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Hydrological processes and water resources management in a dryland environment I: An introduction to the Romwe Catchment Study in Southern Zimbabwe

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Abstract

In Zimbabwe during the 1980s and early 1990s, a sequence of severe droughts caused widespread food shortages and great hardship to rural communities. The droughts exacerbated the problems of environmental degradation in communal lands and highlighted the lack of understanding of the links between the climate, land use and hydrology of dryland regions. The Romwe Catchment Study addresses these issues, and has led to the establishment of the first fully-instrumented research catchment in a communally-managed dryland environment in southern Africa. The key objectives were (a) to improve the understanding of hydrological processes in communal land areas, mostly underlain by crystalline basement aquifers, and (b) to investigate the impacts of variations in climate and changes in land use and management on the hydrology and water resources. In this introductory paper, the physical characteristics of the catchment are described together with the instrumentation to monitor hydrological processes and quantify the catchment water balance.

Introduction

In Zimbabwe, 57% of the population live in communally managed areas which are restricted to only 42% of the total land area, generally that least favourable for agricultural use (Zinyama, 1986). Typically, they receive less than 650 mm of rainfall per year, experience frequent droughts and are marginal for rainfed crops which provide the main source of income for rural communities. Many communal lands are densely populated and overgrazing and deforestation are common problems. Most communal lands are situated on pre-Cambrian basement complex gneisses and granites. These crystalline basement rocks give rise to aquifers that typically have low permeability and storage, but which nevertheless provide an important water resource because of their widespread distribution. Groundwater occurs within both the weathered overburden (regolith) and in the fractured bedrock beneath.

During the 1980s and early 1990s, recurrent and severe droughts caused many wells and boreholes to fail so that the livelihoods of many rural communities were placed in jeopardy. In response to this situation, government and aid agencies launched programmes to improve the provision and management of water resources in rural areas. Such programmes highlighted the lack of knowledge about the processes that control surface and groundwater resources in the crystalline basement aquifers typical of communal land areas.

The Romwe Catchment Study was established in 1993 (Butterworth *et al.*, 1995; Lovell *et al.*, 1998) with two main objectives to support the sustainable development of groundwater resources:

- to improve the understanding of hydrological processes, and particularly groundwater recharge mechanisms, in areas of crystalline basement geology having a land use typical of communal lands;
- to investigate the impacts of changes of climatic variation, land use and management on hydrology and water resources.

The Romwe Catchment Study

The Romwe Catchment Study was set up at a small basement-complex headwater catchment in Chivi district, southern Zimbabwe, in 1993 (Fig. 1). To optimise the use of available resources, the work at Romwe has been carried out in co-operation with the Department of Research and Specialist Services, Zimbabwe (DR&SS) and other local agencies, the Institute of Hydrology (IH) and the British Geological Survey (BGS). The catchment was the pioneer site in Zimbabwe's communal lands for a novel type of dug well (collector well), installed in 1991 and designed to provide enhanced water supplies for small-scale irrigation (Lovell *et al.*, 1996).

Catchment characteristics

The Romwe catchment covers an area of 4.6 km^2 in the Chivi district of southern Zimbabwe, near the northern margin of the Lowveld (altitude < 900 m), close to Ngundu (20° 45′ S, 30° 46′ E) and 86 km south of Masvingo (Fig. 1). Typical of many headwater catchments in communal lands, it possesses a crystalline basement geology and mixed land use of rainfed farming and miombo woodland vegetation. Basic catchment characteristics are summarised in Table 1. Gentle slopes along the valley floor, drained by an ephemeral stream, are flanked by steep rocky hills cut into at intervals by deep saddles (Fig. 2). Cultivation is restricted to the valley floor, while the steep valley sides are covered by miombo woodland.

Rainfall usually occurs in the summer months from October to April. The annual average is 581 mm, based on long-term records (1954–1995) at Chendebvu dam, 12 km to the north of the catchment. The inter-annual variability ranges from 83 mm to 1191 mm (Table 1). Extended periods of above and below average rainfall can be identified from the record. The period from 1981/2 to 1994/5 marked a particularly extended spell of low rainfall and severe droughts (Fig. 3).

Methods

Work carried out to date has included three phases; 1) baseline surveys, 2) instrumentation and 3) monitoring.

BASELINE SURVEYS

Baseline surveys of geology, soil, vegetation, land use, population and settlement, agriculture and water sources are summarised in Table 2. As part of on-going studies, social and economic surveys have subsequently been undertaken.

