A simplistic mass balance of storm-water pollutants for two urban catchments

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Abstract

Two catchments in Johannesburg, one a densely built-up city catchment and the other a suburban catchment were monitored under a storm-water research programme. Continuous flow and conductivity measurements were taken, and spot sampling for selected ions made during storms. Pollution loading is highest from the city catchment and in both cases storm runoff carries most of the pollution. Net atmospheric washout and fallout is of the same order as washoff of pollutants in the case of the suburban catchment. Nitrates exhibit an increase.

Introduction

The Water Systems Research Group have, in the course of research on urban hydrology and drainage, investigated pollution loadings from two catchments in Johannesburg (Green *et al.*, 1986). One, Montgomery Park, is a suburban catchment and the other, Hillbrow, a densely built-up city area. It is reported that non-point source pollution is responsible for 70% of the load in urban runoff (Wanielista, 1979), and it is largely this type of contribution which is detected here. Bradford (1977) attempts to relate pollutant loads to land use, and this paper contributes to his hypothesis. The unpredictability of runoff quality indicated by Simpson and Kemp (1982) is borne out though.

Catchment description

The Montgomery Park catchment is situated 6 km north-west of Johannesburg and measures 10,53 km^2 (1 053 ha). The population is estimated at 15 000. The developed area is 75% of the total and the remainder includes parks, a cemetery and undeveloped land. The development comprises housing and some commercial and light industry. There is a solid waste tip in the catchment from which seepage occurs. The catchment is fairly hilly, with slopes ranging from 0,02 m/m to 0,15 m/m. The main drainage system comprises natural and artificial channels. Rainfall over the catchment is recorded at five locations by autographic rain gauges. Runoff is measured at a gauging station at the catchment outlet in which the measuring element is a Crump weir with a bubble type recorder. Electrical conductivity of the water has been recorded continously since March 1983 (Green *et al.*, 1986).

The Hillbrow catchment measures 67,2 ha and is a fully developed urban area comprising high-rise buildings, some high density housing and a school. The population is estimated at 12 000. There are four rain gauges and a stream gauge in this catchment.

Both catchments have separate storm-water drainage systems (i.e. separate from waste sewerage systems).

Chemical constituents and suspended solids

Spot samples of storm-water runoff were collected during two storm events in Hillbrow and during one in Montgomery Park. In addition several dry weather flow samples were collected in both catchments. The number of samples taken and sampling intervals are listed in Tables 1 to 5.

These samples were analysed to quantify the presence of nitrates, sulphates, chlorides and bicarbonates as it was considered that these were the major anions present in the water. The analyses were undertaken by an independent commercial firm using titration techniques.

The highest anion concentration was found to be bicarbonate, followed by sulphates during storm runoff, and chloride in dry weather conditions. Sulphates appear to be predominant in Johannesburg and could be wind-blown from neighbouring mine waste tips which have high sulphur concentrations which oxidise to sulphates on the surfaces of the waste tips. Sulphates also reach concentrations of over 300 mg/ℓ in water supplies for the area.

The proportion of nitrates, sulphates, chlorides and bicarbonates to the total dissolved solids is much lower in storm runoff than in the dry weather flow analysed. In the latter case 68,6% of the TDS consists of these anions whereas this proportion is as low as 38,8% in the storm runoff (averaged over both catchments) indicating probable washoff of other constituents which do not appear in the dry weather flow.

As one would expect, the concentration of suspended solids in dry weather flow is much lower than in the storm runoff, indicating a higher transport rate of sediments as well as possible erosion during storms. For the samples analysed, the suspended solids in the dry weather flow averaged only 27 mg/ℓ compared with an average of 236 mg/ℓ for the storm flows.

Comparison of Tables 4 and 5 (dry weather flows) with Tables 1, 2 and 3 reveals that the TDS concentrations are considerably higher in dry weather flows than in storm flows. The average TDS for the dry weather flow samples is 772 mg/ℓ for Hillbrow and 612 mg/ℓ for Montgomery Park while average values of TDS for the three storm flows monitored are 125 mg/ℓ, 113 mg/ℓ and 117 mg/ℓ, indicating that the dry weather flow has about five times as high a concentration of TDS as storm-water runoff. The base load of TDS from Montgomery Park appears to be largely from leachate entering a storm-water culvert passing under the refuse tip. This load is of the order of 160 000 kg/a or 150 kg/ha.a averaged over the catchment (Ball, 1984). The reason for the high base load of TDS off the Hillbrow catchment is not entirely clear. It is thought that illegal discharges of effluent into the drainage system may be partly responsible for this.

