Effect of temporal rainfall distribution and soil type on soil moisture and runoff generation in semi-arid Zimbabwe

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Nordic Hydrology **Vol 38 No 3 pp 249–263** © IWA Publishing 2007

Received 21 July 2006; accepted in revised form 11 April 2007

Abstract This paper examines the effect of temporal rainfall distribution on soil moisture and runoff generation in the 5.9 km^2 Mutangi catchment in semi-arid Zimbabwe. Rainfall, soil moisture and runoff were measured during the 1999/00 and 2000/01 rainy seasons during which periods 755 mm and 615 mm of rainfall were received, respectively. The percentage of rainfall totals in these periods were 58% and 69%, respectively, in February. The total catchment runoff was 102 mm and 63 mm, of which 52% and 49% were recorded over 6 and 4 d in 2000 and 2001, respectively. Baseflow was negligible. Rainfall intensities were generally low. In the 1999/00 season there were 2 and 8 h with intensities >20 mm h^{-1} and 10 mm h^{-1}, respectively. Some runoff appears to be generated by Hortonian overland flow (HOF), mainly in the early wet season before ploughing creates a rougher soil surface. The dominant process of runoff in this catchment was saturated overland flow (SOF), which occurs when the soils become saturated from below. The sodic soils along the stream channels appear to generate most of the runoff because of their small capacity to store water before saturation. The ridge soils are coarse sands, with a large capacity to store rainfall. The transitional (slope) soils have an intermediate capacity to store water. If there is a sequence of daily events that completely fills the storage available in both the sodic and transitional soils, and which begins to saturate the ridge soils, there could be very large amounts of runoff (>50% of the daily rainfall). The occurrence of such runoff events depends very heavily on the distribution of rainfall. Dry spells between rain events create storage, thereby reducing the risk of runoff from the next events.

Keywords Rainfall distribution; runoff; semi-arid; soil moisture; soil type

Introduction

In semi-arid Zimbabwe, the rains generally commence in October/November and end in late March or April, with the bulk of the rainfall in February and early March. There is often a mid-season dry spell, usually in December or January (Scoones *et al.* 1996). This rainfall distribution is likely to have an effect on runoff generation because the infiltration capacity of a soil depends on antecedent soil moisture content. Apart from antecedent soil moisture, runoff generation also depends on rainfall quantity, intensity and duration, permeability of the soils and catchment relief and geometry (Dubrueil 1985, 1986). Another important factor relates to the depth to the groundwater table in depressions and the riparian zone where saturation-excess overland flow (SOF) is most likely to occur (Ward 1984).

In semi-arid environments, the main process of runoff generation is usually Hortonian overland flow (HOF) (Sandstrom 1997), although saturation-excess overland flow (SOF) may also occur. HOF occurs when rainfall intensity exceeds the infiltration capacity of the soil (Horton 1933). Saturation-excess overland flow occurs when the water table rises to the

doi: 10.2166/nh.2007.014

ground surface and prevents infiltration as there is no longer any storage capacity. In the areas where it occurs, runoff is maximised. This process normally occurs where the soils are close to saturation during a greater part of the wet season or in areas where there is an impeding layer in the profile, and dry season soil moisture deficits are small.

The generation of runoff in the semi-arid areas exhibits both similarities and differences to that found in humid temperate areas (Sandstrom 1997). The variability is spatial and temporal runoff generation is closely related to the spotty nature of rainfall. The Hortonian generation of runoff in semi-arid areas displays a pattern of partial area contribution to runoff (Yair and Lavee 1982; Lane *et al.* 1978), which is related to the large variability in infiltration capacities (Sandstrom 1997).

The aim of the paper is to investigate the functioning of a small catchment in semi-arid southern Zimbabwe, in particular, the annual cycle of the moisture and groundwater storage and the spatial pattern of, and controls on, runoff generation. The amount of runoff generated in two seasons and that generated during storm events is examined. These results are presented and interpreted with soil moisture data to determine the runoff generation processes and the role of rainfall distribution and antecedent soil moisture in contributing to catchment runoff.

Study site and methods

Site, climate, soils and land use

Mutangi catchment lies in natural region V of Zimbabwe that is semi-arid (Figure 1). The mean annual rainfall is 550 mm with a range of 200–1 000 mm (Vincent and Thomas 1960). The natural regions are a classification of the agricultural potential of the country, from natural region I, which has the highest agricultural potential (the high altitude wet areas) to natural region V, with the lowest agricultural potential, due to low rainfall and a high risk of

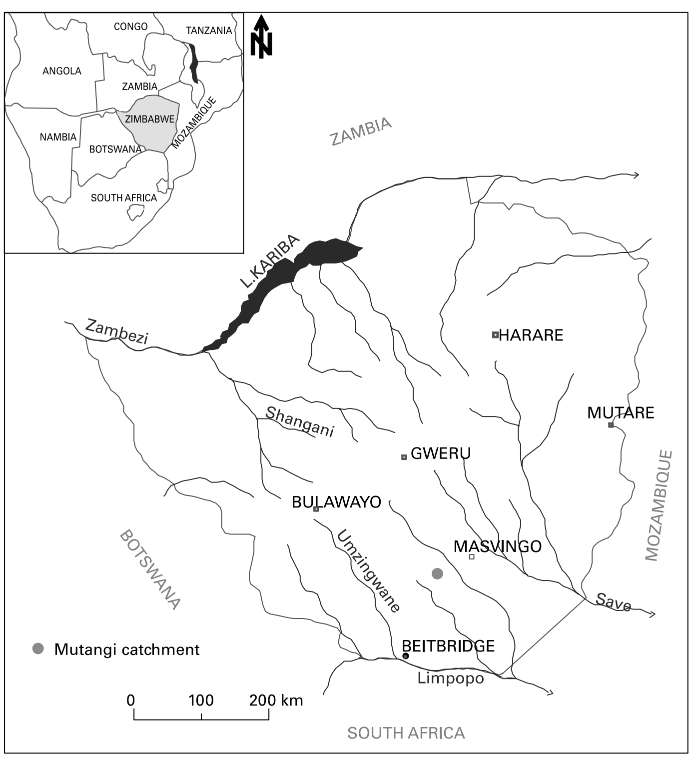


Figure 1 Drainage map of Zimbabwe showing the relative geographic position of Mutangi micro-catchment

drought spells during the growing season. The monthly average daily maximum temperatures vary between about 20°C and 32°C in winter and summer, respectively. Minimum temperatures are approximately 5°C in winter and 20°C in summer. Rainfall usually occurs in the summer months from October to April. The climate of the study area is depicted in Figure 2.

