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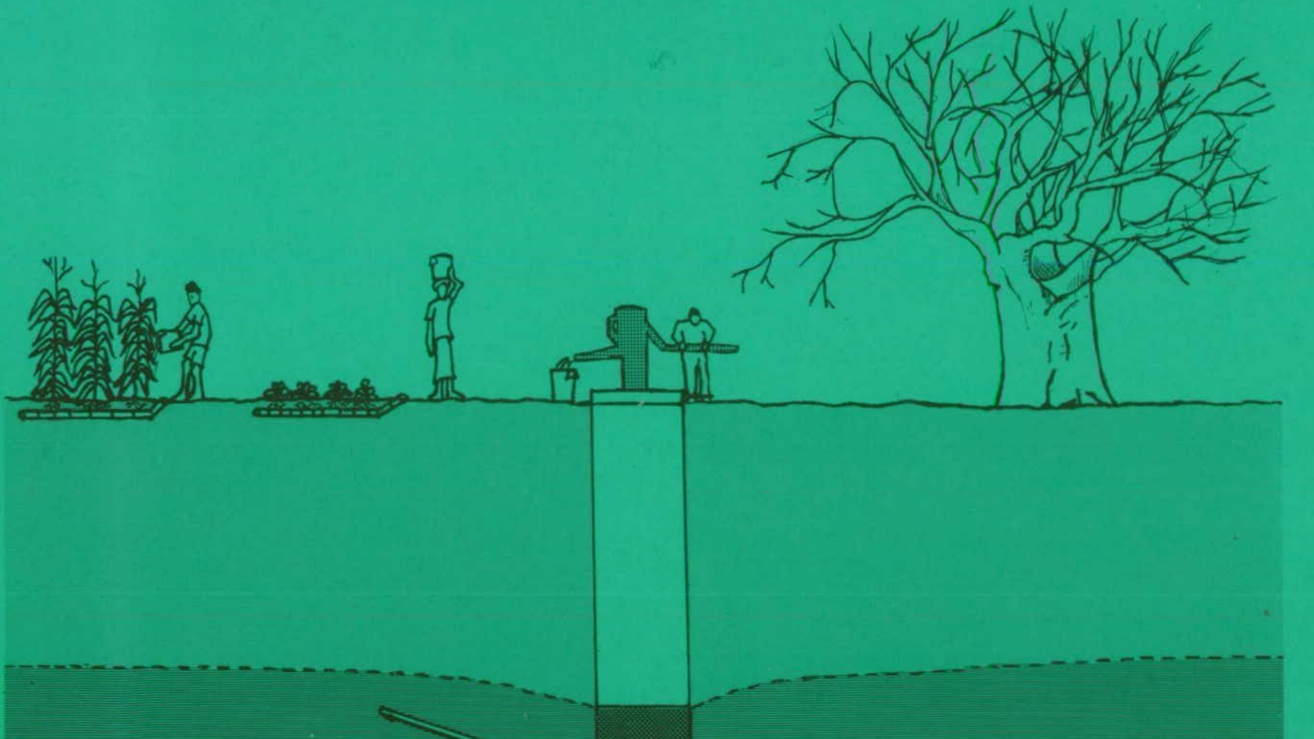

Institute of Hydrology **DFID**

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THE ROMWE CATCHMENT STUDY, ZIMBABWE

The effects of changing rainfall and land use on recharge to crystalline basement aquifers, and the implications for rural water supply and small-scale irrigation

FINAL REPORT

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In May 1997, the Department for International Development (DFID)
took over responsibilities formerly managed within the United Kingdom
Government structure by the Overseas Development Administration (ODA).
However, as the work presented in this report was effectively completed
before May 1997, the former departmental name of
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has not been altered in the text.

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EXECUTIVE SUMMARY

For many people in semi-arid regions of the world, the groundwater stored in crystalline basement rocks is the only source of water for long periods of the year. The provision of reliable and productive water points is essential. This is the final report of DFID TDR project R5846 which has investigated the process of groundwater recharge to basement aquifers in southern Africa.

To quantify available water resources and recharge under present rainfall and land use, a small catchment in a communally-managed dryland area of Zimbabwe was instrumented and monitored with the participation of the local community. The Romwe Catchment has an area of 4.2 km^2 and a population of 250 people. Hydrogeologically, it is representative of a large area underlain by younger undifferentiated gneisses and mean annual rainfall greater than 600 mm. Land use is typical of communal areas in the region, with rainfed crops cultivated on the valley floor and livestock grazed in miombo woodland on the rocky slopes and hills. Soils are highly variable and include red clay soils, sandy grey duplex soils, and small areas of vertic soils. Typical of semi-arid areas, the catchment experiences high inter-annual variation in the amount and distribution of rainfall. These factors, combined with changes in vegetation cover, mean that catchment hydrology can be highly variable between years. This has been observed between 1992-97.

The project has studied the effects of changing rainfall and land use on catchment hydrology and groundwater, the factors that control the sustainable yield of wells and boreholes in basement aquifers, and the implications for rural water supply and development of small-scale irrigation. The policy implications to come from this study are numerous and wide ranging:

Groundwater management

Modelling techniques were used with long-term rainfall records and catchment hydrological data to evaluate the effects of climatic variation and land use change on the groundwater resource. Simulated groundwater levels since 1952 suggest that annual fluctuations are characteristic of basement aquifers, and that these fluctuations are superimposed on long-term trends which reflect cycles of above and below average rainfall. The modelling indicates the main cause of low groundwater levels in the early 1990s to be the extended period of low rainfall from 1981 rather than human impacts on catchment hydrology. The groundwater resource has fully recovered as a result of above average rainfall since 1993.

Catchment recharge rates of up to 300 mm per year have been measured, more than 12 times higher than previous regional or long-term estimates. Recharge is dependent on rainfall distribution within the year and is spatially highly variable. Surface concentration of rainfall is a key process affecting recharge, particularly in years of low or evenly distributed rainfall. However, natural groundwater recession or discharge (through abstraction by deep rooted vegetation, lateral flow and leakage into the fractured bedrock) is also a major process, accounting for up to 230 mm per year. The net gain in groundwater storage is always far less, and of the order 60-100 mm/year in two years of high recharge.

The practical consequence of natural groundwater recession is that recharge in a particular location may have little lasting benefit, and carry-over from year to year is limited by the natural recession. In these environments, groundwater should be managed to make full use of the resource, firstly by enhancing recharge to ensure some replenishment every year, and secondly, by making use of

the water while it is there. In particular, there is considerable potential to increase abstraction while water tables are high, using low-cost wells not necessarily designed to be perennial. The number of seasonal wells in Romwe, for example, could safely be increased tenfold or more and still have negligible impact on the natural recession of groundwater.

Present human abstraction for domestic use and small scale irrigation is trivial at less than 1 mm across Romwe catchment. Groundwater is an under-utilised resource. Furthermore, the belief amongst rural communities that abstraction should be limited to "save" groundwater is a fallacy. Natural recession will predominate irrespective of any local reduction in use. If the groundwater resource is not used while it is there, the opportunity will be lost.

The belief that groundwater should be "saved" comes from a misunderstanding of why wells and boreholes fail. Many fail towards the end of the dry season. This is due in part to natural recession catching up with the limited depth of some wells. It is also due to low aquifer permeability. This can cause steep cones of depression to develop in the water table around pumping wells and boreholes, which on its own, or combined with natural recession, can cause a serious decline in yield. When local people reduce abstraction to "save" groundwater they limit the cone of depression and maintain a low but consistent yield until natural recession causes well failure.

Well siting and design

In low permeability aquifers, well siting and design are critical to yield. Although implemented in 1991 at the time of maximum perceived groundwater stress, the Romwe collector well (sited by exploratory drilling to locate favourable aquifer properties and designed with lateral boreholes to overcome the permeability constraint) has successfully sustained an average yield of 1.6 Ml per year, similar to the sum of the abstraction (2 Ml per year) from all other 26 traditional dug wells in the catchment.

Of the two criteria, siting is of paramount importance. To avoid well failure through natural recession, siting must locate the maximum depth of saturated aquifer. To avoid well failure through localised dewatering, siting must locate reasonable permeability. Well design can help, but data available suggests that improvement in yield by drilling lateral boreholes decreases with decreasing permeability and is minimal if initial siting puts the well in an aquifer of transmissivity less than 1 m^2/day. The present findings reinforce the need for, and the value of, careful well siting. Exploratory drilling appears best to locate optimum well sites because neither water divining nor present geophysical methods have sufficient resolution in terrain of such high spatial variability. It will be important to assess the cost-effectiveness of exploratory drilling, and to quantify by how much the yield and reliability of simple dug wells can be improved using this new siting technique.

Rural water supply and drought mitigation

Groundwater provides a buffer against individual dry years. The massive failure of wells and boreholes in southern Africa in the early 1990s need not have come as a surprise. Long-term trends in groundwater levels are apparent and are shown to reflect cycles in rainfall. If groundwater levels and rainfall are monitored, groundwater drought can be predicted well in advance, allowing long-term drought mitigation programmes to be developed rather than "emergency" drought-relief projects with their associated problems.

Wells and boreholes successfully sited during periods of low groundwater are likely to withstand future periods of drought. However, many being constructed now during a period of generally high water levels will probably not be sustainable. Particularly worrying is the current trend towards traditional family wells rather than reliable, relatively high yielding communal water points.

With increasing population, and increasing reliance on groundwater for domestic use and production, the section of population at risk during low rainfall cycles is growing. Areas of highest groundwater potential are frequently under land already "owned" by individual families. It will become increasingly important in water resource development to ensure equity of access to these water resources. This can best be achieved by developing reliable, relatively high yielding communal water points in these locations. Although traditional family wells offer important advantages of simplicity, individual ownership and low cost, and undoubtedly add to general security and well being in times of plentiful rain, there is equal need to develop reliable communal schemes as a backstop for times of low rainfall and for families without land suited to a family well. Given the variable nature of crystalline basement aquifers and the cyclical pattern of rainfall, a policy to develop a mix of both individual family wells and more reliable communal water points with irrigation schemes is recommended.

The development of small scale irrigation using groundwater in dryland areas underlain by crystalline basement rocks has the potential to be of considerable benefit both to local people and to the local environment. The recent studies emphasise that rehabilitation of under-utilised water points offers the most cost-effective first option in many areas. Rehabilitation in this context is not the same as repair. Many existing water points are under-utilised because pump capacity is far less than potential safe yield. Pumping tests and modelling of groundwater recession are needed to determine the safe yield that can be sustained during drought. This appraisal should form an integral part of future rural water supply programmes, and can provide an immediate basis for increased water supply and development of small scale irrigation with respective communities.

The potential to develop new productive water points in these areas is linked to rainfall, parent rock mineralogy and surface morphology. These factors combine to determine the weathering profile and relative position of the water table, which in turn determine the most appropriate exploration and development strategy. A map of parent rock type and rainfall is a valid projection upon which various groundwater provinces can be plotted. Hydrogeological zones of different groundwater potential are presented for southern Zimbabwe in terms of the relative numbers of productive water points and appropriate development strategies anticipated.

Catchment management

At the catchment scale, runoff from dryland catchments is generally a small part of the water balance. In Romwe, runoff in 1994/95, 1995/96 and 1996/97 was only 0.5, 9 and 7 per cent of rainfall, respectively. In volume however this represented up to 100 times the total groundwater abstracted by the community for domestic use and irrigation. Although a small part of the water balance, runoff still represents a significant volume of water that could potentially be harvested.

The study highlights however that water harvesting to improve crop production is not the same as water harvesting to improve groundwater recharge. Surface management practices such as tied ridge and furrow, which harvest rain where it falls, are of benefit to rainfed crops but the same practices, by preventing surface redistribution and concentration of rainfall behind conservation structures, can prevent groundwater recharge through the soil matrix. In years of low or evenly distributed rainfall there will be a trade-off between the benefits to individual farmers of improved crop production through in-field water harvesting, and the benefits to the wider community of enhanced groundwater recharge through water harvesting at a larger scale. A "whole catchment" approach to water resource management is needed, and modelling the outcome of various management scenarios will be important to achieve the optimum balance.

Substantial structures are needed to produce a significant enhancement of groundwater recharge. Studies in Romwe of a recharge trench showed enhancement to be severely limited by the volume of water stored in the trench. With infrequent but high intensity storms, only numerous low-cost structures such as contour channels, or more substantial structures such as small dams, will store sufficient runoff to enhance recharge. An additional advantage of linking reliable groundwater supply to development of small dams is that local communities can readily see the need to protect the catchment in order to reduce dam siltation, and thereby also protect the groundwater.

Ironically, the contour channels that exist in most communal areas of Zimbabwe today were constructed in the 1950s to carry water away in a controlled manner and thereby reduce soil erosion. In most areas they have not been maintained and presently contribute little to either controlling soil erosion (now recognised to depend more on in-field management) or to conserving water. Adaptation of these contour channels so that they hold rather than transport significant quantities of water would be a cost-effective measure that would immediately enhance groundwater recharge, especially in areas of red clay soils.

Recharge through red clay soils will generally be 4-5 times greater than through grey duplex soils, and in Romwe catchment red clay soils are the principal source of recharge. Although preliminary, this finding suggests that areas of red clay soil overlying pyroxene gneiss should be the focus for development of wells, and should be managed to enhance recharge using modified contour channels (*Fanya juu*) rather than in-field water harvesting. In contrast, areas of grey-duplex soil contribute little to groundwater recharge but are the major source of runoff and interflow. This could be harvested in small dams and used to water livestock and perhaps irrigate pastures. In-field water harvesting would be more appropriate on the grey duplex soils, probably as a system of broad ridges and furrows across the contour which can provide flexibility in this periodically semi-arid, periodically waterlogged environment. In dry years, staple crops such as maize can be grown in the furrows and benefit from localised rainfall concentration. In wet years, when a perched water table forms on top of the impermeable subsoil, maize can be grown on the ridges and rice grown in the waterlogged furrows, the excess water from the furrows flowing to the small dams.

Future work

Many water supply and catchment management programmes in dryland areas are being implemented on the basis of scant and often inappropriate information. The Romwe Catchment Study is an example of the type of study needed to obtain the fundamental hydrological, agricultural and socio-economic information needed to ensure that these programmes do not end in disappointment. It is perhaps worth noting that the present study cost £300 000 and took four years to provide answers. This is a relatively small investment, given that tens of millions of pounds are being spent on water supply and catchment management programmes in Zimbabwe alone. It is recommended that small catchment studies in principal settings of interest should become an integral part of larger water supply and catchment management programmes in the future.

In Zimbabwe, small catchment studies are particularly needed to quantify water resource potential and identify appropriate agricultural development strategies in Communal and Resettlement Areas on basalt, granite and gneiss with mean annual rainfall less than 600 mm. Importantly, this work should also begin to assess if management strategies for micro-catchments such as Romwe can provide the building blocks for catchment management. The research should identify principles and organisational structures best suited for catchment management in these major physical and social settings, and test the institutional relations and bio-physical links between micro-catchments needed to scale up to management at sub-catchment and river-catchment scale. This information is needed to help develop the national Water Resources Management Strategy (WRMS).

As more information becomes available, important trade-offs between resource management options will become clearer. Emphasis should be placed on the development of practical decision support systems such as Bayesian belief networks which can integrate the available information and help policy makers, catchment planners and extension staff to make sound management decisions. The present catchment study also highlights that further detailed investigations of miombo woodland hydrology and natural groundwater recession are justified in order to better understand their importance to overall catchment hydrology and downstream water supplies.

Specific findings from the Romwe Catchment Study apply wherever communally-managed catchments are located in areas of younger undifferentiated gneisses with mean annual rainfall greater than 600 mm (Agricultural Rainfall Index greater than 40). In Zimbabwe, this zone covers an area of about 30,000 km^2 in the south-east of the country. The findings are also relevant to dambo management in wetter areas to the north, and the study has answered many of the questions posed in recent dambo reports concerning the effects of climatic variation and land use change on dambo resilience and appropriate water resource development strategies. For the people and environment of Romwe, and areas like it, the study will be a success if the local participation and infrastructure developed since 1991 can now be used to introduce and quantify the impact of some of the identified management options, and the Romwe research facility can become the first in a number of demonstration catchments for visiting extension staff and communities from similar environments elsewhere in the region.

1. BACKGROUND

1.1 The importance of crystalline basement aquifers

Crystalline basement aquifers underlie much of Africa. They provide a limited but extensive resource which has the potential for greater use. A review of the extent and availability of these groundwater resources in Zimbabwe and other countries of southern and eastern Africa can be found in Anon (1989). For many people in arid areas, they provide the only source of water for long periods of the year.

Basement aquifers are commonly classed as two layer systems, with a shallow weathered layer or regolith overlying fractured bedrock (Chilton and Foster, 1995). The fractured bedrock is exploited by boreholes, typically 50-80 m in depth and often cased in the weathered layer. Siting to intercept bedrock fractures in basement areas is notoriously difficult. Present geophysical methods do not have sufficient resolution in terrain of such high spatial variability, and success rates are low. In Zimbabwe, about half of all boreholes drilled are either dry or cannot support a handpump yield of 0.3 l/s (Wright, 1992). Water shortage remains the principal problem facing many communities and provision of reliable, productive water points remains a critical need.

The regolith is traditionally exploited by hand-dug wells, typically 1-1.2 m in diameter. The depth of these wells is constrained by depth of weathering, which in southern Zimbabwe is often up to 15 m. Weathering is dependent on many factors, including mineralogy of the parent rock, topography and rainfall, past and present. As a result, the regolith is highly variable both spatially and in weathering profile. This has implications for the productivity of wells, affecting depth of saturated aquifer, groundwater recharge and aquifer permeability.

Over the last decade, interest in the regolith aquifer has increased with the recognition that this may provide a more sustainable and less costly source of rural water supply than the underlying bedrock fractures previously targeted (Howard *et al*, 1994). A methodology for increased abstraction of water from the regolith has been developed. The horizontal boreholes of a Collector Well, drilled radially from the base of a large diameter well in several directions to a distance of up to 30 m, are designed to pass through the discontinuities and overcome the permeability constraint. Research has demonstrated the potential to obtain consistent supplies of water sufficient for domestic use and small-scale irrigation (Lovell et al, 1996).

1.2 Sustainability of the groundwater resource

Despite increasing interest, many basic questions relating to the development and sustainability of basement aquifers have only been answered in part. In principle, a sustainable level of abstraction from an aquifer is one that does not exceed the recharge to groundwater. Failure to match abstraction to recharge will result in a non-sustainable well yield and will permanently reduce groundwater levels with consequent effects throughout the ecosystem. Abstractions similar to recharge can still have a deleterious impact; groundwater levels will not rise as much in response to seasonal rains and the flow of ephemeral rivers fed by groundwater during parts of the year will be reduced in volume. Such rivers may be important sources of water for downstream users and will certainly have an ecosystem dependent upon them.

Groundwater recharge in basement areas of Africa

Wright (1992) reported estimates of recharge calculated by a number of methods for areas of Africa that generally have a higher rainfall than south-east Zimbabwe. Recharge calculations using base flow analysis demonstrated the importance of dambos and relief on base flow and hence on recharge. These relationships are also discussed by Farquharson and Bullock (1992). With rainfall in excess of 800 mm, groundwater recharge was estimated by Wright (1992) to be typically in the range 10-20% of mean annual rainfall which he considers to be substantially in excess of the demand of rural populations (1-3 mm). Estimates of recharge using chloride balance, again for an area with rainfall higher than normally experienced in south-east Zimbabwe, were 9-14% of mean annual rainfall. Howard and Karundu (1992) estimated recharge for basement aquifers in south-west Uganda. Annual rainfall in this area is normally in the range 750 - 1000 mm. Using daily water balance techniques, mean recharge was estimated at 30 mm (3-4% mean annual rainfall) over an eight year period. However, median recharge for the same period was estimated at 17 mm (2% mean annual rainfall) and this value was considered to be more representative of annual recharge in the area.

Groundwater recharge in south-east Zimbabwe

Houston (1988) estimated recharge for Masvingo Province of Zimbabwe using three independent methods; baseflow analysis, environmental tracer (chloride) and soil moisture budgets (based on a monthly recharge-runoff model). Data from 22 raingauges and 3 class 'A' evaporation pans were available for an area of 22,000 km^2. Flow data were available from the Chiredzi, Mzero, Musokwesi and Lundi rivers for periods ranging from 8 to 17 years. Houston estimated recharge throughout Masvingo province to be 2-5% of rainfall, a range which was shown by all three methods. Houston further suggested that recharge was very dependent on annual average rainfall with low rainfall areas likely to have a recharge of 2% of annual rainfall. Based on an area receiving 500 mm annual average rainfall and a recharge rate of 2%, Houston calculated that an area of 65 ha was required to sustain a hand pump delivering 6.5 Ml/year.

Meigh (1988) made a first attempt at estimating recharge for the Lowveld region using two independent techniques based on a soil moisture budget model and two empirical models. The soil moisture model was a simplification of the Houston (1988) model but used meteorological data from the Lowveld Research Station and the airport at Buffalo Range. The empirical approach involved relationships developed for a number of catchments between annual average rainfall and runoff and base flow index (BFI) and soil type (Bullock, 1988). A second empirical approach used relationships for annual average rainfall and runoff and annual average rainfall and BFI developed by Meigh (1987). These methods gave recharge estimates of 0.5-6%, a range that encompasses that of Houston (1988).

