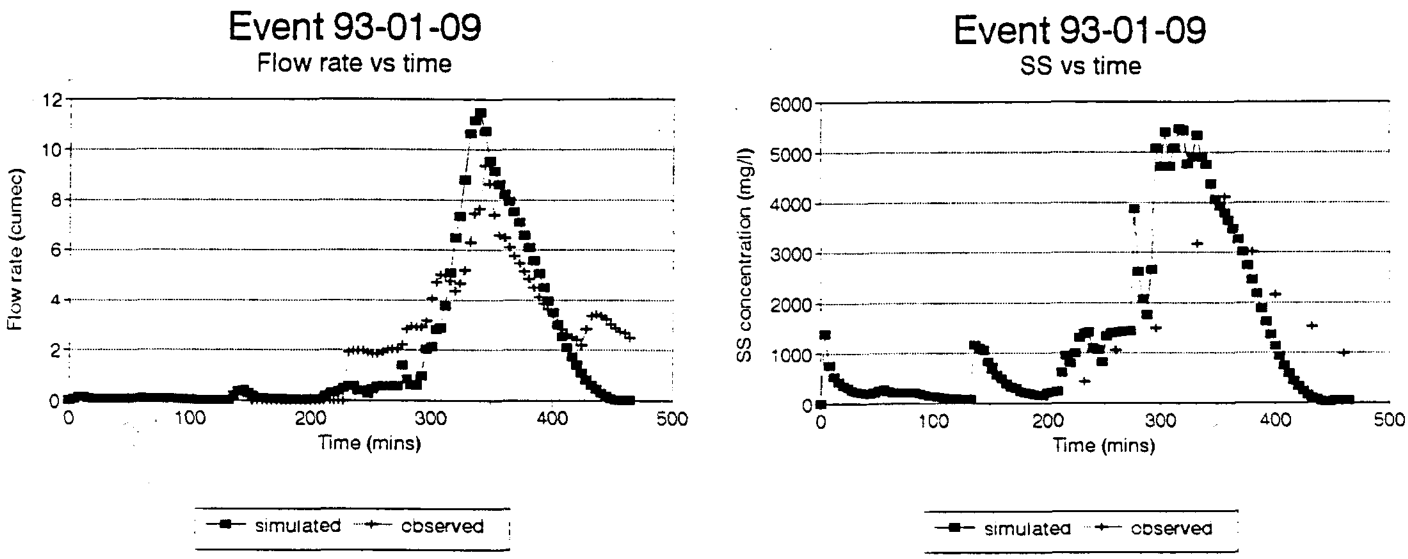
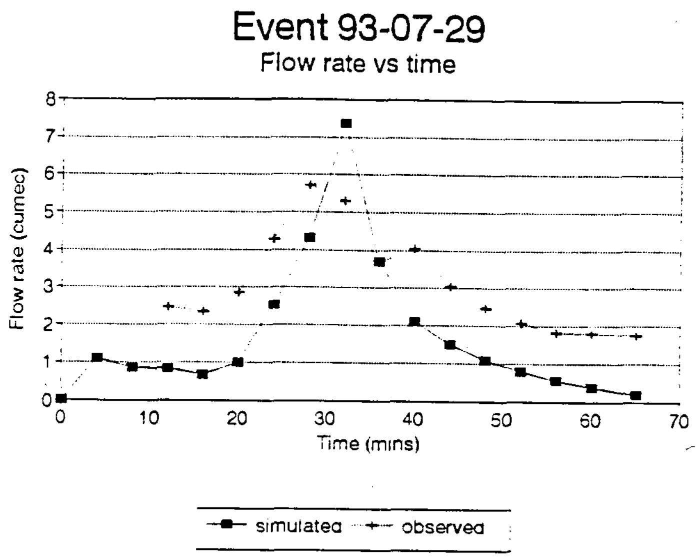


Figure 6.14 : Comparison of simulated and observed SS pollutographs for event 93-01-09



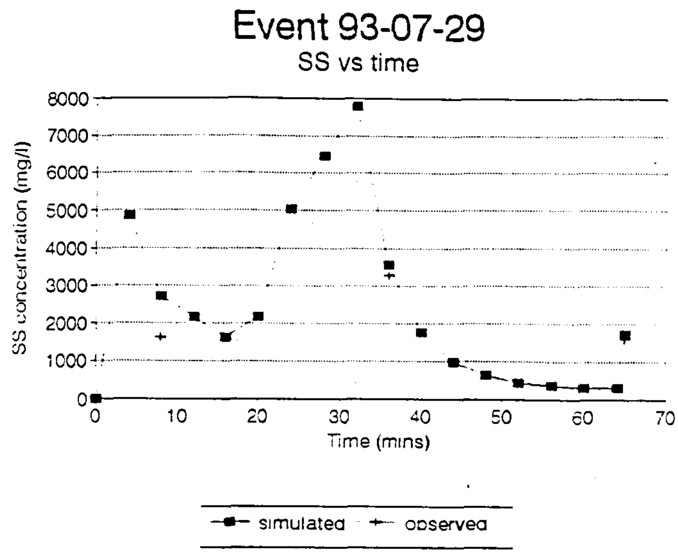


Figure 6.15 : Comparison of simulated and observed SS pollutographs for event 93-07-29

The simulated SS pollutographs were generally peakier than the observed. This generally occurred when the rainfall intensities were high and the rainfall detachment was greatest. This effect was increased when the high rainfall intensities occurred at the beginning of an event and the detached material was entrained into the shallow flow depths which resulted in high concentrations. The introduction of the exponent of the rainfall detachment function as a variable allowing for values less than 2 may well smooth the response achieved by the model.

Most of the events monitored including those for which composite samples were taken, can be used to test the model by comparing simulated and observed SS loads. The model was run for all the events and the simulated and observed SS loads were compared using a histogram of the ratio of the simulated to observed loads (Figure 6.16). This figure shows that the model generally over predicts the SS load largely due to the peakier simulated pollutograph.

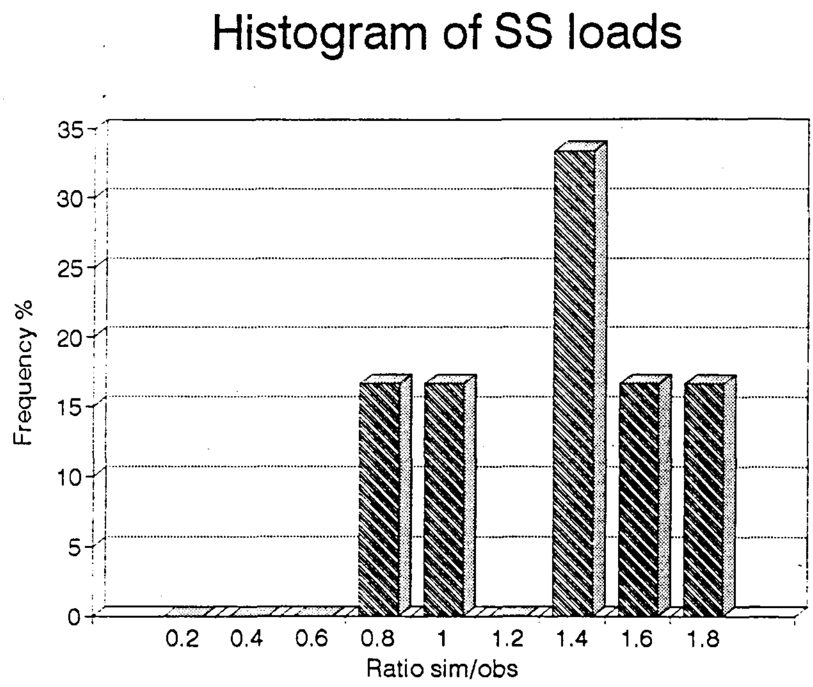


Figure 6.16 : Histogram of ratio of simulated to observed SS loads

6.5 PHOSPHORUS MODELLING

Both the particulate and dissolved forms of phosphorus (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 parameters required for the application of the model are the fraction of the particulate mass on the impervious and pervious surfaces that is P, and a partition coefficient relating the dissolved to the particulate P mass.

The P fraction of the catchment surface particulates depends on the nature of the material deposited. Based on the study of Grobler et al (1987) on the informal settlements of Botshabelo, a large source of phosphorus deposited on the catchment surfaces is faeces, urine and detergents/soaps. Typical fractions of P for muncipal sewage is .022 (g P/g SS) (Ekama et al, 1984) and .08 (g P/g SS) for detergents (Grobler et al, 1987). Another source of P would be vegetation deposited on the catchment surfaces, a typical P content could be about 0.0018 (g P/g solids). This is an average value given for leaves by Prasad et al (1980). The organic content of the surface stores was not specifically measured during the study. Using a 10% organic content and a P fraction of 0.02 of the organic fraction, will give a P fraction of 0.002 for the total particulate mass. This fraction however had to be lowered during calibraton to a value of 0.0015. This value was not changed throughout the simulation period.

The partition coefficient of the equilibrium isotherm depends on numerous factors such as soil types, pH, temperature, chemicals present, and biological activity. Goldberg and Sposito (1984) give plots of adsorption isotherms of phosphate for different soils. A typical value for the partition coefficient was shown to be 4. This value was initially used in the model but later reduced to 3. The entrainment coefficient E for the pickup of pollutants from the porewater was taken as 0,001.

The results for both the dissolved and particulate forms of P for the 6 events modelled are shown in figures 6.17 to 6.22. As the simulated SS concentrations were used as input to the particulate P model, the particulate P pollutographs mimicked the high peaks of the SS pollutographs. These peaks were not present in the observed particulate P pollutographs. Nonetheless the use of a simple fraction that was held constant for all the events produced reasonable matches between the observed and simulated particulate P pollutographs. The simulated dissolved P pollutographs reproduced the trend in the observed pollutographs of an increasing concentration on the recession limb of the hydrograph. However for the larger rain storms of the events of 93-01-09 and 93-07-29 the dissolved P pollutographs were somewhat lower than the observed at the beginning of the runoff event. For these events the entrainment of SS was probably higher at the

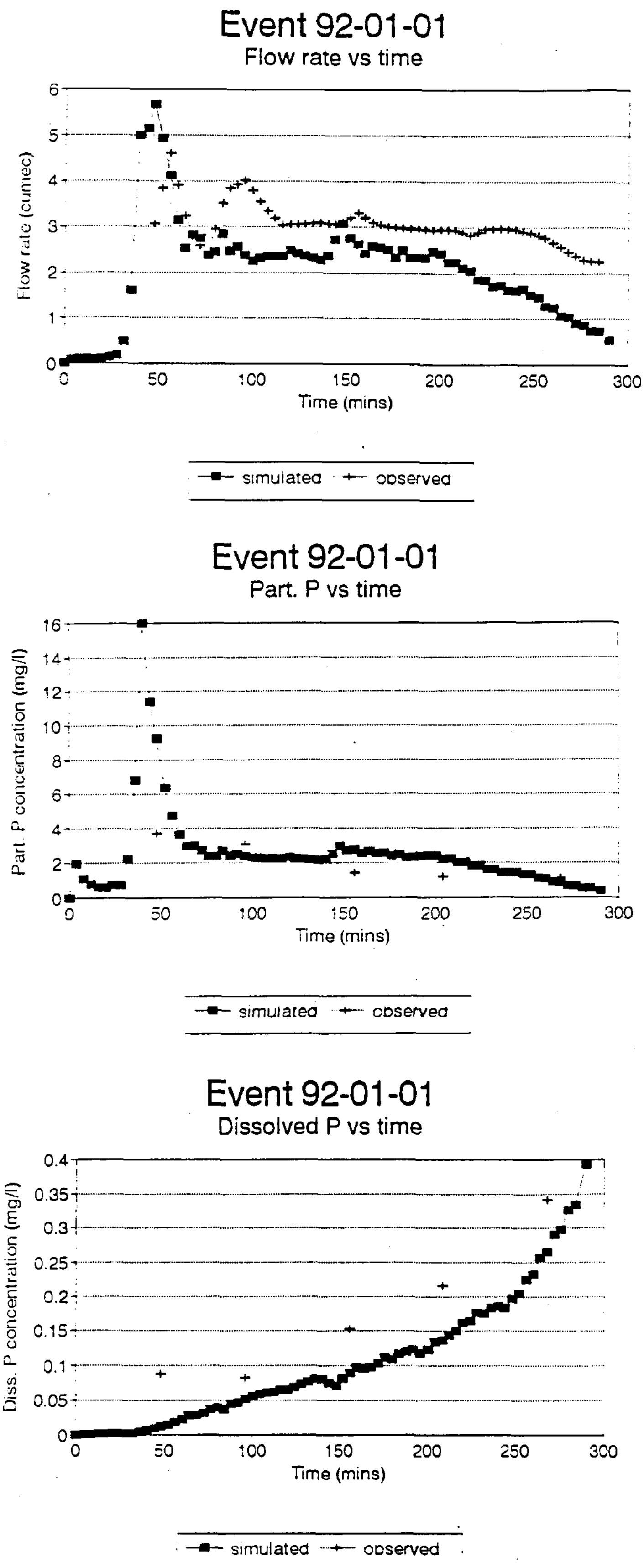


Figure 6.17 : Comparison of observed and simulated particulate and dissolved P for event 92-01-01

