The effect of different urban development types on stormwater runoff quality : A comparison between two Johannesburg catchments

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Abstract

The quality of urban stormwater runoff can be greatly affected by the type of development within the catchment and the level of management of the engineering services. This was investigated using water quality data from 2 areas near Johannesburg, namely Alexandra and Sunninghill Park. Alexandra township supports a mixture of formal and informal (squatter-type) developments, while Sunninghill Park comprises only a formal development. The level of maintenance of the services is considerably different between the 2 areas. The results of the monitoring period have shown that the stormflow off Alexandra is similar to raw sewage, for a number of pollutant concentrations, and the dry weather flow is comparable to settled sewage. The concentrations in the storm- and dry-weather flow off Sunninghill Park are considerably lower. Pollutant loads are greater from the Alexandra catchment by factors of between 20 and 130.

Introduction

South Africa is facing the problem of having to cope with very rapid growth in the urban areas. Much of this urbanisation is in the form of informal or squatter settlements, which generally have poor or non-existent services with regard to sanitation, water supply and refuse removal. The areas also support high population densities. The build-up of pollutants in such areas can be expected to be large, which could adversely affect the quality of stormwater runoff and dry-weather flow. Conversely, some of the formal developments in urban areas have low population densities, high living standards and are generally well serviced. Stormwater runoff from such areas can be expected to be of a relatively good quality.

The above supposition was examined by comparing the results of stormwater quality monitoring exercises from 2 Johannesburg catchments, namely Alexandra (Wimberley, 1992) and Sunninghill Park. The former catchment is a mixture of informal and formal settlements having a population density of some 500 /ha (De Jager, 1990), whilst the latter supports a formal settlement with a high living standard and a population density in the order of 14 /ha.

Catchment descriptions

The geographical setting of the 2 catchments is shown in Fig. 1, and further details on each of the catchments are given in the following sections.

Alexandra

Alexandra township is situated approximately 12 km NE of central Johannesburg and lies on the banks of the Jukskei River, which divides the township into the west and east banks. The west bank area measures 350 ha and contains a combination of formal and informal settlements in a high density residential development. The formal settlement comprises one dwelling unit per stand and is serviced with a piped water supply and water-borne sewerage

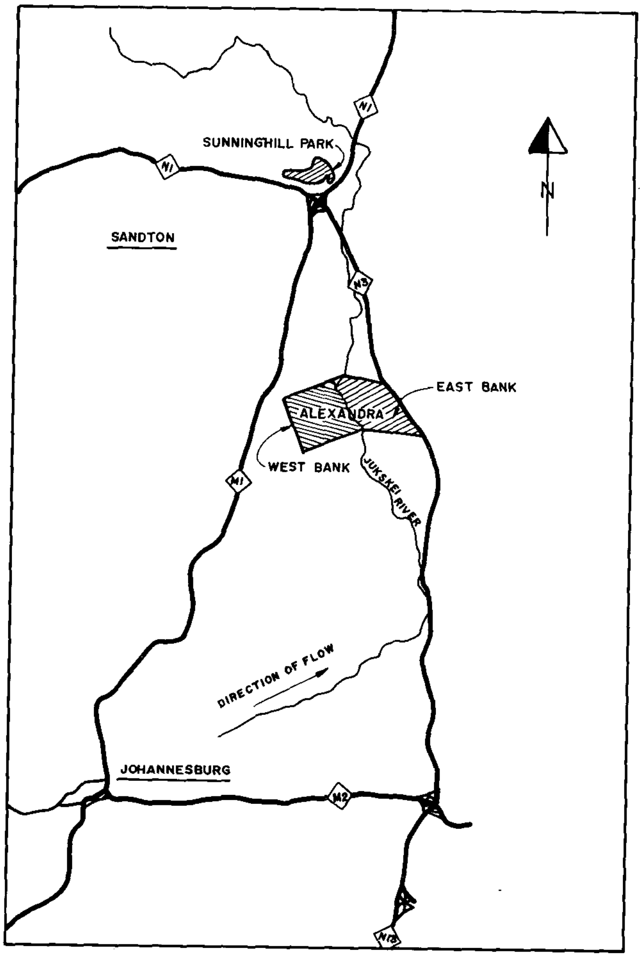

Figure 1
Locality plan

system. In the backyards of the formal settlement, shacks have been erected. The inhabitants of these shacks use the formal dwellings' water and sewerage system. In addition to the backyard shacks, shacks have been erected on any open area in particular along the flood plains and areas set aside for parks. These informal