The proportions of nitrates are also much higher in the dry weather flow than in the storm-water runoff. In the case of the dry weather flow sampled in the winter months of 1982 (Table 4), the levels of nitrate are so high as to suggest possible blockage

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TABLE 1
RESULTS OF CHEMICAL ANALYSES ON RAINFALL AND RUNOFF SAMPLES FOR HILLBROW ON 03/01/85

Sample mark	Time taken	pH	Conductivity mS/m	TDS mg/ℓ	Suspended solids mg/ℓ	Nitrate mg/ℓ	Sulphate mg/ℓ	Chloride mg/ℓ	Bicarbonate mg/ℓ
H1	20h11	6,20	14,37	1 38	1 010	0,2	12	5,1	36
H2	20h14	6,30	13,12	112	242	0,3	10	4,1	34
H3	20h18	6,05	11,87	134	760	0,8	10	3,0	36
H4	20h23	6,00	9,69	102	770	4,1	10	3,0	24
H5	20h26	5,55	9,91	100	512	8,6	11	5,1	10
H6	20h31	5,85	10,88	126	232	5,3	13	5,1	24
H7	20h50	5,45	13,37	120	180	15,0	16	7,1	10
H8	21h01	5,90	15,43	170	102	12,9	21	8,2	27
R*	N/A	5,55	6,60	78	63	2,7	4	3,8	6

* Rainfall sample collected over duration of storm

TABLE 2
RESULTS OF CHEMICAL ANALYSES ON RAINFALL AND RUNOFF SAMPLES FOR HILLBROW ON 18/01/85

Sample mark	Time taken	pH	Conductivity mS/m	TDS mg/ℓ	Suspended solids mg/ℓ	Nitrate mg/ℓ	Sulphate mg/ℓ	Chloride mg/ℓ	Bicarbonate mg/ℓ
18/1	14h27	6,35	46,10	346	64	<0,1	64	37,0	122
18/2	14h32	6,35	35,50	265	84	<0,1	57	30,0	90
18/3	14h38	6,15	24,50	182	380	<0,1	23	12,3	85
18/4	14h44	6,35	13,40	104	130	<0,1	17	10,3	36
18/5	14h50	6,15	8,88	69	204	<0,1	13	8,2	20
18/6	14h52	5,85	8,23	65	44	0,3	14	7,1	14
18/7	14h54	6,20	6,29	55	92	0,1	14	6,1	12
18/8	14h57	5,60	7,03	65	56	0,2	12	10,2	7
18/9	15h00	5,65	6,14	48	8	0,2	11	4,1	10
18/10	15h04	5,70	5,95	60	<1	0,2	10	6,1	7
18/11	15h09	5,85	5,92	49	<1	0,2	11	6,1	7
18/12	15h16	5,70	6,58	50	2	0,3	10	5,1	7
R *	N/A	6,07	2,20	18	<1	0,1	4	8,2	6

* Rainfall sample collected over duration of storm (analysis for this rainfall sample suspect as TDS<sum of anion concentrations)

TABLE 3
RESULTS OF CHEMICAL ANALYSES ON RAINFALL AND RUNOFF SAMPLES FOR MONTGOMERY PARK ON 07/03/83

Sample mark	Time taken	pH	Conductivity mS/m	TDS mg/ℓ	Suspended solids mg/ℓ	Nitrate mg/ℓ	Sulphate mg/ℓ	Chloride mg/ℓ	Ca Carbonate mg/ℓ
SD1/1	***	6,25	13,26	104	95	<0,1	10	6,3	30
SD1/2		5,85	10,37	86	200	0,7	16	5,2	20
SD1/3		6,00	12,97	112	450	2,2	13	6,3	31
SA1/1		6,20	22,30	166	44	1,5	25	16,0	16
RF1/1		7,25	10,86	52	**	0,4	**	**	21

