TEMPORAL AND SPATIAL VARIABILITY OF THE HYDROLOGY OF SEMI-ARID ZIMBABWE AND ITS IMPLICATIONS ON SURFACE WATER RESOURCES

BY

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ABSTRACT

There are 170 Communal lands, totaling 163 500 km^2 or 42% of Zimbabwe. About 75% of these Communal lands are in Natural regions IV and V that are semi-arid. Water development is therefore a key aspect in ensuring sustainable rural livelihoods in such areas where good yields are obtained two out of five years. Both groundwater and surface water resources provide water for domestic purposes and gardening during the dry season, and during droughts. Appropriate management of the limited water resources in the semi arid areas is hindered by inadequate knowledge of how catchments function hydrologically. A study was carried out to investigate how the hydrology of catchments found in the semi-arid areas differ, both spatially and temporarily and how it is affected by rainfall variability and land use changes and the implications on surface water resources.

The temporal and spatial variability of rainfall and runoff of the Runde catchment in south-east Zimbabwe was studied using historical data. A second study compared the hydrology of Romwe and Mutangi micro-catchments that are located in the Runde catchment during two seasons representing a very wet and an average season. The effect of rainfall distribution and soil type was studied at Mutangi catchment and the implications on surface water resources were explored. A modelling approach was used to determine the effect of changing rainfall and land use changes and increased water abstraction on surface water resources.

Rainfall varied from place to place within the Runde catchment. Cycles of variation of annual rainfall were observed and the long-term trends in runoff and surface water resources in dams reflect the effect of such rainfall cycles. Significant ($P < 0.05$) correlations between rainfall and runoff were observed for stream gauging stations E2, E4, E49, E54, E112, E117 that were either in the Mutirikwi or Tokwe sub-catchments. No significant relationships between rainfall and runoff were observed in the Upper and Lower Runde sub-catchments.

The hydrology of Mutangi and Romwe catchments were different in the two seasons because of different amounts of rainfall received. Romwe received (1430 mm) about double the rainfall that was received at Mutangi (755mm) in the 1999/2000 season. The difference was only 140 mm in the following year when Romwe and Mutangi received 756 and 615 mm respectively. Romwe generated about five times the runoff that was generated at Mutangi in the 1999/2000 season, which were 520 mm and 102 mm respectively. The runoff was 82 mm and 69 mm in the 2000/2001 season at Romwe and Mutangi respectively.

Rainfall distribution and soil type had an effect on runoff generation at Mutangi. When there were a sequence of daily rainfall events that completely filled the storage capacity in both the sodic and transitional soils, subsequent events produced very large runoff of more than 50% of the rainfall. The sodic soils at Mutangi appeared to generate the most runoff because of their small capacity to store water before saturation.

The amount of runoff captured by a small dam at Mutangi was a small portion of runoff that was 23% and 30% in the 1999/2000 and 2000/2001 season respectively. Almost 97% of the loss from Mutangi dam was through surface evaporation with only 3% used productively, split approximately as 2% garden irrigation and 1% animal watering.

Validation of the Agricultural Catchment Research Unit (ACRU) simulation model against field data revealed that ACRU adequately simulated measured streamflow, soil moisture and dam water storage changes. Removing all the remnant woodland and leaving all the cropped land fallow did not have significant ($P<0.01$) effects on both runoff and dam water level changes over the 27 year simulation period. However, planting trees in the whole catchment significantly ($P<0.01$) decreased runoff. Water abstraction from the dam could be increased up to 2, 4, 6, 8 and 10 times with the dam drying to acceptable levels for 7%, 7%, 11%, 22% and 30% of the years respectively. Construction of tied ridges significantly ($P<0.05$) decreased runoff from the catchment by 19%

The study proved that rainfall varied both temprorarily and spatially over the Runde catchment and the hydrology of semi-arid catchments is determined by both rainfall totals and distribution during a season and soil type. Enough runoff is generated to fill up the dam in most years except those very dry years. Using the existing practices, where the use of reservoir water for gardening only begins in June, water

use could be increased by a factor of five in most years thereby allowing a 2 ha garden to be irrigated. The resources available can be monitored readily using a staff gauge and a volume/depth curve. Typical monthly open water evaporation rates have been established, and these can be used (with a depth/area curve for the dam) to determine safe rates of water use. This will enable the community to make informed decisions such as the percentage of the garden that may be irrigated safely, which crops to grow, and when to stop using the dam water as it approaches the reserve level.

For my wife Zivai and daughter Franciscar Tadiwa.

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Letters

AET	Actual Evapotranspiration
c	Coefficient of initial abstraction
F*t*	Energy available for transpiration
LAI	Leaf area index
Pg	Gross daily rainfall
PWP	Permanent wilting point
S	Potential maximum retention
SMDDEP	Critical runoff response soil depth
Q	Runoff depth

Acronyms

ACRU	Agricultural Catchment Research Unit (University of Natal, South Africa)
CARE	Cooperative for Assistance and Relief Everywhere
CEH	Centre for Ecology and Hydrology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CV	Coefficient of Variation
DFID	Department for International Development
ENSO	El Nino Southern Oscillation
EPIC	Erosion Productivity Calculator
HOF	Hortonian Overland Flow
ITCZ	Inter-Tropical Convergence Zone
SCS	Soil Conservation Service (US)
SHE	Systeme Hydrologique European
SOF	Saturated Overland Flow
START	System for Analysis Research and Training
TOPMODEL	Physically Based Runoff Production Model
USDA	United States Department of Agriculture
ZINWA	Zimbabwe National Water Authority
ZIMASCO	Zimbabwe Mining & Smelting Company

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1. INTRODUCTION

1.1 THE SEMI-ARID AREAS OF SOUTHERN ZIMBABWE

Zimbabwe is divided into five agro-ecological regions. These natural regions are a classification of the agricultural potential of the country, from natural region I, which represents the high altitude wet areas to natural region V which receives low and erratic rainfall averaging 550 mm per annum (Vincent and Thomas, 1960).

There are 170 communal lands, totalling 163 500 km^2 or 42% of Zimbabwe (Anderson, et al., 1993). About 75% of these communal lands are in Natural Regions IV and V and depend on rainfed crop production that provides the main source of their staple food. The semi-arid areas that is mainly Natural Regions IV and V, receive less than 600 mm per annum with frequent droughts (Vincent and Thomas, 1960). The rainfall is also erratic, poorly distributed and falls predominantly for only a few months each year resulting in livelihood insecurity since water scarcity and food security are interrelated problems (Gowing, 2003). Good crop yields are received in three out of five years (Nyamudeza, 1998) forcing the communities to rely on stored underground water (Lovell, 2000; Mbetu, 1993) or water stored in dams during the dry years. Unlike groundwater, surface water resources, especially from small shallow dams are not an effective buffer against droughts because of high evaporation (Bouwer, 2000) and seepage rates (Sur *et al*, 1999).

Most of the communal areas in southern Zimbabwe are highly degraded because of high population densities, high stocking rates and poor land use practices (Campbell *et al.*, 1988; Elwell, 1983; Scoones, 1992; Whitlow, 1979). These result from poor land management of natural resources in a region characterised by high population growth, normally high livestock numbers, a lack of financial and manpower resources for sustainable land management and a land tenure system which promotes overgrazing (IIED, 1992). Poor land management has a marked impact on surface and groundwater resources through siltation and reduced recharge, respectively (Elwell, 1983).

1.2 JUSTIFICATION

Prime constraints on sustainable development of south-east Zimbabwe are the low and erratic rainfall and availability of ground and surface water resources (Lovell *et al*. 1996). There is therefore, need to investigate the hydrology[1] of catchments in these semi-arid areas and how it affects the availability of water resources, that is, water resources auditing (Batchelor *et al*., 2003). Both temporal and spatial rainfall variability bring about temporal and spatial variability in catchment hydrology and water resources availability. Understanding of the above variabilities assists water resource users and managers in making informed water management decisions. Batchelor *et al*. (2003) argues that a knowledge of the current status of water resources and trends in demand and use is a precondition for successful water management. However, the temporal and spatial variability in rainfall and the spatial variation in land use and geology requires catchment studies to be carried out for a longer period and at a number of sites representing the whole spectrum of the semi-arid areas before any generalized results can be achieved (Lovell, *et al*., 1998).

A substantial amount of work has been carried out on catchment hydrology and how it affects water resources (Butterworth, 1997; McCartney *et al*., 1998; Schulze, 2000; Bosch and Hewlett, 1982; Green and Marsh, 1997; Smith, 1987; Burch, *et al*., 1987) with most of this work focusing on wet areas. The few studies in the semi-arid areas are by Butterworth (1997), Lorup, *et al*., (1998) and McCartney, *et al*. (1998). Results from these semi-arid catchments indicate that:

- Catchments in semi-arid areas can behave like those in wetter areas when similar amounts of rainfall are received (McCartney, *et al*., 1998)
- At a catchment scale, runoff from such areas is generally a small part of the water balance (Butterworth, 1997)
- Runoff generating processes can be saturated overland flow (SOF) or Hortonian Overland Flow (HOF) depending on rainfall quantity, distribution and intensity (McCartney *et al*. 1998)
- Changes in land use can result in changes in runoff amounts (Lorup *et al.* 1998)

These studies represented the semi-arid areas in the regions in which they were carried out, yet there is marked spatial variation in climate, physiography, land use, land management practices and the

[1] The partitioning of rainfall into runoff, evapotranspiration, change in soil moisture and groundwater recharge which is affected by landuse, land management and catchment physiography (slope, shape and soil type).

extend of degradation. McCartney *et al*. (1998) compared the hydrology of two catchments, one in a semi-arid area and the other in a wet environment in a season with similar rainfall totals and found that their hydrology were similar. No study has compared the hydrology of catchments located in the semi-arid areas in Zimbabwe and how this affects their surface water resources. Butterworth's (1997) study was based on a catchment that is not as degraded as most of the communal lands and concentrated on the impact of land use change and changing rainfall on groundwater recharge to the shallow weathered aquifer.

The hydrology of degraded catchments can be improved by practising water harvesting techniques (Elwell, 1996). Most of the work on water harvesting techniques has been done on small plots and concentrated on the benefits to the crop (Nyagumbo, 2002) in terms of the increase in soil moisture and crop production. There has not been an attempt to establish the overall effect of in-field water harvesting techniques on catchment hydrology and water resources. For example, it is not known whether increasing water to crops is the same as increasing water for groundwater recharge. Depending on the rainfall amount and distribution in a season, surface water resources are likely to be decreased because of reduced runoff if these rain water harvesting techniques are adopted at a large scale in a given catchment.

Land use changes are always taking place because of changing government policies, changes in people's attitudes and market trends. Changes in land use and land management practices have an impact on catchment hydrology, depending on the type and extend. Most work has considered extreme hypothetical situations whereby change is implemented on the whole catchment (Bosch and Hewlett, 1982), yet such changes are often in different sections of the catchment.

There are therefore, still many gaps in our understanding of the hydrological functioning of catchments in semi-arid areas, given the variety of land use practices, land management practices, changing climate and the fragile nature of semi-arid areas. The impact of such changes on surface water resources has not been established, yet a lot of households in the semi-arid areas depend on surface water resources, given that groundwater recharge to the shallow weathered crystalline basement aquifer system is strongly controlled by the characteristics of the weathered profile and is restricted to areas of more gneiss where a thick and relatively sandy clay occurs (Butterworth, 1997; Lovell, 2000; Bromely *et al.,* 1999). For example, catchment management issues are currently neglected by Zimbabwe National Water Authority (ZINWA) who are more interested in the visible water supply issues (Manzungu, 2002).

There are about 600 small to medium dams in Masvingo Province, most of which were built in the 1970s, with some dating back to the 1940s (Zirebwa and Twomlow, 1999). There are no records of whether these small dams fill up every year or the quantity of water still retained at the beginning of the wet season. Lack of such information complicates water management decisions for the communities as they do not know how much water can be used in a given season and how much should be left before the onset of the wet season, in which there is a risk that the dam may not refill, because of the typical pattern of rainfall in semi-arid areas

To answer some of the above questions Mutangi catchment was instrumented to enable measurements of rainfall, temperature, wind speed, runoff, soil moisture and groundwater changes. The research was conducted at Romwe and Mutangi catchments to enable comparison of two contrasting catchments. Romwe is wetter and not as degraded as Mutangi. Mutangi catchment has a small dam that would enable measurement of changes in water level due to inputs and outputs. Both Romwe and Mutangi are located in Chivi district of southern Zimbabwe. Romwe is near the northern margin of the Lowveld (altitude < 900 m), close to Ngundu (20^{o} 45’ S, 30^{o} 46’ E) (Bromley *et al*., 1999). Mutangi is located 80 km south west of Masvingo town and close to Chivi centre (20^{o} 15’ S, 30^{o} 30’ E).

1.3 OBJECTIVES

The main objective of this study was to investigate how the hydrology of Mutangi and Romwe catchments, that are located in a semi-arid area differ, both spatially and temporaly and how it is affected by land use change and the implications on surface water resources. The specific objectives of the research are:

(i) To determine how rainfall and runoff vary temporarily and spatially and the effect on surface water resources in the Runde catchment

(ii) To compare the hydrology (rainfall, runoff, soil moisture, water table) of Mutangi and Romwe catchments that are located in the semi-arid areas of southern Zimbabwe

(iii) To establish how temporal rainfall distribution, soil type and land use influence the process of runoff generation

(iv) To determine how the water balance of Mutangi reservoir change during the season, and determine if productive use in gardens can be safely increased

(v) To establish the long-term effect of changing rainfall and land use on runoff and surface water resources

1.4 HYPOTHESES

(i) Rainfall varies both spatially and temporarily and this has an effect on surface water resources in the Runde catchment

(ii) The hydrology of Romwe and Mutangi catchments is not different

(iii) The runoff generation process is affected by temporal rainfall distribution and soil type

(iv) The fraction of water used for productive water use from Mutangi dam is insignificant and use can be increased fivefold without drying up the dam in most years

(v) Long term changes in rainfall and land use has an effect on runoff and surface water resources

1.5 THESIS STRUCTURE

The thesis describes the work undertaken to achieve the objectives listed in section 1.3. The thesis is organized in nine chapters as follows. The first three chapters present background and supporting information to the following five chapters that present thematic topics. The last chapter (nine) summarises the main results concludes the research and gives recommendations emanating from the study and identifies research gaps.

Chapter 1 (this chapter) gives a general introduction of the problems of water resources in semi-arid areas and how the understanding of catchment hydrology can assist to increase and improve use of such water resources. The objectives and hypotheses of the thesis are also described in this chapter.

Chapter 2 describes previous work and presents a general literature review on catchment hydrology and water resources management in the semi-arid areas. Chapter 4 presents rainfall and runoff temporal and spatial variability of the bigger Runde catchment (41 000 km^2) within which the Romwe and Mutangi micro-catchments are located. The hydrology of two micro-catchments, Romwe and Mutangi is compared in Chapter 5 using hydrological data that was collected during the 1999/2000 and 2000/2001 rainy seasons. The effect of soil type, land use and rainfall distribution on runoff generation are presented in Chapter 6. Chapter 7 presents the water balance of a reservoir in Mutangi catchment. Scenarios are run to determine whether present water use can be increased and by how much; without drying up the dam before the next run-in using two years of observed data. A physically based distributed hydrological model, Agricultural Catchment Research Unit (ACRU) is described and validated in chapter 8 using runoff, soil moisture and dam water level data collected from Romwe and Mutangi micro-catchments. Investigations of the long-term effect of changing rainfall and land use practices on surface water resources is carried out using historical daily weather data from Chivi. The results of the scenarios are presented and discussed in view of surface water resources use and sustainability. Chapter 9 summarises the main results, conclusions and practical implications emanating from the thesis. Further areas of research are also identified here.

2. GENERAL LITERATURE REVIEW

2.1 THE PLACE OF GARDENING IN THE SEMI-ARID AREAS

Maize is the staple food of the Communities living in the Communal lands of Zimbabwe. However, crops fail in most years especially in the semi-arid areas such that people resort to gardening as a source of income to purchase food and for subsistance. Maize yields are a function of rainfall (Figure 2.1) in the large-scale commercial, communal lands and Chivi District (which is a Communal Area in is semi-arid Southern Zimbabwe). The average maize yields in Chivi district is about 0.5 tonnes per ha and that is a result of low and erratic rainfall.

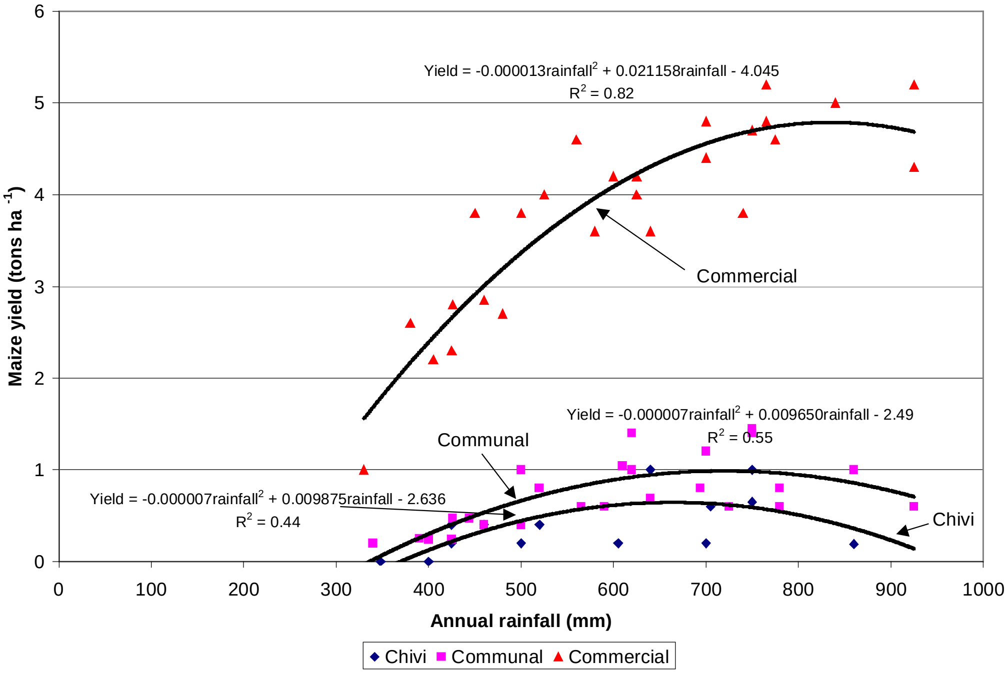


Figure 2:1 Rainfall versus maize yields in the Large Scale Commecial sector, the Communal Areas and Chivi district that is Communal but is located in semi-arid Zimbabwe (Frost, n.d.).

A study carried out by Campbell *et al.*, (2002) in Chivi shows the importance of gardening in the semi-arid areas of Zimbabwe. All the households sampled engaged in dryland crop production with 84% having access to gardens for small-scale irrigation. Slightly more than half of the gross income from gardening comprises cash while about a quarter of the dryland crop gross income is sold with the gross left for subsistence purposes (Campbell *et. al.*, 2002). Campbell *et. al*. (2002) concludes that garden production stands out in three ways – firstly it is something practised by a wide range of household types. Secondly, a high proportion of its income is cash (as compared to dryland production) and thirdly it is predominantly women who provide labour for gardening production.

Despite cash income, specific environmental benefits of community gardens include reduction in pressure to cultivate marginal land, particularly streambank, and the promotion of longer-term management strategies due to decreased risk and increased security of tenure that the schemes bring (Lovell, *et al*. 1996)

2.2 THE NEED TO UNDERSTAND CATCHMENT HYDROLOGY FOR BETTER MANAGEMENT OF WATER RESOURCES.

It is considered by many (Batchelor *et al*., 2003; Lovell *et al*., 1998; Frost, 1999; Yevjevich, 1991; Calder, 2000) that for appropriate catchment management (especially water resources development and management in the semi-arid areas), the understanding of catchment hydrology is a prerequisite. The importance of understanding hydrological processes in water management issues is summarised by Klemes (1971), *'…. the major concern in applied hydrology should be to know to what extent our findings about hydrological processes are relevant to the practical decision-making process in water management, to what extent a more precise knowledge can make the decisions more rational, the results more predictable, and the means of achieving them more economical'.*

An important aspect of understanding catchment hydrological behaviour is the interaction between rainfall (amounts, intensity, distribution) and catchment physiography and land use. The gains and losses must be quantified so that the net water available can then be redistributed taking cognisance of the stakeholders' needs (Batchelor *et al*., 2000). This will also enable the identification of resources management practices that should be promoted in catchments for sustainable water resources development.

However, the stakeholders' use of the catchment affects the hydrological processes and like the factors that affect catchment hydrology are not static; the way the communities living in these catchments use the land changes from time to time. As an example, the partitioning of rainfall into runoff and infiltration differs between grazing and cultivated land. Climatic changes also brings about changes in hydrological processes. These changes can be spatial (due to differences in catchment physiography), intra-seasonal (due to antecedent conditions, rainfall quantity and intensity) and inter-seasonal (due to rainfall distribution and quantity). These factors affect the partitioning of rainfall into runoff, change in soil moisture, evaporation and drainage and have a bearing on both surface and groundwater resources.

2.3 WATER RESOURCES PROBLEMS IN SEMI ARID AREAS

Water is a natural capital (Carney, 1998) that includes soil water, groundwater and surface water (Soussan, 1998). Some of the soil water is available to crops and natural vegetation and its quantity depends on the quantity of rainfall, soil type and depth, slope, land use and management. Water is particulary important in semi-arid areas where rainfall is less than 600 mm. It is used for domestic and irrigation purposes and is seen as the critical natural resource constraint on dryland crop production in Sub-Saharan Africa (Cleaver and Schreiber, 1994).

Some researchers argue that the presence of water points is an entry point to initiating a broader range of community-based management initiatives intended to optimise the use of common-pool resources in the catchments of these productive water points (Frost and Mandondo, 1999). Management of water resources is therefore closely related to the development goals of poverty eradication, socio-economic progress and environmental protection (Gowing, 2003).

In semi-arid areas both surface and groundwater are used for domestic and productive purposes (Lovell, 2000; Batchelor *et al.,* 2000) in gardens to supply domestic needs or generate income through selling of vegetables. However, these water resources fail in some years forcing the communities to walk very long distances to fetch water (Mbetu, 1993). Ground water resources can be obtained from boreholes, deep wells or shallow wells but all can fail although to different magnitudes. As an example, in the prolonged drought of the late 80s and early 90s 20%, 44% and 56% of boreholes, deep wells and shallow wells in communal areas of Masvingo had failed, respectively (Mbetu, 1993). However, groundwater is expensive to access, especially by rural communities, given siting problems on the basement complex (Lovell, 2000) and construction costs. Stored surface water, on the other hand, is easy to access but fails more frequently compared to groundwater due to high evaporative and seepage losses (Bouwer, 2000; Sur *et al.,* 1999).

The high rainfall variability in semi-arid areas results in variability in both surface and groundwater resources hence the need to store water behind dams, and in aquifers through natural and artificial recharge, to save water in times of water surplus for use in times of water shortage. The rainfall conversion efficiency is higher in wet years than dry years. Ground water depends on recharge that tends to be localised in the semi-arid areas (Butterworth, 1997; Sandstrom, 1997).

Surface water resources stabilise water supplies by storing water for use during the dry seasons. They however, suffer from the excesses of the nature including alternating periods of floods and droughts. They also suffer from surface pollution (Bouwer, 2000). Small dams are not sustainable in the long run since they will eventually lose their storage capacity as they fill up with sediments (Bouwer, 2000). Total loss of capacity of up to 30% over 40 years have been recorded in some dams found in Masvingo (Zirebwa and Twomlow, 1999). Sur *et al*. (1999), recorded storage losses due to siltation of the order of 1.2% per year in India. Between 97 to 98% of water loss from surface water has been attributed to evaporation (Bouwer, 2000).

In small dams very little water can be carried over from one season to another especially when a drought of the 1992/3 magnitude occurs, when there is so little runoff that the small dams do not fill to capacity. Apart from evaporative loss and loss of dam capacity due to siltation, seepage losses occur in some dams. For example, Sur *et al*., (1999) reported seepage losses ranging from 61% to 86% in small dams in India.

Soil evaporative losses from underground stored water (Bouwer, 2000) are generally negligible. However, depending on geology, water can be lost from underground stored water through discharge. Butterworth (1997) reported groundwater discharge in Romwe while Mugabe and Hodnett (2001) did not identify any groundwater discharge in Mutangi.

2.4 DATA AVAILABILITY PROBLEMS

Hydrological data is often not available and observation networks are declining in many developing countries because of high costs involved in data collection. National water departments and research organisations alike suffer from a low level of funding, leading to difficulties in retaining staff, and low capacity to manage resources and to investigate improved solutions (SA FRIEND, 2002). Some of the gauging networks are also poorly maintained because of logistical problems (Magowe *et al*., 2004) resulting in data of low quality or gaps in the data.

There are a number of runoff gauging stations in semi-arid Zimbabwe but the data is of limited use in the study of hydrological processes because of the big areas that have a lot of spatial variability. The spatial variability within them is one of the factors which influence hydrological responses hence there is need to study smaller catchments that have very little spatial variability.

2.5 FACTORS AFFECTING CATCHMENT HYDROLOGY

The hydrological behaviour of different catchments varies as a consequence of differences in climate and the geomorphological factors that distinguish them. Key roles are played by the soil-vegetation complex, geology and topography, all of which influence rainfall-runoff transformation (Dubrueil, 1986). The geomorphometric properties that influence hydrologic processes are local slope angle, convergencies or drainage density (Gregory and Walling, 1973).

The effect of rainfall on catchment hydrology is due to both the quantity and distribution of rainfall in a given season. Nichols and Verry (2001) developed multiple regression equations and found out that 93-96% of the variation in annual ground water recharge, stream flow and total water yield was explained by seasonal precipitation amounts, summer and autumn precipitation during the previous year in a humid environment.

A number of studies highlight the importance of soil type on runoff and infiltration (Butterworth, 1997; Kennett-Smith, Cook, and Walker, 1994). The texture and changes of texture down a profile determine the infiltration/runoff relationship and the runoff generation mechanisms.

Results from the Romwe catchment (Table 2.1) in semi-arid Zimbabwe shows that runoff is strongly controlled by soil type Lovell *et al*.). Similarly, groundwater recharge is also strongly controlled by the characteristics of the soil and weathering (Butterworth, 1997). For example, in the Romwe catchment more runoff was generated from the grey soil subcatchment than the red soil subcatchment because the grey soils are duplex in nature with about 40 cm of sandy soil above a hard, less permeable clay soil. The top 40 cm saturates readily, due to ponding at the interface with clay thereby losing most of the subsequent rainfall to runoff.

Table 2.1: Rainfall and runoff from the red and grey subcatchments in the Romwe micro-catchment that is 4.6 km^2.

		Runoff (mm) and in brackets the runoff conversion efficiency (%)	
Season	Rainfall (mm)	Red	Grey
1994/5	738	9 (1.2)	48 (6.5)
1995/6	990	46 (4.6)	203 (20.5)
1996/7	1140	64 (5.6)	335 (29.4)
1997/8	798	67 (8.3)	206 (25.8)
1998/9	1084	22 (2.0)	151 (13.9)

Source: Lovell et al. (1998)

The major land uses in communal areas are cultivation of crops and open woodland that is used for grazing (remnant areas of vegetation). The native vegetation is exploited for grazing, fuel-wood, construction materials and a variety of other uses. The degradation of these resources by overgrazing and deforestation by extension of cultivated areas and over-cutting has been widely documented and represents an important loss to communities dependent on them (Whitlow, 1983; Whitlow, 1988).

The type of land use affects the type of vegetation found in an area and the intensity of degradation. Forests are cleared where cultivation is practiced and the conservation measures practiced depend on whether it is a commercial or a communal set-up. The rapidly increasing population pressure in many rural areas of the developing countries has led to land degradation in terms of soil erosion, reduced productivity and deterioration of fragile natural systems (Du Toit and Campbell, 1989). The soils in the communal areas of Zimbabwe are severely to very severely eroded (Whitlow 1988), due to the reduced vegetation cover.

Du Toit *et al*. (1989) found out that stream flow from the upper Save catchment was 2.53 x 10^8 m^3 greater in the 1970s compared to the 1950s in the upper Save catchment. They attributed the increase to the reduction in evapotranspiration caused by large-scale removal of plant cover to allow cultivation. The intensity of land use also affects infiltration hence runoff. Bangezhano (1983) found that the rate of infiltration in Chiweshe (degraded due to deforestation and grazing pressure) was one quarter of the infiltration rate in the adjacent Romsley Resettlement Scheme area that has similar granitic soils. Lorup *et al*., (1998) assessed the long-term impact of land use change on catchment runoff in semi-arid Zimbabwe, based on the analysis of long hydrological time series. The analysis indicates that the largest changes occurred in catchments located within communal lands, but that a decrease in annual runoff would have occurred had there not been a change in land use.

Lyford and Qashu (1969) found significant differences between infiltration capacities at different distances from the stem of woody desert plants. On average the infiltration capacity near the stems of the plants was nearly 2.7 times higher than that of the area between plants. The same feature was found by Blackburn (1975) on coppice sites and bare interspace sites between coppices. The coppice-dune inter-space areas exhibited relatively low infiltration capacities.

Burch *et al*. (1987) compared the hydrology of a forested and a cleared catchment in Australia and observed that the cleared catchment generated high peak stormflows and large discharge volumes irrespective of antecedent soil moisture, whereas the forested catchment gave little runoff provided antecedent soil moisture content was below 60% of available storage capacity. They attributed the difference in runoff generation to differences in the hydraulic conductivity of the surface layer of the soil under the different land uses.

2.6 PREVIOUS CATCHMENT HYDROLOGICAL STUDIES

Many studies have been carried out on how land use affects catchment hydrology in the wetter areas of the world (Bosch and Hewlett, 1982) but few studies have been carried out in communally managed dryland catchments in the semi-arid areas (Lorup *et al*., 1998; Butterworth, 1997; Lovell et al, 1998). The results from the semi-arid areas are often only representative of the areas in which they were carried out because they suffer from persistent rapid changes in rainfall (spatially and temporarily), variability in soils and geology and an often complex pattern of land use/management practices.

MacCartney *et al*., (1998) compared the hydrology of two small catchments in different rainfall zones in Zimbabwe during the 1995/6 season (a year with similar rainfall). They found that although wet years are less common in dryland environments, when they do occur, the catchment response and runoff totals in catchments in dry areas could be similar to those catchments in wetter areas, despite differences in physiographic features.

The Romwe catchment study has been running since 1993 and many valuable results have been generated. The Romwe catchment is not as degraded as those in most Communal Areas and Resettlement schemes.

Table 2.2 presents some of the catchments studies that have been carried out in Zimbabwe. These studies show a wide year-to-year variation in rainfall, runoff and the runoff coefficients. This variation has been attributed to rainfall distribution in a season.

Table 2.2: Summary of catchment studies that have been carried out in Zimbabwe.

Study catchment	Catchment size (km^2)	Year	Rainfall (mm)	Runoff (mm)	Runoff coefficient (%)
Romwe (dry)	4.6	1994/5	738	4	0.5
		1995/6	1021	95	9.3
		1996/7	1140	84	7.4
		1997/8	798	34	4.3
		1998/9	1084	74	6.8
Marondera (wet)	3.3	1995/6	1085	99	9.1

Source: Lovell et al. (1998) and McCartney et al. (1998)

2.7 RUNOFF GENERATION

Hortonian overland flow was the traditional concept applied for analysis of runoff response. Later studies (Dunne and Black, 1970a) showed that Hortonian overland flow was not applicable to all watersheds, as saturated overland flow is also responsible for some runoff generation.

Runoff generation depends on rainfall quantity, intensity and duration, permeability of the soil and catchment relief, geometry, vegetation and soil cover (Dubrueil, 1985, 1986). Saturated overland flow occurs when the water table rises to the ground surface preventing infiltration, so that any further precipitation is lost as runoff. This process normally occurs where the water table is close to the surface or in areas where the soils are close to saturation most of the time or on soils with very low storage capacity before saturation is reached (Dunne and Black, 1970a). Runoff is produced by saturation from below.

The Hortonian process occurs when rainfall intensity exceeds the soil's infiltration capacity (Horton, 1933) and is the main runoff generation process in semi-arid areas (Sandstrom, 1997). The generation of runoff in semi-arid areas exhibits both similarities and differences to that found in humid temperate areas (Sandstrom, 1997). It is spatially and temporally highly variable and closely related to the spotty nature of rainfall.

Several studies have been conducted to determine the effect of rainfall variability on runoff generation (Lamb, 1999; Loague, 1988; Sepulveda, 1997; Milly and Eagleson, 1988) and they all indicate that the temporal and spatial variability in runoff is due to the temporal and spatial variability in rainfall which substantially affects downward movement of water in the vadose zone.

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) and is related to the great variability in infiltration capacities of soils (Sandstrom, 1997). In the case of saturation overland flow, the spatial variability in runoff generation is due to variable saturated areas in a catchment. The variable saturated areas are controlled by topography, antecedent soil moisture, soil moisture storage capacity and rainfall intensity (Dune and Black, 1970 a,b).

2.8 CONSTRAINTS TO EFFECTIVE USE OF SURFACE WATER RESOURCES

Most of the rivers and streams in the semi-arid areas are seasonal, making it difficult during the dry season for people and livestock to have access to water supplies, hence the need to properly manage the surface water resources. The water resource problems prompted the government to build many small to medium dams to try and reduce the risk of water shortage problems in the semi-arid areas (Zirebwa and Twomlow, 1999). However, the construction of these dams, communities still face water shortages because of a number of reasons.

Communities have insufficient knowledge of their water resources in the reservoirs, in terms of quantity at any given time, and a lack of a clear management strategy. In most cases the resource is not managed at all, and crisis management is employed at the last moment, when shortages are apparent (when wells fail or when dam levels become very low).

Between 97% to 98% of water loss from surface water resources has been attributed to evaporation (Bouwer, 2000) hence the need to accurately estimate evaporative losses from surface water resources (McKenzie and Craig, 2001). These small to medium dams have large ‘surface area to volume’ ratios that promote a lot of evaporation loss (McKenzie and Craig, 2001). McKenzie and Craig (2001) observed that the rates of evaporation from a flowing river (in an arid region) were in the same order of magnitude as a class A pan evaporation data. Apart from evaporative loss, losses of up to 60% of water, through seepage, have been recorded (Sur *et al.,* 1999) from these earthern dams.

Dams are not sustainable since they will eventually lose their storage capacity as they fill up with sediments. High siltation rates of up to 30% of the reservoir (over a period of 40 years) have been recorded in some dams found in Masvingo province in southern Zimbabwe (Zirebwa and Twomlow, 1999).

2.9 APPROACHES USED TO STUDY THE EFFECT OF LAND USE CHANGE ON CATCHMENT HYDROLOGY

There has been an increase in the cultivated land in Zimbabwe since 1900 (Kay, 1970; Stubbs, 1977; Walker, 1975). The high increase in population in the Communal area sector has resulted in land degradation hence dam siltation (Magadza, 1992).

Clearing of vegetation has been shown to increase the annual runoff (Bruijnzeel, 1989) and the actual increase depends on numerous factors such as forest type, rainfall regime, soil type, soil depth and topography (Bosch and Hewlett, 1982). Unfortunately, this increase in runoff does not mean an increase in surface water resources since the dams loose their storage capacity due to siltation (Elwell, 1983).

There are a number of approaches that have been used to study the effect of land use changes on catchment hydrology. The first approach is to study a long data series for a catchment (Lorup *et al.* 1998). By dividing the data record into historically similar periods the statistical significance of change in any target parameter over the different periods may be determined and conclusions drawn. The difficulty with this approach is that the statistical significance is difficult to prove.

The second approach is to identify physically similar catchments (soils and climate). A treatment will be imposed on one catchment e.g. forest clearing and the hydrological variables compared (Burch *et al*., 1987; Gafur *et al*., 2003). Problems such as differences in soil type and topography are encountered such that it becomes difficult to interpret the data and usually the conclusions are based on a few years of experimentation with, in most cases, an unrepresentative rainfall regime.

The third approach is to select paired catchments that have been managed differently over a number of years. Similar to the above approach, the catchment is instrumented and hydrological variables of interest are measured and compared. The problem with these approaches is that they are rigid and cannot be used to explore the effect on catchment hydrology of the numerous land use practices being practiced.

The fourth approach (used in this study) is to use a simulation model that will be calibrated and validated before experimentation (Parkin *et al*., 1996; Ewen and Parkin, 1996; Wagener *et al*., 2001). The model can be used to identify the effect of land use practices on catchment hydrology and the likely impact on water resources.

2.10 EFFECT OF TILLAGE PRACTICES ON CATCHMENT HYDROLOGY

There are a number of cropland management options available to farmers and their uptake depends on the physical and climatic conditions of the area and the farmer's socio-economic status. Work carried out by various researchers shows that soil and water conservation can be achieved by practising the following; ripping into residues, no-till tied ridging, no-till strip cropping and tied ridging, (Elwell, 1996; Nyakatawa, 1996; Nyamudeza, 1993). These tillage practices encourage water infiltration and are important because many of the soils (sandy, loamy sands and sandy loamy) in the semi-arid tropics are poorly structured, self-compacting and have a tendency to crusting/hardsetting.

