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AN INVESTIGATION OF THE HYDROLOGICAL RESPONSE TO INFORMAL SETTLEMENTS ON SMALL CATCHMENTS IN SOUTH AFRICA

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ABSTRACT The hydrological response of an undisturbed Nature Reserve and an adjacent catchment in a developing urban fringe area are compared in an attempt to evaluate the effects of different land uses on sediment and stream water quality. In the disturbed catchment, peak discharge was attenuated, but suspended sediment and phosphate concentrations were higher than in the undisturbed catchment at any flow. Other water quality parameters also differed during low flow and storms. These differences in the hydrological response are attributed to differences in land use.

INTRODUCTION

Southern Africa is a semiarid region with very limited water resources that are being severely affected by a rapidly increasing population which is migrating toward the industrial areas. This large influx of unskilled rural people is producing rapidly expanding informal urban fringe settlements surrounding all the main metropolitan centres. These areas still contribute to agricultural production but in most instances comprise uneconomically viable agricultural units. They are frequently situated in hilly terrain and are usually managed by family units that are not fully conversant with recognized conservation practices. These settlements are producing considerable denudation and degradation of large areas which promotes increased erosion and subsequent pollution of major water resource schemes in Natal/KwaZulu.

One area which is experiencing exceptional growth is the urban and fringe area surrounding the relatively new harbor at Richards Bay (Fig. 1). Most of the local authorities in this region obtain their water from local impoundments which frequently need to be supplemented from other sources. Many of these sources are heavily polluted and require purification to meet health and industrial standards.

With the rapid expansion of the disorganized urban fringe areas, there is an urgent need to determine the influence of these settlements on the hydrological response of the contributing catchments and to develop management strategies for their control. Knowledge of these influences and their incorporation in hydrological models will be beneficial for water resources planning and management in the region.

Within this area of Natal, the hilly Ntuze research catchments near the University of Zululand, support both high density third world settlements and a protected natural ecosystem (Fig. 2). The Ngoye Nature Reserve, controlled by the Department of Nature Conservation, KwaZulu, is a small forest reserve that was scheduled for re-fencing and stocking with indigenous fauna during 1988. This has not been achieved and the area is still used for controlled grazing by the local inhabitants surrounding the reserve. The informal settlements in the Ntuze catchment are concentrated along the access roads and have their greatest density in the south-eastern areas which are closest to the main arterial roads leading to

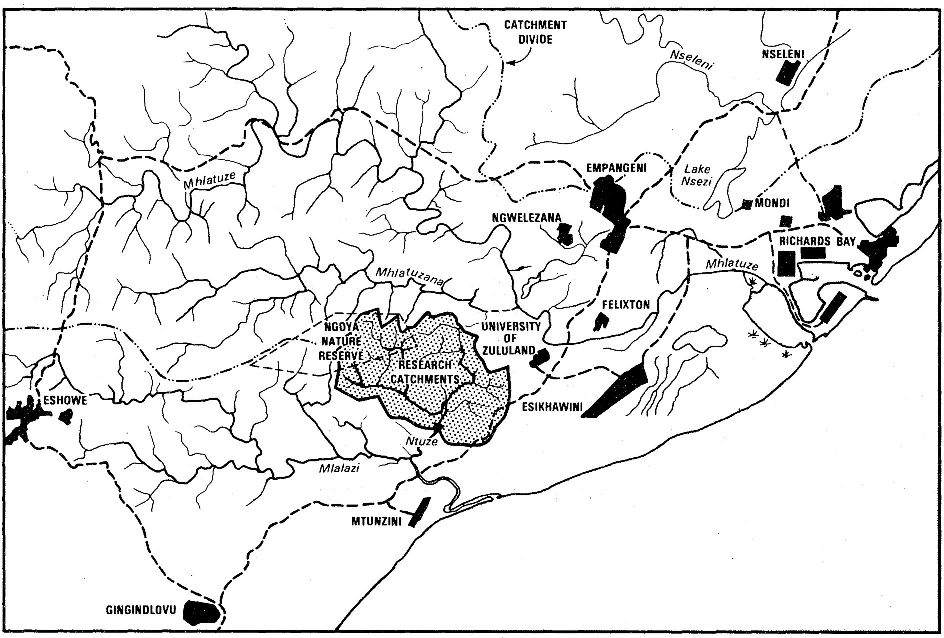

FIG. 1 The location of the Ntuze research catchments.

