Urban Runoff Quality and Modelling Methods

T Coleman

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by

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WATER RESEARCH COMMISSION

EFFECTS OF URBANIZATION ON CATCHMENT WATER BALANCE

LIST OF REPORTS

Report No.	Title	By
1	Analysis of effects of urbanisation on runoff	D. Stephenson
2	Description of catchments and methodology	J.J. Lambourne T. Coleman
3	Geohydrology of Catchments	W.A.J. Paling D. Stephenson
4	A hydrometeorological data management package Wits Data Management System WITDMS	J.J. Lambourne
5	The effect of storm patterns on runoff	N. Patrick
6	Runoff Modelling	A. Holden
7	Streamflow modelling	P. Kolovopoulos
8	Runoff management modelling	T. Coleman D. Stephenson
9	Catchment water balance	J.J. Lambourne F. Sutherland
10	Urban Runoff Quality & Modelling Methods	T. Coleman
11	Compendium of papers published on the research	
12	Executive Summary	D. Stephenson

ABSTRACT

In this report, the results of a stormwater quality and quantity monitoring program of a catchment in Hillbrow, Johannesburg are presented and discussed. The Hillbrow catchment has an area of 67,2 ha and is fully developed with high rise buildings, high density housing, and schools. The catchment has a stormwater drainage system installed which consists of pipe networks feeding a concrete channel running down the centre of the catchment. The study included the monitoring of atmospheric fallout (both dry and wet fallout), the automatic sampling of stormwater runoff, and continuous electrical conductivity and pH measurement. The samples were tested for pH, COD, suspended solids (SS), total dissolved solids, nutrients (nitrogen and phosphorus forms), iron, and lead.

The dry fallout collection results showed that the rates varied both in time and spatially for most of the pollutants measured. For suspended solids, for example, the dry fallout rate ranged from 30 to 403 $mg/m^2/d$. The wet or total fallout rates, which include the washout of pollutants from the atmosphere by rain, were generally higher than the dry fallout rates. The stormwater runoff quality exceeded the general effluent standards in SS, COD, free and saline ammonia, and iron. Mass balances on some of the storm events sampled showed that the pollutants are generated on the catchment with more pollutant leaving the catchment than being imported in the rainfall.

The data collected was further used to examine relationships between runoff volume, peak rain intensity, antecedent dry days and the pollutant loads from the catchment. A multiple regression analysis showed that the number of antecedent dry days play a significant role in predicting runoff quality. The inclusion of the antecedent dry days in the analysis improved the correlation coefficient substantially in particular for total phosphorus, nitrate, and iron. Other methods of modelling runoff quality such as the deterministic methods are also presented and discussed in the report.

TABLE OF CONTENTS

TABLES

FIGURES

CHAPTER 1. INTRODUCTION

1.1 General

Urban stormwater runoff has become a major source of stream pollution in many areas, especially with the advent of more advanced controls for point sources of pollution. In the United States of America in the 1960's monitoring programs were launched to investigate the nature of urban stormwater runoff and its effect on receiving waters. Wanielista (1979) reports that for approximately 80% of urban areas, the downstream water quality is determined by non-point sources of pollution. Similarly Henderson and Moys (1987) report that some 3700 km of rivers in England and Wales are classified as being of poor to bad quality in terms of their chemical composition and the uses that can be made of them. Concern was also expressed about the deterioration of the quality of the Great Lakes due to continued industrialization and urbanization (Weatherbe and Novak, 1977). This led to the formation of the International Joint Commission between Canada and USA in 1972, to establish water quality objectives for the Great Lakes and to address the pollution problems. South Africa is also facing the problem of increasing urbanization. As a result many water courses, previously conveying runoff from predominantly rural catchments, are now fed almost entirely by runoff from urban areas and effluents from point sources such as wastewater treatment plants and industrial outfalls. These water courses are not only subject to increased pollution loads but the flow peaks and volumes are generally higher. These can lead to the degradation of the water course due to increased erosion. The problem of point sources of pollution have received much attention in South Africa with the implementation of the 1 mg/l phosphate standard for treated sewage effluents in sensitive catchments such as the Hartebeespoort Dam and the Vaal Barrage catchments.

However non-point sources of pollution also add to the pollution loads with the Department of Water Affairs (1986) reporting that 40% of the dissolved solids entering the Vaal Barrage can be attributed to the stormwater runoff from the Southern Johannesburg area.

1.2 Nature and Sources of Pollutants in Urban Runoff

A variety of pollutants have been identified by various monitoring programs. These include plant nutrients, oxygen demanding organic compounds, toxic heavy metals, hydrocarbons, sediment, and pesticides. The significance of the levels of pollutants needs however 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 criteria can be set for a particular receiving water body.

The solids in stormwater runoff come in both inorganic and organic form in either colloidal or particulate form. The suspended solids are the cause of the increased turbidity which lowers the light penetration thereby reducing the algal production and the variety of fish species. The recreational and aesthetic appeal of the receiving waters is affected. Chemicals in particular the heavy metals and phosphorous (Simpson, 1986 ; Morrison et al, 1984) are generally associated with the sediments and are deposited in the bed of the receiving waters. Sediment laden rivers also effect the costs of water treatment and in large quantities can fill reservoir storage volume. One of the sources of sediment in an urban environment is the stripping of land during construction activities. Waller and Hart (1985) report an increase from 25 kg/ha-yr to 2100 kg/ha-yr for a 14 ha site in Halifax, Canada.

Phosphorous and nitrogen loadings accelerate eutrophication problems in urban water bodies. Excessive nutrients found in runoff can cause increases in particulate matter such as bacteria, fungi, and shifts in the algal population to less desirable types such as the blue-green algae. (Waller and Hart, 1985). In addition the increased bacterial activity often leads to a chronic oxygen depletion with anaerobic conditions resulting in the receiving waters. These conditions will seriously affect water treatment costs and detract from the recreational opportunities and aesthetics of the receiving waters. Fertilizers and in particular decaying vegetation (Waller and Hart, 1985) have been found to be the major sources of phosphorous.

Stormwater from urban surfaces has been found to carry toxic pollutants such as heavy metals, hydrocarbons, pesticides, and polychlorinated biphenyls (PCB's) (Marsalek, 1985 ; Morrison et al, 1984 ; Simpson, 1986 ; Hermann, 1984). There is evidence that these substances are a danger to human health being carcinogenic and mutagenic. These concerns have been further heightened by the widespread distribution in the environment and by indications of bioaccumulation of many toxic substances. The sources of heavy metals in urban runoff include atmospheric fallout , corrosion processes, tyres, pavement wear, vehicle exhaust emissions, brake linings, paint, and industrial spills.

The discharge of organic and other oxidizable materials in stormwater runoff exerts a substantial oxygen demand on the receiving waters with the resultant depletion of oxygen which could lead to anaerobic conditions. These oxygen demanding substances can also be deposited in the sediments which can cause delayed oxygen demands.

Urban runoff contains large concentrations of bacteria, viruses, and pathogens. Weatherbe and Novak (1977) report that microbial populations in stormwater runoff were high, sometimes approaching those of raw sewage, and therefore constituting a health hazard. These micro-organisms accumulate in the receiving waters and in dry weather pipe and channel deposits.

1.3 Control of Stormwater Runoff Pollution

There are a variety of policies that can be used to improve the quality of stormwater runoff. The policies can be broadly divided into two categories :

1) Control of sources of pollution
2) Treatment of stormwater runoff

The control of the sources of pollution include removal of pollutants by street sweeping, leaf removal, and catch basin cleaning. Street sweeping although improving the aesthetic quality of the urban environment has been reported as being generally ineffective as a technique for improving the quality of urban runoff (Huber, 1985; Prych and Ebbert, 1987). Further control measures of the sources of pollution are the prevention of erosion especially during construction periods in a catchment. The use of grass buffer strips or vegetative filters are a means of slowing down the flow and causing deposition of sediments from construction sites. Runoff from roofs of buildings has been sited as a contributor to runoff pollution. (Ellis, 1985). This detention storage or infiltration of roof runoff is a means of improving runoff quality.

The policies that can be adopted for the treatment of stormwater runoff is the use of detention ponds and diversion of the so-called "first flush" (Hajas et. al. 1978) to a treatment plant or storage facility. Hvitved-

Jacobsen et. al. (1987) report that between 45% and 95% of the SS, Pb, Zn, P and Cu has been removed from urban runoff using a detention pond. Similarly Martin and Miller (1987) reported on the capabilities of a detention pond cum wetland system for the removal of SS, pb and Zn achieving 66%, 42% and 50% respectively. Lawrence and Goyen (1987) report on the use of gross pollutant traps, detention ponds and lakes being used both as landscape features to provide aesthetically pleasing urban environments in Canberra, Australia as well as ensuring sound stormwater management from both the quantity and quality point of view.

1.4 Need for Models

With the recognition of the quality and quantity problems of urban stormwater runoff has come the need for adequate analytical tools. This need led to the Water Systems Research Group (WSRG) of the University of the Witwatersrand developing computer based simulation models viz. WITWAT (Green, 1984) and WITSKM (Coleman and Stephenson, 1990) for the analysis of the hydraulics of stormwater drainage systems for urban catchments. The WITSKM model was developed more for the analysis of best management practices while WITWAT was intended for the design of the stormwater drainage network. Some of the pollution problems presented by urban runoff can be reduced by not only designing the stormwater drainage network from a quantity point of view but also considering the quality aspects of runoff.

To assist in the planning of similar systems in South Africa, the use of water quality models are required. There are no models thus far that have been developed in South Africa for use in the analysis of best management practices (BMP) for urban catchments. Herold (1981) developed a model for TDS for investigating the TDS balances and management policies for the Vaal Barrage. However this model uses a monthly or daily time step which is not suitable for the examination of BMP for urban catchments. Other models such as SWMM (Huber et al, 1982) and STORM (HEC, 1977) have been developed for urban catchments. STORM however operates on an hourly time step and does not have the ability to model storm runoff at small enough time intervals to be applied to urban catchments where storms can have durations of an hour or less. SWMM on the otherhand is a very comprehensive computer model dealing with both the quantity and quality of runoff. Although performing admirably in modelling the hydrology, problems have been found in modelling the runoff quality using default values (Simpson and Kemp, 1982). Doubt has been raised concerning some of the quality algorithms adopted in SWMM especially where no observed data is available for model calibration (Bedient et al, 1978).

1.5 Scope of Report

The purpose of this report is two fold. Firstly to present results of the quality monitoring program carried out on the Hillbrow catchment in Johannesburg. The program included the collection of atmospheric fallout, and the automatic sampling of the stormwater runoff from the catchment. The second objective is to review some of the existing quality modelling approaches that could be used to develop a model for the analysis of BMP for the improvement of the runoff quality from urban catchments. Where possible the applicability of the quality modelling approaches are discussed in terms of the data collected from the Hillbrow catchment.