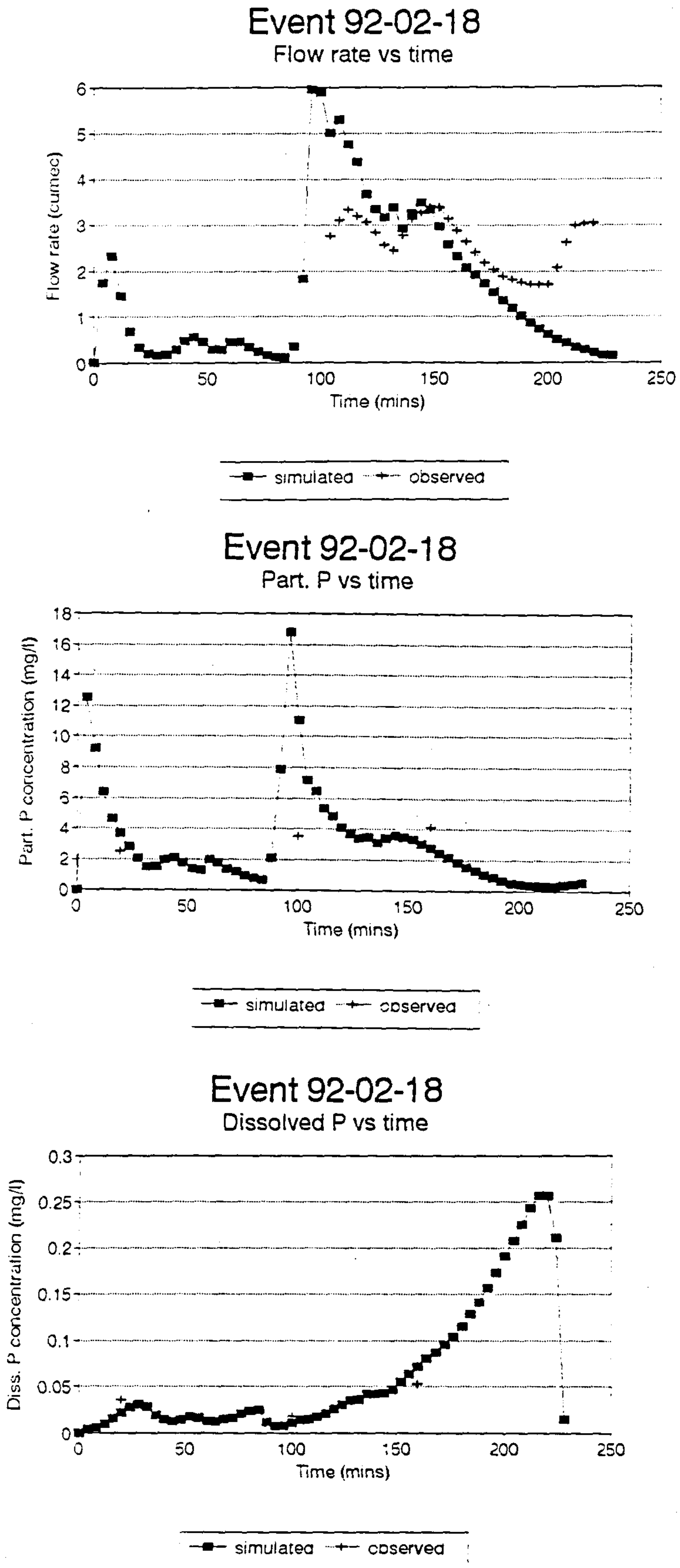


Figure 6.18 : Comparison of observed and simulated particulate and dissolved P for event 92-02-18

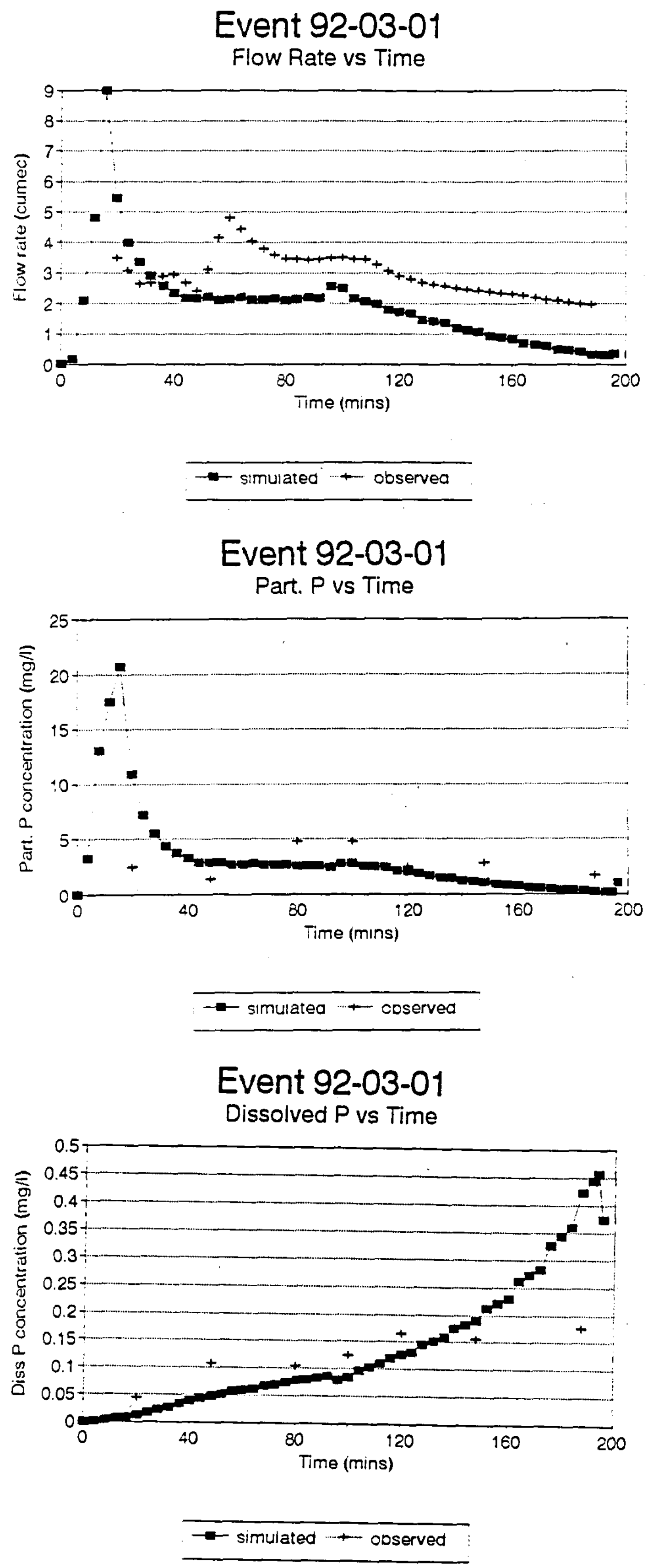
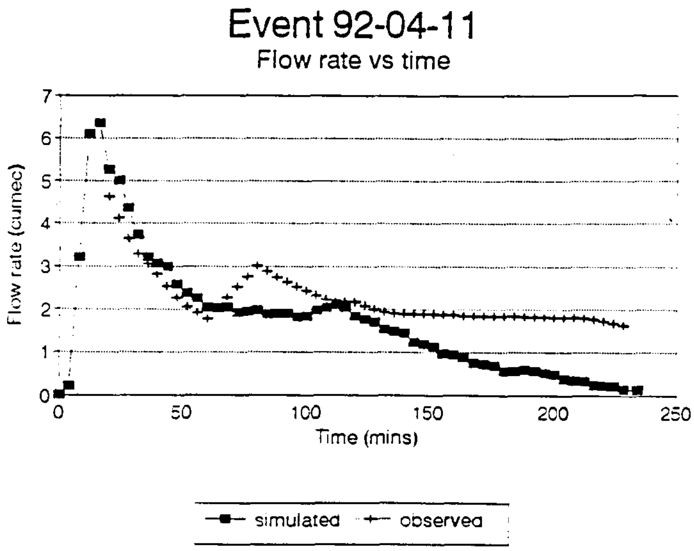
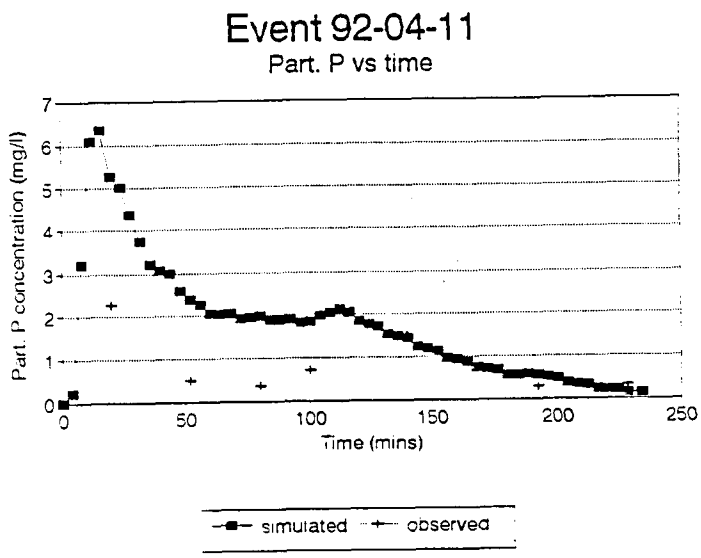


Figure 6.19 : Comparison of observed and simulated particulate and dissolved P for event 92-03-01