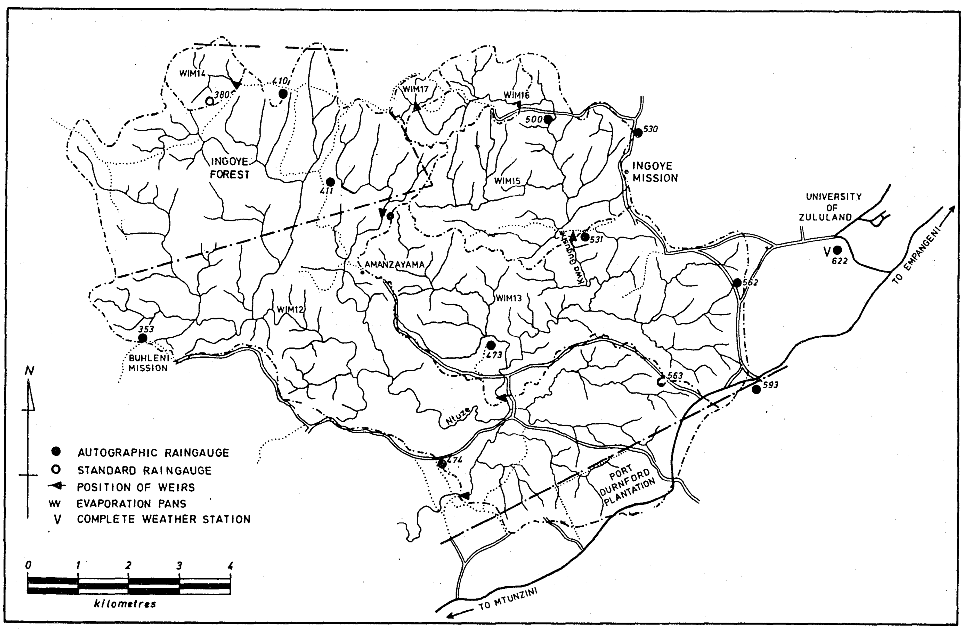

FIG. 2 Features of the Ntuze research catchments.

the industrial centers at Empangeni and Richards Bay. The more developed southeastern area comprise small fields of sugar cane and cash crops. However, sugar cane has been recently established in the northern areas and is expected to increase markedly with the new allocation of quotas to these areas and the shortage of cane at the new Felixton mill. This development is leading to improved roads and other communications which will promote further settlements in the area.

INSTRUMENTATION

The hydrological effects of the third world settlements in the Ntuze catchment are investigated through a direct comparison of the hydrological response of a disturbed catchment with a relatively pristine one (Ngoye Nature Reserve). The undisturbed catchment shares a common divide with a disturbed catchment of similar size which is situated in the same geological structure (Hope & Mulder, 1979). Situated at the same altitude and in such close proximity, these two catchments also share a similar climate.

Discharge for each catchment was monitored continuously from a rated sharp crested weir using a datalogger connected to a piezometer. The dataloggers integrate the flow over time and are programmed to activate automatic water samplers after a specified volume of cumulative discharge. Every two samples are combined for subsequent analyses. The sampler inlets at both weirs are located 200 mm below the V-notch. Bed load was estimated from surveys of sediment accumulation in the weir.

PHYSICAL CHARACTERISTICS OF THE CATCHMENTS

The hydrological response of a catchment is a reflection of the physiography and land use. Consequently it is necessary to quantify any significant differences in the physical features of the two catchments.