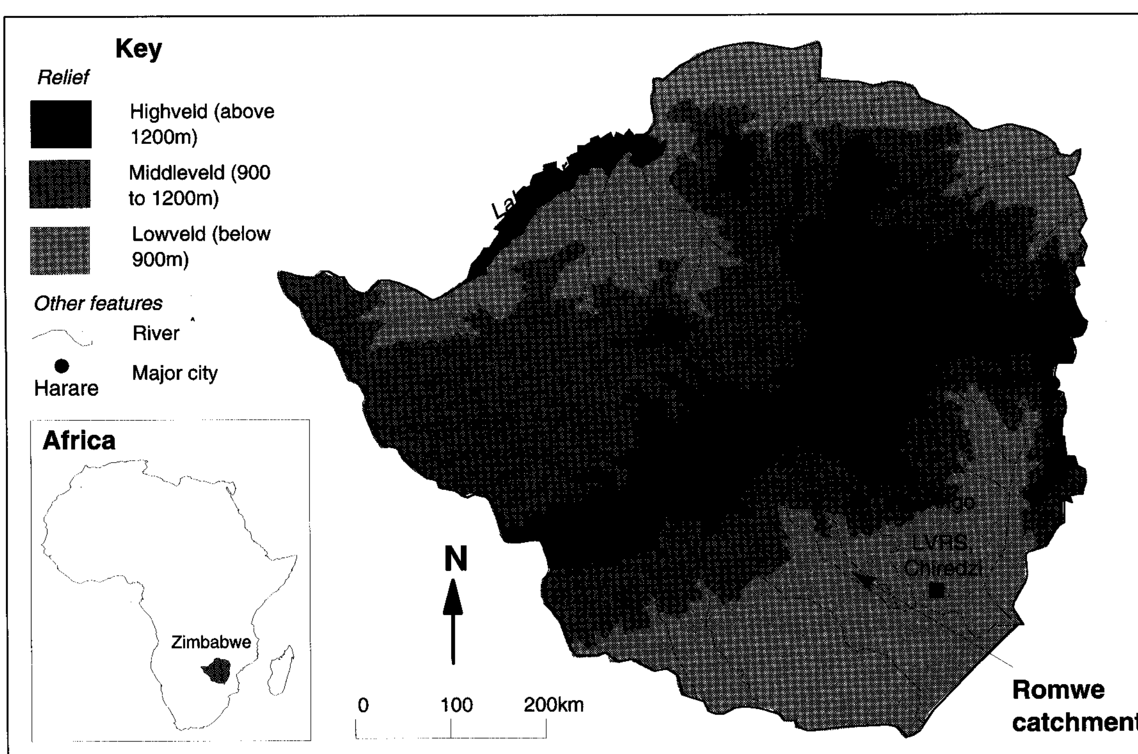


Fig. 1. *Map of Zimbabwe showing location of the Romwe Catchment.*

Table 1. Catchment characteristics

Characteristic					
Area		4.60 km^2			
Altitude		695–955 masl			
Topography (typical slopes)		Valley floor, <5%; Hillslopes, 25–65%			
Climate		Semi-arid			
		mean	*max*	*min*	*CV*
Annual rainfall,1954-95 (mm)		581	1191	83	0.45
Rainfall		Chendebvu dam		Romwe	
	1992–93	501		569	
	1993–94	455		740	
	1994–95	563		738	
Evaporative demand, A-pan (mm)		1942			
Geology		Precambrian gneiss with occasional dolerite intrusions			
Soils		Ferric and chromic lixisols			
Land use		Rainfed cropping			
		Small irrigated vegetable gardens			
		Miombo woodland			
Population		200–250			

Table 2. Summary of baseline surveys

Survey	Methodology and outputs
Geology	Field survey and aerial photograph interpretation (1:2500 scale) to produce a geological map of major lithological units and structural features.
Soils	A grid-based auger survey provided the information for a soil map of the entire catchment. These data were augmented by physical and chemical analyses of samples taken during the installation of soil water monitoring equipment, and measurements of soil hydraulic properties at selected sites using disc permeameters (Price, 1993; Mugabe, 1995).
Vegetation	A botanical survey to determine the main vegetation types in the catchment and a species list, and mapping of the aerial extent of each vegetation type using 1985 aerial photographs. To enable future changes in the condition of woodland to be monitored, three permanent 60 m × 60 m plots were established and surveyed in January 1995.
Population, settlement and land use	Aerial photographs dating back to 1955 were interpreted to determine the history of settlement and land use in the catchment. The location and number of homesteads were used as a measure of growth in population.
Agriculture	Regular walking surveys of the catchment were undertaken to record tillage methods and crop type for each field. More detailed data were collected from diaries kept voluntarily by farmers. Data included; methods of cultivation, crops, planting and harvesting dates, use of fertilizers and yields achieved.
Water use	A survey of all water sources including wells and springs was carried out in 1992. To investigate aspects of water use, the consumption of four families was monitored in October 1994, and abstraction from six wells was recorded continuously.