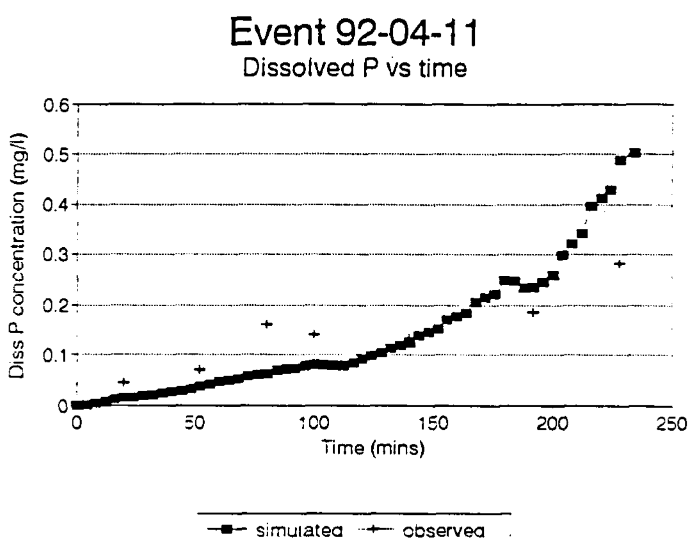


Figure 6.20 : Comparison of observed and simulated particulate and dissolved P for event 92-04-11

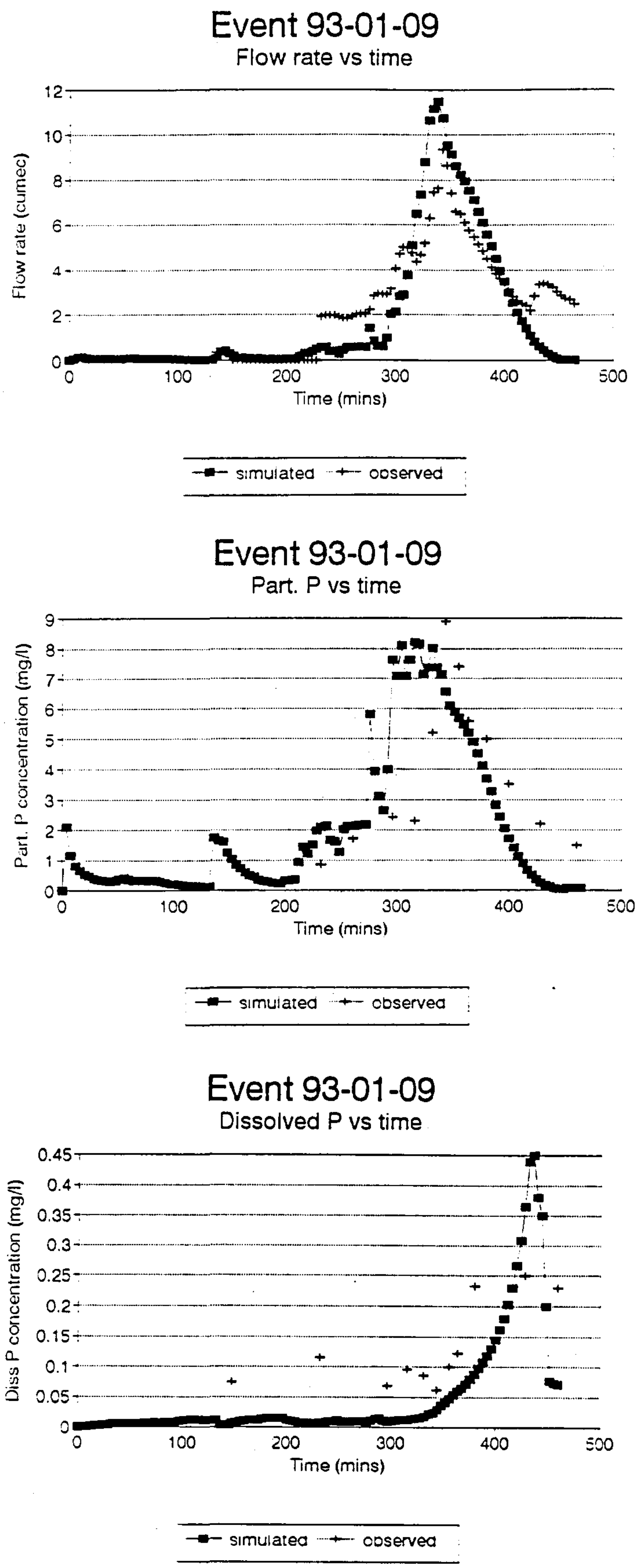


Figure 6.21 : Comparison of observed and simulated particulate and dissolved P for event 93-01-09

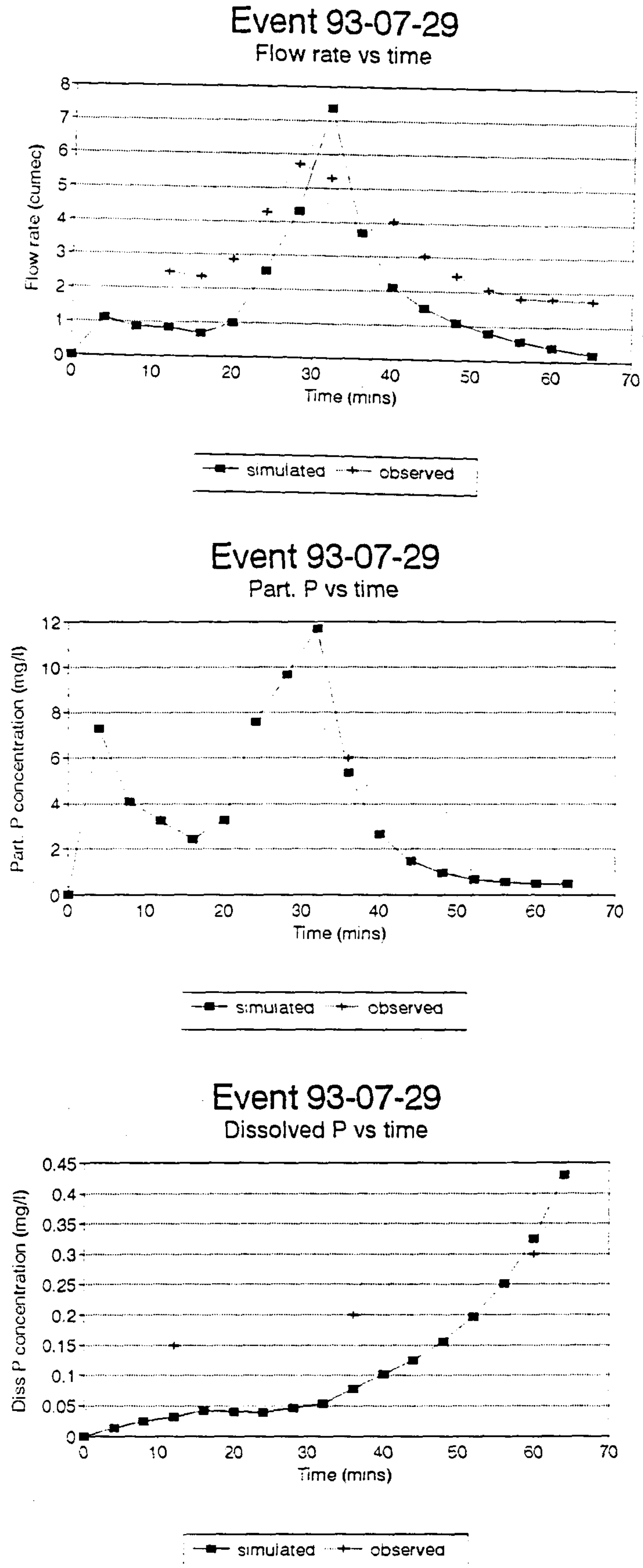


Figure 6.22 : Comparison of observed and simulated particulate and dissolved P for event 93-07-29

at the beginning of the events which could have resulted in the entrainment of particulate forms of the pollutants which would have dissolved while being transported from the catchment.

Frequency histograms of the ratio of the simulated particulate and dissolved P loads to the observed values are shown plotted in Figures 6.23 and 6.24. These diagrams show that the particulate P model like the SS model overpredicted the loads while the dissolved P model generally under predicted the P load.

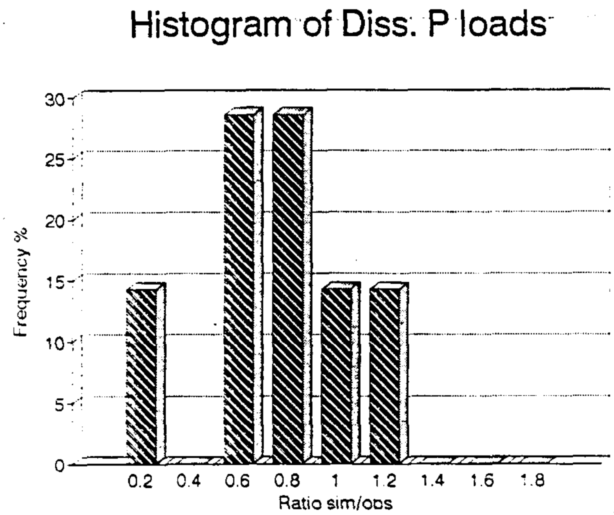


Figure 6.23 : Histogram of the ratio of simulated to observed dissolved P loads

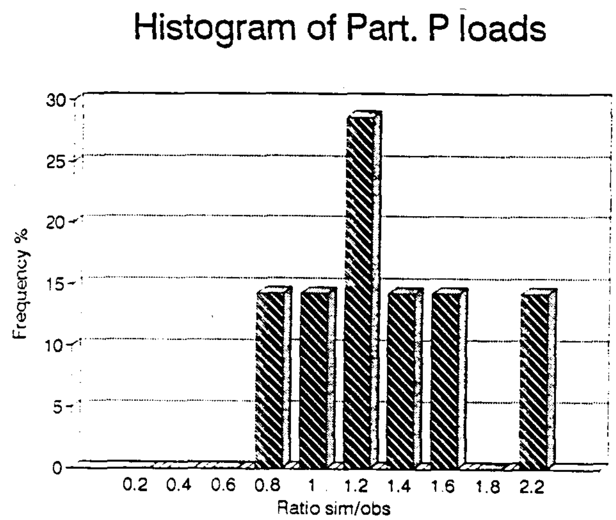


Figure 6.24 : Histogram of the ratio of simulated to observed particulate P loads

6.6 MODELLING OF TDS

The dissolved model was applied to the modelling of the TDS from the catchment for the 6 events. The same entrainment parameter as was used for the modelling of dissolved P was tried in the initial model runs. However this was found to be too high and the parameter was reduced to 0.0005 to get reasonable calibrations. Again the parameter was kept unchanged for all events. The start concentration in the soil was diffficult to assess. A concentration of 850 g/m^3 was used as the initial soil concentration for all the events. TDS was assumed to be conservative and the partition coefficient was set to 0. The initial TDS mass on the impervious areas was taken as 10 g/m^2 with an entrainment coefficient of 0,1 which is in the same range as the coefficient obtained by Akan (1987) for the washoff of sodium chloride from impervious surfaces using the data obtained by Nakamura (1984) from rainfall simulation studies.

The results are presented in figures 6.25 to 6.30. Similar results to the modelling of dissolved P were achieved with the model following the upward concentration trend on the recession limb of the hydrograph. Similar results for the larger runoff events of the 93-01-09 and 93-07-29 were also obtained for TDS. The model was unable to simulate the higher concentrations at the beginning of the hydrographs. A histogram showing the distribution of the ratio of the simulated and observed TDS loads is presented in figure 6.31.