1.3 Effects of land management on groundwater recharge.

Preliminary estimates indicate that increased use of groundwater is viable if the available aquifers can be appropriately developed and managed. In Masvingo Province of Zimbabwe, for example, there are 2161 boreholes and 1225 wells recorded at present. Assuming all to abstract water by handpump at 6.5 Ml/year, present abstraction is about 22,000 Ml/year. A conservative estimate of recharge for this region provided by Houston (1988) is 2 per cent of rainfall. If annual rainfall is 500 mm, annual recharge to the province would be of the order 570,000 Ml/year and current use of groundwater only about 4 per cent of this.

It should be noted, however, that the development elsewhere of relatively high yielding "agro-wells" without appropriate management has led to over-exploitation of the groundwater resource (eg. Shah, 1990). Perhaps of even more concern is the fact that groundwater recharge is not a constant, but is dependent on rainfall, land use change, surface management practices, and associated changes to catchment hydrology. Wright (1992) explains: "*The basement aquifers of this region are distinctive in that their occurrence and characteristics are largely a consequence of the interaction of weathering processes related to recharge and groundwater throughflow. A close relationship exists therefore between groundwater occurrence and relief, surface water hydrology, soil and vegetation cover. Recharge is sensitive to certain land use changes, notably those associated with desertification. Improvements in the understanding of these relationships will be fundamental to the management and planning of groundwater resources in crystalline basement terrain.*"

As populations grow an increasing area of forest and grazing land is being taken for rainfed crop production. Declining productivity of existing cropland is also prompting an expansion in cultivated area and puts increasing pressure on remaining forest and grazing land (Whitlow and Campbell, 1989). The net result is a reduction in vegetation cover. The mechanisms by which reduced vegetation cover can lead to deteriorating water resources are discussed by Whitlow (1983) and more recently by Wallace (1994).

The effects of changing vegetation on groundwater levels are complex. Deforestation can modify the uptake of water by plants, with shallow rooted crops or grass consuming less water than previous deep-rooted trees. However, runoff may increase with deforestation and overgrazing if these processes reduce soil surface protection during rain causing infiltration rates to decline (Kelly & Walker, 1976). The balance between these changes in plant water use and infiltration are not always clear. Overgrazing by cattle and goats has long been considered a problem in Zimbabwe's communal lands (Cleghorn, 1966). Present cultivation methods also tend to deplete soil cover and infiltration rate and there is considerable interest in promoting change (eg. Chuma & Hagmann, 1995; Mashavira *et al.*, 1995; Nyamudeza & Nyakatawa, 1995). Deforestation is widespread, and in the Save Valley for example, is blamed for increases in runoff (Du Toit & Campbell, 1989). In Uganda, however, Howard *et al* (1994) used water balance calculations and aerial photographs and LANDSAT images to assess the influence of land use change on groundwater recharge. Recharge estimates for the period 1954 to 1961 were reported to be just over half those for the period 1988-91, the difference attributed to large-scale deforestation during the intervening 30 years which has increased recharge by causing significant reductions in rates of actual evaporation.

The cited studies of groundwater recharge have all been conducted at scales of hundreds or thousands of km^2. Similarly, most studies of land use change on hydrology have been conducted at river catchment scale, and have tended to focus on high potential environments such as plantation forestry. A review is provided by Calder (1997). These studies have provided valuable information on the impacts of afforestation and deforestation in sparsely populated upland areas. However, the critical soil and water resource problems in Africa occur at a local level, in small catchments that are heavily populated by subsistence farmers and their livestock. There is a shortage of data from such catchments (Pereira, 1961; Whitlow, 1983).

1.4 Studies at small catchment scale

Whitlow (1983) reviewed the hydrological implications of land use in Africa with particular reference to Zimbabwe, and ended with the following plea: "*If a coordinated and vigorous research programme ..... of multi-disciplinary studies on small eroding catchments ..... fails to materialise, the consequences for our natural resources of water and soil could be disastrous ..... all prospects of improving living standards, especially of rural populations, will disappear*"

Improved understanding of the hydrological implications of land use in Africa will be possible only through more detailed studies which allow rainfall to be partitioned to surface runoff, interflow, evaporation from soil and vegetation, baseflow to streams and rivers, groundwater recharge and human abstraction. A catchment study is required but the size of catchment is critical. It should be small enough to allow direct measurement where possible of the separate components of the water balance, to minimise meteorological and geological variability, to study localised recharge mechanisms, and to work closely with the local community, but it should be large enough to integrate spatial variability of groundwater recharge and to reflect the discontinuous nature typical of basement aquifers. The main groundwater flow systems of the basement complex are relatively localised between recharge on watersheds to discharge by runoff and evaporation in valley bottomlands. In southern Zimbabwe this scale is typically of the order 2-20 km^2.

1.5 Aims of the project

Ongoing development of crystalline basement aquifers for domestic use and small-scale irrigation in Zimbabwe and elsewhere has the potential to be of very considerable benefit both to local communities and to the local environment (Waughray et al, 1996). However, the sustainability of groundwater abstraction will ultimately depend on the replenishment of aquifers by groundwater recharge. Despite the importance of groundwater in these dryland areas, there is relatively little information on the amount, temporal and spatial variability, or the factors that control recharge at a local scale in crystalline basement regions. Moreover, many Integrated Catchment Management programmes in dryland areas are being implemented on the basis of scant and often inappropriate information from plot-scale experiments or regional-scale reviews.

The present study was initiated in the early 1990s at a time when the availability of water resources, including groundwater, was declining. Communities throughout southern Africa were reporting serious problems of falling groundwater levels, failure of wells and boreholes, drying up of springs, reduced dry-season river flows, and desiccation of wetland dambos. The causes of these problems were not clear, the most frequently cited being a decline in rainfall, over-exploitation of the groundwater resource, and the effects of poor land management including the impacts of deforestation and overgrazing. The present study was designed to:

- quantify groundwater recharge in an area of crystalline basement as part of a catchment water balance, and identify the main sources of recharge;
- partition the effects of changes in rainfall and land use on the groundwater resource;
- improve understanding of the factors that control the sustainability of yield from wells and boreholes in crystalline basement aquifers;
- provide data on the long-term behaviour of these aquifers;
- assess the implications for development of small-scale irrigation using groundwater;

The study was also designed to begin to provide the fundamental hydrological, social, economic and agricultural information that is needed to underpin Integrated Catchment Management programmes in communally-managed dryland areas. An objective was that the Romwe Catchment should provide a long-term research facility for the region. The problems of natural resource management in communally-managed dryland areas are long-term, and the solutions may not be rapid. Furthermore, there is a danger of misinterpreting research findings obtained from a relatively short window of time. A research facility to enable continued work by local and international scientists and extension staff was considered important. Towards this end, the project has supported post-graduate studies, and much of the work reported here is described in more detail in the theses presented by Mugabe (1995) and Butterworth (1997).

2. THE ROMWE CATCHMENT

2.1 Location

The Romwe catchment is located in southern Zimbabwe, 86 km south of Masvingo and close to Ngundu (20° 45′ S, 30° 46′E). The area of the catchment is 4.6 km^2. The catchment is about 2.75 km long and between 1.5 and 2.5 km wide along most of its length (Figure 2.1). Altitude varies between 695 masl at the catchment outlet and 955 masl at the summit of the hills on the southern boundary. Gentle slopes along the valley floor are encircled by relatively steep rocky hills, although there are three saddles between the hills where the catchment is less clearly defined. The stream is a tributary of the Runde river and drains the catchment from east to west. The catchment partly contains three villages or kraals (Tamwa, Sihambe and Dhobani) and straddles the boundary of two administrative wards of Chivi District (Wards 23 and 25).

2.2 Climate

Rainfall
The 40-year mean annual rainfall from 1952-92 at Chendebvu dam, 12 km to the north of the catchment, is 585 mm. On average, 84% of this annual rainfall is received during the summer rainy season from November to March. However, rainfall amount, intensity and distribution during the wet season are highly variable, and inter-annual variation is large. The long-term mean has a standard deviation of 257 mm, equivalent to a coefficient of variation of 44 per cent. Droughts are recurrent in the region, the most recent in 1991/92 being of exceptional severity when only 83 mm of rain was recorded. Furthermore, consecutive periods of generally high and low rainfall have been observed to affect southern Africa (Tyson, 1986). In Zimbabwe, rainfall cycles with periods of 2.3 and 9 years have been identified as statistically significant (Makarau, 1996). This has resulted in the 1950s being generally wet, the 1960s relatively dry, the 1970s wet, and the 1980s and early 1990s dry. Figure 2.2 shows the cycles of cumulative departure from mean annual rainfall at Chendebvu dam and at Chivi, 50 km to the north-west of the catchment. Recent research has linked the occurrence of low rainfall periods in the sub-continent with the El-Nino phenomenon. It is important to note that the work described here commenced in 1991 towards the end of a long dry period. From 1981-94, rainfall in 11 of the 13 years was below average. Above average rainfall in the 1994/95, 1995/96 and 1996/97 seasons is perhaps the return to a wetter period.

Rainfall in the catchment area is strongly affected by the rain shadow of the Nyoni hills to the east. Average annual rainfall at the catchment is likely to be slightly greater than at Chendebvu dam, perhaps about 620 mm on the basis of interpolation from the Meteorological Department map of annual average rainfall. Meteorological Department rainguages are installed at a height of 0.7 m. In subsequent chapters, rainfall guaged at ground level is used as standard. The average annual rainfall at the catchment, when converted to ground level equivalent, is 704 mm.

Temperatures and evaporative demand
The closest site for which long-duration temperature and potential evaporation records exist is Masvingo, 100 km north of the catchment. Rainfall received at this site is similar to that at the catchment, despite the higher altitude of 1094 m. Monthly average daily maximum temperatures vary between 22°C in June and 29°C in October. Average minimum temperatures range between

5°C in July and 17°C in January. Mean evaporation demand is high, exceeding average rainfall during all months of the year. Potential evaporation measured in Masvingo using a Class A pan varies between 102 mm in June (3.4 mm/day) and 220 mm in October (7.1 mm/day), and amounts to an annual average of 1942 mm. At the lower altitude of the study catchment, temperatures and potential evaporation rates may be expected to be slightly higher than recorded at Masvingo.

2.3 Geology

A series of younger, undifferentiated basement complex gneisses underlie the catchment (Figure 2.3). Folding, fracturing and faulting are widespread, and some of these fractures and faults are intruded by dolerite dykes. The gneisses range from dark-coloured melanocratic or mafic types, rich in ferro-magnesian minerals such as pyroxene, mica, and amphibole (Pyroxene gneiss), to much lighter-coloured leucocratic types composed mainly of feldspar and quartz (Quartzo feldspathic granulite). Between these two extremes of composition are a whole range of gneisses, which grade imperceptibly from one to the other (Leucocratic pyroxene gneiss). The various gneisses are inter-banded at all scales, from a few centimetres to several hundred metres, giving rise to a complex inter-banded sequence which is difficult to differentiate. Generally the pyroxene gneisses are more easily weathered and less resistant than the leucocratic pyroxene gneisses or quartzo-feldspathic granulites. For this reason the lower ground tends to mark the more extensive outcrops of pyroxene gneiss, while the higher ground is generally underlain by leucocratic types. Three dolerite dykes occur in the catchment, all aligned roughly NNW-SSE. A detailed geological description of the catchment is given in the project first interim report (Butterworth et al, 1995).

2.4 Soils

Due to differences in parent mineralogy, three main soil types occur in the catchment:

Red Clay Soils

North of the stream, kaolinitic fersiallitic red clays with granular micro structure (III 5 E; Shona - *mushava*) predominate, derived from the more mafic pyroxene gneiss. The FAO classification is a Chromic Lixisol. These soils are fertile with both good physical and chemical properties. Cation exchange capacities of 6-9 me % were recorded. In Zimbabwe, red clay soils are the most important soils for commercial crop production. A typical topsoil horizon in the plough layer (< 0.15 m) consists of 72% sand, 4% silt and 24% clay. Clay content increases with depth up to a recorded value of 46% but little variation in bulk density was noted, the average value being 1.34 Mg m^{-3}.

Grey Duplex Soils

In the southern part of the catchment, grey-coloured sandy loams overlie a thick and less permeable sandy-clay layer derived from less mafic, leucocratic pyroxene gneiss. These are described as kaolinitic fersiallitic soils (III 5 P; Ndebele - *hlabatha*). The FAO classification is a Ferric Lixisol. These soils are similar to the gleyic, granitic sands described by Vogel (1993) and which cover some 46 per cent of Zimbabwe (Purves, 1976). The depth of the upper horizon is variable, generally between 0.3 and 1.5 m, being shallowest where soil erosion has removed topsoil. Typically this upper horizon contains 79% sand, 11% silt and 10% clay with a bulk density of 1.48 Mg m^{-3}. There is an abrupt transition to the sandy-clay layer (Shona - *chinamwe)* which contains 50% sand, 7% silt and 43% clay and has a higher bulk density of 1.65 Mg m^{-3}. The low permeability of this horizon periodically leads to the formation of a perched water-table and waterlogging of the overlying soil in wetter years. The nutrient status of these soils is poor. Cation exchange capacities of 2-5 me % were recorded. These soils are referred to as grey duplex soils, to differentiate from more freely draining sandy soils found elsewhere.

Vertic Soils
The third and least extensive soil type are soils with vertic properties (III 3 E; Shona - *chidhaka*) 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.

Detailed descriptions of the principal soil profiles and chemical analyses are given in the project first interim report (Butterworth *et al*, 1995).

2.5 Population and land use

Within the catchment there are 32 homesteads and a population of about 250 people. There are also families living outside the catchment, in Sihambe and Tamwa villages, who utilise resources in the catchment. The settlement pattern is one of dispersed homesteads sited around the catchment at the break of slope between miombo woodland on the hills and cultivated lands on the valley floor. Settlement began in 1952. Analysis of aerial photographs (Butterworth *et al*, 1995) shows that by 1955 much of the presently cultivated land had been cleared, although a large area at the eastern side of the catchment was left under grassland. By 1963 land use was similar to that at present with all the lower slopes cultivated. A system of contour channels and storm drains were established by this time and it is noticeable that no further soil and water conservation structures have been constructed since, with many of the early structures allowed to deteriorate over recent years.

Land use is typical for communal areas in this region, with rainfed cultivation on the valley floor and livestock grazing in the miombo woodland on the hillslopes. Cultivated areas cover 38 per cent of the catchment. Rainfed cropping is the main activity and for many families the major source of food and income. Crops grown most extensively are maize (*Zea mays*), groundnut (*Arachis hypogaea*) and bambara nut (*Voandzeia subterranea*), with smaller hectarages planted to cash crops of cotton (*Gossypium spp.*) and sunflower (*Helianthus annuus*) and to sweet potato (*Ipomoea batatas*) and small grains. In theory all land is sown as insurance against poor rains and low yields, but in practice this is rarely possible due to lack of inputs and fields often lie fallow. Fields are generally cultivated by inversion ploughing using an oxen or donkey-drawn mouldboard plough. Draught power is limiting and where farmers fail to plough they may hoe fields by hand or plant seeds directly into untilled land. Maintenance of soil fertility and organic matter is a major problem due to relatively high costs of purchase and transport of inorganic fertiliser and a shortage of manure resulting from the loss of cattle and goats in the severe 1991/92 drought.

Natural vegetation covers 62 per cent of the catchment. Miombo woodland on the rocky slopes and hills accounts for 55 per cent, the remainder being vegetation along drainage lines. Although there is some evidence of wood-cutting the woodland is generally intact, unlike many other communal lands in Zimbabwe, and there has been little encroachment since initial clearance of land for cultivation in the 1950s. There are two types of miombo woodland present in the catchment. The most widespread is *Brachystegia glaucescens* open woodland with an average canopy cover of about 40-60 per cent. Below the main canopy there is a poorly developed shrub layer and a well developed grass community consisting mainly of annual species. The second type is co-dominated by *Julbernadia globiflora, Kirkia acuminata* and *Brachystegia speciformis* with a similar understorey. Within the cultivated land some trees are present, usually left standing for their fruit and shade. A detailed description of the vegetation of the catchment is given by Mapaure *et al* (1995).

2.6 Water resources

Groundwater is the primary water source for domestic use, the irrigation of small privately-owned gardens and since 1991, irrigation of a 0.5 ha community garden. The number of wells in the catchment has increased considerably since the 1960s (Moriarty and Lovell, 1997) through a desire for reliable water sources close to homesteads and, particularly in the 1980s and 90s, because of the failure of many wells and springs. There are now 26 wells in the catchment, although only a small proportion of these are reliable and in regular use. All are narrow hand-dug wells owned by individual families, with the exception of the large diameter collector well at the community garden, and a communal well just outside the catchment boundary. Only one family has a private deep borehole. Groundwater abstraction remains low. A survey of four families during a week in October 1994 showed that water use, including household, irrigation and livestock, averaged 32 litres per person per day (Butterworth *et al*, 1995).

Surface water from springs or streams is normally only available for a few months during the rainy season, although in past decades when the population was lower the community say that springs satisfied most of their water requirements throughout the year. A small dam constructed in 1994 just outside the boundary of the catchment has enabled storage of some surface water which is used for watering cattle and irrigation of private gardens from seepage.

2.7 Experimental set-up and monitoring programme

The physical and hydrological state of the catchment as it stood at the outset of the project was documented through a number of baseline surveys. These included surveys of the geology, vegetation, soil, land use, water sources, population, and agricultural practices. A brief summary of the work carried out is presented in Table 2.1.

Given the spatial variability in parent mineralogy, weathering, soils, topography, vegetation, land use and management in the catchment, different approaches were necessary to encompass the possible important hydrological processes. Standard experimental designs, such as replicated plot studies, were not considered appropriate given the nature of the sites and the need to monitor hydrological processes under current farmer-managed land use practices. In order to instrument a wide range of representative sites a four-tier experimental design was formulated with measurements made at the following scales:

Catchment
Measurements at the catchment scale encompass all variability within the 4.6 km^2 area. Direct measurements made at this scale were catchment runoff and rainfall.

Sub-catchments
Three sub-catchments were established, their locations shown in Figure 2.4.

The **Red sub-catchment** comprises two fields with a total area 0.024 km^2. The cropped area excluding scrub and trees on the flanks is 0.017 km^2. The upper field is relatively flat. A grass bund about 2 m wide separates the two fields, both owned and managed by the same farmer. The lower field is more steeply sloping and is incised by a drainage line which has resulted in the deposition of a fan of red eroded sediment from the upper parts of the field over the more vertic soil towards the base of the field.

The **Grey sub-catchment** has an area of 0.011 km^2 and also comprises two fields, although owned and managed by two different farmers from the same extended family. The area of cropped soil excluding contours and grassed waterways is 0.010 km^2. A contour bund separates the two fields but is breached near the centre where lines of runoff in the upper field converge. The lower field is divided by the subsequent gully that extends from this break in the bund. In both the Red and the Grey sub-catchments, cultivation was carried out by the respective farmers with limited assistance in the form of seed, fertiliser and pesticides to ensure some uniformity in crop spacing. In return each farmer maintained a diary of field operations. During the 1994/95 cropping season maize was grown by the farmers of both sub-catchments.

The **Woodland sub-catchment** has an area of 0.5 km^2 and contains mature open miombo woodland typical of the area. There is much exposed rock and the soil depth is very variable. Like all woodland in the catchment, the woodland sub-catchment is utilised by the community for grazing livestock and extracting forest products.

Transects
Three transects of neutron probe access tubes and piezometers were installed to enable measurements of soil moisture profile and groundwater levels, respectively. These were sited down the hillslope profile from the large inselberg in the north-west of the catchment, across the main stream, and across a tributary draining from the wooded hillslopes (Figure 2.4).

Point scale measurements
A range of measurements were made at points within the catchment. These include a network of rainguage sites and a network of monitored dug wells and drilled piezometers. Additional neutron probe access tubes were sited above and below the edge of a contour channel in which a farmer had dug large pits (6 x 1.5 x 0.75 m) known as infiltration pits. Fourteen plots measuring 10 x 10 metres each with a single neutron probe access tube were located around the catchment on cropped land of the various soil types (Mugabe, 1995).

Rainfall

A network of automatic and manual rain guages was established in the catchment. Daily, hourly and 2 minute rainfall intensity data are recorded using a 203 mm diameter tipping bucket rainguage set at ground level with an anti-splash grid. This guage is connected to an Automatic Weather Station (AWS) located near the centre of the catchment. At the AWS site and at locations at the eastern and western ends of the catchment, 127 mm diameter high-capacity copper storage guages are installed. At these locations and at a further 10 sites around the catchment (at different altitudes and including the 3 sub-catchments), 127 mm diameter plastic funnel-type storage guages are sited. All storage guages are read daily between 6 and 9 am.

Evaporation

Potential evaporation for the catchment is calculated using the Penman (1948) equation and the automatic weather station data (wet and dry bulb temperature, solar and net radiation, wind speed). Direct measurement of soil evaporation was made in the Red and Grey sub-catchments using PVC micro-lysimeters of 0.07 m internal diameter and 0.1 m depth. Undisturbed soil cores were taken soon after rain events and replaced at regular intervals over drying cycles as recommended by Daamen et al (1993). Between January and February 1995, measurements were made over three drying cycles at positions within and between crop rows on both soil types.

Runoff

Runoff gauging stations were constructed at the outlets of the sub-catchments and the main catchment (Figure 2.4). At the Red and Grey sub-catchments, 0.4 m V-notch weirs were installed to measure flows up to a maximum discharge of 0.14 m^3/s. The plate and weir box were constructed following recommended designs of the US Bureau of Reclamation (1984). At the woodland sub-catchment, a 0.5 m V-notch weir was installed to record discharges up to 0.24 m^3/s. At the main catchment outlet, two gauging structures were built: a trapezoidal flume to measure high discharges up to 13.5 m^3/s and, located 160 m downstream, a 0.3 m V-notch weir with a maximum rating of 0.07 m^3/s for accurate low-flow measurement. Measurement of stage at all guaging stations was made within 0.6 m diameter stilling wells connected to the flow by 25 mm tubing. All sites were fitted with Munro chart recorders set to record over 24 hour periods because of the importance of short duration flow events. At the trapezoidal flume a digital float recorder and pressure transducer were used to record stage digitally. Manual stage measurements were also made by local community observers during all flow events. Gulp water samples were collected during key events to determine suspended sediment and nutrient load lost from the catchments.