The investigation by Nyagumbo (2002) reveals that conservation tillage systems effectively reduced runoff compared to conventional mouldboard ploughing. On a fersialitic red clay soil, the runoff conversion efficiency ranged from 0.9 to 4.2% under conservation tillage compared to 20% under conventional ploughing. For a granitic soil, conservation tillage resulted in a runoff conversion efficiency of 3.3 - 9% while the figure was 22% for the conventional ploughing system.

Tillage influences local surface runoff, infiltration and surface storage by altering soil hydraulic properties and soil surface roughness (Larson, 1964; Mwendera and Feyen, 1993, 1994; Ahuja *et al.* 1998; Leonard and Andrieux, 1998). Infiltration is increased due to increased soil porosity and breaking up of surface crusts. Tillage operations have been reported to increase the infiltration capacity by 1 to 50 mm h^{-1} on crusted soils (Leonard and Andrieux, 1998). Some studies (Logsdon *et al*. 1990; Reynolds et al, 1995) have shown that tillage can reduce infiltration capacity because it disrupts pore continuity between the top and subsoil. Natural reconsolidation as a result of raindrop impact and the redistribution of soil particles by splash and flow (Cassel, 1983; Mapa *et al.,* 1986) after tillage gradually reduces soil porosity and surface roughness hence the COIM (coefficient of initial abstraction).

2.11 MODELS THAT HAVE BEEN USED TO STUDY THE EFFECT OF LAND MANAGEMENT IN THE SEMI-ARID AREAS.

A model is a conceptualisation of the real system that retains the essence of that system for a particular purpose. Models attempt to capture the essence of the complex nature in hydrological processes in a manageable way but it is important to recognise that this conceptualisation also involves a considerable degree of simplification (Singh and Woolhiser, 2002).

Models can be used to evaluate the evidence of hydrological change, and the relative effects of rainfall and land use change. Models like Agricultural Catchment Research Unit (ACRU) (Schmidt and Schulze, 1987; Butterworth, 1997) Physically Based Runoff Production Model (TOPMODEL) (Beven and Kirkby, 1976, 1979; Beven, 1995), Systeme Hydrologique European (SHE) (Refsgaard and Storm, 1995) and Erosion Productivity Impact Calculator (EPIC) (William *et al*., 1990) have been used in other parts of the world to assess changes in catchment hydrology and water resources.

Rigorous model testing, calibration and validation is required before a model's capabilities can be used to assess the effect of changes in land use on catchment hydrology (Ewen and Parkin, 1996; Parkin *et al*., 1996). Model testing involves the evaluation of the accuracy with which the computer code represents the model. Calibration is the quantification of parameters in the model using simulation outputs and observed data of the real system until the two sets match with a close agreement or acceptable error. Validation is the process of comparing simulated results to real system data not previously used in calibration or parameter estimation.

However, models have their own shortfalls. Models are developed for specific uses and often for specific regions but they have often been applied in other regions with different conditions. There is also a problem of unavailability of some parameters, long term data especially weather for validation and scenario building (Woods, 1997; Beven, 1989).

3. SITE CHARACTERISTICS

3.1 THE RUNDE CATCHMENT

Runde catchment is located in Southeast Zimbabwe (Figure 3.1). The Department of Water Development has divided Zimbabwe into 6 hydrological zones, A to F, and the Runde catchment falls within the Hydrological zone E, which comprises areas drained by Runde, Tokwe, Mutirikwi and Chiredzi rivers and finally draining into the Limpopo river.

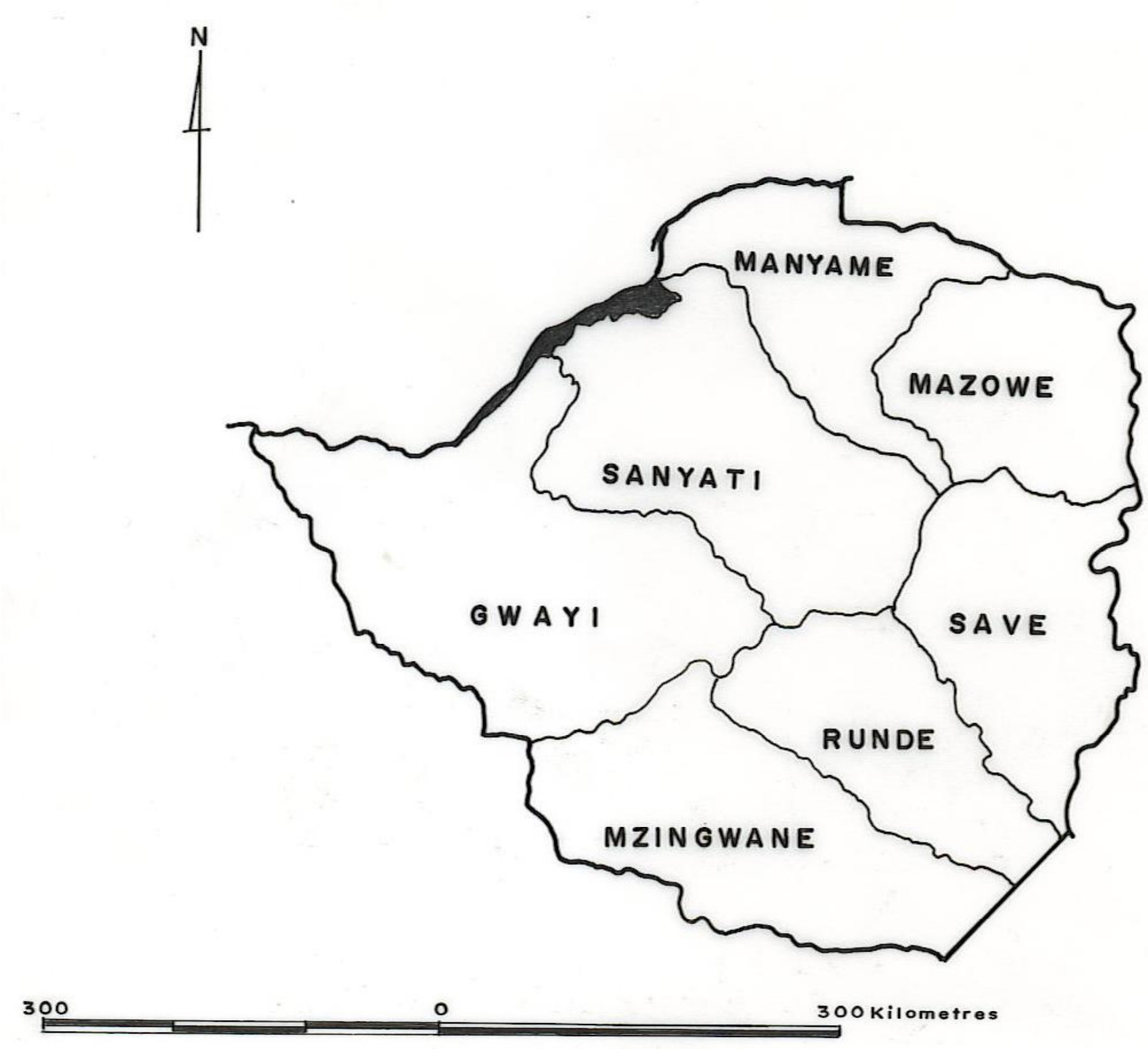


Figure 3.1: Zimbabwean catchments (WRMS, n.d.).

3.2 ROMWE AND MUTANGI STUDY MICRO-CATCHMENTS

Romwe and Mutangi sub-catchments (Figure 3.2) are located in Southern Zimbabwe and are headwater catchments of the Runde River. They are about 80 km apart. They are similar in area and basic geology but the soils and physiography are very different (Table 3.1). Romwe is in natural region IV while Mutangi is in natural region V. Rainfall usually occurs in the summer months from October to April and generally 84% of the rainfall is received between November and March. January is often characterised by midseason droughts (Scoones *et al*.. 1996).

3.2.1 Romwe catchment

The Romwe catchment (Figure 3.3) has an area of 4.6 km^2, and is about 2.75 km long and between 1.5 to 2.5km wide along most of this length (Butterworth *et al.,* 1995). Altitude is between 695 metres above sea level (masl) at the catchment outlet and 955 masl on the summit of the hills on the southern side of the catchment. Gentle slopes with cultivated soils are found along the valley floor, which is border to the north south by relatively steep rocky hills with saddles between the hills. An ephemeral stream drains from east to west. The rainfall average is 590 mm.

The soils of Romwe have been described by Butterworth (1997). Three major soil types occur within the catchment due to differences in parent material and topographic effects. These are grey duplex soils, red clay soils and vertic soils (Appendix B).

The grey duplex soils of sandy loam over sandy clay formed from the more leucocratic gneiss are found on the southern part of the stream. These are described as kaolinitic, fersiallitic soils (5P) according to the Zimbabwe Classification system (Thompson & Purves, 1978) and are equivalent to a Ferric Lixisol (FAO/UNESCO/ISRIC system). These soils are similar to the gleyic, granitic sands described by Vogel (1993), which cover some 46% of Zimbabwe (Purves, 1976).

Red clays kaolinitic fersiallitic (5E) soils with granular microstructure derived from the more mafic pyroxene gneiss predominate north of the stream. The FAO/UNESCO/ISRIC system classification is a Chromic Lixisol.

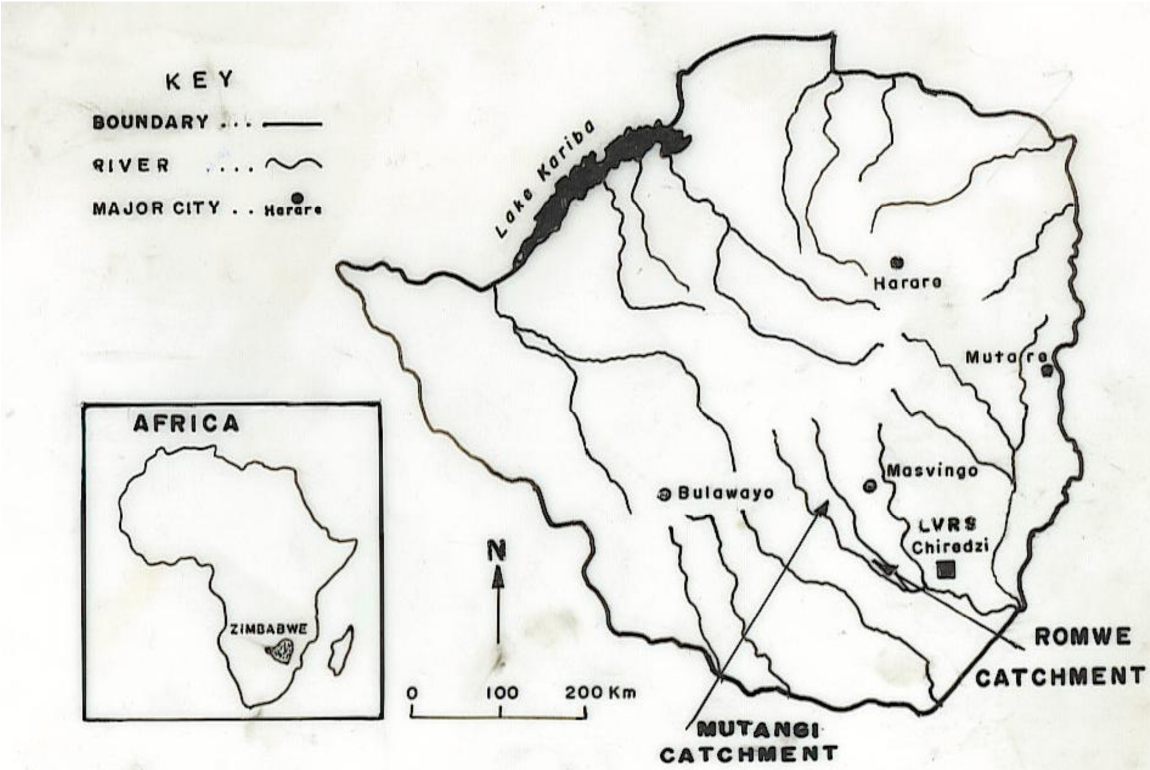


Figure 3.2: Map of Zimbabwe showing the location of Romwe and Mutangi catchments in Chivi district.

The third and least extensive soil type are soils with vertic properties which occur as the lower members of the catenal sequence in parts of the catchment to the north of the stream. These black, heavy clay soils were formed as a result of colluvial transport of fine particles and deposition in lower-lying areas.

The vegetation of Romwe (Figure 3.3), has been described by Mapaure (1999). *Brachystegia glaucescens* woodland (250.51ha) is the most widespread woodland type with an average canopy cover of about 40-60%. Other notable species occurring in this type include *Diplorhynchus condylocarpon, Psuedolachnostylis maprouneifolia, Combretum molle, Euphobia ingens, Albizia tanganyicensis* and *Aloe* species are common in places where soils are shallow and rocky.

Julbernardia globiflora mixed woodland (19.17 ha*)* is a small miombo woodland dominated by *Julbernardia globiflora*. It has a canopy cover of 40-50%. Other tree species include *Kirkia acuminata, Lonchocarpus capassa, Xeroderris stuhlmannii, Combretum collinum* and *Ficus sur*.

Table 3.1: Comparison of topography, rainfall, geology, soils, vegetation and land use of Romwe and Mutangi catchments.

	ROMWE	MUTANGI
Location	Chivi -close to Ngundu 20^o 45'S, 30^o 46'E	Close to Chivi centre 20^o 15'S, 30^o 30'E
Area	4.6 km^2	5.9 km^2
Altitude	695-955 masl	878-939 masl
Topography (typical slopes)	Hillslopes: 25-65% Valley floor: <5%	< 2%
Rainfall (mm)	Mean 590 Max 1600 Min 83 CV 0.42	Mean 545 Max 1160 Min 83 CV 0.37
Geology	Precambrian gneiss with occasional dolerite intrusions	Precambrian gneiss with occasional dolerite intrusions
Soils	Acidic, strongly leached sandy soils overlying sandy clay loam (grey duplex soils); acidic, well structured sandy clay soils (red clay soils); vertic soils in the valley varying with parent material and topography.	Acidic, sandy soils overlying Loam sandy soils (on the ridge); acidic sandy loam overlying sandy clay loam (between the ridge and drainage lines); sodic soils (along drainage lines). Shallow depth of weathering. Bedrock at shallow depth (max 3 m)
Vegetation	Miombo woodland on the hillslopes (55%); cultivated and settled (38%) mixed vegetation along drainage lines (7%)	Mopane woodland along the drainage lines (13%); mixed vegetation on the hill and north western part of the catchment (17%); cultivated and settled (53%); fallow fields (11%).
Water resources	Ground water 2 boreholes and 32 wells, depth range 10-20 m . Water not saline	Both ground and surface water. 1 dam, 3 boreholes (1 working) and 16 wells shallow (max 3m). Water saline.
Population density	54.3 persons km^2	27.1 persons km^2
Landuse	Rainfed cultivation on the valley flow and livestock grazing in the miombo woodland on the hillslope and along drainage lines	Rainfed cultivation on the eastern half (56%) and livestock grazing (30%) on the western half of the catchment with many fallow fields (12% of the catchment)

* masl – metres above sea level.

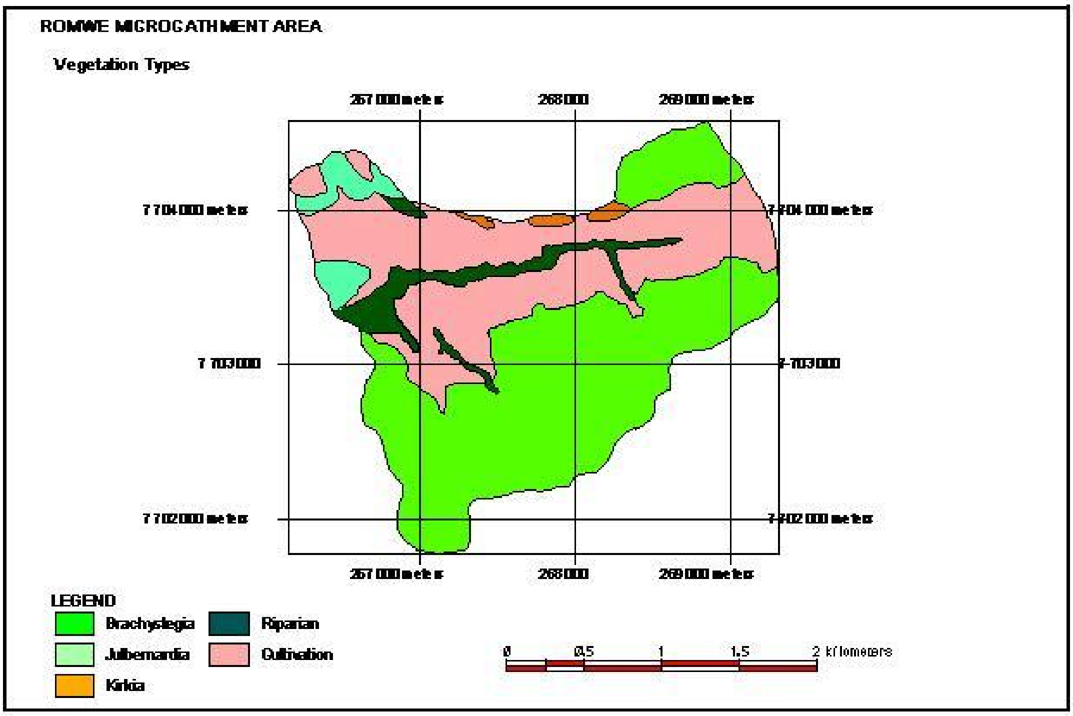


Figure 3.3: Romwe Catchment Vegetation Type Map (after Mapaure, 1999)

Kirkia Acuminata (4.98 ha) is an open woodland found on low rock hills and is dominated by *Kirkia Acuminata - Xeroderris stuhlmannii* with a canopy cover ranging between 10-20% and tree height between 8-10 m. Other tree species found in this type are *Sclerocarya birrea, Afzelia quanzensis, Albizia tanganyicensis, Brachystegia glaucescens Strychnos madagascariensis* and *Commiphora edulis*. The grasses found in this type include *Myrothamus flabellifolius, Danthoniopsis pruinosa and Celeochloa setifera, Panicum maximum, Melinis repens*, and *Aristida* species.

The Riparian *Bauhinia galpinii* thicket (28.67 ha) are found as narrow bands of up to 30 m wide along watercourses dominated by *Bauhinia galpinii* with a canopy cover averaging about 60%. Other tree species found in this type are *Tarbenaemontana elegans, Diospyros mespiliformis, Acacia galpinnii, Bridelia mollis, Combretum adenoginium, Hexalobus monopetalus, Phyllanthus reticulatus, Antidesma venosum and Holarrhena pubescent*. Lianas and vines found in this type are *Cyphostemma* *paucidentatum, Cissus integrifolia, Adenia digitata, Paederia bojeriana, and Ampelocissus obtusa.* The Common grass is *Panicum maximum.*

Acacia polyacantha woodland type is found mainly along the main stream water courses on black vertic soils. The canopy cover is 30% or less and tree height is up to 8m. Other species found are *Pilostigma thonningi, Combretum adenogonium* and *Combretum imberbe.* Grasses found are *Urochloa trichopus , Erogrostis rigidior* and to a lesser extent *Tragus berteronianus*.

The *Acacia-Combretum* mixed woodland mixed woodland thicket have a tree canopy cover of up to 70% and a height range between 8-12 m. It is found along the main stream running east-west through the centre of the catchment area. The dominant species are *Acacia karoo, Acacia polyacantha, Acacia xanthophloea, Acacia rehmanniana* and *Combretum adegonium.* Other trees associated with this type are K*igelia africana, Piliostigma thonningii* and *Ziziphus mucronata*. The main tree thicket forming species are *Combretum microphylum, Grewia flavescens Artabotrys brachypetalus, Rhoicissus revoilli and Senna bicupsularis.*

3.2.2 Mutangi catchment

Mutangi micro-catchment is 5.9km^2 in area, about 5 km long and 1-2 km wide, along most of its length. Its altitude is between 880 masl at the catchment outlet and 940 masl at the top of the catchment. The catchment has an average gradient of 0.8% and is bordered by a very low divide. It is drained by an ephemeral stream that branches into four tributaries about half way to the top end (Figure 3.4) of the catchment. The main stream drains into a dam that is at the lower end of the catchment. The long-term rainfall average at a nearby station (Chivi) that is 14 km east of the catchment is 545 mm per annum.

There are three main soil types in the Mutangi catchment (Figure 3.4), three of which follow a clearly defined toposequence, grading from one to the other down the slope (Muzuva and Gotosa, 1999) (Appendix B). Climatic and ecological conditions have little effect on soil properties of Mutangi catchment. The highest lying members of the catena are shallow to moderately permeable deep coarse sands merging to coarse loamy sands, into soft weathering gneiss. Small areas of stony phase soils (lithosols) occur associated with rock outcrops (not always on the ridge crests). These soils have good permeability, are infertile and have a very low available water capacity. The lowest lying members of the catenary sequence, along the stream channels, are strongly sodic and characterised by mopane scrub, which is often very stunted. Between the sandy, permeable ridge crest and the sodic soils, the soil properties are dependent on slope position, with a gradual transition down slope to the highly sodic conditions.

The mid slope soils 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 clayey (15% clay content) and beginning to show sodicity.

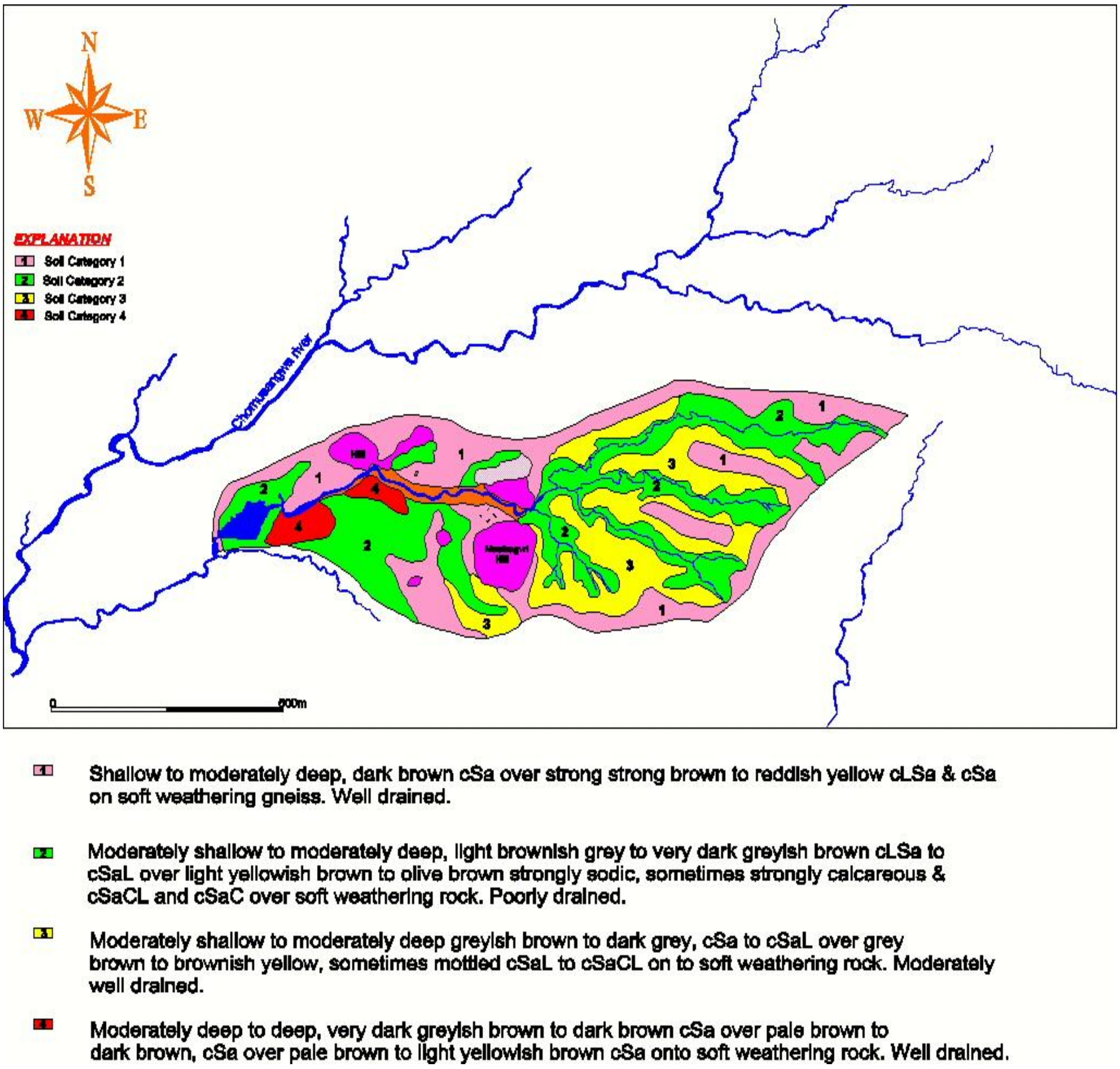


Figure 3.4: Soil map of Mutangi catchment

The vegetation of Mutangi (Figure 3.5) 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 with shallow soils (Figure 3.6). Along first and second order streams, *Colophospermum Mopane* tree and shrub regrowth are dominant on the heavy textured sodic soils. A mixture of deciduous woodland occurs on the hills and the main stream. On the hills, the woodland comprises *Combretum* spp., *Commiphora* spp. and *Adansonia digitata*. On the light textured soils, *Terminalia sericea* trees species are dominant together with *Dicrostachys cineria*, *Albizia amara* and *Sclerocarya birrea*.

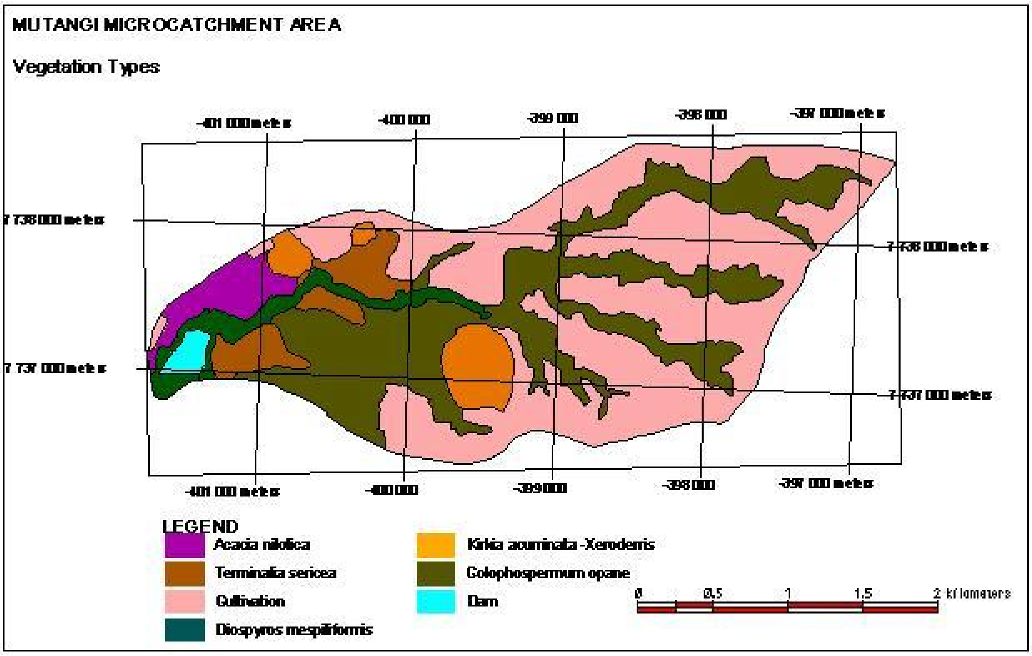


Figure 3.5. : Mutangi Catchment Vegetation Type Map (after Mapaure, 1999)

Figure 3.6: Showing the eastern half of the catchment where most of the cultivation is taking place between the drainage lines. [The trees along the drainage lines are *Mopani* trees that are associated with sodic soils on the catenary sequence. (Picture taken from Mushugwi hill overlooking North East of the catchment].

4. RAINFALL AND RUNOFF VARIABILITY IN THE RUNDE CATCHMENT AND IMPLICATIONS ON SURFACE WATER RESOURCES.

4.1 INTRODUCTION

Zimbabwe has been divided into 7 catchments (WRMS, n.d.) each defined by a major river system and its associated tributaries. Catchment delineation was done in order to effectively manage water resources with the participation of all stakeholders in a given catchment. Of these catchments, the Runde (41 000 km^2) is one of the three catchments that lie in the driest parts of the country covering Natural Regions III, IV and V and major districts and towns (Gweru, Masvingo, Zvishavane, Mberengwa, Shurugwi, Mwenezi, Gutu, Zaka, Ndanga, and the Lowveld areas of Chiredzi and Triangle). It constitutes 22% in area (Figure 3.1) of the country and 40% of this catchment is in communal lands (Anderson, *et al*., 1993). It receives about 684 mm of rainfall per annum with frequent droughts (Anderson, *et al*., 1993).

The catchment contains 45 large dams (15 – 30 m high) (Kabell, 1986) that are used by communal, resettled and commercial farmers for irrigation and domestic water supply. Some are also used for mining purposes. The Lowveld sugar industry is the major user of water in the catchment. The main estates are Triangle, Hippo Valley and Mkwasine which obtain their irrigation water from Mutirikwi, Bangala, Manjirenji and Siya dams. There are also a number of small scale irrigation schemes including Mushandike, Banga, Zananda, Mavhaire, Mabwematema, Musaverema, Mhende, Muchigwe and Musvuvugwa which obtain their water from some of the dams in the catchment. The six major municipal areas that obtain raw water from Runde catchment are Gweru, Masvingo, Zvishavane, Shurugwi, Chiredzi and Gutu. The ZIMASCO mine in Shurugwi, Shabani and Mimosa mines, the Gaths mine and the Renco mine use water from Impali, Palawani, Muzhwi and Nyajena dams respectively.

It is therefore apparent that rainfall and runoff has an impact on the socio-economy of the people living in the Runde catchment and Zimbabwe as a whole hence the need to understand the temporal and spatial variability of both rainfall and runoff which determines the reliability of water supply. The very high inter-annual variability of mean annual rainfall and El Nino Southern Oscillation (ENSO) impacts results in high vulnerability of the water supply system (Peel, 1999). However, there are difficulties associated with forecasting seasonal runoff as a result of low rainfall forecast accuracy and the unavailability of skills/methods to translate rainfall forecasts to runoff forecasts.

4.2 OBJECTIVES

(i) To establish the relationship between rainfall and runoff in the Runde catchment from previous rainfall and runoff records.

(ii) To determine how rainfall and runoff varies both temporally and spatially and the implications on dam water resources in Runde catchment.

4.3 HYPOTHESES

(i) A significant relationship exists between rainfall and runoff in the Runde catchment based on previous rainfall and runoff records.

(ii) The temporal variability in rainfall and runoff of the Runde catchment is reflected in the dam water resources.

4.4 MATERIALS AND METHODS

Annual rainfall data for Chivi Office, Masvingo, Chivi, Chiredzi, Zvishavane, Gweru and Chendebvu stations was obtained from the Department of Meteorology. Rainfall recording using plastic rain gauges started in different years but data used in this analysis starts from 1960 for purposes of uniformity. The altitudes of Masvingo, Chivi, Chiredzi, Zvishavane, Gweru and Chendebvu are 1200, 870, 430, 1200, 1480 and 820 m respectively.

Data from 13 streamflow gauging stations were used in this thesis (Figure 4.1). The gauging stations were installed in the 1960s and early 1970s and all the stations have been in continuous operation since then. Water flow is measured using Kent recorders.

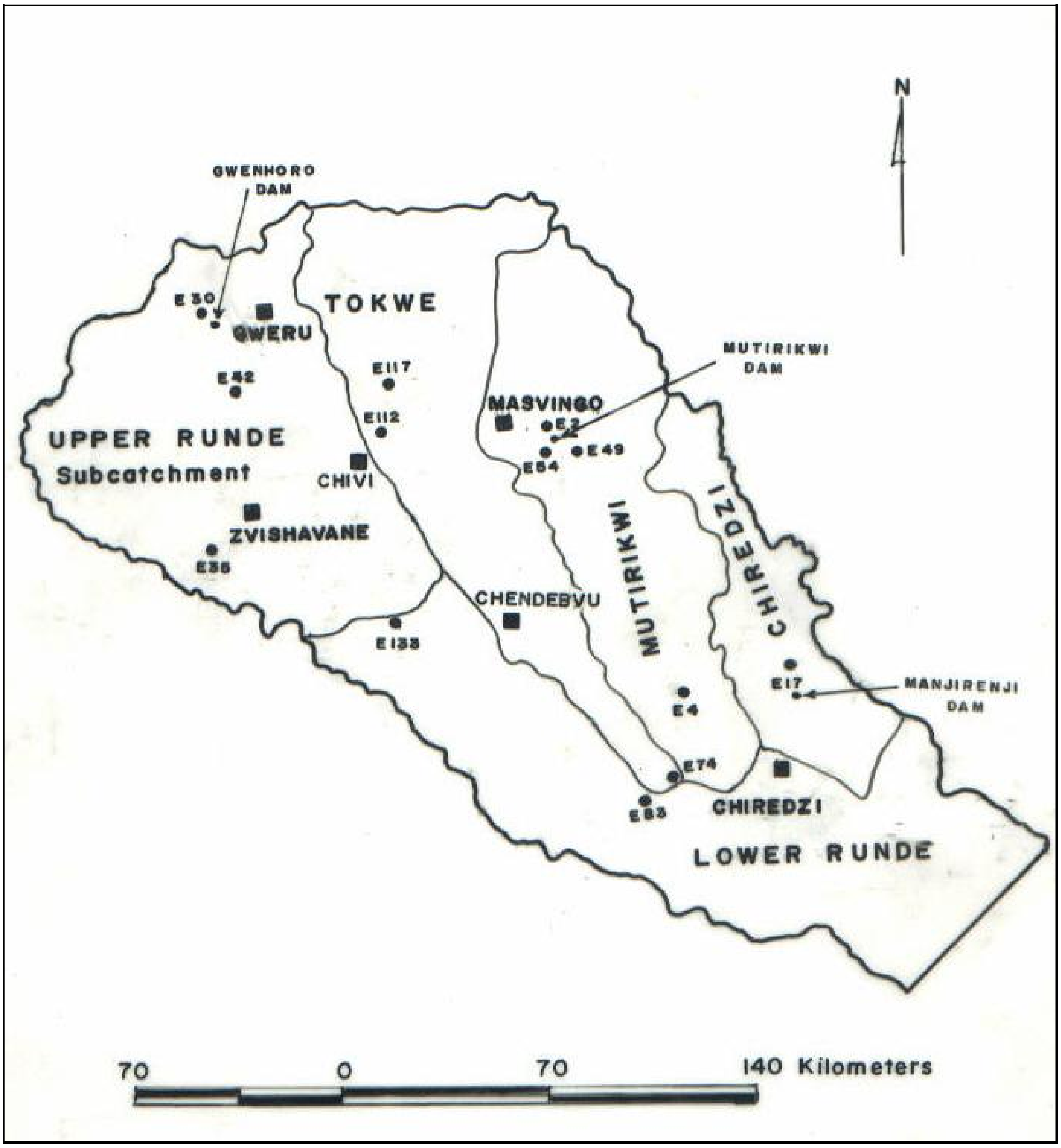


Figure 4.1: Runde catchment distribution of rainfall (■) and streamflow (●) gauging stations that were used in the study. E's are streamflow gauging stations.

Dam water level changes for three dams (Mtirikwi, Gwenhoro and Bangala) were obtained from the Data and Research Unit of ZINWA.

4.5 RESULTS

4.5.1 Rainfall

Mean annual rainfall and coefficients of variations differ from location to location within the Runde catchment (Table 4.1). Figure 4.2 illustrates 5-year running means of annual rainfall totals for the six stations. Each of the six sites displays a broadly similar characteristic except the magnitude for most of the period. Masvingo differed with the other stations from 1960 to 1965 in that it displayed very low rainfall during this period. Gweru had the highest rainfall in most years while Chivi had the least. A cyclic trend is apparent; rainfall was below average in the 1960s and 1980s and above average in the 1970s. A long-term trend at Chivi from 1914 shows a similar cyclic nature (Figure 4.3) when (using a 10 year running average) rainfall was below average in the mid 1940s to mid 1950s and the 1990s and above average in the mid 1950s to 1980. The long-term rainfall data at all of the six stations displayed an insignificant decline over the period.