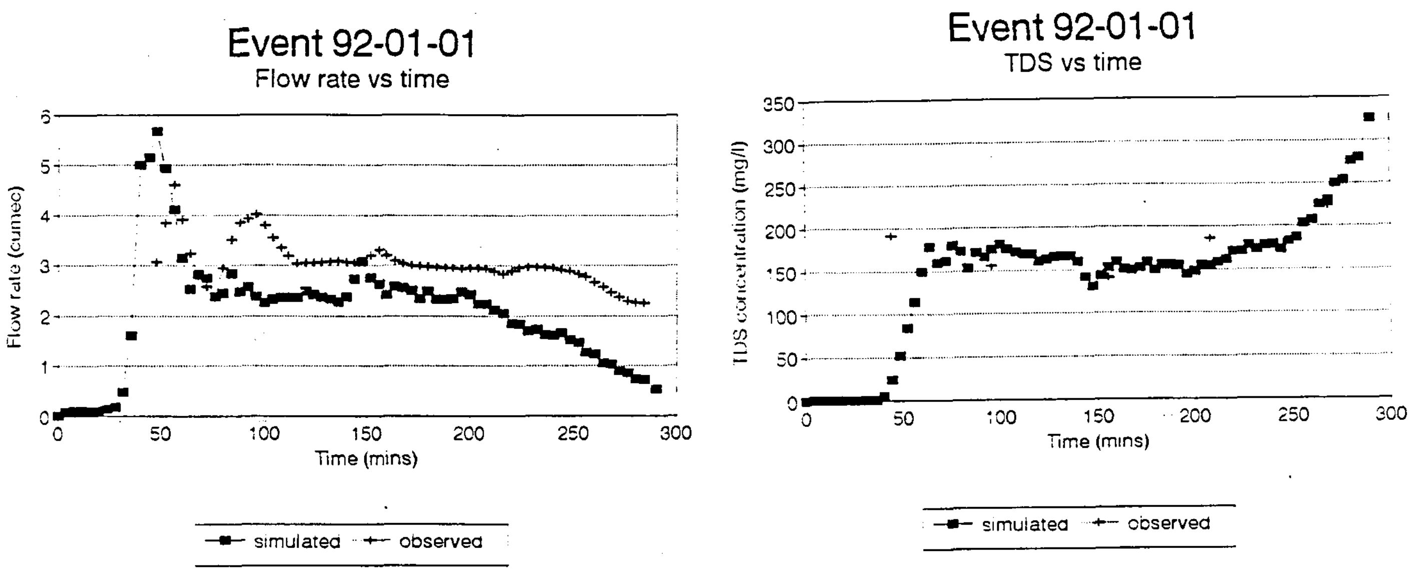


Figure 6.25 : Comparison of simulated and observed TDS pollutographs for event 92-01-01

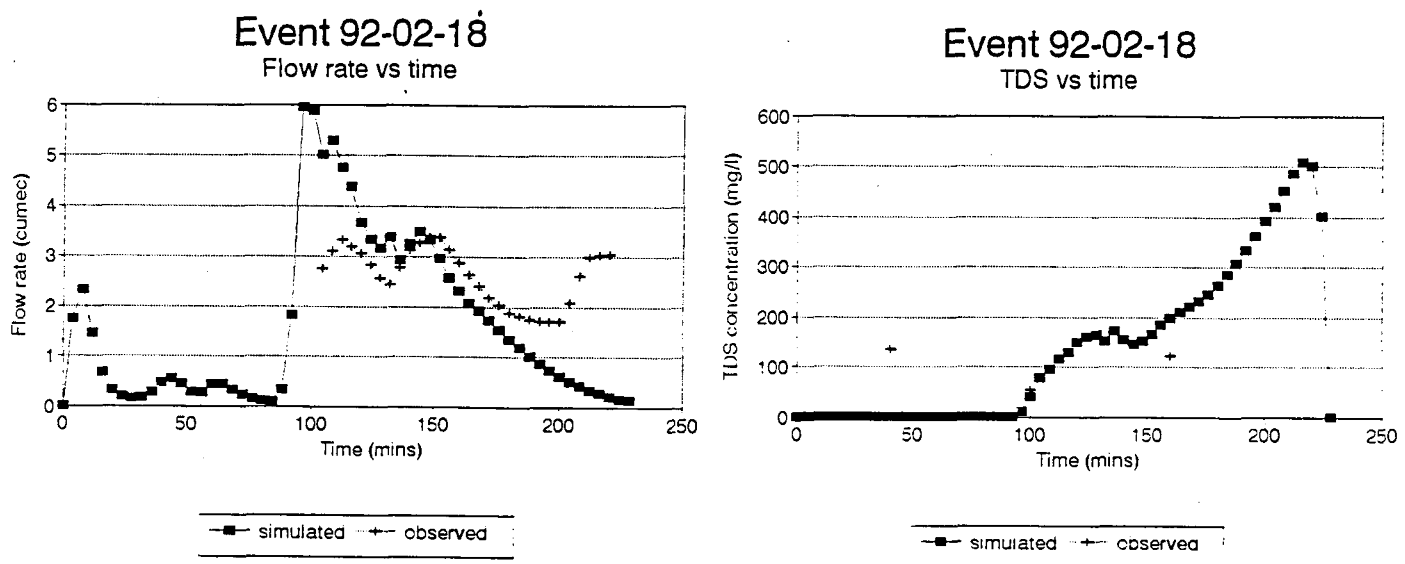


Figure 6.26 : Comparison of simulated and observed TDS pollutographs for event 92-02-18

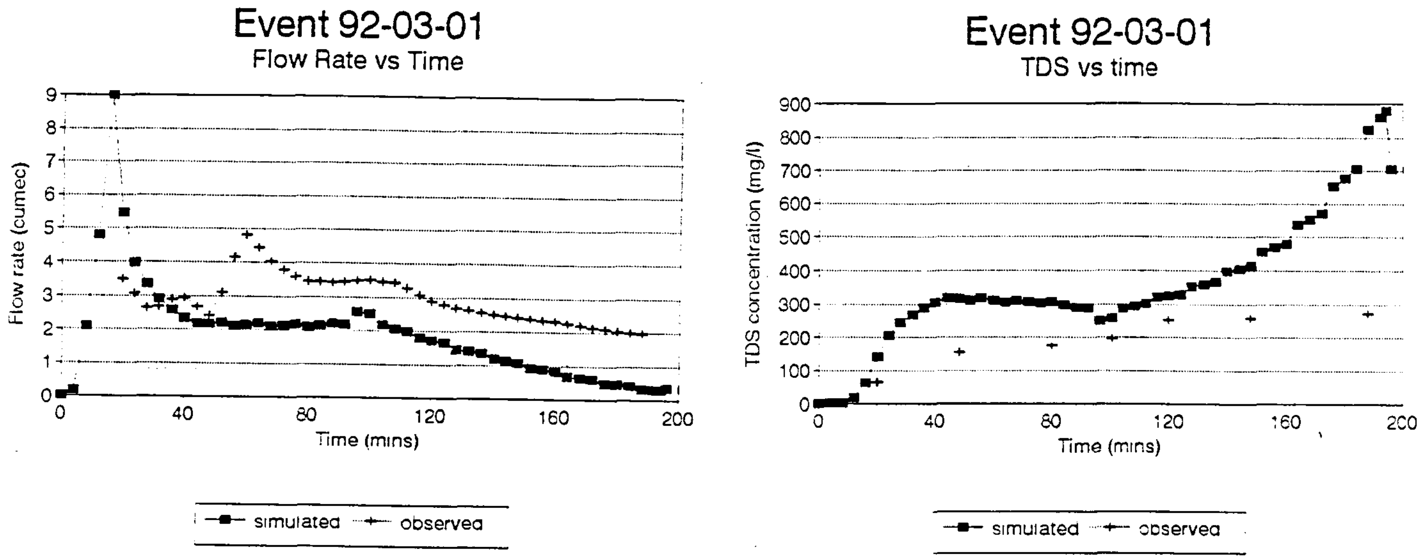


Figure 6.27 : Comparison of simulated and observed TDS pollutographs for event 92-03-01

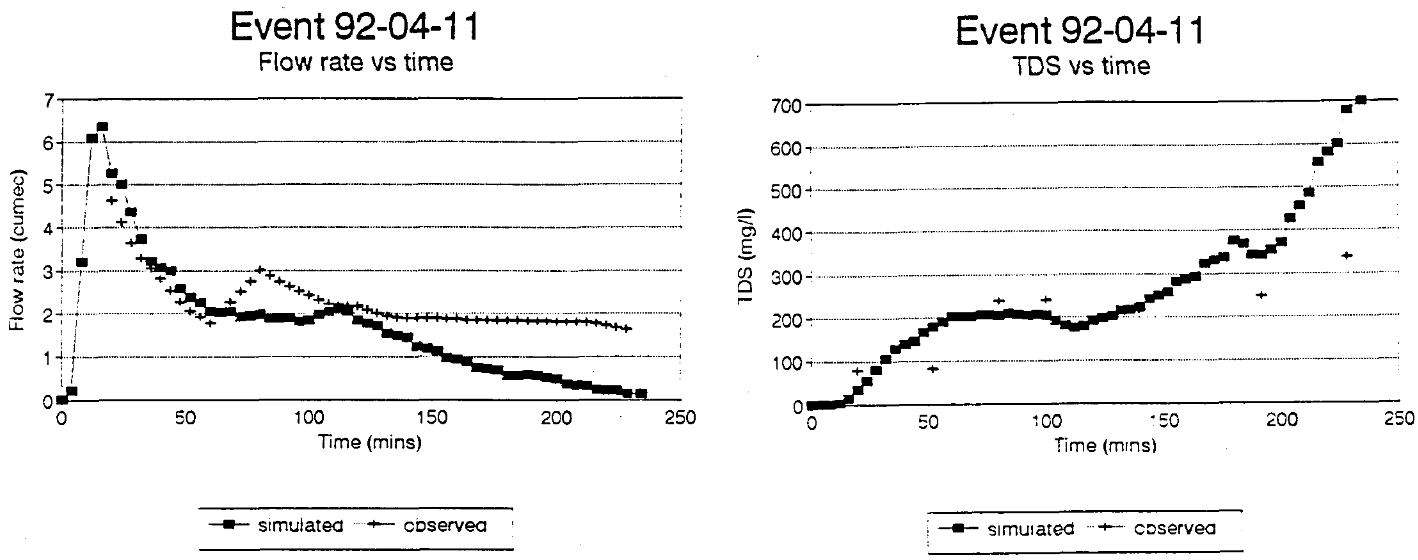


Figure 6.28 : Comparison of simulated and observed TDS pollutographs for event 92-04-11

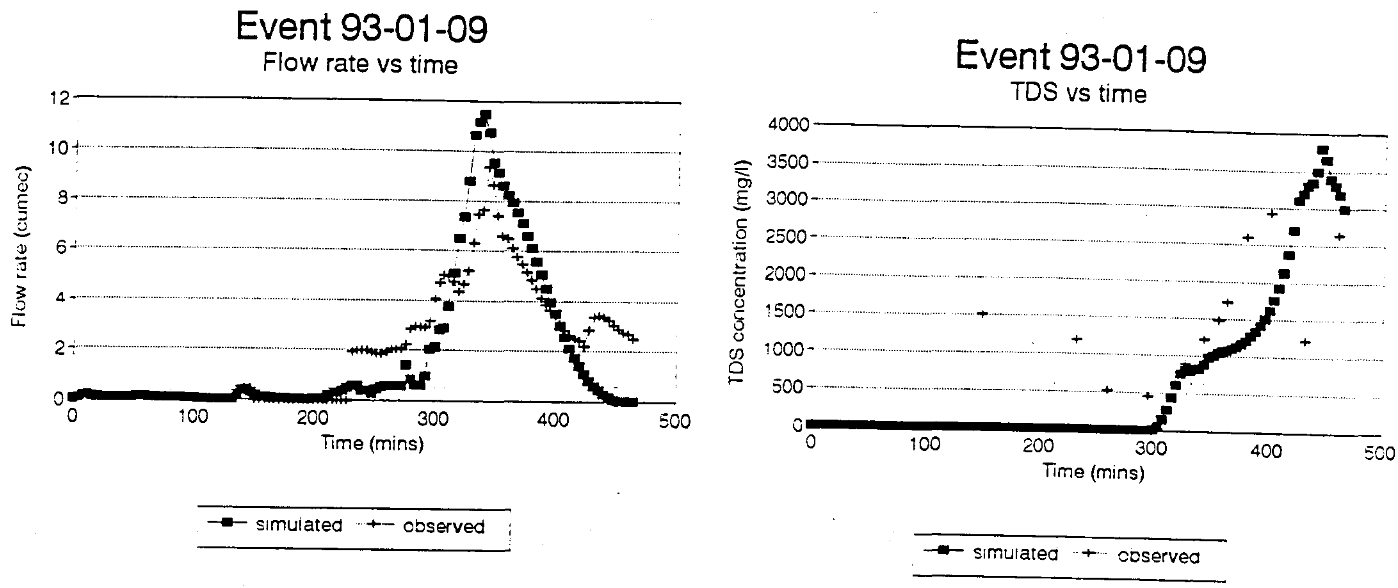


Figure 6.29 : Comparison of simulated and observed TDS pollutographs for event 93-01-09