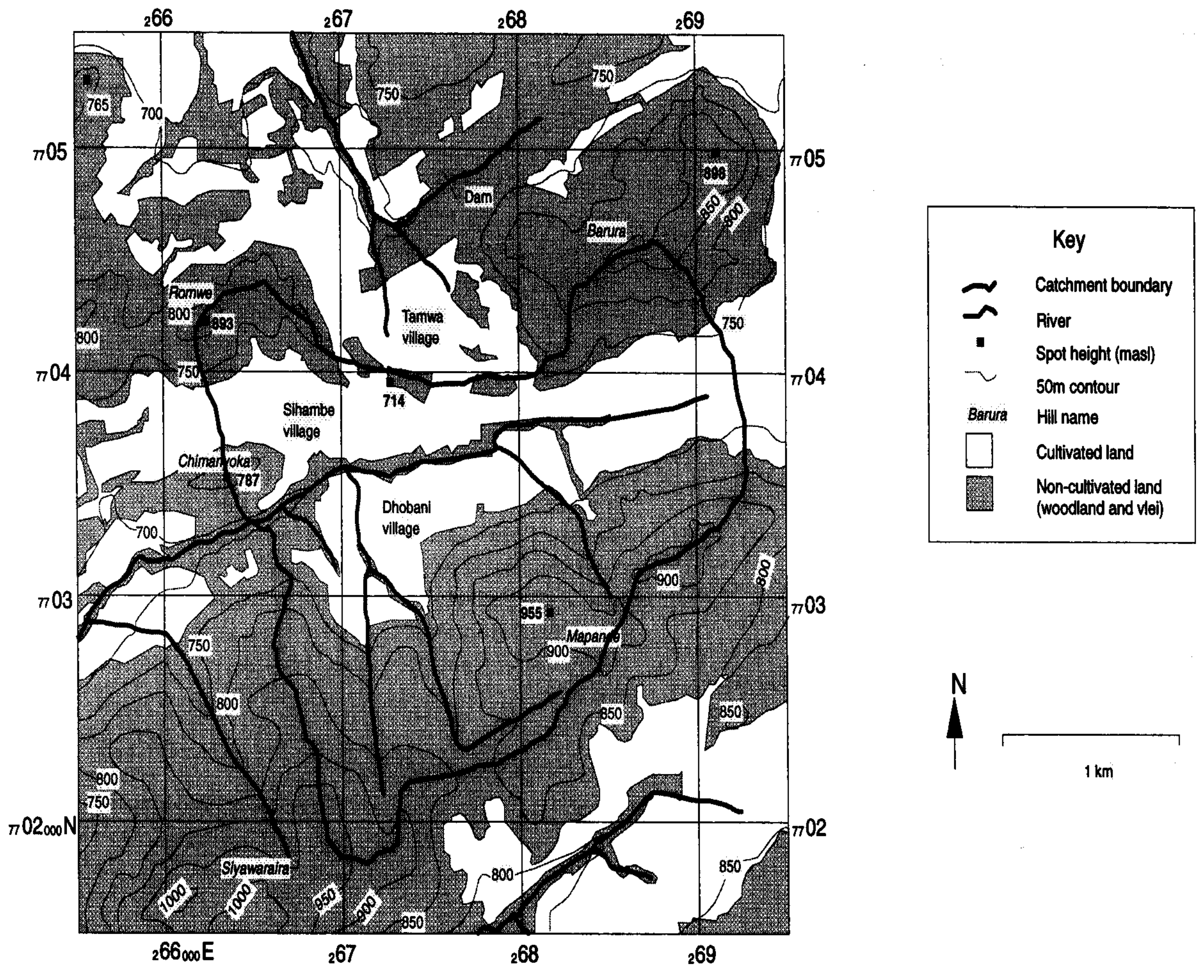


Fig. 2. *Catchment topography and land use.*

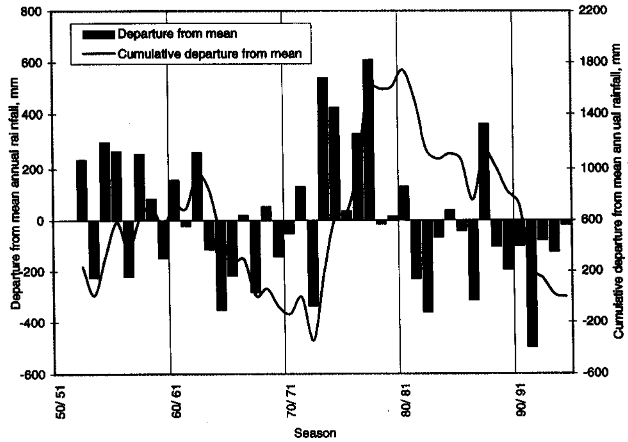
INSTRUMENTATION

To tackle the problems of scale dependency associated with the measurement of hydrological processes, instrumentation to quantify components of the water balance was installed at the following four scales;

- point
- transect
- sub-catchment
- catchment

This approach facilitated the comparison of results from measurements at different scales, and assisted in upscaling from the smaller (point) to higher (catchment) scale. The instrument network was designed to measure the main elements of the water balance including rainfall, surface runoff, soil moisture storage, evaporation from soil and plants, groundwater recharge and groundwater flow. Particular attention was paid to the process of groundwater recharge and the role played by traditional land management techniques in controlling this process.

Three sub-catchments, representative of the main soil and vegetation types, were selected for intensive instrumentation; two were sited in cultivated areas and the third in an area of miombo woodland on a hillslope (Fig. 4). The cultivated sub-catchment (Red) positioned to the north of the stream occupies an area of 0.024 km^2 and is underlain by red clay soils derived from pyroxene rich gneisses. The second cultivated sub-catchment (Grey), located to the south of the stream, covers an area of 0.011 km^2 and has grey duplex soils derived from granulite gneisses. The woodland catchment on the hillslopes on the southern side of the catchment has an area of 0.5 km^2.



Note: Long-term mean calculated as 578 mm over period 1952-95.

Fig. 3. *Annual rainfall (Chendebvu dam, 1952-1995).*

The instrumentation installed in the catchment is described in this paper along with summary details of methodologies and equipment specifications. The hydrological and related instrumentation can be divided into six groups of measurements, metereology, runoff, groundwater, soil water, crops and hydrochemistry.