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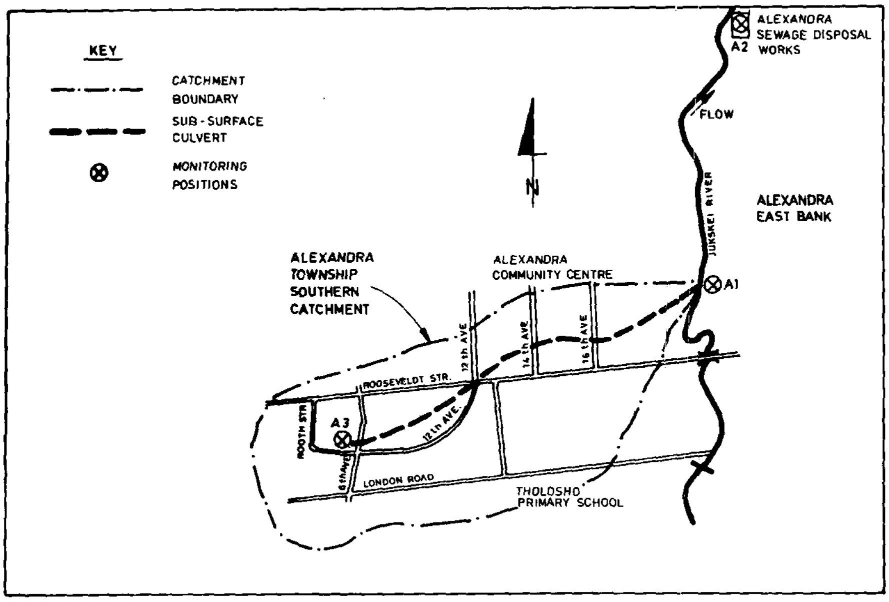

Figure 2
Alexandra catchment - layout and monitoring positions

settlements have stand pipes for water supply and a bucket system for sewage removal. These buckets are apparently emptied on a daily basis.

The west bank catchment is divided into 2 subcatchments by tributaries of the Jukskei River. The southernmost of these 2 subcatchments, measuring 162 ha, was chosen as the study area, and is shown in Fig. 2. This catchment contains sections of the formal and informal settlements, a primary and secondary school, a number of flats, and 2 hostels. The area has a network of tarred roads and the percentage imperviousness is estimated to be 70%. A fully developed stormwater pipe network services the area. Stormwater flow is via the pipe reticulation network to a subsurface concrete box culvert which follows the natural valley of the catchment and discharges into the Jukskei River. Stormwater flowing overland enters the subsurface culvert via grid inlets along its length. In this way all stormwater runoff exits the catchment at the discharge point of the subsurface culvert. In many cases shacks have been erected in the flood plain on top of these grid inlets. The vegetation cover in the catchment is sparse, with large areas being devoid of vegetation, and there are also very few trees.

The Alexandra area is underlain by highly weathered and decomposed granite (Partridge, De Villiers and Associates, 1980). The granite has decomposed to form a residual soil layer of loamy sand which varies in depth from 0,5 to 6,0 m.

Sunninghill Park

The Sunninghill Park catchment is situated to the north of Johannesburg in the municipality of Sandton. The catchment area is 75 ha and supports a formal development comprising houses, townhouses, flats, a shopping centre and office complexes (Fig. 3). The percentage imperviousness of the area is estimated at 20%. A well-defined water course runs through the central park area of the catchment. The park is well covered with grass and scattered trees. The area is served by a tarred road network, a stormwater reticulation network consisting of pipes and grass-lined channels and a water-borne sewerage network. Plot sizes in the catchment vary from 1 000 to 1 500 m^2. The gardens are generally well kept and grassed.

Analysis methodology

A pollutant mass balance approach was used to compare the effects of the different land-use types on the pollutant loads in the stormwater runoff and dry-weather flow. Pollutant contributions from the atmosphere due to dry fall-out and wash-out by rainfall can be considered as an input of pollutants to the catchment, and the ensuing runoff is the mechanism for the loosening up, suspension and subsequent transport of pollutants off the catchment surface. The mass of pollutants contributed from the atmosphere and in the runoff can be determined directly from a monitoring exercise, and the difference between these masses will give an indication of the catchment contribution to the pollutant mass balance.