Mutangi catchment covers an area of 5.9 km^2. The altitude ranges from 878 m above sea level (masl) at the catchment outlet (dam) to 930 masl at the head of the catchment. The highest point is the summit of Mashagwe (939 masl), an isolated rocky hill on the southern side of the middle of the catchment. The average catchment gradient is 0.8%. To the NE of the hill, 4 stream channels (subcatchments 1–4), which drain the mainly cultivated eastern end of the catchment, converge within a short distance to join the main sand bed channel. Several smaller tributaries join the channel to the west of the hill, draining mainly open woodland grazing areas. Above the dam, the main channel has a sand bed of about 30 m width, which is aggrading with the deposition of sand.

There are four soil types in the catchment (Figure 3), three of which follow a clearly defined toposequence, grading from one to the other down the slope (Muzuva and Gotosa 1999) (Figure 3). Climatic and ecological conditions have little effect on soil properties. The highest lying members of the catena are shallow (0.3 m) to moderately permeable deep (1.2 m) coarse sands merging to coarse loamy sands, into soft weathering gneiss. Small areas of stony phase (lithosols) occur associated with rock outcrops (not always on the crest). These soils are described as having good permeability. These soils are infertile and have a very low available water holding capacity. The lowest lying members of the catenary sequence, along the stream channels, are strongly sodic and characterised by mopane shrub (*Colophospermum Mopane)*, which is often very stunted. These soils are generally duplex in character, with coarse-grained loamy sands overlying calcareous and saline sandy clay loams and sandy clays, below which is soft weathering gneiss. The sandy clay lower horizons have an exceptionally high bulk density (~2 200 kg m^{-3}) and permeability is correspondingly very poor.

Between the sandy, permeable ridge crest and the sodic soils, the soil properties are dependent on slope position. The mid-slope soils also have a duplex character; the topsoil properties are similar to those of the ridge crest soils, but the lower horizons (below about 60 cm) are more clayey (clay content 15–22%) and beginning to show sodicity.

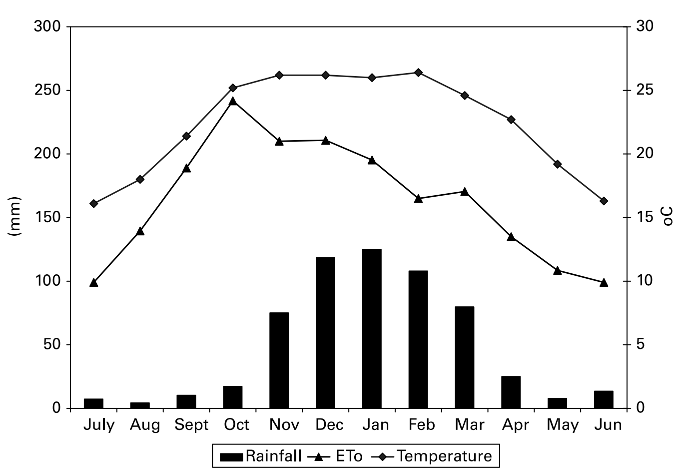


Figure 2 Monthly average temperature and monthly rainfall and evapotranspiration totals at Chibi office, i.e.12 km east of the study catchment