Climatology

Rainfall generally is derived from both free and forced convective activity. In winter, rainfall is dominated by widespread forced convection (frontal and orographic), and in summer numerous thunderstorms occur. The winter rainfall comes from the opposite direction than the summer rainfall. Along the east coast of southern Africa, the summer cumulonimbus generally tend to move toward the east-northeast under the influence of the upper level winds, whereas the forced convection is derived mainly from a low level southeasterly flow caused by invading synoptic systems moving along the east coast. The weather systems effect both catchments similarly, because the slopes are oriented southwest-northeast and the weather systems will move parallel or perpendicular to the topography. The catchments are at the same altitude and have the same orientation, consequently their rainfall regimes are very similar (Hope & Mulder, 1979).

Geomorphology

One of the prime factors controlling soil loss from a catchment is the velocity of runoff which is related to the topographical gradients. The disturbed catchment has approximately 10% more area with slopes between 10% and 20% and a correspondingly lower frequency of less than 10% slopes. However, the relative areas of slopes steeper than 20% are almost identical.

Because soils also effect the hydrological response of a catchment, the relative area of all the main soil types for each catchments was determined (Table 1). There is very little difference in the type (MacVicar *et al.*, 1977) and aerial distribution of the soils of the catchments. Nearly 70% of each catchment is covered by fairly deep Glenrosa (Robmore series; Gs18) soils, broadly classified as an inceptisol in the USDA system. Soils in the valley bottoms generally are Fernwood (Trafalgar series; Fw), have a high sand content, and cover more than 10% of each catchment. These and other hydrological factors are used to derive hydrological response units for SCS curve numbers. Comparisons of these integrated indices and other morphological parameters (Gupta & Waymire,1983) indicate that the unit hydrographs for the catchments should be similar.

Studies by Mulder (1988) of the deep, highly permeable, midslope, Glenrosa soils with a complete grass cover at the University of Zululand campus (Fig. 1) have shown that there is little or no significant overland flow. Most of the runoff during storms is derived from variable source areas from the footslopes and midslopes as through-flow. Consequently, the degradation of the catchment by denudation, cultivation and compaction of the soils is likely to cause changes in the hydrological response.

TABLE 1 Aerial distribution (%) of soil types (MacVicar et al., 1977).

Soil type	CV16	WE13	FW	HU16	GS18	MS	ROCK
Disturbed	0	3.80	7.40	0	67.2	6.90	14.65
Natural	1.19	5.94	7.57	1.09	69.1	4.96	10.16
Difference	1.19	2.14	0.17	1.09	1.90	-1.94	-4.49

LAND USE CHARACTERISTICS OF THE CATCHMENTS

Population and housing

There has been a significant change in development of the disturbed catchment since runoff data have been acquired. Because no population register is available for this catchment, the change in the density of dwellings was used to estimate demographic changes. The dwellings within the disturbed catchment have increased three fold in the last 18 years from approximately 100 in 1970, to nearly 300 in 1988. Extrapolations indicate the population will double in 10-12 years.

The individual dwellings (usually 4-m diameter circular huts) usually are clustered in small settlements. A demographic survey of the area revealed that the settlements comprised an average of 6 dwellings. Most of the vegetation within the settlements is cleared to produce an area of approximately 300 m^2 which is devoid of ground cover. The cleared area in some cases is 600 m^2 which includes outhouses (grain and fowl huts) and cattle stockades. The result is that about 1% of the catchment area is denuded by these settlements. Assuming an equivalent denuded area for paths and roads, then the total denuded area is 2% of the disturbed catchment at present. If the population continues to increase then the urbanization will double in the next 10-12 years. This estimate may be conservative because the area has ample water, a formal road infrastructure, and public transport.

Cultivation

The area affected by different cultivation practices was estimated from aerial photographs of the research catchment taken in 1978 and 1988 (Table 2 & Fig. 3). Land use patterns did not appear to change during this period in the undisturbed catchment. However, in the disturbed catchment, the percentage of the area used for exotic timber plantations has increased by 75% and sugarcane was not cultivated in 1978 but accounts for about 2% of the area in 1988.

TABLE 2 Total area of each land use type (km^2) in both catchments.