* Rainfall sample collected over duration of storm
** Insufficient sample collected for this analysis
*** Samples collected in order listed – no times taken

TABLE 4
RESULTS OF CHEMICAL ANALYSES ON DRY WEATHER FLOW SAMPLES FROM MONTGOMERY PARK

Sample mark	Date taken	pH	Conductivity mS/m	TDS mg/ℓ	Suspended solids mg/ℓ	Nitrate mg/ℓ	Sulphate mg/ℓ	Chloride mg/ℓ	Bicarbonate mg/ℓ
SAD1	Aug 82	6,35	77,80	708	10	210,0	100	34	15
SAD2	Oct 82	8,45	249,00	1 625	4	91,0	15	480	456
SCD1	Oct 82	8,45	51,60	374	12	10,0	16	45	175
SAD3	Oct 82	8,40	78,80	544	12	11,8	64	101	202
SBD1	Oct 82	8,25	66,30	446	10	30,4	42	86	183
SDD2	Mar 83	7,45	41,90	320	24	4,0	18	29	not done
SED2	Mar 83	5,45	37,70	262	14	0,7	25	10	not done
SAD5	Mar 83	7,85	88,90	620	18	2,8	40	120	not done

TABLE 5 RESULTS OF CHEMICAL ANALYSES ON DRY WEATHER FLOW SAMPLES FROM HILLBROW									
Sample mark	Date taken	pH	Conductivity mS/m	TDS mg/ℓ	Suspended solids mg/ℓ	Nitrate mg/ℓ	Sulphate mg/ℓ	Chloride mg/ℓ	Bicarbonate mg/ℓ
HDWF17	Feb 86	6,55	87,10	580	80	<0,1	80	130	183
HDWF24	Feb 86	7,15	126,00	964	82	<0,1	177	160	307

of a sanitary sewer with the resulting overflow entering the stream. It was observed for all three runoff events that the nitrate concentrations increased over the duration of each hydrograph, reaching their maxima on the recession limbs of the respective hydrographs. A possible explanation for this phenomenon is that lightning activity will increase the nitrate levels in the rainfall during the course of the storm, resulting in increasing nitrate concentrations in the runoff with time. There were, however, large differences in magnitudes of nitrate concentrations between events, these concentrations ranging from as low as 0,2 mg/ℓ to 12,9 mg/ℓ. The latter value is considerably in excess of the recommended limit in domestic water, viz. 6,0 mg/ℓ with an upper limit of 10,0 mg/ℓ (SABS, 1984).

Samples of storm-water runoff were obtained on the rising limb of the hydrograph of 18 January 1985 in Hillbrow, making it possible to detect a flushing effect at the start of the runoff. The high TDS concentrations at the early stages of the runoff, viz. 346 mg/ℓ and 265 mg/ℓ, followed by a time-dependant decrease in TDS concentration to final levels of about 60 mg/ℓ indicate a "first flush" effect in accordance with the findings of many others (e.g. Cordery, 1977; Helsel *et al.*, 1979).

There does not appear to be any definite time-related decrease or increase in the levels of the other constituents in the runoff. For example, sulphate concentrations increased with time in the runoff from Hillbrow on 3 January while the converse is true for the runoff on 18 January 1985 from the same catchment.

Plots of pollutant concentrations with time for the Hillbrow events are presented in Figs. 1 and 2.