Soil Water Measurements

The main technique used to monitor soil moisture profiles is the neutron scattering method. A neutron probe (Didcot Instruments, Abingdon) was used with aluminium access tubes following the procedure described by Hodnett (1986). The probe was calibrated for the main soil types and soil horizons using parameters determined from samples analysed by CEA (Caderache, France) using the neutron-capture technique (Couchat *et al.*, 1975). Corrections were determined for 0.1 and 0.2 m depths to account for neutron loss near the surface. Calibration results are provided by Butterworth (1997). Probe readings in the field were made weekly during the wet season and monthly during the dry season, with additional measurements made as soon as possible after large rainstorms (>20 mm), and to the maximum depth achieved during the installation of the access tubes. Soil water potential profiles to 2 m depth were measured in the Red and Grey sub-catchments using mercury manometer tensiometers. Daily readings were made at 0600 h to minimise the effects of temperature variation. Soil moisture characteristic curves equating moisture content and potential were determined for the main soil types and soil horizons using a combination of tension table and pressure plate apparatus.

Crop Measurements

In both Red and Grey sub-catchments, tube solarimeters (Delta-T Devices Ltd., Cambridge) were used to measure radiation interception and provide a measure of crop cover during the season. Grain yield and dry matter production were measured at the end of each growing season. Measurements were made in 5 x 5 m plots around each neutron probe access tube (24 and 23 sites in the Red and Grey sub-catchments respectively). Details are provided by Butterworth (1997).

Groundwater Measurements

Sixty-four piezometers were drilled to complement 26 existing dug wells and create a network of observation holes to allow measurement of groundwater levels throughout the catchment, determine the position of groundwater divides, identify perched and deep groundwater tables, monitor cones of depression around pumping wells and boreholes, identify recharge as a result of transmission losses from ephemeral streams, and investigate areas of potential localised recharge and interflow (Figure 2.4). Construction of the piezometers is described by Macdonald *et al* (1995). Groundwater levels were measured weekly, or daily for a week after rainfall events > 20 mm. Aquifer properties were determined by pumping tests at 5 wells chosen to typify the range found within the catchment (Macdonald et al, 1995).

Chloride Balance

A balance of chloride concentration in rainfall and groundwater can be used to calculate a regional value of groundwater recharge from the magnitude of effective rainfall (Edmunds *et al*, 1988). Samples of rainfall in the Romwe catchment have been collected and analysed for chloride since November 1993. Groundwater samples were taken and analysed for all piezometers and wells in the catchment in the 1994 dry season and 1994/95 wet season.

Monitoring programme

The first hydrological measurements began in August 1991 during one of the most severe droughts in recent years. At this stage monitoring was restricted to groundwater level data obtained from some existing wells in the catchment. By the end of 1993, however, the range of measurements was increased to cover rainfall, groundwater levels from piezometers, and sample collection of rainfall and groundwater chemistry; in 1994 run-off and soil moisture measurements were started. With the exception of tensiometer data all these hydrological measurements have been carried through to the time of writing. The monitoring timetable, together with details of sampling frequency, is summarised in Table 2.2.

Table 2.1 Summary of baseline surveys

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

Table 2.2 Summary of instrumentation and monitoring

Parameter	Method(s)	Scale(s)	Site(s)	Instrumentation	Monitoring frequency
Meteorology					
Rainfall	Storage gauges	Point	-	Three 127 mm gauges (copper) & Thirteen 127 mm gauges (plastic)	Daily
	Recording gauge	Point	Centre of catchment	One 203 mm tipping bucket rainguage	2 min/hourly/daily
Potential evaporation	Penman	Point	Centre of catchment	One automatic weather station (wet and dry bulb thermometers, wind vane, anenometer, solar radiometer, net radiation, soil heat flux plates, atmospheric pressure sensor)	Hourly/daily
Runoff					
Surface runoff	Permanent flow-gauging stations	Catchment	Catchment outlet	Trapezoidal flume ($Q<13.5$ m^3sec^{-1}) & 0.3 m V-notch weir ($Q<0.07$ m^3sec^{-1})	Continuous
		Sub-catchment	Red Sub-catchment	0.4 m V-notch weir ($Q<0.14$ m^3sec^{-1})	Continuous
			Grey Sub-catchment	0.4 m V-notch weir ($Q<0.14$ m^3sec^{-1})	Continuous
			Woodland Sub-catchment	0.5 m V-notch weir ($Q<0.24$ m^3sec^{-1})	Continuous
Ssspended sediment load	Gulp sampling	-	At flow gauging stations	-	
Groundwater	Dip measurements	Point	35 existing wells	-	Weekly/daily
		Point/transect	65 observation boreholes	102 mm diameter observation boreholes	Weekly/daily
Soil water					
Soil water content	Neutron probe	Point		14 aluminium access tubes in different fields to 1.0 m depth	Event related
		Transect			Event related
		Sub-catchment	Red Sub-catchment	24 aluminium access tubes	Event related
			Grey Sub-catchment	23 aluminium access tubes	Event related
Soil water potential	Tensiometers	Point	Red/Grey Sub-catchments	3 arrays at 15 depths to 2.0 m	Daily
	Gypsum blocks	Point	Red Sub-catchment	2 sites at 5 depths to 1.0 m	Continuos
Soil evaporation	Microlysimeters	Point	Red/Grey Sub-catchments	(0.07 m diameter and 0.10 m deep cores)	Event related
Crop					
Canopy light interception	Tube solarimeters	Point	Red/Grey Sub-catchments	Fixed pegs to ensure consistent placement	Every 2 weeks
Yield/dry matter production	Destructive sampling	5×5 m square	Red/Grey Sub-catchments	-	Once per season
Hydrochemistry					
Rainfall chemistry	Chloride/isotopes	-			Each event
Streamflow chemistry	Chloride/isotopes	-			Event related
Groundwater chemistry	Chloride/isotopes	-			Twice

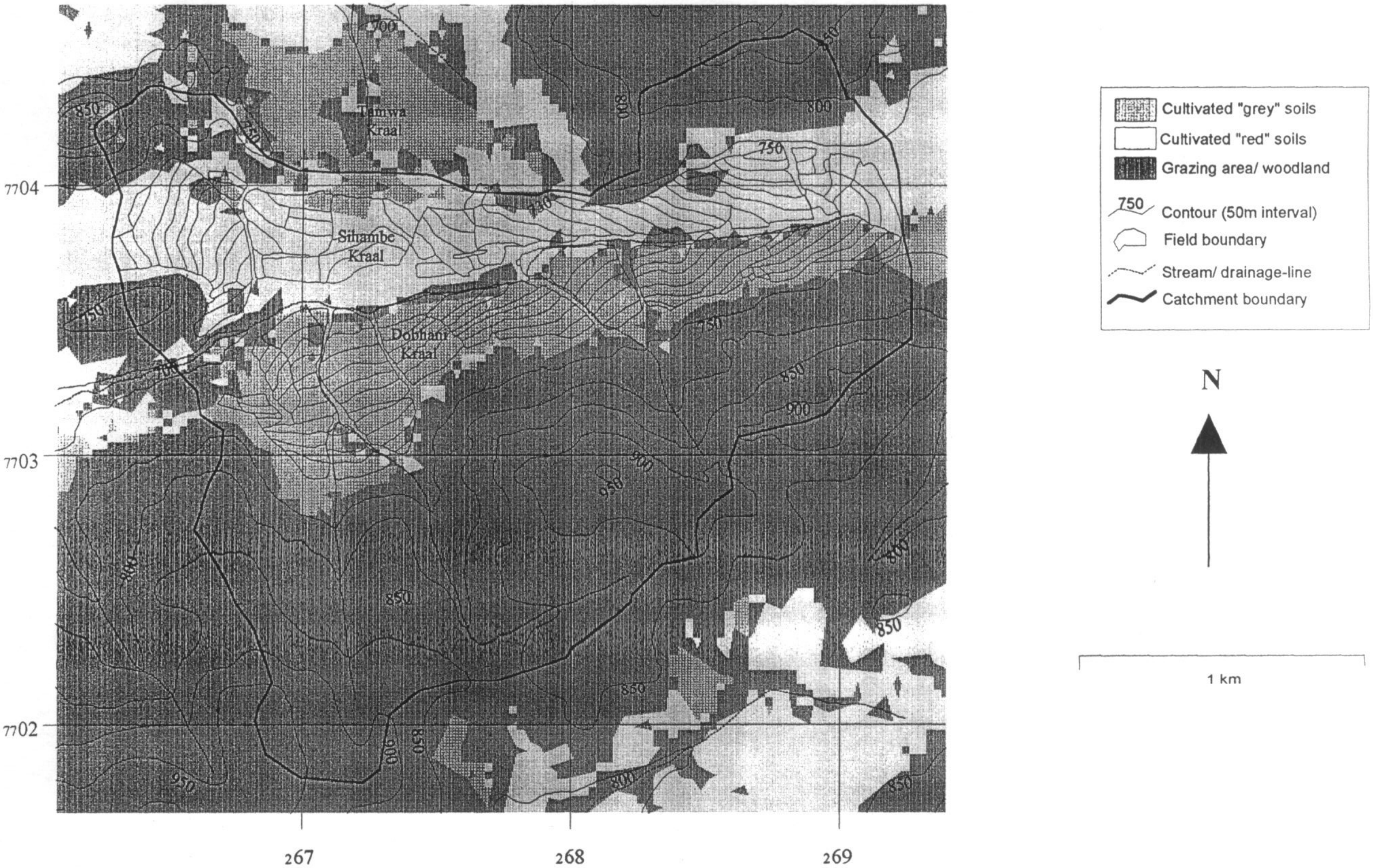
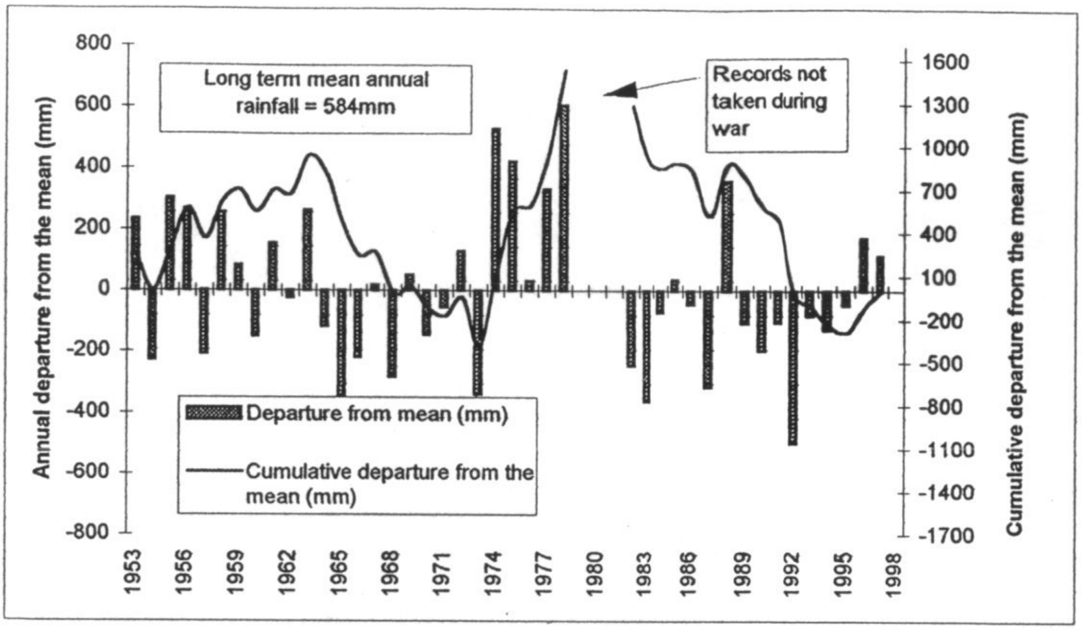


Figure 2.1 Romwe catchment, topography and land use

a)



b)

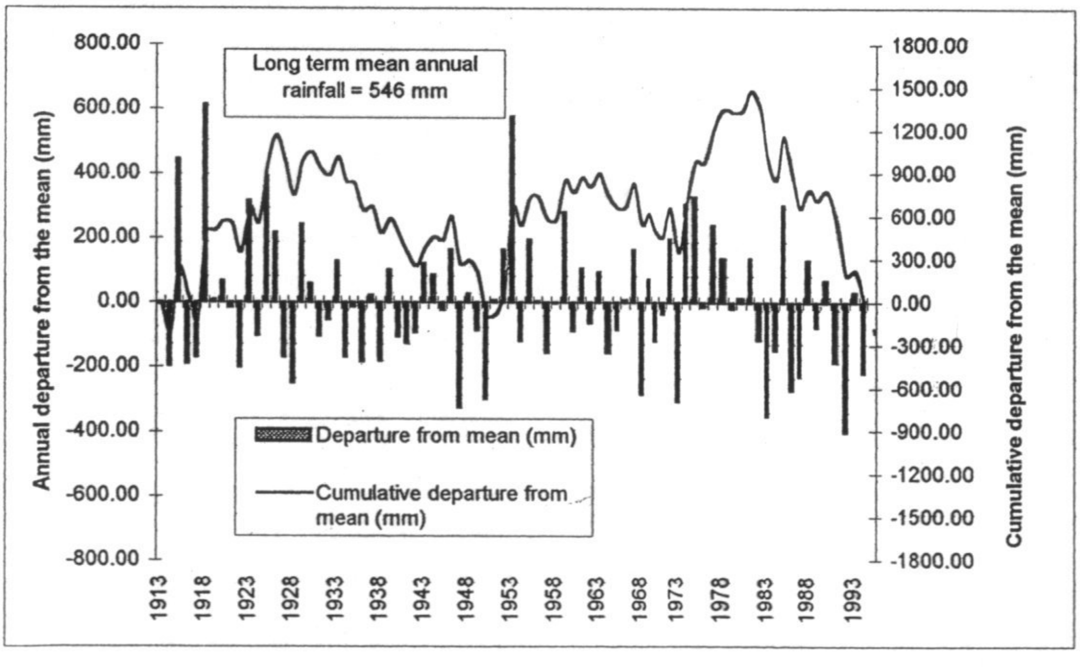


Figure 2.2 Annual and cumulative departure from the long term mean
a) Chendebvu dam, b) Chivi

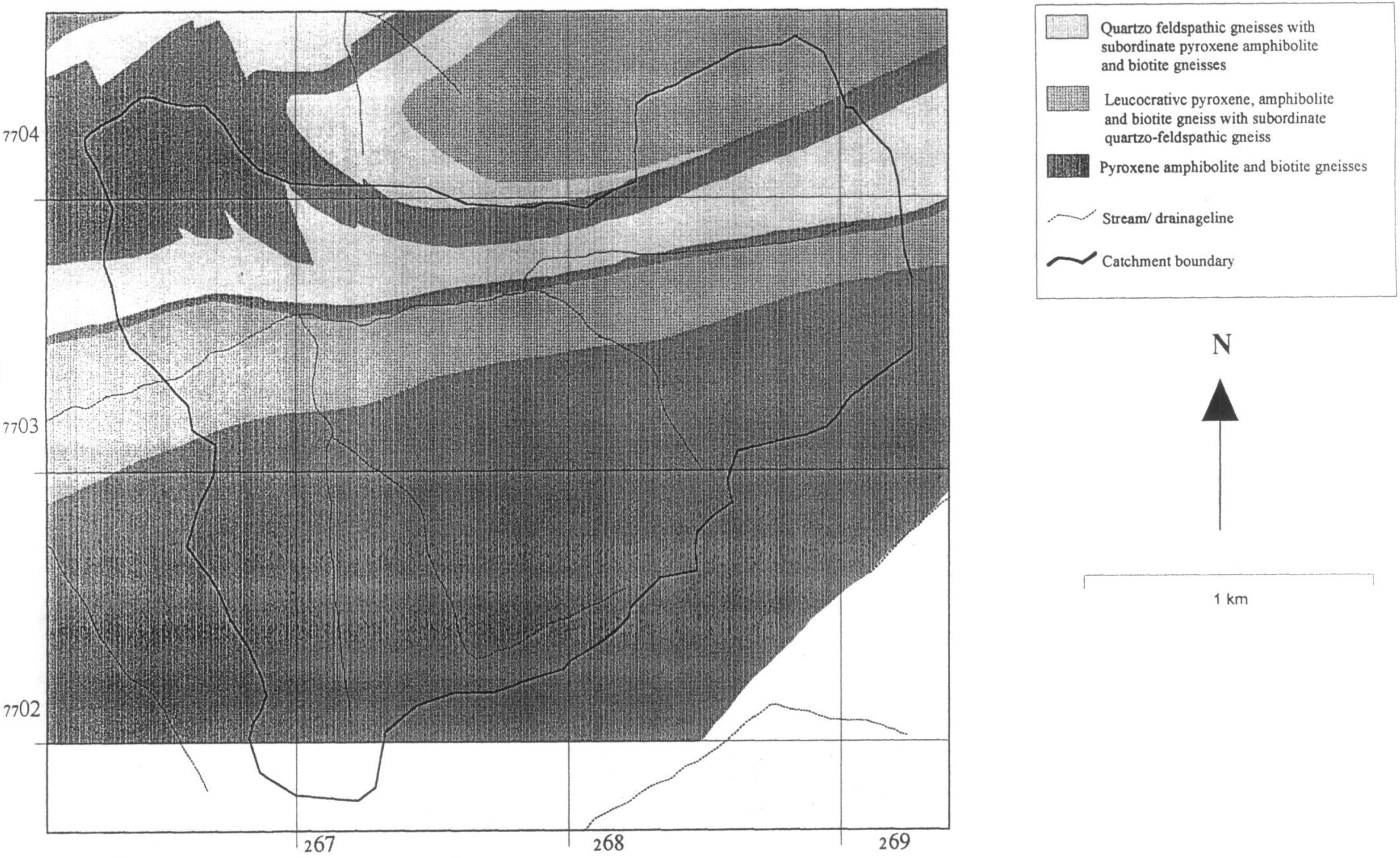
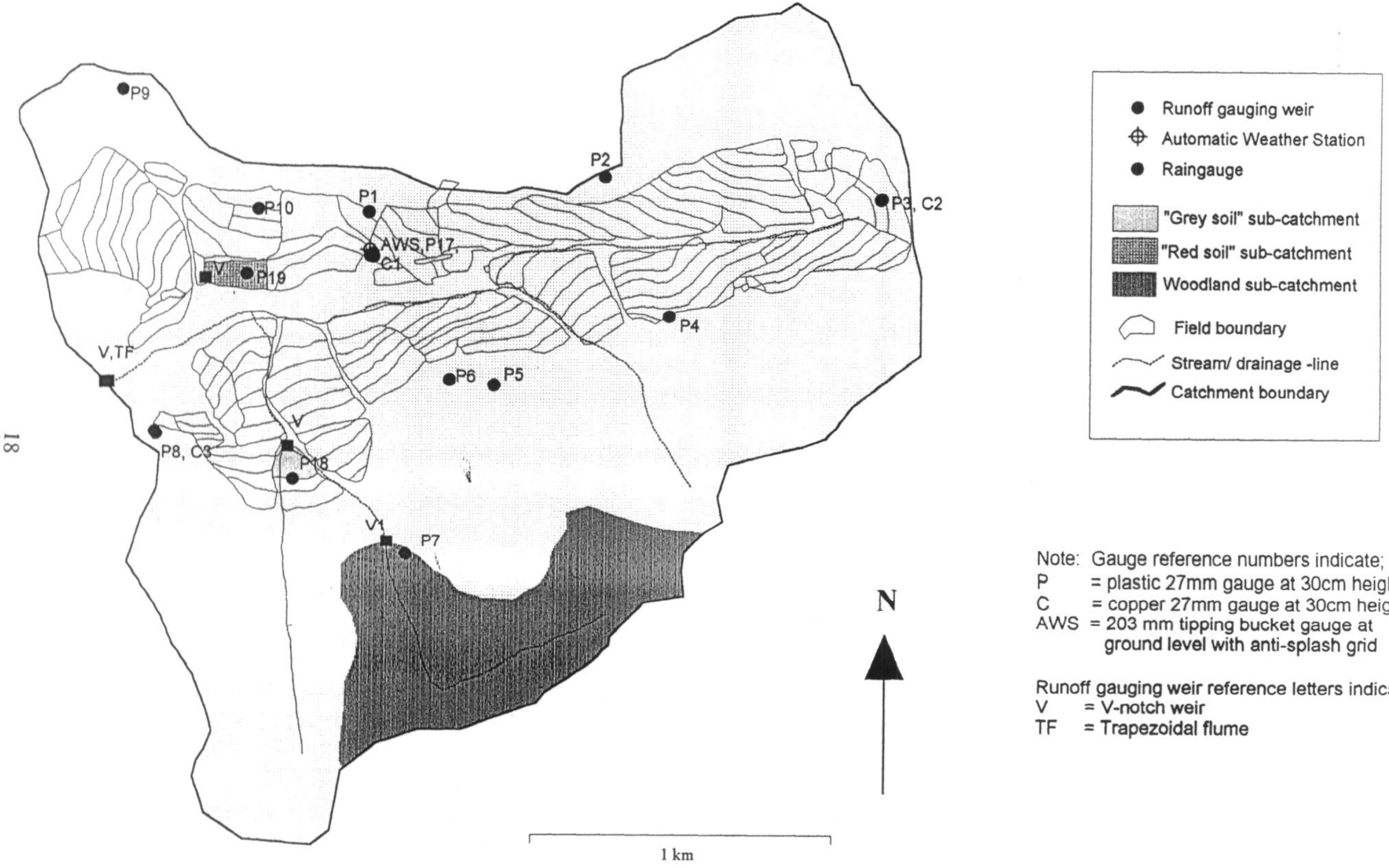