CHAPTER 2. HILLBROW MONITORING PROGRAM

2.1 Introduction

A water quality monitoring program was established in a catchment in Hillbrow in Johannesburg. The catchment area is 67,2 ha and is a fully developed urban area comprising high-rise buildings, high density housing, and schools. The population of the area is estimated at some 12500 people giving 186 people/ha. The catchment boundaries and the pipe and channel drainage system are shown in figure 2.1. The Hillbrow catchment is a subcatchment of the Jukskei River catchment which has been declared a sensitive catchment and a special effluent standard in particular the 1 mg/l phosphorus standard for point sources has been implemented.

The program included the monitoring of atmospheric fallout, and automatic sampling of stormwater runoff,and continuous electrical conductivity and pH measurements at the catchment outlet. The rainfall over the catchment and the flow depth in the main drainage channel were also monitored.

2.2 Instrumentation

The atmospheric fallout was sampled at two sites viz on the roof of the 8 storey high Mimosa Hotel and on the cover of a walkway connecting two buildings at the Roseneath primary school. Both of the fallout collectors were situated next to raingauges and there positions are shown on Figure 2.1. The collectors are at different levels with the Mimosa Hotel and Roseneath collectors some 25m and 3m above ground level respectively. The collectors were placed in exposed positions away from any structures that could inhibit the collection of fallout.

The equipment used to collect fallout was based on that

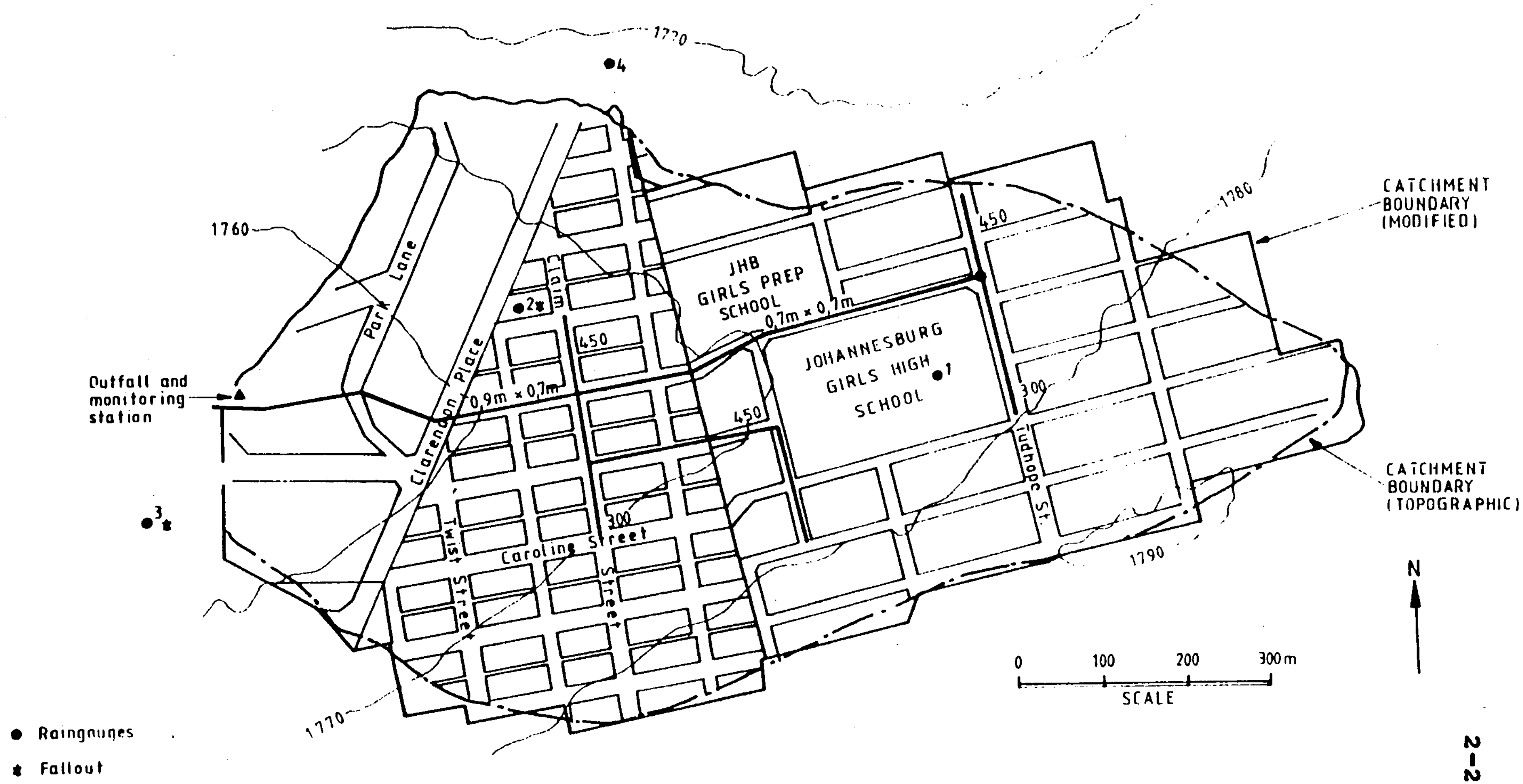

Figure 2.1 : Plan of the Hillbrow Catchment

used by Simpson (1986) and consists of a plastic funnel having a diameter of 450 mm supported in a metal frame. A plastic bucket was placed under the funnel to collect any rainfall and the distilled water used to wash the fallout off the funnel. The main purpose of the fallout and rainfall collection is to determine a mass of pollutant per unit area per unit time. To do this the volume of the samples collected using the above procedure is important and must be measured when the samples are collected. In some cases the rainfall depth was such that the buckets overflowed. In these cases the raingauges located at the fallout sites were used to estimate the total depth of rainfall which was used with the area of the funnel to obtain an estimate of the volume. Thus assuming that the average pollutant concentrations found in the buckets are representative for the period, the calculated rainfall volume was used to determine the mass loading rate. The collection interval for the dry samples of fallout varied from 1 to 2 weeks. However the samples were collected as soon as possible after rainstorms. As a result of this policy during a series of closely spaced rainfall events, some of the samples collected could be considered to represent rainfall alone without contamination by dry fallout.

To measure the flow rate at the catchment outlet a V notch weir was constructed in the stormwater channel at the catchment outlet. The flow depth was measured using a Druck pressure transducer connected via an amplifier to a DDS IDLE 816 logger. To sample the runoff from the catchment an automatic sampler was used. The sampler consisted of a delivery pipe with its inlet positioned in the middle of the channel behind the V notch weir. The delivery pipe had a strainer on the end with 3mm holes drilled into it. A pump was used to extract the water from the channel into plastic bottles in the sampler. The sampler has 13 bottles that can be used to collect samples of the stormwater over a runoff event. The sampler was originally triggered using a float system but this was found to jam up with grit and the float system was replaced by a system of electric relays that are activated by the DDS logger. When the depth exceeds a limit set in the logger, the logger triggers the relay which sets off the sampler. The sampler is switched off when the depth drops below the depth limit. The time that the sampler is switched on is recorded by the logger. The sampler then samples on a time basis, the time interval between samples being set on the sampler. A total time interval of 6 minutes including pumping was found to sample the runoff adequately using the 13 bottles. The samples were collected from the sampler as soon as was practically possible. The samples were stored in a fridge before dispatch to a commercial laboratory for testing. However when samples were taken for bacterial analysis they were taken to the laboratory immediately.

The electrical conductivity was measured using a carbon electrode conductivity probe with a conductivity range of 0-200 ms/m. The probe was set to read the dry weather flows every 20 mins while during a storm event the time interval was changed to 2 min intervals. The probe had to be cleaned on a two weekly basis as a slime layer tended to build up around the carbon electrodes. Sediment also deposited around the probe and on occasions the electrodes were found buried in sand. The calibration of the probe also had to be checked regularly using standard conductivity solutions. The probe was often found to be out of calibration. During storm events the probe gave erroneous readings probably due to the sand and debris collecting around the probe. The electrical conductivity gives an indication of the TDS and a regression analysis between the conductivity in ms/m and the TDS in mg/l was carried out. The equation obtained was

$$TDS = 6{,}46EC + 6{,}55 \qquad 2.1$$

The correlation coefficient for the regression analysis was 0,72. This equation was used to convert the dry weather flow conductivities to TDS. The probe was only considered to give accurate readings during the dry flow periods.

The pH probe used was an IMC probe. The probe also required regular maintenace. The probe was washed on a two weekly basis using distilled water and on occasions using an acid cleaning solution. The calibration of the probe also had to be checked on a regular basis using standard solutions. The dry weather flow was sampled on a 20 minute basis until an event occurred and the interval was reduced to 2 minutes.

The rainfall was measured using 4 tipping bucket raingauges connected to MC Systems single channel digital data loggers. Three of the tipping bucket raingauges had a 0,2 mm tip with one having a 0,5 mm tip. The positions of the raingauges are shown in Fig. 2.1.

2.3 Sampling and Testing Procedures

The sample analysis was undertaken by a commercial laboratory, McLachlan and Lazar, using methods as set out in the "Standard Methods for the Examination of Water and Wastewater" (1985). A complete chemical and physical analysis to determine all the contaminants in the stormwater runoff would have been very costly and to a large extent would be unwarranted. To ascertain the general quality and the relative quantities of the pollutants present in the runoff, a relatively thorough chemical analysis was undertaken on two storm runoff events and two grab samples of dry weather flows. These samples were tested for the major cations and anions viz Na, K, Ca, Mg, SO_4, CO_3, HCO_3, and Cl as well as for pH. As far as the solids were concerned both the total dissolved solids (TDS) and the suspended solids were tested for together with the conductivity of the samples. The samples were analysed for the various forms of phosphorus and nitrogen. For the phosphorus both the total phosphorus and dissolved phosphorus as orthophosphate were determined. Nitrogen is present in a number of forms and the following tests were carried out viz Total Kjeldahl Nitrogen (TKN), free and saline ammonia, and nitrate. To determine the organic content of the samples a Chemical Oxygen Demand (COD) on a filtered sample was undertaken together with a loss on ignition of the TDS at 500 degrees Celsius. To determine the bacterial content of the runoff limited faecal coliform tests were done on the dry weather flows. The samples were also tested for the heavy metals Pb and Fe.