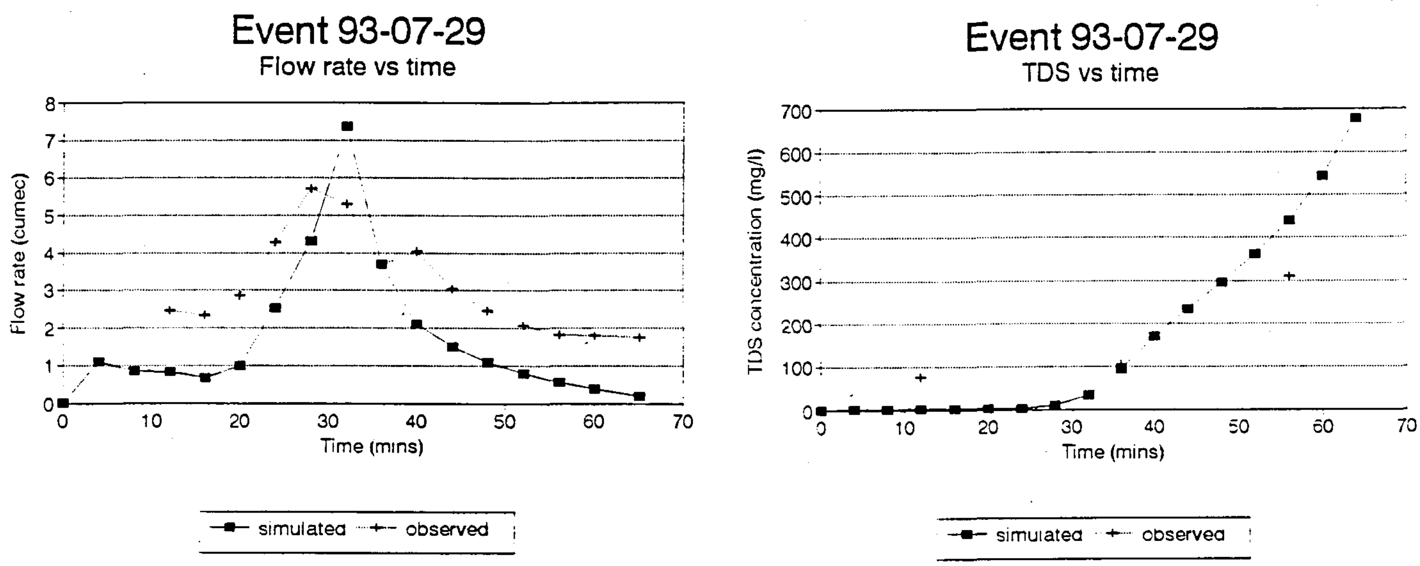


Figure 6.30 : Comparison of simulated and observed TDS pollutographs for event 93-07-29

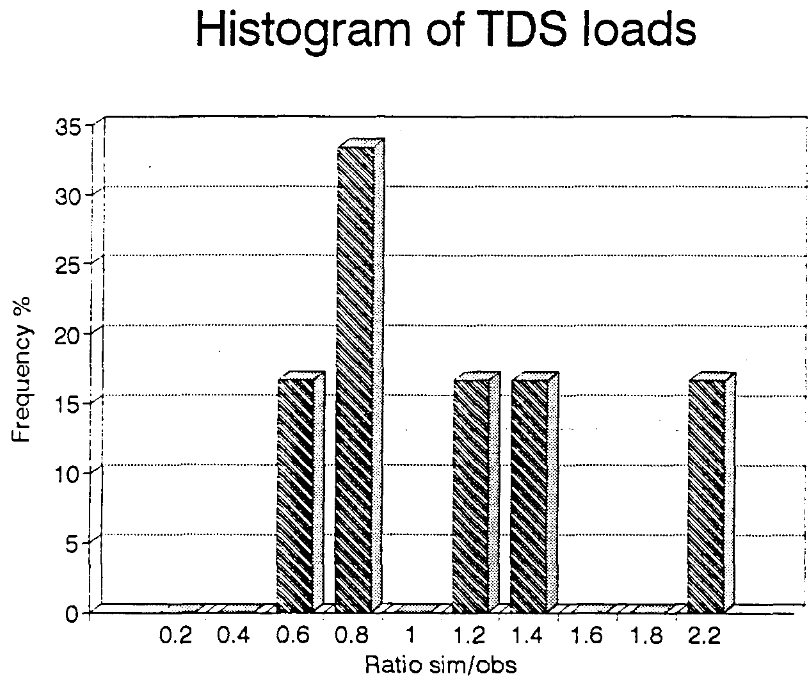


Figure 6.31 : Histogram of ratio of simulated to observed TDS loads

CHAPTER 7 SUMMARY AND CONCLUSIONS

The monitoring of the Shembe and Amanzimnyama catchments showed that both their dry weather and storm flows exceeded the special and general effluent standards and aquatic quality criteria for ammonia, heavy metals, E-coli, SS, and COD. The impacts that these pollutants could have on a receiving water are eutrophication, toxicity, oxygen depletion, and a health hazard. The results for Shembe are similar to the results of other monitoring programs of catchments developed with informal settlements in that the runoff is rich in nutrients, organic matter, and have a poor bacterial quality. The monitoring program certainly indicates that depending on the assimilative capacity of their receiving waters, treatment of the stormwater and dry weather flow from the catchments may be necessary.

The application of the model to the data collected from the Shembe catchment revealed that although algorithms having some physical basis were used in the model, calibration is still required at this stage. The model can only be applied with confidence if some water quality data has been collected for a catchment. The model however may be able to be used if it has been applied to a catchment of similar land-use, climate, and topography. Based on the application of the model to the data collected on the Shembe catchment, the following conclusions can be drawn concerning the abilities of the model:-

1. The model generally over predicted the SS and particulate P loads due to the peaky shapes of the SS pollutographs when compared to the observed ones.
2. The model predicted the rising concentrations of the TDS and dissolved P on the recession limbs of the hydrographs.
3. The model generally under predicted the dissolved P loads.
4. The model was unable for the larger runoff events to model the initial concentrations of TDS and dissolved P.

5. The WITSKM model generally under predicted the runoff volumes.

Despite these shortcomings, the WITQUAL and WITSKM models were able to achieve hydrograph and pollutograph fits that are sufficiently accurate for the examination of "what if" management scenarios. The WITQUAL model was able to achieve this without the use of the pollutant buildup functions operating during the dry periods between the storm events. There always seemed to be sufficient material available for washoff and the pollutographs appeared to be a function of the storm and runoff characteristics rather than the availability of pollutant. This is not unlikely considering the population densities, standards of service, and the informal nature of the settlement. However this hypothesis could not be properly tested as the rainy seasons monitored had rainfall well below the average. If a more average rainfall season were monitored, the catchment may well be flushed clean over the rainy season. The problem found in applying the model was the estimation of the soil and impervious area pollutant concentrations and masses. This was particularly true for the TDS and dissolved P modelling.

Considering the dynamic nature of the Shembe catchment and the complexities of 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 urban areas. The model can also be used to estimate pollutant loads from urban areas for input to receiving water quality models. The output will be particularly useful for the examination of "What If" scenarios in the planning of stormwater management systems and the provision of input for the assessment of receiving water impacts.

In terms of the study objectives, a set of computer programmes have been developed that can model flow, dissolved and particulate pollutant forms as well as suspended solids on a continuous basis using rainfall and catchment parameters. The suite of programs has the ability to model the "best management practices" of detention/retention storage, diversion structures, and the effects of infiltration on the removal of pollutants from urban runoff. The model was tested on the data collected from the Shembe catchment. Although data was collected on the Amanzimnyama catchment, it was not used to test the model. This was due to the influence that the industrial discharges and groundwater inflow into the channel had on the water quality. In addition the development of a benthic layer on the canal bed would influence the water quality. The water quality model does not have the ability to model these influences. Nonetheless the data collected on the Amanzimnyama catchment has provided useful information on the pollutant loads and concentrations that can be expected from an industrial/commercial catchment.

CHAPTER 8 RECOMMENDATIONS

The following aspects should be considered for further research if the model is to be further developed:-

1. To improve and verify the model algorithms, studies of the buildup and pollutant changes on the catchment surfaces will have to be undertaken. Preferably buildup should be related to catchment land-use activities such as population and vehicle densities, and the level of services and service maintenance.
2. Consideration should be given to expanding the management options by adding wetland, oxidation pond, and engineering treatment modules to the dams and diversion structures included at this stage.
3. The model should be applied to different land-use catchments to assess the transferability of the model parameters and the hypothesis that there is always sufficient material available on the catchment for entrainment.
4. The trapping mechanisms of SS and the associated pollutants by vegetation and gabion lined channels has not been well researched and should be further investigated.

This research, together with the results of other monitoring programs, has shown that urban runoff pollution is at levels that can have impacts on the receiving water bodies such that the original use envisaged for the water bodies are seriously affected. Many water bodies, particularly below informal settlements, are in fact a health hazard. The environmental impact of the runoff from urban developments, both future and existing, should be assessed in a similar fashion to that required of the mining industry. Environmental Management Programs (EMP) should be a legal necessity for urban developments. The WITQUAL and WITSKM programs will be an essential element of formulating EMP documents and providing strategies for the management of urban runoff.

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APPENDIX A TECHNICAL DESCRIPTION OF QUALITY MODEL

A.1 INTRODUCTION

In this appendix, the numerical framework for the model is presented together with the algorithms used to describe the various processes that have been included in the model. The entrainment/deposition, biochemical and chemical processes are represented in the numerical framework by source/sink terms. The numerical framework will be presented first based on the general description of the model presented in Chapter 3. The source/sink terms representing the various exchange processes are discussed to complete the description of the quality model.

There are two forms of pollutant which have been included in the model viz a dissolved and a particulate form. There are interchanges between the particulate and dissolved forms both in the surface and soil stores and during transport from the catchment in the surface runoff. In the model only the interchange between the two forms in the soil is considered. The pollutant in the dissolved form in the surface runoff is assumed to be entrained from the pollutant dissolved in the porewater and the particulate form is entrained with the solids. Mass balance equations will be developed for each of the forms.

A.2 NUMERICAL FRAMEWORK

The numerical framework is a series of mass balance or conservation equations accounting for the pollutant inputs and outputs. The primary pollutant is the solids. By assuming that the pollutant store is dry before a storm event and the buildup of pollutants in the surface pollutant stores is in particulate form, the other pollutants including those in dissolved form such as TDS can be expressed as a fraction of the solids. There are two mass balance equations required for each of the pollutant forms viz (1) an equation describing the transport of pollutants in the surface water and (2) the surface pollutant stores and catchment soils.