Figure 2.3 Geological map of the catchment



Note: Gauge reference numbers indicate;
P = plastic 27mm gauge at 30cm height
C = copper 27mm gauge at 30cm height
AWS = 203 mm tipping bucket gauge at ground level with anti-splash grid

Runoff gauging weir reference letters indicate
V = V-notch weir
TF = Trapezoidal flume

Figure 2.4a Gauging stations, sub-catchments and meteorological instrumentation

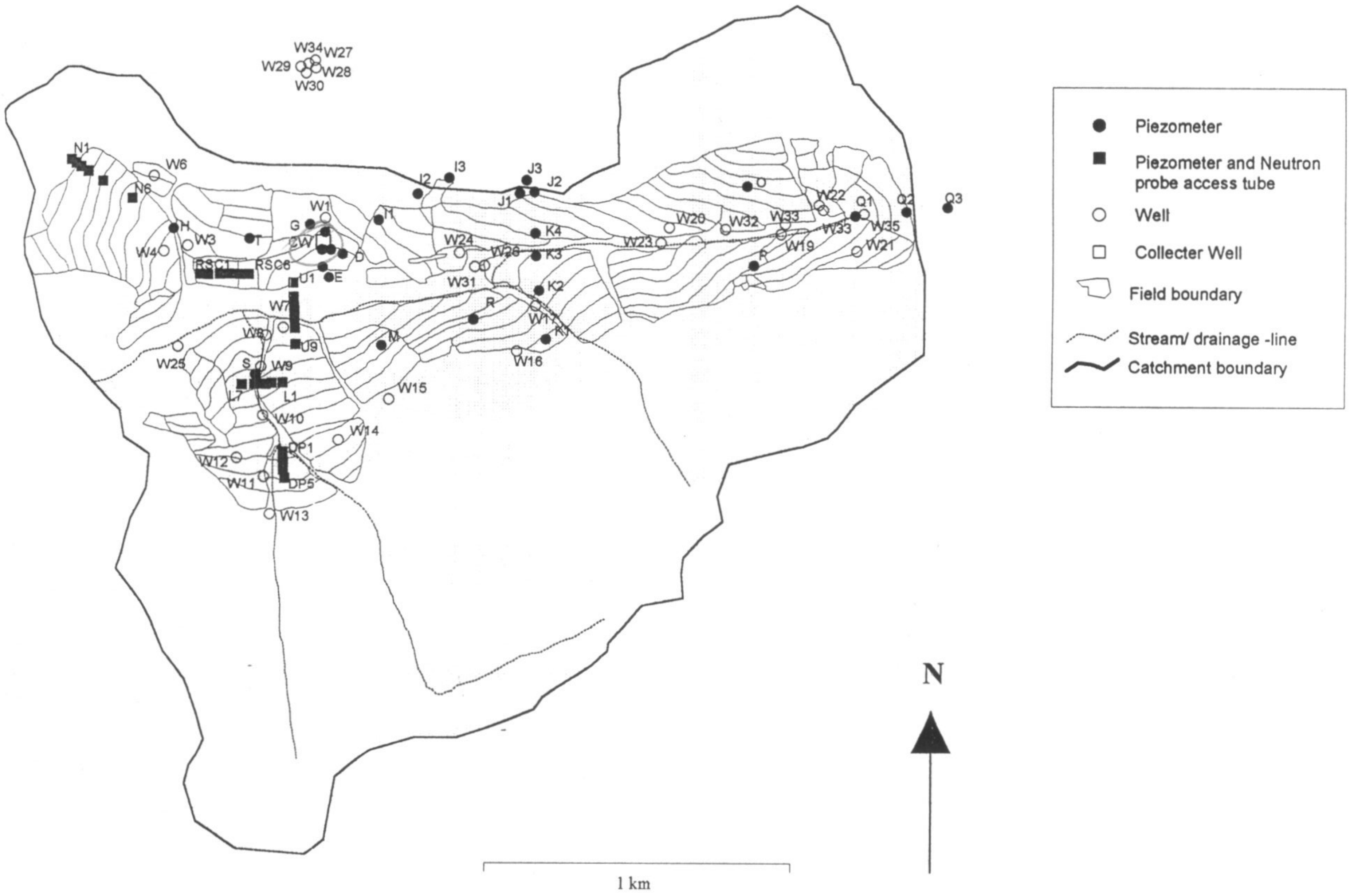


Figure 2.4b Groundwater and soil moisture monitoring sites

3. SURFACE MANAGEMENT PRACTICES AND GROUNDWATER RECHARGE

3.1 Introduction

In cropped areas, surface redistribution of rainfall has been shown to be an important hydrological process affecting infiltration and runoff in dryland environments (e.g. Harris *et al.*, 1994; Gaze *et al.*, 1997). This is partially attributed to the rainfall characteristics in semi-arid regions, where a large proportion of rainfall often falls in a relatively small number of high intensity storms. Sloping fields, contour channels, paths and roads, termite mounds, surface crusts, sparse crop cover and microtopography created by cultivation can also all encourage surface redistribution of rainfall.

In Zimbabwe, many fields in communal areas are on noticeable slopes or have been partially eroded since clearance, resulting in considerable height differences within fields. Contour channels are a particularly widespread feature due to colonial agricultural policies introduced in the 1930s (Hagmann & Murwira, 1996). However, rills and gullies commonly form in fields where an up-slope contour channel has been over-topped and damaged. In a survey of 115 fields in a smallholder farming area in southern Zimbabwe, Hagmann (1995) found that contour ridges were broken in 16 per cent of cases and overflowed in 50 per cent of cases, and that on average each field was cut across by 4.2 rills.

In Romwe catchment, the deeper soils on the more gentle slopes of the valley floor are important to the community for the cultivation of rainfed crops. However, the valley floor is also where the shallow weathered aquifer occurs and from where groundwater is abstracted to meet community water requirements. It was considered important to know whether the cropped fields on the valley floor are a major source of recharge to the underlying aquifer and, if so, the effects that present surface management has on recharge.

3.2 The water balance of farmers' fields

The variability of infiltration was investigated within both the Red and Grey sub-catchments. In both, the contour bund between two fields in the sub-catchments had been breached and runon to the lower field concentrated at a single point. Management of the sub-catchments was carried out by the farmer, with limited intervention other than to ensure some uniformity in crop spacing and fertilizer application. During the season reported here (1994/95), maize was grown in both sub-catchments.

Infiltration

In-situ soil water measurements were made using a neutron probe at a grid of 24 aluminium access tubes in the Red sub-catchment and 23 in the Grey sub-catchment (Figure 3.1) and six along the inselberg hillslope transect (Figure 3.4). The tubes were installed to a maximum depth of 3 m. Measurements were made weekly, with extra measurements made as soon as possible after rainfall events exceeding 20 mm. Specially constructed stands were placed next to all access tubes to minimise disturbance when making measurements. Neutron probe readings were made using a 16 s count time at depths of 0.1 and 0.2 m below the ground surface and then at 0.2 m depth intervals to the depth of the tube. Infiltration was calculated as the difference in profile soil moisture before and after the event. To determine profile soil moisture just before a rainstorm, evaporative losses between the time of the last neutron probe measurement and the rainstorm were modelled using the ACRU soil water balance model (Schulze, 1995; Smithers & Schulze, 1995). Drainage losses were negligible in the periods just before major rainfall events in 1994/95 because of the long dry spells between rainstorms. Profile soil moisture after a rainstorm was determined normally on the same day as the rainstorm, but always within 48 hours. To allow for evaporative losses between the storm and time of soil water measurement, the measured change in profile water storage was reduced by the potential evaporation rate determined after Penman (1948). Rainfall concentration factors (RCF) at each neutron probe site were calculated for major rainstorms after Gaze *et al.* (1997), where:

$$RCF = \frac{I}{P}$$

and I is the measured infiltration and P is the recorded rainfall.

Drainage to groundwater

Soil moisture potential profiles were measured at two sites in the Red sub-catchment and one site in the Grey sub-catchment using mercury manometer tensiometers. These were constructed using procedures similar to those described by Stannard (1986) and installed at 0.1 m increments up to 0.2 m and then at 0.2 m increments up to 2.0 m. Readings were generally made daily throughout the rainy season. On the red clay soils a clearly defined zero flux plane (ZFP) could be identified from soil moisture potential profiles and was used with soil water content changes to calculate evaporation and drainage losses from the profile using the ZFP method (Cooper, 1979). This method could not be used on the grey duplex soils where soil water movement was strongly influenced by lateral flow across the sandy-clay layer.

Crop measurements

In November and December 1994, the Red sub-catchment soils were ploughed to 0.15-0.20 m depth with a tractor-drawn disc plough. The farmer adopted different secondary cultivation and sowing practices between fields because of delays in hiring a tractor to finish ploughing the lower field. In the upper field, ridges were made using an oxen-drawn plough and maize seeds (hybrid variety R201) dropped into the furrows approximately 1 m apart on 15 December 1994. In the lower field, seeds were sowed into the relatively flat surface on the day after ploughing using an oxen-drawn single-row planter at roughly 0.23 m spacing along rows, and again with about 1 m between rows. Where germination was poor gaps were filled with new seeds on 2 January 1995.

The Grey sub-catchment soils were ploughed in November and early December using an oxen-drawn mouldboard plough, to a depth of about 0.12-0.15 m. On 12 December 1994 the surface was harrowed and maize seeds (hybrid variety R201) were sown using an oxen-drawn single-row planter at about 0.23 m spacing along rows. Gaps between plants were filled in the lower field on 26 December 1994.

Grain yield and total dry matter production were measured at the end of the growing season at all neutron probe sites. Measurements were made in 5 × 5 m plots around each access tube. Plant material was weighed in the field using a spring balance when plants had dried for a period of 3 to 4 weeks. A plant sample was taken from each plot and dried at 80°C in order to correct field-dry measurements to dry-matter mass. Maize grain was harvested, stripped from the cobs, air-dried and weighed. A 100 g sample was taken from sample bags containing approximately 1 kg grain, and oven-dried to determine the grain yield at 12.5 per cent moisture content.

Rainfall

The total rainfall in 1994/95 (1 July 1994 to 30 June 1995) was above average with 738 mm recorded (Table 3.1). The cropping season was confined to rainfall between 9 December 1994 and 29 March 1995 when a total of 502 mm rainfall was received. Of this amount 444.5 mm was received in 5 single rainfall events. A large proportion of rainfall (56%) was at intensities above 15 mm hr^{-1}. There were dry spells of two to five weeks duration between these events. Frequent light rainfall in April, May and June resulted in considerable weed growth after crops were harvested.

Runoff at sub-catchment scale

Runoff from both sub-catchments is shown in Table 3.1. Three discrete runoff events occurred in the Red sub-catchment in 1994/95. Two minor runoff events during the period 16-18 January 1995 resulted in 2.1 mm runoff. Most of the runoff (5.8 mm) occurred as a result of a single event, on 17/18 February 1995 when the rainfall total was 141 mm. Total runoff from the Red sub-catchment during the 1994/95 season amounted to only 1.0% of the rainfall. Only two rainstorms resulted in runoff from the Grey sub-catchment. The first storm of 44.5 mm on 16 January 1995 produced runoff amounting to 0.9 mm. The second runoff event was caused by the 141 mm rainstorm on 17/18 February 1995 which resulted in 42.6 mm runoff. Total runoff from this sub-catchment during 1994/95 was 43.6 mm or 5.9% rainfall, a larger component of the water balance than for the Red sub-catchment in this year.

Within-field variation in infiltration

By subtracting runoff at the sub-catchment outlet from rainfall, average sub-catchment infiltration was determined for the major rainfall events. This measurement of infiltration at sub-catchment scale is compared in Tables 3.1 and 3.2 with point measurements of infiltration made at the neutron probe access tube sites. In the Red sub-catchment total infiltration in 1994/95 varied between 658 and 891 mm (89-121% of total rainfall) for a sample of 16 sites with a coefficient of variation (CV) of 8%. The mean total infiltration of 719 mm for these sites was close to the sub-catchment scale measure of 730 mm. In the Grey sub-catchment, total infiltration ranged from 548 to 1087 mm (74-147% rainfall) for a sample of 20 sites with a CV of 17% which was considerably greater than in the Red sub-catchment. Mean total infiltration determined from the neutron probe sites was 664 mm, which was 30 mm less than the average derived at a sub-catchment scale.

Figure 3.3 shows point measurements of infiltration for the largest rainstorm of 17-18 February 1995. In the Red sub-catchment a range of values between 97 and 227 mm (69-161% rainfall) was observed with a CV of 23%. Mean infiltration at 16 sites was 136 mm, very close to the 135 mm determined at the sub-catchment scale. In the Grey sub-catchment average infiltration for this event was 102 mm, with a CV of 51% and a range between 33 and 254 mm (23-180% rainfall). The mean of 102 mm is again very close to the sub-catchment scale value of 98 mm. Interestingly, along the inselberg hillslope transect a large range in infiltration was also observed. At six sites infiltration ranged from 31 to 235 mm with a mean of 128 mm and CV of 65%. The mean is close to the average infiltration measured on similar soils in the Red sub-catchment.

In the Red sub-catchment, the site with greatest infiltration was in an obvious zone of concentration where surface water ponded up-slope of the contour bund close to where it was breached. Runoff out of the sub-catchment was low, indicating that localised redistribution occurred but in-field and generally along furrows. In the Grey sub-catchment, the greatest infiltration was observed at site GSC2 in the lower field, near the centre of the gulley which drains the whole sub-catchment. The four next highest values were all observed in relatively low areas (GSC14 and GSC9, 10 and 12 just up-slope of the contour bund). No significant relationship was found between the depth to clay layer and the amount of infiltration. It was expected that infiltration might be limited where the clay layer was close to the surface and causes saturation-excess runoff. Instead, infiltration was not sufficient to cause a persistent perched water table above the clay layer in this year, except at site GSC2 in the gully. Infiltration-excess runoff was the dominant process of runoff generation in the Grey sub-catchment in 1994/95 because of the distribution, size and intensity of the rainfall events.

Two sites in the Red sub-catchment (RSC14 and 18) responded consistently as runon sites, both located near the bund between fields close to the position at which it is breached. At these sites infiltration was affected not only by micro-topography created by cultivation but also by redistribution of water over a larger scale (tens of metres) because of the general slope of the fields and the location of the bund and breach. There were six sites from which runoff occurred during all events, most located on the field margins. In the Grey sub-catchment only one site was consistently a site of runon, GSC2 in the gulley in the lower field. Two sites, GSC10 behind the contour bund and GSC16 sited in a relatively high area, also always had infiltration above the mean of all sites. There were 13 sites from which runoff occurred consistently, located in the more steeply sloping parts of the field down-slope of the contour bund and at the field edges.

In similar studies in Botswana, infiltration in cropped areas was found to be 2.5 times greater in the low areas than the high areas, with a range between 1.6 to 3.8 (Harris *et. al.*, 1994; Miller *et al.* 1994). Elevated areas were associated with termite activity which resulted in increased clay content, greater water-holding capacity and better nutrient status than the low areas with sandier, less fertile and more leached soils attributed to the greater infiltration rates.

The degree of surface redistribution varies considerably between the two sub-catchments and over time. For the first two rainfall events the range and CV of infiltration values is greater in the Red sub-catchment than the Grey sub-catchment. The degree of redistribution increases during the season in the Grey sub-catchment and in the latter two events, the range and CV of infiltration values is greater in the Grey sub-catchment. This change with time may reflect changes in surface detention and infiltration capacity of the soils. The grey duplex soils in particular tend to lose surface roughness more rapidly.

Drainage to groundwater

In both sub-catchments, drainage to groundwater from the soil profile indicated by changes in soil water contents at depth, was almost entirely associated with the 17/18 February 1995 event. Drainage was spatially variable within both sub-catchments and did not occur at all sites. In the Red sub-catchment the soil water potential profiles measured at two sites indicated almost identical movement of the Zero Flux Plane during the season. These two sites were both locations at which drainage was observed, and the ZFP depths were applied to estimate drainage at nine other sites where drainage was indicated by soil water content changes. Total drainage for the year is shown in Figure 3.5. The maximum drainage of 75 mm occurred at the site of highest infiltration (RSC18) located up-slope of the contour bund close to where it is breached. The average drainage for 16 sites was 24 mm. Where drainage was observed, it commenced soon after the 17/18 February 1995 event and had ceased by the end of April.

In the Grey sub-catchment, drainage could not be calculated from soil water content and potential measurements because of lateral water movement across the clay layer. However, at four sites significant changes in soil water content occurred throughout the profile to at least 1.8 m depth, indicating that some drainage occurred (Figure 3.5). At all other sites there was no seasonal change in soil water content in the clay layer, implying that drainage through the layer did not occur.

The relationship between measured infiltration and drainage to groundwater for the red clay soil is shown in Figure 3.9. For nine sub-catchment sites where drainage was observed, there was a significant linear relationship between the amount of infiltration and drainage (R= 0.79). Enhanced infiltration due to runon resulted in increased drainage. However, the remaining sites where drainage did not occur were not sites of particularly low infiltration indicating that at a local scale, other factors such as spatial variability in soil properties are also important in controlling the amount of drainage from the soil profile. In the Grey sub-catchment, the four sites where drainage was indicated by soil water content measurements were all sites of relatively high infiltration during the 17/18 February 1995 event. Mean infiltration at these sites was 178 mm, compared to the sub-catchment average of 102 mm.

Crop yields

Maize grain yields around each access tube in both sub-catchments are shown in Figure 3.6 . In the Red sub-catchment, yields varied between 0.87 and 4.24 t ha^{-1} with an average of 1.77 t ha^{-1} (excluding site RSC20 which is located at the edge of a termite mound and was only partially cropped). In the Grey sub-catchment maize yields averaged 1.96 t ha^{-1} and varied between 0.50 and 4.29 t ha^{-1} (excluding site GSC2 which is located in the gulley in the lower field and was not cropped but left under grass to reduce soil erosion). The mean yield was 11% greater than in the Red sub-catchment although a similar range was observed.

Annual water balance of the red and grey sub-catchments

Table 3.3 provides a summary of the annual water balance of the Red and Grey sub-catchments during 1994/95 (1 July 1994 to 30 June 1995). In this year of relatively low rainfall, runoff at field scale was a small component of the water balance accounting for only 1.2 and 6.5 per cent of rainfall for the Red and Grey sub-catchments respectively. The higher runoff from the grey soil this year was a result of lower infiltration rate, although in wetter years runoff is due more to saturation of the thin soils above the impermeable sandy clay layer . .The largest component of the water balance was evaporation, which accounted for 89 and 79 per cent of rainfall on the Red and Grey sub-catchments respectively. Only a small proportion of this evaporation (13 and 16 per cent on red and grey respectively) was estimated to be due to uptake by the maize crop. Most evaporation was from the soil surface and from leaves after interception by the crop canopy, with some further uptake by weeds. Drainage was a relatively small fraction of rainfall, although important because it constitutes the recharge to groundwater. Drainage was estimated to be 24 mm in the Red sub-catchment and 16 mm in the Grey sub-catchment, equivalent to 3.3 and 2.2 per cent of rainfall respectively. These results are indicative of generally higher recharge recorded on the red clay soils than the grey duplex soils and discussed in later Chapters.

3.3 Implications for soil and water conservation

Effects of surface redistribution of rainfall

On both soil types, surface redistribution of rainfall in 1994/95 was important in determining whether recharge occurred. Although total rainfall was above average, the rainfall distribution was poor in terms of generating recharge, due to the wide spacing of rainstorms. In this type of year, surface redistribution of rainfall becomes particularly important because without this process recharge would not occur in many areas. In wetter years or on more freely draining soils, where drainage is more likely to occur at all locations, the benefits of surface redistribution of rainfall will be less and increased recharge at runon sites may be cancelled to some extent by reduced recharge at runoff sites. The process of surface redistribution of rainfall presents a challenge in modelling the soil water balance, particularly in semi-arid regions where accurate prediction of recharge is important. Simulations that neglect this process are likely to be most in error in years when groundwater recharge is low and when accurate assessment of the resource is most crucial.

Effects of micro-topography

Many neutron probe sites in both sub-catchments were not consistent locations of either runon (infiltration > rainfall) or runoff (infiltration < rainfall) during the four major rainstorms of 1994/95. Figure 3.7 shows point measurements of infiltration grouped according to sites of runon, runoff and inconsistent behaviour. Rainfall Concentration Factors (RCF) are calculated after Gaze (1997). Of 17 sites in the Red sub-catchment, 10 were locations where both runon and runoff were observed during the year. Similarly, in the Grey sub-catchment 6 out of 20 sites behaved inconsistently. In both sub-catchments, the soil surface was regularly disturbed by cultivations between runoff events, and infiltration varied due to the changes in micro-topography caused by this weeding and the gradual flattening of ridges left after the initial cultivation. As might be expected, soil surface micro-topography has less impact on groundwater recharge than conservation structures that create sites of consistent and substantial concentration of water.