To reduce the costs of analysis, the range of pollutants tested for was reduced by making up a composite sample for storm events. The composite sample was made up from the discrete samples by using the recorded hydrograph. The volume of runoff that each discrete sample represented was calculated from the hydrograph. These calculated volumes were expressed as a fraction of the total runoff volume. The calculated fractions were then used to determine the fraction of each discrete sample to be included in the composite sample. In this way a more representative composite sample could be made up with larger fractions of the samples taken at the high flow rates included in the composite sample. The pH, TKN, nitrate, TP, orthophosphate, free and saline ammonia, Fe, Pb, and COD were determined for the composite samples. The individual samples were tested for conductivity, TDS, SO_4, NO_3 and suspended solids.

A similar testing procedure was followed for the fallout and rainwater samples as was undertaken for the stormwater samples. A relatively thorough analysis was undertaken on some of the dry fallout samples. This was then reduced to pH, SO_4, NO_3, SS and TDS.

CHAPTER 3. HILLBROW STORMWATER RUNOFF AND FALLOUT QUALITY

3.1 Introduction

A number of sources of pollution in an urban catchment have been discussed in chapter 1. They can be broadly broken into contributions from the atmosphere, and those generated within the catchment. As far as the contribution from the atmosphere is concerned, the possible sources of wind blown pollution around the Hillbrow catchment are a power station, chemical and explosive factories, mine dumps, and the burning of coal and wood for heating and cooking. Annegarn et al (1981) in a study of urban aerosol pollution in the Johannesburg/Soweto area found that the concentration of sulphur in the atmosphere increased markedly above base levels in Soweto in the morning and evening during peak periods of coal burning. The area to the south and east of the Hillbrow catchment is dotted with mine dumps. There are therefore many pollutants which could be carried into the catchment area by wind. However the mine dumps are the closest sources of pollution and would probably make a more significant contribution than the others to the pollutant loads from the catchment. Other sources of pollution for the Hillbrow catchment will be vehicular exhaust emissions, oil and grease, litter, vegetation, and animal faeces and urine.

3.2 Fallout Quality

3.2.1 Introduction

The way in which the atmosphere provides pollutants to an urban catchment is usually divided into dry fallout and wet or bulk fallout. Dry fallout is the settling out of heavier particles during dry periods between storms. This type of fallout is subject to redistribution after settling by wind and eddies caused by vehicles. Wet or bulk fallout is the scavenging of pollutants from the atmosphere by rain drops.

The extent to which the atmosphere contributes pollutants to the overall mass balance of pollutant loads in runoff from an urban catchment varies considerably. Ellis (1985) reports that dry fallout is a relatively minor contributor to the buildup of pollutants in the catchment. The wet deposition rates being 2 to 3 times higher than the dry deposition rates. Ellis (1985) reports that some workers assign up to 50-70% of the runoff loads to atmospheric inputs, while others attribute less than 15% of any pollutant to fallout. Simpson (1986) found that the contribution from atmospheric fallout varies from pollutant to pollutant. The suspended solids constituting some 12%, TDS 26%, COD 22%, soluble nitrogen 48%, and copper 30% of the runoff loads. The figures quoted above are average figures and it was found that the percentages varied from year to year, being lower during the wetter than dry years. Ng (1987) investigated the contribution of rainfall to stormwater loads for a 10,3 ha industrial site in Ontario, Canada and found that the contributions of the various forms of nitrogen and the heavy metals copper and nickel were significant.

The quantity of a pollutant available in the atmosphere for fallout during dry periods and for scavenging by raindrops during a storm depends on type and position of the source areas of pollutants relative to the catchment, as well as physiographic, and climatic conditions. Wind in particular is the main (James and Boregowda (1985)) mover of atmospheric pollution into and out of a catchment. This is due to the general mean air motion, the turbulent velocity fluctuations that disperse the pollutants in all directions, and the diffusion of particles due to concentration gradients. The scavenging or washout of pollutants from the atmosphere by rain, depends to a large extent on the concentration of pollutant in the atmosphere, the intensity of the rainfall, and rain drop size (Shivalingaiah and James, 1984; Shiba et al, 1990)

3.2.2 Dry Fallout

A relatively thorough analysis was carried out on 2 dry fallout samples. The average percentage composition of the cations and anions making up the TDS are given in Table 3.1 for the two collection sites. From the results the major constituents can be seen to be Ca, SO_4, HCO_3, and Cl.

Table 3.1 : Relative proportions and concentrations (mg/l) of constituents in dry fallout

	ROSENEATH	MIMOSA
PARAM	AVE %	AVE %
Ca	13	12,4
Mg	1,2	1,5
Na	5,5	5,9
K	3,3	4,0
HCO_3	32,0	30,0
Cl	6,1	8,8
SO_4	13,0	15,7
NO_3	0,5	0,34
PO_3	0,3	0,17
LOSS ON IGNITION OF TDS	21,0	18,2

The SO_4 present in the atmosphere is an indication of the burning of fossil fuels such as coal, and petrol. Wind blown mine dump sand could also contribute to the SO_4 and Cl levels found in the fallout collected. The organic content in the fallout could be pollen, spores and minute particles of vegetation.

The loading rates for the dry fallout for the 2 sites are given in Table 3.2. The suspended solids showed the highest loading rates with maximum loading rate of 268 $mg/m^2/d$ at Mimosa and 403 $mg/m^2/d$ at Roseneath. The loading rates of the nutrients phosphorus and nitrogen are relatively low. In general however the fallout rates at the Roseneath site are higher than those at the Mimosa site. This is probably due to the positions of the collection sites. The Mimosa site is higher and is therefore subject to higher wind velocities and therefore greater risk of redistribution of the fallout off the funnels.

The fallout rates for all the pollutants varied for the six week period over which the samples were collected. This is shown in figures 3.1 and 3.2 which show plots of the variation in the SS and TDS loading rates with time for Roseneath and Mimosa. The variation of the buildup rates over time are different for the two sites.

Table 3.2 : Dry Fallout Rates ($mg/m^2/d$)

	MIMOSA		ROSENEATH	
PARAM	AVE	MIN-MAX	AVE	MIN-MAX
TDS	31,0	22,3-45,3	34,1	25-47,2
SS	106,0	53,1-268	185,0	30-403
COD	55,0	26-89	37,2	27-51
TP	0,67	0,28-0,92	1,47	0,48-4
NO_3	0,28	0,06-0,7	0,35	0,13-0,65
Fe	4,66	2,3-8,6	7,3	3,9-10,3

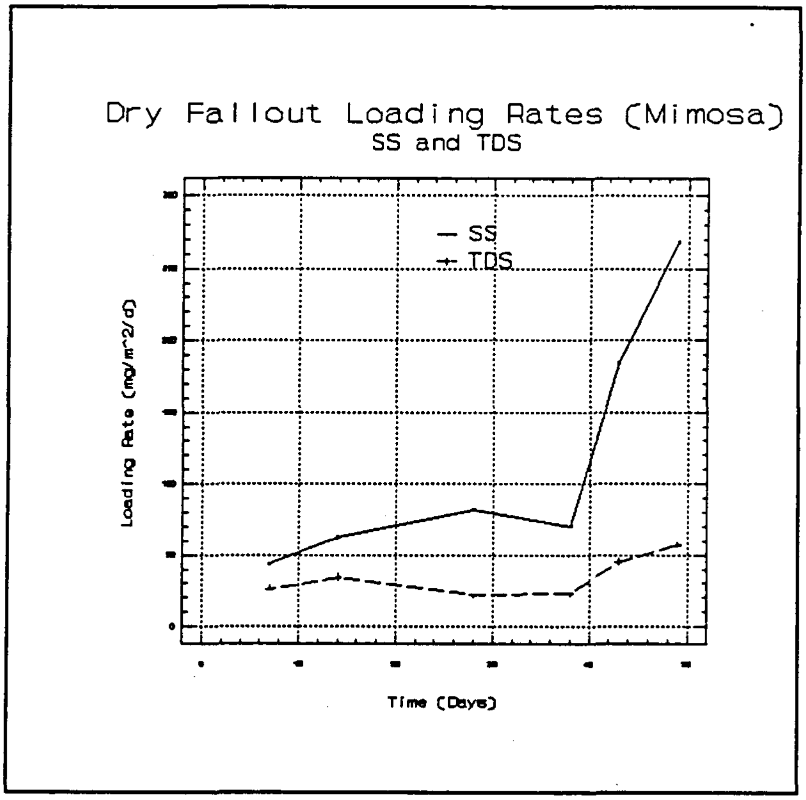

Figure 3.1 : Plot of SS and TDS dry fallout rates for Mimosa

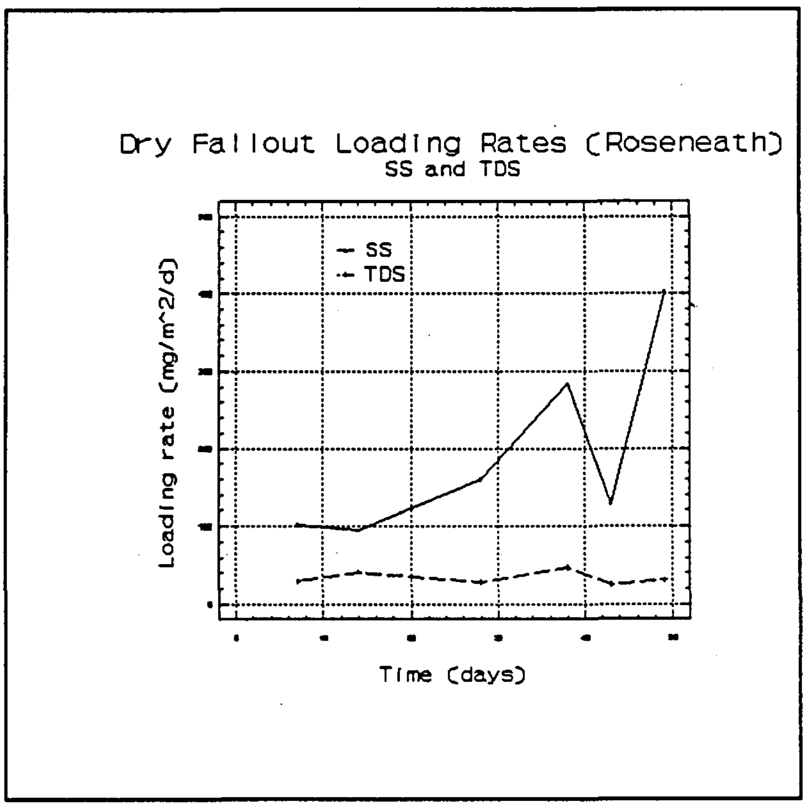

Figure 3.2 : Plot of SS and TDS dry fallout rates for Roseneath

However both showed an increase towards the end of the period before the first rains occurred. Another point that can be observed from the plots is that at the Mimosa collection site, the buildup rate levelled off around day 30 while the Roseneath site the buildup rate continued to increase. This could again be explained by the redistribution of the fallout by wind. The local conditions around the collectors could also play a role. The Mimosa Hotel is amongst a number of tall buildings and wind could be channelled or eddies setup from the buildings which could effect the results. The Roseneath site is much more open in terms of the effects of nearby buildings. The TDS loading rates follow a different pattern to that of the suspended solids with the variation in the loading rate far less pronounced than in the case of the suspended solids. This type of variation is also shown by the nutrients, and that of iron.