Meteorological measurements

To sample the spatial variability of rainfall induced by altitude and slope aspect, thirteen raingauges were sited throughout the valley and on the surrounding hillsides (Fig. 4). Three types of gauge were employed; a tipping bucket raingauge installed at ground level for measurement of rainfall intensity during storms, and copper and plastic storage gauges installed at 0.3 m height.

Meteorological data to calculate potential evaporation were obtained from an automatic weather station located in the valley near the centre of the catchment (Fig. 4). In addition to rainfall, wet and dry bulb temperatures, wind run, wind direction, solar radiation, net radiation, atmospheric pressure and soil heat flux were recorded.

Runoff measurements

Flow gauging stations were located at the outlets of the main catchment and of each of the three sub-catchments. Two structures were required at the catchment outlet to measure both floods and low flows adequately. Each station was equipped with a stilling well and chart recorder, and a gauge board for manual stage measurement by local observers. At the catchment outlet, digital recording water level meters and pressure transducer sensors were also used.

Groundwater measurements

A groundwater monitoring network incorporated existing wells and boreholes with purpose-drilled observation bore-

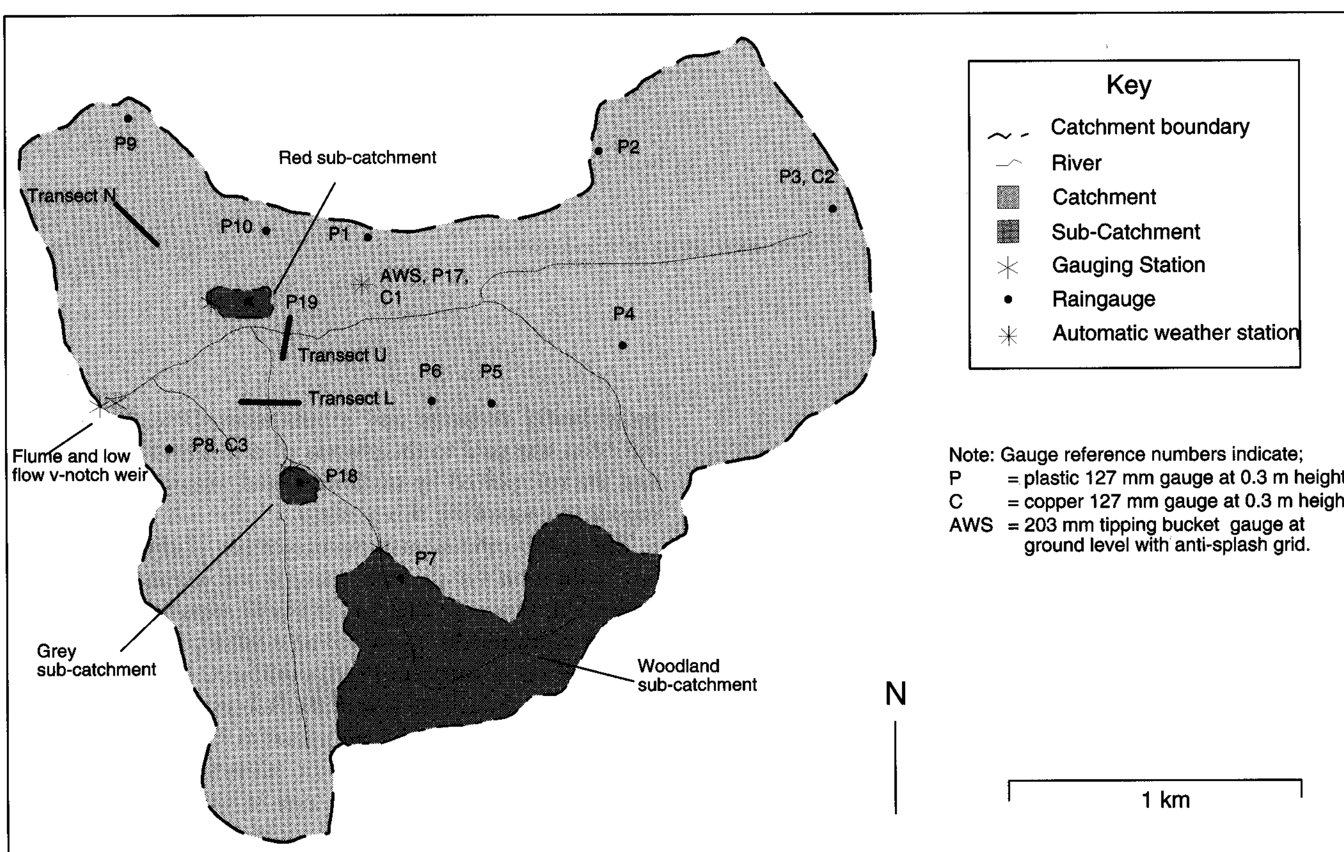


Fig. 4. *Location of sub-catchments, transects, flow gauging stations and metereological instrumentation.*

holes. In and around the catchment, 65 observation boreholes were sunk; these, with 35 existing wells and boreholes provide a total of 100 groundwater monitoring sites with the following roles:

a) Twenty were installed as monitoring points to assess the extent of the crystalline basement aquifer in the catchment;
c) Eleven were sited around the collector well (Chilton and Talbot, 1992), to monitor drawdowns around this well which was installed to provide water for domestic use and irrigation of a community garden;
e) Nine were located adjacent to a recharge trench constructed on the northern side of the catchment, to investigate methods of enhancing groundwater recharge.
g) Twenty two were used to investigate areas of potential localised recharge along three transects, two across ephemeral streams (Transects L and U) and one along a hillsope below a large inselberg (Transect N);
i) Three shallow observation boreholes were drilled adjacent to deeper boreholes to establish head differences between the main aquifer and any perched aquifer.