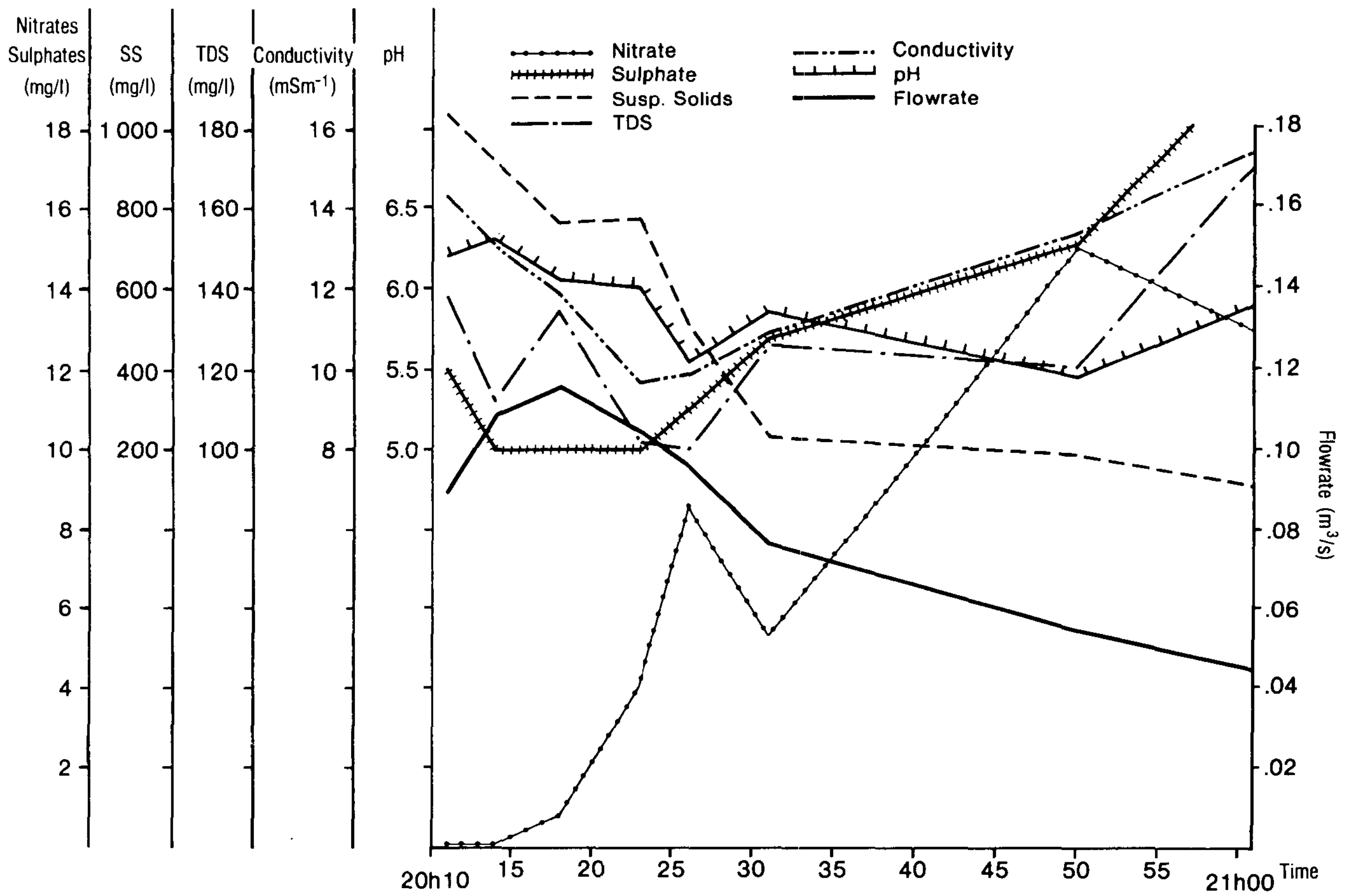

Figure 1
Plot of pollutant concentrations vs. time for rainfall-runoff event in Hillbrow on 03/01/85.

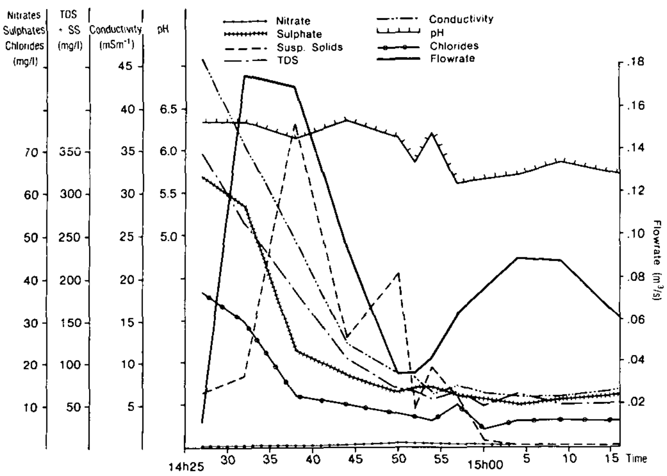

Figure 2
Plot of pollutant concentrations vs. time for rainfall-runoff event in Hillbrow on 18/01/85.