3.2.3 Wet Fallout

The so called wet fallout collected at the two sites in Hillbrow was sometimes a mixture of dry fallout and washout by rain. There were occasions where the rain was collected at short intervals and some of the samples could be considered to be representative of pollutants washed out by rain alone. In Table 3.3, the average wet buildup rates together with the maximum and minimum rates found during the monitoring period are presented for both collection sites. The bulk fallout rates are higher than the dry fallout rates due to the scavenging action of the rain. The Roseneath site for most cases produces higher fallout figures than Mimosa. The pH of the fallout also varies considerably. There is evidence of acid rain with the minimum pH as low as 4,29 and 4,86 for Roseneath and Mimosa respectively. The average pH was 5,5 and 5,4 which is below the drinking water standards.

Table 3.3 Wet Fallout Rates(mg/m_2/d)

	MIMOSA		ROSENEATH	
PARAM	AVE	MIN-MAX	AVE	MIN-MAX
pH	5,4	4,86-6,08	5,55	4,29-6,01
TDS	113,0	0-503	290,0	4,5-824
SS	153,0	5,5-490	260,0	35-381
TP	1,14	0,23-4,7	1,44	0,07-9,3
PO_3	0,29	0,03-1,6	0,43	0-3,1
NO_3	2,31	0-15,5	1,35	0,82-5,67
Fe	5,21	1,24-14,3	8,3	0,1-44,02
SO_4	24,1	7,6-47,5	21,3	4,9-51,0
Pb	< 0,01		< 0,01	
Cu	< 0,01		< 0,01	
Cr	< 0,01		< 0,01	

There are 6 fallout samples that could be considered to be representative of the washout process alone i.e not contaminated with dry fallout previously deposited on the funnel surfaces. The concentrations are presented in Table 3.4.

Table 3.4 : Rainfall concentrations (mg/l)

EVENT	MIMOSA Concentrations (mg/l) except pH					ROSENEATH Concentrations (mg/l) except pH				
	pH	TDS	SS	SO_4	NO_3	pH	TDS	SS	SO_4	NO_3
90-12-06	5,35	32	9	-	0,1	5,89	104	10	-	0,1
91-01-23	5,69	80	42	9	0,1	5,27	44	65	4	0,2
91-01-24	5,3	60	20	2	0,1	5,23	88	72	2	0,4
91-01-25	5,37	48	12	12	0,1	5,22	20	3	7	0,1
91-01-28	5,48	92	79	8	0,1	5,1	52	48	16	0,1
91-02-07	4,83	84	6	5	0,1	5,0	88	20	11	0,1

3.3 Runoff Quality

3.3.1 General

The runoff from the Hillbrow catchment consists of stormwater runoff caused by rain and a base or dry weather flow caused by seepage into the pipe and channel network and by discharges of water into the channel. These discharges during dry periods are often wash water from the blocks of flats and town house complexes along the main drainage channel. The channels are also used for the disposal of litter such as cans, paper, plastic bottles and bags, and vegetable matter.

To gauge how serious a source of pollution an urban area, such as Hillbrow, could be on a receiving water body, event mean concentrations (EMC) were calculated for the storm events sampled at the catchment outlet. These averages and the minimum and maximum concentrations for the storm events and the dry weather flow grab samples are presented in Table 3.5. The averages are repeated together with the recommended limit for drinking water standards (Kempster and Smith, 1985) and the general effluent standard as given by the Department of Water Affairs (1986) in Table 3.6.

Although based on limited samples, the dry weather flow from the catchment violates a number of the effluent standards given in Table 3.6. As far as the nutrients are concerned the ammonia, and soluble ortho-phosphate concentrations exceed the standards. The ammonia standard quoted in Table 3.6 is the special standard. The general standard for ammonia is 10 mg/l as N which is not exceeded by the dry weather flow. The presence of the relatively high ortho-phosphate concentrations could be due to the presence of detergents in the wash water flushed down the channel. The dry weather flow has possibly been contaminated with sewage as is borne out by the ammonia, COD, and faecal coliform count levels. The dry weather flow is high in organic matter as is indicated by the high COD level. The extent to which the COD is readily biodegradable is not known but the runoff is likely to encourage bacterial and algal growth due to the excess organic matter, ammonia and high levels of phosphorus. The algae growth can be seen on the bottom and walls of the drainage channel. The flow rate during dry periods from the catchment is however low at some 1 -4 l/s. Assuming that there are 310 dry days in a year gives a load from dry weather flow of ortho-phosphate and ammonia of 79 kg/a and 462 kg/a respectively.

Table 3.5 : Table of Average Concentrations (mg/1), and Range for Stormwater Runoff and Dry Weather Flow

	STORM RUNOFF			DRY WEATHER FLOW		
Param.	Ave.	Range Min-Max	No. of samples	Ave.	Range Min-Max	No. of samples
pH	6,49	6,11-6,91	15	7,69	7,2-8,1	36
COND	13,7	6,4-24,7	15	54	22-104	66
TDS	106	28-191	15	350	142-725	66
Loss on ignition	29	-	1	-	-	-
S.SOLIDS	328	69-1071	15	47	20-778	3
Ca	8,2	7,7-8,7	2	58	58-58	2
Mg	0,27	0,18-0,36	2	15,1	15,0-15,2	2
Na	2,4	1,6-3,3	2	108	99-116	2
K	2,4	-	1	28	28-28	2
HCO_3	17,8	13-22,6	2	269	259-341	3
Cl	3,09	2,85-3,3	2	67	62-72	3
SO_4	20,5	10,9-27,8	10	175	135-210	3
F	0,26	0,2-0,33	2	-	-	-
NO_3 as N	0,84	0,1-2,0	15	0,52	0,47-0,54	3
Free & Saline Ammonia as N	2,87	1,9-4,11	10	6,9	-	1
TKN	6,43	3,54-13,9	14	-	-	-
KN	4,73	-	1	-	-	-
Total P as P	1,2	0,46-2,59	15	-	-	-
PO_4 as P	0,39	0,24-0,62	15	2,96	-	1
TURBIDITY	6,2	-	1	-	-	-
COD	95	61-131	5	570	-	1
faecal coli /ml	-	-	-	>1000	-	1
Tot Fe	11,18	3,3-59,5	15	-	-	-
Pb	<0,01	-	-	<0,01	-	-

Table 3.6 Average Concentrations (mg/1) for Dry and Storm Runoff for comparison with Drinking and Effluent Standards

Property	General Effluent Standard	Drinking Water Standards	Dry Weather Flow	Storm Runoff
pH	5,5-9,5	6,0-9,0	7,69	6,49
faecal coli/ml	nil	nil	>10^3	-
COD	75	-	570	95
Suspended solids	25	0	47	328
NH_4 (N)	1,0*	1,0	6,9	2,9
Nitrate (N)	1,5*	6,0	0,52	0,84
Lead (Pb)	0,10	0,05	<0,010	<0,010
Soluble PO_4 (P)	1,0*	-	2,96	0,39
Iron (Fe)	0,3*	0,1	-	11,18
Fluoride (F)	1,0	1,0	-	0,26
SO_4		200	175	20,5
Cl		250	67	3,09
K		200	28	2,4
Na		100	108	2,4
Mg		70	15,1	0,27
Ca		150	58	8,2
Turbidity (NTU)		1,0		6,2
Conductivity ms/m @ 25°C		70	54	13,7

* Special effluent standard

The concentrations in the stormwater runoff are more dilute than the dry weather flows and only exceed the effluent and drinking water standards for SS, COD, free and saline ammonia, and Fe. In stormwater runoff the pollutants can either be in the soluble form or associated with the solids in the water. The different fractions that go to make up the TDS of the water are summarized below in Table 3.7. The figures presented are averages of the detailed analyses of two storm events.

Table 3.7 : Relative proportions of constituents in stormwater runoff

Parameter	Average %
Loss IGN	24
Ca	14,5
Mg	0,1
Na	3,13
K	5,2
HC03	28
Cl	5,8
SO_4	14,8
NO_3	2,4
F	0,4
PO_4	0,9

The major constituents are Ca, HCO_3, SO_4, and loss on ignition. The loss on ignition gives an indication of the organic content of the TDS. This constitutes some 24% of the TDS. This together with the relatively high COD, and TKN values indicates that the runoff has a large soluble organic component. The sources of the organic content could be the hydrocarbons from exhaust emissions, contributions from fallout, decomposing vegetation, and animal or human faeces. The runoff will exert an oxygen demand on a receiving water both for the synthesis of the organic matter and the oxidation of the ammonia present in the water to nitrate by the nitrifying bacteria. The pH of the stormwater is within drinking water standards and the acid rain is neutralized during its passage out of the catchment.

3.3.2 Relationships between pollutants

A linear regression analysis using the Statgraghics version

4 statistical package was carried out between the EMCs of the various pollutants in the 15 events sampled. The results are presented in Table 3.8. The results show that the Fe, TKN and to a lesser extent TP are associated with the suspended solids. The test carried out for Fe was a total Fe test i.e for both soluble and Fe associated with the suspended solids. The TKN was carried out on unfiltered sample and the regression analysis shows that the organic nitrogen is high when the suspended solids are high. Similarly the TDS is relatively strongly related to the SO_4 concentration as the sulphates are one of the major soluble pollutants. The other relationships highlighted by the analysis shows that ammonia is related to the other nutrients via soluble ortho-phosphate and TKN. There is not a particularly significant linear relationship between ammonia and nitrates.

Table 3.8 : Correlation coefficients between pollutant EMCs

	TDS	SS	TP	OP	TKN	NO_3	Fe	SO_4	NH_4
TDS		0,27	-0,13	-0,44	0,11	-0,39	0,37	0,79	-0,31
SS			0,33	-0,18	0,55	-0,02	0,78	0,26	0,21
TP				0,12	0,02	0,37	0,63	-0,02	0,53
OP					0,13	0,42	-0,4	0,11	0,82
TKN						0,09	0,26	-0,27	0,86
NO_3							0,15	-0,46	0,22
Fe								0,07	0,33
SO_4									-0,11

The relationships discussed above between the SS and fe, TP, and TKN suggests that detention storage might be a means of improving the quality of the stormwater runoff from the catchment. If the solids could be settled out in a storage facility the Fe, much of the phosphorus and TKN could be removed.