Soil water measurements

A network of soil water monitoring sites was established to collect data to quantify evaporation from plants, soil evaporation and drainage. The neutron scattering method measured soil water contents, mercury manometer tensiometers and gypsum blocks measured soil water potential and microlysimeters measured soil evaporation. For neutron probe measurements, 14 aluminium access tubes were installed to a depth of 1 m in fields with different soil and crop types for use in soil water balance studies at the plot scale (Mugabe, 1995). Within each of the two cultivated sub-catchments, a grid of sites was instrumented with up to 24 tubes installed to depths of up to 3 m in each sub-catchment.

Further access tubes for soil water content measurements were installed along the three transects of observation boreholes (Transects U, L, N, Fig. 4). Access tubes were installed adjacent to boreholes to allow the simultaneous measurement of soil water content changes and groundwater level fluctuations. These were all sites at which preferential recharge was anticipated and where detailed spatial and temporal monitoring of soil water and groundwater was of particular interest. Where possible, access tubes were installed sufficiently deep to allow soil water content measurements to be made within the zone of water table fluctuation but, at most sites, the installation depth was restricted to less than 3 m by stones in the lower part of the soil profile. One transect was sited across the main stream channel (Transect U) to identify whether or not recharge took place via the bed of the stream during the few occasions throughout the year that it flowed. A second transect of seven paired sites was located across a tributary of the main stream (Transect L), again to investigate preferential recharge via the stream bed. The third transect was located from the foot of a large expanse of steeply sloping bare inselberg which generates large volumes of runoff, and is thus a potential site of recharge. A transect of six paired access tubes and observation boreholes (N1 to N6) was installed extending downslope across cultivated land.

To monitor changes in soil moisture potential, three arrays of mercury manometer tensiometers were located in the cultivated sub-catchments; tensiometers were installed at 0.1 m increments to a depth of 1.0 m, then at 0.2 m increments to a maximum depth of 2 m. Two sets of gypsum blocks linked to Campbell CR10 loggers were also installed in the Red sub-catchment with blocks placed at depths of 0.1, 0.2, 0.3, 0.5 and 1.0 m.

Measurements of soil evaporation were made in the two cultivated sub-catchments using a large number of microlysimeters. Soil cores were taken soon after rainfall events and thereafter at regular intervals to represent surrounding field conditions as closely as possible.

Crop measurements

Throughout the growing season, radiation interception by the crop canopy was measured to estimate evaporation from plants, using tube solarimeters located above and below the canopy. Crop yield data were collected at the sites of soil water measurement, and dry matter production was determined to estimate evaporation by the crop using empirical relations between dry matter production and crop water use.

MONITORING

The first hydrological measurements began in July 1992 at the end of one of the most severe droughts in recent years. At this stage, monitoring was restricted to groundwater levels within a network of existing wells. By the end of 1993, the range of routine measurements covered rainfall, groundwater levels from observation boreholes, and sampling of rainfall, runoff and groundwater for hydrochemical analysis. In 1994, runoff and soil moisture monitoring was started. Except for the tensiometer data, all the hydrological measurements have been continued to the time of writing. A dataset spanning six rainy seasons since the severe 1991/92 drought has now been compiled.

COMMUNITY PARTICIPATION

A unique aspect of the study has been the close involvement of the local community in the research, at all stages from planning, through to instrumentation and monitoring. During each phase of the study, regular meetings have been held with villagers. In addition, a liaison committee was set up specifically to discuss ideas and to implement the research in a manner which was respectful of the community and incorporated indigenous knowledge. The efforts of the community enabled the installation of a wide range of equipment, and local people have been trained to carry out much of the routine monitoring. A full-time project member has been resident in the catchment throughout the study. In addition to encouraging good relations between researchers and the community, this has made it possible to monitor hydrological processes during the unpredictable and brief, but vitally important, convective rainstorms typical of the area.

Results

BASELINE SURVEYS

Geology

Strongly banded pre-Cambrian gneisses, which form part of the northern margin of the Limpopo mobile belt, underlie the catchment (Robertson, 1974). The gneissic foliation has an ENE-WSW strike which is clearly picked out by the trend of the topography. Within the catchment, the dip of the foliation is generally, though not invariably, steeply northward. The gneisses range from dark coloured pyroxene gneisses to light coloured quartzo-felspathic granulites. Between these extremes of composition is a wide range that grades imperceptibly from one to the other. The various types are interbanded at all scales from a few centimetres to several hundred metres; a complex interbanded sequence results. The south side of the catchment is dominated mainly by quartzo-feldspathic and leucocratic pyroxene gneisses, while pyroxene gneisses are more common on the northern side (Fig. 5).