	Catchment and year			
	Natural		Disturbed	
Land use form	1978	1988	1978	1988
Indigenous forest	0.88	0.88	0.15	0.16
Exotic Plantation	0.00	0.00	0.12	0.22
Sugar Cane fields	0.00	0.00	0.00	0.06
Subsistence	0.00	0.00	0.09	0.09
Rocky outcrops	0.19	0.19	0.46	0.46
Grass & unidentified	2.06	2.06	2.51	2.35
Total area	3.13	3.13	3.34	3.34

The household fuel requirements and building materials in this area are derived frequently from the indigenous forest. Consequently, the disturbed catchment shows a significantly lower proportion of indigenous forest area than the undisturbed catchment. However, the area of indigenous forest has not changed much since 1978, which could indicate a shift toward more modern energy sources (paraffin) and the utilization of exotic timber. With the introduction of electricity and mortar, wood use will diminish further.

The area under other crops (subsistence) shown in Fig. 3 does not include small fields scattered around the individual settlements because they were difficult to digitize. Although changes in the total area of these fields could not be detected, it is probable that the number of small fields surrounding the settlements increased consistent with the tripling dwellings from 1978 to 1988.

Many land use features were sufficiently concentrated to be identified on aerial photographs, but not large enough to quantify. They include foot paths, roadways and smaller cultivated patches surrounding the settlements. Consequently, the cultivated area (approx 15%) is underestimated.

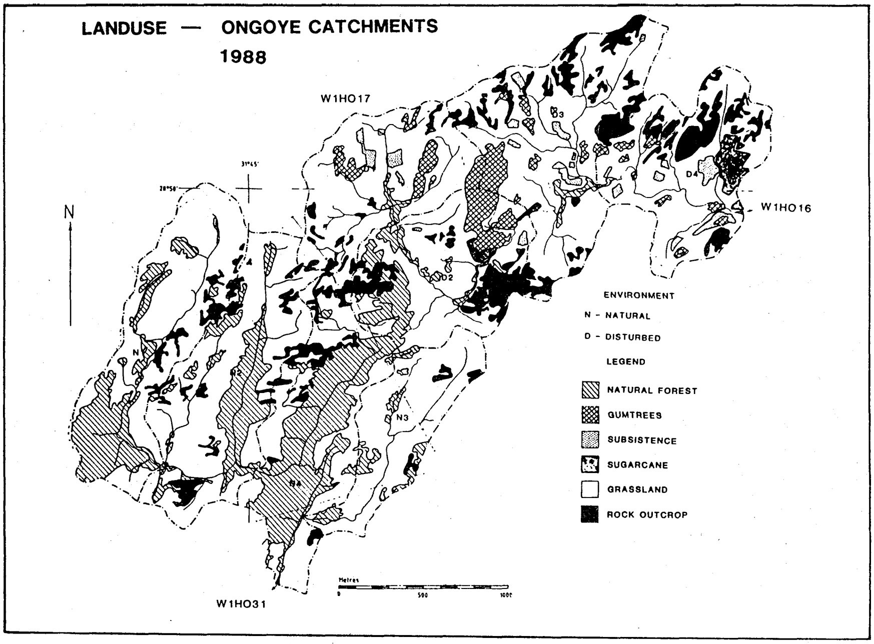

FIG. 3 Map showing the main land use forms for both catchments.