3.4 Contribution to Runoff by Fallout

To assess the contribution of the atmosphere to the overall pollutant mass balance, the mass of pollutant that was caught by the collectors was compared to the mass of pollutant leaving the catchment in the runoff. There were a total of 4 events that could be used for this purpose where both the automatic sampler had sampled the runoff and the fallout collected could be considered to represent the fallout during the dry period preceding the storm and the washout during the storm. For these comparisons the fallout is considered to be a total fallout representing both the contributions due to dry fallout and washout. The results are presented in Table 3.9 for the 4 events. The ratio presented in the table is the ratio of the fallout pollutant mass to the mass of pollutant in the runoff. To calculate the fallout pollutant mass an average of the Roseneath and Mimosa fallout figures was taken. The details of the storm events are shown in Table 3.10. The figures presented in the table show that there is in general, a net

Table 3.9 : Ratios of fallout pollutant mass to pollutant mass in the runoff

Event	TDS	SS	COD	TP	OP	TKN	NO_3	SO_4	Fe
90-12-6	0,59	0,3	0,78	0,2	0,5	1,5	0,41	-	0,1
91-01-19	0,91	0,65	-	-	-	-	0,1	0,63	-
91-01-23	0,63	0,41	-	-	-	-	0,30	0,67	-
91-01-24	1,4	1,2	-	-	-	-	0,45	0,80	-

export of pollutants from the catchment. In particular the catchment seems to be able to produce nutrients especially phosphorus and to a lesser extent the nitrates. This could however be due to the contamination of the stormwater flow by the dry weather flow. The amount exported tends to depend on the number of preceding dry days and the characteristics of the rain storm that causes

Table 3.10 : Peak rain intensities, depths and peak flow rates

Event	Peak Intensity (mm/h)	Rain Depth (mm)	Peak Flow (cumec)
90-12-6	108	31,4	4,8
91-01-19	26,4	3,4	1,3
91-01-23	60,0	12,0	2,45
91-01-24	30,0	8,5	0,74

the runoff. For instance the event of the 90-12-6, there were no dry days preceding the rainfall event as it occurred immediately after a event on the 90-12-5. The import of pollutants was low as the atmosphere had been cleaned out the previous day by the rain. The storm of the 91-12-6 was large with a peak intensity of 108 mm/hr. Due to the large rainfall intensities and therefore energy the pollutants would have been loosened from the catchment surfaces and the high flow rates in the conduit systems would have flushed out any pollutants that may have been deposited in the system. The storms of the 91-01-19 and 91-01-23 were smaller storms with peak intensities of 26,4 mm/h and 60 mm/h respectively. There had been 5 and 4 dry days between the events respectively. There had therefore been time between the events for the pollutants to build up in the atmosphere and dry fallout to have accumulated on the catchment. The extent to which the pollutants built up would depend on the wind and other factors. Hence the higher the contribution by the atmosphere. The event on the 91-01-24 the export ratio for TDS and suspended solids are the largest and the antecedent dry days is 0. The storm however is small and therefore not much of the catchment contributed in terms of scour and runoff as much of the rain would have infiltrated.

CHAPTER 4 APPLICATION OF EXISTING MODELLING METHODOLOGIES TO THE HILLBROW CATCHMENT

4.1 Introduction

There are a number of models available that can be used to predict the quality of urban runoff. Huber (1985) gives a summary of six operational models i.e models that are used by users other than the model developer, are documented, and are backed up by the model developers. The type of model that is chosen for a particular analysis depends on the objectives for which the analysis is being undertaken and on the available data. The types of objectives for which models can provide information are:

1. The characterization of the quality of the runoff.
2. The assessment of the impacts of the stormwater runoff on the receiving waters.
3. The design and analysis of stormwater drainage systems and water quality control structures.

Considering the above three objectives, the requirements of quality models can vary from simply providing information on the total pollutant loads to having a detailed pollutograph and hydrograph for a catchment. The methods that can be used to provide this information range from regression equations through to detailed deterministic models. In this chapter the existing approaches to quality modelling will be discussed together with their applicability to the modelling of the runoff quality from the Hillbrow catchment.

4.2 Statistical Methods

The statistical methods most often used are those of regression analysis where relationships between catchment, runoff, and pollutant characteristics are examined. This type of analysis has however produced inconsistent results. Some researchers Colwill et al (1984), Sartor et al (1974), and Weatherbe and Novak (1977) have found that pollutant concentrations were dependant on the number of antecedent dry days. However other researchers viz Whipple et al (1977), Bedient et al (1980), and Green et al (1986) found that there was very little correlation between pollutant loadings or concentrations and the antecedent number of dry days. Green et al (1986) found a better correlation between antecedent moisture condition as proposed by Terstriep and Stall (1974) and the peak total dissolved solids concentration. The correlation coefficient of 0,29 was still considered to be to low to use the equation for predictive purposes. In analysing data from several catchments in Houston, Bedient et al (1978) found that a linear relationship existed between pollutant mass loading rates and total storm runoff volume. This type of relationship can be used in conjunction with a hydrological model to predict pollutant loads. This approach has been used on a catchment in Pinetown by Simpson (1986) where the WITWAT model was used to provide the necessary hydraulic input for the regression model. However a number of regression models have been investigated by Jewell and Adrian (1981), using data for various storm events, basins and geographical regions. They found that when one model was superior to others for one basin within the same geographic area, the estimated parameter values varied significantly among the basins. The application of these models requires local data but they do prove useful in providing a first estimate of the pollutant loads that can be expected from a catchment.

A regression analysis was carried out on the data obtained from the Hillbrow monitoring program. A multiple regression analysis was performed on the data. The dependent variable in the analysis was the load (kg) for a particular pollutant for the 15 runoff events sampled. The decision as to which variables should be used as independent variables was based on the analysis in chapter 3 on the quantity of pollutant contributed to the runoff from the atmosphere. In that analysis, although based on only 4 events, seemed to show that the peak intensity and the number of dry days preceding the events played a role as to the mass of pollutant that was made available for transport out the catchment. The rain intensity providing the energy to loosen pollutants from the catchment and would give an indication of the flow rates that could be expected to erode and scour the pollutants from the catchment. The number of preceding dry days would be the contribution from the atmosphere both in terms of dry fallout and the buildup in the atmosphere for subsequent washout by the rain. The rain intensity also plays a role in the removal of pollutants from the atmosphere. The number of dry days preceding an event, and the peak rainfall intensity were therefore used as independent variables together with the volume of runoff. The regression analysis performed with the independent variables being introduced one at a time to gauge the improvement, if any, that was achieved in the correlation coefficient. The correlation coefficients and the coefficients of the best fitting model are presented in Table 4.1. The analysis was based on the 15 events monitored except where the particular pollutant monitored was not tested for. This was the case for ammonia, sulphate and TKN where the number of events for which the pollutants were tested was 8, 8 and 14 respectively.

Table 4.1 : Correlation Coefficients, and Model Coefficients for the Regression Analysis

Depend Variable	Independent Variable	Correl Coef(R)	Model Coeff	Const
TDS	Volume	0,69	0,1708	
	Dry Days	0,91	-60,49	
	Peak Intensity	0,93	-2,67	110
SS	Volume	0,87	0,828	
	Dry Days	0,85	-160,72	
	Peak Intensity	0,86	-1,141	-189
TP	Volume	0,56	0,00513	
	Dry Days	0,85	-3,574	5,59
	Peak Intensity	0,82	-	-
OP	Volume	0,76	$-1,6x10^{-5}$	
	Dry Days	0,81	0,32	
	Peak Intensity	0,90	0,0486	-0,29
TKN	Volume	0,97	0,00408	
	Dry Days	0,96	0,113	
	Peak Intensity	0,97	0,0967	1,347
NO_3	Volume	0,31	-0,00207	
	Dry Days	0,70	3,287	
	Peak Intensity	0,81	0,228	-7,156

Table 4.1 Continued

Depend Variable	Independent Variable	Correl Coef(R)	Model Coeff	Const
Fe	Volume	0,46	0,0732	
	Dry Days	0,78	-37,363	
	Peak Intensity	0,76	-1,117	32,18
SO_4	Volume	0,98	0,0522	
	Dry Days	0,97	-5,506	
	Peak Intensity	0,98	-1,346	22
NH_4	Volume	0,95	0,0148	
	Dry Days	0,93	-1,342	
	Peak Intensity	0,95	-0,46	5,398

The analysis above shows that the load for the pollutants measured can be predicted using the above multiple regression equation with dry days, peak rainfall intensity, and volume as independent variables. The analysis shows that in the cases of nitrate, Fe and TP, the number of dry days played a significant role in improving the correlation coefficient. In the cases of TP and Fe, the inclusion of the peak rainfall intensity in the model tended to lower the correlation coefficient although not significantly. The only drawback in applying the model directly to a catchment is that the runoff volume is required. The regression equations presented above can be used in conjuction with a hydrological simulation model such as WITSKM to predict the runoff loads for input to a receiving water model. However this type of analysis does not produce the variation of the pollutant load for a specific event and therefore cannot be used for the analysis of BMP. For this type of analysis a more detailed approach would be required. In addition the regression coefficients obtained for the Hillbrow catchment would probably differ from those obtained for another catchment having different characteristics and in a different geographical region.

4.3 Deterministic Models

4.3.1 Introduction

Deterministic models attempt to model the processes taking place on a catchment. In figure 4.1, a schematic showing the interaction of the various pollutant processes is presented. Most catchments can be divided into surface and conduit sub-systems. The processes that need to be considered are the buildup, washoff, and transport of the pollutants through the drainage system. The use of the buildup and washoff technique is probably the most common physically based formulation used in urban runoff quality modelling (Huber, 1985).