Fractures and faults at all scales are numerous. Most trend in a NNW direction, normal to the gneissic foliation, though a few examples are oriented NE-SW. In general, the fractures are vertical or steeply dipping and tend to follow a sinuous course often intersecting with others to form a complex network. At least two of the NNW trending fractures are intruded by dolerite dykes, which range from between 4 m to 10 m in thickness.

Soils

The geology strongly controls the distribution of soil types in the catchment. Three main soil types are present and the properties of typical profiles are summarised in Table 3. On the southern side of the stream, quartz-rich resistant granulites give rise to grey duplex soils (Ferric Lixisols) of sandy loam, 0.3 m to 1 m thick, over sandy clay. The sandy clay layer, up to 3 m thick and above essentially unweathered gneiss, results in the formation of a perched water table in wet years. These soils are generally of low chemical fertility but are often useful to farm-

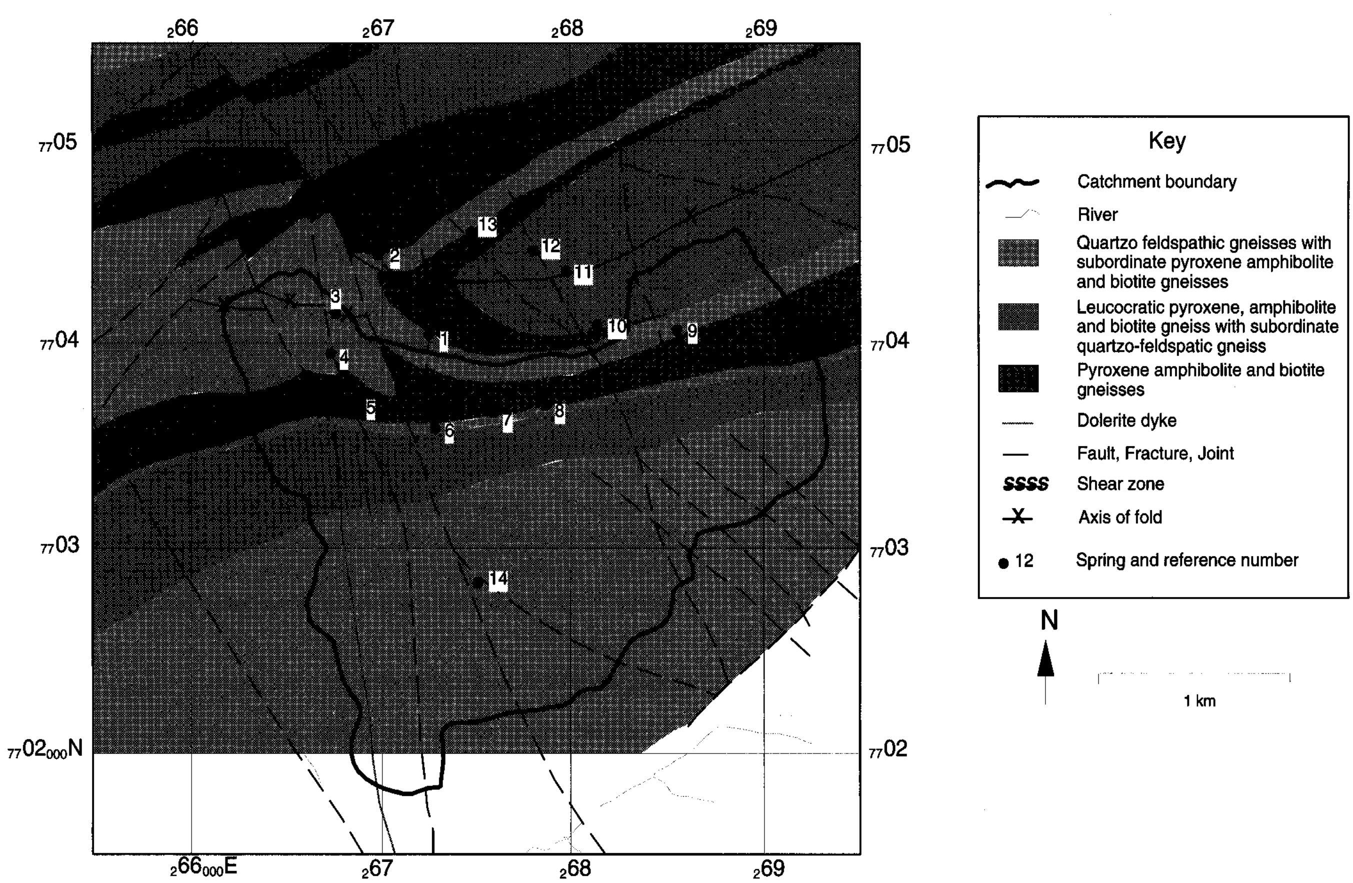


Fig. 5. *Catchment geology and location of springs.*

Table 3. Properties of main soil types

Classification				
Name used		Grey duplex soils	Red clay soils	Vertic soils
Zimbabwean classification		Kaolinitic, fersiallitic (III 5 P)	Kaolinitic, fersiallitic (III 5 E)	(III 3 E)
FAO equivalent		Ferric Lixisol	Chromic Lixisol	
Local name		*hlabatha,* and *chinamwe* (sandy clay layer)	*mushava*	*chidhaka*
Typical profile				
Horizon 1	Depth (m)	0-0.17	0–0.10	0–0.15
	Texture	Med. sandy loam	Med. sandy clay	Med. sandy clay
	% clay	11	24	37
	pH	4.2	4.6	6.2
	CEC (me %)	4.1	5.9	26.2
Horizon 2	Depth (m)	0.17-0.53	0.10–0.156	0.15–0.46
	Texture	Med. sandy loam	Coarse sandy clay	Clay
	% clay	10	41	49
	pH	4.5	5.1	7.3
	CEC (me %)	4.8	6.7	32.5
Horizon 3	Depth (m)	0.53–		0.46–1.2
	Texture	Med. sandy clay		Clay
	% clay	44		61
	pH	6.1		8.0
	CEC (me %)	19.6		38.1

ers with a shortage of draught power, owing to the friable texture of the surface horizons.

To the north of the stream, the less resistant and more easily weathered pyroxene gneiss has given rise to red clay soils (Chromic Lixisols). The weathered profile, or regolith, extends to depths of 10 m and is much deeper than that under the grey duplex soils. The strongly developed micro-structure of these soils makes them more freely draining than the grey duplex soils. The red clay soils are more fertile but require considerably greater draught power for ploughing.