Relationship between total pollutant load and runoff volume

As the determination of TDS of a sample of water generally requires laboratory analysis, it has been found more convenient to use electrical conductivity for field measurement of salinity. By means of a regression analysis on data from 25 storm-water samples collected from Hillbrow, a relationship between electrical conductivity measurements and TDS was established. Continuous monitoring of electrical conductivity and flow rate thus enabled the computation of pollutant loads.

A regression analysis was performed on the pollutant load – flow volume data for the events listed in Table 6 to determine whether any definite relationship could be established between these parameters.

Considering data from Montgomery Park alone results in the equation

$$W = 3395{,}96 + 0{,}23V \quad (1)$$

with a correlation coefficient of 0,84. W is the mass of transported dissolved solids in kg and V is the volume of runoff in m^3.

With the inclusion of the data from Hillbrow, the equation becomes

$$W = 1186{,}29 + 0{,}27V \quad (2)$$

with a correlation coefficient of 0,90.

Treated separately, the relationship between pollution load and dry weather flow volumes is

$$W = 3{,}24 + 0{,}55V \quad (3)$$

with a coefficient of correlation of 0,97.

Relationship between TDS concentrations and antecedent dry period

Certain researchers have observed a correlation between the number of dry days preceding a storm and the level of pollution of the resulting runoff (e.g. Sartor *et al.*, 1974; Colwill *et al.*, 1984) while others maintain that no such relationship exists (e.g. Whipple *et al.*, 1977; Bedient, 1980).

An attempt was made to see whether the peak concentration of TDS could be related to the number of antecedent dry days with a maximum of 5d. A regression analysis was performed on all the data available and the best fit resulted from a linear relationship having a correlation coefficient of 0,12.

In a further test, TDS was correlated with antecedent moisture condition. The four antecedent moisture condition classes proposed by Terstriep and Stall (1974) were used and the correlation coefficient in this case increased to 0,29.

It is therefore apparent that from the data available no relationship between TDS and antecedent moisture condition could be found.

Fallout measurement

An attempt was made to assess the level of TDS occurring as atmospheric fallout on the Montgomery Park catchment. After a period of 28d without any rainfall during the winter months of 1984, the rain gauges in the catchment were "washed down" with distilled water, this water being collected in a sample bottle. It was found that the TDS within the funnels averaged 9,5 mg. Since this was deposited onto a funnel area of 0,020 m^2 it was deduced that the equivalent fallout loading on the Montgomery Park catchment was 4,75 kg/ha over 28d. If washout were omitted this would represent 62 kg/ha.a. Atmospheric fallout was collected in a funnel with an area of 0,72 m^2 at a location near the Hillbrow catchment over a period of 18d with no rainfall during the summer of 1985. It was found that the TDS within the funnel in this case was 188 mg resulting in an atmospheric loading rate of 48 kg/ha.a. A longer monitoring period would, however, be required to confirm these figures.

Mass balance for event of 18/01/85 on Hillbrow catchment

A rainfall depth of 6 mm was measured for this event and the TDS concentration in the rainfall was 18 mg/ℓ (Table 2). This can also be expressed as a rainfall loading rate of 0,18 kg/ha.mm of rain or 1,08 kg/ha in total. For a catchment size of 67,2 ha this depth of rainfall corresponds to 4 030 m^3 of rainfall over the catchment with a mass of 73 kg of pollutants.

For this event a runoff volume of 475 m^3 and a total load of 121 kg of pollutant were estimated. There was thus a net washoff of 48 kg of pollutant from the catchment. Expressing the pollutant load in the runoff in terms of catchment area and rainfall gives 0,30 kg/ha.mm or 1,8 kg/ha total.

The sources of these pollutants have not been identified, but in a densely developed area like Hillbrow, the most likely sources are washoff of deposits from wind and motor vehicles and soluble fractions of litter which is usually present.

Since the runoff was only 12% of the rainfall and the catchment still experienced a net washoff of pollutants, with 66% more pollutant being washed off than was deposited by the rainfall, it is conceivable that this washoff may reach even higher percentages for events where the proportion of runoff to rainfall is greater. Such events would result from storms having a greater depth of higher intensity rainfall. It is also possible that input during one storm is stored and released after loss of moisture, to be washed off during a subsequent storm.