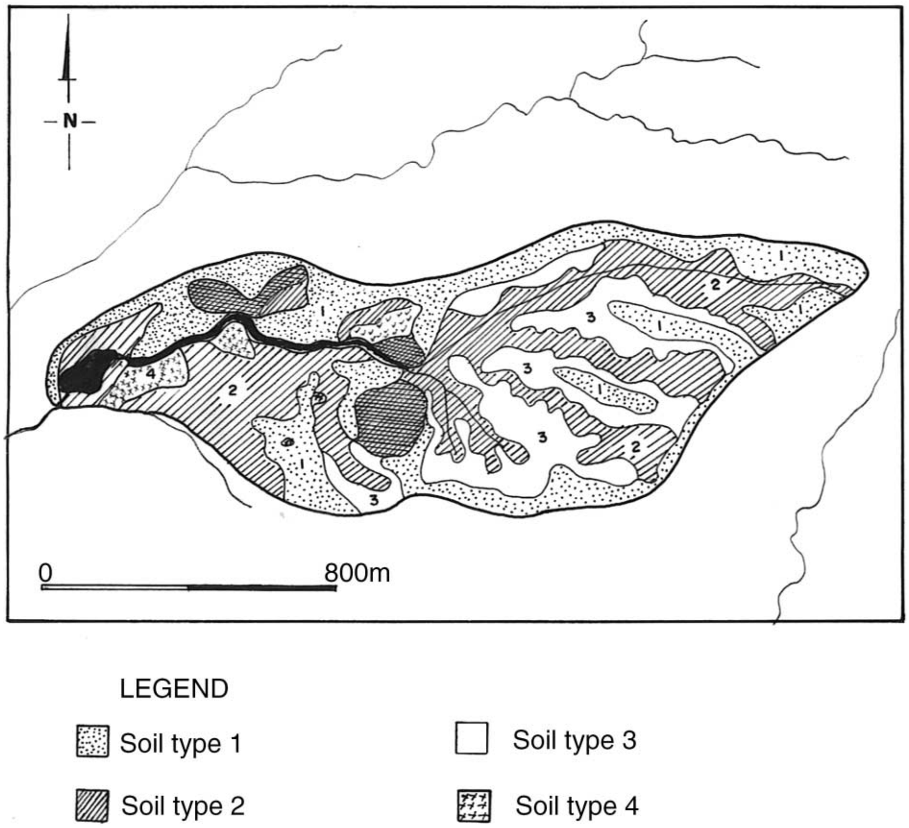


Figure 3 Soil map of Mutangi catchment

The vegetation of Mutangi catchment has been described by Mapaure (1999). In the eastern half of the catchment, much of the natural vegetation has been cleared for cultivation and is now confined to corridors along the stream channels, field edges and rocky areas. Along the first- and second-order streams, *Colophospermum Mopane* trees and shrub regrowth are dominant on the heavy textured sodic soils. To the west of Mashagwe hill, there is some cultivation on the northern and southern edge of the catchment, but the remainder is open woodland and grazing areas. A mixture of deciduous woodland occurs on the hills and the main stream. On the hills, the woodland comprises *Combretum* spp., *Commiphora* spp. and Baobab trees. On the light textured soils, *Terminalia sericea* tree species are dominant together with *Dicrostachys* spp., *Albizia amara* and *Sclerocaria* spp.

Farming is dryland crop production and the major crops grown are maize, cotton and groundnuts. Most of the cultivation is carried out in the eastern half of the catchment, on the sandy and transitional soils on the low ridges between the stream channels. However, about 12% of the area that used to be cultivated 10 or so years ago is now fallow due to a lack of animal draft power, especially after the 1992 drought. These areas generally have a sparse cover of weeds. Grazing is carried out in these fallow areas and in the area between Mashagwe hill and the dam.

Experimental design

Rainfall

Seven manually read rain gauges and one automatic gauge were installed in the catchment (Figure 4). The manual gauges were read every morning between 0600 and 0800 hours.

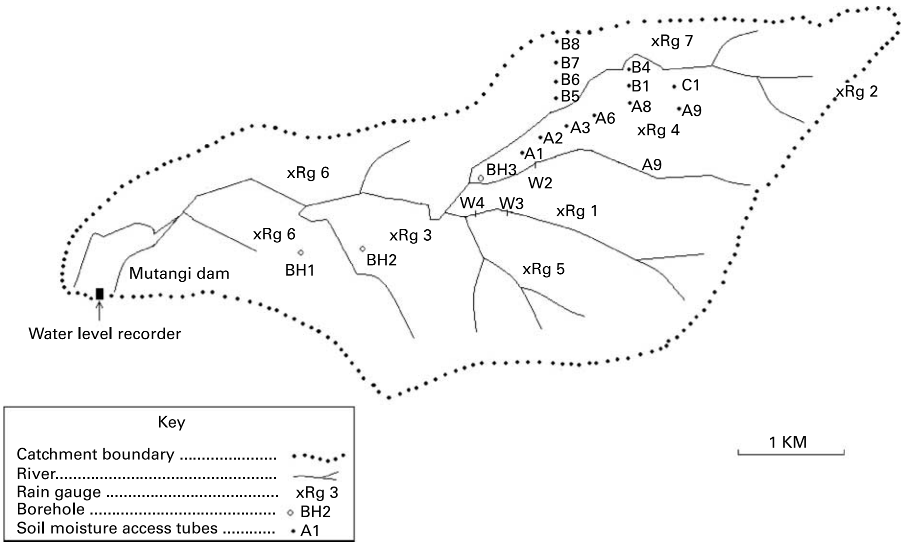


Figure 4 Mutangi instrumentation water level recorder, soil moisture monitoring, boreholes, rain gauges and automatic weather station

The automatic gauge was located near the centre of the catchment and is part of an automatic weather station (AWS) and data are logged hourly and at one minute intervals when it was raining.

Soil moisture

Two transects of neutron probe access tubes were installed (Figure 2). The first transect (A) runs along the low ridge that forms the divide between subcatchments 1 and 2, starting close to the confluence of the two channels. The second transect (B) starts on the ridge close to transect A and runs at right angles to it, across channel 1 and onto the ridge that forms the northern boundary of the catchment. This covers the catenary sequence from the sandy soils on the ridge, through the transitional soils on the mid-slope, to the more clayey sodic soils, which are the lowest members of the sequence, close to the streams. The access tubes in both transects were located on different soil types, different land uses and different crops. The tubes were installed to the maximum depth possible, which was usually limited by stones or weathered rock that was too hard to penetrate. Depths ranged from 1 m to 2.5 m. A neutron probe (IH II) was used to measure soil moisture at approximately weekly intervals. Readings were taken at 0.1, 0.2 and 0.3 m and then at 0.2 m intervals for the remainder of the depth of the tube using a counting rate of 16 s. Three calibration equations were developed for the sandy soil, the intermediate soils and the sodic soils on the catena (Mugabe 2005).

Infiltration measurements

A CSIRO Disc Permeameter (1988) was used to determine the infiltration of the different soil types (sand, sodic and intermediate). The sodic soils are under woodlands while the sandy and intermediate soils are under arable. A thin band was cleared on the soil where the edge of the steel was in contact with the soil. The ring was inserted about 4 mm into the soil surface by placing a cover plate over the ring until the cover plate was in contact with the spacer. The cover plate and the spacer were removed and the outside ring was sealed with local clay paste. The empty permeameter was set on the ring so that it was as level as possible and that the supply potential was properly adjusted. The permeameter was removed from the ring and placed in a bucket of water. The permeameter was filled with water and the side tube was filled to the required level that would fill the ring.

The permeameter was placed on the ring and to begin the measurements the stopcock on the side of the tube was opened. The stopwatch was started when the side tube was empty. Times at constant 5 and 10 mm scale increments on the reservoir tube were recorded for clay and sandy soils, respectively. Measuring continued till the flow was steady (when the time taken for equal scale increments did not change). Fifteen measurements were taken to ensure that accurate values of steady state flow were obtained. Two replications were done on each soil type.