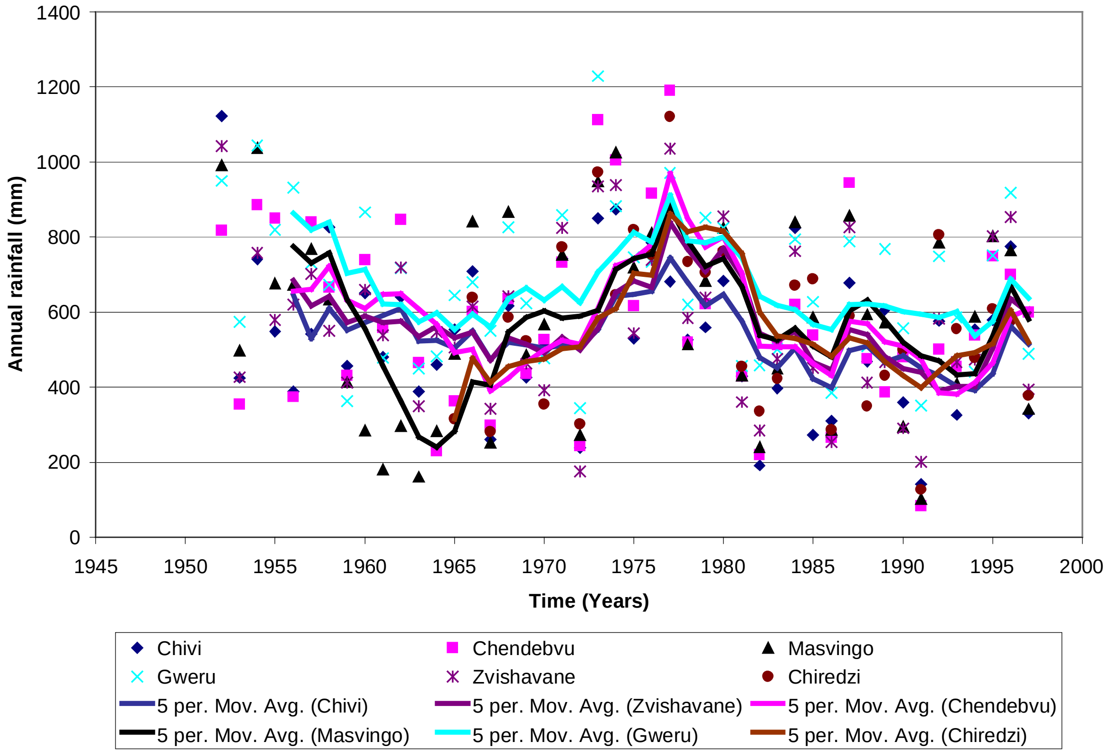


Figure 4.2: 5-year running averages of annual rainfall totals at Chendebvu, Chiredzi, Chivi, Gweru, Masvingo and Zvishavane.

Table 4.1: Parameters of annual rainfall for some of the rainfall stations in the Runde catchment.

Station	Period of record	Mean rainfall (mm)	Min (mm)	Max (mm)	Std dev	CV (%)
Chendebvu	1953 – 1998	591	83	1191	253	43
Chivi	1914 – 1998	544	143	1123	203	37
Chiredzi	1965 – 2000	562	127	1120	219	39
Gweru	1952 - 1999	676	344	1229	203	30
Masvingo	1953 – 1998	582	102	1037	255	44
Zvishavane	1952 - 1999	576	176	1042	217	38

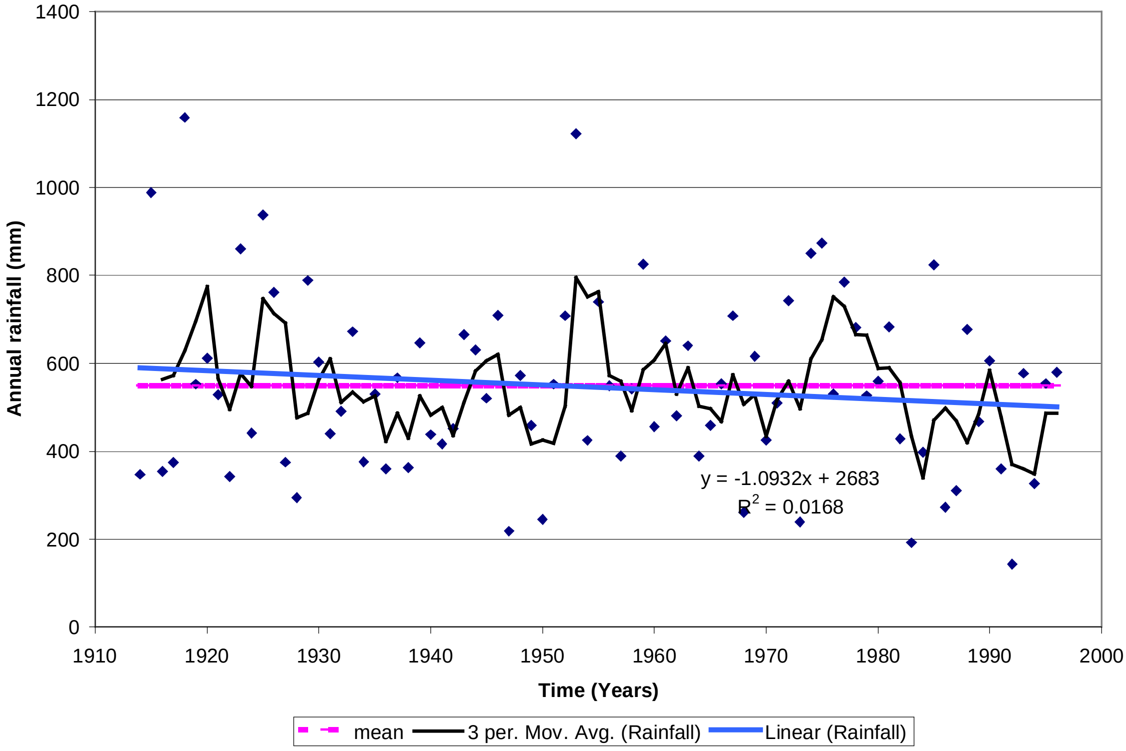


Figure 4.3: 3-year running average of annual rainfall totals at Chivi (1914-1998).

4.5.2 Runoff

All the thirteen gauging stations display the same general runoff pattern (Figure 4.4) with the highest runoff being recorded in 1977 at all the locations. However, there is much variation, even for gauging stations that are in the same subcatchment. The Tokwe subcatchment produced the most runoff in most of the years, while the least runoff was recorded at Chiredzi and Lower Runde subcatchment (Table 4.3).

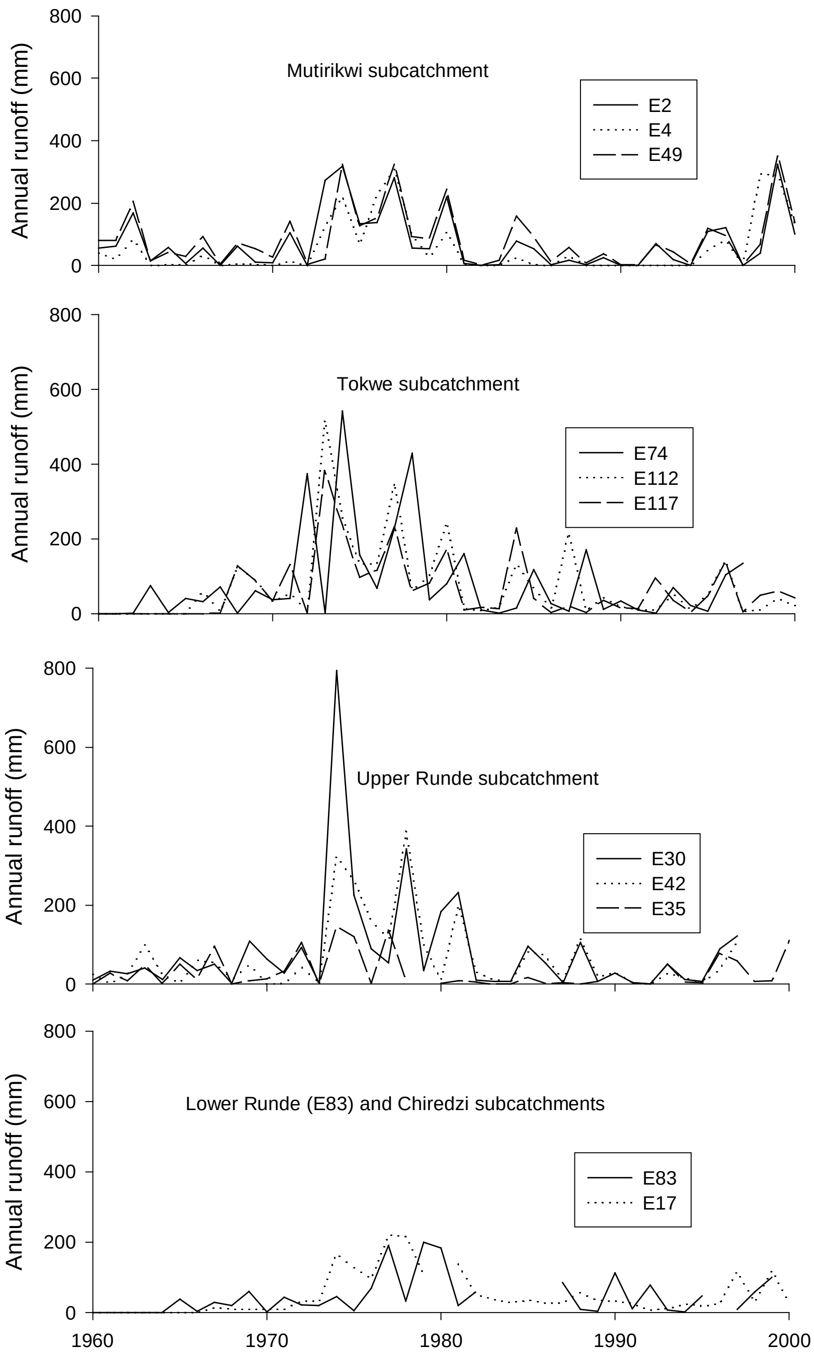


Figure 4.4: Annual runoff for selected gauging stations in the Runde catchment. The E's are gauging stations.

Table 4.2: Statistical parameters of runoff at the different gauging stations in the Runde catchment and their levels of significance.

Sub-catchment	Gauging stations	Area (km^2)	Max runoff (mm)	Min runoff (mm)	Mean runoff (mm)	CV (%)
Mutirikwi	E2	541	385	0.0	78.6	104
	E4	7058	309	0.0	59.2	161
	E49	1010	358	1	85.8	107
	E54	212	215	0.0	52	105
Tokwe	E74	23000	542	0.7	88	142
	E112	1200	519	4	87.3	129
	E117	1090	383	2	76.5	113
Upper Runde	E133	5390	259	0.7	54	111
	E30	254	794	0.3	92.2	170
	E42	648	387	0	72.7	137
	E35	1630	146	0.0	30.3	140
Lower Runde	E83	17100	199	0.3	50	112
Chiredzi	E17	1700	220	6	57.6	104

4.5.3 Rainfall-runoff relation

E2, E4, E49, E54, E112 and E117 showed significant regression equations (Table 4.3) as indicated by the coefficient of determination (r^2) values. The coefficient of determination is a measure of the proportion of the variability of runoff accounted by for by the variations in rainfall. E74, E133, E30, E42, E35, E83 and E17 were not significant. All the four gauging stations from Mutirikwi subcatchment were significant, while two were significant in the Tokwe subcatchments and non at all in the Upper Runde, Lower Runde and Chiredzi subcatchments. The coefficient of determination from the regression between rainfall and runoff decreases with increase in catchment area (Figure 4.5).

Table 4.3: Linear equations of rainfall-runoff relation in the Runde catchment.

Sub-catchment	Rain-gauge station	Stream gauging station	Equations	R^2
Mutirikwi	Masvingo	E2	R = 0.2209P – 60.07	0.413*
	Masvingo	E4	R = 0.1846P – 58.04	0.305*
	Masvingo	E49	R= 0.2032P – 40.25	0.361*
	Masvingo	E54	R = 0.1491P – 32.77	0.435*
Tokwe	Chivi	E74	R = 0.0585P + 63.90	0.008
	Chivi	E112	R = 0.3395P – 89.80	0.361*
	Chivi	E117	R = 0.3118P – 86.27	0.493*
Upper Runde	Chivi	E133	R = 0.0678P + 17.06	0.057
	Gweru	E30	R = 0.0747P + 32.94	0.012
	Gweru	E42	R = 0.0108P + 59.30	0.0005
	Zvishavane	E35	R = 0.0271P + 14.09	0.0201
Lower Runde	Chivi	E83	R = 0.0019R + 48.966	$4x\ 10^{-5}$
Chiredzi	Masvingo	E17	R = 0.0426P + 31.211	0.0293

* Significant at the 0.05 level; P = rainfall; R = runoff.

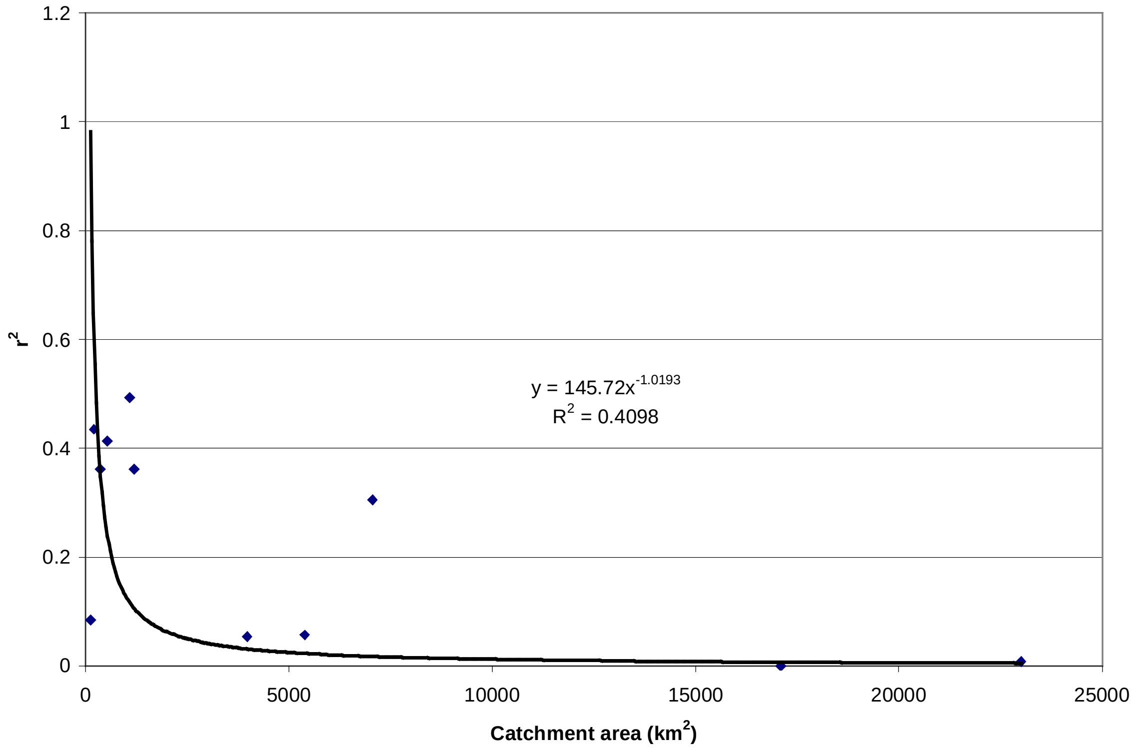
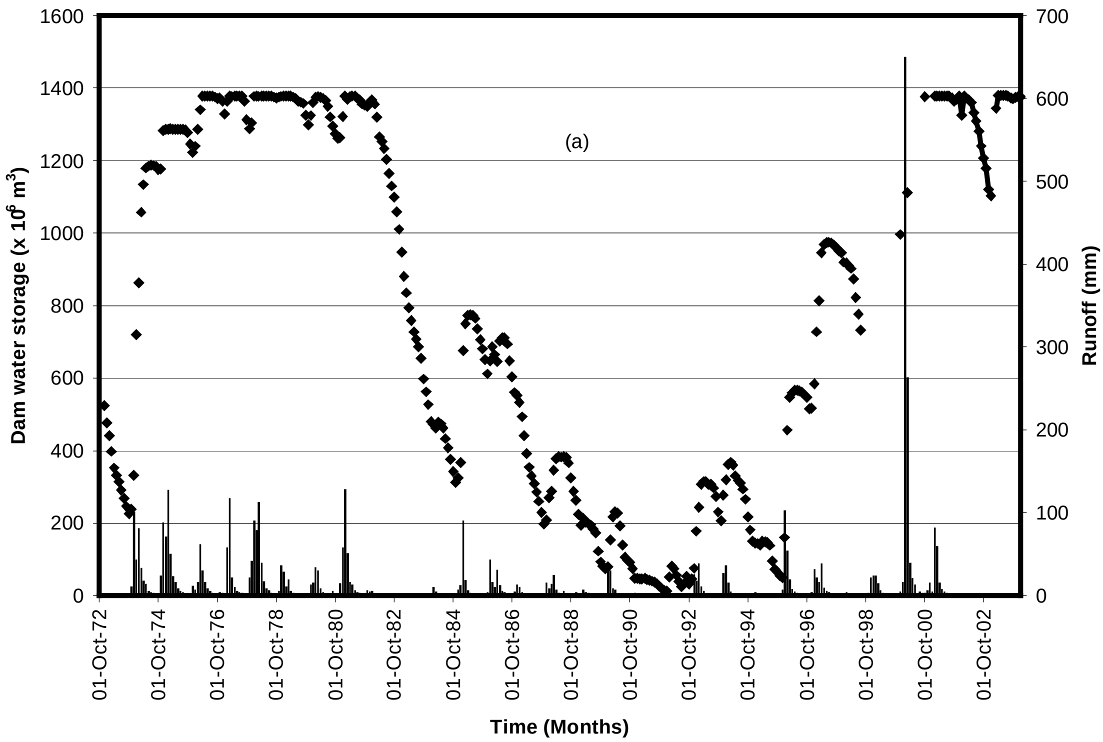


Figure 4.5: The relationship between catchment area and the rainfall-runoff coefficients of determination in the Runde catchment.

4.5.4 Dam water level changes

Changes in the Mutirikwi dam water storage reflect the temporal variability in runoff of the Mutirikwi catchment that is measured at E2 above the dam (Figure 4.6). The cyclic nature of rainfall and runoff is displayed in all the three dams (Mutirikwi, Gwenhoro and Manjirenji). The droughts of the early eighties and early nineties are clearly reflected in the dam water storage while the wet periods of the seventies and the Cyclone Eline of the late nineties are also reflected in the dams though they are in different sub catchments (Figure 4.7).



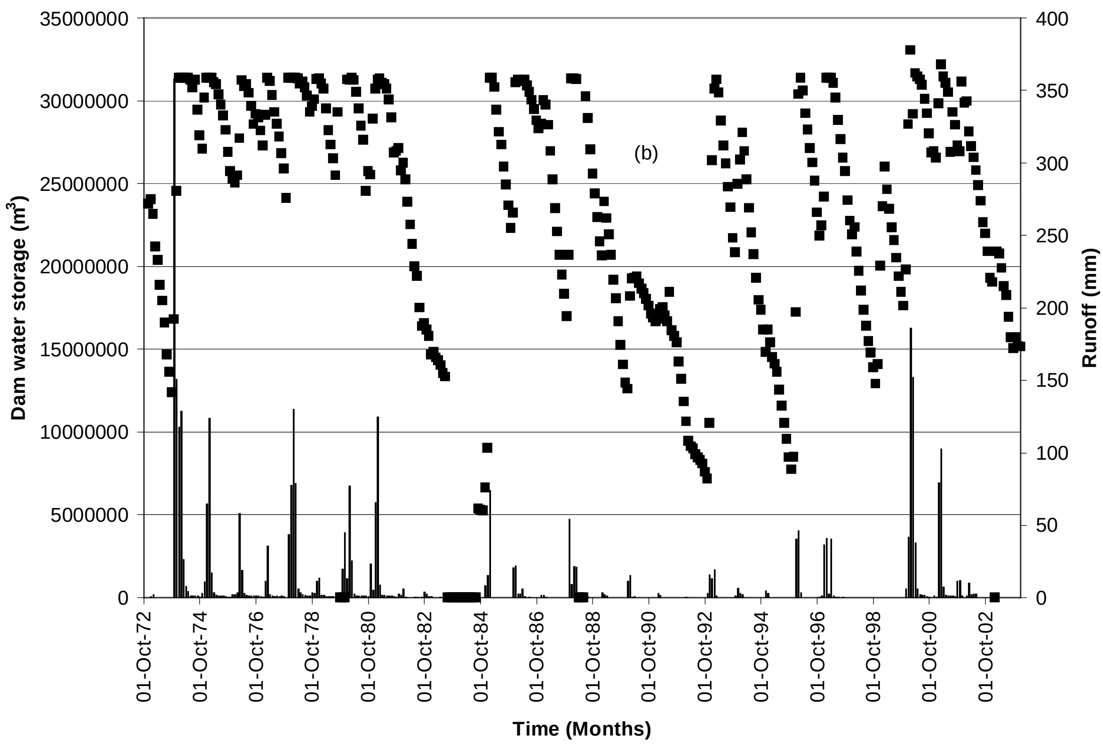


Figure 4.6a&b: Monthly dam water levels and rainfall at (a) Mutirikwi and (b) Gwenhoro dams that are in Mutirikwi and Upper Runde sub-catchments respectively.

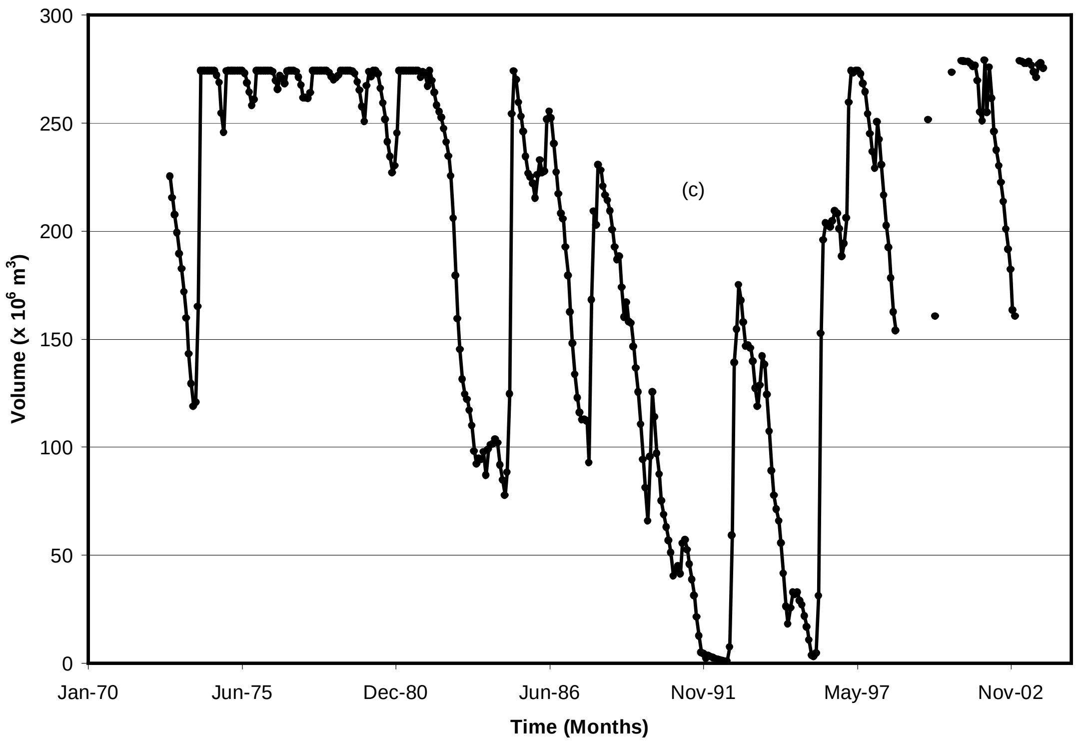


Figure 4.6c: Monthly dam water levels and rainfall at Manjirenji dams that is in Chiredzi sub-catchments.

4.6 DISCUSSION

Though the general pattern of rainfall at the rainfall stations was similar but different in magnitude over the period, the annual totals were different indicating both temporal and spatial variability in rainfall over the Runde catchment.

Runoff from all the gauging stations displays a similar general pattern to rainfall which both show an increase that had a peak in 1977 and then declined. The lack of similarity in the pattern of the runoff from the same subcatchment is an indication of high variability in runoff. This might be due to land use practices, that was not accounted for in this study. The 13 gauging stations show differences in runoff that might be emanating from differences in the average rainfall received, land use type or soil type. The runoff data from all the stations reflect the annual rainfall variability. The land use types in the catchment are commercial (that occupies almost half of the catchment), communal and natural parks.

There were both significant and insignificant relationships between rainfall and runoff, with those from the drier Upper and Lower Runde and Chiredzi showing insignificant relationships. The low values of the coefficients of determination was due to the large variability in rainfall, landuse, soil and vegetation cover in the Runde catchment. Thiam and Singh (2002) observed relationships between rainfall and runoff that had coefficient of determination above 0.5 in Southern Senegal. Rainfall distribution is often more important in runoff generation mechanisms in semi-arid areas than rainfall totals (Sandstrom, 1997). Runoff normally occurs in a few months (February and March) of the year, when there are closely spaced rainfall events.

One of the characteristic features of the rainfall within the semi-arid areas of Zimbabwe is that it comes mostly in the form of convective thunderstorms that are highly isolated resulting in a high spatial variability. More representative catchment rainfall values could have been obtained if there was a network of raingauges in each catchment, thereby enabling application of the Thiessen Polygon method.

The lack of a significant relationship between rainfall and runoff in some subcatchments is due to a considerable temporal and spatial variability exhibited by rainfall-runoff generation processes (Sivakumar *et al*., 2000). The considerable spatial and temporal variability exhibited by the rainfall-runoff process is due to the various physical mechanisms (rainfall distribution, rainfall intensities, soil type) that govern the dynamics of the process.

The change in land use also affect the relationship between rainfall and land use. For example the Lundi E83 catchment stretches from Gweru to Ngundu and there are a number of soil types and land use types (communal use, natural vegetation and commercial use). Whitlow (1979) observed an increase of over 36% of cultivated land area between 1963 and 1977 in Communal lands in Zimbabwe. Lorup *et al*., (1998) observed a decrease in the annual runoff with time in catchments that were located in communal land, which they attributed to increases in population and agricultural intensity.

The factors that affect runoff are more uniform for smaller catchments and we would have expected the coefficients of determination to increase with decrease in area. This results in smaller catchments having the highest coefficients of determination while bigger catchment have smaller coefficients of determination. A similar trend was observed by Lacobellis *et al*., (2002), which they ascribed to the limited spatial extent of extreme events, which leads to a decrease of CV of areal rainfall intensity.

The wet period between 1974-1980 and 1985-88 are reflected in both the runoff and dam water level while the dry periods of 1981-1984 and 1988-1992 are also shown in both parameters indicating that both rainfall and runoff have a bearing on surface water resources. Gwenhoro is not affected much during these dry periods because it is a smaller dam that has a relatively larger catchment area as shown by a dam capacity/catchment area ratio of 0.076 compared to 0.346 mm and 0.179 for Mutirikwi and Manjirenji respectively.

The dry periods during the study period had a serious impact on the agricultural productivity of the sugar cane industry especially in the 1991/2 season when irrigation demands could not be met (Scoones *et al.* 1996). This resulted in some sugar cane fields being neglected or planted to dryland crops and it took four years for the sugar industry to recover to full capacity.

4.7 CONCLUSIONS

The cyclic nature of rainfall in all the six gauging stations was displayed in both runoff and dam water levels indicating that surface water resources are determined by temporal variability in rainfall. However, significant relationships ($P < 0.005$) between rainfall and runoff were observed in six out of the 13 gauging stations used in this analysis. The spatial extend of the subcatchments determine whether there is significant relationship between rainfall and runoff. It was established in this study that the co-efficient of determination between rainfall and runoff decreased with increase in area. These catchments are large and there is spatial variability in rainfall, topography, soils and land use hence smaller catchments should be studied if the effect of all these factors is to be isolated. In Zimbabwe most of the small to medium dams have small catchment sizes (2 - 55 km^2) and this is a further reason to study the hydrology of smaller catchments; to benefit the smallholder farmers who rely on these resources for irrigation and water supply.

5. COMPARISON OF THE HYDROLOGICAL BEHAVIOUR OF ROMWE AND MUTANGI MICRO-CATCHMENTS

5.1 INTRODUCTION

The semi-arid areas of the world are characterised by frequent droughts, resulting in poor crop production and starvation. There are also seasonal patterns of water availability, with insufficient water for both domestic and productive use in dry seasons, further leading to insecurity of livelihoods in such areas.

The frequent droughts, coupled with poor land use/management practices, inadequate knowledge about how the catchments function and insufficient knowledge of the available quantities of water resources exacerbate the shortages of water in the semi-arid areas. The effect of climate and land use practices on water resources has been the focus of a number of studies (Pilling and Jones, 2002; Bultot *et al*., 1990; Kienzle and Schulze, 1991; New, 2002; Moussa *et al*., 2002) in order to generate improved and quantitative hydrological understanding that could be used to improve water resources development. Much of this work has been carried out in wetter areas of the world, while in Africa the focus has been on South and Eastern Africa (Lorup *et al.*, 1998).

The importance of adequately understanding the hydrology of small catchments has been identified by many authors (Lovell *et al.,* 1998; Sandstrom, 1997; Ziemer, 1998; Woods, 1997). However, small catchment studies are expensive and time consuming (Ziemer, 1998) resulting in very few catchments being selected for study. Ziemer (1998) comments that it is dangerous to make generalisations from one catchment and reiterates the need to generalise by considering information from similar studies at other locations.

Sandstrom (1997) emphasised the need to appraise the volume of water available over space and time in order to successfully manage water resources in the tropics. However, the assessment of water resources are hindered by the scarcity of hydrological data both in time and space (Piper *et al*., 1980). Lovell, *et al.* (1998) suggest that small catchment studies are particularly required in Zimbabwe to quantify water resource potential and identify appropriate agricultural development strategies in the driest and most degraded catchments that typify Communal and Resettlement Areas. Such catchment studies are particularly important in the heavily populated communal areas where most of the land use changes and the likely hydrological impacts are likely to occur.

Seven catchment councils (WRMS, n.d.) have been formed in Zimbabwe. One of the aims of these catchment councils is to protect the environment. Unfortunately, currently no work is being done to understand and address how these catchments function and how factors like land use change and climatic change would affect their hydrology and the associated water resources (Manzungu, 2002).

5.2 OBJECTIVE

To compare the hydrology (rainfall, runoff, soil moisture, groundwater levels) of Romwe and Mutangi catchments located in the Runde catchment.

5.3 HYPOTHESIS

The rainfall and runoff yield of Mutangi and Romwe catchments are not significantly different

5.4 MATERIALS AND METHODS

Romwe and Mutangi catchments (5.1a&b) were fully instrumented to enable measurements of all components of the hydrology including rainfall, runoff and groundwater levels. The Romwe catchment was instrumented in 1993 while Mutangi catchment was instrumented in 1999. The instrumentation at Romwe is more intensive than that at Mutangi because the purpose of the instrumentation was different. The instrumentation at Mutangi was aimed at quantifying surface runoff and surface water resources while that at Romwe concentrated on both surface runoff and groundwater recharge.

5.4.1 Rainfall, radiation, temperature and wind speed

A network of raingauges was installed in each catchment to capture rainfall variability. The raingauges were designed to capture rainfall spatial variability and at the same time were located at secure places (gardens or households) so as to minimise vandalism. These were installed 0.3 m above the ground so as to avoid rainfall splashing into the raingauges. Twelve and seven plastic raingauges were installed in Romwe and Mutangi respectively. More raingauges were installed at Romwe than Mutangi because it was believed that there would be more variability in Romwe given the big difference in altitude due to the presence of hills and rock outcrop that might affect wind movement hence precipitation. Daily rainfall readings were taken every morning between 0600 and 0800.

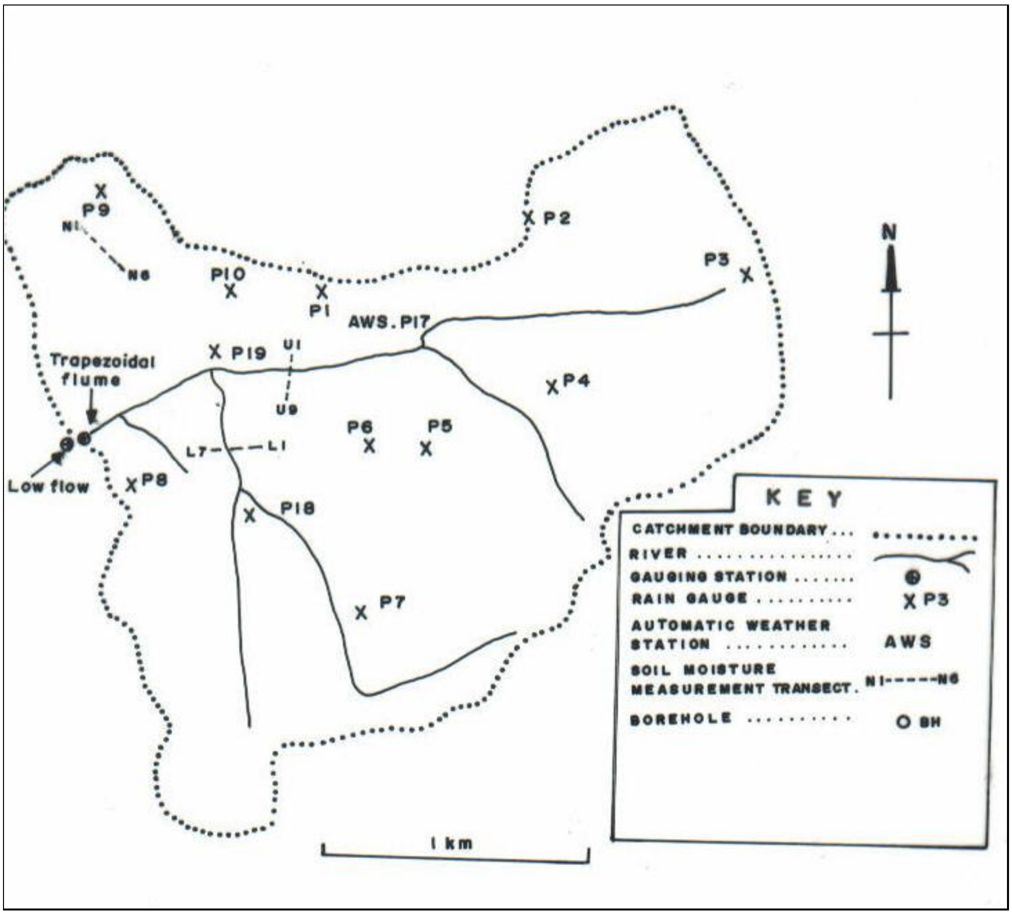


Figure 5.1a: Romwe instrumentation gauging stations, soil moisture monitoring, boreholes, rain gauges and automatic weather station.

A Campbell Automatic Weather Station (Figure 5.2) was installed in each of the sites. These were installed as close as possible to the camp sites for security reasons. They were placed in open space so that trees would not disturb wind movement. The automatic weather stations consisting of tipping bucket, thermometer, cup anenometer, wind vane, wet & dry bulb thermometer and solar panel measured rainfall (amount and intensity), maximum and minimum temperature, wind speed wind direction, humidity and solar radiation respectively.

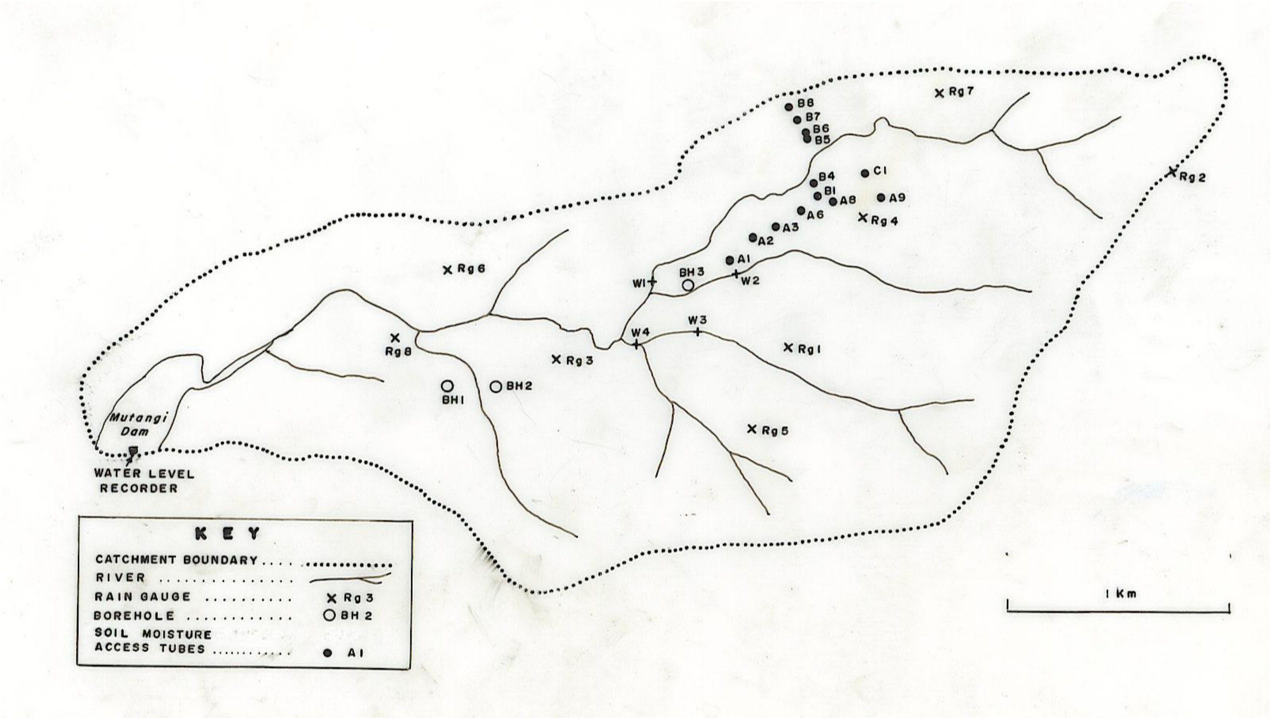


Figure 5.1b: Mutangi instrumentation water level recorder, soil moisture monitoring, boreholes, rain gauges and automatic weather station.