Finally, vertic soils occur in small areas at the lower end of catenal sequences on the north side of the stream bed in central areas of the catchment. In the remaining steeper parts of the catchment, on the hillslopes surrounding the valley, there is a great deal of rock outcrop and, where present, the soils are very variable from shallow stony soils to deep organic-rich soils.

Settlement history and land use change

Until the early 1950s, the catchment was probably uncultivated or cultivated on a periodic and temporary basis. In 1952, the families which make up most of the existing community were settled in the catchment, after being displaced from their lands due to land redistribution in favour of soldiers returning from the Second World War. By 1955, much of the existing cultivated area had been cleared and given over to rainfed crops (Fig. 6). The current land use pattern became fully established by 1963, including the introduction of an extensive system of contour bunds and storm drains. There has been little further clearance of land to the present day.

Contemporary land use and vegetation

Within the catchment there are three kraals or villages; Tamwa, Sihambe and Dhobani. In 1995 there were 32 homesteads with an estimated total population of 200 to 250. The homesteads are located around the catchment at the break of slope between the woodland on the hills and the cultivated lands on the valley floor (Fig. 2). Land use in the catchment determined from 1985 aerial photography was: 55% miombo woodland on the hillslopes, 38% cultivated land and settlements in the valley and 7% vegetation along drainage lines on the valley floor.

In common with other communal lands in Zimbabwe, subsistence farming is the main activity and for many is the major source of food and income. Maize is the most important crop and provides the staple food. Other crops include groundnuts, bambara nuts, cotton, sunflowers and sweet potatoes. Most fields are contour ploughed using an oxen- or donkey-drawn mouldboard plough. Because of the shortage of land, fields are not routinely set aside as fallow. As a result, the maintenance of organic matter levels in the soil is a major problem. Compost, cattle manure