4.3.2 Buildup

Buildup is the term used to describe the processes that take place during the dry periods between storm events. These include atmospheric deposition, wind erosion, deposition of exhaust emissions, street cleaning and accumulation of leaves and litter. These processes lead to the accumulation of, or in the case of street sweeping, the removal of pollutants on the street surfaces. These pollutants are subsequently washed off during a rain event. Studies have been undertaken such as the APWA study in Chicago (Huber, 1985) where vacuum cleaners and brooms have been used to collect the dust and dirt that have accumulated on the street surfaces. The resultant data has then been normalised to provide data on the mass of dust

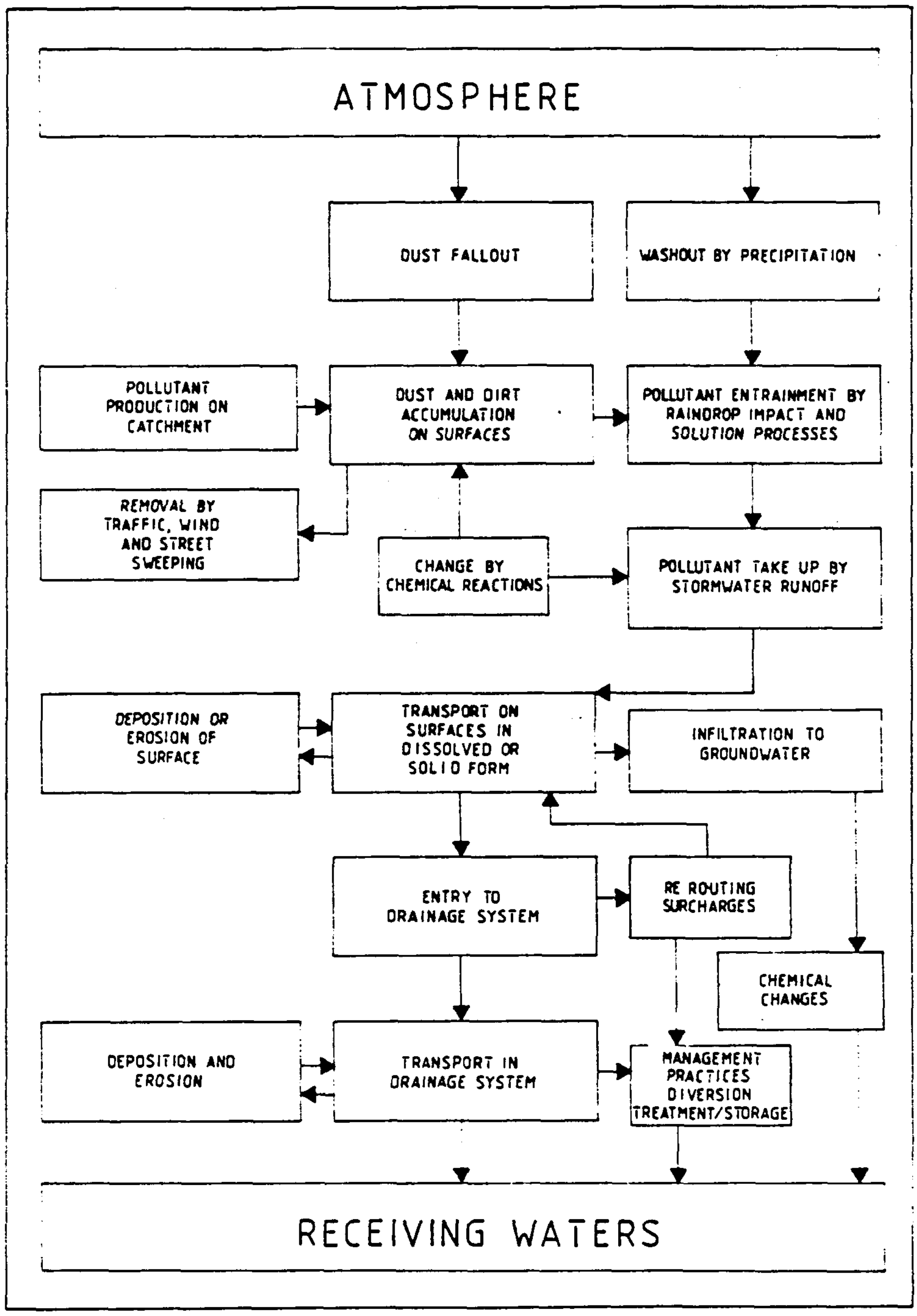

Figure 4.1 : Schematic of processes involved in the quality of urban runoff

and dirt that can accumulate per dry day per length of gutter. The dust and dirt was then analysed for pollutants such as COD, BOD, coliforms, total nitrogen and phosphate. The results of these analyses were presented in terms of the mass of pollutants as a fraction of dust and dirt. These fractions or potency factors are a method of determining the buildup of a specific pollutant if the buildup of dust and dirt is known.

This potency factor method is used in models like SWMM and STORM. This was tried for the dry fallout results using linear regression between the pollutants tested for and the suspended solids. However the suspended solids would only represent dry fallout and not the pollutants contributed by sources within the catchment as would have been found in the APWA survey where the dust and dirt was collected directly from the street surfaces. The results are presented below in Table 4.2 for both Roseneath and Mimosa.

Table 4.2 : Correlation Coefficients between SS and other pollutants

	TDS	COD	TP	OP	TKN	NO_3	Fe
Rose	0,26	0,05	-0,52	-0,59	0,91	-0,44	0,89
Mim	0,33	0,72	0,32	-0,57	0,81	-0,37	0,80

The analysis was only based on 6 samples for each of the collection sites but there is a significant correlation between SS and the TKN, Fe and less significant correlation between TDS and SS for both sites. The analysis shows discrepancies as far as the TP and COD are concerned. On examining the data in both cases for Roseneath there was a single sample that showed unusually high values for COD and TP. IF these were excluded from the analysis the correlation coefficients were found to be 0,7 and 0,49 for COD and TP respectively. This brings the two analyses more into line with each other. The analysis shows that it could be possible to predict the Fe, TKN, and COD from the buildup of dust and dirt.

Empirical relationships are generally used to describe the buildup of pollutants on catchments between storm events. The types of relationships used are: linear, power functions, exponential, or Michaelis-Menton. A plot of these functions is shown in figure 4.2. The accumulation of dust and dirt however involves the continuous interaction of the addition and removal processes due to activities

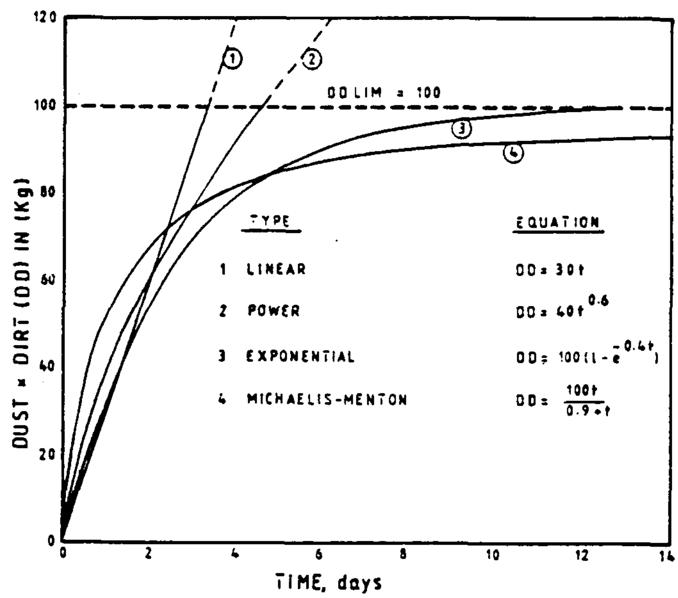

Figure 4.2. Pollutant buildup functions

within the catchment and the redistribution processes related to meteorological parameters. A daily mass balance approach of the accumulation process has been used by James and Boregowda (1985). This approach involves calculating the mass flux of pollutants from various sources such as atmospheric fallout, vehicle pollutants, population related activities, and vegetation. This input of pollutants is reduced by the various redistribution mass fluxes such as street sweeping, removal by wind, and vehicle generated eddies. This approach was tested by the authors by revising the buildup subroutines in the PCSWMM3 program and applying the program on a continuous basis to a catchment in Hamilton, Canada. Comparisons with results from the original version of SWMM showed that this type of process modelling approach was more successful.

The dry buildup rates for Mimosa and Roseneath showed different patterns (Figs 3.1 and 3.2). The Roseneath site seeming to display a continuous increase in fallout rate while Mimosa tended to level off as in an exponential or Michaelis-Menton type equation. These conclusions however are only general as there were variations around these patterns. The mass balance approach of James and Boregowda is difficult to assess with the data collected as no attention was given to wind velocities nor was the atmosphere specifically sampled.

4.3.3 Washoff

Washoff is the process of erosion and solution of pollutants from the catchment surface during periods of runoff. This process is not fully understood and like the process of pollutant buildup, is still subject to empiricism. This has limited the application of water quality models to catchments having measured data. There are basically two approaches that can be adopted in describing this process. They are the application of sediment transport theory coupled with the modelling of the chemical processes of dissolution, adsorption, desorption, or the use of empirical washoff formulations.

Plots of some of the variations of the pollutant load with time are shown plotted in figures 4.3 to 4.7. The plots are of the pollutant mass rate (kg/s) and included in the plots for comparison is the hydrograph. The plot for event 2 in figure 4.3 shows a number of flow peaks in the hydrograph.