A.2.1 Pollutant transport in surface waters.

The transport of pollutants in overland flow and through the conduit system requires the selection of a pollutant routing method that is capable of accounting for the entrainment and deposition of pollutants, the possible decay of pollutants, and sources and sinks to account for sorption and dissolution processes. The longitudinal dispersion equation is an equation that is often used to model the one dimensional transport of pollutants (Schoellhamer, 1988 ; McQuivey and Keefer, 1976 ; Thomann, 1973). However in river or flow in upland channels, Thomann (1973) showed that the inclusion of the dispersion term in the routing equation was unnecessary over the lengths and at the typical flow velocities encountered in the streams. The dispersion of pollutants in the overland flow and through the conduits will not be included in the model. The pollutant mass balance equation for use in the model is derived based on the following assumptions.

1. The pollutant concentration is represented by the cross sectional average concentration.
2. The pollutant is completely mixed laterally at right angles to the flow direction
3. The flow can be considered to be one dimensional.
4. The biochemical processes can be modelled using a first order decay process.
5. The pollutant concentrations are sufficiently low that the fluid density can be considered to be that of water.
6. The flow being considered is unsteady non uniform.

A general mass balance equation will be derived. The concentration C can represent the dissolved concentration, or the concentration of a particular size density group of the particulates. Consider the fluid element of length Δx (m) and cross sectional area A (m^2) (Figure A.1). The flow and pollutant concentration through the upstream face are Q (m^3/s) and C (g/m^3) and through the downstream face are $\delta Q+\delta Q\ \Delta x/\delta x$ and $C+\delta C\Delta x/\delta x$ respectively. The mass rate J (g/s) at any cross section is given by QC. Let the pollutant decay coefficient be K(/s), the entrainment and deposition rates be ENT ($g/m^2/s$) and DEP ($g/m^2/s$) respectively, the average cross sectional area and concentration in the element be A and C respectively, and the concentration in the rainfall be C_i (g/m^3), and i (m/s) is the rainfall intensity. A mass balance can be carried out over time interval Δt (s) by considering the inputs and outputs of pollutant mass from the element.

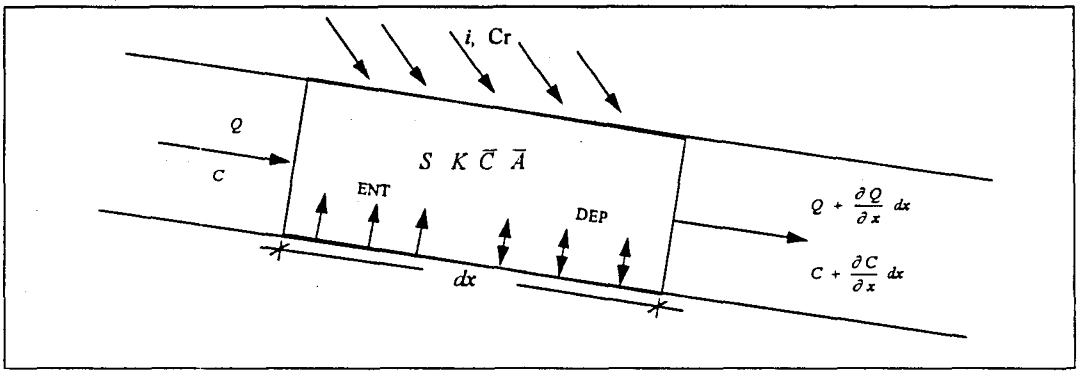

Figure A.1: Pollutant fluxes, sources, and sinks for an element Δx long.

Pollutant inputs

$$QC\Delta t + ENT\Delta x\Delta tP + TiC_i\Delta x\Delta t \qquad \text{A.1}$$

Pollutant outputs

$$(Q+\frac{\partial Q}{\partial x}\Delta x)\,(C+\frac{\partial C}{\partial x}\Delta x)\,\Delta t+k\overline{CA}\Delta x\Delta t+DEP\Delta xP\Delta t \qquad \text{A.2}$$

Simplifying gives

$$\frac{\partial(QC)}{\partial x}\Delta x\Delta t+k\overline{C}\overline{A}\Delta x\Delta t+DEP\Delta x\Delta tP \qquad \text{A.3}$$

where P (m) is a representative wetted perimeter for entrainment and deposition and T (m) is the flow top width. The mass in the element at time t is given by

$$(\overline{A}\,\overline{C}\,\Delta x)_t \qquad \text{A.4}$$

and at t+Δt is

$$(\overline{C}\overline{A}\Delta x)_{t+\Delta t} \qquad \text{A.5}$$

Summing the inputs and outputs, dividing through by Δx and Δt, and taking limits as Δt tends to 0, gives

$$\frac{\partial(AC)}{\partial t}+\frac{\partial(QC)}{\partial x} = P(ENT-DEP) - KCA + TiC_i \qquad \text{A.6}$$

Similar equations are used by Koussis (1983), Ingram and Woolhiser (1980), and Cunge et al (1980) for modelling pollutant transport. For overland flow, the wetted perimeter can be taken as the width of the catchment W (m). By expanding the partial derivatives and dividing through by A the following equation results

$$\frac{\partial C}{\partial t}+U\frac{\partial C}{\partial x} = \frac{P}{A}(ENT-DEP)+S-KC-\frac{C}{A}\left(\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}\right)+\frac{TiC_i}{A} \qquad \text{A.7}$$

where U (m/s) is the average velocity for the cross section. For an overland flow plane, the continuity equation for the conservation of water mass is

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t} = W(i-f) \qquad \text{A.8}$$

and for a conduit

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \qquad \text{A.9}$$

where i (m/s) and f (m/s) are the rainfall and infiltration rates respectively. Substituting into the above equations gives for an overland flow plane

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = \frac{W}{A}(ENT-DEP) - \frac{WC}{A}(i-f) - KC + \frac{W}{A}iC_i \qquad \text{A.10}$$

and for a conduit, ignoring the pollutant contribution by rainfall

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = \frac{P}{A}(ENT-DEP) - KC \qquad \text{A.11}$$

The above partial differential equations only have analytical solutions for simple cases (Li, 1972) and have to be solved numerically.

The mass balance equation derived above can be used to describe the movement of pollutants in dissolved or particulate form. The particulate form of a particular pollutant is expressed as a fraction of the solids concentration. The concentration C in the above equations can be replaced by $f_{rp,k}C_{rs,k}$ where $C_{rs,k}$ is the concentration of the solids in runoff in size density group k and $f_{rp,k}$ (g/g) is the fraction of the solids concentration in size density group k that is the particulate form of the pollutant of interest in the surface runoff.

A.2.2 Surface pollutant store and the soil

Pollutants are built up on the catchment surfaces during the periods between storm events. These pollutants are assumed to be in particulate form and will form a layer of particulate material on the catchment soils and the impervious surfaces. These deposited pollutants will mix to a certain extent with the catchment soils to form a layer of available material for entrainment and transport from the catchment surfaces.

Let $M_{s,k}$ (g/m^2) be the mass of available particulate material in size density group k per unit catchment surface area, then the mass balance equation for the particulates in size density group k is given by

$$\frac{d}{dt}M_{s,k} = Det_{s,k} - Ent_{s,k} \qquad \text{A.12}$$

where $Det_{s,k}$ ($g/m^2/s$) is the detachment of the catchment soils by raindrops and flow during runoff and $Ent_{s,k}$ ($g/m^2/s$) is the rate of entrainment of particulates in size density group k into the surface flow. For the particulate form of a pollutant, the mass balance equation can be written as

$$\frac{d}{dt}(f_{sp,k}M_{s,k}) = f_{dp,k}Det_{s,k} - f_{sp,k}Ent_{s,k} - S_{ad}\Delta z \qquad \text{A.13}$$

where $f_{sp,k}$ and $f_{dp,k}$ (g/g) are ratios of the mass of the particulate form of the pollutant in size density fraction k to the mass of particulates in size density group k. $f_{sp,k}$ applies to the mass of available particulate material and $f_{dp,k}$ to the mass of material detached from the soil mass and added to the mass of available material. S_{ad} ($g/m^3/s$) is a source/sink term representing the exchange between the dissolved and particulate forms of the pollutant and Δz is an elemental depth of the soil or pollutant store.

The mass of pollutant in dissolved form in the soil or the detached mass on the catchment surface is given by the product of the moisture content θ and the concentration of the dissolved pollutant in the porewater C_{sd} (g/m^3). The movement of pollutant through the soil is only considered in the vertical or z direction. The origin of the z axis is taken at the surface with the positive direction down into the soil. By taking a mass balance around a soil element of unit area and Δz deep, the following equation can be derived

$$\frac{\partial(\theta C_{sd})}{\partial t} + \frac{\partial(q C_{sd})}{\partial z} - D\theta\frac{\partial^2 C_{sd}}{\partial z^2} = S_{ad} \qquad \text{A.14}$$

where D (m^2/s) is the diffusion coefficient assumed to be constant and q (m/s) is the flux of soil water. For the surface pollutant stores, q will be the infiltration rate. The above 2 equations can be added to give a single mass balance equation for both forms of the pollutant. In equation A.15 the mass of particulates per unit surface area in size density group k is replaced by ρ_b Δz where ρ_b (g/m^3) is the bulk density of the soil and $f_{s,k}$ is the fraction of the particulate mass that is in size density group k. Dividing through by Δz gives equation A.15.

$$\frac{\partial(f_{sp,k}\rho_b f_{s,k})}{\partial t} + \frac{\partial(\theta C_{sd})}{\partial t} + \frac{\partial(q C_{sd})}{\partial z} - D\theta\frac{\partial^2 C_{sd}}{\partial z^2} = \frac{f_{dp,k}Det_{s,k}}{\Delta z} - \frac{f_{sp,k}Ent_{s,}}{\Delta z}$$

A.15

A relationship between the particulate and dissolved form of the pollutant is required to make the above equation useful. Wallach and Shabtai (1992) and Thomann and Mueller (1987) suggest that an equilibrium isotherm describing the sorption processes suffices for a wide range of cases. The linear isotherm is used in the model because of its mathematical simplicity. The linear isotherm has the form

$$\sum_{k=1}^{6} f_{sp,k} = K_d C_{sd} \qquad \text{A.16}$$

where K_d (m^3/g) is the partition coefficient. A value of 0 for the partition coefficient implies no particulate or particulate associated form of the pollutant in the soil i.e a completely soluble and non-adsorbing pollutant.

A.2.3 Pollutant buildup

The buildup of pollutants on the catchment surfaces has been included in models such as SWMM and HSPF. Others such as MOSQITO do not include buildup assuming that there is always sufficient material on the catchment surface for washoff. A buildup algorithm has been included in the model. Buildup is assumed to occur during the periods between the storm events. The buildup is of particulates with the other forms of the pollutants expressed as a fraction of the particulate build up. The sources and pollutant make up of the particulates deposited on the surface are difficult to assess for a catchment. In general buildup is taken as a function of the number of antecedent dry days. The function used is often a linear or power relationship between the number of dry days and the mass of particulates on the catchment surfaces. James and Boregowda (1985) attempted to model all the sources of pollutants such as vehicle emissions, atmospheric deposition, and vegetation during the dry periods between events. The model required a large number of input parameters which included wind speeds and directions. This buildup model was reported to have improved the performance of the SWMM model however no indication was given as to the extent of the improvement.