Catchment runoff

An automatic water level recorder (WLR) was installed on a platform extending from the dam wall to reach sufficiently deep water to record the lowest likely water levels. The recorder used a float in a stilling well and was of the shaft encoder type, with an accuracy of 1 mm. Water levels were recorded at intervals of 10 min.

Two compound rectangular weirs were constructed on the spillway to enable measurement of both high and low flows. The water level data were used to calculate the runoff through the weirs. Total catchment runoff was calculated from storage increases in the dam, and the gauged spillway discharge. Evaporation from the dam was accounted for by subtracting potential daily evaporation that was calculated using Penman 1948 equation.

Runoff plots

Three runoff plots that were 5 m by 15 m were constructed in the mopane sodic soils, intermediate soils and the fallow sandy soils along the catena. Metal sheets were driven into the soil with at least 15 cm of height above the ground to stop water flowing from outside into the plot and vice versa. A gutter was constructed at the lower end of the plot to collect the runoff. The gutter had a gradient of 1% towards the collection tank. The soil around the gutter was backfilled and compacted. The joint between the gutter and the lower side of the plot was cemented to form an apron in order to allow a smooth flow of water from the plot into the gutter. The collection tank was constructed from concrete blocks. The tank was covered with a metal sheet to protect water loss and addition from evaporation and rainfall, respectively. The storage capacity of the tank was 3 m^3, which was large enough to collect 30 mm of runoff from the plot.

The volume of water collected in the rain gauge and in the runoff tank was measured following every storm. The tank was empted after every rainfall event. Any silt that may have deposited in the tank and in the gutter was cleared.

Results

Rainfall

Table 1 shows the monthly rainfall totals for the 1999/00 and 2000/01 seasons. The rainy season commenced in November 1999 and October in 2000. Seasonal rainfall totals were 755 and 615 mm, respectively. February was the wettest month in both seasons, with about 34% of the annual rainfall in both cases. In 1999/00 and 2000/01, there were a total of 57 and 46 rainy days and maximum rainfalls of 72 mm d^{-1} and 65 mm d^{-1}, respectively. Rainfall distribution was similar in both years with almost half the season's rainfall falling on just 6 or 7 days.

Rainfall intensity data (on an hourly basis) are available for the 1999/00 season, but the gauge malfunctioned in the 2000/01 season. Analysis of the rainfall intensity data focused on identifying occasions with high intensity rainfall, which is likely to promote Hortonian overland flow (HOF). Two sets of intensity criteria were selected (Tables 2 and 3).

Table 1 Monthly rainfall distribution in the 1999/00 and 2000/01 seasons

	Monthly rainfall (mm)	
	1999/00 season	2000/01 season
October	0	42
November	136	70
December	73	153
January	153	42
February	253	219
March	42	77
April	12	11
May	65	10.5
June	21	0
July	0	0
August	0	0
September	0	0

In the 1999/00 season, there were only two occasions with a rainfall intensity $>25\,\text{mm h}^{-1}$, and eight occasions with intensity $>10\,\text{mm h}^{-1}$ (Table 2) An intensity $>10\,\text{mm h}^{-1}$ also never occurred for more than a single hour in any rainfall event. Greater intensities almost certainly occurred, for short periods (<1 h), but generally these intensities are relatively low. Table 3 shows that there were only seven occasions when rainfall intensity exceeded $5\,\text{mm h}^{-1}$ for two hours or more consecutively. On these occasions the average rainfall intensity ranged from 5.8 to $17.9\,\text{mm h}^{-1}$ and rainfall events from 13.7 to 83.6 mm.

The spatial variability of rainfall, represented by the coefficient of variation (CV) of the mean rainfall recorded at the seven rain gauges, decreased with increasing rainfall. For events less than 10 mm, the CV ranged from 8% to 96% (typically 30%), but for the longer events the consistency of rainfall over the catchment was notable. For the 13 mean daily rainfall totals which exceeded 30 mm, the CV ranged from 10.5 to 26%, with 11 CVs in the range from 10 to 17%.

Soil moisture

Figure 5 shows the wettest and driest profiles from the access tubes at different positions in the catenary sequence, from sodic soil close to the channels (A and B) through transitional soils (C, D and E) to coarse sandy soils on the ridge tops (F). The wettest data are typically from late February to early March, and the driest from September to October, at the end of the dry season. The difference in soil properties is clearly reflected in the shape of the water content profile (Figure 5) and the seasonal changes in water content (Figure 6).

Except for the fallow ridge top soils (Figure 6), there was not much difference between soil moisture between the two seasons. These soils still had some capacity to store water during the 2000/01 season, suggesting that runoff from this land use type was less likely than in the 1999/00 season, when storage reached higher levels (water levels closer to the surface).

The fallow sodic profiles (A) showed very small seasonal changes in the water content, limited to only the upper 0.4 m of the profile (Figure 5). These soils have a very high bulk density, suggesting high mechanical impedance, which limits their available water capacity. There was also little vegetation cover to abstract water, and as a result the profile has only a limited capacity to store rainfall before runoff occurs. The seasonal water content changes may also be small because there is a slow inflow of water from upslope.

The sodic soils under Mopane scrub near the stream channel (B) showed much more seasonal changes of water content. However, most of the decrease from the wettest state

Table 2 Dates and times with rainfall intensity exceeding 10 mm h^{-1} and rainfall event total during the 1999/00 season

Date	Time	Rainfall intensity (> 10 mm h^{-1})	Event total (mm)
19 November 1999	1900	18.3	27.4
21 November 1999	2200	28.6	59.6
9 December 1999	2300	12.0	39.2
3 January 2000	0400	11.4	28.0
17 January 2000	1200	14.1	19.2
28 January 2000	1300	16.1	17.7
16 February 2000	1800	11.5	26.8
5 May 2000	0100	28.9	46.3

Table 3 Dates and times with rainfall intensity exceeding 5 mm h^{-1} for more than 2 consecutive hours during the 1999/00 season

Date	Time (included)	Hours	Total (mm)	Mean intensity (mm h^{-1})	Event total (mm)
21 November 1999	2100–2300	3	41.7	13.9	59.6
9 December 1999	2300–2400	2	17.4	8.7	39.2
5 February 2000	0400–0500	2	11.7	5.8	69.8
15 February 2000	1900–2000	2	12.4	6.2	13.7
16 February 2000	1700–1800	2	19.6	9.8	26.8
22–23 February 2000	2300–0500	6	46.9	7.8	83.6
5–6 May 2000	2400–0100	2	35.8	17.9	46.3

occurred within two weeks at a rate that indicated that most of the changes must have been due to drainage, not root uptake. The higher water contents are caused by the profile becoming saturated in very wet periods during the wet season.