The monitoring programme included data collection on both the quantity and quality of dry-weather and stormwater flow off the catchments. Bulk fall-out samples (wash-out by rainfall and dry fall-out) were collected after each event and analysed. The mass balance was developed for November 1991, and the concentration data presented in the paper are an average for October and November 1991.

Data collection

Data collection in the Alexandra catchment was done manually, due to the security difficulties of installing monitoring equipment in the area. The locations of the data collection points are shown in Fig. 2. The flow depth was measured at the discharge point of the subsurface culvert (Point A1). Dry-weather and stormflow samples were also taken at this point. Two tipping bucket rain gauges were installed, each coupled to an electronic data logger. The first of these was situated in the Alexandra sewage works (Point A2), and the second was installed in an old-age home within the catchment (Point A3). Rainfall samples were collected at the Alexandra sewage works using a funnel to guide the water into a collection bucket.

Data collection in the Sunninghill Park catchment was undertaken using electronic monitoring equipment. Details of the collection points are shown in Fig. 3. A DDS IDLE 816 data logger was

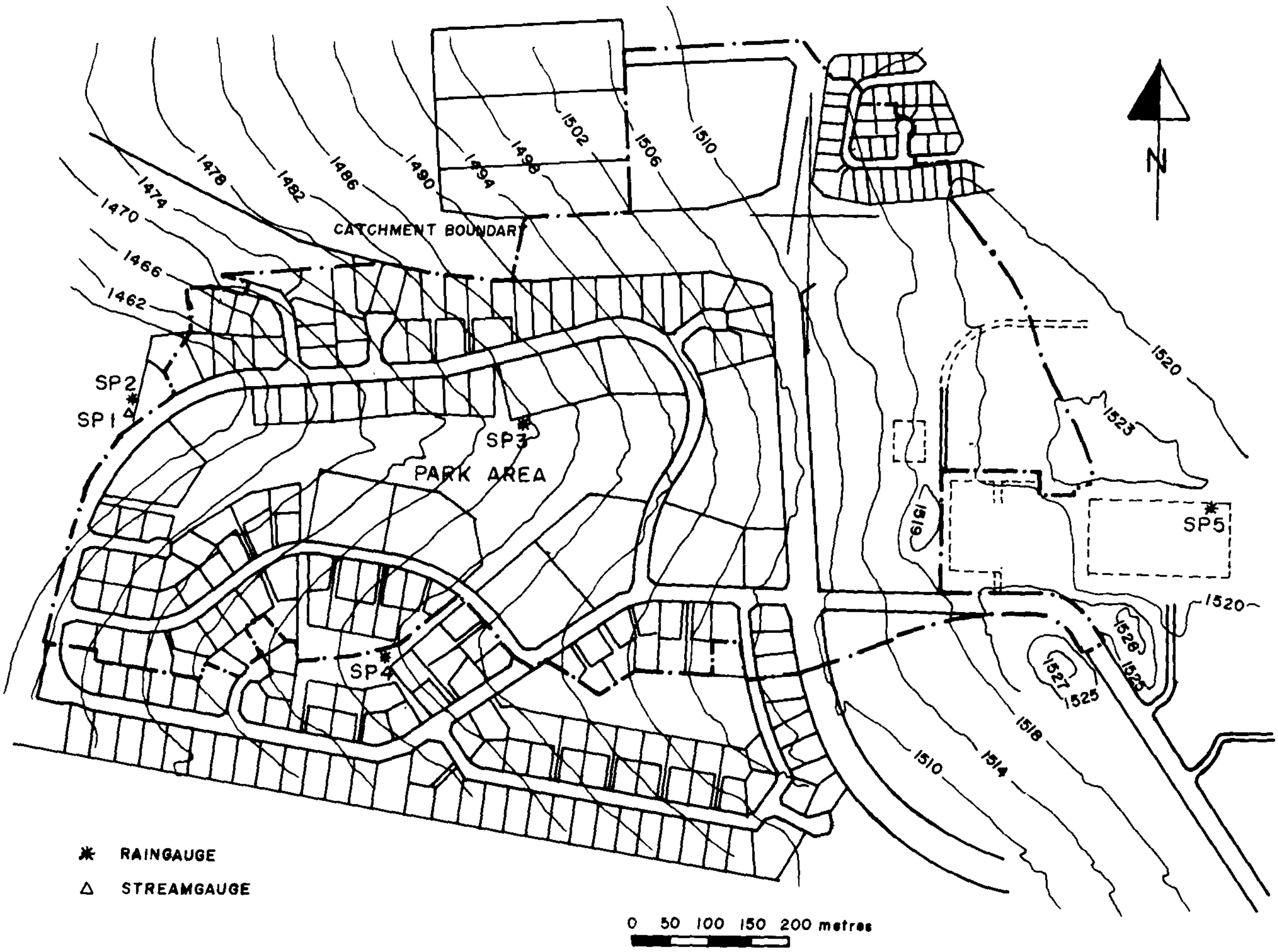

Figure 3
Sunninghill catchment - layout and monitoring positions

used, together with a WIKA pressure transducer, to measure stormwater and dry-weather flow depths at a crump weir situated at the catchment outlet (Point SP1). Water samples were collected at the same point using an ISCO 2900 sequential sampler. The sampler was operated on a volume basis, i.e. samples were collected after a preset water volume had been recorded by the logger. This method of operation ensured an adequate spread of samples through each storm event. Rainfall data were collected using 4 tipping bucket rain gauges connected to data loggers (Points SP2 to SP5). Rainfall samples were collected using a funnel to guide the water into a bucket, as in the Alexandra catchment. The samples collected by this method would therefore also include dry fall-out of pollutants settling on the funnels between storm events.