In the model, a simple buildup function as used in HSPF has been included. The buildup function is as follows

$$\frac{d}{dt} M_{s,k} = M_{bs,k} - K_r M_{s,k} \qquad \text{A.17}$$

where $M_{bs,k}$ (g/m^2/d) is the buildup rate of particulates on the catchment surface in size density group k, K_r (/d) is a removal or decay rate of the pollutants present on the catchment surfaces. The buildup of the mass of a particular pollutant type on the catchment surface is expressed as a fraction of the particulate buildup. The equation will be as follows

$$\frac{d}{dt}(f_{sp,k}M_{s,k}) = f_{bp,k}M_{bs,k} - (K_r + K_{dec})\, f_{sp,k}M_{s,k} \qquad \text{A.18}$$

where $f_{bp,k}$ is the ratio of the pollutant mass to the particulate buildup mass, K_{dec} (/d) is a decay rate for the pollutant in the surface store.

A.3 ENTRAINMENT AND DEPOSITION OF PARTICULATES

The hydraulics of the flow on the catchment surfaces are generally not as well defined as in the conduit system. In urban drainage models very often different methods are used for the entrainment and transport of particulates from the catchment surfaces to those used for the transport of particulates through the conduit system. More empirical approaches such as the exponential decay function (Huber et al, 1982), rating curves (Bath, 1989), entrainment functions (Price and Mance, 1978), and methods based on the USLE are generally used for the pollutant washoff from catchment surfaces. These approaches combine the transport and entrainment processes by generating particulate mass rates at the catchment outlet. Consideration is not given to the ability of the flow to transport the available sediment nor to the characteristics of the particulates. This approach does not allow for the prediction of particle size distributions of the runoff. Models such as that of Li (1979), Foster (1982), and Alley et al (1980) use a more fundamental approach founded in sediment transport theory. These models allow for a prediction of the particle size distribution in the runoff which is necessary for the modelling of removal in detention facilities. However these methods are particularly difficult to apply to impervious areas such as roads and roofs as the mass and nature of the particulates present before a storm are difficult to determine. With a better description of the hydraulics in the conduit system, the more fundamental and physically based methods can be more readily employed to model the transport through the conduit network.

A.3.1 Pollutant entrainment from catchment surfaces

The approach adopted in the model is based on the conceptualization of the erosion process of Meyer and Wischmeier (1969) shown in figure A.2. The erosion process is considered to

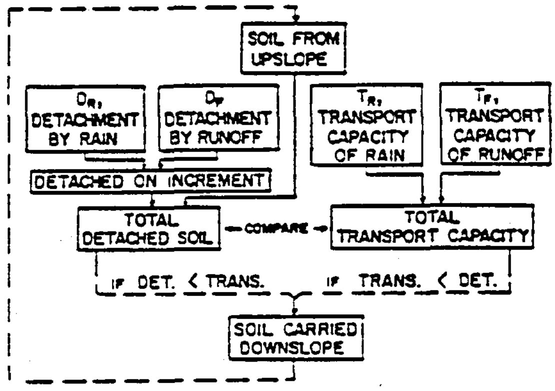

Figure A.2: Conceptualization of the erosion process

consist of detachment and transport subprocesses. The detachment processes consist of that due to the rainfall impact on the catchment surfaces and the movement of water over the surface. The transport of the detached sediment is by flow and raindrop splash. Young and Wiersma (1973) experimented with simulated rainfall on plots and found that the transport by rainfall was small generally less than 5%. The overland or sheet flow was largely responsible for the transport of detached soil over the catchment surface. The model for the entrainment of particulates from the catchment surfaces consists of a rainfall detachment model which determines the availability of particulates for transport and a function which determines the capacity of the flow to transport material overland. For the pervious catchment areas, the particulate entrainment process is considered to consist of an active store or layer from which the particulates are removed by the flow. The parent material below the active store is detached by the rainfall impact forces. The detached mass is assumed to have the same particle size distribution and density as the parent material. The detached mass of each particle size is than added to the mass of the particle size in the active layer or store.

A.3.1.1 Raindrop detachment

The factors that effect the degree of detachment from a surface are the raindrop size, velocity, nature of the surface, soil type, and the depth of water on the surface at the time of impact. The method of approaching the problem range from the examination of changes of momentum to energy considerations. The momentum approach was used by Tan (1989) to formulate his model. Li (1979) and Foster (1982) use an energy type approach where the rate of detachment is related to the raindrop energy which is normally taken as proportional to the square of the rainfall intensity i (mm/hr). The general form of the function is

$$D_i = a_e i^2 (1 - \frac{y}{y_p}) (1 - C_v) \qquad \text{A.19}$$

where D_i ($g/m^2/s$) is the detachment rate due to raindrop impact, a_e is a parameter to account for the soil erodibility, Cv is a vegetation cover factor, yp is the depth of penetration of raindrops through the surface water layer and detached soil depth, and y is the depth of water and detached soil. The penetration depth of the raindrops is taken as 3 times the median raindrop diameter which is given by $2.32i^{.182}$. The vegetation cover factor Cv has a value between 0 and 1. A value of 0 means no vegetation cover while 1 means a very good cover. The soil erodibility parameter a_e has been given by Foster (1982) as 0,0138Ke ($g/m^2/hr$). The soil erodibility factor in the USLE is suggested as a guide for the value for Ke.

For the pervious areas, the material detached is assumed to have the same particle size distribution as the in situ material of the catchment. This material is added to the available soil material store from which the particulates are removed based on the transport capacity of the flow. In the case of the impervious surfaces such as roads, parking areas, and roofs the material has been deposited on the surface from the atmosphere, by previous rain events, or by the activities of man. The material can therefore be considered to be cohesionless. The material does not form a thick layer of particulates over the surface as would be found in an alluvial bed of a river. The material is rather sparsely scattered by actions such as wind or traffic to collect in isolated deposits on the impervious surface. In the model, the material is assumed to be spread out evenly over the entire surface. The rainfall detachment function then becomes more of an entrainment function and represents the mass of material splashed into the overland flow from the crevices and cracks in the impervious surfaces.

A.3.1.2 Transport capacity

The mass of material that is entrained into the flow depends on the capacity of the flow to entrain the available material. The capacity of the flow is normally determined using a transport capacity relationship for bed material. Expressions such as the stream power approach of Yang (1973) which predicts total bed material load has been suggested by Rooseboom (1992). Bed load predictors such as those due to Meyer-Peter Muller (Yalin, 1977) and Yalin (1963) have been used in RAFLER and the WEPP technology (Nearing et al, 1989) respectively. The depths of the overland flow are considered sufficiently shallow that the sediment transport will be by saltation, sliding, or rolling and there will be no need to consider the transport by suspension. In the model of Li (1979), the bed load and the suspended load are included but this is probably an unnecessary refinement considering the uncertainties in the hydraulics and the shallow water depths generally encountered in surface flows. In WITQUAL the bed load formulation due to Yalin (1963) has been used. This expression has been tested on the transport of sediment in shallow flows by Foster and Meyer (1972) with reasonable success. The Yalin equation seems most applicable based on the assumptions made for its derivation. This equation assumes that sediment motion begins when the lift force of the flow exceeds a critical lift force. Once a particle is lifted from the bed, the drag force of the flow carries the particle downstream until the particle weight forces it out of the flow and back to the bed. The number of particles in motion at a given time is a linear function of δ, the dimensionless excess of the tractive force. The Yalin equation requires only 2 common flow parameters viz the hydraulic radius R, and the slope of the energy gradeline Sf. The transportability of a soil is given by the particle density, $SG\rho_w$, the diameter d, and the critical lift force Y_{cr}, which is given by the Shields diagram. The Yalin equation used is as follows

$$W_s = 0.635\,SG\rho_w d U_* \delta \left(1-\frac{1}{\sigma}(\log(1+\sigma)\right) \qquad \text{A.20}$$

$$\sigma = A\delta \qquad \text{A.21}$$

$$\delta = (Y/Y_{cr})-1 \;\; (when\ Y<Y_{cr}, \delta=0) \qquad \text{A.22}$$

$$A = 2.45\,SG^{.4}\,Y_{cr}^{.5} \qquad \text{A.23}$$

$$Y = \frac{U_*^2}{(SG-1)\,gd} \qquad \text{A.24}$$

$$U_* = (\tau_g/\rho_w)^{0.5} \qquad \text{A.25}$$

where U_* is the shear velocity, g is the acceleration due to gravity, ρ_w is the density of water taken as 1000 kg/m^3, τ_g is the shear stress on the soil grains, and W_s (kg/m/s) is the mass rate of sediment particle transport. If the surface is covered with vegetation the total shear stress $\tau_0=\rho g y S_0$ is divided between the vegetation and the soil grains. The shear stress to be used in the Yalin equation is the shear stress acting on the bed grains. The shear stress is divided between the form roughness due to vegetation and the bed grains based on the assumption that the total shear stress can be expressed as

$$\tau_0 = \rho g R (S_g + S_v) \qquad \text{A.26}$$

where S_g and S_v are the friction losses due to the grain roughness and the vegetation roughness respectively. Due to the kinematic flow routing employed in WITSKM, the friction slope S_f is taken as the bed slope S_0. Assuming that the total Mannings roughness n is the sum of n_g and n_v which are the Mannings roughnesses for the soil grains and the vegetation respectively. Repeated applications of the Manning equation yields

$$S_g = \left(\frac{n_g}{n}\right)^2 S_0 \qquad \text{A.27}$$

This slope is used to determine the grain shear stress for use in the bed load prediction equation.

The material to be entrained will be made up of a mixture of sand grains of different sizes and densities. To calculate the transport capacity for a particular particle size, the follwing steps are followed:-

1. The total excess shear $T=\Sigma\delta$ is determined for the number of particle sizes np
2. The transport capacity T_i is determined for a active layer of made up of size i only.
3. The transport capacity for particle size i is then adjusted using the expression $Ti=Ti(\delta i/T)$

A.4 Entrainment and deposition in conduits

The methodologies used in existing urban drainage models include the completely mixed tank approach as used in SWMM and those based on sediment transport theory such as the approach used in MOUSE (DHI, 1993). The approach used in SWMM models the transport through the conduit system as a completely mixed tank and uses the Shield entrainment criterion and the particle settling velocities to determine the scour and deposition of the material in the bed. The completely mixed tank approach as a routing method results in the severe attenuation of the pollutograph unless provision is made for a cascade of tanks. The models such as MOUSE incorporate the more recent approaches based on sediment transport theory such as that of van Rijn (1984a, 1984b). Other models such as MIDAS (van Niekerk et al, 1992), MOBED (Krishnappen, 1981), and SEDICOUP (Holly and Rahuel, 1990) deal specifically with the transport of sediment in channels. The emphasis of the models varies. MIDAS was developed to model bed sorting to predict the deposition of minerals. The model assumes the flow to be quasi-steady and the emphasis is placed on the sorting and entrainment of bed material than on the deposition of the particulate load washed into the channel from the catchment surfaces. SEDICOUP uses unsteady non-uniform flow routing and deals with the routing and deposition of particles down the channel for example from a dam break.

The aim of routing the particulates through the conduit system is to determine from the input concentrations, particle sizes and densities, and the flow and bed conditions which of the particulates will deposit out in the conduit. In most urban catchments the conduits can be considered as rigid or fixed bed systems rather than a loose boundary of sediment. No provision is therefore made at this stage to entrain any sediment that maybe present in the conduit system before a storm event. This type of consideration is normally given to combined sewer systems. In this model, the material that has settled out in a conduit is assumed to be cleaned out of the system during the dry periods or become part of the bed and vegetation system. The advection equation is used to route the sediment through the conduit system. The entrainment and deposition of particles from a loose material boundary is a dynamic process. There is an interchange of particles between those in the bed and those in suspension. The modelling of this dynamic process is undertaken in the methodologies suggested by Celik and Rodi (1988), Cheng (1984), Bennett and Nordin (1977), and Holly and Rahuel (1990). These approaches to the transport of particulates through the conduit system are considered too complex for inclusion in the WITQUAL model.