Figure 5.2: The automatic weather station at Mutangi catchment.

5.4.2 Runoff

Catchment runoff at Romwe was measured using a trapezoidal flume (Figure 5.3) to measure high discharges of up to 13.5 $m^3 s^{-1}$ and a V-notch weir with a maximum rating of 0.07 $m^3 s^{-1}$ for accurate low-flow measurements. The stage discharge equations used for the trapezoidal flume and V-notch are depicted in equations 5.1 and 5.2 respectively.

$$Q = 7x10^{7} \; S^{2.289} \qquad \text{Equation 5.1}$$

where Q is flow m^3s^{-1} and S is flume stage in mm

$$Q = 0.028317 \times 2.49 \left(\frac{S}{30.48} \right)^{2.48} \qquad \text{Equation 5.2}$$

where Q is discharge in $m^3 s^{-1}$ and S is V-notch stage in cm

At Mutangi total catchment runoff was measured at the dam. An automatic water level recorder (Figure 5.4) was installed on a platform extending from the dam 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 ten minutes from October 1999 to September 2001. The stage volume curve (equation 5.3) for the dam was supplied by CARE who were working on a DFID dam rehabilitation project which covers a number of small dams in Masvingo province, including Mutangi dam. This equation was obtained from a topographic survey of the reservoir. The stage volume curve allowed the changes in the dam (resulting from evaporation, human abstraction, animal watering and runin) to be determined.

$$V = 16440WD^{2.02} \qquad \text{Equation 5.3}$$

where V is dam volume in m^3 and WD is the water depth in metres.

The spillway was modified to allow the construction of two rectangular weirs to measure high and low flows when spilling occurred. The water level data was used to calculate the runoff through the rectangular weirs using a theoretical rating equation that is depicted in Figure 5.5 (Ferguson, 1998). The total catchment runoff was calculated from the storage increases in the dam (Figure 5.4), and the gauged spillway discharge.

Figure 5.3: Trapezoidal flume used to measure runoff from Romwe catchment.

Figure 5.4: A view of the digital water level recorder (in the box) at Mutangi dam.

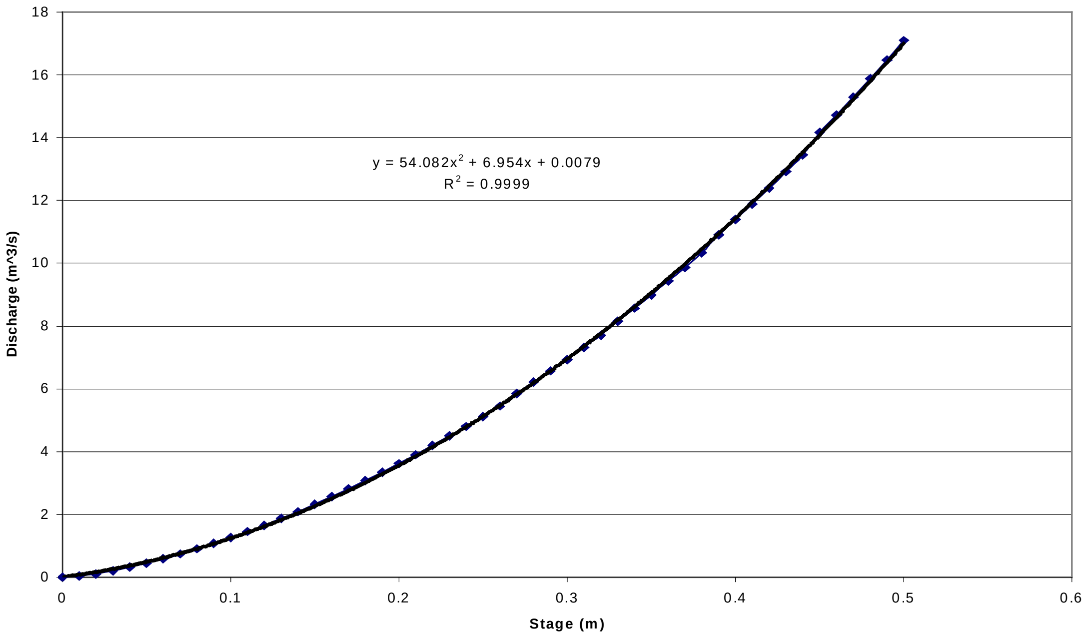


Figure 5.5: Rating curve for the spillway at Mutangi catchment (y = discharge and x = stage).

5.4.3 Soil moisture

Changes in soil moisture are due to infiltration, deep recharge, soil evaporation, plant water uptake and transpiration. The soil moisture changes were measured in-situ using a neutron probe (Figure 5.6). At Romwe, access tube installation (1.5 m to 3.0 m) was done using both hand and hydraulic-powered augers in 1993 and 1994 (Buttwerworth, 1997) while at Mutangi access tube (1.0 m to 2.5 m) installation was done using hand augering in 1999. Installation was done following the procedures described by Bell (1987) and Hodnett and Bell (1991).

However, for best results, a soil specific calibration is required for the neutron probe to convert the count rate of the probe to volumetric water content. The calibration equation can vary (within a fairly limited range) due to differences in texture, dry bulk density and proximity to soil surface. The presence of certain elements such a boron and iron, can also affect the calibration equation (Bell, 1987). In addition to the effect of soil properties, the calibration equation is specific to the type of probe, and the diameter and material of the access tubing used (Hodnett and Bell, 1991). Neutron probe calibration at Romwe was done by Butterworth (1997), while that at Mutangi is presented in appendix A. Standard counts in a water drum were used to normalise for the effect of drift (Hodnett and Bell, 1991).

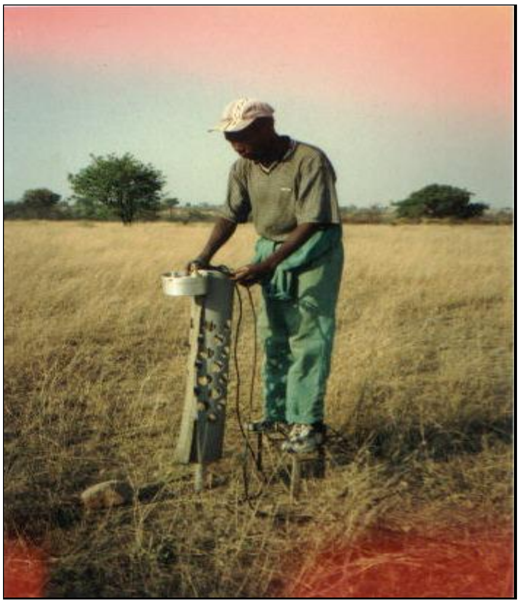


Figure 5.6: Soil moisture measurements using a neutron probe.

Three transects of neutron probe access tubes were installed at Romwe (Butterworth, 1997). The inselburg transect extended down a hillslope from the large inselburg in the north-west of the catchment (Figure 5.1a) towards the valley bottom. The two other transects were sited across ephemeral streams, one across the main stream and the other across a tributary draining from the wooded hillslope. The access tubes in both transects were located on different soil types, different land uses and different crop types.

Two transects (one with 7 and the other one with 6 access tubes) of neutron probe access tubes were installed (5.1b) at Mutangi. The first transect (A) runs along the low ridge that forms the divide between streams 1 and 2 from the north and starting close to the confluence of the two streams. 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 samples 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 are 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 1m to 2.5m.

A neutron probe (Wallingford MK III) was used to measure soil moisture. Neutron probe readings were taken weekly at both sites during the wet season and monthly during the dry seasons. Readings were taken at 0.1, 0.2 and 0.3 m and then at 0.2m intervals for the remainder of the depth of the tube using a counting rate of 16s.

5.4.4 Groundwater

Piezometers (5 – 10 m deep) were installed one meter away from each of the access tubes in Romwe (Buttwerworth, 1997) for measuring groundwater fluctuations. In Mutangi groundwater fluctuations were monitored from two deep wells (12 m deep), one borehole and 18 shallow wells (< 5 m). Monitoring from the shallow wells was stopped in the second year because it was considered that localized run-in was dominating the water table response. At both Romwe and Mutangi groundwater fluctuations were monitored once a week and after rainfall events of more than 30mm.

5.5 RESULTS

5.5.1 Rainfall

The amounts of rainfall received in the two study areas in the two years were quite different dispite the catchments being 80 km apart. Figure 5.7 shows the monthly distribution of rainfall at Romwe and Mutangi during the 1999/00 and 2000/01 seasons. Romwe and Mutangi received 1430mm and 755mm respectively in the 1999/00 season. In the following 2000/01 season, Romwe and Mutangi received 756 and 625mm of rainfall respectively. Rainfall was above the average in the 1999/00 season while the 2000/01 season was still above the long term average, although it was drier compared to the 1999/00 season. Though this was only a two-year record, a similar trend of high year-to-year variation in rainfall is reflected in the long-term record for stations close to these sites. Chendebvu station (close to Romwe) has a rainfall coefficient of variation of 42% while that at Chivi, (close to Mutangi), is 37%.

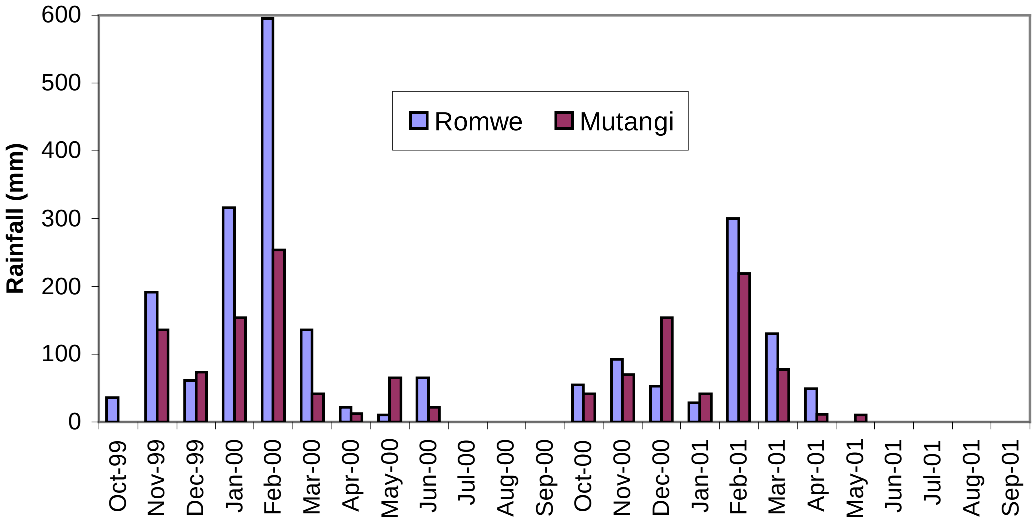


Figure 5.7: Monthly rainfall distribution at Romwe and Mutangi during the 1999/00 and 2000/01 seasons.

The distribution of the rainfall was highly skewed in both years. At Romwe and Mutangi 68% and 58% of the annual total rainfall was received in February of the 1999/00 season, respectively. In the 2000/01 season 63% and 69% of the annual total rainfall was received in February at Romwe and Mutangi, respectively. Both catchments received 28% of the total rainfall in January of the 1999/00 season. January of the 2000/01 season experienced some midseason droughts when only 6% and 12% of the total annual rainfall was received at Romwe and Mutangi respectively.

The cumulative rainfall figures for daily rainfall totals of more than 60, 50, 40 and 30 mm were almost similar for Mutangi in both years and Romwe in the 2000/01 season but there were some slight differences in the 20, 10, 5 and 0 mm categories (Figure 5.8). In the 1999/00 season, the rainfall at Romwe was exceptionally much above the other 3 in the cumulative totals in all the 6 daily rainfall classes.

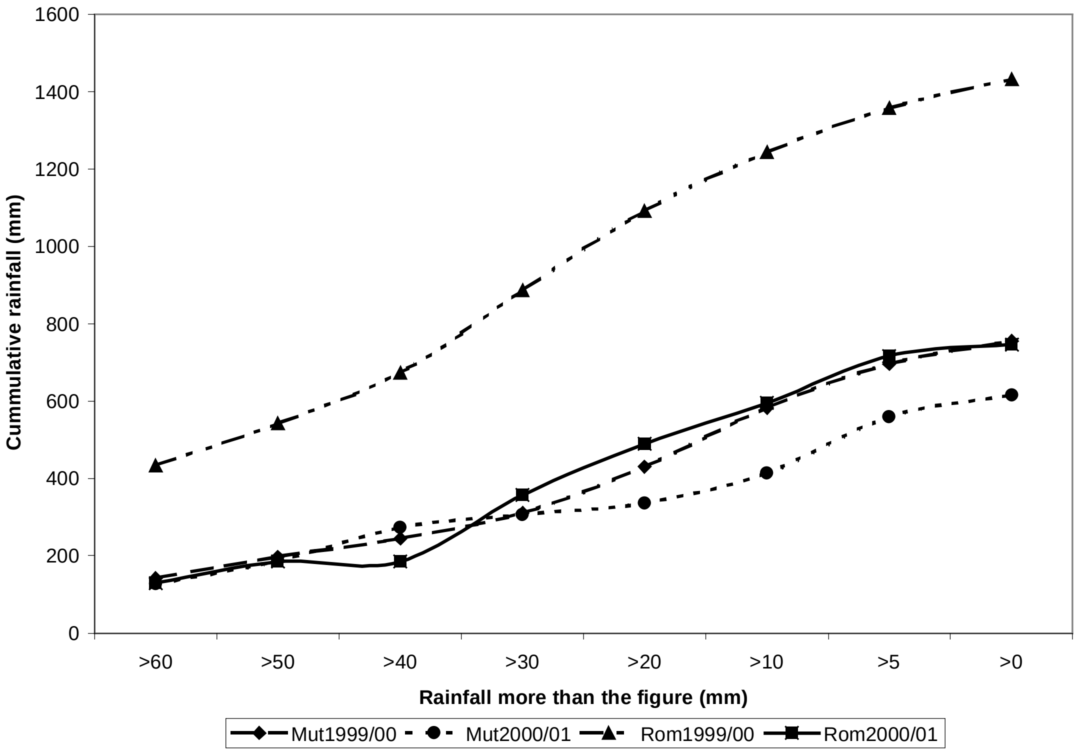


Figure 5.8: Frequency analysis of the daily rainfall at Romwe and Mutangi (Mut and Rom are Mutangi and Romwe respectively)

5.5.2 Soil moisture

Soil moisture responded to rainfall at both catchments, increasing after rainfall events and decreasing during dry periods (Figure 5.9). However, different sites demonstrated different patterns depending on their soil type.

Total profile soil moisture storage to a depth of 120 cm was higher at Romwe than Mutangi for the entire study period reflecting the higher clay content of the soils (Appendix B). Storage was greater in the 1999/00 season than the 2000/01 season. February was the wettest period in both catchments and a similar pattern is reflected in the soil moisture storage. The soils in Romwe were close to saturation in February of 1999/00 and this is also shown by the water table (Figure 5.11) that was almost at the surface. At Romwe (the red soils) there were soil moisture storage increases of 234 mm and 159 mm from October, when the first rains were received, to the wettest month in February, during the 1999/00 and 2000/01 seasons respectively. The increases for the same periods were 322 and 236 mm on the grey soils. On the sandy soils at Mutangi the changes were 284 and 169 mm during similar periods for the 1999/00 and 2000/01 season, while the changes were only 32 and 28 mm on the sodic soils respectively.

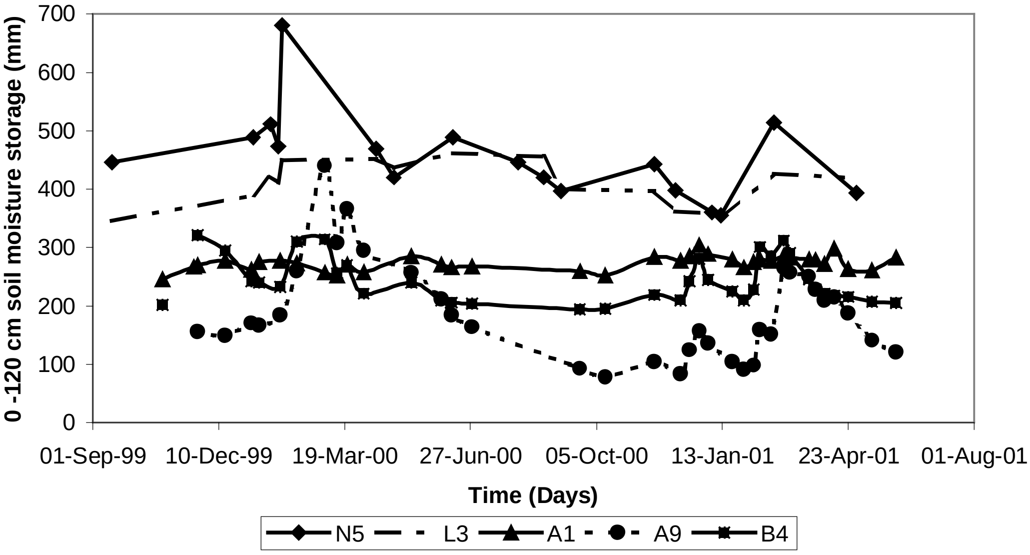


Figure 5.9: Total soil moisture for different soil types at Romwe. (N5 red and L3 grey) and Mutangi (A1 sandy, B4 sodic and A9 intermediate) catchments.

Figure 5.10 shows the extreme wettest and driest profiles from selected tubes at Mutangi and Romwe. The wettest data are typical from late February or early March, and the driest from September or October at the end of the dry season. The differences in soil properties are clearly reflected in the shape of the water content profiles, and the seasonal changes in water content.

At Romwe the soil moisture changes occur throughout the profile on the red soils while most of the changes were limited to the top 50cm on the grey subcatchment. A similar behaviour can be seen at Mutangi where soil moisture changes were mostly limited to the top 40 cm on the grazing sodic soils while they extended throughout the measured profile on the sandy soils. In the 2000/01 season the wettest profile at Mutangi was less wet than that observed in the previous season. Such comparison at Romwe cannot be made because only one measurement was taken during this wet period in 2000/01 because of lack of transport to take the neutron probe from Romwe to Mutangi.

5.5.3 Water table

At Romwe, ground water levels in the two soil types (red and grey) responded more quickly to rainfall compared to Mutangi (Figure 5.11). Water levels in most of the peizometers at Romwe rose to 25 cm below the surface in February of 1999/00 season. In the following season highest water levels were 1 metre below ground surface.

At Mutangi, the response to rainfall in both the School (BH1) and Madamba (BH2) wells were slow, and with a large time lag, particularly in the Madamba well which only began to respond at the end of the wet season in both years. Water levels in both wells continued to rise throughout the dry season, with the rate of rise only slowing in the early stages of the following wet season. Water levels in both boreholes actually rose slightly during the dry season and, over the 2 seasons studied, levels rose by about 3m. There was a larger rise in the wetter 1999/2000 season than the drier 2000/2001 season.

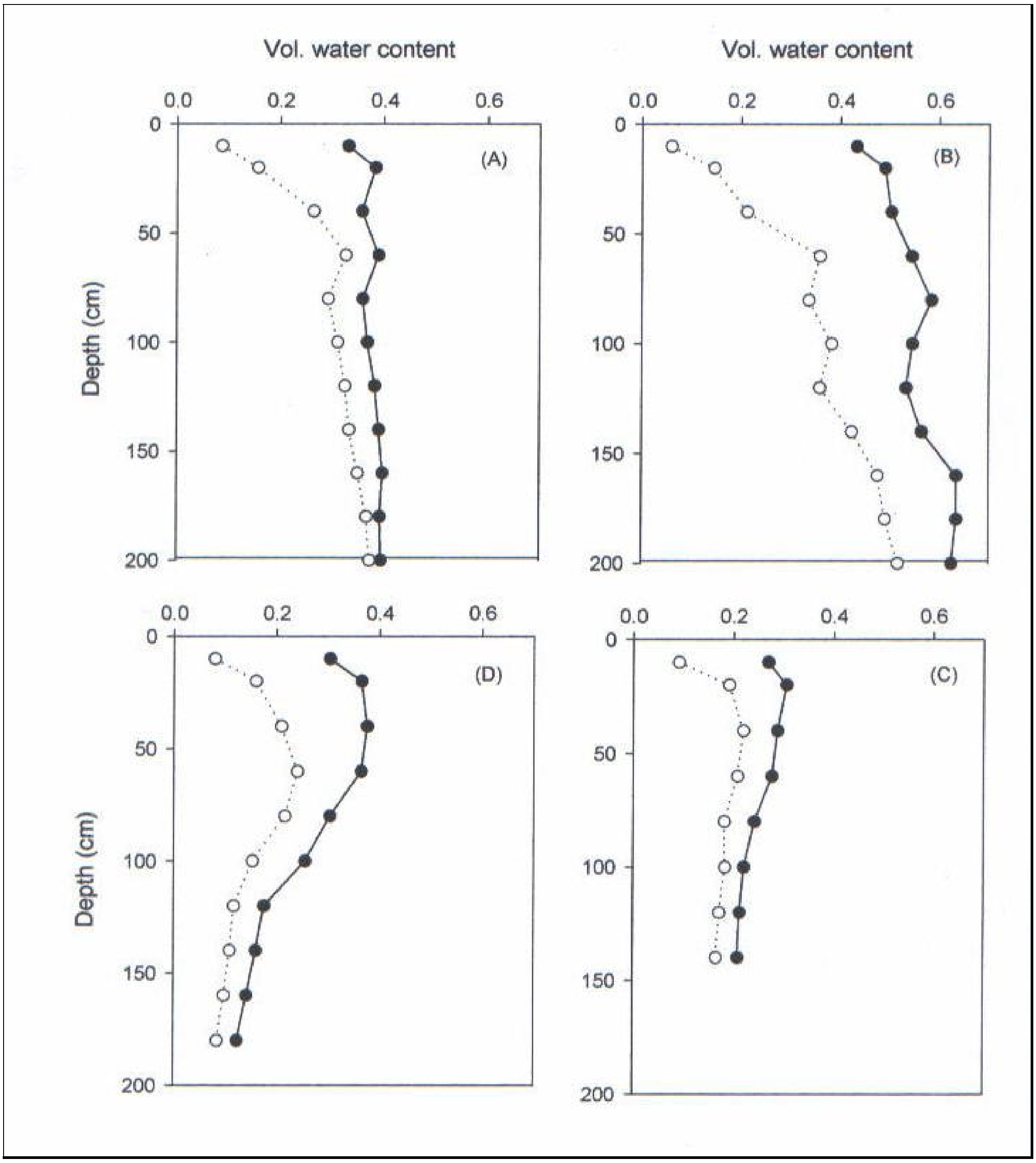


Figure 5.10: Wettest (●) and driest (❍) water content profiles. A and B are from Romwe grey soil and red soil respectively. C and D are from Mutangi sodic and sandy soil respectively.

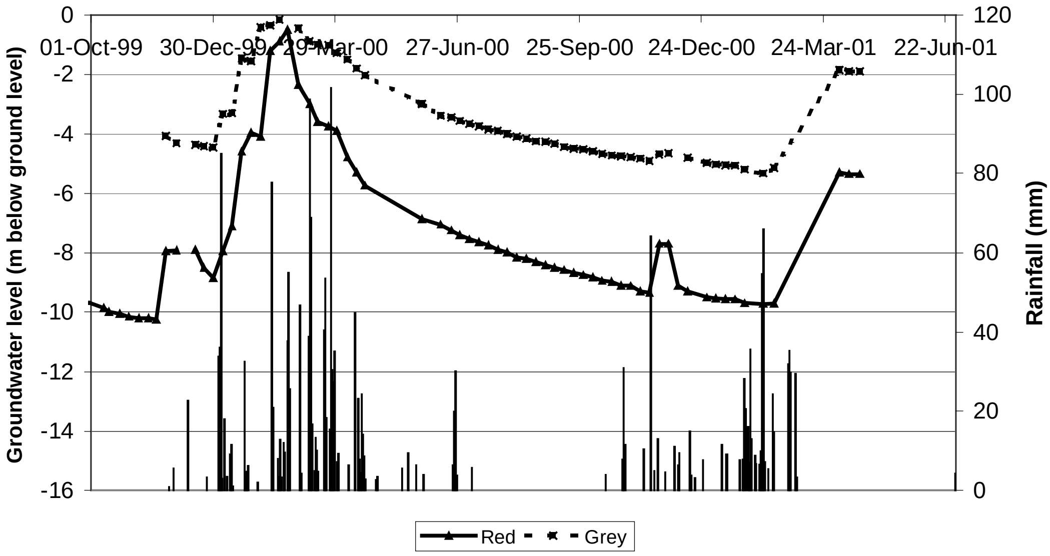


Figure 5.11a: Water table response to rainfall at Romwe during the study period. Grey and Red means that they are grey and red soils on the grey and red subcatchments respectively.

There were significant (P<0.05) relationships between profile soil moisture and the water table level at Romwe for both the grey and the red soil types (Figure 5.12). A similar relationship was not found at Mutangi catchment.

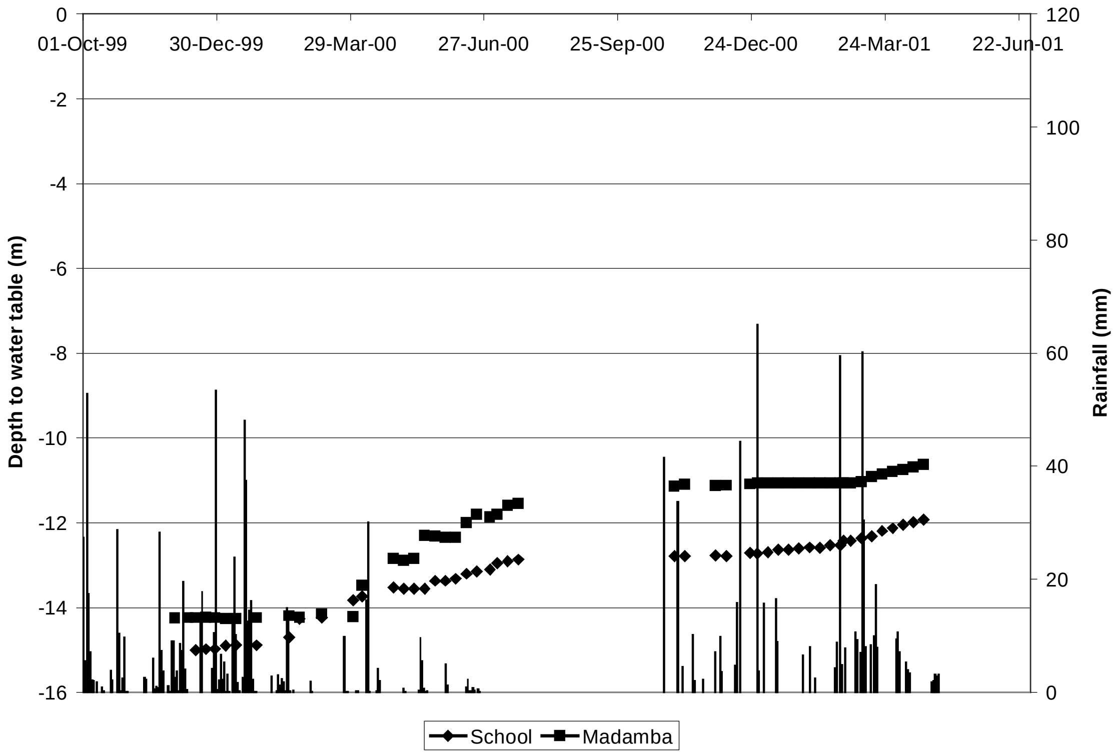


Figure 5.11b: Water table response to rainfall at Mutangi during the study period. Data for July to October 2000 is missing.

5.5.4 Runoff

Figure 5.13 shows the cumulative rainfall and runoff at Romwe and Mutangi. Total runoff amounts of 520 and 82 were recorded in the 1999/00 and 2000/01 seasons respectively at Romwe. At Mutangi, runoff amounts of 102 and 69 mm were generated during the 1999/00 and 2000/01 seasons respectively.

Mutangi produced runoff earlier than Romwe in both seasons. In the 1999/00 season runoff commenced on the 20th of November and 18th of December at Mutangi and Romwe respectively. Runoff amounts of 7.6 mm and 0.02 mm were generated after cumulative rainfall amounts of 46 and 286 mm at Mutangi and Romwe respectively. In the following season (2000/01) the first runoff of 3 and 5.1 mm were recorded on the 27th of October and 18th of November after cumulative rainfall amounts of 42 and 64mm respectively at Mutangi and Romwe.

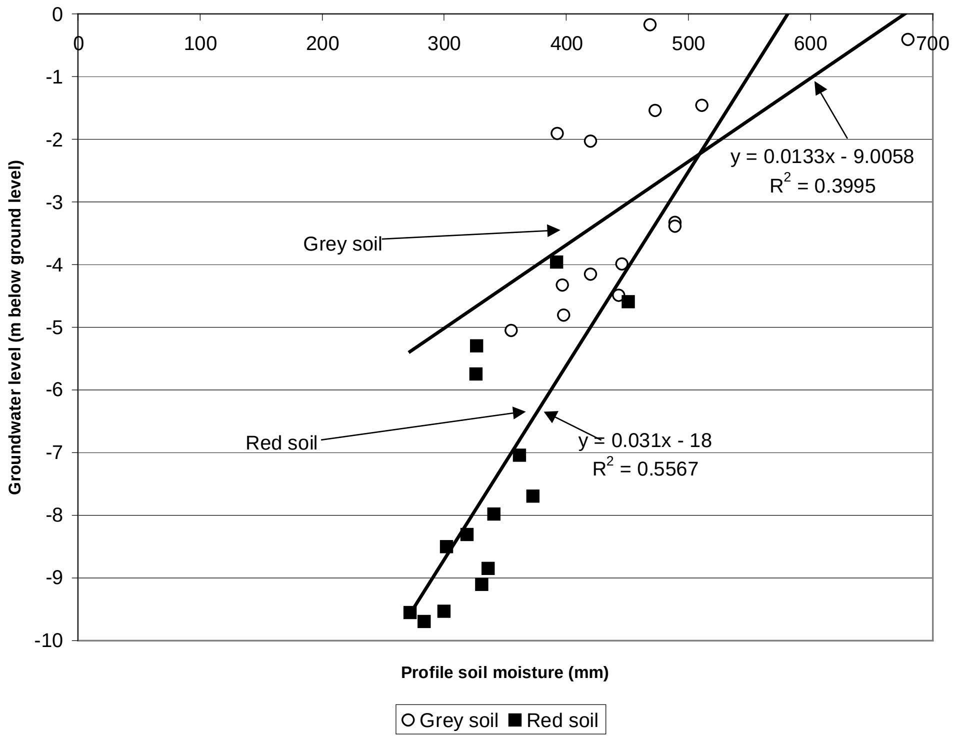


Figure 5.12: Relationship between soil moisture profile (x) and water table level (y) at Romwe catchment.

Of the total seasonal runoff 56% and 60% was generated in February at Romwe and Mutangi during the 1999/00 season, while in the following season 24% and 57% was generated in the same months respectively. At Romwe, February of 2000/01 received slightly more than double the rainfall received in March of the same season, but March had slightly more than double the runoff.

In the two seasons continuous runoff was recorded at Romwe during the wet season reflecting the presence of base flow (Figure 5.14). Except for one very wet period in February 2000, runoff stopped 3 or less hours after a rainfall event at Mutangi. There was very little baseflow in Mutangi that was intermittent and ends 1-3 hours after a rainfall event.

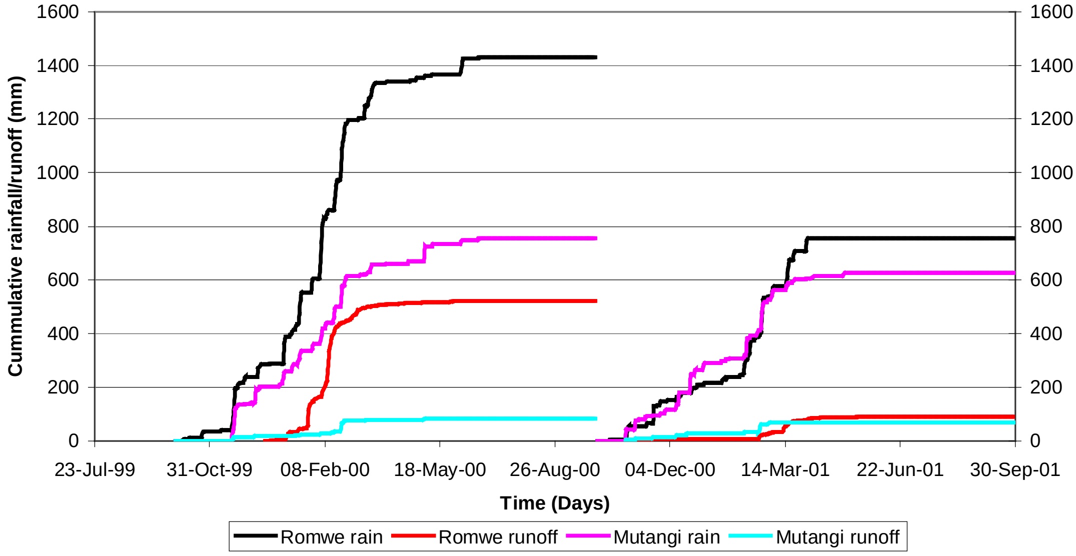


Figure 5.13: Romwe and Mutangi cumulative rainfall and runoff during the 1999/01 and 2000/01 seasons.

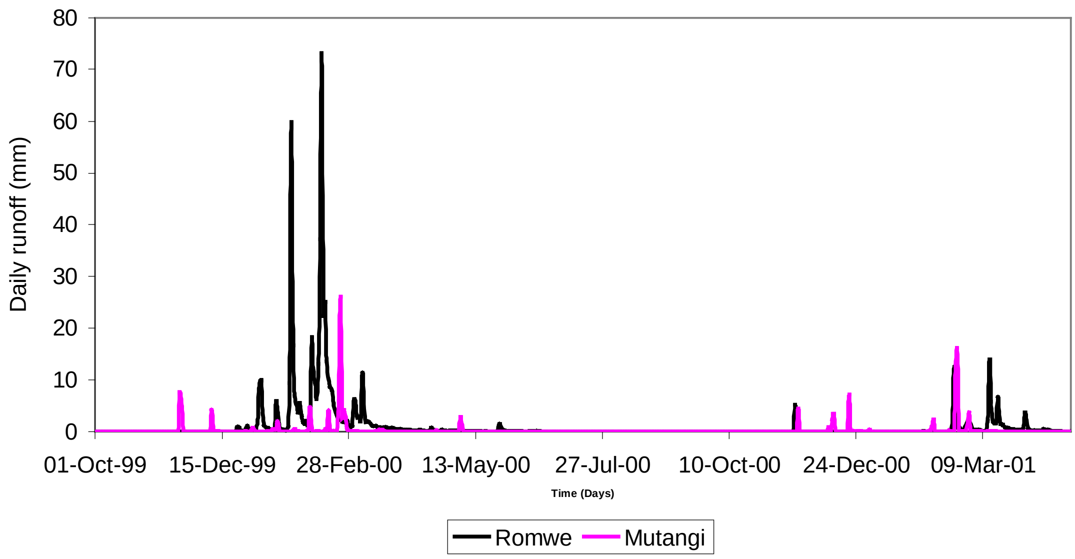


Figure 5.14: Daily hydrographs at Romwe and Mutangi during the study period.