The bulk fall-out and runoff samples, collected during the monitoring exercise, were analysed at the Johannesburg City Council laboratory (CYDNA). The pollutant types investigated were suspended solids, chemical oxygen demand (COD), total dissolved solids (TDS), soluble phosphates (PO_4) and lead (Pb). These parameters were selected to give a general indication of the quality of the stormwater runoff and will enable comparisons to be made to drinking-water standards and typical muncipal waste waters. All tests were undertaken according to *Standard Methods* (1989). The test results were given as pollutant concentrations in mg/ℓ.

Results of the monitoring programme

The average pollutant concentrations over the monitoring period (October and November 1991) are given in Table 1, for the rainfall, stormflow and dry-weather flow. The average concentrations for the stormflow and rainfall given in Table 1 are based on 14 events. The event mean concentrations for each of the 14 events were used in determining the average stormflow concentrations presented in the table. The averages for the dry-weather flow concentrations were based on 9 samples. In this table, the PO_4 concentration is expressed as P and the Pb and COD concentrations are those from unfiltered samples. Data on the average pollutant concentrations in raw sewage, settled sewage (Ekama and Marais, 1984) and drinking water (Kempster et al., 1982 ; Pieterse, 1989) are also given in Table 1 for comparative purposes.

The pollutant mass balance details for the catchments are given in Table 2 for the period of November 1991. The pollutant loads are given in kg/ha of catchment. The load contribution from the catchment is calculated as the difference between the measured outflow and rainfall loads. A negative contribution, i.e., the pollutant load in the rainfall is greater than that in the outflow, indicates that the pollutant is not removed by stormwater runoff but by some other means such as infiltration into the soil or storage on the

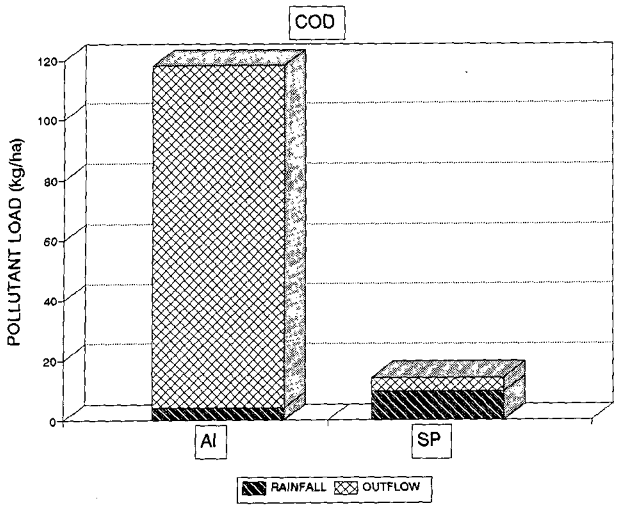

Figure 4 (a)
Pollutant loads (COD) for rainfall and outflow from Alexandra (Al) and Sunninghill Park (SP) catchments