In WITQUAL a simpler approach has been adopted similar to that used in erosion modelling. The transport capacity of the flow is determined using the Yang (1973) stream power equation for each particle size. The approach of Borah et al (1982) is used to divide the transport capacity between the various particle size fractions. The residual capacity for a particular particle size group k is determined using the following equation

$$T_{rk} = T_i [1 - \sum_{j=1}^{N} (\frac{C_j}{T_j})] = \Omega T_i \qquad \text{A.28}$$

where N is the number of particle sizes, T_i and T_j is the transport capacity for a particular size class, and T_{rk} is the residual transport capacity. The term Ω is the remaining fraction of T_k available for transporting additional material of size d_k. Thus a $\Omega>0$ implies an eroding bed in that there is spare transport capacity while $\Omega<0$ implies an aggrading bed or deposition of suspended material. The following solution procedure is used:-

1. The transport capacity T_k for each particle size k is determined.
2. The value of Ω is determined.
3. If $T_k <= 0$ then particle size group k is assumed to settle out during transport through the conduit i.e C_k is set to 0. The mass of particle size k is added to the bed material for possible resuspension later during the event.
4. If $\Omega > 0$ then bed material is entrained for all size classes for which $T_k > 0$ according to the residual

capacity T_{rk} until $\Omega = 0$.

5. If $\Omega < 0$ then deposition is started with the largest particle size and continued until Ω is close to 0.

A.5 ENTRAINMENT OF DISSOLVED POLLUTANTS

A.5.1 INTRODUCTION

Urban stormwater runoff carries significant quantities of pollutants that are dissolved in the runoff water. These are found as ions such as sulphates, chlorides, phosphates, and nitrates, as well as organic compounds. In the case of urban catchments there are both impervious and pervious areas that have to be considered in developing a model. Generally the runoff from urban areas is dominated by that from impervious areas so more attention is normally given to the modelling of the entrainment or washoff of pollutants from these areas. However Irving et al (1987) monitored pervious areas of urban catchments in Hamilton, Canada and found them to be significant contributors of pollutants to the storm water runoff. Attention should therefore be given to both the pervious and impervious areas of a catchment. The modelling of pollutant entrainment from pervious areas will be particularly important in the modelling of the informal urban developments.

In this section, the existing approaches to the modelling of solute pickup from pervious and impervious catchment surfaces will be revued in the light of the results of plot studies undertaken on the entrainment of dissolved pollutant into the surface runoff.

A.5.2 PERVIOUS AREAS

A.5.2.1 Present modelling methods

Urban drainage models such as SWMM pay little attention to the entrainment of dissolved pollutants into the overland flow from the pervious areas. The method normally offered is a potency factor approach coupled to the Universal Soil Loss Equation (USLE). Most of the models that include the modelling of the uptake of pollutants into the overland flow from the soil porewater have been developed for agricultural purposes, such as the prediction of the fate of pesticides, herbicides and fertilisers.

The approach most often used in these models is to assume that there is a thin surface layer of soil where there is mixing between the overland flow and the surface chemical. This is often conceptualised as a completely mixed tank reactor of a fixed depth in which the surface, infiltration, and soil water concentrations are the same (fig. A.3).

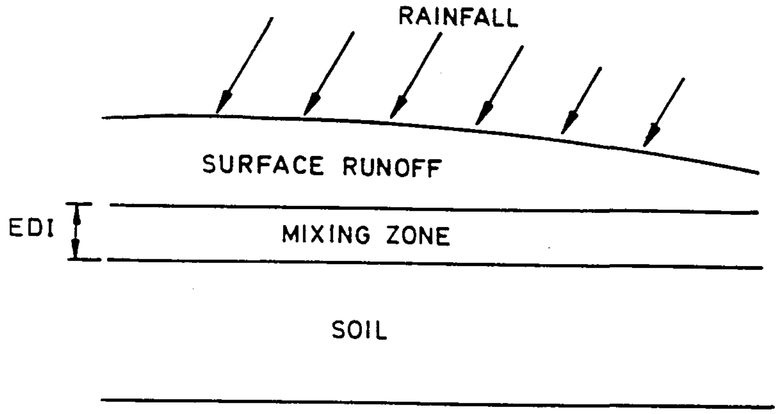

Figure A.3 : Conceptualization of the EDI type models

This assumes that there is instantaneous equilibration or complete mixing between the soil and surface water. A mass balance around such a reactor will give the following equation.

$$\frac{d}{dt}(EDI\theta C) = -(R+I)\,C \tag{A.29}$$

where C (mg/l) is the concentration of the dissolved pollutant in the reactor, infiltration water, and the surface runoff, R and

I are the runoff and infiltration rates respectively, EDI is the effective depth of interaction, and θ is the moisture content of the soil.

Assuming that EDI and θ are constant with time t, equation 4.42 can be integrated to give

$$C = C_0 \exp\left[\left(\frac{-(R+I)}{EDI\theta}\right) t\right] \qquad \text{A.30}$$

The above equation or similar forms of this equation are used to model washoff of TDS in the model of Herold (1981). The thickness of this EDI layer is unknown at the beginning of a modelling exercise. The thickness of the mixing layer was found by Sharpely (1985) during plot studies, using simulated rain, to vary from 1,3 to 37,4 mm. The depth being dependent on rainfall intensity, slope, and surface cover. Sharpely ultimately related the EDI to the soil loss.

This equation implies that the runoff concentration will be linear with time for constant EDI, θ, R, and I. This hypothesis has been tested in plot studies by Ahuja and Lehman (1983) and Ingram and Woolhiser (1980) using the nonadsorbable chemical, Bromide (Br). They found that the runoff concentration was in fact lower than that in the soil and plots of the log of the runoff concentration with time were not straight lines. In addition, the determination of the Br concentrations of the soil water at various soil depths, at the end of the simulated events, showed that the depletion was not uniform with depth but decreased rapidly with depth in an exponential manner. The depth of the EDI was also investigated for phosphorus by Ahuja et al (1981) and showed similar trends as for Br. These tests were carried out for different types of soils.

Further results that were brought out by the plot studies are that the depletion of the chemical in the soil is affected by infiltration rate. The greater the infiltration rate the more rapid the depletion of the soil water concentration and the lower the runoff concentration. Parr et al (1987) showed that the type of soil and the surface roughness has an effect on the runoff concentrations. Greater pollutant masses being entrained from the coarser soils. Ingram and Woolhiser (1980) and Sharpely (1985) showed that the slope of the catchment and the kinetic energy of the rainfall played a role in the pickup of pollutants.

A.5.2.2 Model Development

The following assumptions are made in the development of the model describing the entrainment of dissolved pollutants from the pervious areas :-

1. The concentration of the chemical in the porewater of the surface store is much higher than that in the surface runoff. The entrainment rate is then described by a constant E times the pollutant porewater concentration C_{sd} (g/m^3).
2. A soil layer having a depth Z is assumed to contribute dissolved pollutant to the surface runoff.

A mass balance equation around the effective depth of transfer Z yields the following equation

$$Z\theta \frac{dc}{dt} = -EC-fC \qquad \text{A.31}$$

where the moisture content θ is taken as the porosity of the upper soil layer, f (m/s) is the infiltration rate, and E is the entrainment coefficient. The entrainment coefficient E is taken as being directly proportional to the shear velocity u_* as the shear velocity can be considered to be an indication of the flow turbulence or the rate at which the flow can mix pollutant from the boundary into the flow.

A.5.3 Impervious areas

Nakamura (1984) found that the washoff of dissolved pollutants from impervious surfaces is dependent on factors such as slope and surface roughness. Akan (1987) assumed the rate of pollutant removal to be proportional to the bottom shear stress and the mass of material available on the surface to give

$$\frac{dP}{dt} = -k\tau_0 P \qquad \text{A.32}$$

where P is the pollutant mass on the catchment surface at time t, k is a constant for a particular pollutant, τ_0 is the bottom shear stress normally taken as $\gamma y s_0$ for a wide plane. γ is the unit weight of water. Akan (1987) tested the algorithm against some of Nakamura's data and found reasonable fits. The algorithm of Akan has been adopted in WITQUAL for the entrainment of dissolved pollutant mass from the impervious surfaces of the catchment.

List of Symbols

a_e	Soil erodibility parameters
$A(m^2)$	Flow cross sectional area
$C(g/m^3)$	Cross sectional averaged pollutant concentration in surface flows
$C_i(g/m^3)$	Pollutant concentration in rainfall
$C_{rs,k}(g/m^3)$	Solids concentration in surface flows in size class k
$C_{sd}(g/m^3)$	Concentration of dissolved pollutant in soil mass
c_v	Vegetation cover factor for raindrop impacts
$D(m^2/s)$	Pollutant diffusion coefficient in soil
$DEP(g/m^2/s)$	Deposition pollutant flux
$Det_{s,k}(g/m^2/s)$	Rate of detachment of the catchment soils by raindrop impact and flow
$D_i(g/m^2/s)$	Soil detachment rate due to raindrop impacts
$d_k(m)$	Particle size in size class k
$E(m/s)$	Entrainment coefficient for dissolved pollutants
$EDI(m)$	Effective depth of Interaction
$ENT(g/m^2/s)$	Entrainment pollutant flux
$f(m/s)$	Infiltration rate
$f_{bp,k}(g/g)$	Ratio of pollutant mass to the particulate surface mass
$f_{dp,k}(g/g)$	Fraction of detached soil mass in size class k that is the particulate form of the pollutant of interest
$f_{rp,k}(g/g)$	Fraction of SS concentration in size class k that is the particulate form of the pollutant of interest
$f_{s,k}(g/g)$	Fraction of particulate mass in size class k
$f_{sp,k}(g/g)$	Fraction of soil particulates in size class k that is the particulate form of the pollutant of interest
$g(m/s^2)$	Acceleration due to gravity
$i(m/s)$	Rainfall intensity
$J(g/s)$	Mass rate of pollutant transport
$K(/s)$	Decay coefficient

$Kd(m^3/g)$	Partition coefficient
$K_{dec}(/d)$	Decay rate for pollutants in surface store
$K_r(/d)$	Removal rate of pollutants present on catchment surfaces
$M_{bs,k}(g/m^2/d)$	Build up rate of particulates on catchment surface in size class k
$M_{s,k}(g/m^2)$	Mass of available particulate material in size class k per unit catchment area
N	Number of particle sizes
n	Total Manning roughness
n_g	Manning roughness for soil grains
n_v	Manning roughness for vegetation
$P(g/m^2)$	Pollutant mass on impervious catchment surfaces
P(m)	Wetted perimeter
q(m/s)	Soil water flux
$Q(m^3/s)$	Flow rate
$S_{ad}(g/m^3/s)$	Source/sink term between solid and dissolved soil pollutant forms in the soil
S_g	Friction loss due to soil grains
S_o	Bed slope
S_v	Friction loss due to vegetation
T(m)	Flow top width
T_i	Transport capacity for size i
T_{rk}	Residual transport capacity
U(m/s)	Average velocity of flow
W*(m/s)	Shear velocity
W(m)	Width of catchment
$W_s(kg/m/s)$	Mass rate of sediment particle transport
y(m)	Depth of water surface
Y_{cr}	Critical lift force in Yalin equation
$y_p(m)$	Depth of penetration of raindrops
$\Delta t(s)$	Time interval
$\Delta x(m)$	Length of flow element
$\Delta z(m)$	Elemental depth of soil or pollutant store
θ(vol/vol)	Soil moisture content
$\rho b(g/m^3)$	Soil bulk density

$\rho w (kg/m^3)$	Density of water
$\tau_g (N/m^2)$	Shear stress on soil grains
Ω	Remaining transport capacity