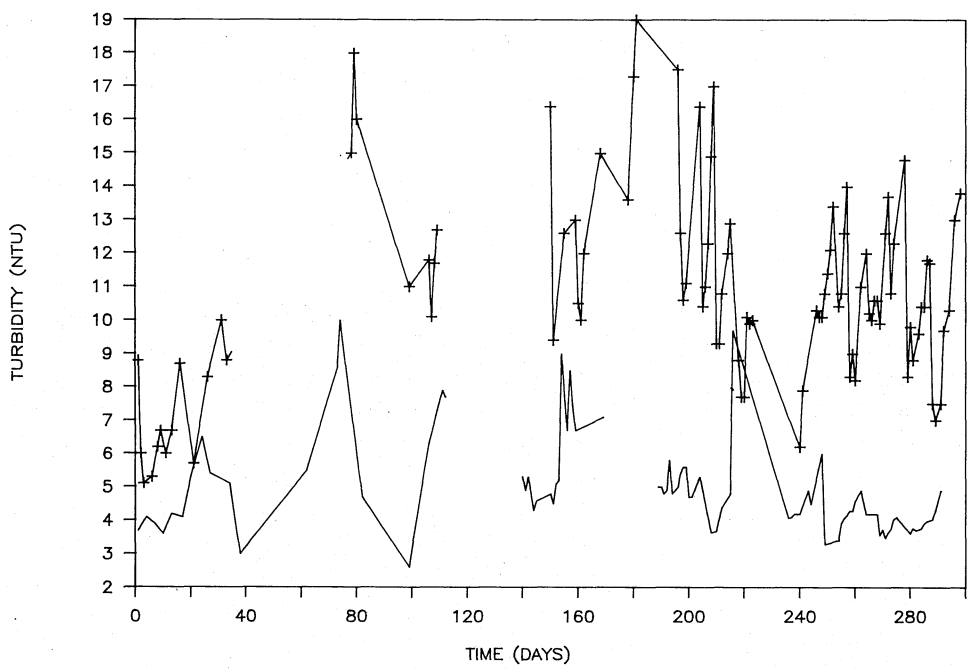

FIG. 4 Seasonal variation in turbidity (+ = disturbed catchment).

CHARACTERIZATION OF SUSPENDED AND DISSOLVED LOADS

Several factors play an important role in determining the water quality of a stream. Physical features of the catchment as well as hydrological factors will play a major role in defining the variability of water quality characteristics in a catchment. The sediment composition of a stream generally is a function of the erodibility of the soils and the ability of the precipitation to dislodge and transport soil particles to the stream. Consequently, water quality was expected to vary as a function of discharge. Water quality was examined seasonally and in relation to position on the hydrograph.

TABLE 3 Average sample characteristics for different flow regimes in the undisturbed (Nat) and disturbed (Dist) catchments.

Flow regime	Rising		Peak		Recession		Base	
Catchment	Nat	Dist	Nat	Dist	Nat	Dist	Nat	Dist
Flow sample 1	1.94	1.20	7.64	5.55	5.22	4.58	.19	.18
($l\ s^{-1}$) 2	2.65	1.63	7.17	5.47	4.84	4.26	0.18	0.17
pH	6.41	6.66			6.19	6.51	6.68	6.79
Conductivity ($\mu S\ cm^{-1}$)	15.5	15.4	15.1	12.1	12.2	12.9	16.3	16.3
Turbidity (NTU)	9.5	21.4	14.0	36.9	11.7	33.0	5.1	11.6
Suspend sed. ($mg\ l^{-1}$)	112	144	137	325	70	156	51	98
Soluble PO_4^{3-} ($mg\ l^{-1}$)	9.5	17.3	11.5	16.5	8.5	13.2	9.9	25.2
Total PO_4^{3-} ($mg\ l^{-1}$)	105	116	131	223	84	125	64	115
NO_3^- ($mg\ l^{-1}$)	92	360	179	166	162	663	74	68
Min # sample	34		6		9		17	

Seasonality in base flow

Water quality is known to vary considerably during a storm. Consequently, water samples were classified according to their position on the hydrograph such as rising limb, peak flow, recession, and base flow.

At base flow throughout the year, pH is similar for each catchment (Table 3). However, a small decrease in pH occurs at each catchment when the base flow increases during the summer.

In winter 1989, when the discharge from the catchments decreased to a minimum, the conductivity, a surrogate for dissolved solids concentration, increased in both catchments, but was always higher in the undisturbed catchment. However, immediately after heavy rains, as in September 1989, the conductivity of the undisturbed catchment decreased to values similar to those of the disturbed catchment. The conductivity also increased during the most recent winter period when the flow again decreased to a minimum.

Turbidity (and suspended sediment concentrations) differ considerably between the catchments (Fig. 4). Turbidity (and suspended sediment concentration) is much lower in the undisturbed catchment than in the disturbed catchment, particularly during the rainy season.