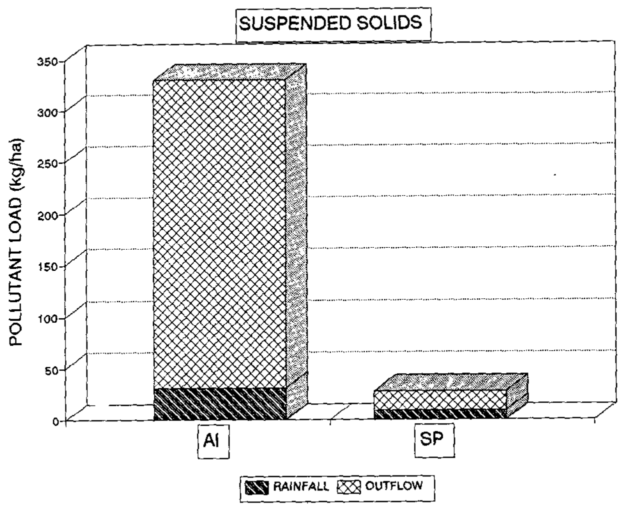

Figure 4 (b)
Pollutant loads (suspended solids) for rainfall and outflow from Alexandra (Al) and Sunninghill Park (SP) catchments

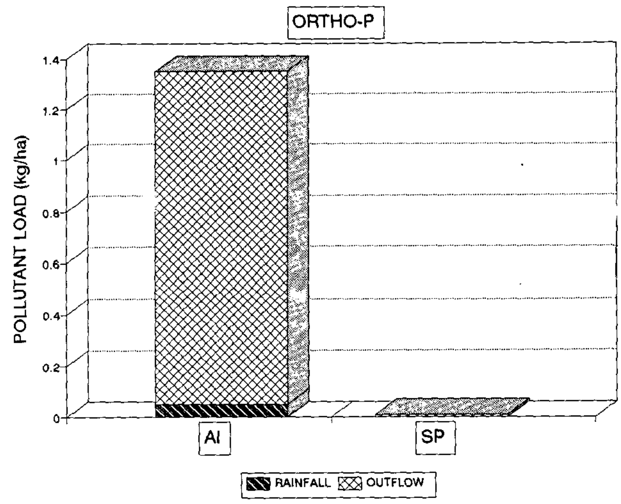

Figure 4 (c)
Pollutant loads (ortho-P) for rainfall and outflow from Alexandra (Al) and Sunninghill Park (SP) catchments

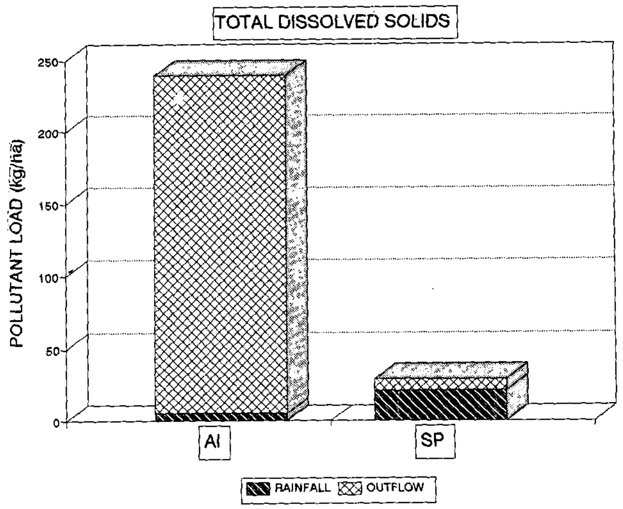

Figure 4 (d)
Pollutant loads (total dissolved solids) for rainfall and outflow from Alexandra (Al) and Sunninghill Park (SP) catchments