Effect of contour bunds within fields

Infiltration up-slope and down-slope of contour bunds in the Red and Grey sub-catchments and along the inselberg hillslope transect during the 17/18 February 1995 rainstorm is shown in Table 3.2. Considerably greater infiltration was observed at sites immediately up-slope of bunds. In the Grey sub-catchment the infiltration up-slope was 2.5 times greater than below (104 mm upslope compared to 42 mm down-slope). On red clay soils on the inselberg hillslope transect, up to 3 times greater infiltration was measured at sites above a contour bund than below (150 mm compared to 49 mm). In the Red sub-catchment the largest single value was obtained up-slope of the bund at site RSC18, although elsewhere there was little difference, apparently due to lower redistribution of water in the Red sub-catchment (5.8 mm runoff compared to 42.6 mm in the Grey). Soil and water conservation structures such as contour bunds clearly do affect groundwater recharge, especially when runoff volumes are large and where the structures concentrate and hold water. Ironically, the contour channels present in Romwe and across much of Zimbabwe were installed in the 1950s to carry water away in a controlled manner and thereby reduce soil erosion. In 1994/95, recharge through both soil types was actually dependent on surface redistribution of rainfall and concentration, principally behind contour bunds. Without redistribution and relatively large water holding structures, this form of recharge would not have occurred in this year.

Effects of surface redistribution of rainfall on crop production

Surface redistribution of rainfall was an important hydrological process at field scale on both soil types in 1994/95. Rainfall concentration factors for four events ranged from 0.20 to 2.68 in the Red sub-catchment and from 0.23 to 2.59 in the Grey sub-catchment. In a year with 738 mm rainfall, surface redistribution of rainfall resulted in infiltration varying between 658 and 891 mm on the red clay soils and 548 and 1087 mm on the grey duplex soils. With relatively low runoff this year, only sites behind contour bunds or on the field margins were consistently locations of either runon or runoff. Crop yields in the Red sub-catchment could not be related to the effects of variable infiltration, and field observations suggest that the most important factors were catenal variation in soil properties and differences in crop management. The best yields were obtained towards the base of the slope in the lower field, averaging 2.5 t ha^{-1} for sites RSC1-8, where soils have vertic properties and a high proportion of 2:1 clay minerals. In addition to better chemical fertility, germination and crop establishment were better in this part of the sub-catchment due to better soil moisture conditions at planting. In the upper part of the lower field (RSC9-16) where soils are more eroded and crop establishment was poor, yields averaged only 1.18 t ha^{-1}. In the upper field, yields averaged 1.64 t ha^{-1} for tubes RSC17-24 (excluding RSC20 which was only partially cropped). Better crop establishment was achieved here because seeds germinated later with a different sowing method adopted by the farmer, seeds being sown into relatively dry soil delaying germination until after the 24-28 December rainstorms.

The grey duplex soils, although of poor nutrient status, are valued by farmers because of the reduced tillage requirements in cultivating the sandy loam topsoil. This enables farmers to plant quickly after rainfall and get crops established in the narrow window when soil moisture conditions are favourable for germination. However, because of limited water holding capacity, crops cultivated on these soils are prone to moisture stress during dry spells. By 17 February 1995 the sandy loam horizons contained very little available moisture following a four week dry spell. By this date, 66 days after sowing, the maize plants were between 1.1 and 2.1 m tall, were tasselling, and showed signs of moisture stress. Crop yields in the Grey sub-catchment were highly variable (0.5 to 4.29 t ha^{-1}) and were highly correlated with the amount of infiltration following the 17/18 February 1995 event (Figure 3.10). In fact, it was the critical factor affecting yield on this soil type in this year. The correlation coefficient of 0.82 was significant at the 0.1% level of the F-distribution. Yield was not significantly correlated with infiltration prior to this event. There was also no significant relationship between crop yield and depth to the clay layer.

The relationship shown between infiltration and yield indicates that significant improvements in crop yield can be achieved in difficult years by management practices designed to enhance infiltration and reduce runoff. Such practices include tied-ridging and mulch ripping (Chuma & Hagmann, 1995). Runoff recorded during the 17/18 February 1995 storm amounted to 33 per cent of rainfall and, if retained in-field, could have significantly increased crop yields this year.

Table 3.1 Rainfall, runoff and infiltration at sub-catchment and point-scales during the four major rainfall events of 1994/95

	Rainfall event data				Total
	24-28 Dec 1994	16-20 Jan 1995	16-18 Feb 1995	26-29 Mar 1995	1994/95
Rainfall					
Total rainfall (mm)	75.5	75.5 (Red)[1] 90.5 (Grey)	141.0	75.5 (Red)[2] 81.0 (Grey)	738
Peak rainfall intensity (mm hr^{-1})	60	135	90	90	
Rainfall at intensities > 15 mm hr^{-1} (mm)	35.0	49.0	111.5	30	
Sub-catchment runoff					
Red sub-catchment runoff (mm)	0.0	2.1	5.8	0.0	7.9
Grey sub-catchment runoff (mm)	0.0	0.9	42.6	0.0	43.6
Sub-catchment scale infiltration					
Red sub-catchment (mm)	75.5	73.4	135.2	75.5	730
Grey sub-catchment (mm)	75.5	89.6	98.4	81.0	694
Point-scale infiltration - Red sub-catchment					
No. of observations	8	17	17	17	17
Minimum	46	15	97	41	658
Maximum	144	202	227	85	891
CV %	53	64	23	22	8
Mean	83	66	136	57	719
Point-scale infiltration - Grey sub-catchment					
No. of observations	20	20	20	10	20
Minimum	57	37	33	51	548
Maximum	100	180	254	210	1087
CV %	15	43	51	63	17
Mean	70	68	102	76	664

Notes: [1] Rainfall for period 16-19 Jan 1995.
[2] Rainfall for period 26-28 March 1995.

Table 3.2 Infiltration above and below contour bunds for 17/18 February 1995 rainstorm

Site	Infiltration above bund			Infiltration below bund		
	Mean (mm)	Std. dev. (mm)	No. of sites	Mean (mm)	Std. dev. (mm)	No. of sites
Red sub-catchment	161	125	3	154	99	4
Grey sub-catchment	104	57	5	42	36	3
Inselberg hillslope transect	150	26	2	49	38	2

Table 3.3 Annual water balance of the Red and Grey sub-catchments in 1994/95

Site	Rainfall	mm water *(in brackets as % rainfall)*					
		Runoff	Total evaporation[1]	Evap. of intercepted water and from soil and weeds	Evap. from crop[2]	Drainage (recharge)	Change in storage
	P	Q	E_a	$E_i + E_w$	E_c	D	ΔS
Red sub-catchment	737.5	9 *(1.3)*	655 (88.8)	556 (75.3)	99 (13.4)	24 *(3.3)*	50 *(6.8)*
Grey sub-catchment	737.5	48 *(6.5)*	654 (88.6)	540 (73.2)	114 (15.5)	16 (2.2)	20 (2.7)

[1] Total evaporation was calculated as the difference between rainfall and measured runoff, drainage and change in soil water storage.

[2] Evaporation by the crop was estimated from dry matter yield measurements. Evaporation of intercepted water, evaporation from the soil, and evaporation by weeds was calculated by difference from total evaporation.

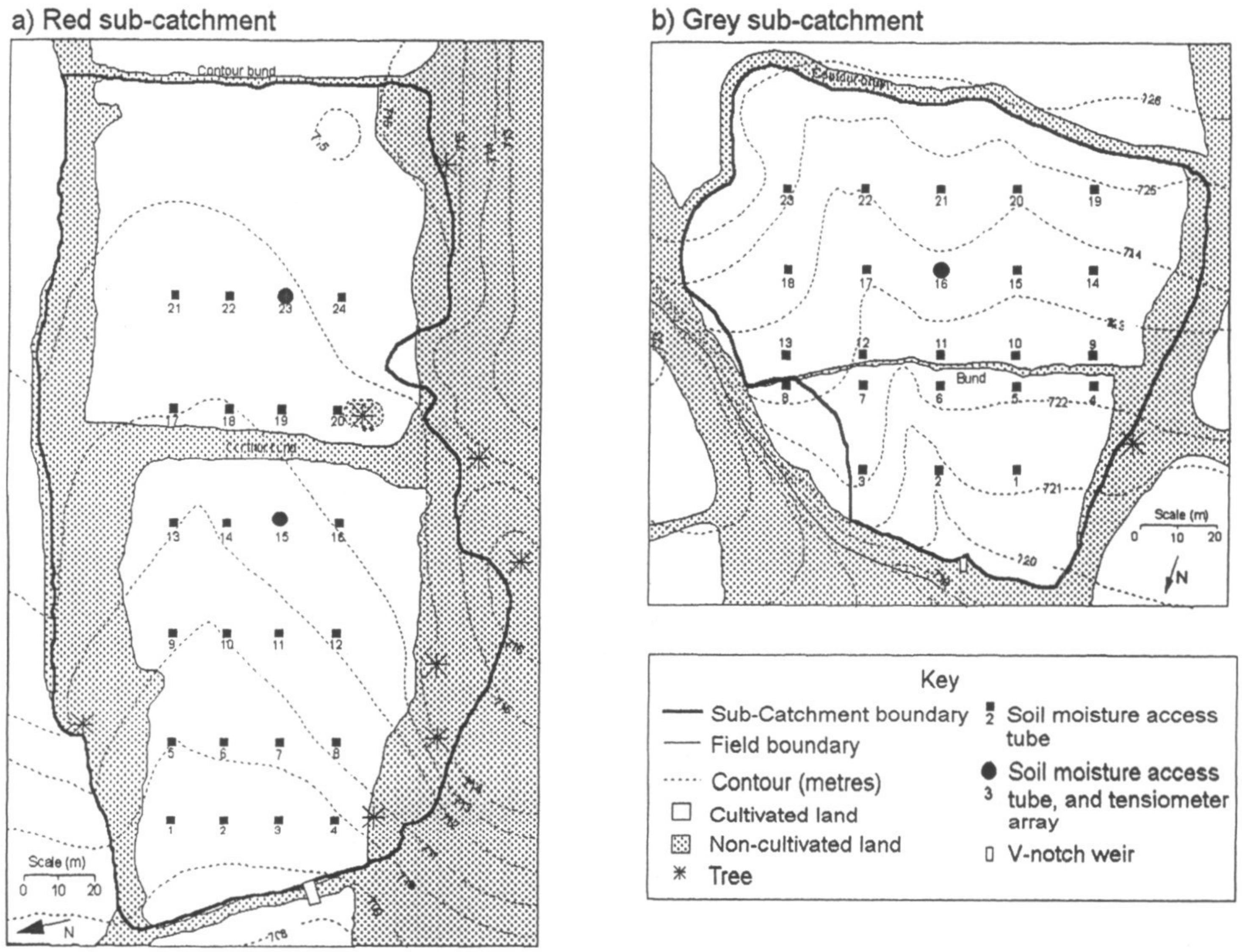
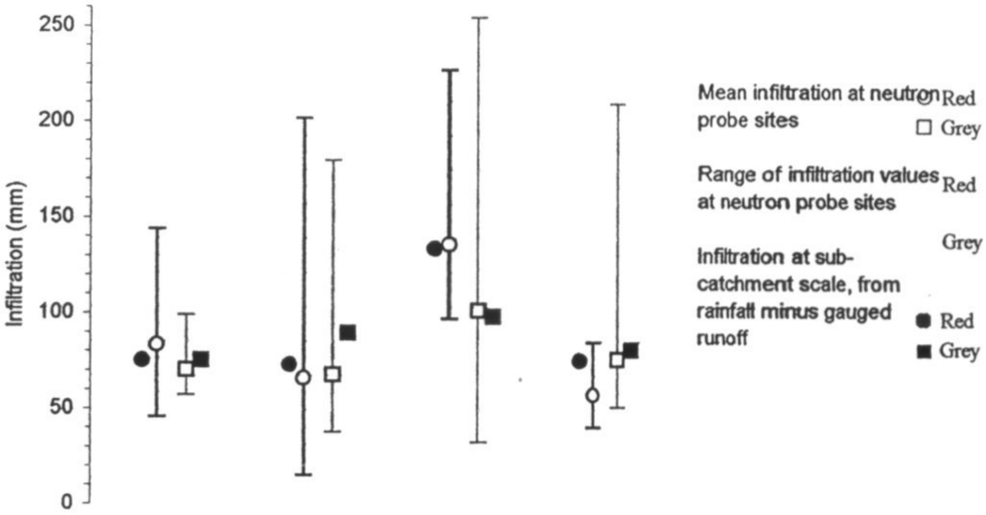


Figure 3.1 Red and Grey sub-catchment study sites

a) Infiltration at point and sub-catchment scales



b) Event rainfall

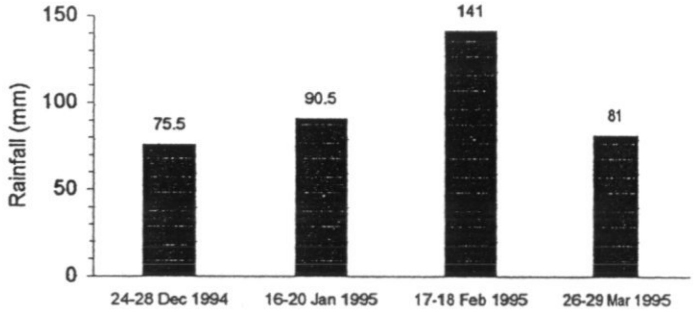


Figure 3.2 Infiltration at point and sub-catchment scales, 1994/95

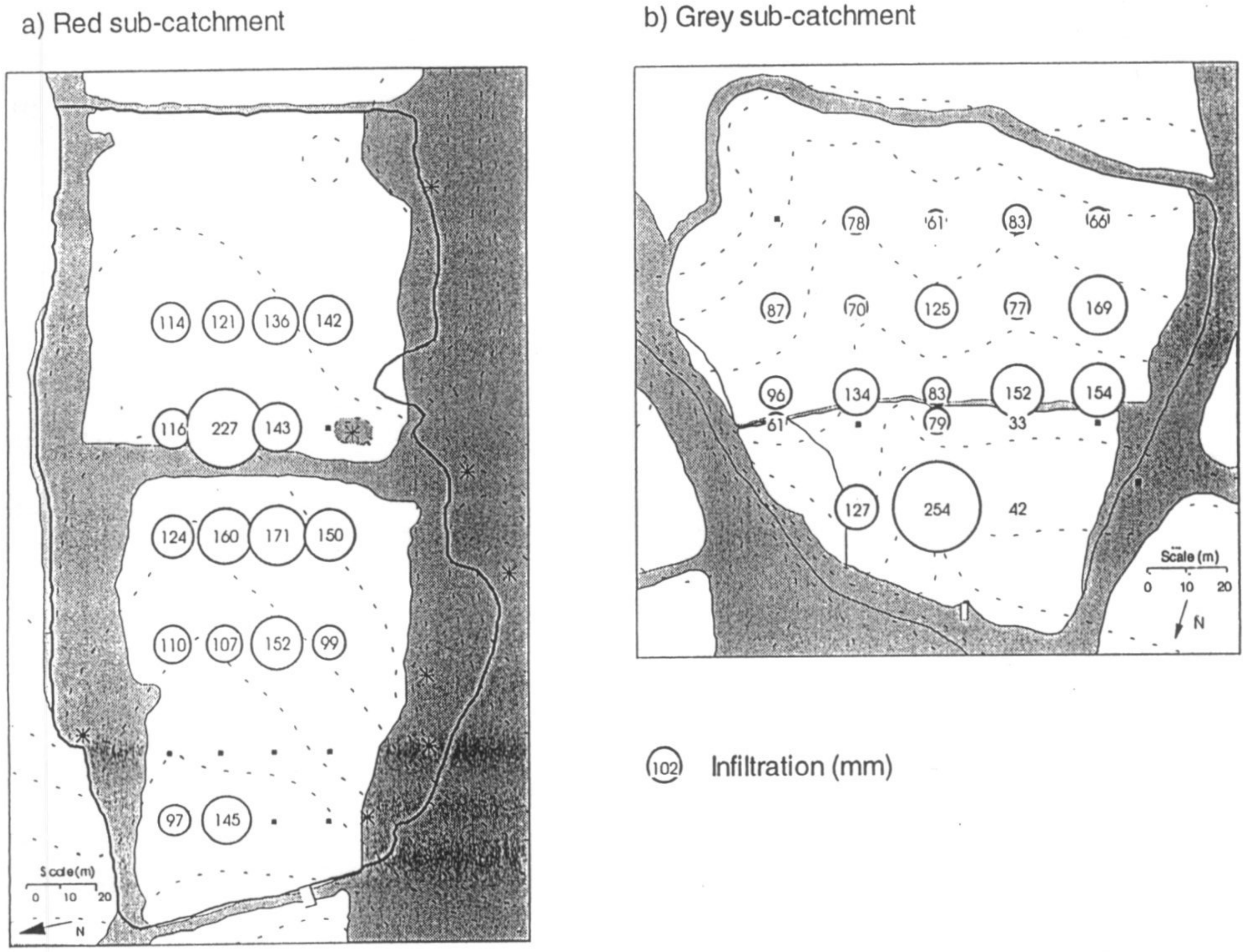


Figure 3.3 Infiltration measured after 17/18 February 1995 rainstorm, a) Red sub-catchment, b) Grey sub-catchment.

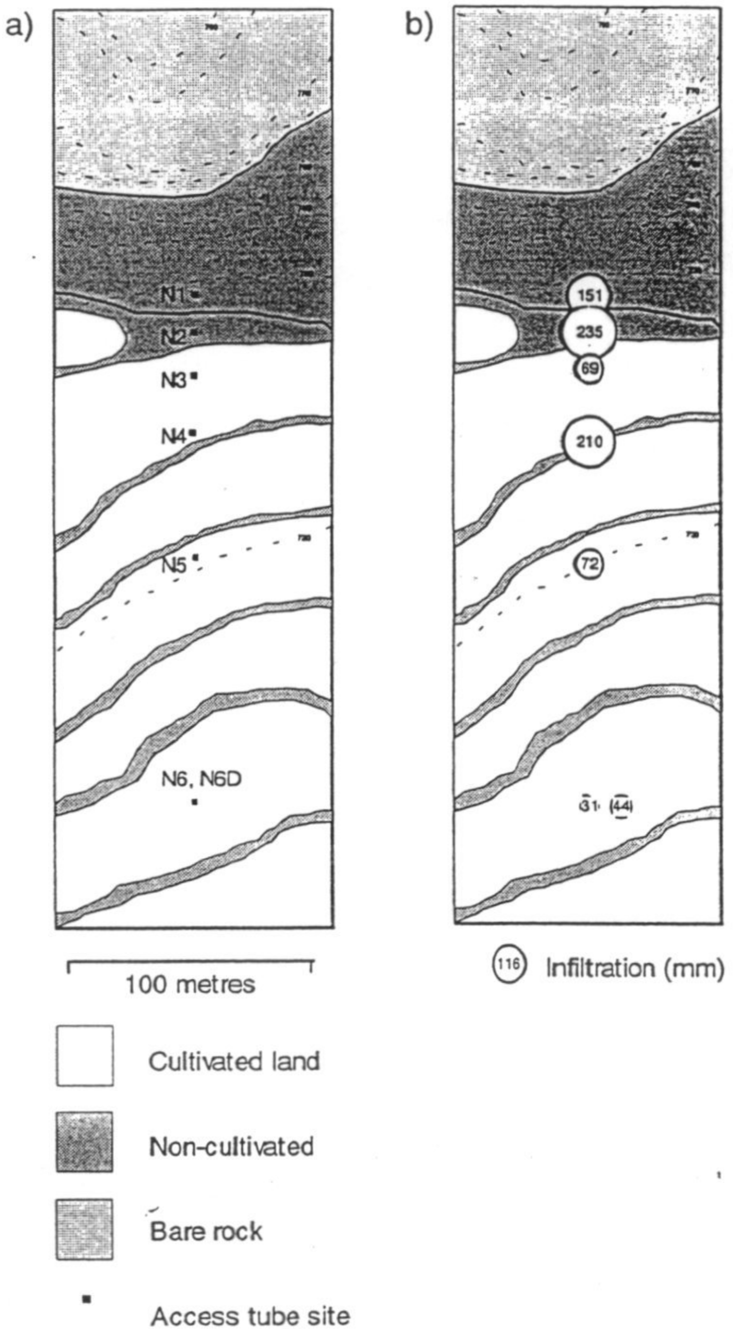
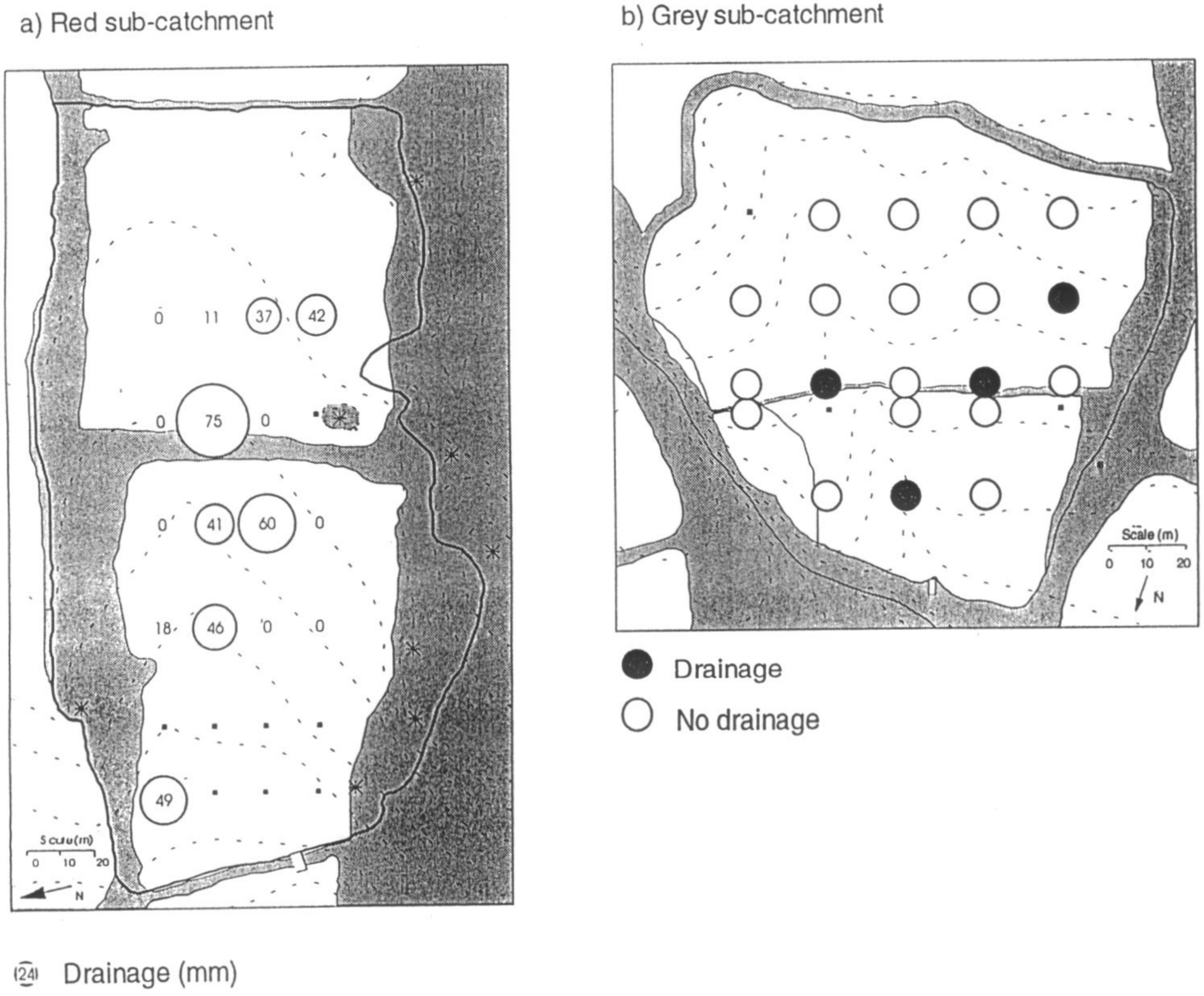


Figure 3.4 Infiltration measured after 17/18 February 1995 rainstorm along the inselberg hillslope transect.



a) Red sub-catchment

b) Grey sub-catchment

Figure 3.5 Drainage in 1994/95, a) Red sub-catchment, b) Grey sub-catchment.