Variability in water quality during storms

The sampling technique provided a composite of every two sub-samples for subsequent analysis. All the composite samples were classified according to the flow regime of each sub-sample. Those composite samples that contained sub-samples in different flow regimes were not used in this analysis. Because samples were not collected at the same time in both catchments, the mean values of the physical and chemical characteristics for each flow regime were computed for comparison (Table 2). The mean flow rate for each sub-sample (Table 2), generally, is highest in the undisturbed catchment. The water quality parameters, on the other hand show consistently higher values in the disturbed catchment, particularly for turbidity, and concentrations of suspended sediment and phosphates.

The rainfall preceding each flow regime was similar in nearly all cases, however, the discharge was always higher in the undisturbed catchment. Because higher discharge was expected to cause higher sediment loss, the higher sediment loss from the undisturbed catchment could not be attributed to discharge.

For any of the flow regimes, pH and conductivity differences between catchments was insignificant. However, turbidity and suspended sediment concentrations were significantly different for most flow regimes. Because the suspended sediment is associated with high phosphate concentrations, total PO_4^{3-} concentrations would be expected to show the same significant differences as the suspended sediment concentrations between catchments.

TABLE 4 Flow and particle size analysis for samples after every 1000 m^3 of discharge.

Flow conditions		base	rising	peak	recession	base
Discharge ($l\ s^{-1}$)	Dist	0.165	0.714	0.892	.575	0.282
	Nat	0.103	0.525	1.38	1.255	0.468
Turbidity (NTU)	Dist	12.0	24.0	17.3	14.0	13.9
	Nat	3.90	4.10	5.10	4.30	4.10
Number ($10^5\ ml^{-1}$)	Dist	0.39	3.70	2.30	0.84	0.56
	Nat	1.00	0.89	0.77	0.42	0.32
Median size (μm)	Dist	3.16	2.71	2.70	3.63	3.55
	Nat	3.67	3.89	4.05	4.39	3.72

High NO_3^- concentrations, generally, were observed in samples from the disturbed catchment, particularly on the rising limb of the hydrograph and on recession, but at base flow the average NO_3^- concentration was slightly higher in the undisturbed catchment.

The particle size of the suspended sediment was determined for one storm event for which the discharge in the disturbed catchment increased slightly more than that in the undisturbed catchment (Table 2.). The number of the suspended sediment particles decreased slightly from 1.0 x 10^5 to 0.77 x 10^5 particles ml^{-1} during the rising limb of the hydrograph for the undisturbed catchment. The particles size increased slightly from 3.67 to 4.05 μm in the process (Table 4). For the disturbed catchment, however, the number of particles increased one order of magnitude from 0.39 x 10^5 to 3.70 x 10^5 particles ml^{-1}. This result is reflected in the turbidity measurements.

Bed load

In general, the bed load of a stream does not move very fast as it is stored and released by depressions and reservoirs within a given reach. Therefore, it is difficult to associate a particular bed load sample with a specific hydrological event. Consequently, this component of water quality was not considered in the initial phase of this project. However, since this information also is required for model verification, an effort is now being made to estimate the bed load component of the disturbed catchment through regular bottom surveys in the weir. Fourteen permanent transects have been establish in the weir and these are used to measure the depth to the bed surface at regular intervals along each cross-section. The initial survey was conducted in August 1990 after the stilling basin had been cleaned. A second survey was conducted in November 1990, several weeks after a significant storm event (130 mm of rainfall) occurred in each catchment. This storm caused 4.64 m^3 of sediment to be transported from the disturbed catchment and deposited in the weir.

SUMMARY AND CONCLUSIONS

Hydrographs are similar between catchments. However, superimposing the hydrographs revealed one consistent difference which could not be attributed to differences in the rainfall pattern. The peak discharge from the disturbed catchment was usually lower than that from the undisturbed catchment, despite similarities on the rising limb and on recession. Although it is unclear why the peak flow rates from the disturbed catchment are lower than the corresponding rates from the undisturbed catchment, this attenuation in the discharge hydrograph is unlikely to induce greater erosion since the geomorphology of the catchments are very similar. Consequently, the higher suspended sediment concentrations and turbidity in the disturbed catchment are most likely caused by the land development there.

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