The total days with flow (Table 5.1) were 153 and 68 at Romwe and Mutangi during the 1999/00 season respectively. The numbers were fewer in the following 2000/01 season with Romwe and Mutangi having 43 and 39 days respectively. The highest daily runoff flows were 73mm and 26 mm at

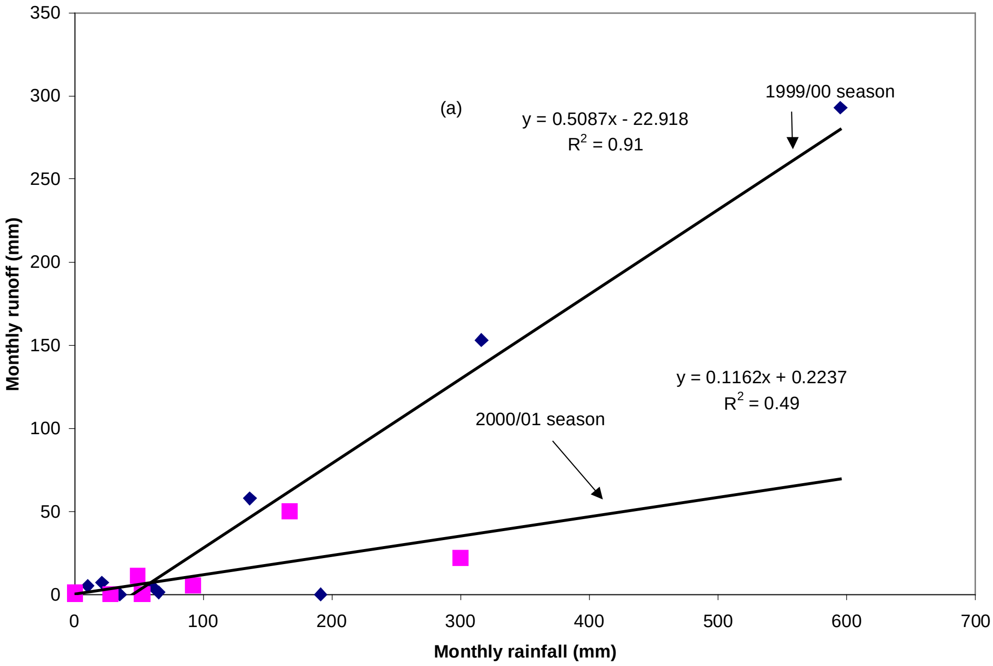
Romwe and Mutangi respectively in the 1999/2000 season and were 14 and 16 mm in the 2000/01 season respectively.

Table 5.1: Frequency analysis of daily runoff flows at Romwe and Mutangi.

	Class (mm)							
Class (mm)	>20	10-20	5-10	2-5	1-2	0.5-1	0-1	Total days
Romwe 1999/2000	2	7	14	15	20	19	76	153
Mutangi 1999/2000	1	0	3	7	2	5	50	68
Romwe 2000/2001	1	0	3	7	2	1	29	43
Mutangi 2000/2001	0	2	1	5	1	2	28	39

5.5.5 Rainfall runoff relationships

Figure 5.15a and figure 5.15b shows that monthly rainfall runoff relationships at Romwe and Mutangi were significant ($P < 0.05$) during the two seasons of study. They however, were different in their slopes. At Romwe and Mutangi 91% and 76% of the runoff variation was accounted for by rainfall in the 1999/2000 season. The rainfall-runoff relationship are different at Romwe for the two seasons, it was higher in the 1999/00 season than the 2000/01 season when 91% and 49% of the runoff variation was due to rainfall respectively. The relationships were almost similar at Mutangi during the two seasons.



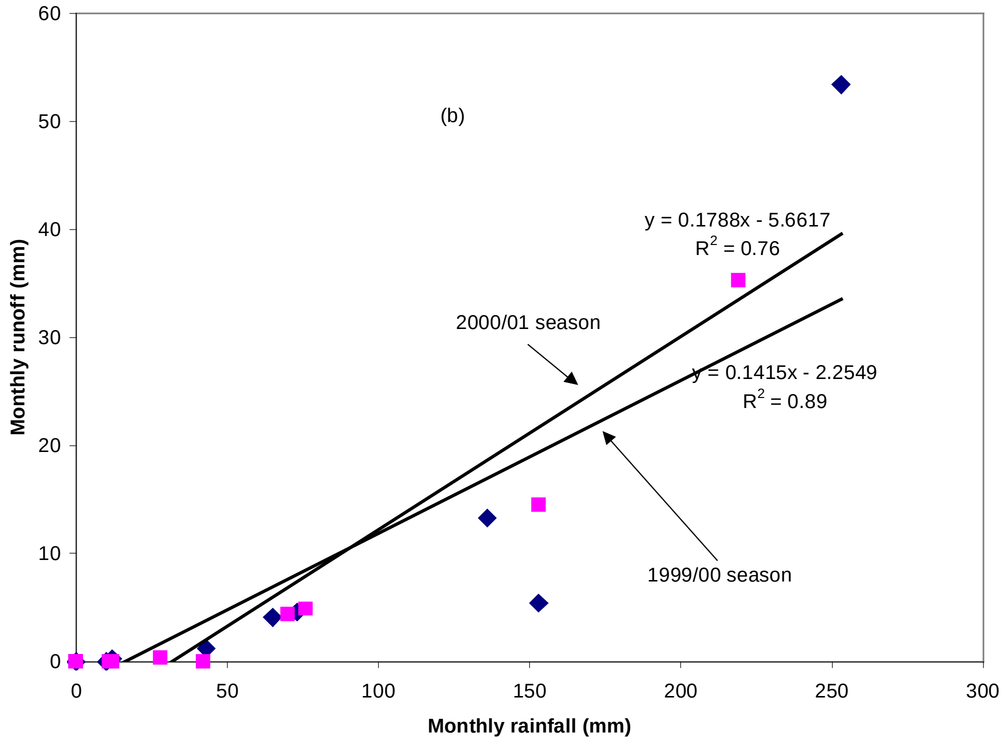


Figure 5.15a&b: Monthly rainfall-runoff relationships at (a) Romwe and (b) Mutangi catchments during the 1999/00 and 2000/01 seasons.

5.6 DISCUSSION

The two years of study had different rainfall totals that were above the long term averages in both catchments. Romwe catchment received more than double the rainfall that was received at Mutangi catchment in the first season (1999/2000) and the difference was just 100 mm in the second 2000/2001 season. Though the difference in rainfall was almost double in the 1999/2000 season, the runoff generated at Romwe was six times that generated at Mutangi; while in the second 2000/2001 season Romwe generated slightly less than one and a half times the runoff that was generated at Mutangi. The difference in the runoff totals between the two catchments could be explained by differences in rainfall.

Rainfall was almost continuous at Romwe in the 1999/2000 season and this resulted in higher soil moisture levels and a higher water table than at Mutangi where less continuous rainfall was received in the same year. Both soil types at Romwe were close to saturation, particularly the duplex soils on the southern side which occupy more than 50% of the whole catchment. Such conditions (as occurred at Romwe) favoured saturated overland flow (SOF) (Dunne and Black, 1970b) thereby resulting in most of the rainfall that was received, especially in the grey duplex soils, being converted to runoff in the 1999/2000 season hence the higher runoff conversion factor of 36%. At Mutangi although the sodic soils reached saturation early in the wet season, the midslope and ridge soils only attained saturation later in the season around late February and early March when SOF likely occurred.

Mutangi produced runoff earlier than Romwe catchment and even soon after a dry spell because the streams are bordered by sodic soils (Muzuva and Gotosa, 1999). These have very low infiltration and storage capacities hence runoff is produced through SOF (Mugabe and Hodnett, 2001). Sidle *et al*., (1995) observed a similar pattern that narrow riparian zones have significant contributions to runoff at the beginning of the typhoon season in Japan. The Mopani trees associated with the sodic soils are not in leaf when the first rains are received hence there is little interception of rainfall, unlike in Romwe. The miombo woodlands that cover 55% of Romwe catchment have leaves when the first rains are received and both interception and evapotranspiration loses will be greater. The streams at Romwe are also bordered by evergreen vegetation that takes up water throughout the dry season increasing the deficit in these soils. This vegetation also intercepts rainfall. The soils are also deep and have very high storage capacity and require a large amount of rainfall or very high rainfall intensities before any SOF or Hortonian Overland Flow (HOF) takes place respectively. These conditions favoured delayed generation of runoff at Romwe compared to Mutangi in the 1999/00 season.

Rainfall was well distributed in the 1999/2000 season while there was a midseason break in January of 2000/2001. January of 1999/2000 and 2000/2001 seasons received 316 and 29 mm of rainfall respectively at Romwe. At Mutangi 153 and 43 mm of rainfall were received in January of 1999/2000 and 2000/2001 seasons respectively. The continuous rainfall in both catchments in the 1999/2000 season and in particular the high rainfall in February and early March resulted in very high soil water contents and ground water levels. This is when most of the runoff was generated in this first season (1999/00) of the study. The 2000/2001 season was contrasting in that January was drier in both catchments and dry soil moisture conditions and low groundwater levels occurred before the wettest part (late February to early March) of the season and this resulted in less runoff being generated than in the preceding season.

The three times difference in the runoff conversion efficiency between the two seasons at Romwe is probably an indication of differences in runoff generating mechanisms. The wet conditions in the 1999/2000 season caused so much recharge that the water table was close to the surface during the extremely wet February to early March. This period resulted in saturated overland flow from these areas where most of the rainfall is lost as runoff because the water table is at the surface.

The amount of rainfall received at Romwe in the 1999/00 season is typical of wet areas and this resulted in similar runoff conversion efficiencies of about 30% as reported from similar areas by Bosch and Hewlett (1982). The Romwe catchment behaved like a semi-arid catchment in the 2000/2001 season when 655 mm of rainfall was received with corresponding runoff conversion efficiency of 12%. Mutangi catchment behaved in a similar way in both years when 756 mm and 615 mm of rainfall was received in 1999/2000 and 2000/2001 season resulting in rainfall conversion efficiencies of 12% and 10% respectively. The rainfall-runoff relationship is different for Romwe and almost similar for Mutangi. The difference in Romwe suggests that the runoff producing mechanisms differed in the two years while they were similar at Mutangi.

The presence of baseflow at Romwe (especially in the 19999/00 seaosn), can be attributed to the large amount of recharge, and the presence of the grey soils where lateral flow is significant above the low permeable clay layer (Butterworth, 1997). The water table at Romwe rose above the stream during the wet season resulting in baseflow. At Mutangi the drainage lines are bordered by sodic soils and the water table is about 12 metres below the stream hence there was no baseflow at all.

5.7 CONCLUSIONS

Rainfall and runoff was significantly different between Romwe and Mutangi catchment. This study highlights that the difference in the hydrological response of these two catchments is mostly attributed to rainfall. At Romwe 50% and 90% of the runoff that was generated was attributed to rainfall in the 1999/00 and 2000/01 seasons respectively. At Mutangi 76% and 90% of the generated runoff was attributed to rainfall during the 1999/00 and 2000/01 seasons respectively.

At Romwe the huge differences in rainfall conversion efficiencies between wet years and dry years is an indication of shifts in the runoff generation mechanisms depending on rainfall distribution that affects soil moisture and the amount of recharge. Mutangi catchment behaved like a semi-arid area in the two years of study where about 12% of the rainfall was lost as runoff. Romwe showed a humid catchment response in 1999/00 and a semi-arid catchment response in the 2000/01 season with conversion efficiencies of 36% and 12% respectively. This supports the belief that catchment hydrological response is strongly dependent on rainfall, but however, the distribution of rainfall is critical to runoff generation.

6. EFFECT OF RAINFALL DISTRIBUTION AND SOIL TYPE ON SOIL MOISTURE AND RUNOFF GENERATION AT MUTANGI CATCHMENT

6.1 INTRODUCTION

The rainfall distribution in semi-arid Zimbabwe commences in October/November and a mid season drought is normally experienced in January (Scoones *et al*., 1996). The bulk of the rainfall is received in February and early March and the rainy season ends in late March to April. Such a distribution is likely to have an effect on runoff generation because of the fluctuations in soil moisture and the extent of the variable saturation area. Despite a long history of experimental catchment work in southern Africa, there remains a lack of knowledge regarding the intricacies of runoff generation (Andrews and Bullock, 1994)

Data from larger catchments within the Runde catchment, presented in Chapter 4, shows that runoff generation is temporary and spatially variable even in years with similar rainfall totals. The year-to-year variation in runoff might be due to differences in the rainfall distribution pattern while the catchment to catchment variation is due to the spatial variations in catchment physiography. Such variations have an impact on surface water resources that depend entirely on stream flow runoff. Shortages in surface water resources are apparent when droughts occur and this leaves communities depending on these water resources, which may not be adequate.

6.2 OBJECTIVES

1. To determine the amount of runoff generated during storm events and annually in Mutangi catchment.
2. To determine where most of the runoff comes from in the catchment (cultivated fields, fallow fields, grazing area/woodland).
3. To determine the runoff generation mechanisms in Mutangi catchment.

6.3 HYPOTHESES

1. Spatially runoff is uniformly generated in Mutangi catchment
2. Most of the runoff is generated from the sodic soils in Mutangi catchment

3. The runoff generation process is Hortonian Overland Flow in Mutangi catchment.

6.4 MATERIALS AND METHODS

The instrumentation at Mutangi catchment is described in section 5.4.

6.4.1 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 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.

6.4.2 Infiltration measurements

A CSIRO Disc Permeameter (1988) was used to determine the infiltration of the different soil types at Mutangi (sodic, sand 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.

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 increment 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.

6.5 RESULTS

6.5.1 Rainfall

The monthly rainfall totals for the 1999/2000 and 2000/2001 seasons are shown in Figure 5.7. The higher rainfall in the 1999/00 season was caused by cyclone Eline, which caused extensive flooding elsewhere in Zimbabwe and in Mozambique (Smithers *et al*., 2001). January 2001 was notable for very low rainfall, which caused near crop failure.

Rainfall intensity data (on an hourly basis) are available for the 1999/2000 season, but the gauge malfunctioned in the 2000/2001 seasons. Analysis of the rainfall intensity data focused on identifying occasions with high intensity rainfall, as this is likely to promote Hortonian overland flow (HOF), which occurs when the rainfall intensity exceeds the infiltration capacity of the soil. Table 6.1 and 6.2 shows dates and times with intensities exceeding 10 and 5 mm h^{-1}, respectively.

Table 6.1 shows that in the 1999/2000 season, there were 2 occasions with a rainfall intensity exceeding 25mm h^{-1}, and 8 occasions with an intensity exceeding 10 mm h^{-1}. An intensity of more than 10 mm h^{-1} also never occurred for more than a single hour in any rainfall event. Table 6.2 shows that there were 7 occasions when the rainfall intensity exceeded 5 mm h^{-1} for 2 hours or more consecutively. On these occasions the average rainfall intensity ranged from 5.8 mm h^{-1} to 17.9 mm h^{-1} and total rainfall ranged from 13.7 mm to 83.6 mm.

Table 6.1. 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 Nov 1999	1900	18.3	27.4
21 Nov 1999	2200	28.6	59.6
9 Dec 1999	2300	12.0	39.2
3 Jan 2000	0400	11.4	28.0
17 Jan 2000	1200	14.1	19.2
28 Jan 2000	1300	16.1	17.7
16 Feb 2000	1800	11.5	26.8
5 May 2000	0100	28.9	46.3

Table 6.2. 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 Nov 1999	2100 - 2300	3	41.7	13.9	59.6
9 Dec 1999	2300 - 2400	2	17.4	8.7	39.2
5 Feb 2000	0400 - 0500	2	11.7	5.8	69.8
15 Feb 2000	1900 - 2000	2	12.4	6.2	13.7
16 Feb 2000	1700 - 1800	2	19.6	9.8	26.8
22 – 23 Feb 2000	2300 - 0500	6	46.9	7.8	83.6
5 – 6 May 2000	2400 - 0100	2	35.8	17.9	46.3

6.5.2 Soil moisture

Figure 6.1 shows the extreme wettest and driest profiles from access tubes at different positions in the catenary sequence, from sodic soils close to the channel (A & B) through transitional soils (C, D & E) to coarse sandy soils on the ridge tops (F). The wettest data are typically from late February or early March, and the driest from September or October, at the end of the dry season. The differences in soil properties are clearly reflected in the shape of the water content profiles, and the seasonal changes in water content.

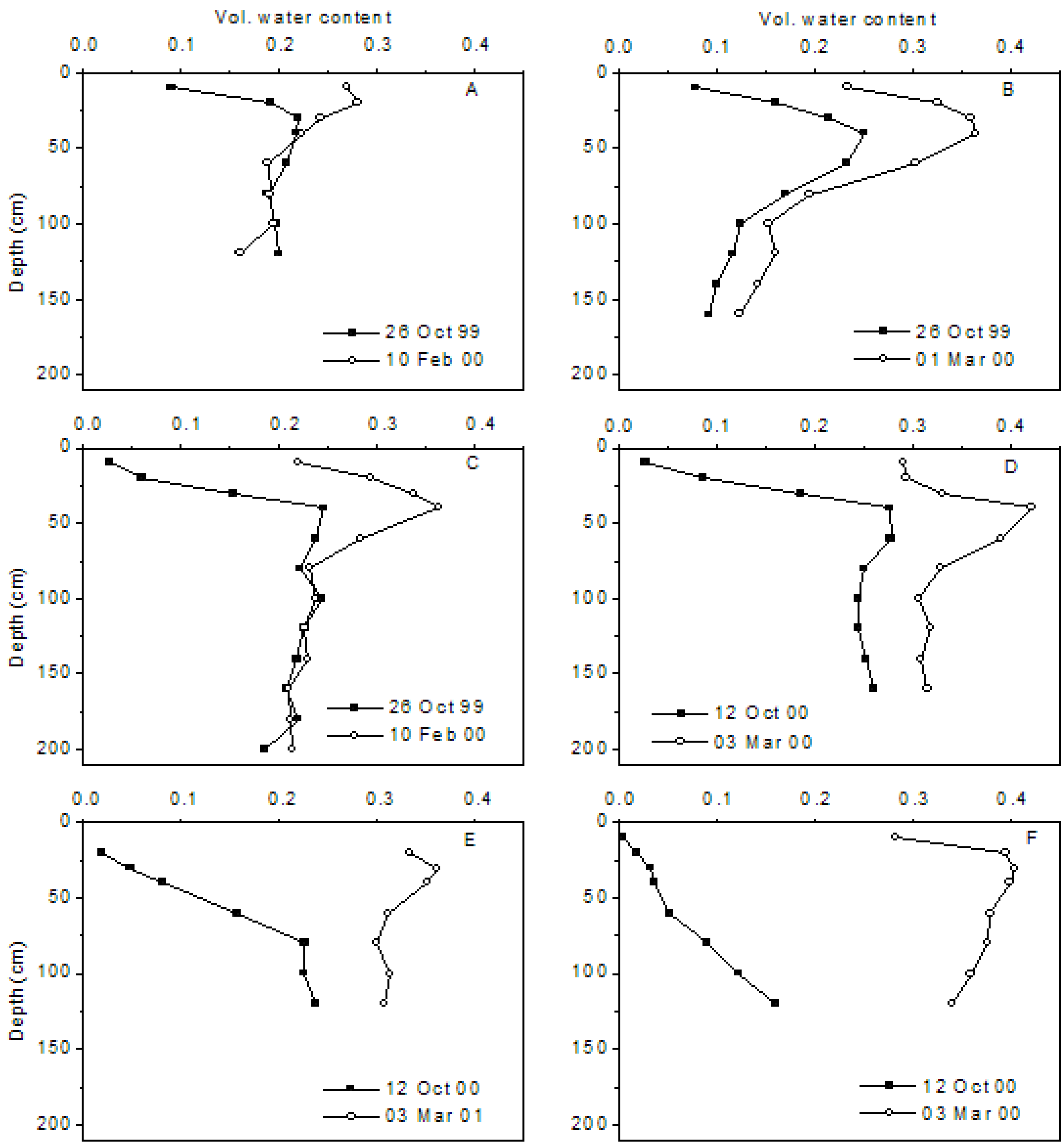


Figure 6.1: Wettest and driest water content profiles. (A) sodic bare soil, (B) sodic soil under mopani, (C, D & E) transitional soils that have a duplex character and (F) ridge top site at Mutangi during the 1999/00 and 2000/01 seasons.

The fallow sodic profile (A) showed very small seasonal changes in water content, which were limited to only the upper 0.4 m of the profile. These soils have a high bulk density (2.1 Mg m^{-3}), 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 limited because there is slow movement of water from upslope, maintaining a high water content.

The sodic soils under mopane scrub near the stream channel (B) showed much larger seasonal changes of water content. However most of the decrease from the wettest state occurred within a two week period, indicating that most of the change was due to drainage, not root uptake. The high water contents are caused by the profile becoming saturated in very wet periods during the wet season.

The cultivated transitional soils (C, D & E) have a duplex character, with sand overlying a more clay rich (22%) layer with a high bulk density (2.1 Mg m^{-3}) and a porosity of about 20%. This is reflected in the maximum water contents that were measured, and in the small range of water content change observed in the lower profile. At site C, large water content changes were limited to the sandy 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 change from the wettest condition occurred within a very short period. 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) is transitional, but has 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.

Ridge top site (F), entirely on deep coarse 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 occurs when the profile is saturated almost to the soil surface. This happened at this site in March 2000, but not in March 2001, when the highest water table level observed was 80 cm below ground level.

The average maximum seasonal water content changes for each of the soil types are shown in Table 6.3. In the sodic soils there was little water content change at the maximum measured depth, implying that the measurements had captured almost all of the seasonal change. Most of the transitional soils also 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.

Table 6.3. 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[a]
Mean	145
CV%	29.77
LSD (0.05)	131.1

[*] Numbers with the same letter are not significantly different at the 5% level.

The sandy soils had significantly the highest maximum seasonal water changes than both the transitional and the sodic soils. The sodic soils had the smallest seasonal change, and the sandy, ridge soil had 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 (Figure 6.2).

Except for the fallow, ridge sandy topsoils, there was not much difference in soil moisture between the two seasons for the remaining three soil types. The fallow sandy soil had more soil moisture in the 1999/00 season than the 2000/01 season.

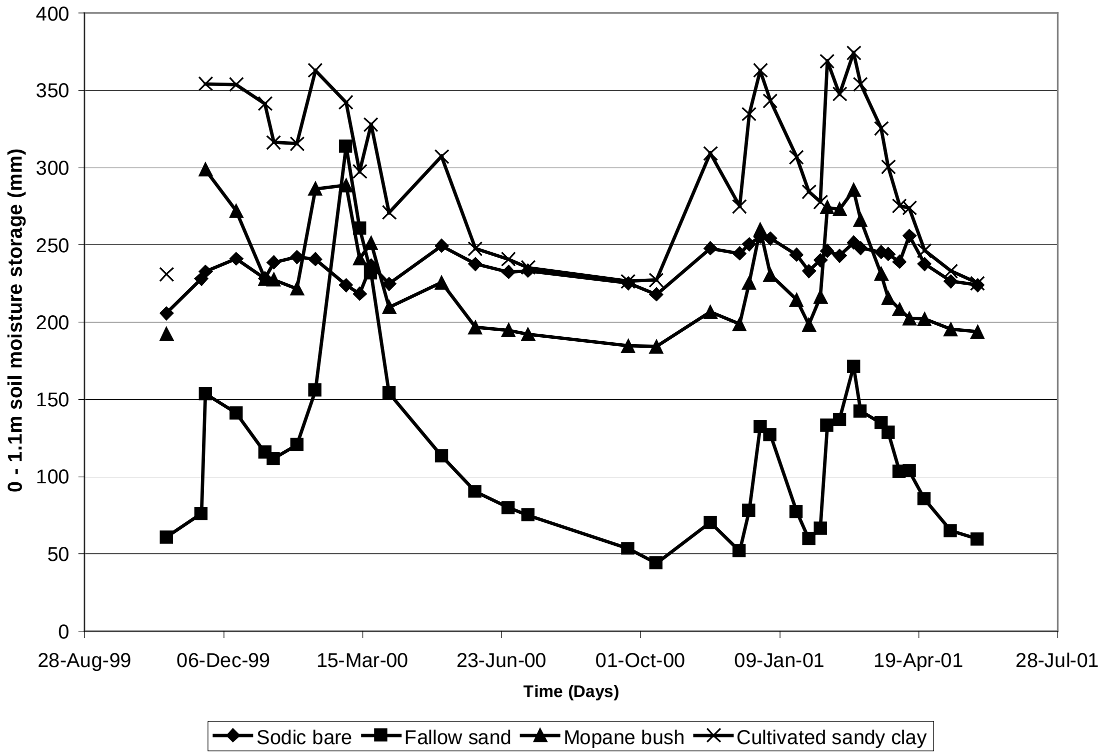


Figure 6.2: Soil moisture storage at four access tubes representing different land use practices at Mutangi.

Near surface soil (0 – 15 cm) moisture increased from the bottom to the top of the catena. The Mopane sodic soils had the highest amount of near surface soil moisture followed by the intermediate soils (Figure 6.3). The fallow sandy soil at the top of the ridge had the least amount of near surface soil moisture which did not exceed 15 mm during the enter study period.

6.5.3 Infiltration

Infiltration decreased along the catena (Fig 6.4) 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 stream. The sandy soil, intermediate soil and the mopane sodic soils have steady state infiltration rates of 640, 260 and 33 mm/hr respectively.

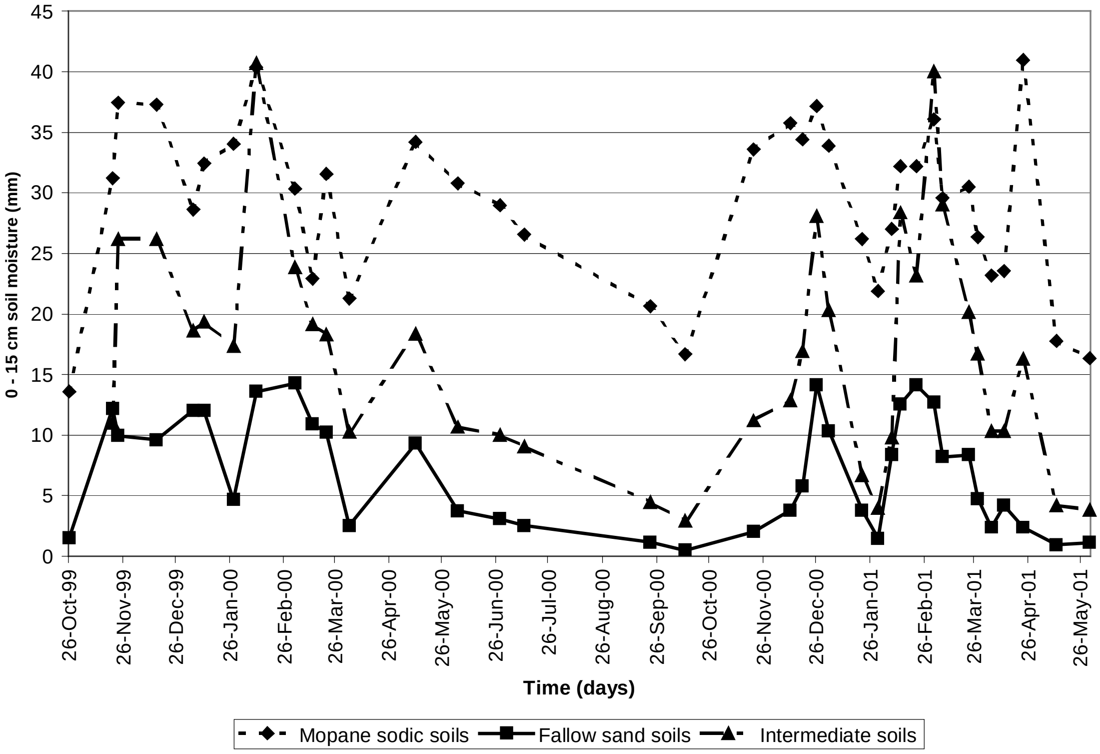


Figure 6.3. : Time series of near surface (0 – 15 cm) soil moisture at Mutangi.

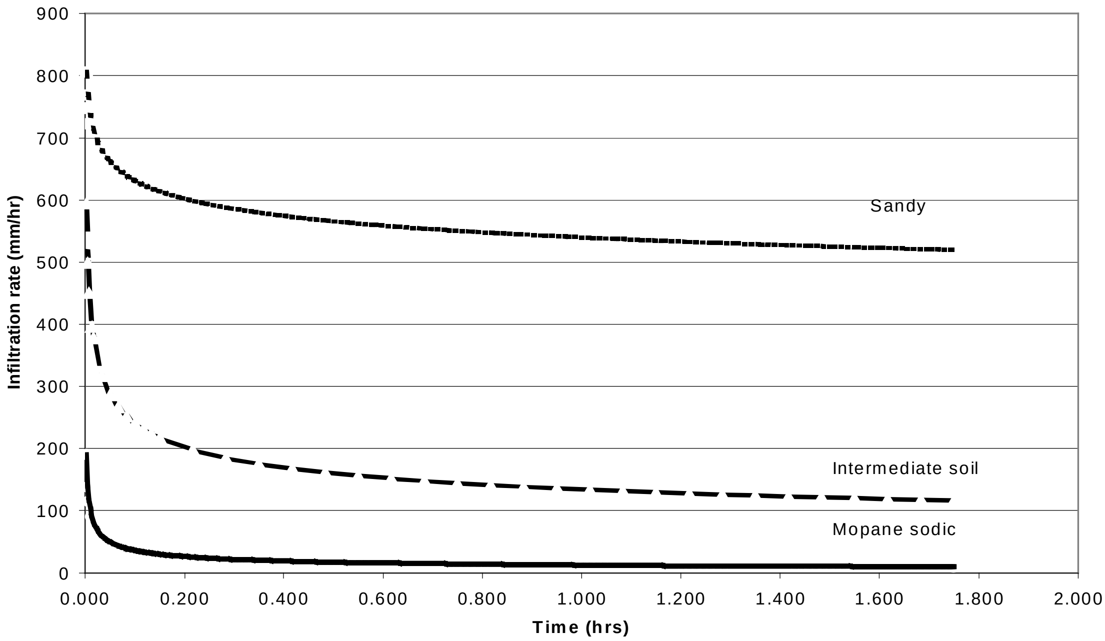


Figure 6.4: Infiltration rate for the Mopane sodic soil, transitional soil and the sandy ridge soil at Mutangi catchment.

6.5.4 Runoff

Figure 6.5 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 mm 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.

The amount of runoff generated from both the mopane sodic soils and the intermediate soils increased from 2nd of January 2001 to a maximum on the 23rd February 2001 and then decreased again (Table 6.4). Almost all (95%) of the rainfall was lost as runoff on the 24th of 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 6.4: Rainfall, runoff and runoff coefficients (in brackets) for runoff plots located on mopane sodic soils, intermediate soils and fallow sandy soils at Mutangi catchment.

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

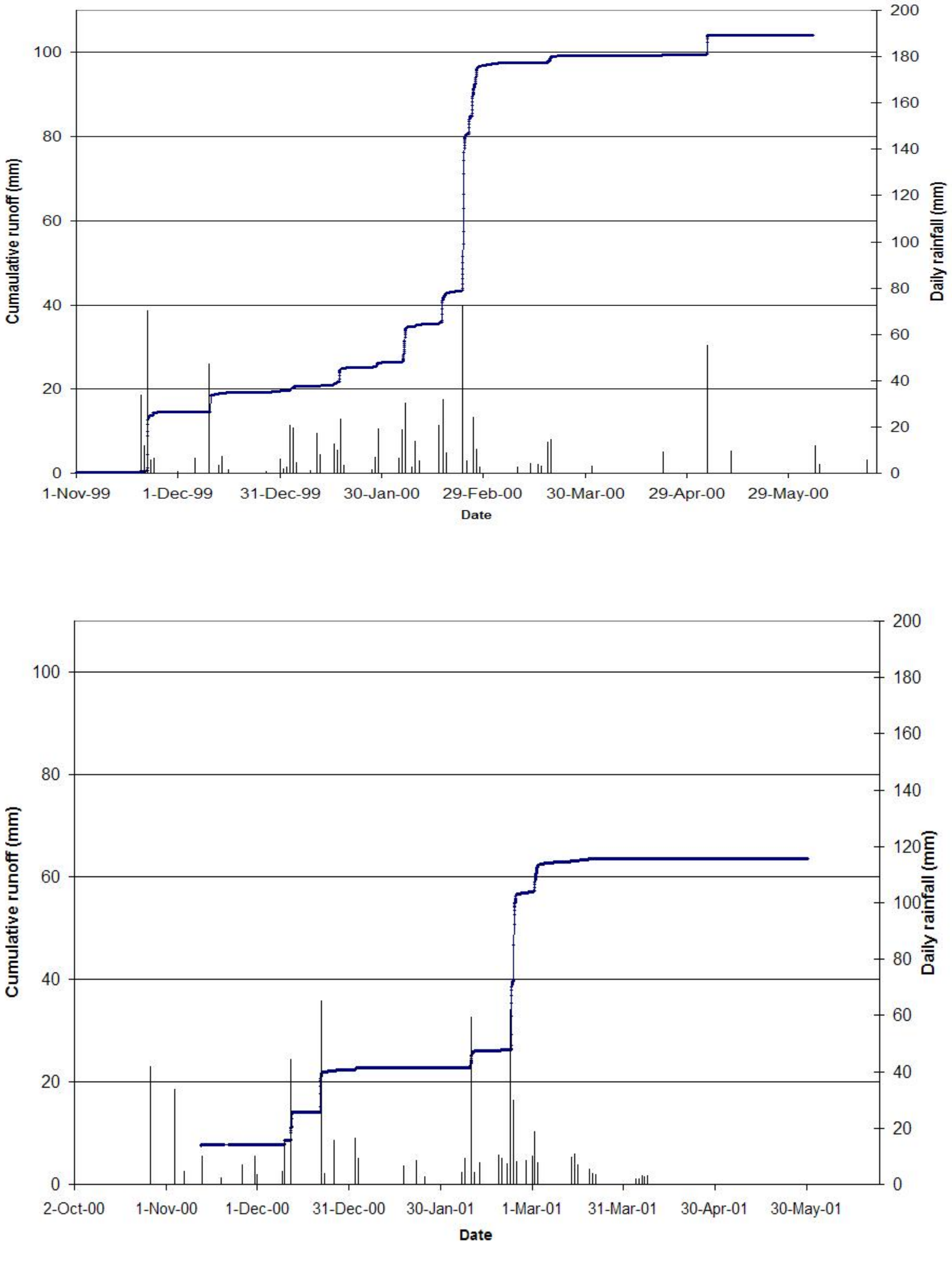


Figure 6.5: Cumulative total runoff and daily rainfall during the 1999/00 and 2000/01 seasons at Mutangi.

6.6 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, sandy clay horizons of low permeability on the slope, causing this shallow groundwater to approach the surface. The transitional soils also have less storage available, and may saturate due to rainfall inputs alone.

Soil moisture under fallow fields responded to rainfall during wet periods in February while the woodland did not respond during the same period (Figure 6.2). 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 soil moisture changes under mopane bushes during the wet season and very limited changes during the dry season when the mopane bushes have shed their leaves. The fallow areas on the sandy ridge soils show high 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 down slope 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 at 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 days 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, 31mm of runoff (49% of the seasonal total) was generated from a total rainfall of 101mm. 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 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 capping 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 acceptance of rainfall (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 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 soil moisture data (Figure 6.3) 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 hence a high runoff conversion coefficient as this area increases 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, (1970a,b).

SOF takes place in late February and early March when the storage capacity of the ridge soils are 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 6.4) 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. Near surface soil moisture increased from the bottom to the top of the catena as the season progressed. Partial area contribution to runoff first identified by Lane *et al*. (1978), is also evidenced here due to this catenary sequence of the soils. As the storage capacity of the soils are satisfied, first from the bottom to the top of sequence, runoff generation through SOF progressively takes place from the bottom to the top as the season progresses given sufficient rainfall. 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).

The sandy soils at the ridge top and most of the intermediate soils have very high infiltration rates (Figure 7.3) such that HOF is not likely on these soils. They have steady states infiltration rates of more than 500 mm/hr while the highest observed rainfall intensity during the two seasons was 28 mm/hr. HOF is likely to occur on the sodic soils because they have low infiltration rates of 33 mm/hr.

6.7 CONCLUSIONS

Runoff is not uniformly generated in the catchment both in time and space. From this chapter it is evident that rainfall distribution and soil type are very important in runoff generation and brings about differences in runoff generation between years with similar rainfall totals but different rainfall distribution patterns. Closely spaced rainfall events results 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 latter in the season.

There is a limitation in the data collected and additional studies could have been conducted to quantitatively determine how much runoff is generated by each of the three main soil types. Hydrochemical analyses for hydrography separation would provide a way of identifying recent water and old water in the flow hydrographs.

7. SEASONAL CHANGES IN THE DAM WATER BALANCE AND SAFE WATER USE

7.1 INTRODUCTION

Water is a very important natural capital in the semi-arid areas where rainfall is less than 600 mm and is seen as the critical natural resource constraint on dryland crop production in Sub-Saharan Africa (Cleaver and Schreiber, 1994). Poor distribution of rainfall within a wet season (Scoones *et al*., 1996) is often a cause of crop failure even in years with close to average rainfall, because of dry spells at critical stages of crop growth. The frequent crop failures force the communities to rely on ground and surface water stored during wet seasons and years. The water is used for domestic or productive purposes (Lovell, 2000; Waughray *et al.*, 1998) in gardens to supply domestic needs or generate income through selling of vegetables. However, these water resources fail in some years so that the communities are forced to walk very long distances to fetch water (Mbetu, 1993).