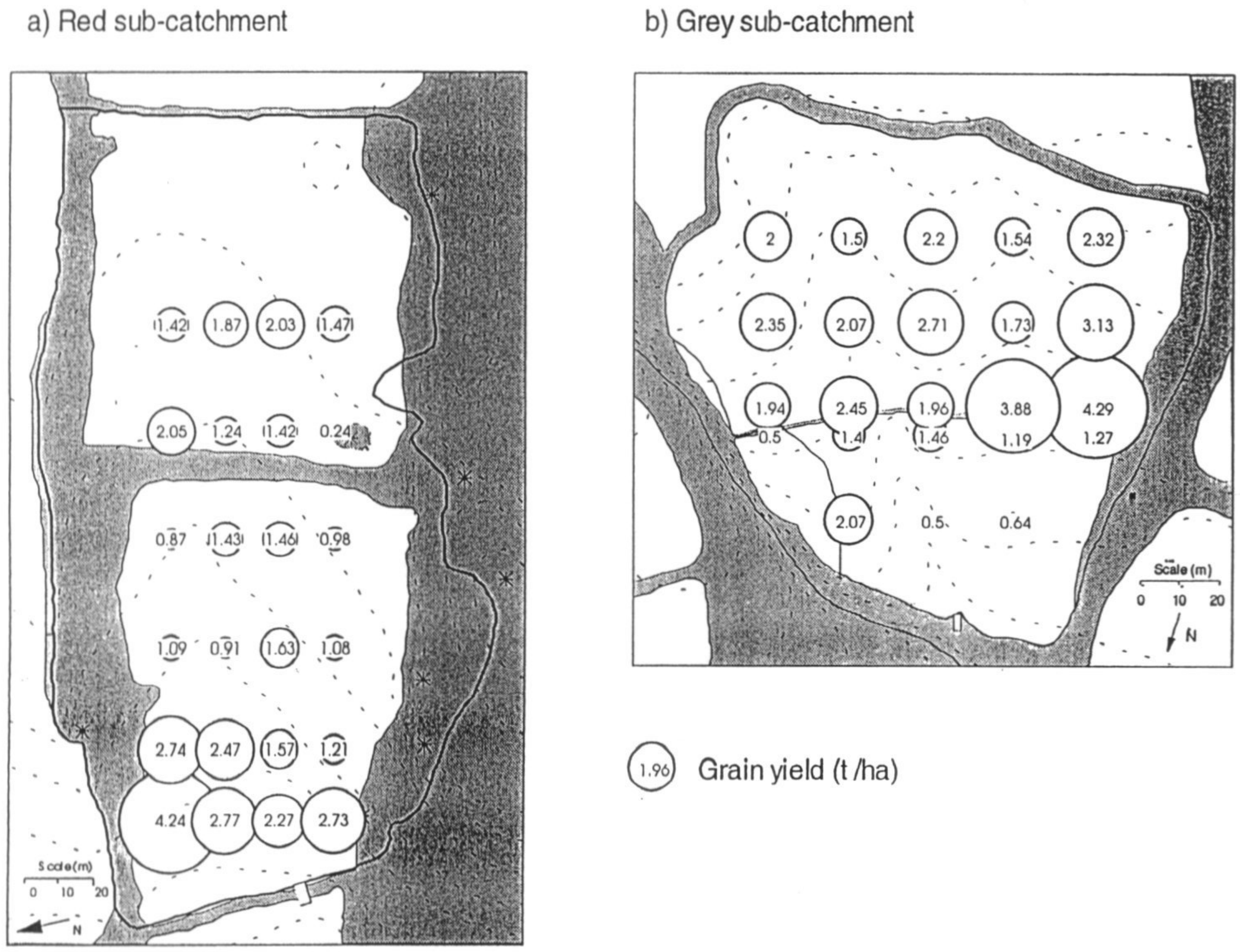


Figure 3.6 Maize grain yields in 1994/95, a) Red sub-catchment, b) Grey sub-catchment.

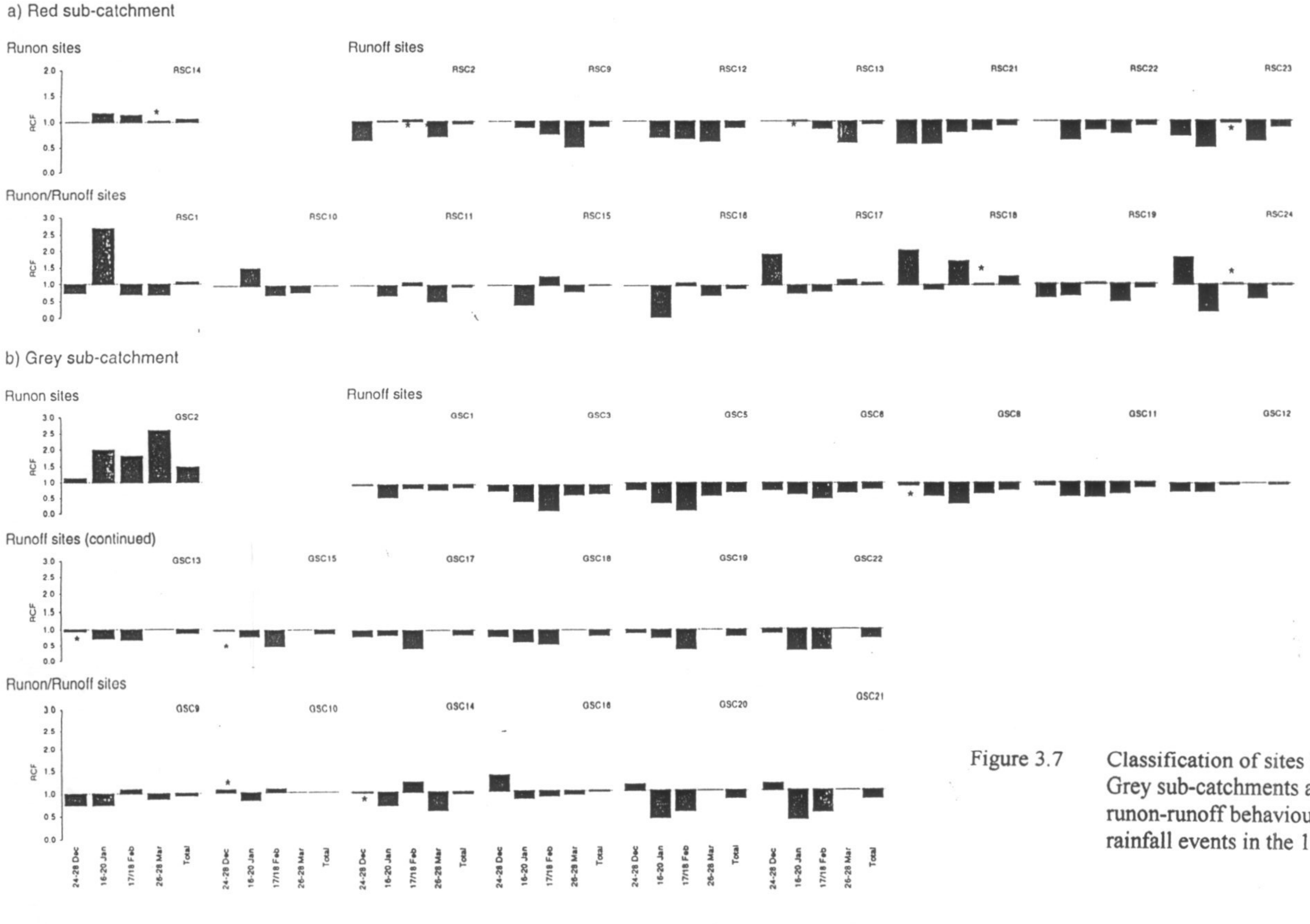


Figure 3.7 Classification of sites in the Red and Grey sub-catchments according to runon-runoff behaviour during 4 main rainfall events in the 1994/95 season

Notes: * symbol indicates where RCF was within estimated range of measurement error.

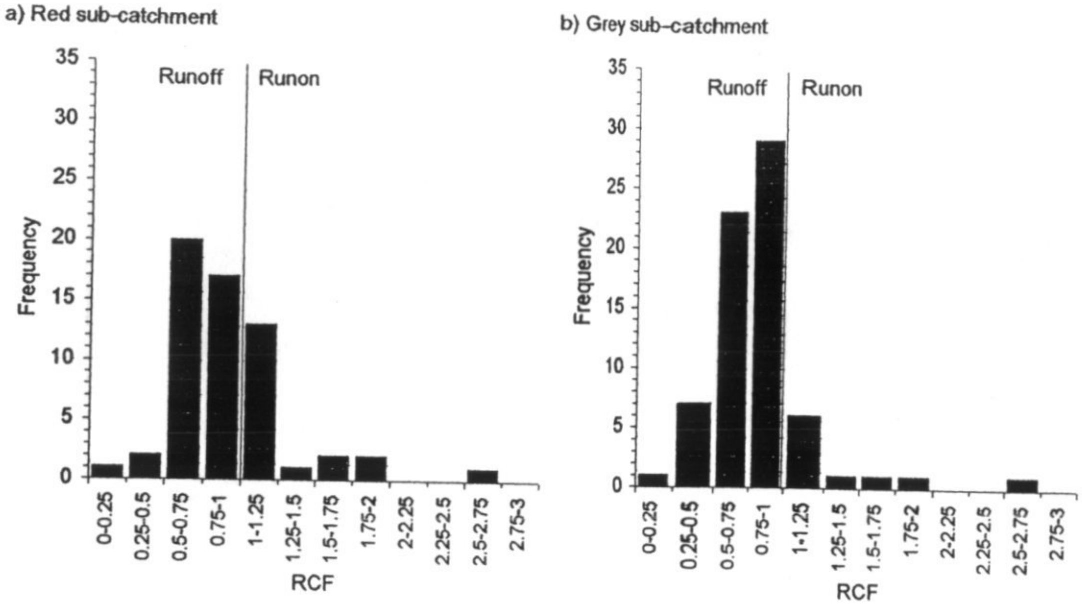


Figure 3.8 Frequency plots of rainfall concentration factors (RCF) for rainstorms in 1994/95 which resulted in surface redistribution of rainfall

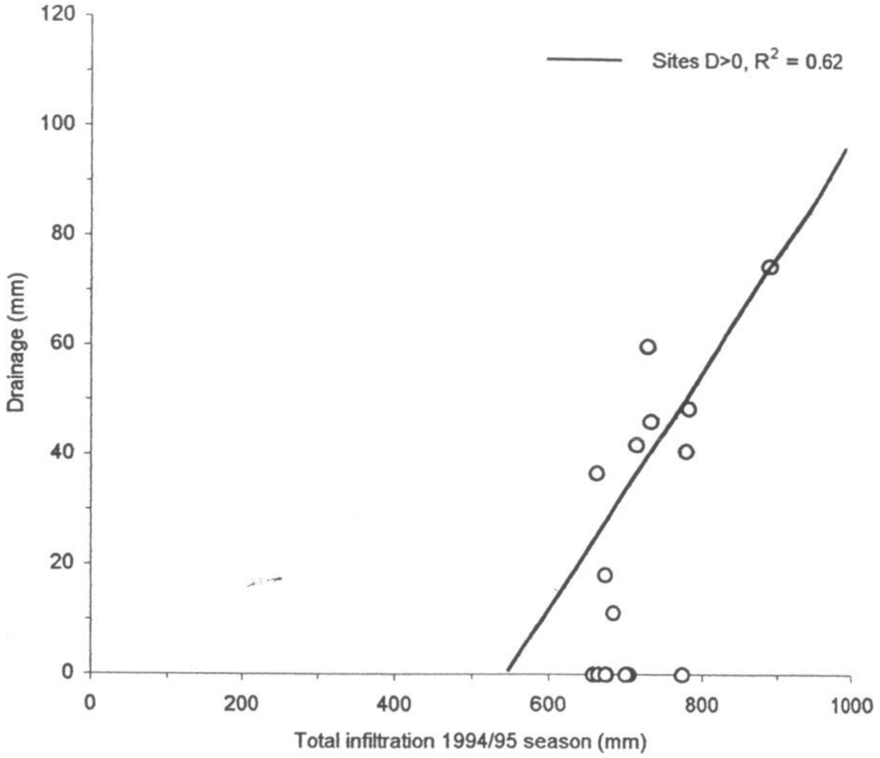


Figure 3.9 Relationship between total infiltration and drainage in 1994/95, Red sub-catchment

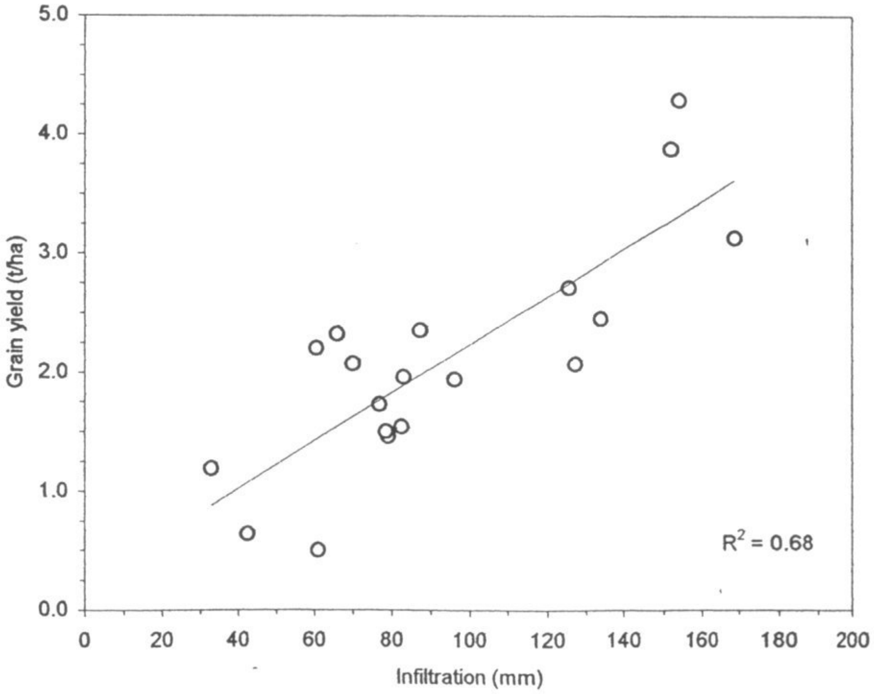


Figure 3.10 Relationship between infiltration measured after the 17/18 February 1995 rainstorm and maize yield, Grey sub-catchment

4. GROUNDWATER RECHARGE DYNAMICS

4.1 Introduction

In this chapter, characteristics of the observed groundwater level fluctuations within the catchment are presented, and inter-annual variation in recharge is discussed.

Groundwater levels

Groundwater levels were measured at up to 65 locations in and around the catchment at locations shown in Figure 4.1. The observation boreholes or piezometers were drilled using drag bits switching to the down-the-hole hammer technique when the formation became hard. All piezometers were 0.1 m in diameter and open-holed with plastic slotted screen to ensure access for a water-level dipper. The piezometers were drilled through the shallow weathered layer just into the bedrock, and drilling depth varied from 1.5 to 29.3 m. They were completed at the surface with a cement seal and metal casing. At some sites monitoring commenced in late 1992 and have now been measured over four rainy seasons. Other sites were monitored from late 1993 over three rainy seasons. In the southern part of the catchment where leucocratic pyroxene gneiss occurs, depth to bedrock averaged 7.0 m. On the northern side in areas of pyroxene gneiss, average depth to bedrock was 10.3 m.

Groundwater hydrographs

Measured groundwater response to rainfall was spatially highly variable within the catchment. In the northern part where pyroxene gneisses predominate, and particularly towards the north-west, levels respond rapidly to rainfall within a few days of major rainstorms. In contrast, in the southern part of the catchment where leucocratic gneisses occur, levels rise much more gradually. Groundwater hydrographs from sites typical of these two areas are shown in Figure 4.2. At site G in the north-eastern part of the catchment, groundwater levels rise more rapidly than at site K2 in southern part of the catchment. At site G, the red clay soils are relatively permeable due to the well developed micro-granular soil structure. At site K2 the thick sandy-clay layer at depth is much less permeable, impeding recharge to the weathered aquifer below. In wetter years a perched water table forms in the upper soil horizons above this layer resulting in considerable interflow of water at the interface rather than deep percolation.

A cross-section across the catchment constructed from borehole drilling logs is shown in Figure 4.3. Water levels in 1993/94 at times of high levels (13 January 1994) and low levels (30 June 1994) are shown. The limited fluctuation in levels in the weathered aquifer on the southern side of the catchment below the sandy clay layer contrasts with the larger fluctuations in levels in the northern part of the catchment where annual fluctuations of up to 7 m were observed. The most productive traditional wells and the high yielding collector well are all sited in the northern part of the catchment. Good well performance in this area is considered to be due to; increased recharge; greater depth of saturated weathering; the influence of faults and fractures on aquifer permeability; and the retention of groundwater behind a band of quartzo feldspathic gneiss running approximately east-west. The influence these factors have on the sustainable yield of wells and boreholes in crystalline basement aquifers is discussed further in Chapter 7.

4.2 Rainfall - recharge relationships from measured data

The magnitude of groundwater rise observed in the four rainy seasons since 1992 has been markedly different. Annual rainfall and maximum rise in groundwater level are shown in Table 4.1. Rainfall in 1992/93 was below average. The total of 570 mm was only 81 per cent of the estimated long term mean of 704 mm (corrected to ground-level rainfall). Rainfalls in 1993/94 and 1994/95 were similar at 740 and 738 mm and close to the estimated long term mean. Rainfall in 1995/96 was 990 mm, or 141 per cent of the estimated long term mean.

For a small number of sites near the collector well for which water level measurements were available from 1992, the average maximum rise in groundwater level in 1992/93 was 2.06 m. This compared to 2.81 m in 1993/94 and 0.64 m in 1994/95. The greater rise in 1993/94 compared to the previous year reflects the higher rainfall. However, the smaller rise in 1994/95 despite similar rainfall reflects the pattern or distribution of rainfall in this year. For the larger number of sites recorded since 1993, the average maximum rise in 1993/94 was 2.72 m, still considerably greater than 1.09 m recorded in 1994/95. The major difference between the 1993/94 and 1994/95 seasons was the distribution of rainfall. In 1993/94 rainfall distribution was skewed towards the early part of the season and the largest monthly rainfall total was recorded in November. In 1994/95 the rainfall was distributed over a longer period and skewed towards the latter part of the season, with the largest monthly rainfall recorded in February. The effect of this distribution of rainfall in 1994/95 was to significantly reduce the amount of groundwater recharge. At some sites there was no rise at all in groundwater levels during this season. Groundwater level rises in 1995/96 when total rainfall was 990 mm were considerably greater than in all three previous seasons (Figure 4.2).