Mass balance for event of 07/03/83 on Montgomery Park catchment

On 07/03/83 a total depth of 14 mm of rainfall was recorded on the Montgomery Park catchment. This event was preceded by a time period exceeding five days of no rain, so it is not surprising that the TDS concentration of the rainfall is much higher than that measured in Hillbrow on 18/10/85 when only two dry days had passed. The measured TDS of the rainfall was 52 mg/ℓ (Table 3), resulting in a rainfall loading rate of 0,52 kg/ha.mm. The total mass of soluble pollutants deposited on this 10,53 km^2 catchment was thus 7 666 kg in 147 420 m^3 of rainfall.

A runoff volume of 5 508 m^3 with a corresponding cumulative runoff load of 1 479 kg of dissolved pollutant was measured. In terms of rainfall this pollutant load can be expressed as 0,10 kg/ha.mm. The runoff volume represents only 4% of the rainfall and the TDS washed off 19% of that deposited by the rainfall. In this case the catchment therefore experienced a net gain of 6 187 kg of pollutant, or 81% of that deposited. This corresponds to a net gain of 5,87 kg/ha or 0,42 kg/ha.mm of rain-borne pollutant i.e. net deposition of pollutant occurred in the peri-urban catchment while net washoff occurred in the densely developed catchment. Since there is a deposit (loss of matter) from rain as indicated by the Montgomery Park catchment it can be expected that a similar deposit would occur in Hillbrow, so the litter load must be higher.

Once again it is difficult to attempt to identify the sources of pollutants washed off this catchment. Referring to Tables 2 and 3 it will be seen that nitrate levels in the runoff are higher for this catchment than for the Hillbrow catchment of 18/01/85, signifying the possible washoff of decaying vegetation, animal faeces and garden fertilisers. This seems a reasonable deduction as the Montgomery Park catchment consists of predominantly suburban residential developments with gardens. Another source in Montgomery Park could be leachate from the ground (either previously deposited by rain seeping in or from soil minerals). It is noted that the proportion of sulphates in runoff is similar to those in the rain, but chlorides exhibit an increase.

It appears that sulphates in chlorides are unaffected by the two different land uses, the respective levels being of the same order for both catchments which also indicates they may be air-borne into the chatchment. It has also been observed that there are (illegal) discharges of industrial wastes into the separate storm-water system in Hillbrow.

Generalised mass balance of pollutants

In the mass balance of pollutants outlined above it was found possible in both the Hillbrow and the Montgomery Park catchments to relate the pollutant load in the runoff to the load in the rainfall causing that runoff. To determine whether the catchment has experienced a net loss or gain of pollutants it is also necessary to know the TDS concentration of the rainfall as well as the runoff. In the present project rainfall quality was analysed for only three events (Tables 1, 2 and 3), TDS levels in the rainfall being 18 mg/ℓ (Hillbrow), 52 mg/ℓ (Montgomery Park) and 78 mg/ℓ (Hillbrow). A TDS concentration of 118 mg/ℓ in rainfall was observed by Madisha (1983) at a location near the Hillbrow catchment.

Assuming a rainfall loading rate of 0,52 kg/ha.mm for Montgomery Park and an average rainfall loading rate of 0,71 kg/ha.mm for Hillbrow, albeit from a sparse data base, the total weight of dissolved solids deposited on the two catchments was computed for twelve rainfall-runoff events for which both discharge and electrical conductivity data were available. These results are presented in Table 6.

It can be deduced from Table 6 that the average pollution load of runoff expressed in terms of rainfall is 0,40 kg/ha.mm of rainfall for Montgomery Park and 1,54 kg/ha.mm of rainfall for Hillbrow. While these findigs are based on reasonably sparse data, they are nevertheless in accordance with the findings of other researchers (e.g. Polls and Lanyon, 1980; Mikalsen, 1984), viz. that in general the level of pollution of storm water is higher from commercial and downtown land-use developments than for residential developments.