More than 600 small to medium dams have been constructed in the drier parts of the country over the last 30 years (Zirebwa and Twomlow, 1999) to ease water shortage problems. They vary in capacity between below 0.06 x 10^6 m^3 to 3 x 10^6 m^3 and in catchment area between 2 and 55 km^2. Such surface water resources depend on the runoff generated, which in turn depend on the amount and distribution of rainfall as described in chapter 5. About 10% and 30% of rainfall is lost as runoff in the semi-arid areas (Sandstrom, 1997) and the wetter parts (Bosch and Hewlett, 1982) of the world respectively. This implies that such small to medium dams, that the rural communities depend on, may not fill in years of low runoff (occasionally none at all). Improved water resource management can therefore help to reduce the vulnerabilities of communities who depend on surface water. At Mutangi the community use water from Mutangi dam to irrigate their gardens. This chapter investigates the quantities of water used for garden irrigation, animal watering, evaporation and further goes on to determine whether the present water use for gardening can be increased without drying up the dam.

7.2 OBJECTIVES

1. To determine how Mutangi dam water balance changes during a season.
2. To model how much dam water use can be stretched for productive use without depleting the resources especially for years with below average run-in.

7.3 HYPOTHESES

1. The runoff water captured by small dams is less than half the total annual runoff
2. The fraction of water used for productive use is insignificant and use can be increased up to five times without drying the dam in most seasons.

7.4 MATERIALS AND METHODS

7.4.1 Study site

The study site, Mutangi dam is described in Sections 3.2.2 and 5.4.2. The smallholder farmers in this catchment, like the other smallholder farmers in semi-arid Zimbabwe, practice rainfed crop production and the major crops grown are maize, groundnuts, cotton, sorghum and millets. Except for cotton that is sold to the cotton companies of Zimbabwe, the other crops are mainly grown for home consumption or local sale to neighbours who do not get enough grain. In years with good harvests farmers keep grain for the next season. In drought years, they depend on the government's drought relief programme, where grain is given freely to the elderly and as a grain loan or food for work to the rest. The loan would be serviced when they get good yields in wet years (Dhlembeu, 1998).

There are 18 unlined shallow wells (Figure 7.1) that tap the ephemeral soil/weathered zone aquifer. These dry up 2-4 months after the end of the rainy season. They are typically 1 – 4 m in depth and 1 – 4 m in diameter and are usually located in fenced gardens in the cultivated areas that are found halfway up the catchment.

They are used for domestic supply, and to irrigate vegetables grown during the wet season, up to harvest time. After harvest, the gardens in the fields are used less, and more gardening then takes place in a community garden, which is irrigated from the dam. The dam (Figure 7.2) was constructed in 1947 and its full capacity is 111 300 m^3 which is equivalent to 18.8 mm over the 5.9 km^2 catchment area. The reservoir has a maximum depth of about 2.5 m, and its area when full is 8.7 ha. The garden (Figure 7.3) is about 200 m from the reservoir, and above it, so labour is a major constraint in irrigation.

Figure 7.1: An unlined shallow well in one of the fields in Mutangi catchment (May 1999).

Figure 7.2: The dam on one of the two irrigation days per week. Women are carrying buckets of water and children carrying 200 litre drums of water on scotch carts to irrigate vegetables in the garden upslope (Figure 7.3).

Figure 7.3: The community garden (that is irrigated by water from the dam in figure 7.2) showing vegetables during the dry season.

7.4.2 Calculation of dam water use and loss

The changes in the reservoir volume ΔV can be attributed to direct rainfall (P), run-in (R_{in}), evaporation (E), runoff out of the dam through the spillway (R_{off}), human use (H), animal watering (A) and seepage (S) as given in equation 4.4.

$$\Delta V = P + R_{in} - (E + R_{off} + H + A + S) \qquad \text{Equation 7.1}$$

Evaporation rates are calculated from the rate of decrease of water level logged by the water level recorder during periods when there was no rainfall and when the dam was not spilling out. Evaporation figures for February and March are missing because it was raining or the dam was spilling during these months. Evaporation rates were corrected by subtracting an estimate of human water use. This was taken to be exclusively for irrigation because better quality water for drinking is available from other sources.

There are 280 beds in the garden that are 1 m by 7 metres. Irrigation water use was calculated taking cognisance that half the garden area is cultivated and irrigated. The other half (Figure 7.3) is in the form of paths between the beds. Irrigation is carried out twice a week. Water use in the garden through the growing season was estimated based on 50 litres per bed irrigating twice a week (Lovell, 2000).

About one hundred and fifty head of cattle are watered from the dam daily, and each animal is estimated to drink 50 litres a day (Lovell, 2000). Changes in reservoir due to evaporation and water use were calculated from monthly (daily averages) evaporation rates and irrigation abstractions for the three sizes of garden (0.4 ha of the current size, 1 ha and 2 ha). Two scenarios were used, a very wet season, with the dam last full (spilling) in May, and a much drier season, in which the dam filled completely but was last full at the beginning of February.

7.5 RESULTS

7.5.1 Reservoir storage changes

The storage in the dam between May 1999 and October 2001 is shown in figure 7.4. The point for the 12th of May 1999 was derived from a water level estimated from a photograph of the spillway taken on that day.

The date of the minimum storage reached in October 2000 corresponds with the first major rainfall event (42 mm) of the wet season. The dam filled up with the second and third rainfall event in the 1999/00 and 2000/01 season respectively. The estimated water storage for 12 May 1999 (72000 m^3) is much lower than on the same dates in 2000 and 2001 (105000 m^3 and 92000 m^3 respectively), indicating that the last date that the dam filled in the 1998/99 wet season would have been in late February when there was about 90 mm of rain over 2 days. The estimated data indicate that the dam may not have spilled in that year. The minimum storage recorded during the study (19 November 1999) was largely the result of the long period without run-in, between February and November.

The water level data show that the dam was 18% and 36% full when the first rains were received in 1999 and 2000 respectively. The high storage at the end of the 2000 dry season was because the “effective dry season” was short: the last spill was on 5 May 2000 and the first major rainfall was also relatively early, on 24 October.

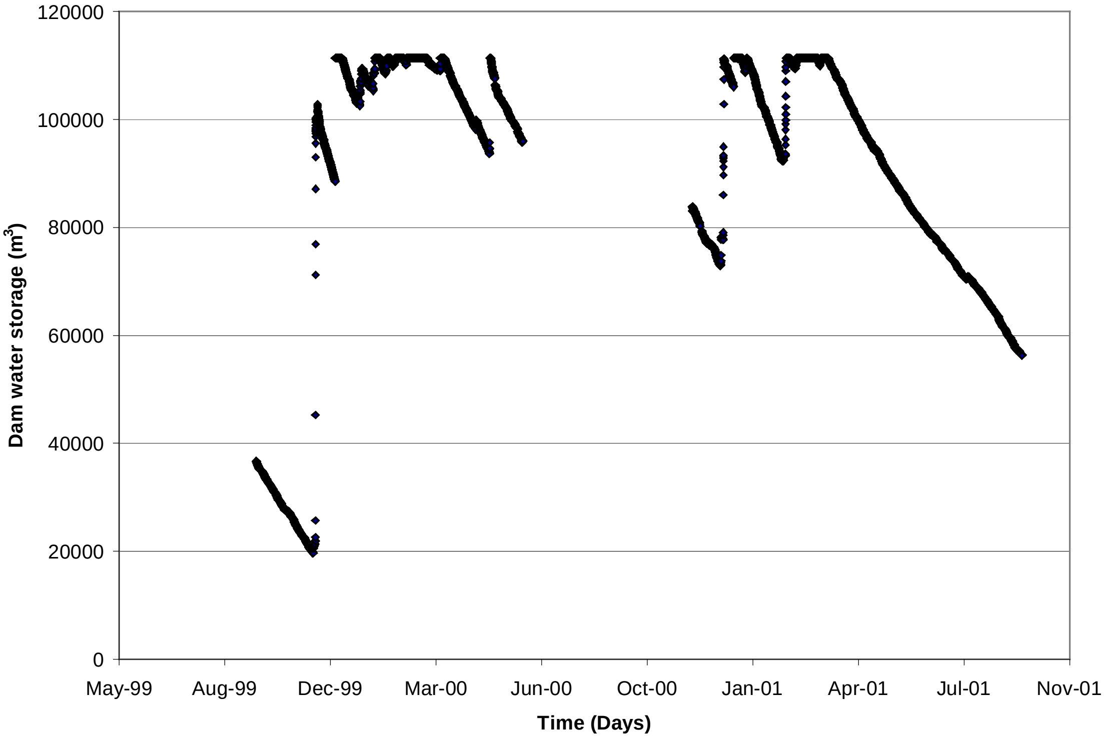


Figure 7.4: Storage in the dam between May 1999 and October 2001 seasons at Mutangi catchment.

7.5.2 Run-in and runoff

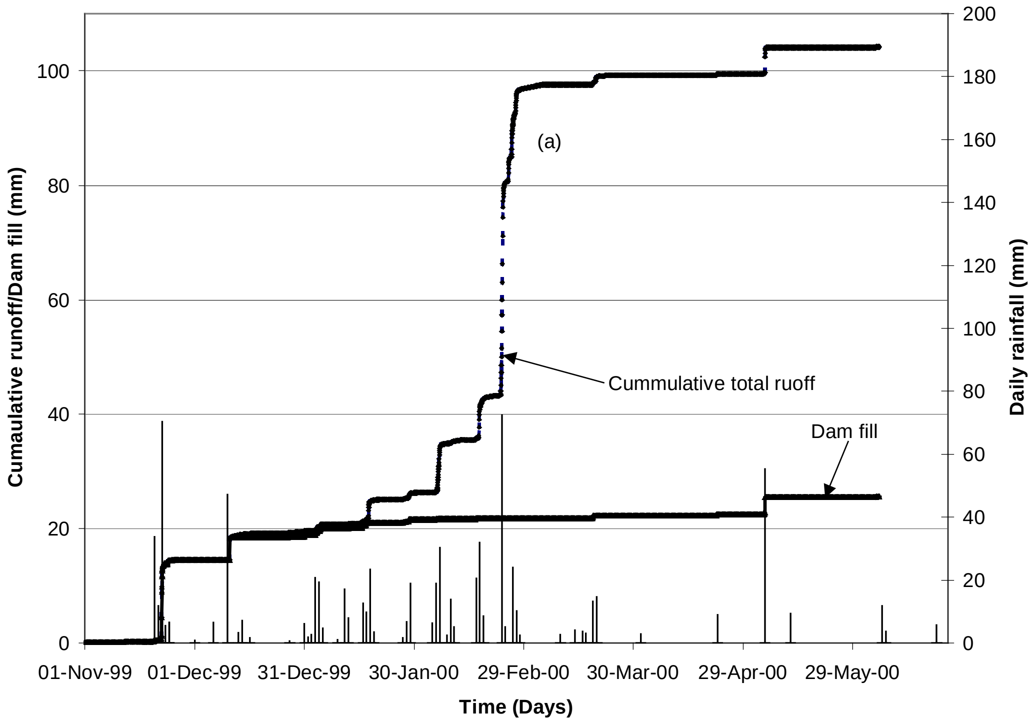
Figure 7.5 shows the cumulative amount of water caught by the dam (dam fill), and the cumulative total runoff from the catchment (as if the dam had not been there), in the 1999/00 (a) and 2000/01 (b) seasons respectively. The two curves are the same until the dam spills. After the dam first spills, some runoff can still be captured, after evaporation losses have lowered the water level during dry spells. The amounts of runoff captured by the dam were 23 and 30% (Table 7.1) of the total runoff in the 1999/2000 and 2000/2001 seasons, respectively.

7.5.3 Evaporation from the dam

The data from the water level recorder showed that at night, there was no decrease in water level, except on windy nights when evaporation continued indicating that there was no deep seepage from the dam. The lack of change on still nights indicates that there was no significant leakage from the dam. Figure 7.6 shows the monthly rates of evaporative loss from the dam expressed in mm d^{-1} and in m^3 d^{-1}. The evaporation rates figures were calculated from the rate of decrease of water level logged by the water level recorder during periods when there was no rainfall or when the dam was not spilling over. Evaporation figures for February and March are missing because it was raining or spilling during these months. Evaporative water loss decreases from January (7.3 mm d^{-1}) to June (3.8mm d^{-1}) and then increases to reach a peak in November (8.6 mm d^{-1}). This very high rate was recorded in November 1999, before the start of the rainy season.

Table 7.1: Mutangi dam rainfall, runoff, runin and spill-off analysis.

	1999/2000 season	2000/2001 season
Rainfall (mm)	755	620
Catchment runoff (mm)	102.3	63.7
Total dam catch (mm)	23.7	19.1
Total spill (mm)	78.6	44.6
Total dam catch as a % of runoff	23.2	30.0
Total runoff as a % of rainfall	13.5	10.3



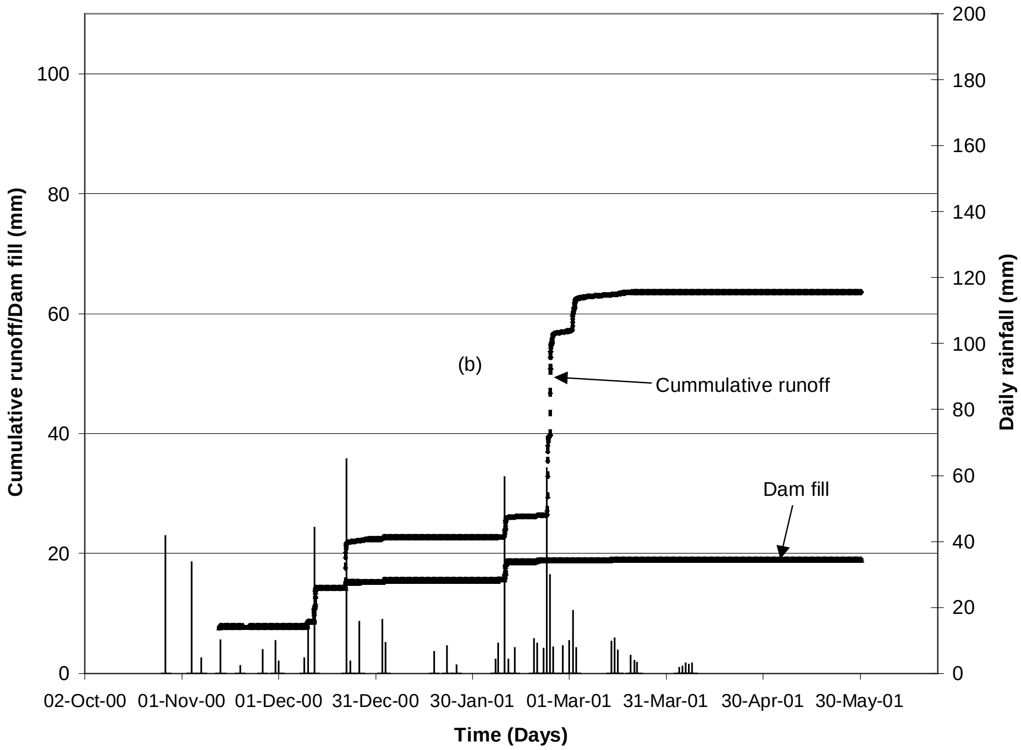


Figure 7.5: Cumulative total runoff and dam fill and daily rainfall during the (a) 1999/00 and (b) 2000/01 seasons at Mutangi.

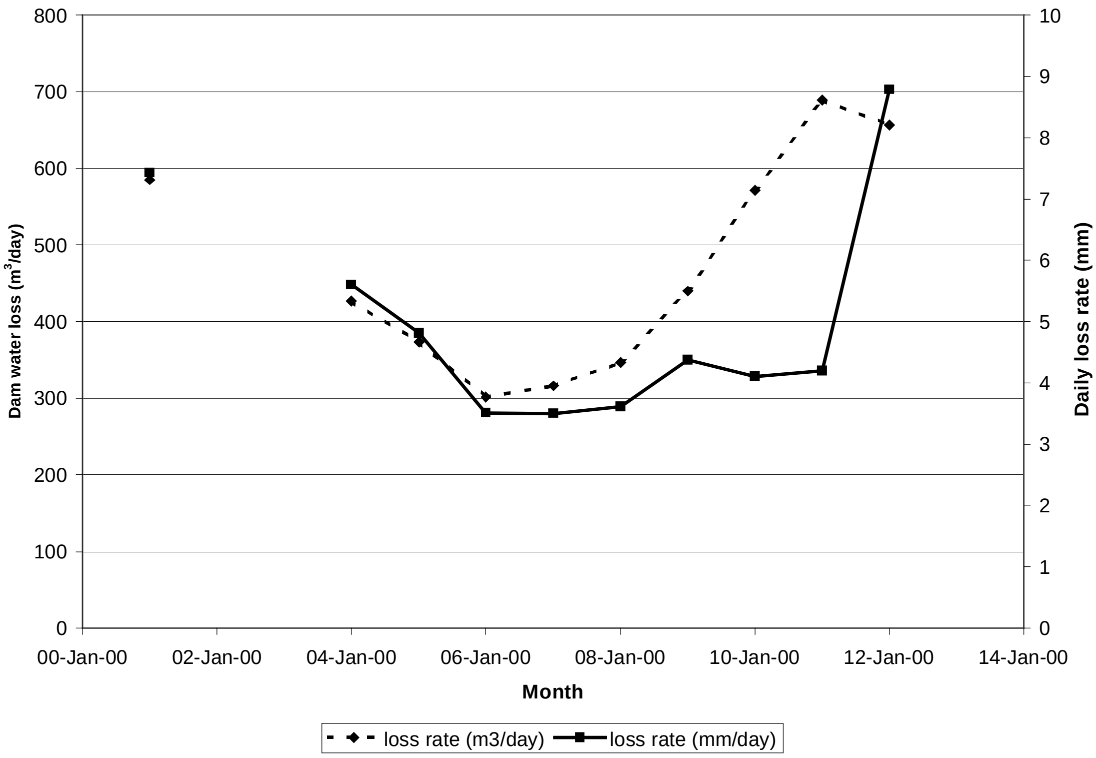


Figure 7.6: Monthly evaporation (mm) and volume loss from Mutangi dam (based on the 1999 to 2001 data)

7.5.4 Partitioning water use

Table 7.2 summarises the monthly dam water balance. There is no gardening from January to May in the garden irrigated from the dam because the communities are busy in their dryland fields. The community in Mutangi has small gardens that are irrigated from shallow wells during the harvesting period. Animals also mainly drink from streams and wells dug in the sand beds of the streams during this wet period.

Of the total annual water loss from the dam, only 3.3% of the water is put to productive use (garden and animal watering). Almost 97% is lost to evaporation.

Table 7.2: Monthly water use (m^3) through gardening, animal watering and evaporation at Mutangi.

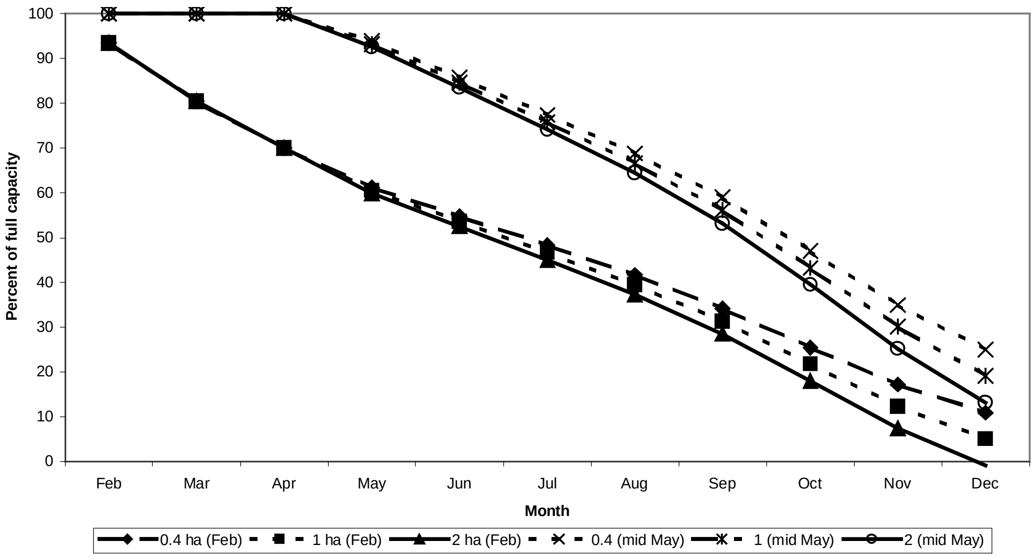
Monthly evaporation loss was calculated using the average daily water lost rates (Figure 7.6).

Month	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	% of Total
Gardening (m^3)	0	0	0	0	0	117	191	277	343	457	268	0	1653	2.0
Animal watering (m^3)	0	0	0	0	0	112	116	174	169	233	225	116	1146	1.4
Evaporation (m^3)	18414	15232	15376	13440	11935	8430	8680	8959	10500	10168	10080	21793	153007	96.6

7.5.5 Can the current garden size be increased from 0.4 ha to 1 ha or 2 ha without the danger of depleting the dam?

In 2001, a new 2 ha garden was established with the assistance of CARE International about 1 km downstream of the dam. Concrete storage tanks in the garden are gravity fed by pipeline from the dam, so that the labour requirement for irrigation has been much reduced. This implies that the community can use more of the dam water but it is not known by how much can dam water use be increased without drying the dam in any given season before the next fill-up.

Figure 7.7 shows that by mid-October (when the first rains are expected) the dam would be 25% and 47% full if it last filled in February and May respectively, for a garden of 0.4 ha. If the dam last fills up in February, the storage would be 22% and 18% full in mid-October if the current garden size is increased to 1 ha and 2 ha respectively. The corresponding figures for a last fill in mid-May are 43%



and 39%.

Figure 7.7: Predicted reservoir storage if last full in February, and if last full in mid-May, for three garden sizes at Mutangi.

Table 7.3 shows the probability of getting a certain amount of rainfall in a given month using historical (1915-1998) rainfall data from Chivi. The expected monthly rainfall between 50 – 100 mm increases from September to January and decreases from February to May while the monthly rainfall between 100 – 200 mm starts decreasing in February though the January amount is lower than the December because of frequent dry spells in January. There is a probability of 27%, 8% and 2% of receiving a monthly total rainfall of between 50 and 100 mm. This indicates that the chances of getting enough rainfall to cause run-in the dam are very limited in May and April and from this data we expect that the dam normally last fills up in March. However, the monthly totals are misleading and different runoff coefficiences can be recorded for month with similar rainfall totals because the amount of runoff generated in a month depends on closeness of rainfall events and intensity of the rainfall, as highlighted in Chapter 6.

Table 7.3: Probability (%) of receiving different amounts of rainfall in a given month based on rainfall data for Chivi (1914-1997).

Month	0 mm	0-25 mm	25-50 mm	50-100 mm	100-200 mm	200-300 mm	>300 mm
Sept	45	40	6	4	0	0	0
Oct	15	60	18	5	1	0	0
Nov	1	25	12	35	26	0	0
Dec	0	6	15	32	29	14	2
Jan	0	7	14	36	20	14	8
Feb	2	18	8	25	33	11	4
Mar	5	30	14	27	19	5	0
Apr	12	62	17	8	1	0	0
May	33	57	7	2	0	0	0

7.6 DISCUSSION

The amount of runoff captured by the dam was 23% and 30% of total runoff respectively in the 1999/00 and 2000/01 seasons respectively and showing that the amount of runoff captured by these small dams is a small fraction of the total runoff.

The highest levels of evaporation were recorded between November and March, but at this time of the year, the high rates generally do not have much effect on water resources, because there is sufficient rainfall during the same period to replace the losses. In the period April to October when there is no significant rainfall input, the water use should be matched to the amount of water in the dam.

The volumetric loss rate depends on the water surface area, which in turn depends on the depth of water in the dam. The loss rates varied from year to year depending on whether the dam filled completely and on the latest date that it was full. The data shown are based on the period 2000 – 2001. The rate of water loss decreases from January (595 m^3 d^{-1}) to June (280 m^3 d^{-1}) and then increases slightly until October. In this period the sharp increase in evaporation rate (mm d^{-1}) is almost balanced by the reduction in evaporating area. In November, in the scenario shown, there is a large increase in volumetric loss to a peak of 740 m^3 day^{-1}, because the dam was almost full and evaporation rates were at their maximum.

The amount of water from the dam used by the communities for productive use is negligible and there is considerable scope for increasing water use in years when the dam fills completely, without depleting the dam below a “safety margin” level (10%). This is based on the two years studied in which rainfall was above average and the distribution was also good. In years with poor rainfall or poor distribution the dam might not fill completely, and water use would have to be adjusted accordingly, using storage predictions based on the evaporation rates given above and the depth/volume curve for the dam.

How far can the community stretch the current water level resource without the danger of depleting it especially in years when the dam does not fill up, or during the period between last spill and the first rains increases? The date when the dam last fills is critical in that it marks the start of the period when water will be lost as evaporation before the next major filling (run-in) event. In 2000 this period was only six months long, but it is estimated to have been almost 9 months in 1999. If the rainfall season starts in November 2001 then there will have been 8 months of evaporation in the current dry season. This means that the water available for use will be rather lower than in 2000.

At the start of the rainy season in 1999, 2000 and 2001 the dam storage figures were 20,500, 35,600 and 29,400 m^3 respectively (2001 figure is an extrapolation assuming that the rains start in mid November). Allowing a safety margin of 10% capacity after which there should be no abstraction for irrigation, 9,379, 24,442 and 18,300 m^3 of water could have been safely used by increasing water use in 1999, 2000 and 2001 respectively. Even in 1999, when the evaporation period was the longest in the study, the amount of water that could safely have been used was four times the amount that was actually used for gardening (2320m^3) during the two years of the study.

The analysis in section 7.5.5 shows that the changes in dam water storage are very small even if the water use is increased five times. This would not pose a danger even if the dam last fills up in February, provided the first rains are received in October or November. However, the dam is likely to dry up if increased abstraction is sustained during a period when the rains are delayed, as in 1995. In that year, the first rains were received in January. There will also be years when the dam hardly fills, as in 1991/2, when less than 100 mm of rain was received.

7.7 CONCLUSIONS

Less than half the total annual runoff was captured by the dam in all the two years of study. The percentage of total annual runoff captured by the dam were 23.2% and 30% respectively in the 1999/00 and 2000/01 season. Of the total water use/loss from the dam only 2% is currently used for gardening. Dam water use could be increased up to 5 fold without drying up the dam. Water use should be synchronized with the amount of water available in the reservoir - where use is increased when the dam last fills up later in the years and reduced when the reservoir last fills up early in the season because the duration of use will be much longer. The communities depending on these dams should monitor the amount of water in the dam and know the amount available to them before the expected rains. Surface water, unlike groundwater, is visible and its quantity can be monitored from a staff gauge and a volume/depth curve.

Monthly evaporative water loss can be used to predict the annual water loss depending on when the dam last filled up. This way the amount of water available for productive use can be predicted thereby enabling the community to make informed decisions like, what percentage of the garden should be cultivated/irrigated, which crops to grow and when to stop using the dam water (when it goes below the dead level). However, the unpredictability of when the first runoff will be generated in a given season is a setback to proper management of surface water resources. Garden irrigation continues till the first rains when the community shifts to dryland farming. This implies that pressure on dam water will be high in years when rains delay, but where monitoring is done farmers will know when to stop using dam water when it goes below the dead level (which is 10% of dam capacity).

8. MODELING THE EFFECT OF CLIMATIC CHANGE, LAND USE CHANGE AND INCREASED ABSTRACTION ON SURFACE WATER RESOURCES

8.1 INTRODUCTION

Management of land and water resources is continually and universally recognized as necessary to improve the living standards of rural communities. Integrated Catchment Resource Management is increasingly being promoted as an appropriate model for development of water resources in semi-arid areas of the world (Manzungu, 2002; Lovell, 1998). However, important gaps in the understanding of catchment hydrology are a major constraint in successfully implementing improved management strategies.

Chapter six highlighted that at both Romwe and Mutangi, rainfall was above the Runde catchment long-term average in both the 1999/2000 and 2000/2001 seasons. The corresponding runoff was much more than the small to medium dams require to fill up when they are empty. Of that runoff, the small dam captured only 23 % and 30 % in the 1999/2000 and 2000/2001 seasons at Mutangi respectively. It is not known how runoff and surface water resources would respond to below average annual rainfall, which is common in these semi-arid areas (Scoones *et al*. 1996).

The agricultural sector, especially the smallholder sector is dynamic and is gradually changing with the socio-political situation. For example a decrease in the population density is expected in the communal areas with the land redistribution exercise that would result in a lot of fallow fields and reduced pressure on grazing lands. On the other hand, pressure is expected (in some instances) on both agricultural and grazing land because retrenched workers are expected to come back to the communal lands to farm. Du Toit and Campbell (1989) observed an increase in stream-flow in the Save river which he attributed to reduced evapotranspiration because of large-scale removal of plant cover. This was also coupled with an increase in erosion. This has resulted in siltation of dams, therefore reducing their storage capacity and useful life.

Land management practices are also changing as a result of agricultural extension services by Agricultural Research and Extension (AREX) and Non Government Organisations (NGOs) like CARE and AFRICARE who are promoting efficient utilisation of rainfall and surface water resources from dams. The effect of the above changes on water resources needs investigation so that good advice can be given to policy makers to ensure sustainable water resources management in the smallholder farming sector.

The type of land use envisaged in most of the previous modelling studies is hypothetical and involves clearing of the whole catchment or planting the whole catchment with trees (Bosch and Hewlett, 1982). The changes in the communal areas are gradual and involve small increments/reduction on land under grazing or cultivation.

The effects of the above changes on the hydrology and water resources of communal land catchments are not known at present and would require a number of years of study and at a number of sites in order to capture both the temporal and spatial variability in rainfall and land use.

Modelling approaches have been used in other studies (Schulze, 2000) to reduce timescales and extend our understanding on the effect of varying land use and management on catchment hydrology and water resources using historical climatic data and climatic change scenarios and therefore offer an opportunity to make informed decisions.

8.2 OBJECTIVES

1. To investigate the effect of the historical cyclic nature of rainfall on Mutangi dam water resources
2. To investigate the effect of changing land use practices and management on Mutangi dam water resources.
3. To investigate by how much surface water resource use can be stretched without drying Mutangi dam in most years.

8.3 HYPOTHESES

1. Runoff and surface water resources at Mutangi respond to the cyclic nature of rainfall.

2. In-field water-harvesting techniques have significant effect on runoff generation and dam water storage changes at Mutangi.
3. Mutangi dam water use can be increased up to ten times without the danger of drying it.

8.4 MODEL SELECTION AND DESCRIPTION

The ACRU model developed in South Africa was selected because it was extensively used to provide solutions to a wide range of water resources related problems in different climatic and physiographic conditions in Southern Africa (Tarboton and Schulze, 1992; Jewitt and Schulze, 1993; Smithers and Schulze, 1995; Kienzle and Schulze, 1992; New, 2002). In South Africa the ACRU model was used before to (a) assess the effect of climatic change on water resources (New, 2002; Morrison *et al*., 2002), (b) design flood estimation (Smithers *et al*., 2001) and (c) assess the impact of land use changes on water resources (Schulze, 2000; Smithers and Schulze, 1995; Kienzle and Schulze, 1992). In Zimbabwe the ACRU model has been used in the Romwe catchment to (a) evaluate evidence for the potential effect of climatic fluctuations over recent decades on the water balance of the catchment and (b) to evaluate evidence for the potential effect of land use and land management change on the water balance of the catchment (Butterworth, 1997; Butterworth et al, 1999d) and in the Mupfure catchment as a tool for improved water resources management.

The model has several modules and can be used as an integrated modelling system to assess the individual and combined effects of a combination of different land and water use and management systems in different spatial locations in a catchment (Schulze, 1989). This is the recommended approach to the integrated management of catchment resources.

ACRU is based around a two layer 'bucket' type soil water budgeting model (Figure 8.1). ACRU is a daily time step, physically-conceptual and multi-purpose model with options to output, inter alia, daily values of streamflow, peak discharge, reservoir status, recharge to groundwater, sediment yield, irrigation water supply and demand (Schulze, 1989). The most important input variables into the ACRU modelling system include daily rainfall, daily potential evaporation, monthly land-cover information such as leaf area index, crop coefficients, root distribution and interception, soil physical variables such as texture class, porosity, field capacity, wilting point, depth of A and B horizons and geo-hydrological data, including specific retention, specific yield, hydraulic conductivity, gradient of the water table and initial water-table data (Kienzle and Schulze, 1992). The simulations performed are based on physically measurable or derivable catchment characteristics.

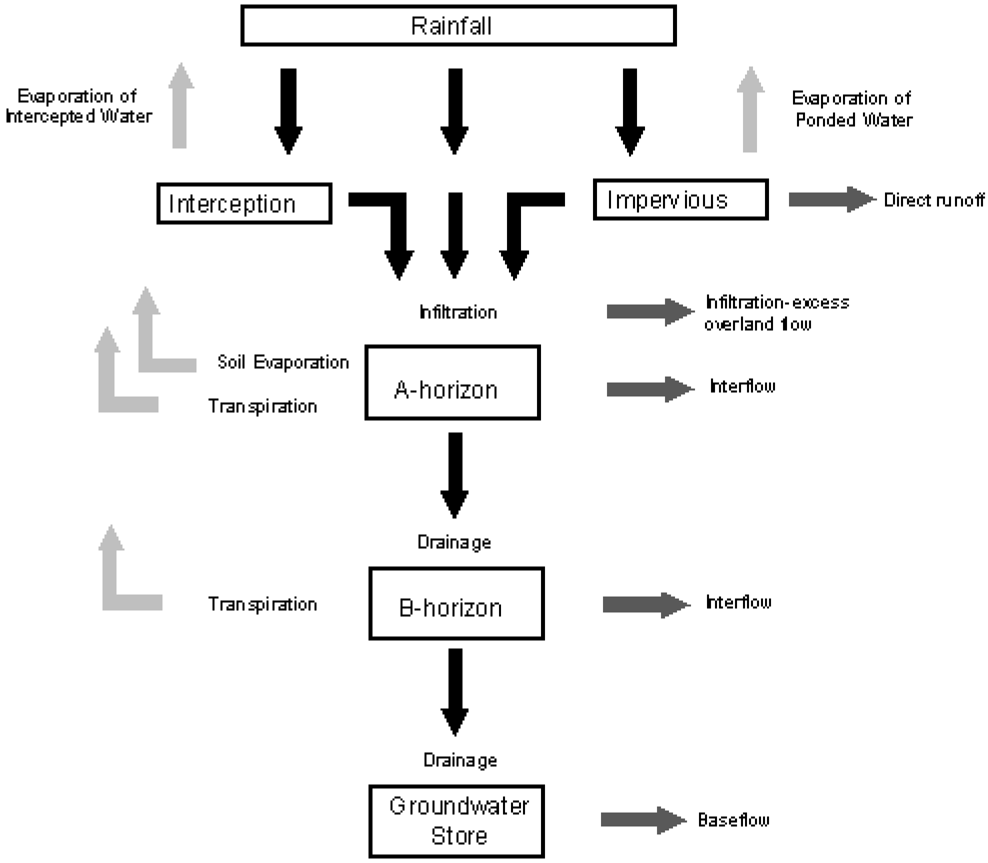


Figure 8. 1. General structure of soil moisture budgeting and streamflow generation in ACRU. (Source: Schulze, 1994)

Surface runoff and infiltration are simulated using a modified form of the Soil Conservation Service (SCS) stormflow equation (Equation 8.1) (Schmidt and Schulze, 1987), *viz:*

$$Q = \frac{\left(P_{\mathrm{g}} - cS\right)^2}{P_{\mathrm{g}} + S(1-c)} \qquad \text{Equation 8.1}$$

Q is the runoff depth; P_g is the gross daily rainfall, S is the potential maximum retention (a function of soil texture and antecedent soil moisture); and c is the coefficient of initial abstraction.

Essentially, for a given amount of net rainfall, runoff depth is proportional to the antecedent soil moisture content. The coefficient of initial abstraction, *c*, relates *S* to initial abstractions due to depression and other surface storages, and increases with increasing litter and surface roughness.

The critical runoff response soil depth (*SMDDEP)* in the model, controls the "speed" at which overland flow is generated. A small value of *SMDDEP* produces a rapid initiation of surface flow, and *SMDDEP* therefore has higher values where soils are deep and/or have high infiltration capacity, and where rainfall is gentle and persistent.

Evaporation is simulated from the soil surface and from vegetation. The uptake of water by plants occurs from each soil layer according to atmospheric demand (i.e. potential evaporation), Leaf Area Index (LAI), soil moisture content and the relative distribution of active roots between the two horizons. The energy available for transpiration (F_t) is determined from potential evaporation and modulated by LAI according to equations by Ritchie (1972) (Equation 8.2).

$$F_t = 0.7\ LAI_D^{0.5} - 0.21 \qquad \text{Equation 8.2}$$

where LAI_D is daily leaf area index

Actual transpiration equals potential transpiration when there is no soil moisture stress on plants. The level at which moisture limiting conditions for transpiration commence depends on the vegetation critical leaf water potential and atmospheric demand. Soil evaporation may only occur from the upper soil layer and is calculated for wet and dry stages following the analysis of Ritchie (1972).