A crude relationship exists therefore between annual rainfall and recharge with the greatest groundwater level rises observed in 1995/95 when the highest rainfall was received, and greater rises observed in 1993/94 than 1992/93 again due to the higher rainfall in the later year. However, groundwater level rises observed in 1994/95 show this comparison to be too simplistic. Even in a year of above average rainfall, recharge may be low or absent if the distribution of rainfall is not favourable. The intensity of rainfall received will also be important to recharge because of the effects on runoff generation and hence surface redistribution of water (Chapter 3).

In 1993/94, groundwater level rises were initiated by 153 mm of rain over a 7 day period from 24-30 November 1993, including 96 mm on a single day. These were the first significant rains of the season, and occurred when soil water deficits were at a maximum after the long dry season. In 1994/95 groundwater level responses at most sites were linked entirely with 141 mm of rain received in a single storm on 17/18 February 1995. This event occurred late in the rainy season, but followed a dry period of 27 days which allowed a large soil water deficit to accumulate. In 1995/96 groundwater rises were observed after 162 mm rain during the period 14-17 January. This followed a dry period of 23 days during which only 3.5 mm rain fell and after moderate rains in mid-December 1995. Observations like these show that rainfall between 141 and 162 mm received over a number of days is sufficient to result in widespread groundwater recharge.

It is also instructive to consider rainfall events in the years which did not result in recharge in most parts of the catchment. In 1993/94 there were no large rainstorms prior to the main recharge event. However, in 1994/95 and 1995/96, rainfall events of 57 mm (3 days), 76 mm (5 days), 91 mm

(5 days), 61 mm (2 days), and 53 mm (5 days) did not result in recharge. Variations in antecedent soil moisture, rainfall intensity, vegetation cover, runoff and surface redistribution of rainfall are all important to recharge, in addition to rainfall amount. However the above analysis suggests that more than 100 mm of rainfall in less than one week is generally required to initiate recharge.

4.3 Rainfall - recharge relationships from model simulations

To extend the measured data from a limited number of seasons, rainfall/recharge relationships were studied over the period 1953-96 for a profile with red clay soils using the two-layer tank-type soil water balance model in the ACRU modelling system (Schulze, 1995; Smithers & Schulze, 1995). Daily rainfall data for this period was taken for Chendebvu Dam and potential evaporation was determined using temperature data from Masvingo. The parameterisation of the ACRU model and testing of results against measured runoff, soil water content, soil evaporation and drainage for the Romwe catchment are described in more detail in Chapter 5.

Figure 4.4 shows a simulated relationship between rainfall and drainage for a profile with red clay soils and pyroxene gneiss geology. Drainage is simulated to occur in all years with annual rainfall greater than 610 mm, although significant drainage occurs in 3 seasons with rainfall below this threshold. The best-fit line between rainfall and drainage in years where drainage occurs actually predicts a threshold rainfall value of 507 mm (correlation coefficient of 0.83). The slope of this relationship is 0.50 which suggests that above 507 mm, each additional 1 mm rainfall results in 0.5 mm drainage. This estimate of annual rainfall required for recharge to occur is greater than the threshold value of 400 mm suggested by Houston (1988) for the region, although it is based on ground-level rainfall values and relatively low permeability soils which both result in calculation of a higher threshold. Simulated annual drainage is relatively high with a mean of 100 mm, which is about four times greater than the estimate of 24 mm for historical recharge on this soil type using the chloride balance method (Macdonald *et al.*, 1995). Temporal variability is high with a standard deviation of 130 mm and a range between 4 and 420 mm.

In Figure 4.4, a number of years where simulated drainage is close to the average rainfall/recharge relationship (within arbitrary limits of ± 50 mm rainfall) can be identified (Group 1). Either side occur groups of years with high drainage (Group 2) and low drainage (Group 3) for the rainfall received. Another group of years with zero or very low drainage can be identified (Group 4) and there is a final cluster of years with expected high rainfall and drainage (Group 5).

The annual distribution of rainfall for years belonging to the first four of these groups is shown in Figure 4.5. In years with an average rainfall/recharge relationship (Group 1) there is considerable variation in rainfall distribution, although all years have a single month of high rainfall (over 200 mm). In the three years with relatively high drainage for the rainfall received (Group 2) a large proportion of rainfall occurs within a single month fairly early in the rainy season, in December or January. In the years with relatively low drainage for the amount of rainfall received (Group 3), rainfall is distributed more evenly and if there is a high rainfall month (over 200 mm) this tends to occur later in the rainy season in February or March. Years with zero or very low drainage (Group 4) are characterised by evenly distributed rainfall and generally lack a single month with high rainfall (over 200 mm). These years cover a large range of annual rainfalls and include years of up to 619 mm rainfall when drainage was still close to zero.

Comparison between simulated drainage and maximum weekly rainfall over the 43 year period from 1953 to 1996 generally supports the observation that 100-140 mm rainfall in a week is necessary to initiate recharge (Figure 4.5c). There was significant drainage in only two years with maximum weekly rainfall below 100 mm, and considerable drainage in all but one year where maximum weekly rainfall exceeded 140 mm.

Groundwater recharge processes

The rapid response of groundwater to rainstorms, with levels at many locations rising only a few days after rainfall, raises important questions about the processes responsible for groundwater recharge. The most rapid responses were observed along the inselberg hillslope transect (Figure 3.4) where groundwater hydrographs were particularly 'flashy'. Combined measurements of soil moisture content and groundwater level made at this site from February 1994 were analysed to compare response in the unsaturated and saturated zones.

Deep soil moisture storage and groundwater levels along the inselberg hillslope transect are shown in Figure 4.6 together with monthly rainfall totals. Soil moisture storage is shown as the total amount of water stored at depths between 1.3 m and 2.1 m, with the exception of site N3 where limited tube depth permitted measurement to 1.9 m. Over this depth in fields cropped mainly with maize, the amount of water extracted by plants is likely to be negligible, as shown by maximum observed ZFP depths of 1.2m within fields of maize on this soil type (Chapter 3). However, at site N2 (Figure 3.4) deep rooting trees and shrubs close to the piezometer and neutron probe access tube mean that it is unreasonable to assume that extraction of water by plants is small.

In 1994/95 significant fluctuations in deep soil moisture content occurred at only two sites (N2 and N4). Run-on enhanced infiltration at these two sites, with runoff resulting in lower infiltration and wetting to only limited depth at other sites (Chapter 3). In the previous 1993/94 season large fluctuations were indicated at four of the five sites with only a small fluctuation at site N3. These observations suggest that drainage from the soil profile occurred over a larger area in 1993/94 than in 1994/95. In 1993/94 significant rainfall early in the season was sufficient to overcome soil moisture deficits at most sites and thus initiate drainage. In 1994/95 drainage was only initiated at sites where surface redistribution of rainfall resulted in enhanced infiltration. Although recharge did occur in 1994/95 at both piezometers N5 and N6, with a groundwater response to rainstorms in mid-January, mid-February and late March, wetting of the lower soil profile did not occur. At these sites, located just below a contour and in the middle of a field respectively, the source of recharge was therefore not the soil matrix in the immediate surroundings.

An alternative source of recharge down the hillslope are sites where enhanced infiltration occurs due to surface redistribution of rainfall, such as N2 and N4 located just above contour bunds. For the period in which groundwater levels responded to rainfall in 1994/95, moisture content deep in the soil profile at sites N2 and N4 and groundwater levels at sites N5 and N6 are compared in Figure 4.7. Groundwater at both sites rose by one metre or so during the week after the 16 January 1995 rainstorm. Although deep soil water content at site N2 did not change due to this rainfall, there was wetting at 2 m depth at site N4. Larger rises in groundwater level of up to 3 metres followed the 17/18 February 1995 rainstorm. Wetting of the deep soil profile at site N4 continued and an increase in soil water content at 2.2 m was observed at site N2. Rainfall in late March caused further increases in soil water content at site N4 but not at site N2.

The movement of soil water through the entire unsaturated zone to depths of up to 12 m was not studied. However, drainage at 2 m is strong evidence that direct recharge through the soil matrix beneath cropped fields is an important source of groundwater recharge in the catchment. Even where the response of groundwater to rainfall is rapid, it appears that direct recharge probably through macro-pores in the soil profile is the important process. However, in the year studied, rainfall was relatively evenly distributed and recharge by this process was confined to the red clay soils and to locations just behind contour bunds where surface redistribution of rainfall resulted in enhanced infiltration. In cropped fields, therefore, soil profile and surface management are the two major controls on groundwater recharge. This confirms the potential importance in groundwater protection of soil and water conservation methods such as contour bunds and infiltration pits, particularly in areas of the deeper red-clay soils.

Table 4.1 Annual rainfall and mean groundwater level rise

Season	Rainfall[1], mm	Mean groundwater level rise, m	
		Collector well observation boreholes	All sites
1992/93	570	2.06	
1993/94	740	2.81	2.72
1994/95	738	0.64	1.09
1995/96	990		
1996/97	1140		

Note: [1] corrected to ground-level gauge.

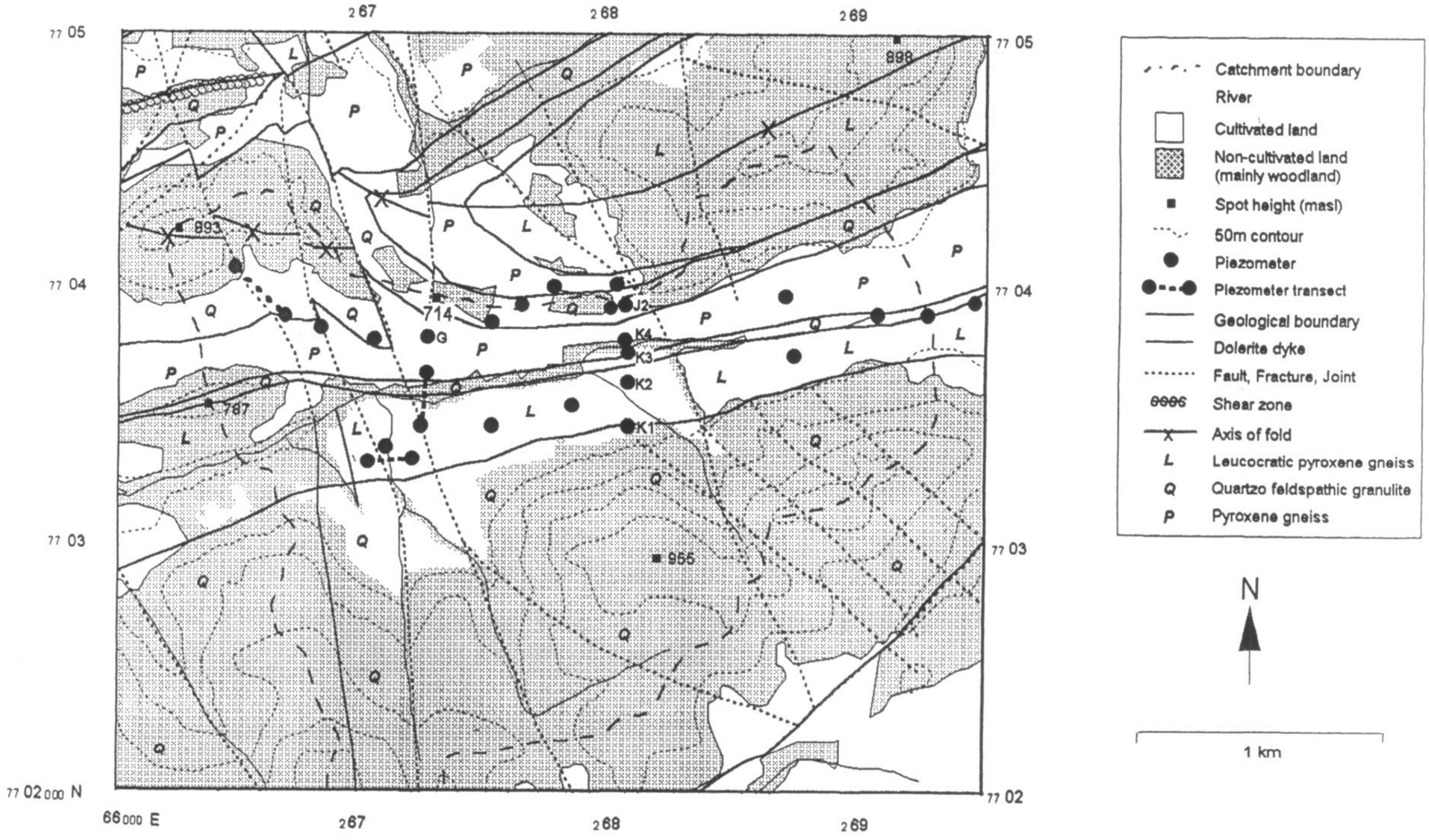


Figure 4.1 Catchment geology and monitoring sites

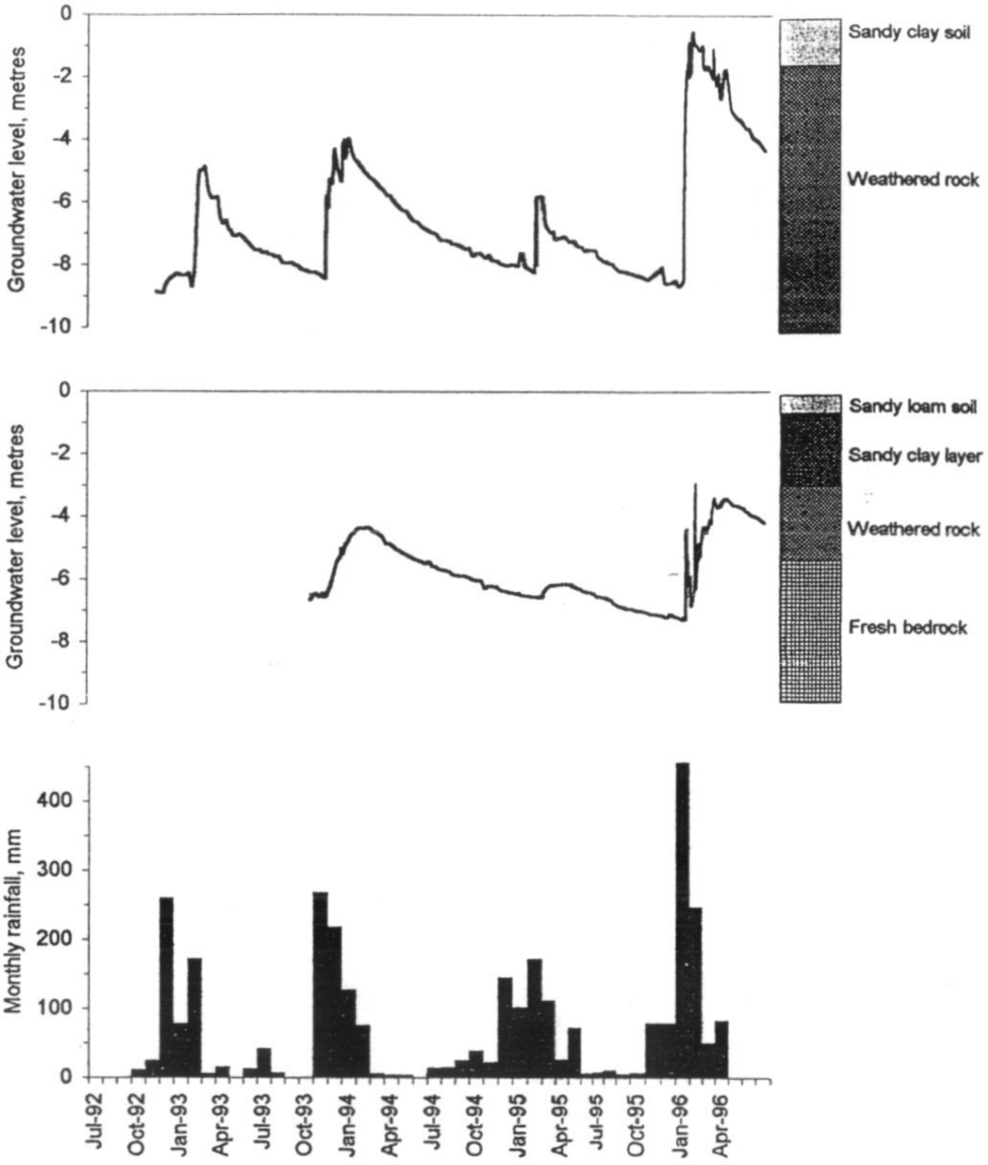
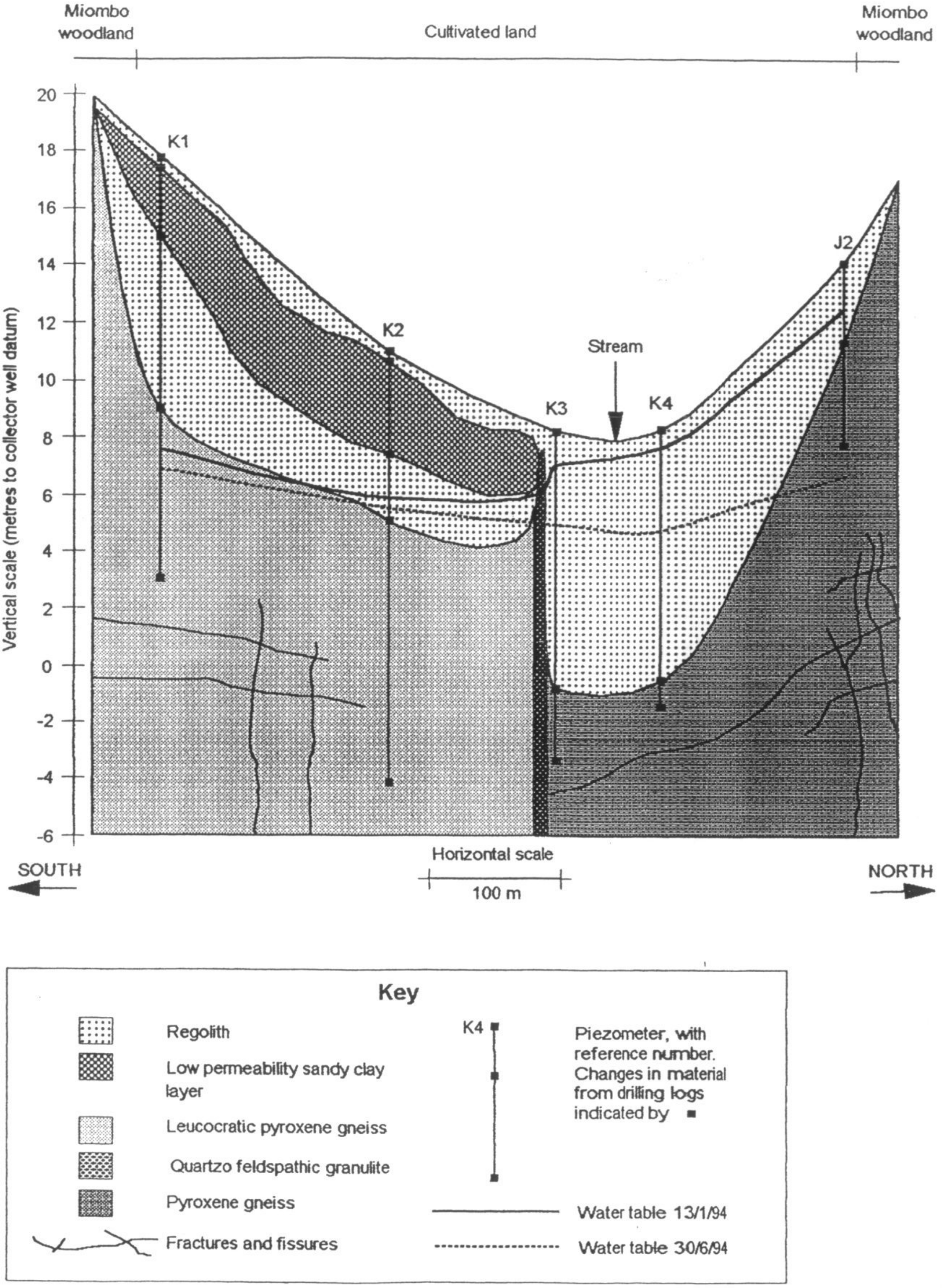


Figure 4.2 Monthly rainfall totals and groundwater hdyrographs at two contrasting sites on pyroxene gneiss (red clay soils) and leucocratic gneiss (grey duplex soils)



Note: Water level estimated at J2 on 30/6/94 when piezometer was dry.