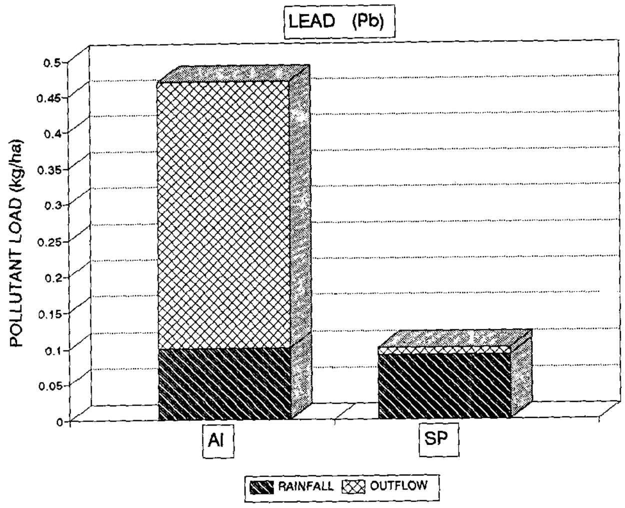

Figure 4 (e)
Pollutant loads (lead) for rainfall and outflow from Alexandra (Al) and Sunninghill Park (SP) catchments

catchment surface. The ratio of pollutant mass in the Alexandra outflow to that in the Sunninghill Park outflow is shown. Table 2 also gives various percentage details obtained from the pollutant mass balance. The first 2 rows of this section indicate the percentage of the outflow occurring in either the dry-weather flow or the stormflow. The last row shows the percentage contribution of pollutant load from the rainfall.

The pollutant mass data given in Table 2, are shown graphically in Figs. 4 (a) to (e), for the rainfall and outflow processes of the 2 catchments.

Discussion

Pollutant concentrations

The data in Table 1 indicate the magnitude of the pollution originating from Alexandra and the severity of the problem. The pollution concentrations for the stormflow from the township are approaching those of raw sewage, while the concentrations in the

TABLE 1
POLLUTANT CONCENTRATIONS FOR ALEXANDRA AND SUNNINGHILL PARK AND SELECTED POLLUTANT CONCENTRATIONS FOR SEWAGE AND DRINKING WATER

Catchment	Physical process	Pollutant concentration (mg/ℓ)				
		COD	SS	PO_4**	TDS	Pb
Alexandra	Stormflow	498	2 360	3,0	335	4,1
	DWF*	171	189	3,7	732	0,1
	Rainfall	30	160	0,2	38	0,6
Sunninghill Park	Stormflow	74	190	0,1	145	0,1
	DWF*	33	18	0,9	170	0,0
	Rainfall	16	18	0,0	36	0,2
		Pollutant concentration (mg/ℓ)				
Raw sewage		500-800	270-450	6-13	-	-
Settled sewage		300-600	150-300	4-10	-	-
Drinking water		-	25	0,1	-	0,05

* Dry-weather flow
** PO_4 expressed as P

TABLE 2
POLLUTANT MASS BALANCE FOR ALEXANDRA AND SUNNINGHILL PARK

Process	Pollutant loads (kg/ha) for selected pollutant types									
	COD		SS		PO_4*		TDS		Pb**	
	Al	SP	Al	SP	Al	SP	Al	SP	Al	SP
Rain	4	9,5	31	9	0,05	0,0	5	21	0,1	0,09
Catch.	110	-4,6	268	10	1,25	0,01	229	-14	0,27	-0,08
Outflow	114	4,9	299	19	1,30	0,01	234	8	0,37	0,01
	Ratio of pollutant loads : Alexandra to Sunninghill Park outflow									
	23		16		130		29		37	
	Percentages									
% Dry	48	5	36	2	89	0	90	15	45	0
% Storm	52	95	64	98	11	100	10	85	55	100
% Rain	3,5	194	10	47	4	0	2	274	28	818

* PO_4 expressed as P
** Pb as total lead concentration

dry-weather flow are similar to settled sewage. The ortho-P concentrations in the storm- and dry-weather flow from Alexandra are 30 times greater than the recommended criteria for drinking water. The ortho-P concentrations exceed the 1 mg/ℓ limit as P set for the Crocodile and Pienaars Rivers. Conversely, the COD and ortho-P concentrations in the flow off Sunninghill Park are well below those for settled sewage.

The pollutant concentrations for COD, SS and Pb are higher in the stormflow than in the dry-weather flow for both catchments. This would be as expected for the latter 2 pollutants, being transported to a larger extent in the faster flowing stormflow. The TDS concentrations are higher in the dry-weather flow for both catchments and the differences are marginal for PO_4.

Alexandra experienced higher rainfall concentrations for all pollutant types, but in the case of TDS the difference was again marginal. This indicates an apparent anomaly, as the pollutant load brought into Sunninghill Park was larger, despite the similar pollutant concentrations. This can be ascribed to the higher rainfall depths and intensities that occurred over Sunninghill Park.