8.5 MATERIALS AND METHODS

8.5.1 Parameter definition and parameterisation

ACRU requires six key soil moisture and/or streamflow parameters that control the total soil depth, rate of saturated soil-water redistribution, the relative importance of throughflow and vertical drainage, and the fractional release of baseflow from groundwater store.

The catchment characteristics used in the modelling exercises are reported in Chapter 5 (catchment size, soils, vegetation, landuse). The ACRU input parameters used for Romwe are described by Butterworth (1997) for the red subcatchment. The Permanent Wilting Point (PWP), Drained Upper limit (DUL), porosity, thickness of A and B horizons for Mutangi catchment were obtained from Gotosa and Muzuva (1999) who did a soil survey of the catchment. Soil water redistribution factors (ABRESP and BFRESP) were taken from values proposed by Smithers and Schulze (1995) according to soil texture. The Coefficient of initial abstraction (COIAM) and monthly mean values of LAI (ELAIM) used for Mutangi were those recommended by Shulze (1994) for similar regions of the semi-arid areas. Butterworth (1997) validated the ACRU model at Romwe site using two years of climatic data. Five years of climatic data (representing both wet and dry conditions) at the same site (Romwe) is used in this study.

The simulations were done using ACRU operated in a lumped mode and on a daily time step. The Romwe red subcatchment is small in size (0.024 km^2) and relatively homogeneous. There are three main land covers in Mutangi that are communal land (54%), woodland (29%) and fallow (12%). Areal weighting of the three main land uses were done in Mutangi to come up with the CAY (the average crop coefficient for the pervious land cover of a catchment i.e. the proportion of water consumed by a plant under conditions of maximum evaporation in relation to that evaporated by an A-pan in a given period) and ROOTA (fraction of effective root system in the topsoil horizon, specified month-by-month). The input parameters used at Romwe and Mutangi are presented in Tables 8.1 and 8.2.

Table 8.1: Measured and optimised input parameters for simulation of the water balance at Romwe and Mutangi respectively. (Source: Gotosa and Muzuva, 1999; Butterworth, 1997)

Parameter	ACRU name	Romwe Red-subcatchment	Mutangi catchment
Texture	ITEXT	10 (sandy clay)	5 (sandy loam)
PWP of A horizon	WP1	0.10	0.10
PWP of B horizon	WP2	0.22	0.15
DUL of A horizon	FC1	0.20	0.20
DUL of B horizon	FC2	0.32	0.25
Porosity of A horizon	PO1	0.42	0.40
Porosity of B horizon	PO2	0.45	0.40
A/B response factor	ABRESP	0.40	0.40
B/I response factor	BFRESP	0.40	0.40
Thickness of A horizon	DEPAHO	0.50	0.30
Thickness of B horizon	DEPBHO	0.80	0.70
Effective depth of soil for stormflow response	SMDDEP	0.50	0.20

Table 8.2: Coefficient of initial abstraction (COIAM) for Romwe and Mutangi (recommended in ACRU User manual) and Monthly mean values of LAI (ELAIM)

	COIAM		ELAIM	
	Romwe	Mutangi	Romwe	Mutangi
Jan	0.30	0.30	0.99	0.99
Feb	0.30	0.30	1.60	1.60
Mar	0.30	0.30	1.48	1.48
Apr	0.20	0.20	1.09	1.09
May	0.20	0.20	0.70	0.70
Jun	0.20	0.20	0.50	0.50
Jul	0.20	0.20	0.20	0.20
Aug	0.20	0.20	0.20	0.20
Sept	0.20	0.20	0.20	0.20
Oct	0.20	0.20	0.20	0.20
Nov	0.20	0.20	0.20	0.20
Dec	0.30	0.30	0.60	0.60

8.5.2 Observational data

Measured data used to validate the model (rainfall, temperature, wind speed, humidity, radiation and evaporation) were obtained from the automatic weather stations that are located almost in the centre of Romwe and Mutangi catchments (Chapter 5). Daily streamflow values for the red subcatchment and Mutangi are available for the period 1995 to 1999 (Butterworth, 1997; Lovell *et al.*, 1998) and 1999 to 2001 inclusive respectively and these were used to validate the ACRU model. Soil moisture data is available for the red subcatchment at Romwe for the period 1995 to 1999 (Butterworth, 1997; Lovell *et al.*, 1998) while daily reservoir changes are available from 1998 to 2001 at Mutangi and these were also used to validate the ACRU model.

Historical rainfall and temperature data for Chivi and Masvingo were obtained from the Meteorological department. Altitudinal temperature corrections for Mutangi and Romwe were made following the recommendations by Schulze and Maharaj (1994) (Equation 8.3a and 8.3b). Figure 8.2 shows the relationship between actual and corrected temperature data for Romwe during the period 1994 to 2000. Potential evapotranspiration (ETo) was calculated using the Hargreaves and Samani (1985) equation (Equation 8.4).

$$T_{mxc} = T_{mx} + L_{mx}\,(z_{mc} - z_{mt})/1000 \qquad \text{Equation 8.3a}$$

$$T_{mnc} = T_{mn} + L_{mn}\,(z_{mn} - z_{mt})/1000 \qquad \text{Equation 8.3b}$$

where:

T_{mxc}, T_{mnc} are monthly mean estimates of daily maximum and minimum temperatures (^oC) for the mean altitude of the catchment, T_{mx}, T_{mn} are the monthly mean estimates for the daily maximum and minimum temperature (^oC) for the nearby control temperature station, z_{mt} is the altitude (m) of the control temperature station, z_{mc} is the mean altitude (m) of the catchment for which temperature is to be estimated from the control station and L_{mx}, L_{mn} is the regional dry adiabatic lapse rate for the maximum and minimum temperature.

$$ETo = 0.0023\,(T_{max} - T_{min})^{0.5}\,(T_{mean} + 17.8)Ra \qquad \text{Equation 8.4}$$

where T_{max}, T_{min}, T_{mean} and Ra are maximum temperature, minimum temperature, mean temperature and radiation, respectively.

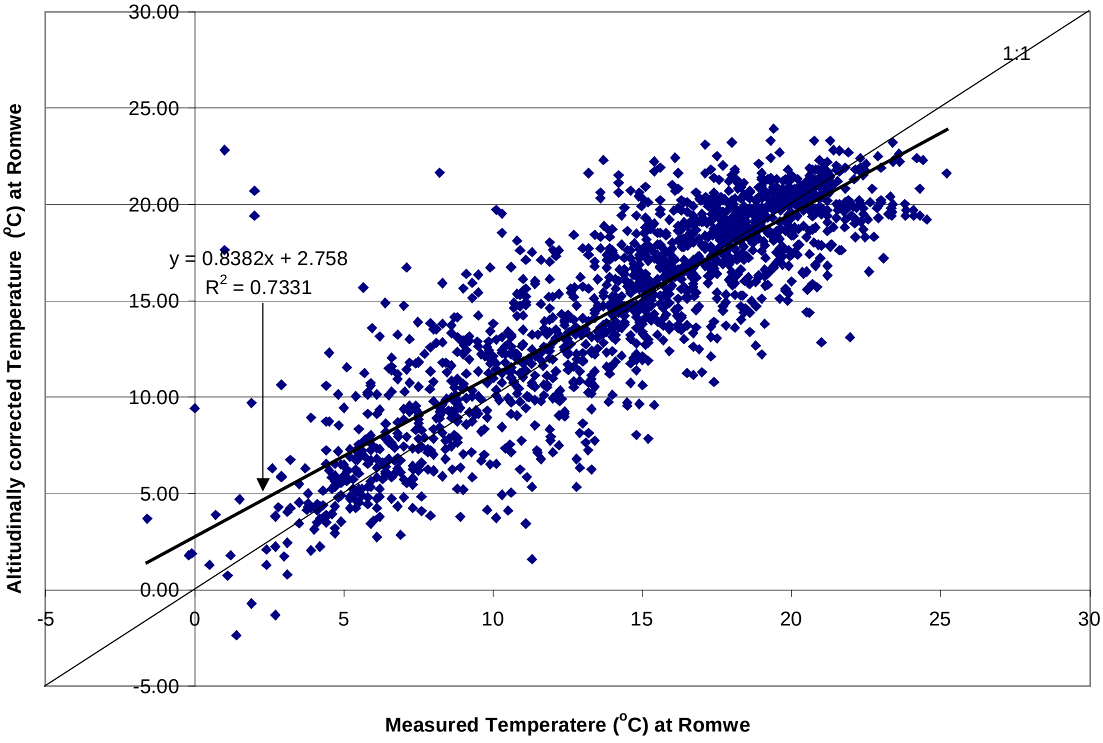


Figure 8.2: Comparison of actual temperature at Romwe and altitudinally corrected temperature using data from Masvingo during the period 1994 to 2000.

8.5.3 Scenario building

The ACRU model was used to model the impacts of different land use and management practices on streamflow and surface water resources. The period of record that was used was 1972 to 1998, which includes dry and wet periods and shows a slightly negative rainfall trend (Figure 8.3).

Effect of in-field water harvesting techniques

Cultural practices have been adopted that harvest water, thereby reducing runoff and extending the period of water availability to the crop. These cultural practices include in-field (tied-ridges, contour ridges, no till tied ridges, mulch ripping) and in-contour water harvesting techniques (infiltration pits, *fanya juus*[2])

[2] Is like a contour ridge, but the soil is thrown upslope rather than down slope to capture runoff generated from the field.

Water harvesting techniques were modelled by increasing the coefficient of initial abstraction by 0.05 as recommended by Butterworth, (1997). The coefficient of initial abstraction is a coefficient given month by month that is used to estimate abstraction by surface storage and infiltration before stormflow commences.

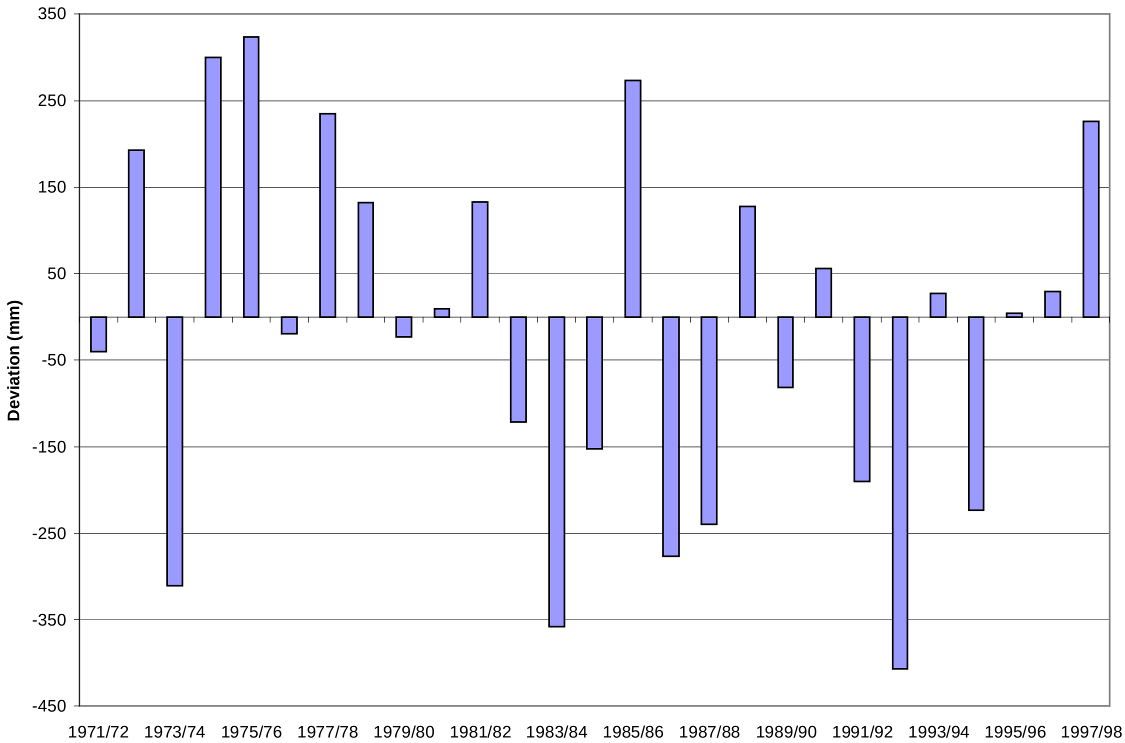


Figure 8.3: Deviation from mean annual rainfall for Chivi office.

Effect of deforestation

Effect of deforestation was mimicked by replacing all the remnant trees in the catchment by veld in poor condition (land cover 2030102 in ACRU) to represent land that is badly degraded as a result of deforestation and overgrazing. The dynamic land use file option was used to simulate harvesting and regrowth since the simulation was for twenty-five years.

Effect of leaving half the land fallow

Fifty percent of the catchment is under cultivation where most of the crop grown is maize. Half of the cultivated fields was replaced with veld in poor conditions in order to mimic increased fallow conditions that are expected to occur due to shortages in draft power that have characterised the smallholder farming sector after the 1991/2 drought (Scoones *et al*., 1996) and lack of money to buy inputs (maize and fertilizers) that have become very expensive in recent years.

Effect of increased abstraction on surface water resources

It was established in Chapter 7 that abstraction of water from the dam could be increased up to 5 times without drying Mutangi dam before the next rains. It was also established that the date of last fill determines the water that would be available for use by farmers. However, these results are from two years of study when rainfall was above normal.

Groundwater and surface water resources are a buffer against unreliable rainfall in the semi-arid areas and normal use for gardening purposes is increased in such dry years. It is not known by how much to increase abstraction without depleting the resources before the next rains that refill the water source. Various levels of abstraction were explored using historical rainfall data to determine "by how much water abstraction could be safely increased without drying the dam in most years".

8.6 RESULTS

8.6.1 Validation

Model validation was achieved by comparing measured data from Romwe (runoff and soil moisture) and Mutangi (runoff and reservoir water changes) with the corresponding ACRU soil moisture, runoff and reservoir changes output. Four and two years of measured data were used at Romwe and Mutangi respectively.

Runoff

Runoff model validation is presented in figure 8.4 at Romwe and Mutangi. Though the model reproduced the monthly trends relatively well, there was some slight mismatch in some months.

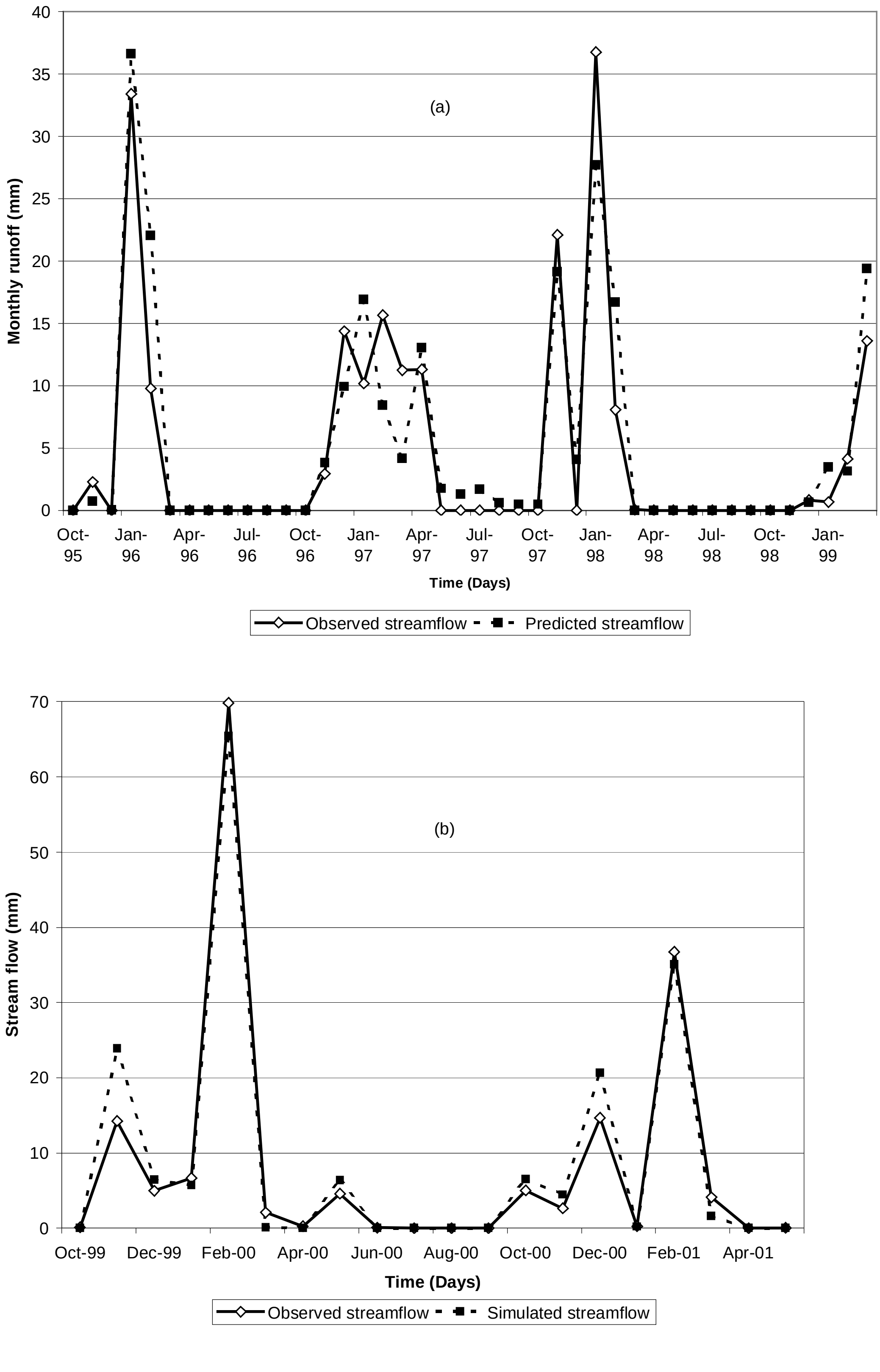


Figure 8.4: Monthly observed and predicted streamflow at (a) Romwe catchment (1995 to 1999) and (b) Mutangi catchment (1999 to 2001).

Table 8.3: Statistical comparison of monthly totals of simulated and observed streamflow at Romwe and Mutangi

Site	Sample size (n)	Coefficient of determination (R^2)	Correlation coefficient (r)	Regression significance F-prob	Slope estimate	Standard error of slope	t-statistic of slope	t-probability of slope	Intercept estimate	Standard error of intercept	t-statistic of intercept	t-probability of intercept
Romwe	24	0.778	0.888	<0.001	0.8599	0.0951	9.04	<0.001	1.93	1.25	1.54	n.s
Mutangi	15	0.964	0.983	<0.001	0.9510	0.0489	19.45	<0.001	1.24	1.04	1.20	ns

n.s not significant at 5% probability; F-prob = F-probability

Though the ACRU model slightly overestimated runoff by 9%, the statistics (Table 8.3) produced are good enough to allow the use of the model to simulate runoff on similar catchments. The R^2 values and correlation coefficient (r) for Romwe were 0.778 and 0.888 respectively while the corresponding values for Mutangi were 0.964 and 0.983. This indicates that the simulated and observed data were well correlated at both Romwe and Mutangi. The linear relationships of simulated and observed streamflow were significant (Fprobability < 0.001). The slope of the regressions were found to be significantly different from zero (t-probability = 0) at both Romwe and Mutangi and close to 1. There were no significant differences in the fitted slopes from 1 at t-probability of 0.001.

Soil moisture

At Romwe the general pattern of the estimated A and B-horizon soil moisture was similar though the model underestimated B-horizon soil moisture especially between March and October of 1998 (Figure 8.5).

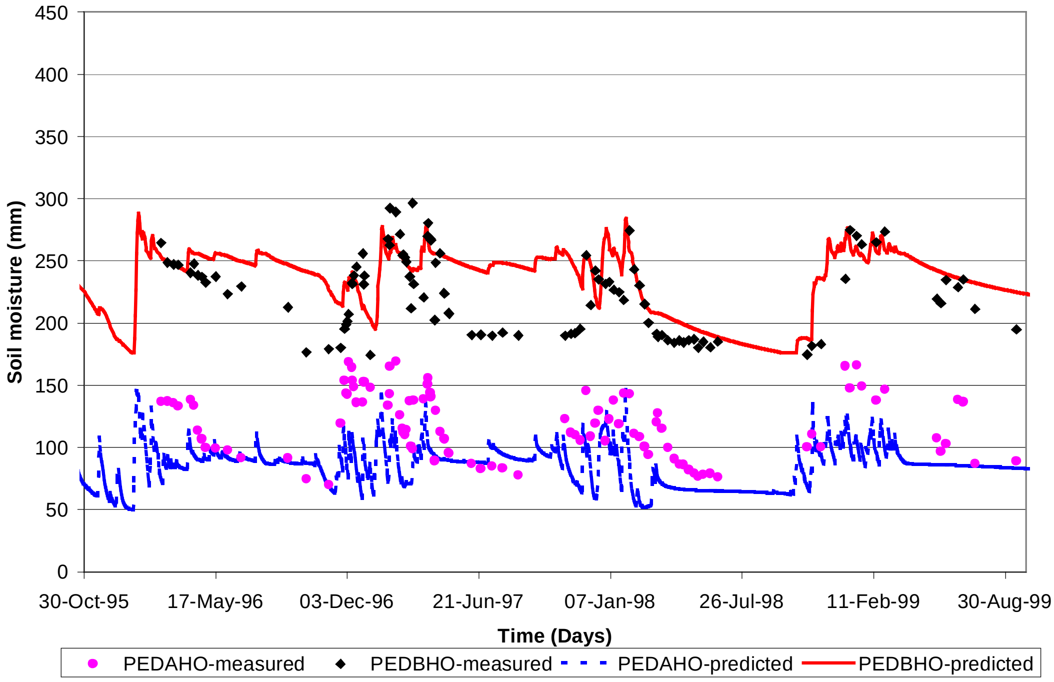


Figure 8.5: Measured and predicted soil moisture data for the A-horizon. (PEDAHO-thickness of A horizon) and B-horizon (PEDBHO – thickness of B horizon) during the study period at the red subcatchment at Romwe.

The soil moisture content for the A-horizon was better simulated than the B-horizon. Simulation was lumped at Mutangi and therefore soil moisture validation was not possible.

Changes in reservoir

Reservoir water changes at Mutangi are well replicated (figure 8.6). The model over predicted dam water at the later part of the dry season in the 2000/01 season. A similar pattern could not be established for the 1999/00 season because of missing recorded data.

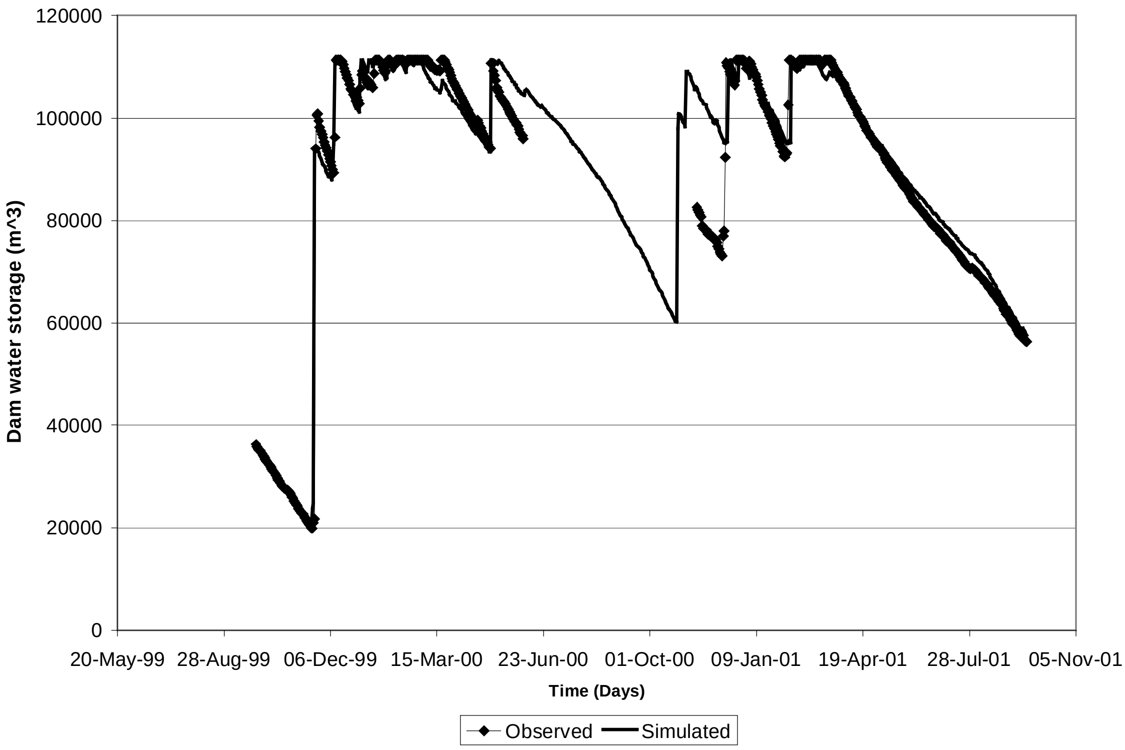


Figure 8.6: Measured versus predicted dam water level during the study period at Mutangi.

8.6.2 Effect of removing trees, planting trees and leaving all the cropped land fallow on catchment runoff.

The present land use, leaving all the cultivated fields fallow and removing all the remnant woodland (30%) along the drainage lines and in the western part of the Romwe catchment had almost the same effect on catchment runoff (Table 8.4). Planting trees in the rest of the catchment resulted in a significant (P<0.01) decrease of 50% in annual catchment runoff. This resulted in the dam not filling in all but 5 years because of reduced runoff (Figure 8.7). The dam was at full capacity for less than three months during the wet season in the five years it filled up. Replacing remnant woodland on the valley floor (30% of the catchment area) with ACRU ‘grass in poor condition’ had relatively little impact on surface water hydrology.

Table 8.4: Effect of leaving all the field fallow, defforestion, afforestation and present land use on catchment runoff at Romwe.

Treatment	Runoff (mm)
Present land use	172.8 [a]
Defforestation	177.3 [a]
Leaving all land fallow	167.4[a]
Afforestation	84.3[b]
F probability	<0.01
LSD	46.21

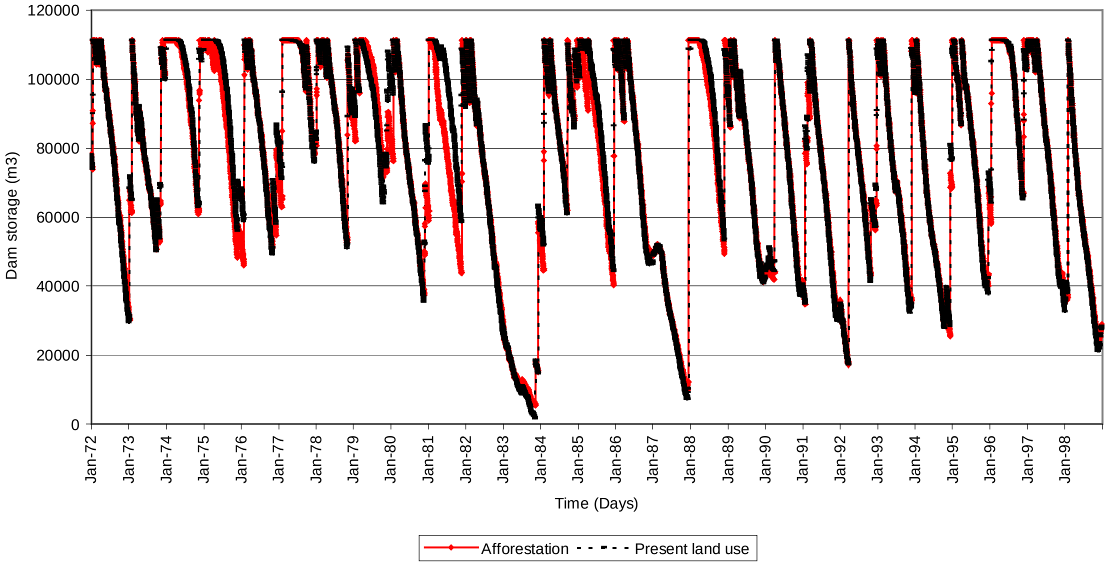


Figure 8.7: Effect of planting the whole catchment with trees on dam water storage at Mutangi.

8.6.3 Effect of in-field water harvesting techniques

The simulation shows that over the 25 years, the use of in-field water harvesting through tied ridges increases the average annual drainage by only 6% but significantly (P < 0.001) decreases runoff from the micro-catchment by 19% (Table 8.5). The highest decrease of 28% resulting from in-field water harvesting techniques was recorded in 1988.

Table 8.5: Effect of construction of tied ridges on runoff generation at Mutangi.

Mean (No Tied Ridges)	21.32 (mm)
Mean (Tied Ridges)	16.99 (mm)
Standard Deviation	27.74
Degrees of Freedom	25
t- value	7.59
t- probability	0.001

Even with in-field water harvesting techniques, the dam never dried at all during the analysis period. There were 10 years when dam water level dropped to below 20% of dam water level and six years when the dam dropped to below 10% (dead level storage) of the dam water level. These periods coincided with years of below average rainfall.

8.6.4 Effect of increased abstraction on surface water resources.

Figure 8.8 shows the simulated effect of increasing water abstraction from the dam. The dam would have gone below the 10% storage level in 1984 and 1987 for all the six abstraction levels that ranged from double to ten times the current abstraction rates from the dam. Increasing abstraction levels twice and four times would have resulted in the dam falling below the 10% level for only two years while increasing the abstraction rate six times, eight times and ten times the current abstraction rate resulted in the dam falling below the 10% storage level for 3, 6 and 8 times respectively over the 27 year simulation period. Increasing abstraction rates by four, six and eight times the current abstraction rate would have dried up the dam in 1984 and 1987 while the dam would have dried up in 1972, 1984, 1987 and 1998 if the current abstraction rate was increased ten times.

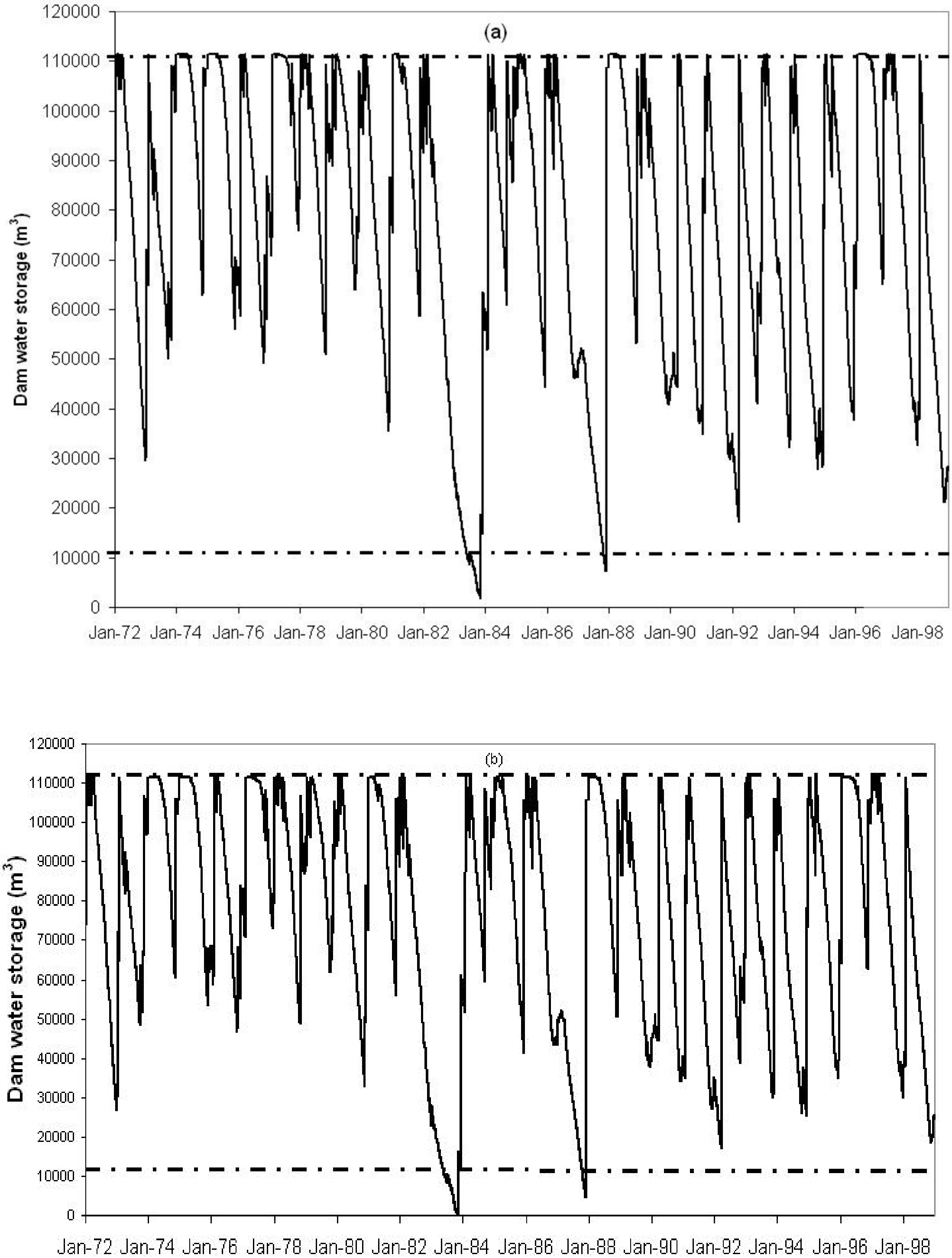
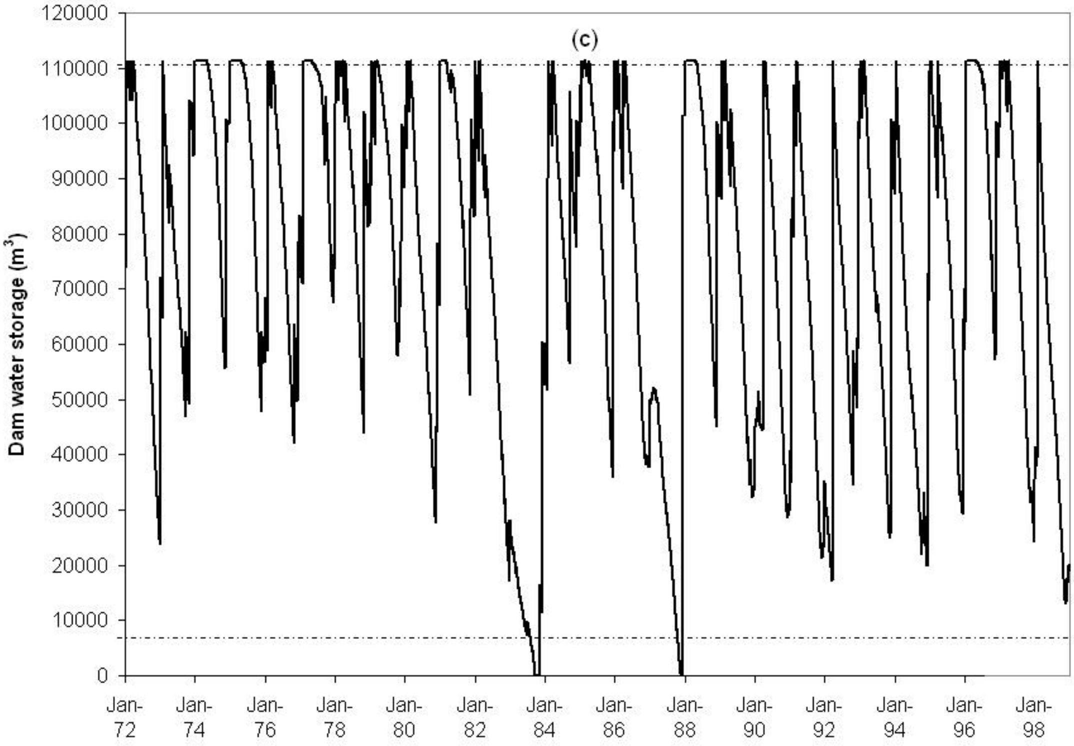


Figure 8.8a&b: Effect of (a) normal abstraction and (b) doubled abstraction on dam water storage.