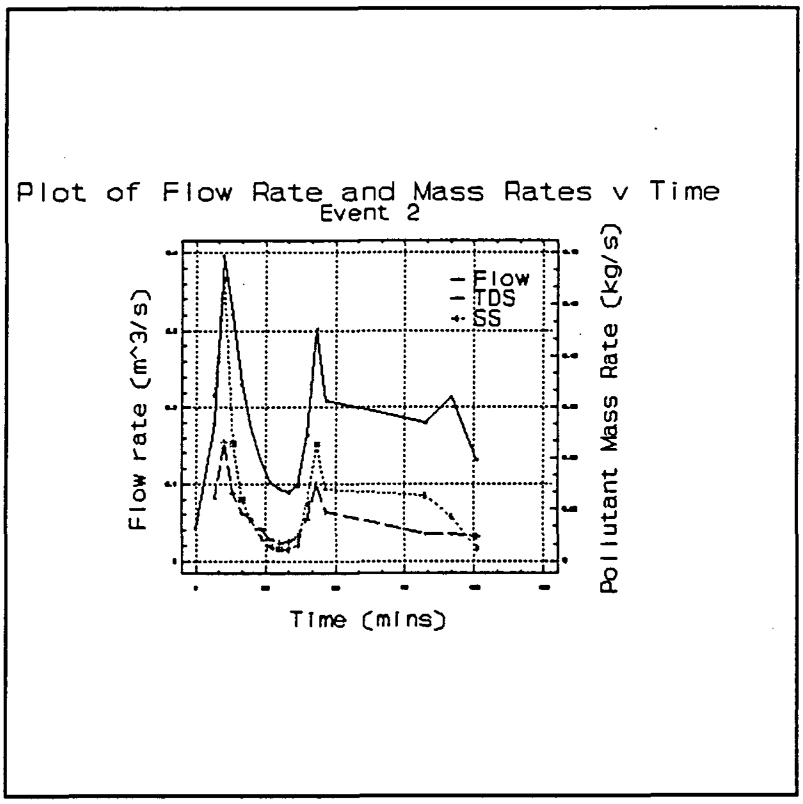

Figure 4.3 : Plot of Flow Rate, pollutant mass rate against time

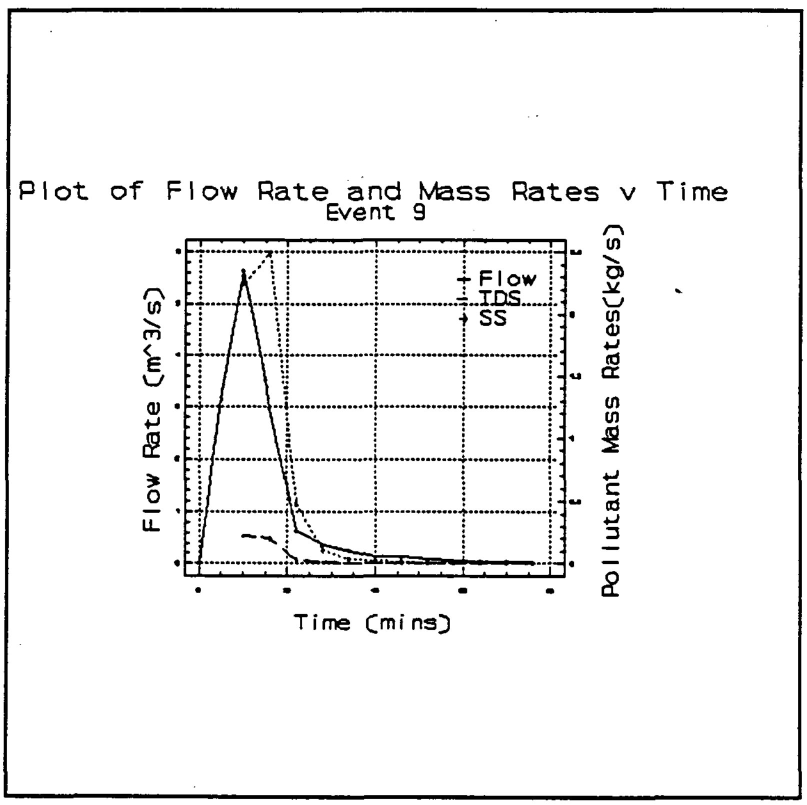

Figure 4.4 : Plot of Flow Rate, pollutant mass rate against time

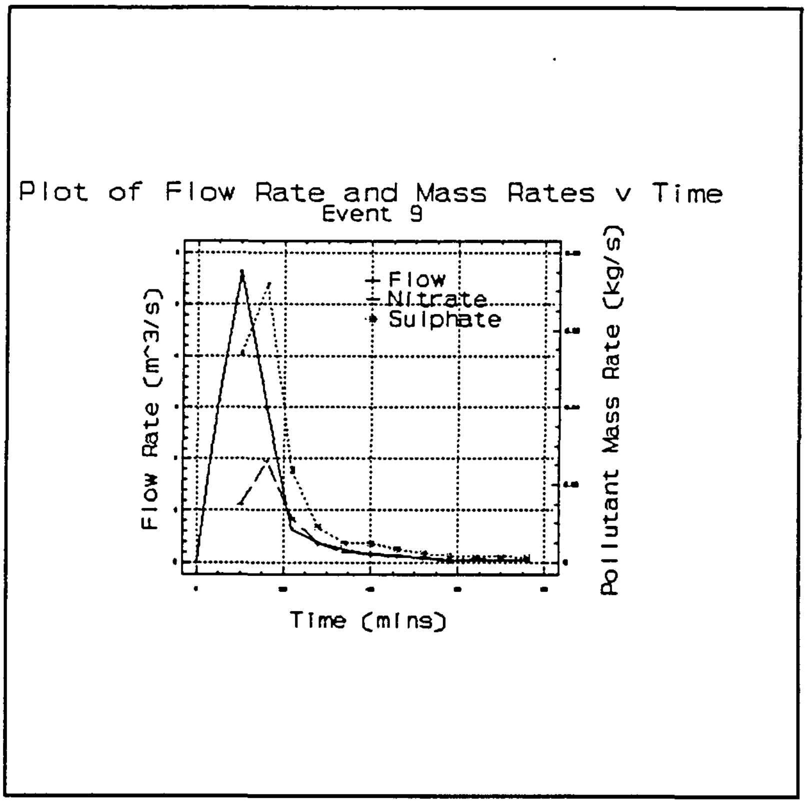

Figure 4.5 : Plot of Flow Rate, pollutant mass rate against time

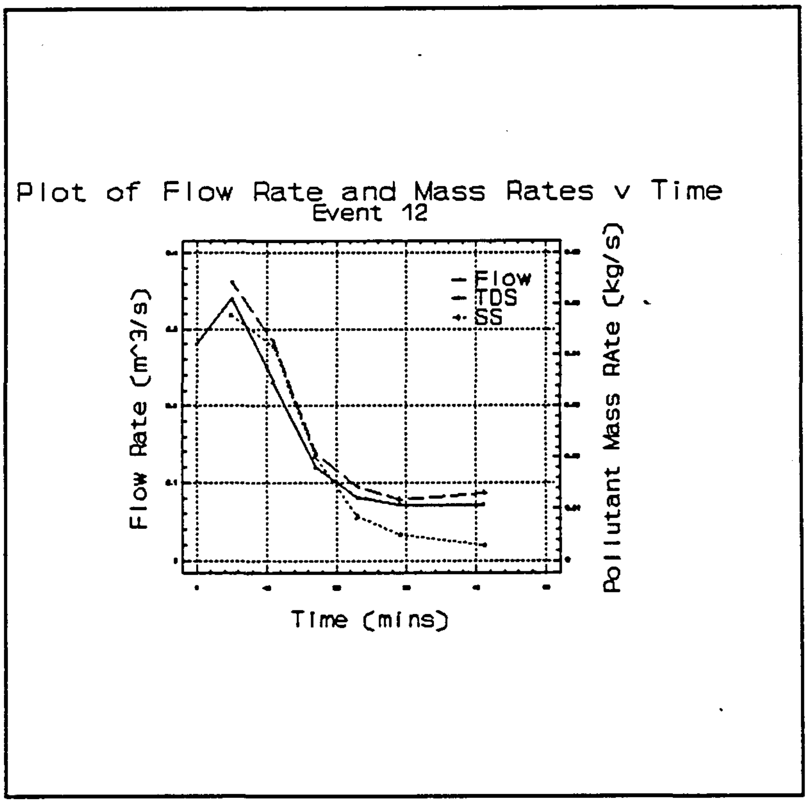

Figure 4.6 : Plot of Flow Rate, pollutant mass rate against time

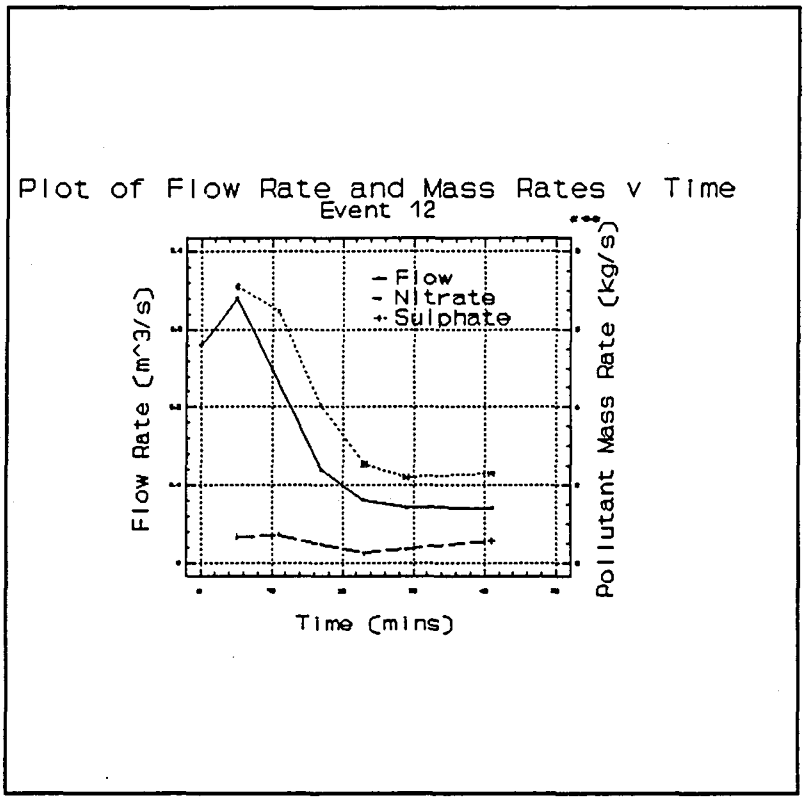

Figure 4.7 : Plot of Flow Rate, pollutant mass rate against time

The TDS and SS mass rates followed the hydrograph closely for first two peaks but not the third. This was particularly shown up in the case of the SS. This could be due to a settling out of the SS in the conduit network or a depletion of the supply of SS. The drop in TDS mass rate was not as marked as that of the SS. This could also be due to the depletion of the supply of pollutant on the catchment surface. The mass rate plots shown in figures 4.4, 4.5, 4.6, and 4.7 also show that the mass rates for the pollutants generally follow the shape of the hydrograph. An exception is the that of nitrate for event 12 (fig 4.7) where the nitrate load rate increased towards the end of the event on the recession limb of the hydrograph. This implies that the concentrations of nitrate increased towards the end of the event. This phenomenon was reported by Green et al (1986) for the Hillbrow catchment and the explanation was given that this was caused by the concentration of nitrate increasing in the rain over an event due to lightning activity. For event 9 shown in figures 4.4 and 4.5, the peak mass rate for all the pollutants except TDS comes after the peak flow rate. This was a particularly large event with a peak flow rate 5,62 m^3/s and peak rainfall intensity of 108 mm/h. This type of behaviour could be due to the pollutants having different travel times through the conduit system from the various source areas in the catchment. The high rainfall intensity could have loostened soil and pollutants in the permeable parts of the catchment in particular the schools in the centre of the catchment for subsequent transport through the conduit system.

One of the empirical approaches used is the rating curve approach. This approach is a form of regression analysis in which the pollutant load rate is regressed against flow rate, or total load against runoff rate. The regression equation used is normally a power function of the form

$$F=aQ^b \qquad 4.1$$

where F is the load rate mass/time
or total load, mass
Q is the flow rate, volume/time or
runoff volume and
a, b are regression coefficients

This power function is based on empirical sediment transport relationships (Graf, 1971 ; Vanoni, 1975) found in streams. A regression analysis for the measured events was undertaken using an equation of the form of equation 4.1. The results are presented in Table 4.3.