The cultivated transitional soils (C, D and E) have a duplex character, with sand overlying a more clay rich (22%) layer with a high bulk density (2 100 kg m^{-3}) and a porosity of about 20%. This was reflected in the maximum water contents that were measured, and in the small range of water content changes observed in the lower profile. At site C, large water content changes were limited to the upper 0.4 m of the profile and the annual change in storage was small.

At site D there were changes of water content down to a depth of 1.6 m. However, as in (B), most of the changes from the wettest condition occurred in very short periods. Within 6 weeks of the wettest conditions observed, the profile was almost as dry as at the end of the dry season.

The upper slope site (E) was transitional, but had a greater depth of sandy soil. The wettest profile occurred when the water table was almost at the surface. The largest changes of storage in the profile occurred as the water table level fell at the end of the wet season.

(F) is a ridge top site, entirely on deep course sand. The seasonal water content change is much larger than at any of the sites, except the others in the same position in the catena. As at the other sites, the wettest condition occurred when the profile was saturated almost to the soil surface, on 2 March 2000. The wettest conditions at this site in 2001 were recorded in March, but the storage was much lower, and the highest water table level observed was 80 cm bgl. Saturation excess runoff only occur from these sites once the storage available has been entirely filled. These ridge top sites have a large amount of storage available in the sandy profile, and thus will only generate runoff in very wet periods.

The average maximum seasonal water content changes for each of the soil types are shown in Table 4. In the sodic soils there was little water content change at the maximum

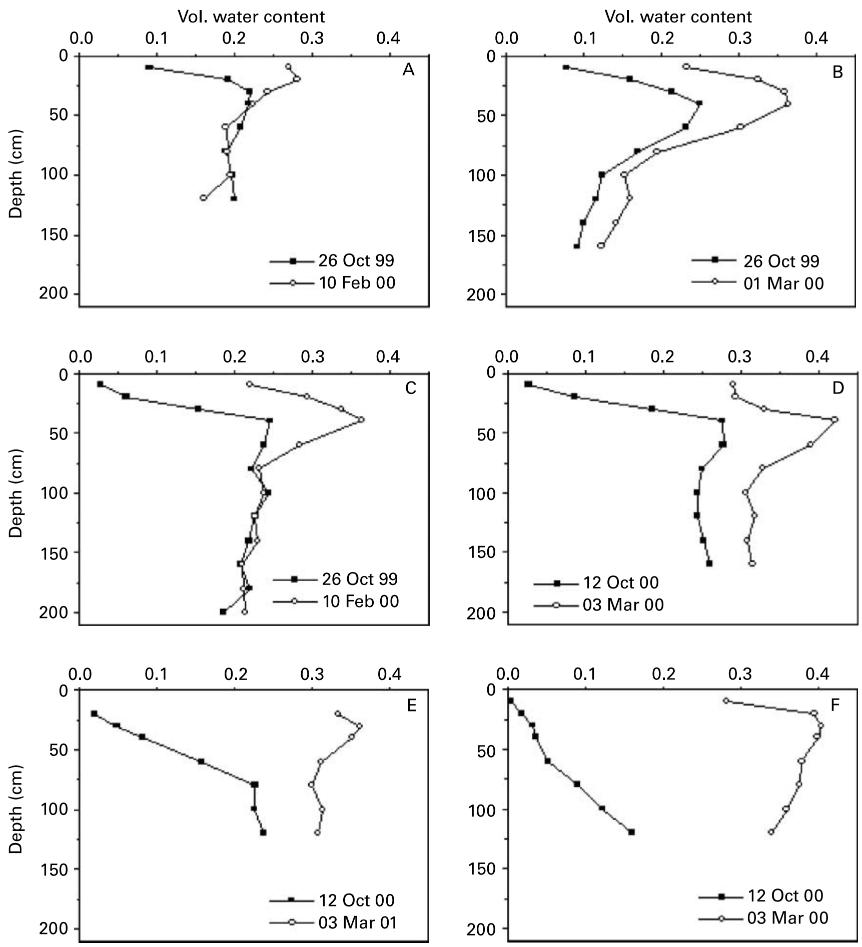


Figure 5 Wettest and driest water content profiles: (A) sodic bare soil, (B) sodic soil under mopani, (C, D and E) transitional soils that have a duplex character and (F) ridge top site at Mutangi during the 1999/00 and 2000/01 seasons

measured depth, implying that the measurements had captured almost all the seasonal change. Most of the transitional soils showed little change at the maximum depth. However, the sandy ridge soils showed large water content changes at the maximum depth of measurement, indicating that there must have been significant water content changes below the maximum depth of measurement. At these sites, the overall seasonal water content change was much higher than in the other soil types, but was an underestimate–actual changes would have been perhaps 20% higher, depending on the depth to the unweathered rock. Nonetheless, the data show very clear differences in the seasonal storage changes in each of the soil type, with the sodic soils showing the smallest seasonal change and the sandy ridge soil showing by far the largest change, almost twice that of the intermediate, transitional soils. In most cases, the wet season measurements were made when the soils were saturated, so that these figures give a good indication of the amount of storage available in the soils at the end of the dry season.