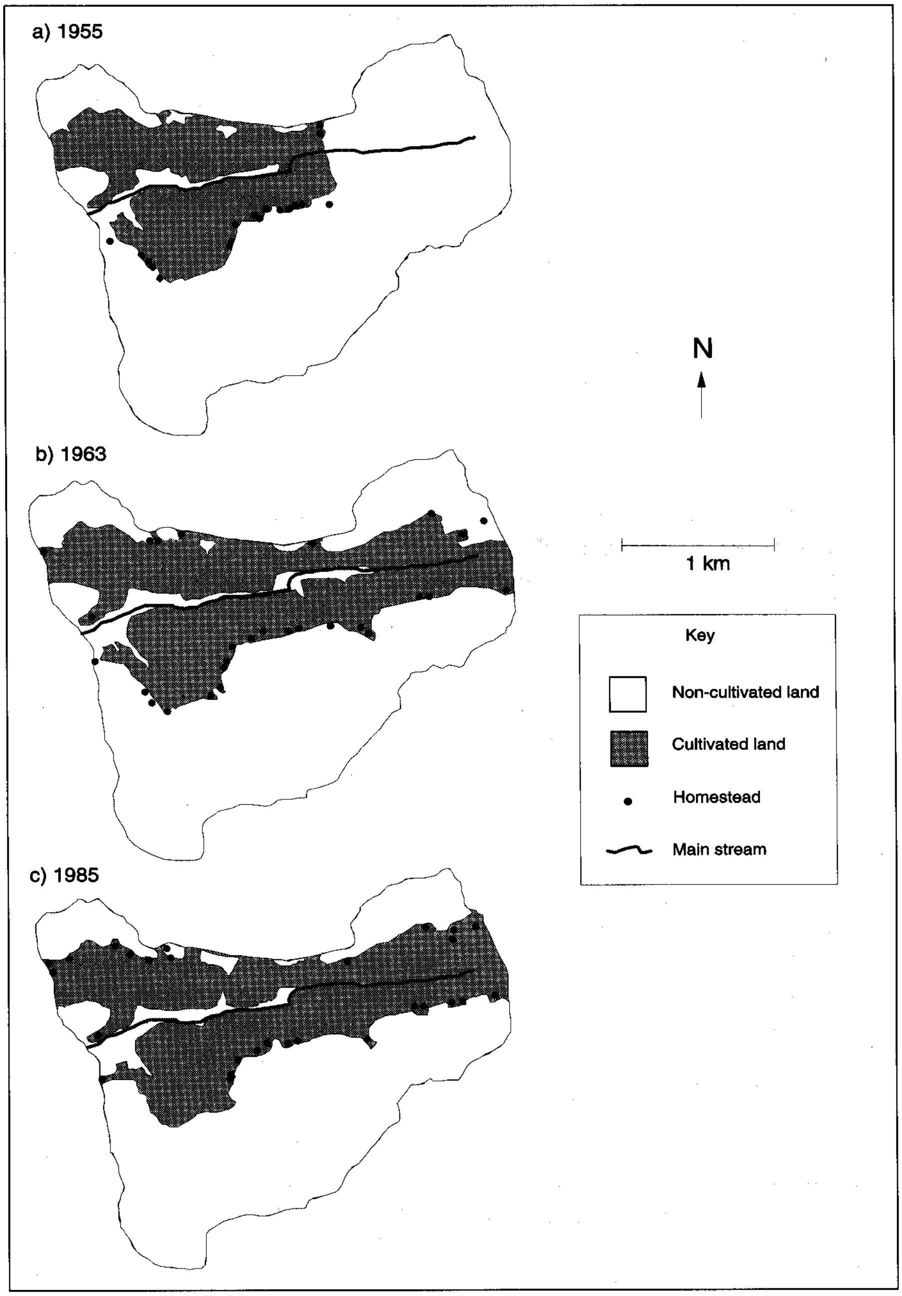


Fig. 6. *Land use change and settlements.*

and crop residues are all used to help sustain organic matter levels, but supplies are generally in short supply. Other agricultural problems include seasonal shortages of labour for carrying out intensive tasks such as weeding, and crop protection from pests.

The miombo woodland which covers the flanking hills is used for grazing goats and cattle and is a source of firewood and building material. Unlike many other communal areas in Zimbabwe, the woodland is generally well managed and shows little sign of degradation. Two main types of woodland are present. The most widespread is *Brachystegia glaucescens* open woodland. The second type, covering a smaller area, is open woodland dominated by *Julbernardia globiflora*, *Kirkia acuminata* and *Brachystegia speciformis*. A more detailed description of vegetation types is given in Mapaure *et al.* (1995).

Water resources

Although surface water is exploited in the rainy season, particularly during wet years, most water to meet irrigation, domestic and livestock needs is abstracted from wells. There are 26 hand-dug wells in use from which an estimated 2000 m^3 yr^{-1} is abstracted (Macdonald *et al.*, 1997).

Abstraction was increased by about 2500 m^3 yr^{-1} in 1991, when a collector well was installed to improve the domestic water supply and provide water to irrigate a community garden (Lovell *et al.*, 1994, 1996). The benefit of the collector well was demonstrated during the severe drought of 1991/92; it continued to supply water while most of the traditional wells in the area failed. Even at times of severe stress on water resources, sufficient supplies are now available to meet all basic requirements. A survey of water use in October 1994, towards the end of a long period of low rainfall and droughts between 1981/82 and 1994/95, showed that total water use (including household, irrigation and livestock) by four families averaged 32 litres per person per day.

In the past, springs were the major water supply for the community throughout the year. However, the survey in 1995 revealed that several of the larger springs no longer flowed, or flowed only for short periods during good rainy seasons. Most springs are located in the north west of the catchment and are associated with the zone of folding, deformation and fracturing in the vicinity of Romwe hill (Fig. 5). Other springs along the line of the main stream channel result from the presence of a narrow band of impermeable quartzo-feldpathic granulite which cuts across the regional direction of groundwater flow.

ANALYSES OF DATA

Although conditions have varied widely, the period of monitoring since instrumentation of the catchment has generally been a period of above average rainfall and recovery of the catchment ecosystem following the severe 1991/92 drought. Detailed results of hydrological research carried out in the catchment up to 1996 can be found in (Butterworth, 1997) and in the papers in this series.

Butterworth *et al.* (1999a) discuss the importance of the process of surface redistribution of rainfall at a field scale in dryland regions. This can be a key factor in controlling deep drainage to groundwater and variable conditions in farmers fields can be exploited to cultivate different crops, vary management practices and reduce the risks of crop failure. The effects of the composition and depth of the regolith (weathered zone), and temporal variation in rainfall on recharge and groundwater level fluctuations are considered in Butterworth *et al.* (1999b). In Butterworth (1999c) modelling techniques are used to investigate historical fluctuations in groundwater levels, and to evaluate the causes of falling groundwater levels in the 1980s and early 1990s.

Future work

Hydrological, economic and social monitoring continues at the Romwe Catchment. A comprehensively instrumented research catchment and an extensive dataset are now available, and these facilities are being utilised by local researchers to undertake research with the community in a communal land setting. In the long-term it may be possible to promote integrated catchment management practices in the catchment and to monitor in detail the impact of the components of such programmes.

Acknowledgements

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