Table 4.3 : Regression and correlation coefficients for power function

Param	Average Coeff b	Min-Max	Average Coeff a	Min-Max	Ave Corre Coeff	Min-Max
TDS	0,894	0,44-1,29	0,0985	0,034-0,261	0,92	0,75-0,996
SS	1,517	0,89-2,04	0,395	0,177-0,934	0,90	0,5-0,998
no_3	0,417	-0,692-1,234	-6,702	0,00015-0,011	0,40	-0,41-0,96
SO_4	0,82	0,67-1,128	0,02	0,01-0,034	0,97	0,923-0,996

The nitrates showed the lowest average correlation coefficient and for some of the events the analysis showed a strong negative correlation. This was due to the rise in the nitrate concentrations towards the end of the events. The analysis for the sulphates gave the best results with the smallest ranges for the coefficients of the power function. The analysis showed that the coefficient b for all the pollutants varied from event to event giving values that were both above and below 1. For the TDS analysis the coefficient b was for all except 1 event below 1 while for SS the coefficient was always above 1 except for event 1. The analysis also gave a low correlation coefficient of 0,5 for this event for the SS.

This approach, although modelling the variation of the pollutant load over an event, will have to be used with caution as the coefficients of the power function vary from event to event and would probably be different from catchment to catchment. The method does not take into account the depletion of the supply of pollutants on the catchment surface nor can the variation of the washout contribution by rain be considered from event to event or over a particular rainfall event as in the case of nitrates.

To take into account the depletion of the storage of pollutants on the catchment, it is often assumed that the mass of pollutant washed off a catchment is taken to be proportional to the mass of pollutant remaining on the catchment. This can be coupled with the power function to give the following equation.

$$\frac{dp}{dt}=-aQ^{b}P \qquad 4.2$$

where P is the amount of pollutant remaining
Q is the runoff rate mm/h
and a and b are coefficients

The earliest quality models such as SWMM and STORM and later ILLUDAS-QUAL have used this exponential decay equation to model the washoff of pollutants off impermeable surfaces.
Equation 4.2 can be integrated to give

$$P=P_{o}e^{(-aQ^{b}t)} \qquad 4.3$$

where Po is the initial amount of pollutant. The quantity of pollutant washed off is therefore given by

$$G=Po-P \qquad 4.4$$

$$\Delta G=P(t)\ (1-e^{-aQ^{b}\Delta t}) \qquad 4.5$$

The primary assumption for use of equation 4.2 and 4.3 is that the rate of constituent washoff is proportional to the amount remaining on the land surface. Nakamura (1984) studied the validity of equation 4.2 without the exponent b under different runoff conditions and found that the decay coefficient a was not a constant and that the rate of removal of the sodium chloride pollutant used, was dependent on the roughness and slope of the catchment as well as the overland flow intensity. The work of Nakamura was used by Akan (1987) to further to test a model that states that the rate of pollutant detachment is proportional to both the mass of pollutant on the surface and the bottom shear stress.

$$\frac{dP}{dt}=-kSyP \qquad 4.6$$

where P is the mass of pollutant per unit surface area.
S_0y is the bottom shear stress on a wide rectangular plane S_0 being the bed slope and y the flow depth.
k is a constant dependent only on the type of pollutant

If the kinematic wave theory is used to route the runoff over the catchments, the flow depth is given by

$$y=\left(\frac{qn}{\sqrt{S_0}}\right)^{\frac{3}{5}} \qquad 4.7$$

where q is the flow per unit width
n is Mannings roughness coefficient
s_0 is the bed slope

This equation can be substituted into 4.6 to yield

$$\frac{dP}{dt} = -ks_0^{.7} n^{.6} P \qquad 4.8$$

Equation 4.8 is very similar to the exponential decay function except that that the roughness and slope term have been introduced into the coefficient a of 4.2. The exponent of the flow rate is also fixed at 0,6.

In trying to reduce the extent of the empiricism, methods have been used which attempt to model the dynamics of the chemical processes taking place during washoff. There are a number of mechanisms or processes which a pollutant undergoes during its entrainment into overland flow during washoff. Bailey et al (1974) identified four mechanisms by which a pollutant is picked up during the washoff process. These are :-

1 The diffusion of the dissolved pollutant from the soil water into the overland flow.
2 The desorption of the chemical from the soil particles into the soil water or directly into the overland flow.
3 The dissolution of the solid phase chemical into the soil water or into overland flow.
4 The scouring of the solid phase chemical by hydraulic forces and subsequent transport and moving dissolution.

The washoff process is therefore a complex interaction between the chemical processes of dissolution, desorption-adsorption and the hydraulic properties of the flow. In addition non-conservative pollutants, such as the nutrients, can be assimilated or released by microorganisms and vegetation. Furthermore a pollutant can be removed from the overland flow by means of infiltration. The processes involved are dynamic, the kinetics of which are not as yet fully understood in particular the uptake or diffusion of a pollutant into the overland flow from the catchment surface or soil water.

Lee et al (1989), in modelling the removal of phosphorus by grass buffer strips, divided the pollutant between that in its particulate or sediment bound form and its dissolved state. Their conceptualization of the processes are shown in figure 4.8. They then developed two models viz a sediment transport model and a dissolved constituent model. The sediment transport model involved modelling the movement of different particle sizes while the adsorption - desorption kinetics were used to link the dissolved to the sediment bound or particulate form. The model also includes the modelling of the biological uptake of phosphorus by the grass buffer strips and the removal of the pollutant by infiltration.

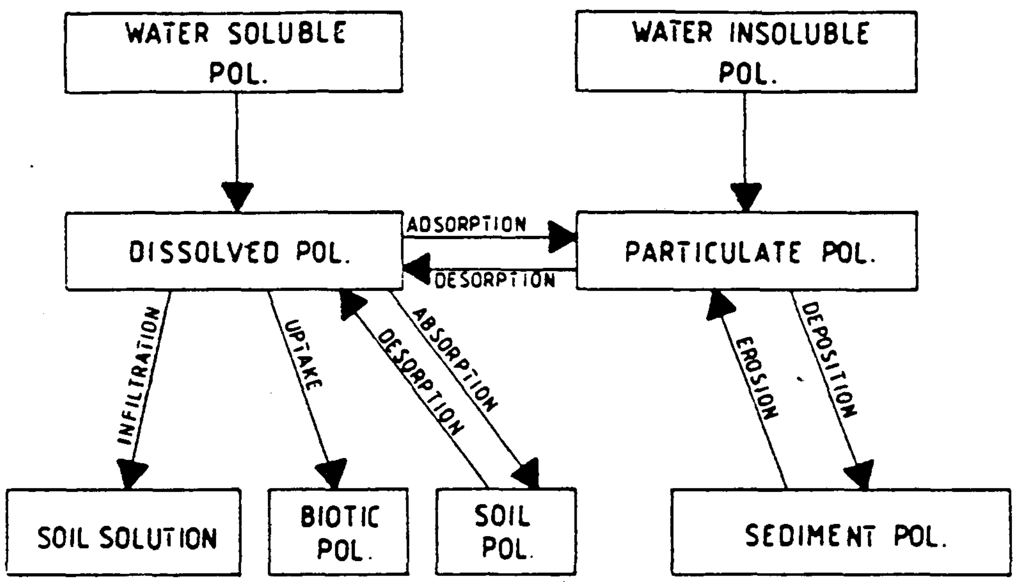

Figure 4.8. Conceptualization of the transport of phosphorus due to Lee et al (1989)

By balancing the mass fluxes of the various processes taking place between the pollutant in its dissolved and sediment bound form, equations were developed describing the movement and removal of phosphorus through vegetative filter strips.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

The quality monitoring program of the Hillbrow catchment showed that the dry weather flow could be considered to be an effluent when compared to the general effluent standards given by the Department of Water Affairs (1986). The quality of the dry flow could be improved by treatment at a sewage works or by using a series of oxidation dams. The storm runoff COD, SS, Fe, and ammonia concentrations exceeded those specified in the effluent standards. A detention storage facility could be used to improve the quality of storm runoff by removing the settleable portion of the suspended solids. This would remove much of the Fe, TKN, and the phosphorus as these showed significant correlations with the suspended solids. The runoff is high in COD and together with the nutrients in the runoff would cause eutrophication and possibly oxygen depletion in the receiving waters. The other major source of pollutant is the use of the main drainage channel from the catchment as a garbage disposal system. The decaying vegetable matter acts as a source of nutrients in the catchment and this combined with sewage leaks into the storm drainage system cause odours about which many of the residents have complained. During a runoff events this debris is picked up and transported downstream to the receiving waters.

Both the dry and wet fallout rates were different for the Mimosa and Roseneath sites. The time series of dry fallout rates for the two sites varied showing different trends. This could be due to a possible shortcoming of the fallout collection technique as the fallout on the funnels are subject to redistribution by wind and the local conditions around the collectors seem to play a role as well. More information about sources of wind blown pollution and the buildup of pollutants in the atmosphere had wind directions and possibly speeds been measured.

There is in general a net export of pollutants from the catchment. The contribution of the washout of pollutants from the atmosphere to the overall mass balance of pollutants varied from event to event. The extent of the contribution however seems to be dependent on the number of dry days, and the characteristics of the rain storm such as the peak intensity and rainfall depth. The atmospheric contribution to runoff does play a significant role in the overall pollutant mass balance for a catchment. An improvement to the fallout collection technique would be to be able to separate the dry fallout from the washout by rain so that the relative importance of the dry fallout can be compared to that washed out by the rain. Relationships could then also be sought between the antecedent dry days and the buildup of pollutants in the atmosphere and the subsequent washout by rain. Such relationships would prove useful in modelling the quality of runoff from a catchment.

The analysis of the quality data collected showed that BMP could be implemented for the Hillbrow catchment to improve the quality of the runoff. The stormwater drainage designer and planner needs the necessary analytical tools to be able to undertake such designs. The regression equations developed for the Hillbrow catchment could be used together with a hydrological model such as WITSKM for the generation of total loads. However for the analysis of BMP a more detailed output pollutograph and hydrograph will be required. To achieve this the deterministic approach will have to be adopted where the processes such as buildup, washoff and the deposition and scour of pollutants from the catchment surface and in the conduit system will have to be modelled. A quality model can be run with the necessary hydrological and hydraulic input being provided by a hydrological model, such as WITSKM. The model should be run on a continuous basis so that the buildup of pollutants between events both in the atmosphere and on the catchment surface can be modelled.

The successful modelling of the various processes involved in urban runoff pollution is difficult in that these processes are not fully understood. The application of the power function to the Hillbrow data showed that factors other than the flow rate effected the mass rate of pollutants removed from the catchment. The exponential decay function as used in SWMM and STORM includes the mass of pollutant available for washoff together with the power function. The use of this equation has also met with limited success with Huber et al (1982) stating that the application of the quality algorithms in SWMM can only be used with confidence if local data is available. A mass balance approach similar to that of Lee et al allows for greater modelling flexibility in that more of the processes that could be taking place during the washoff process can be included in the model. For instance variations of pollutant concentrations over a rainfall event can be included as well as the scour of pollutants from the catchment due to the energy of the rainfall. It is recommended that a quality model based on the mass balance approach be developed to model the quality of runoff to be run in conjunction with the WITSKM model.

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