Infiltration

Infiltration decreased along the catena (Figure 7) where highest rates were recorded at the ridge top sandy soils while the least rates were recorded at the mopani sodic soils close to the

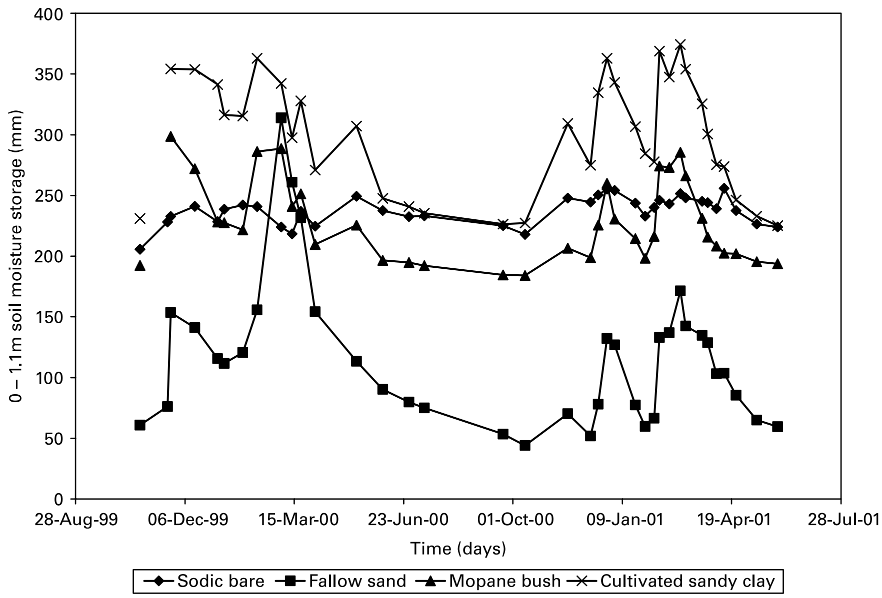


Figure 6 Soil moisture storage at four access tubes representing different land use practices at Mutangi

stream. The sandy soil, intermediate soil and the mopane sodic soils have steady state infiltration rates of 640, 260 and 33 mm/h, respectively.

Runoff

Figure 8 shows the cumulative total runoff from the catchment, in the 1999/00 (a) and 2000/01 (b) seasons, respectively. The results show that the total runoff in the 1999/00 and the 2000/01 seasons was 102.2 and 63.0 mm, or 13.5% and 10.3% of the total rainfall received in these two seasons, respectively. In both seasons there was a very large amount of runoff in late February. Most of the runoff occurred in discrete rapid events and there was little or no baseflow, particularly following the early wet season events.

The amount of runoff generated from both the mopane sodic soils and the intermediate soils increased from 2 January 2001 to a maximum on 23 February 2001 and then decreased again (Table 5). Almost all (95%) of the rainfall was lost as runoff on the 24 February 2001 on the mopane sodic soils while slightly more than half (58%) was lost at the intermediate soils. No runoff was recorded at all on the fallow sandy soils.

Table 4 Average maximum seasonal water content changes for each of the three main soil types in Mutangi

Soil type	Average maximum profile (0–110 cm) seasonal water content changes
Sodic (bottom)	82[b]
Transitional (slope)	109[b]
Sandy (ridge)	244
Mean	145
CV%	29.77
LSD (0.05)	131.1

[b] Numbers with the same letter are not significantly different at the 5% level. LSD is least significant difference

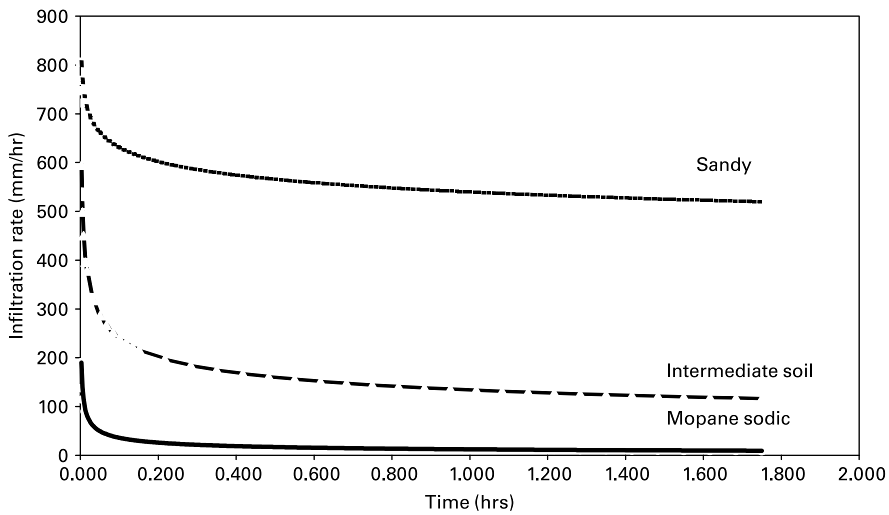


Figure 7 Infiltration rate for the Mopane sodic soil, transitional soil and the sandy ridge soil at Mutangi catchment