An interesting observation evident from Table 1 is the large Pb concentrations in both the rainfall and the stormflow.

The concentration in the Alexandra stormflow is almost 100 times greater than the recommended limit for drinking water, while the rainfall Pb concentration is 12 times greater in Alexandra and 4 times greater in Sunninghill Park.

Pollutant mass balance

An inspection of the rainfall loads input into the pollutant mass balance shows that rainfall over Alexandra generally contributes less than 10% to the output load. The remainder originates from the catchment surface. In Sunninghill Park, the rainfall loads were the major contributor to the mass balance. This is adequately illustrated by the COD, TDS and Pb mass balances, where rainfall loads were 2 to 8 times greater than those in the outflow. This would indicate a build-up of pollutants on the catchment surface or possible infiltration of pollutants into the soil with subsequent percolation to the ground water. These pollutants could be transported off the catchment in subsequent storm- or dry-weather flow.

Research into the contribution of rainfall loads to the pollutant mass balance has shown a large variability of results. Simpson (1986) has shown that the contribution from atmospheric fall-out varies between pollutant types, being 12% for suspended solids, 22% for COD, 48% for soluble nitrogen and 30% for copper. Ng (1987) found rainfall contributions to be significant for various forms of nitrogen and heavy metals (copper and nickel). Coleman (1990) undertook an investigation in Hillbrow, Johannesburg, and found ratios of fall-out pollutant mass to runoff pollutant mass of 0,59 to 1,4 for TDS, 0,5 for ortho-P and 0,63 to 0,80 for sulphate.

The data in Table 2 and the graphs in Fig. 4 show that the outflow of pollutants per hectare from Alexandra is far greater than that from Sunninghill Park. The large pollution loading originating from Alexandra can be attributed to the following :

- The greater availability of pollutants on the catchment surface in Alexandra.
- The greater percentage runoff from Alexandra catchment as a result of the greater percentage imperviousness of the area. This is true even for the smaller, less intense storms.
- Inadequate street cleaning and refuse removal.
- Overflow and disposal of sewage from portable toilets servicing the informal settlements through the grid inlets into the stormwater culvert.
- Backyard mechanical operations.

Table 2 also shows that the dry-weather flow contributes to a significant portion of the total load off the Alexandra catchment, with 89% of ortho-P and 90% of TDS occurring in this flow. This is due to the constant stream of effluent (measuring approximately 20 ℓ/s) that was recorded in the subsurface culvert. Frequent visits to the catchment and the collection of samples from the culvert revealed that this flow originates largely from the emptying of sewage from buckets into the stormwater system and the washing of clothes and vehicles in the catchment.

The availability of pollutants on a catchment can be related to the management and upkeep of the engineering services and the population densities. Alexandra township is faced with the problem of overcrowding and poor living conditions in the area, which have stressed the engineering services. Emergency services have been provided for those people without access to formal networks, but maintenance of these services is poor and there is a lack of discipline by the local populace in using the services provided. The pollution loadings can only be reduced by reducing the population densities of the area, or providing adequate sanitary and refuse removal facilities for all of the residents. The problem is therefore both of a social and engineering nature and should be tackled accordingly. Sunninghill Park has well-maintained services and the population densities are such that these services are not unduly stressed. Pollution loads in the stormwater runoff from the area are therefore fairly low.

Conclusions

The significant pollution loads originating from Alexandra are due to overcrowding and poor living conditions in the area, which have stressed the management of the engineering services provided. The level of services would need to be increased, or the population density decreased, before the pollution loading from Alexandra would be reduced to the level of that from Sunninghill Park. These are both social and engineering solutions.

The water quality data from Alexandra have shown the stormwater runoff to be approaching the pollutant concentrations of raw sewage and to be well in excess of the recommended limits for drinking water. This would have an obvious health effect for the recreational use of the Jukskei River downstream of Alexandra.

The comparisons presented in this paper are based on measurements for one month only, and can therefore only give a window on the actual time series of pollutant loading. More extensive monitoring may indeed indicate different results. Notwithstanding this drawback, the data presented show quite conclusively the effect of different development types on the water quality of stormwater runoff and the pollution loading from an area.

Acknowledgements

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