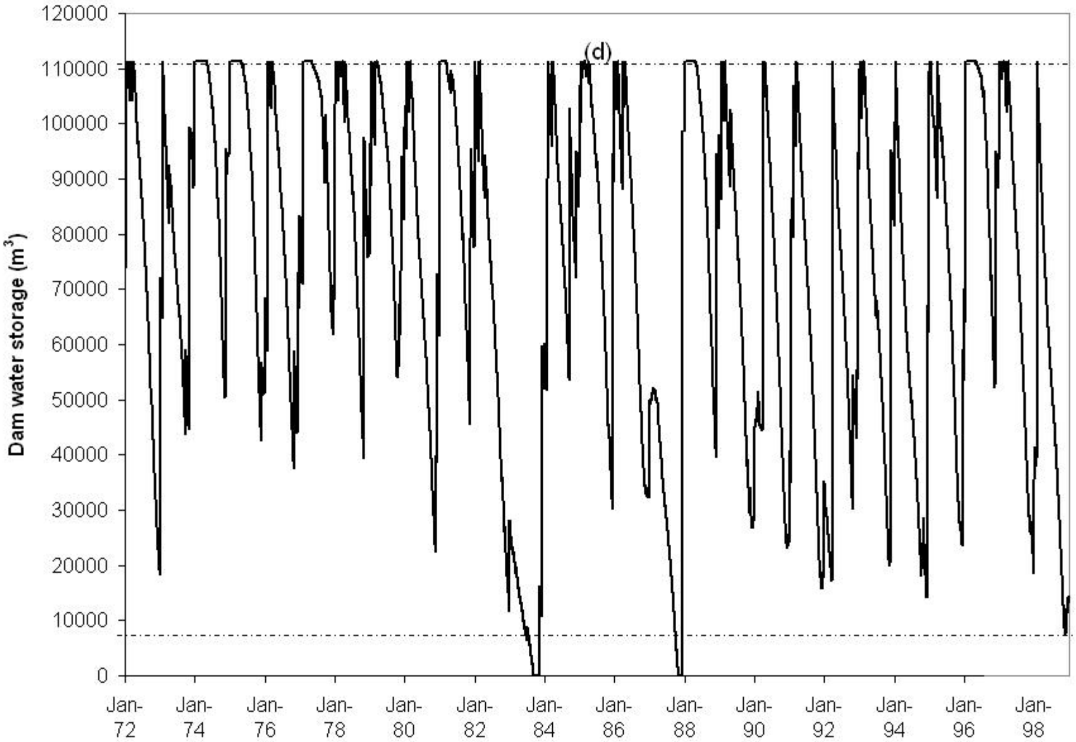
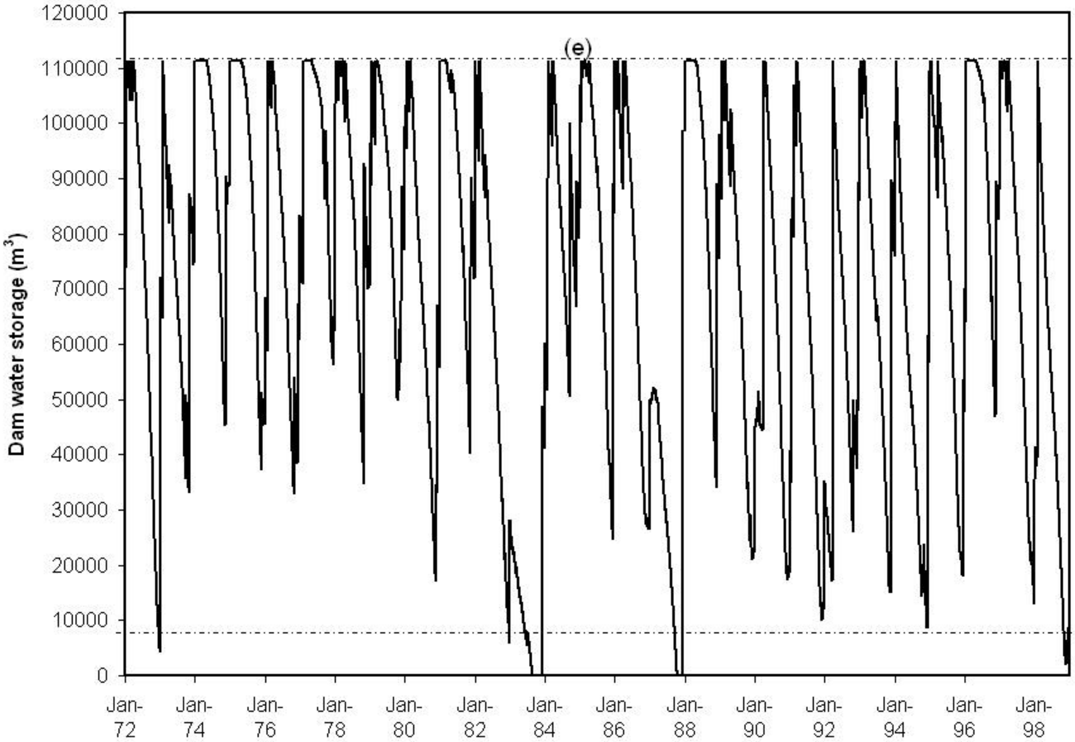


Figure 8.8c&d: Effect of increasing abstraction by (c) four times and (d) six times on dam water storage



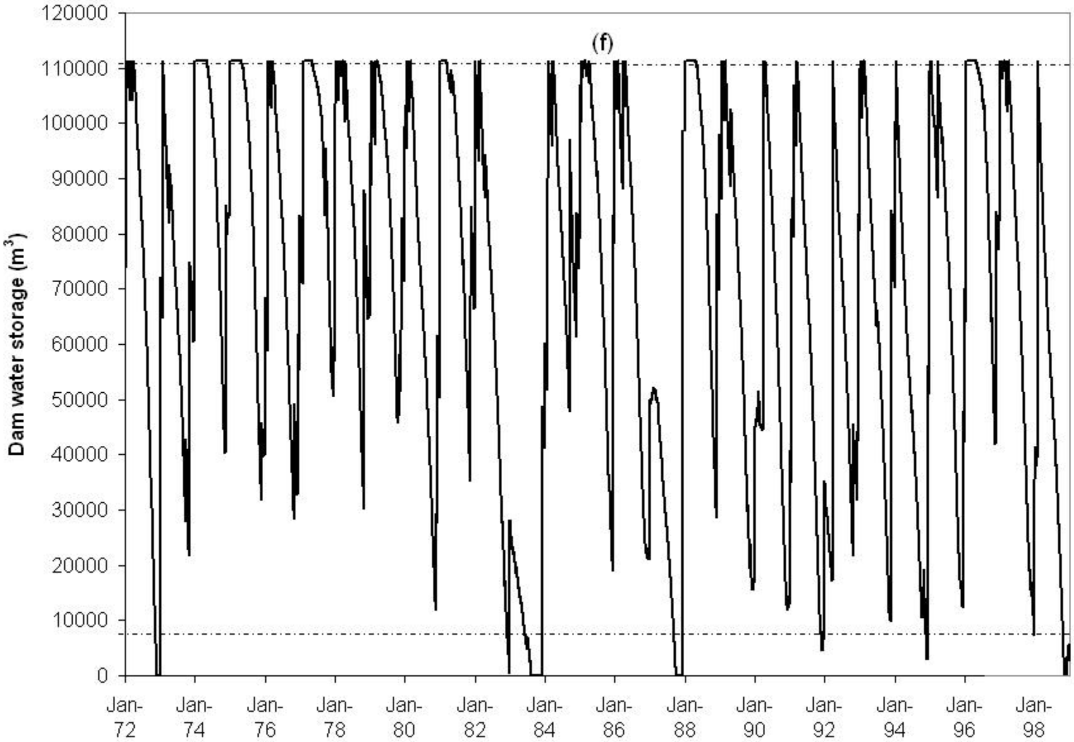


Figure 8.8e&f: Effect of increasing abstraction by (e) eight times and (f) ten times on dam water storage.

8.7 DISCUSSION

There are four soil types at Mutangi (Muzuva and Gotosa, 1999) and mixed land cover and this made Mutangi catchment difficult to model. The red subcatchment at Romwe was easy to model because of its small size and relatively uniform soil type and land use. However, most goodness of fit statistics are significant for both catchments with the red subcatchment showing better association between the simulated and the observed values.

Accumulated totals of simulated and observed streamflow follow very similar patterns at both sites except that the magnitude for the predicted was higher than the simulated during very wet periods. Similar overestimation of streamflow was also observed by Jewitt and Schulze (1999), Butterworth (1997) and New (2002). The model also slightly over-predicted stormflow during dry seasons at both Mutangi and Romwe especially in wetter years. A similar phenomenon was observed by New (2002) which he attributed to the inability of the model to simulate the wetting up of the catchments at the beginning of the wet season, which resulted in an over-prediction of runoff, and a tendency to underestimate winter baseflow. He also observed that such systematic errors were exacerbated under dry conditions, but were not as severe under wet conditions.

Inability of the model to simulate sufficient infiltration (including wetting of the B-horizon) on days (periods) of large rainfall events results in overestimation and wetting up of the catchment at the beginning of the wet season as was also observed by New (2002) and Butterworth (1997). Unlike this study, previous verification studies (Schulze, 1995; Butterworth, 1997) for other sites have shown that ACRU overestimates the B-horizon soil moisture because the model generally overestimates water movement into the B-horizon especially after large rainstorms or during wet periods. Butterworth (1997) noted that hourly time steps would improve ACRU simulations, but however this is hindered by lack of hourly rainfall data.

Based on the above simulation results, the ACRU model is appropriate for simulating streamflow in the semi-arid areas hence is a good decision support tool for water resources management in these areas. However the model was used on a daily time step where daily rainfall is distributed equally throughout the day and this brings about errors in the results because in reality rainfall is not distributed equally throughout the day. Availability of data is a major limitation in using the model in other catchments. Apart from rainfall data that can be readily available the model also requires temperature, humidity, wind speed, radiation data that are not readily available in most catchments.

Leaving the entire land fallow, which is expected if communal area farmers leave the farms for the new land, and cutting down the remnant woodland did not have an effect on both runoff and surface water resources. Lorup *et al*., (1998) observed no indication of any change in runoff from a catchment located within commercial land – which had not experienced any change in population density within the last 30 years, but observed a slight decrease in runoff in other four catchments characterised by 60 – 100% coverage with communal land with population growth ranging from 2.1 to 3.2%. However, planting of trees decreased runoff and surface water resources (Lorup *et al.,* 1988). This is in agreement with previous research that shows that forested catchments gave little runoff (Burch *et al*., 1987) but increased evapotranspiration.

Infield water harvesting using tied-ridges has little impact on dam water storage because the amount of water captured by the dam is a small fraction of the annual catchment runoff. This reduces the fear that infield water harvesting techniques would reduce the surface water resources that are so important during the dry season. Water harvesting techniques are also beneficial in that they reduce soil erosion (Elwell, 1996) thereby increasing the lifespan of dams. Also they could moderate runoff and increase baseflow during the dry season.

Modelling results show that there was enough runoff to fill up the dam to full capacity in most years except in the 1982/3 and 1986/7 seasons when only 15 and 16 mm of runoff were produced. The dam requires 18.8 mm to fill it up when it is empty.

All the scenarios resulted in the dam going below 10% in 1982/1983 and 1986/1987 even though they were wetter than the 1991/1992 season which had only 192 mm of rainfall. The 1991/1992 season received rainfall that might have been closely spaced which favoured runoff generation compared to the 1982/1983 and 1986/1987 seasons that had rainfall events that were probably more evenly spaced.

The long term simulation shows that there is a 7%, 7%, 11%, 22% and 30%, chance of depleting the dam below the 10% (dead level/safe yield) if abstraction rates are increased 2, 4, 6, 8 and 10 times respectively. Increasing abstractions corresponds to increased area under irrigation from the current 0.4 ha garden, and increasing abstractions by 2, 4, 6, 8 and 10 times corresponds to areas of 0.8, 1.6, 2.4, 3.2 and 4 ha respectively. This analysis shows that the current productive water use can be increased up to 10 times without drying the dam below the 10% dead level in at least 22% of the years. However, just like the conclusions that were given in the previous chapter, there is need to monitor the water resource in the dam so that water use can be (flexibly) increased or reduced depending on the quantity of the resource in a given year. Such an approach was successfully implemented in the Romwe catchment during the 1991/2 season when they reduced their garden to half the area because of shortages of water from the well (Lovell, 1998).

8.8 CONCLUSIONS

The simulation study shows that both runoff and surface water resources reflect the cyclic nature of rainfall where dam water levels were very low in the driest years like 1993/84, 1987/88 and 1991/92. In-field water harvesting techniques have significant effects on runoff generation but did not have significant effects on dam water levels even though there was a 19% decrease in runoff due to the presence of in-field water harvesting techniques. More runoff was generated to fill up the dam even where water harvesting techniques are in place. Deforestation and leaving all the land fallow did not have significant effect on runoff compared to the present land use while afforestation could have resulted in significantly lower runoff. Increasing dam water use ten times could have resulted in the dam drying up thirty percent of the years that would have coincided with the driest years.

9. OVERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

9.1 GENERAL DISCUSSION

Measurements made at the two catchments do not support the hypothesis that the rainfall and runoff yield of Romwe and Mutangi are not significantly ($P < 0.05$) different. Romwe received almost double the rainfall that was received in Mutangi in the 1999/00 season. Mutangi received 140 mm less rainfall than Romwe in the following 2000/01 season. Dry areas have runoff conversion coefficients that are below 15% while wet areas have runoff conversion coefficients of between 15 and 50% (Bosch and Hewlett, 1982). Mutangi behaved as a semi-arid area in both years when the runoff conversion coefficients were 13.5% and 10% in the 1999/00 and 2000/01 seasons respectively. Romwe behaved like a wet area in the 1999/00 season and a dry area in the 2000/01 season when the runoff conversion coefficients were 36% and 12%, respectively. Rainfall plays an important role in the hydrology of catchments. For sub-catchments of the Chiredzi river of area typically 40 – 50 km^2, figures quoted for average annual runoff range from 200 – 350 mm (Lovell *et al*., 1998). Runoff was only higher than that reported from larger catchments in the same physical setting at Romwe in the 1999/00 season but lower in the 2000/01 season at Romwe and Mutangi in both years. This study highlights that micro-catchments found in the same bigger catchment behave differently and therefore results from one micro-catchment cannot be extrapolated to other catchments hence the need for small scale studies to quantify water resources potential and identify appropriate agricultural development strategies in the driest and most degraded catchments that typify Communal and Resettlement Areas (Lovell *et al*., 1998).

Hortonian Overland Flow (HOF) is believed to be the major runoff generating process in the semi-arid areas (Sandstrom, 1997). There is evidence from the study that Saturated Overland Flow (SOF) was the major runoff generating process in the Mutangi catchment. The area contributing to SOF increased as the season progressed from bottom to the top of the slope on the catena hence the hypothesis that runoff is uniformly generated in the catchment is disapproved. This is due to the nature of the soils and rainfall distribution. The soils' available water capacity significantly ($P<0.05$) decreased from the top to the bottom of the catena. Rainfall was closely spaced during the middle of the season from mid

February to the beginning of March and the soils were saturated during this period such that most of the rainfall that was received was lost as runoff. A similar phenomenon of variable SOF was observed by Dunne (1978) in a wetter environment. The amount of runoff generated in this semi-arid environment is highly dependent on the size and distribution of rainfall events. Intense events may cause Hortonian overland flow, but sufficient rainfall in smaller, more closely spaced events may lead to the generation of significant amounts of runoff (>50% of rainfall) through saturated overland flow.

Water is one of the most valuable resources in the semi-arid areas hence the need for a 'water resource audit' (KAWAD, 2001) if sustainable water resources management is to be achieved. Measurement of the dam water balance in Mutangi supports the hypothesis that runoff water captured by small dams is less than half the total annual runoff. At Mutangi 23.2 and 30% of the 1999/00 and 2000/01 annual runoff was captured by the dam, respectively, while the remainder ran off the dam over the spillway.

9.2 CONCLUSION

The study showed that both runoff and dam water levels in the Runde catchment respond to the temporal variability of rainfall. However, 5 out of 13 of the runoff gauging stations displayed significant relationships between rainfall and runoff and the lack of significant relationships in some of the gauging stations is due to such factors as rainfall distribution, soil type, topography, land use which were not accounted for in this study. Hydrolological comparison of two micro-catchments (Romwe and Mutangi) that are 80 km apart and in the Runde catchment shows that both rainfall and runoff varied temporally and spatially in the two years.

Small dams are generally very shallow and rates of water loss in the late wet season/early dry season are very high, because the evaporation rate is high and the open water surface area is at its maximum. Under current gardening practices, there is almost no productive use of water from the dam in this period. Overall, productive water use from the dam over the period between the last filling at the end of one wet season and the first run-in at the start of the next is only 2%. The remainder is lost by evaporation. It was also established that using existing practices, where the use of dam water for gardening only begins in June, water use could be increased by a factor of 5 in most years. This would allow a 2 ha garden to be irrigated compared to the current 0.4 ha. However, the amount of water available for productive water use depends on how much the dam filled, and in particular, when it was at its maximum, as this determines the start of the period of almost uninterrupted water loss.

However, communities depending on surface water resources should monitor their resources in order to effectively manage them. The resources available can be monitored readily using a staff gauge and a volume/depth curve. Typical monthly open water evaporation rates have been established, and these can be used (with a depth area curve for the dam) to determine safe rates of water use. This will enable the community to make informed decisions such as the percentage of the garden that may be irrigated safely, which crops to grow, and when to stop using the dam water as it approaches the reserve level.

Long term simulation study using historical rainfall data showed that in-field water harvesting techniques have significant ($P < 0.05$) effects on runoff generation and dam water storage changes. Though the construction of tied ridges resulted in a significant decrease in runoff, it had no effect on dam water levels because the runoff that was generated annually was more than the amount of runoff required to fill up the dam – and the dam has water when the first runoff is received anyway.

Deforestation and leaving all the land fallow did not have significant effects on runoff compared to the present land use while afforestation could have resulted in significantly lower runoff. These results highlight that cutting trees (as will be expected in the newly resettled areas) and leaving land fallow (as will be expected where communities will move out of communal lands to resettled land) will not have an effect on surface water resources.

9.3 RECOMMENDATIONS

There were limitations of the data collected especially for identifying where most of the runoff comes from in the catchment. Hydrochemical analysis for hydrograph separation could provide a way of identifying recent water and old water in flow hydrographs (McCartney *et al*., 1998). This would enable the quantification of where the runoff is coming from (actual values from the different land uses and the different soil types).

Dams are threatened by siltation therefore shortening their life span. Such silted (more usually sand-filled) dams are abandoned, although they still fill up and store water. This is another area that needs further research. It is important to quantify the amount of water available and the losses in silted dams and how they can be productively utilised.

There is a need to understand and quantify better the shallow groundwater resources. This is a very important source of water during the pre-harvesting and harvesting period in semi-arid areas. The current water use from these sources needs to be estimated through survey of the number of shallow wells, the period during which they are used, the average number of beds irrigated per well, the irrigation frequency and the number of buckets applied.

The study addressed the technical issues regarding the effect of spatial and temporal variability on surface water resources and the best ways of using such water resources. The study, however, failed to address the socio-economic issues regarding how the communities would respond to the recommended controls on their water use. This is a gap that needs further research in order to come up with acceptable/user-friendly recommendations.

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APPENDIX A

Neutron probe calibration

Five sets of access tubes were installed at the grazing field and sandy site for neutron probe calibration. Two, 64 seconds counts were taken at depth 10, 30, 40 and 60cm relative to the soil surface in early February, early March, mid April, early May and early August 2001 which represented different stages of soil moisture levels at each site. Two cores at each depth were taken from immediately around the access tube, the cores being centred on the depth in question. The core samplers were pushed into the soil until they were flush with the surrounding surface. The cores were carefully removed from the profile and the ends trimmed flush. The soil was put in a sealed plastic bag and taken to the laboratory where they were weighed, dried at 105^{o}C for 48 hours and reweighed. This data was used to calculate the gravimetric soil moisture and then the bulk density that was used to calculate the volumetric soil moisture using equation A1.

$\theta_v = \theta_g BD$ equation A1

where θ_v is volumetric soil moisture, θ_g is gravimetric soil moisture and BD is bulk density.

Calibration equations of the form (equation A2) were developed to relate volumetric soil moisture (θ_v) and count ration (CR). Count ratio is the ratio between neutron count in the soil and neutron count in a large drum of water. Table A1 shows the calibration equations developed for the two main soil types that were used in the study. Figure A1 shows the relationships between neutron count ratio and volumetric soil moisture.

$\theta_v = a\mathrm{CR} + b$ equation A2

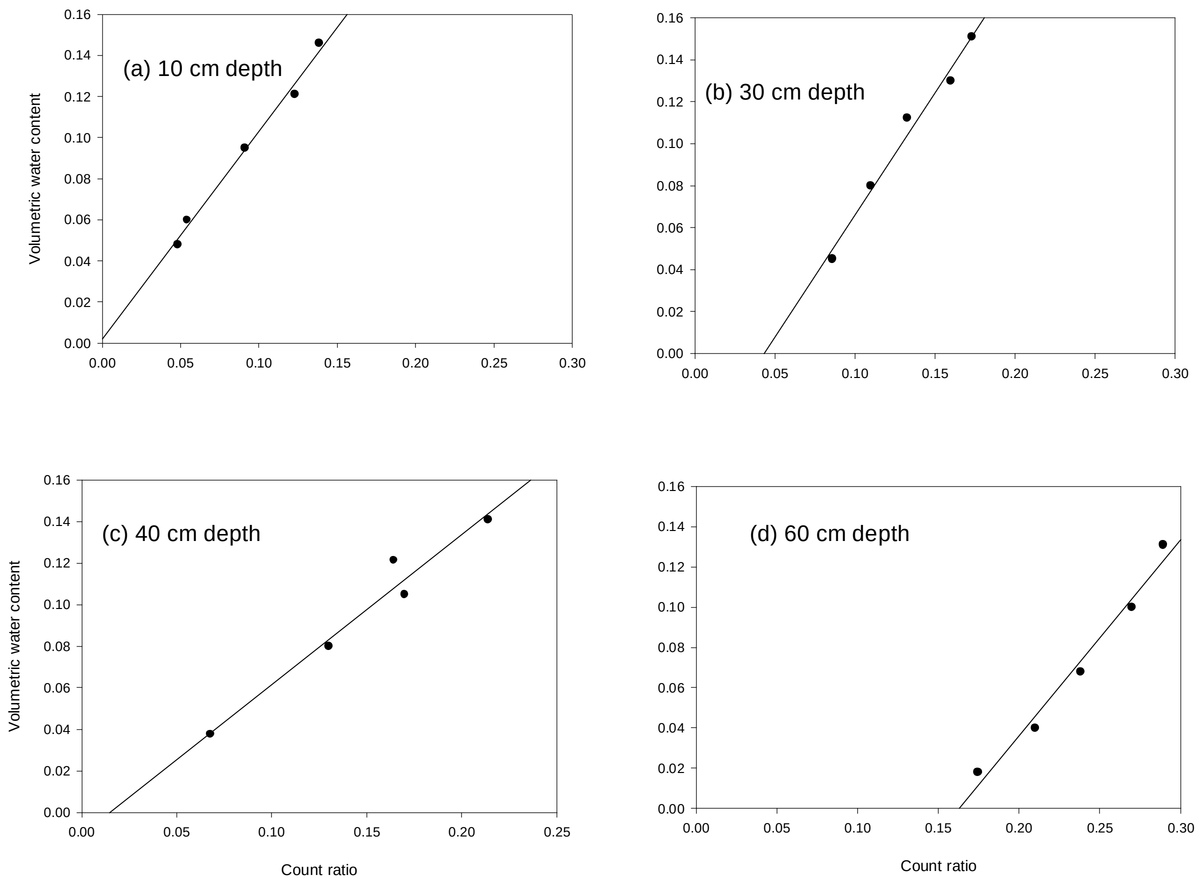

Figure A1: Neutron probe calibration data for 45 mm external diameter access tube for the sodic soils at Mutangi.

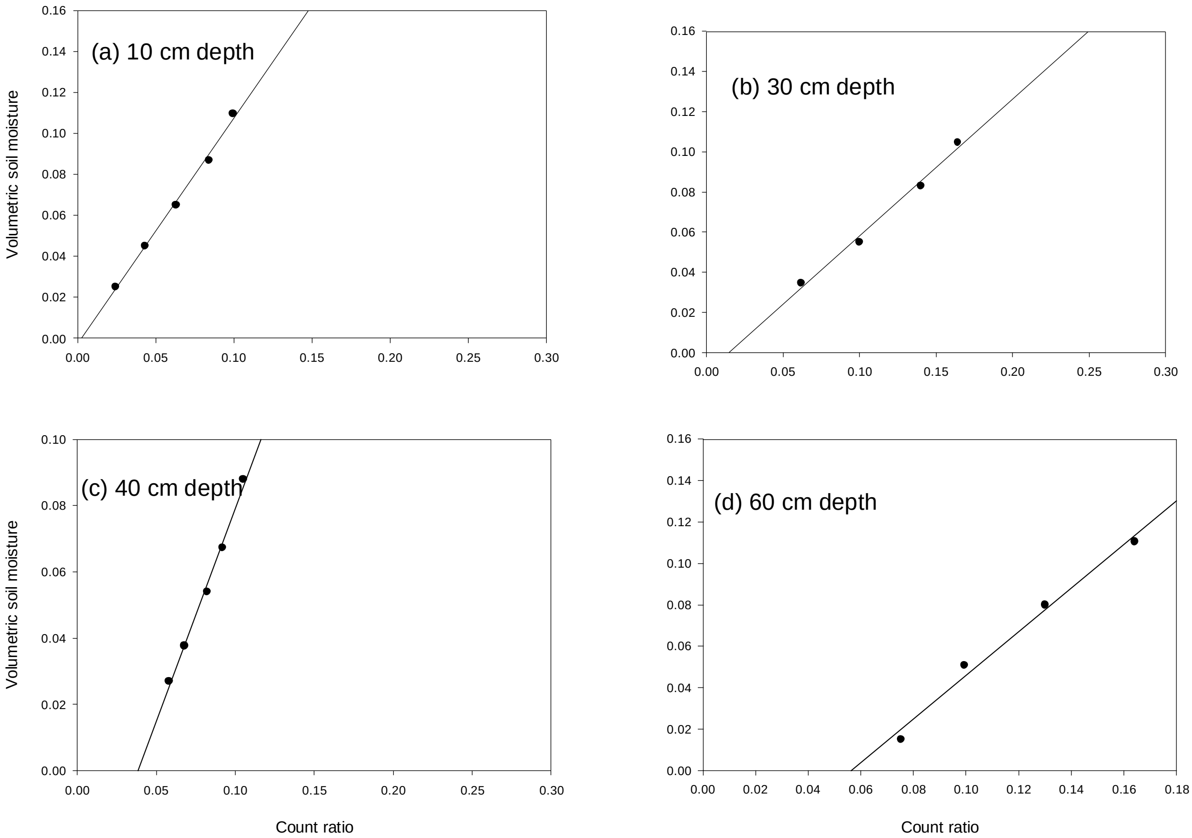

Figure A1: Neutron probe calibration data for 45 mm external diameter access tube for the sandy soils at Mutangi.

Table A1: Calibration coefficients for 45 mm external diameter neutron probe access tubes, using IH II neutron probe for the sandy and sodic soils.

The number of data points used n, and r^2 are also given.

Soil type	Depth (cm)	Equation form	*a*	*b*	n	r^2
Sodic	10	$\theta = a\text{CR} + b$	1.042	-0.002	5	0.995
Sodic	30	$\theta = a\text{CR} + b$	1.136	-0.044	5	0.966
Sodic	40	$\theta = a\text{CR} + b$	0.709	-0.005	5	0.936
Sodic	60	$\theta = a\text{CR} + b$	1.083	-0.186	5	0.911
Sandy	10	$\theta = a\text{CR} + b$	1.107	-0.0002	5	0.991
Sandy	30	$\theta = a\text{CR} + b$	0.734	-0.011	5	0.989
Sandy	40	$\theta = a\text{CR} + b$	1.340	-0.052	5	0.972
Sandy	60	$\theta = a\text{CR} + b$	1.022	-0.543	5	0.977

APPENDIX B

Soil Profile description and analysis of the red soils, grey soils at Romwe catchment, sandy soil, and sodic soil at Mutangi catchment.

Romwe red soil

Profile description

0-10 cm	Yellowish red 5YR 4/6 (dry), dark reddish brown 2.5YR 3/4 (moist) medium sandy clay; few, very small, sub-angular stones, medium sub-angular blocky structure with strongly developed micro-structure; moderately firm; no fissures, slightly-sticky, very-plastic; no roots; clear transition.
10-156 cm	Red 2.5YR 4/6 (dry), dark red 2.5YR 3/6 (moist) coarse sandy clay; common very small, sub-angular stones, medium sub-angular blocky structure with strongly developed micro-structure; moderately firm; no fissures, moderately-sticky, very-plastic; no roots; gradual transition.
156-185 cm	Red 2.5YR 4/8 (dry), dark red 2.5YR 3/6 (moist) coarse sandy clay; few very small, sub-angular stones, well developed coarse sub-angular blocky structure with strongly developed micro-structure; moderately firm; no fissures, moderately-sticky, very-plastic; no roots; gradual transition
185 cm -	Red 2.5YR 4/8 (dry), dark red 2.5YR 3/6 (moist) coarse sandy clay; abundant large sub-angular stones.

Chemical analysis

	Horizon and depth (cm)			
	1 0 - 10	2 10 - 156	3 156 - 185	
Clay (%)	24	41	36	
Silt (%)	4	7	11	
Fine sand (%)	26	14	22	
Medium sand (%)	29	20	16	
Course sand (%)	17	18	15	
PH (CaCl2)	4.6	5.1	5.4	
Ex Ca (me %)	3.0	3.7	3.0	
Ex Mg (me %)	1.1	2.0	2.3	
Ex Na (me %)	0.05	0.006	0.05	
Ex K (me %)	0.45	0.06	0.05	
TEB (me %)	4.6	5.9	5.3	
CEC (me %)	5.9	6.7	6.1	
Base saturation (%)	79	87	88	
E/C	23.9	16.5	16.9	
S/C	18.7	14.4	14.8	
ESP	0.9	0.8	0.8	
EKP	7.7	0.8	0.8	

Romwe grey soil

Profile description

0-17 cm Dark brown/brown 7.5YR 4/3 (dry), dark brown 7.5YR 3/3 (moist) medium sandy loam; stoneless, weakly developed coarse sub-angular blocky structure; moderately weak, brittle; no fissures, non-sticky, non-plastic; few fine fibrous roots; abrupt, smooth transition.

17-37 cm Greyish brown 10YR 5/2 (dry), very dark grey 10YR 3/1 (moist) with few, fine, sharp mottles, medium sandy loam; stoneless, weakly developed coarse angular blocky structure; moderately weak, brittle; no fissures, non-sticky, non-plastic; few fine fibrous roots; clear, wavy transition.

37-53 cm Grey 10YR 5/1 (dry), very dark greyish brown 10YR 3/2 (moist) with common, fine, sharp mottles, medium sandy loam; stoneless, weakly developed coarse angular blocky structure; moderately weak, brittle; no fissures, non-sticky, non-plastic; few fine fibrous roots; abrupt, irregular transition.

53 cm - Dark grey 10YR 4/1 (dry), very dark grey 10YR 3/1 (moist) with common, medium, clear mottles, medium sandy clay; stoneless, weakly developed coarse angular blocky structure; moderately weak, brittle; no fissures, non-sticky, non-plastic; few fine fibrous roots.

Chemical analysis

	Horizon and depth (cm)			
	1 0 - 17	2 17 - 37	3 37 - 53	4 53 -
Clay (%)	11	9	10	44
Silt (%)	12	13	11	7
Fine sand (%)	41	40	39	22
Medium sand (%)	27	30	30	16
Course sand (%)	9	8	10	11
PH (CaCl2)	4.2	4.3	4.8	6.1
Ex Ca (me %)	2.7	3.0	2.0	11.1
Ex Mg (me %)	1.0	1.2	0.9	7.0
Ex Na (me %)	0.07	0.08	0.008	0.15
Ex K (me %)	0.12	0.03	0.03	0.003
TEB (me %)	3.9	4.3	3.0	18.3
CEC (me %)	4.1	5.4	3.2	19.6
Base saturation (%)	95	80	93	93
E/C	37.1	56.9	32.5	44.8
S/C	35.2	45.5	30.2	41.8
ESP	1.8	1.6	2.4	0.8
EKP	3.0	0.5	0.8	0.1

Mutangi sandy soil

Profile description

0-16 cm Light brownish grey (10 YR 6/2 d) dark brown (10 YR 3/3 m) course grained sand; dry soft moist loose, non plastic, non sticky consistence; weak fine granular structure; good permeability; well drained; very numeraous very fine roots; few fine vescicular poors; gradual smooth transition to:

16 - 37 cm Grey (7.5YR 7/4 d) strong brown (7.5YR 5/8 m) coarse grained sand; dry slightly hard, moist very friable, non plastic, non sticky consistence; weak fine subangular blocky structure; good permeability; well drained; fairly numerous very fine roots; few subrounded coarse gravel (quartz &parent); common fine tubular pores; clear smooth transition to :

37 - 79 cm Grey (7.5YR 7/4 d) strong brown (7.5YR 4/6 m) coarse grained sand; dry slightly hard, moist very friable, non plastic, non sticky consistence; weak fine subangular blocky structure; good permeability; well drained; few very fine roots; occasional subrounded small stones (quartz &parent); abrupt wavy transition to:

79+ Soft weathering rock

Chemical analysis

	Horizon and depth (cm)			
	1 0 - 16	2 16 - 37	3 37 – 79	4
Clay (%)	0	2	1	
Silt (%)	3	3	4	
Fine sand (%)	21	15	16	
Medium sand (%)	36	31	29	
Course sand (%)	41	49	50	
PH (CaCl2)	5.0	4.4	4.7	
Ex Ca (me %)	0.6	0.6	0.7	
Ex Mg (me %)	2.0	1.9	2.2	
Ex Na (me %)	0.04	0.07	0.04	
Ex K (me %)	0.07	0.03	0.04	
TEB (me %)	2.1	2.6	2.0	
CEC (me %)	2.1	2.6	2.0	
Base saturation (%)	100	100	100	
E/C	-	-	-	
S/C	-	-	-	
ESP	1.8	2.5	1.8	
EKP	3.5	1.3	1.8	

Sodic soils at Mutangi

Profile description

0 - 12 cm Light brownish grey (10YR 6/2 d) very dark greyish brown (10YR 3/2 m) coarse grained sandy loam; dry hard, moist firm, slightly plastic, slightly sticky consistence; strong coarse subangular blocky structure; good permeability; well drained; occasional medium roots; clear smooth transition to :

12 - 46 cm Light brownish grey (10YR 6/2 d) brown (10YR 5/3 m) coarse grained sandy clay loam; dry hard, moist firm, plastic, sticky consistence; moderate medium subangular blocky structure; slightly restricted permeability; well drained; very many coarse CaCO3 concretions; strong effervesence; occasional medium roots; gradual smooth transition to :

46 - 70 cm Dark greyish brown (2.5Y 4/2 m) coarse grained sandy clay loam; moist friable, plastic, sticky consistence; massive structure; slightly restricted permeability; well drained; common medium CaCO3 concretions; strong effervesence; occasional medium roots; diffuse transition to :

70-100 cm Light yellowish brown (2.5Y 6/4 m) coarse grained sandy clay loam; moist friable, plastic, sticky consistence; massive structure; moderately restricted permeability; well drained; few fine CaCO3 filaments; strong effervesence; occasional medium roots;

Chemical analysis

	Horizon and depth (cm)			
	1 0 - 12	2 12 - 46	3 46 - 70	4 70 - 100
Clay (%)	13	21	25	25
Silt (%)	6	6	5	8
Fine sand (%)	32	21	21	21
Medium sand (%)	22	29	26	25
Course sand (%)	26	24	23	22
PH (CaCl2)	7.6	8.5	9.0	9.0
Ex Ca (me %)	0.4	24.0	11.3	8.2
Ex Mg (me %)	4.3	6.5	5.6	5.8
Ex Na (me %)	4.9	21.03	18.36	17.65
Ex K (me %)	12.02	0.25	0.31	0.29
TEB (me %)	0.16	14.2	16.7	17.9
CEC (me %)	13.3	14.2	16.7	17.9
Base saturation (%)	100	100	100	100
E/C	-	68.6	67.1	72.1
S/C	-	68.6	67.1	72.1
ESP	90.2	147.9	109.7	98.5
EKP	1.2	1.8	1.8	1.6

APPENDIX C

Published Papers

Mugabe, F.T., Hodnett, M. and Senzanje, A. 2003. Opportunities for increasing productive water use from a small dam: A case study from semi-arid Zimbabwe. *Agricultural Water Management*, 62(2): 149 - 163.

Mugabe, F.T., Hodnett, M. and Senzanje, A. (Accepted). Comparative hydrological behaviour of two small catchments in semi-arid Zimbabwe. *Journal of Arid Environments*

Mugabe, F.T and Senzanje, A. 2004. Challenges for managing water resources in semi-arid areas: A case study from two rural communities in Zimbabwe. In: Stephenson, D' Shemang, E.M. and Chaoka, T.R. Proceedings of International Conference on Water Resources of Arid and Semi Arid Regions of Africa (WRASRA) 3- 6th August 2004, Gaborone, Botswana.