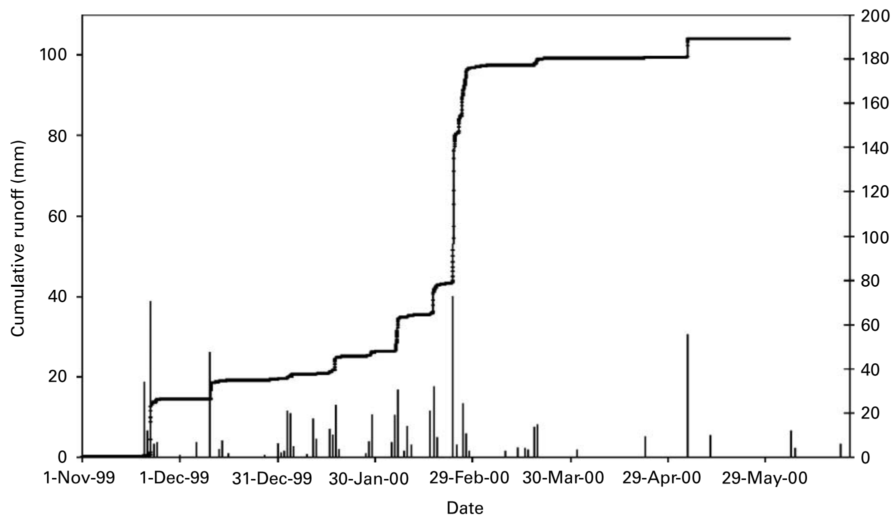
Discussion

The catenary sequence is very important in influencing the distribution of shallow groundwater (hence the variable saturated area) and the hydrological response of the catchment. On the ridge crest, the soils are highly permeable but overlie almost impermeable weathered rock at only a few metres depth. In the wet season, infiltrated water will pond on the impermeable horizon and move laterally. This lateral flow is impeded by the dense, sodic soils of low permeability on the slope, causing this shallow groundwater to approach the surface. However, it is not likely that the water that resurfaced on the sodic soil reinfiltrated because the sodic soils are of low infiltration rate and its total soil moisture (Figure 6) did not change at all during those periods when water was resurfacing from above. It is likely that the resurfaced water was lost as evaporation as it was running off from the sodic soil surface.

Soil moisture under fallow fields responded to rainfall during wet periods in February while the woodland did not respond during the same period. There were very limited changes in soil moisture on the bare sodic soils and this indicates that most of the rainfall is lost as runoff from such areas. There were very limited soil moisture changes during the dry season when the mopane bushes have shed their leaves. The fallow areas on the sandy ridge soils show large increases of soil moisture during the wet season and decreases during dry periods. Most of the rainfall is retained because of the high storage capacity as a result of the perched water table. It is then lost by downslope drainage and through transpiration by grass. The highest amounts of runoff and highest runoff percentages occurred in February, when soil moisture storage was at its maximum. It was also during this period when the near − surface soil moisture was at its highest.

Between 22 and 28 February 2000, 53 mm of runoff (52% of the season's total) was generated in 6 d from a total rainfall of 111 mm. Over these 6 days 48% of the rainfall falling on the catchment ran off. Similarly, between 22 and 25 February 2001, 31 mm of runoff (49% of the seasonal total) was generated from a total rainfall of 101 mm. On 23 February, over 50% of the rainfall was lost as runoff. These events were notable for the very high percentage of the rainfall that ran off compared to earlier and subsequent rainfall events.

An example of a contrasting event occurred on 4 May 2000, when there was a rainfall event of 55 mm, which included the highest hourly rainfall recorded in that season (28.9 mm). Despite the quantity of rain and the high intensity, only 4.5 mm of runoff was



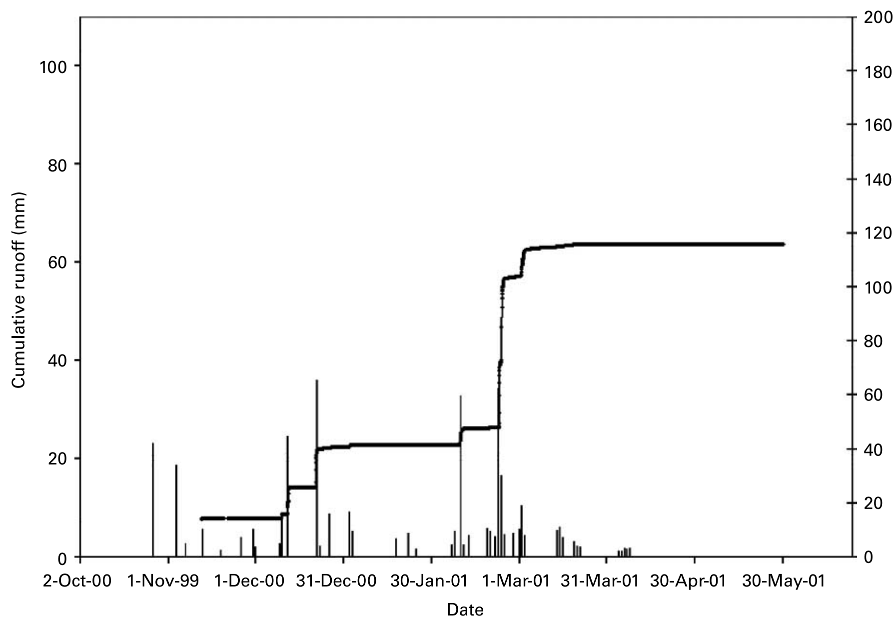


Figure 8 Cumulative total runoff and daily rainfall during the 1999/00 and 2000/01 seasons at Mutangi

Table 5 Rainfall, runoff and runoff coefficients (in brackets) for runoff plots located on mopane sodic soils, intermediate soils and fallow sandy soils at Mutangi catchment

		Runoff (mm) (runoff coefficient in brackets %)		
Date	**Rainfall received (mm)**	**Mopane sodic**	**Intermediate soils**	**Fallow sandy soil**
2 January 2001	18	0.65 (3.6)	0	0
9 February 2001	60	3.49 (5.8)	1.09 (1.8)	0
22 February 2001	48	17.88 (37.2)	9.59 (20.0)	0
23 February 2001	34	20.93 (61.6)	17.00 (50.0)	0
24 February 2001	9	8.51 (94.6)	5.01 (55.7)	0
2 March 2001	20.2	9.17 (45.4)	10.03 (49.6)	0
3 March 2001	9	2.62 (39.6)	0	0

generated. The difference between the February and May events is related to the ability of the soil to accept rainfall, determined by its water content and the depth of the shallow groundwater. Between 21 March and 4 May 2000, there was almost no rainfall and, as a result of drainage, soil evaporation and uptake by vegetation, water levels had fallen, and the soil had a significant capacity to store water. In contrast, in late February, a closely spaced series of moderate sized rainfall events had brought the water table close to the surface such that there was then little capacity for the soil to accept water. The following rainfall events then led to runoff generation as "saturation-excess overland flow" (SOF) from a large proportion of the catchment.