TABLE 6
COMPARISON OF POLLUTION LOADS IN RAINFALL AND RUNOFF WITH RAINFALL DEPTHS

Location and date	Rain-fall depth (mm)	Weight of deposited TDS (kg)	Weight of TDS in runoff (kg)	Ratio of runoff load to rainfall load	Pollution load in runoff (kg/ha.mm)
Montgomery Park					
07/03/83	14	7666*	1479	0,19	0,10
09/12/83	13	7118	7356	1,03	0,54
12/12/83	17	9309	13086	1,41	0,73
21/01/85	46	25188	23451	0,93	0,48
30/10/85	55	30116	15872	0,53	0,27
31/10/85	24	13141	7688	0,59	0,30
01/11/85	67	36687	26391	0,72	0,37
Hillbrow					
13/08/84	1	48	247	5,15	3,68
16/09/84	14	669	217	0,32	0,23
20/10/84	2	96	81	0,84	0,60
21/10/84	1	48	193	4,02	2,87
18/01/85	6	73*	121	1,66	0,30

Average TDS for Montgomery Park = 52 mg/ℓ
Average TDS for Hillbrow = 71 mg/ℓ
* Denotes measured TDS in rainfall used

TABLE 7
SUMMARY OF DISSOLVED LOADS IN kg/ha.a

Catch-ment	Atmos. fallout	Atmos. washout	Total washoff	Runoff net gain(+) or loss(−)	Storm washoff only
Montgomery Park	62	397	363	−96	305
Hillbrow	48	541	1520	+931	1190

Another interesting deduction from Table 6 is that more pollutant was deposited on the Montgomery Park catchment than was washed off for five out of the seven events while this was only the case for two out of five events in the Hillbrow catchment. The higher percentage imperviousness in the Hillbrow catchment is possibly the reason for this phenomenon.

Having established relationships between depth or rainfall and amount of pollutant washed off a catchment, annual pollutant loads can be computed.

Considering the Hillbrow catchment for example and assuming a mean annual precipitation of 763 mm (Adamson, 1981), the total mass of pollutants washed off this catchment will be of the order of 80 000 kg/a or 1 190 kg/ha.a. For the Montgomery Park catchment the amount of annual pollutant loading will be approximately 320 000 kg or 305 kg/ha.a.

Assuming an average dry weather flow of 0,0015 m^3/s or 130 m^3/d in Hillbrow and 310 dry days per annum results in an annual dry weather flow volume of approximately 40 300^3. This results in an annual dry weather pollutant load of approximately 22 100 kg or 330 kg/ha.a. The average dry weather flow in Montgomery Park is about 0,004m^3/s so the annual dry weather flow off this catchment is approximately 110 000 m^3 which corresponds to a total pollutant load of 60 500 kg or 57 kg/ha.a. Therefore it can be deduced that the annual pollutant load due to direct storm-water runoff is about 3,6 times that due to dry weather flow for the Hillbrow catchment and about 5,3 times that due to dry weather flow for the Montgomery Park catchment.

The pollutant loading rates derived from the different sources are summarised in Table 7.

Conclusions

Despite the limited monitoring and the resulting sparse data, the following tentative conclusions can be drawn:

The total dissolved pollution load in storm water and surface drainage from Hillbrow, a densely populated city area, is about 1 500 kg/ha.a which is about 3 times as great as from a suburban catchment, Montgomery Park. The majority (70% to 80%) occurs during storm runoff in both cases. Only about 430 kg/ha.a falls or is washed out of the atmosphere. The majority is therefore litter and from vehicles in the case of Hillbrow, and decaying vegetable matter or leachate from Montgomery Park.

There is a net gain of pollutants from Hillbrow but in Montgomery Park the total washoff is about the same order as the total deposited from the atmosphere. As a large proportion of rain seeps into the ground, it could store TDS to be released in future runoff. There is a net gain of nitrate in Montgomery Park, however.

Dry weather concentrations are higher in both catchments, due to seepage from a polluted landfill and the case of Montgomery Park (Ball, 1984) and illegal waste discharge in Hillbrow.

The majority of dissolved salts is washed off during the rising limb of the storms except nitrates which exhibit a lag. Release from the ground or alternatively the influence of atmospheric lightning could be the cause of this. Before prediction by modelling can be undertaken, intensive further investigation will be required.

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