The 1999 wet season started with three consecutive days of rainfall (34 mm, 12 mm and 70 mm), the last day of which included an intensity of 27 mm h^{-1}. This event produced 14 mm of runoff (20% of the rainfall). This relatively large runoff percentage has three likely contributing causes: (a) cultivation takes place after the first rains, so the soil surface is very flat and prone to surface sealing in heavy rain. This may have led to Hortonian overland flow (HOF), when the rainfall intensity exceeds the infiltration rate, especially for the clay soils. Later in the wet season, after ploughing has taken place, the greater roughness of the soil surface will increase the infiltration rate (Schulze 1994), (b) the 46 mm on the days before the large and intense event would have filled some of the storage in the sodic soils, leading to the generation of SOF in those areas, and (c) the presence of actively growing natural vegetation and growing crops will increase evaporation rates, increasing the storage capacity available between rainfall events.

It is of note that, in both years, had the late February rainfalls not occurred when they did in relation to previous events, the seasonal runoff totals would have been halved, but the rainfall totals would have been reduced by only 15%. It is clear that the distribution of rainfall is critical to runoff generation. If events are well spaced, evaporation and drainage create the capacity to store water, but a series of closely spaced rainfall events will fill the storage to the surface such that following events cause large amounts of SOF. Near-surface soil moisture data (Figure 9) show that the area contributing SOF increases progressively as the catchment wets up, starting with the sodic soils and progressing through the transitional soils to the sandy ridge soils, which have the largest storage capacity. This indicates a variable saturated area, and hence a high runoff conversion coefficient, as this area increases

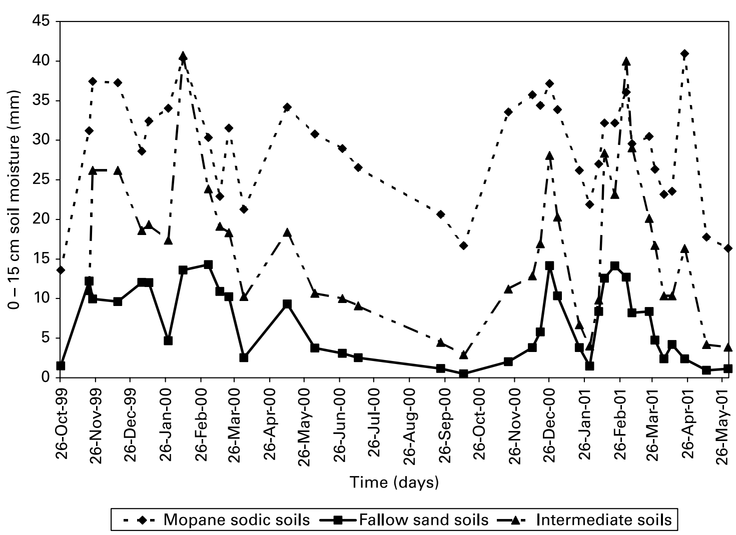


Figure 9 Time series of near surface (0 – 15 cm) soil moisture at Mutangi

in late February to early March. This is attributed to progressively increasing antecedent soil moisture and soil moisture storage capacity as was observed by Dunne and Black (1970*a,b*).

At the ridge, SOF was identified in the wettest part of the season when the storage capacity was completely filled up. Saturation-excess runoff can only occur from these sites once the storage available has been entirely filled. These ridge top sites have a large amount of storage available in the sandy profile and will only generate saturation overland flow in very wet periods (Dunne 1978).

SOF takes place in late February and early March when the storage capacity of the ridge soils is filled up with water. However, SOF is predominant in the bare sodic soils because they have very little capacity to hold water and that is where most of the catchment runoff is generated from, especially in the early part of the season. The plot runoff data (Table 5) also supports that the sodic soils produce the most runoff than both the transitional and the sandy soils. The fallow sandy soils did not produce any runoff at all during the study period. A similar phenomenon, when runoff is produced due to storage capacity being filled up and all the rainfall onto these areas is lost as runoff, was also observed by Kirkby and Chorley (1967) and Dunne (1978).

The difference between the maximum and minimum soil moisture determines the amount of water required to fill the profile before any SOF occurs. The sodic, transitional and sandy soils require 82, 109 and 244 mm, respectively, to fill the profile to saturation.

The sandy soils at the ridge top and most of the intermediate soils have very high infiltration rates (Figure 6) such that HOF is not likely on these soils. They have steady state infiltration rates of more than 500 mm/h while the highest observed rainfall intensity during the two seasons was 28 mm/h. HOF is likely to occur on the sodic soils because they have low infiltration rates.

Conclusions

Runoff is not uniformly generated in the catchment both in time and space. It is evident that rainfall distribution and soil type are very important in runoff generation and bring about differences in runoff generation between years with similar rainfall totals but different rainfall distribution patterns. Closely spaced rainfall events result in increased runoff because there is little chance for the soil to lose water by evaporation or drainage between events.

There is no one process (HOF or SOF) that dominates runoff generation in Mutangi catchment. Rainfall is lost as SOF during wet periods. HOF dominates, on the lower members of the catena, early in the season and later in the seasons when the soils are dry with a lot of storage capacity. However, HOF is not likely to occur on the sandy soils because they have very high infiltration rates.

Most of the runoff is coming from the mopane woodland that is associated with sodic soils. Such soils have low infiltration rates to allow HOF when rainfall intensities exceed their infiltration rates and their storage capacity can be easily filled up during the early part of the season to allow SOF to occur later in the season.

Acknowledgments

This publication is an output from a project funded by the UK Department of International Development (DFID) for the benefit of developing countries. The views expressed are not necessarily those of DFID. The research was partially supported by an African Doctoral Fellowship provided by START and the Pan-African Committee for START. The authors would particularly like to thank the people of Mutangi for their assistance and participation in the research.

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