Figure 4.3 Cross-section across valley showing depth of weathering and zone of water table fluctuation

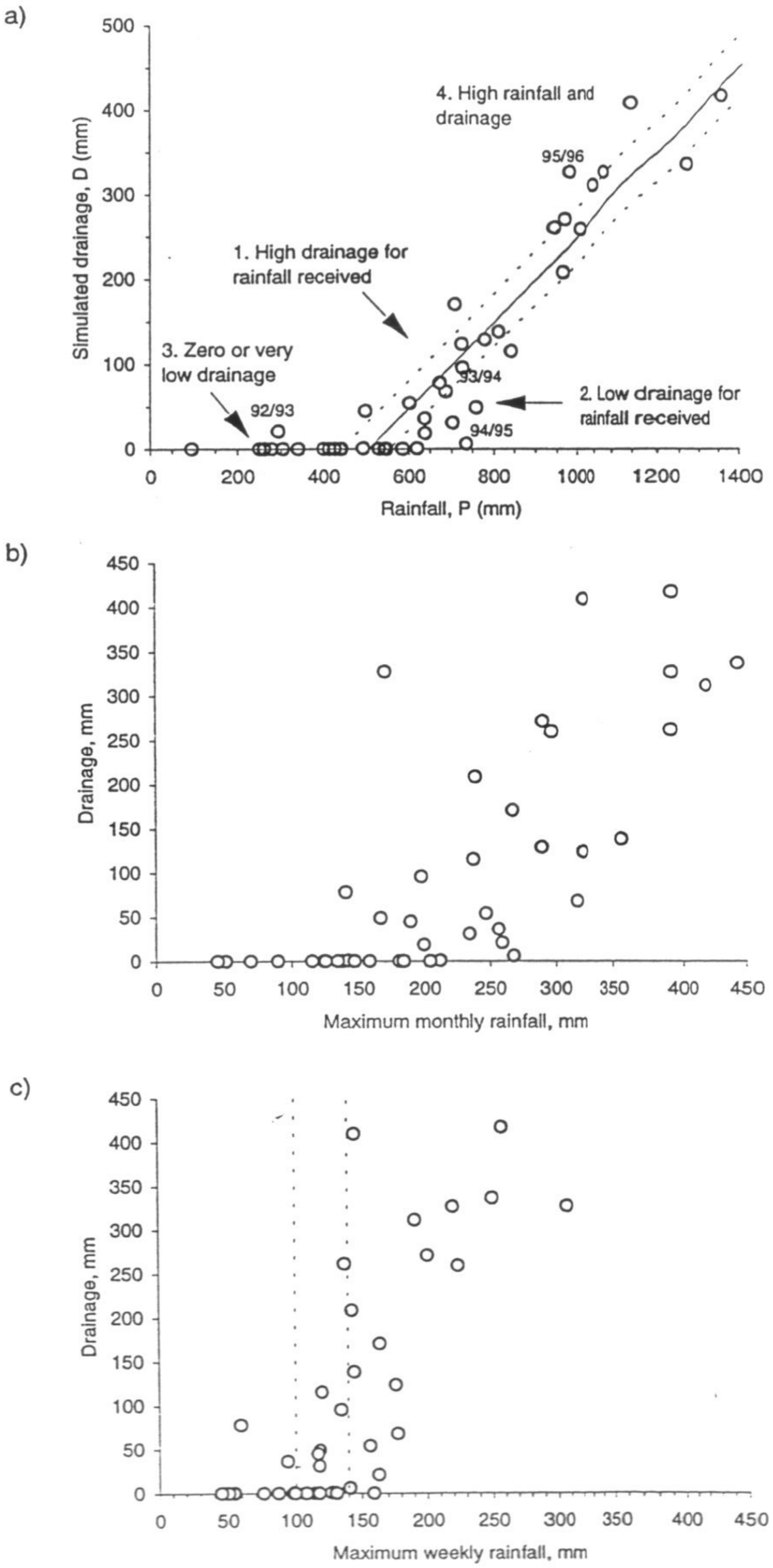
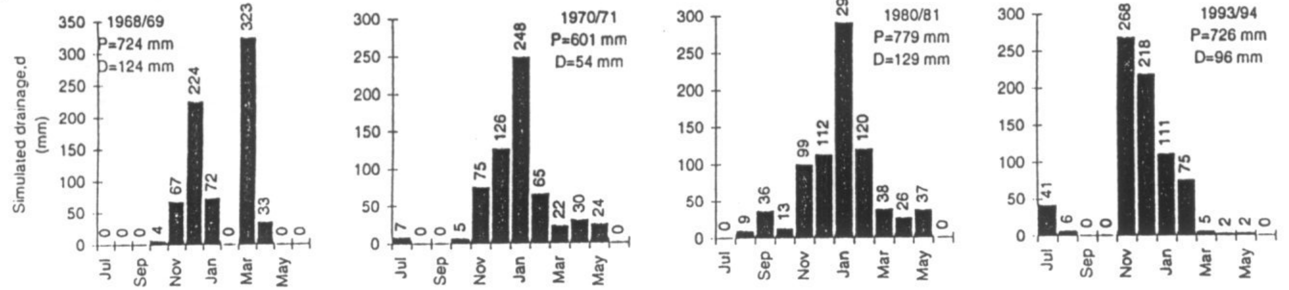
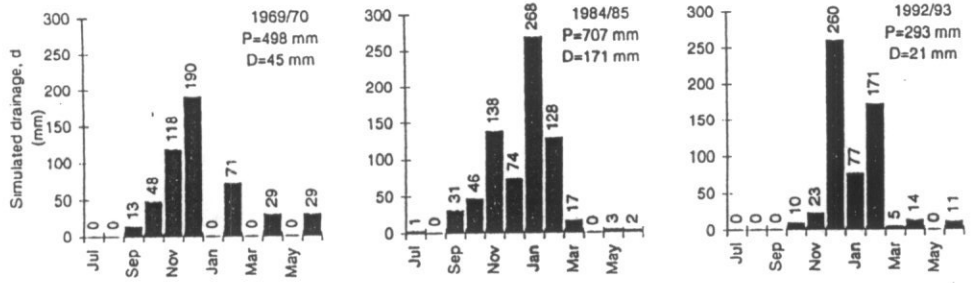


Figure 4.4 Rainfall - recharge relationships from model simulations for red clay soil profile, 1953-96

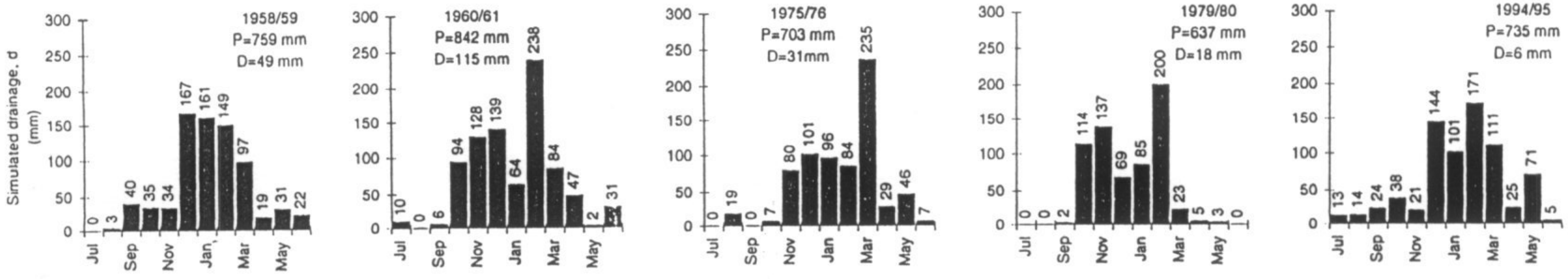
a) 1. Selected years with average rainfall/drainage relationship



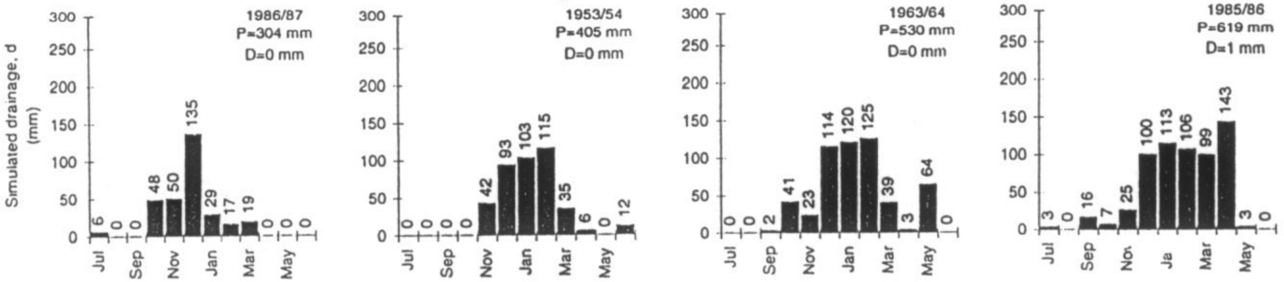
b) 2. Years with high drainage for rainfall received



c) 3. Years with low drainage for rainfall received



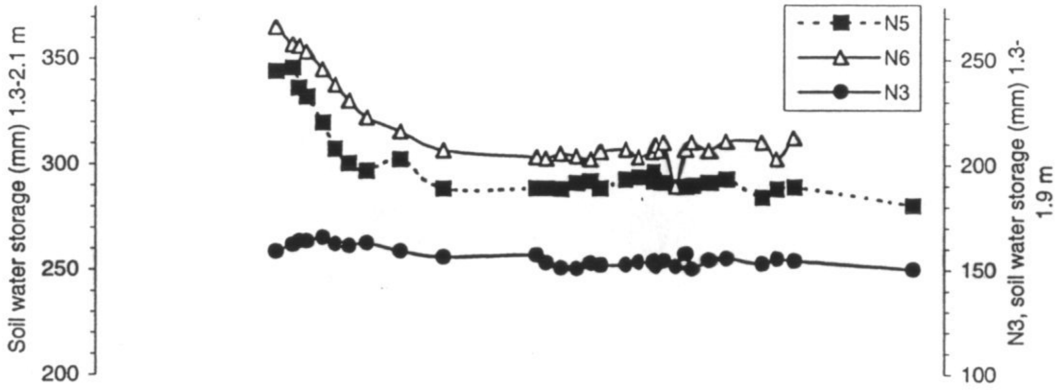
d) 4. Selected years with zero or very low drainage



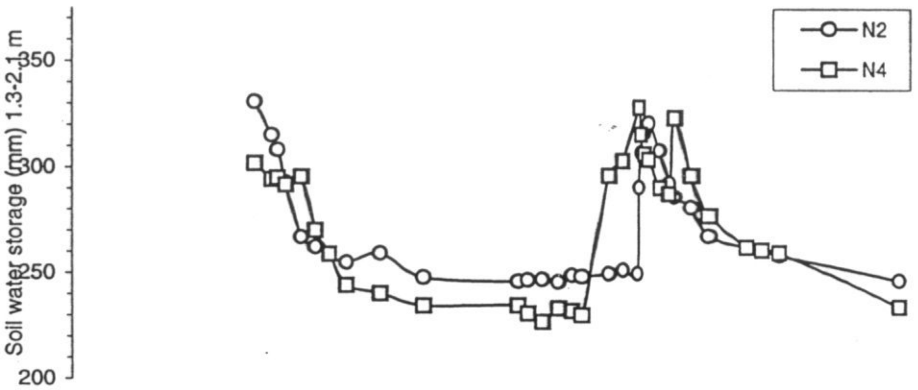
Note: P = total annual rainfall, D = simulated total annual drainage

Figure 4.5 Rainfall distribution in years with different rainfall - recharge relationships

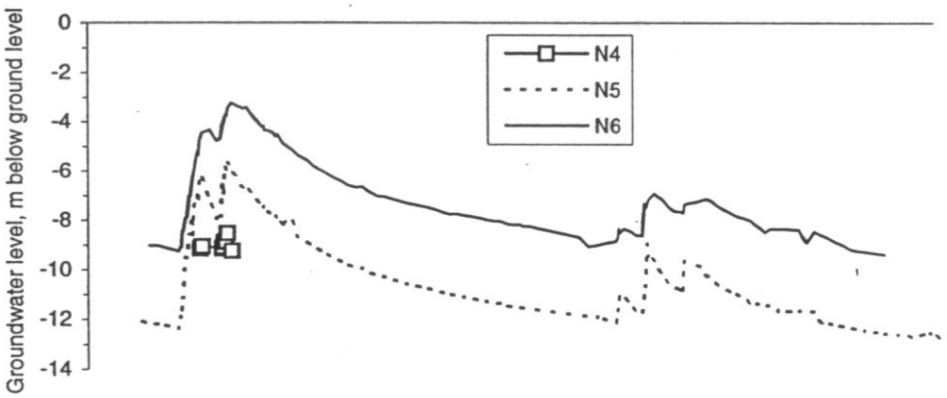
a) Soil water contents, sites N3, N5, N6



b) Soil water contents, sites N2, N4



c) Groundwater levels



d) Rainfall

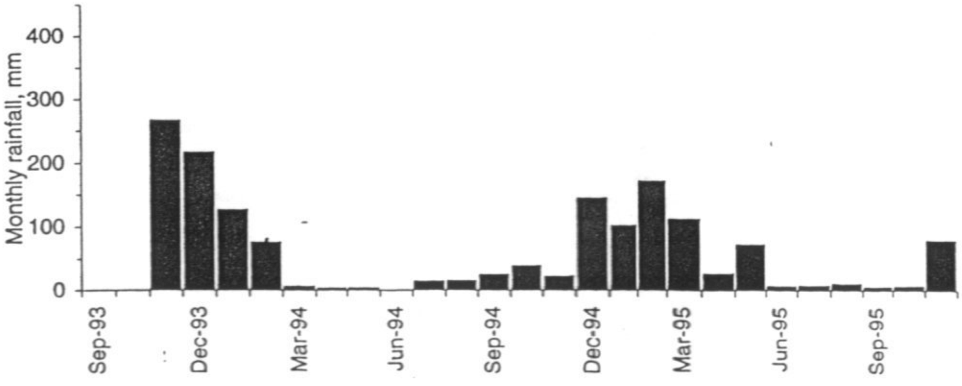
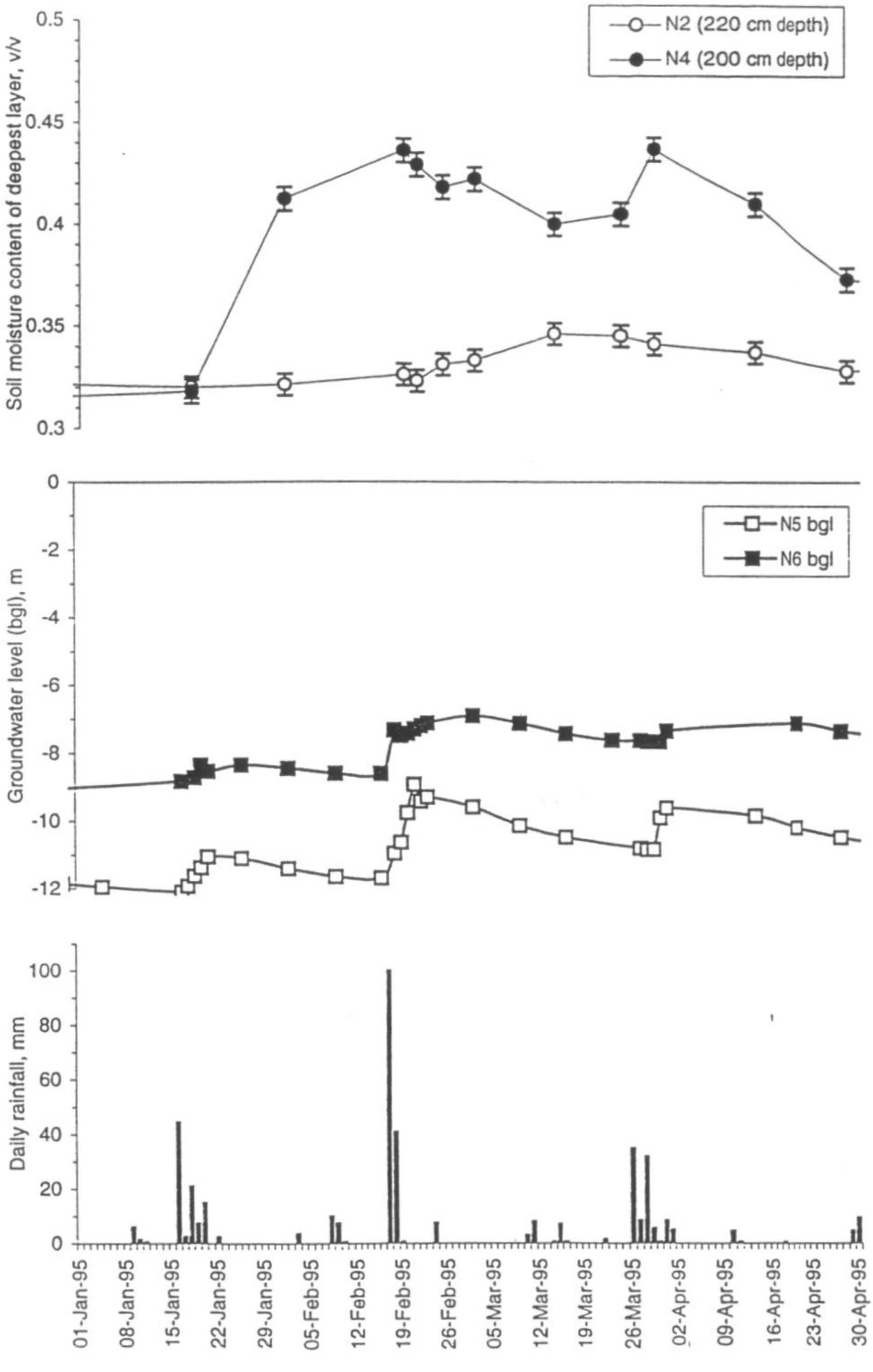


Figure 4.6 Comparison between rainfall, soil moisture storage and groundwater fluctuations along the inselberg hillslope transect.



Note: Error bars shown are calculated at maximum water content.

Figure 4.7 Comparison of deep soil water content fluctuations and groundwater level rises along the inselberg hillslope transect.

5. MODELLING HYDROLOGICAL CHANGE IN THE CATCHMENT

5.1 Introduction

In comparison to many communal areas in Zimbabwe, the Romwe catchment is an area where there has been relatively little land use change since settlement in 1952. The present layout of cultivated land on the valley floor was developed by 1955, and by 1963 the current field pattern including the contour bund and storm drain system was established (Butterworth *et al.*, 1995). There has subsequently been almost no further increase of the cultivated area and the miombo woodland on the rocky slopes and hills remains relatively undisturbed.

In this chapter, long-term rainfall records are used to simulate groundwater levels in Romwe catchment over the period 1952-96, and to evaluate the effects on groundwater of variations in rainfall and land use. Two different modelling methods were adopted. First, a soil water balance model (*ACRU*) was used to simulate drainage from daily rainfall and evaporative demand, and groundwater levels were predicted as a function of drainage, aquifer storage and water table height. Secondly, the Cumulative Rainfall Departure model (CRD) was used to model groundwater levels from monthly rainfall.

5.2 The ACRU Model

ACRU is a physically-based model for distributed catchment simulations on an irregular cell or sub-catchment basis, developed at the University of Natal, South Africa. In this study, the soil water balance component of *ACRU* Version 323 was used in lumped mode to calculate drainage. Groundwater levels were simulated separately, due to limitations in the groundwater module of the *ACRU* model for this particular study site. Currently *ACRU* can only simulate an aquifer which is permanently connected to surface water courses. In areas such as Romwe the aquifer is disconnected from surface water courses for most of the year and only discharges to streams for a limited period in wet years.

The *ACRU* model can be configured in many ways to suit different conditions and the level of input data available. Full details of the model and the supporting suite of utility programs are given by Schulze (1995) and Smithers & Schulze (1995). *ACRU* is based around a two layer 'tank' or 'bucket' type soil water budgeting model. Infiltration into the soil profile depends upon net rainfall after runoff and canopy interception losses. Interception losses were determined using the Von Hoyningen-Huene method (1983), which relates interception to gross rainfall and canopy leaf area index (LAI). Stormflow is simulated according to net rainfall, antecedent moisture conditions, and surface roughness, using a modified version of the SCS stormflow equation (United States Department of Agriculture, 1985). Soil water storage for a two-horizon soil profile is determined by parameters for permanent wilting point, field capacity and porosity. 'Saturated' and unsaturated drainage are simulated from the A to B horizon, and from the B horizon into the intermediate store below the soil layers. 'Saturated' movement occurs when the soil water content of the layer is in excess of field capacity, and varies with soil texture. Slow unsaturated soil water movement is simulated both upwards and downwards when a soil water content gradient exists between the upper and lower horizons. Evaporation from both the soil surface and by vegetation is simulated. Uptake of water and evaporation by plants occurs from both soil layers according to atmospheric demand (ie. potential evaporation), LAI, soil moisture content and the relative distribution of active roots between the two horizons. The energy available for transpiration is determined from potential evaporation and modulated by LAI according to equations by Ritchie (1972). 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).

On days when drainage from the B-horizon was simulated, groundwater level rise was predicted using the equation:

$$h_{t2}-h_{t1}=\frac{D}{S_y}$$

where $h_{t2} - h_{t1}$ is the groundwater rise between times t_1 (start of day) and t_2 (end of day) due to an amount of drainage D at a site with aquifer storage or specific yield S_y expressed as a fraction (Price, 1996). Owing to the difficulty of obtaining reliable measurements of S_y for the Romwe aquifer (Macdonald *et al.*, 1995), this parameter was optimised over the period for which observed groundwater levels were available. Preliminary analysis showed that a poor correlation between simulated and observed groundwater levels was obtained using a depth-constant value for S_y. The degree of weathering decreases towards the base of a profile (Chilton & Foster, 1995) and this was represented using a linear function to describe S_y as a function of depth. Minimum and maximum values were specified for the base and top of the weathered aquifer at the soil surface.

Groundwater discharge was predicted using a groundwater recession function parameterised from observed measurements of falling groundwater levels during periods when recharge was assumed to be zero, following procedures described by Bredenkamp *et al.* (1995) and based on the work of Ernst (1962), De Vries (1974) and Gieske (1992). An exponential equation of the form:

$$h_{t2(NR)}=h_{t1}e^{yt}$$

was used to describe the groundwater recession curve at a given site, where $h_{t2(NR)}$ is the groundwater level above the base of the aquifer at the end of a day given no recharge, and y is a response factor which describes the exponential decay in groundwater level over time t. This response factor is inversely proportional to the specific yield of the aquifer and directly proportional to the permeability or transmissivity. Groundwater levels were therefore calculated on a daily basis as the sum of the initial groundwater level and calculated rise if drainage occurred less the expected recession due to groundwater discharge. This may be expressed as

$$h_{t2}=h_{t1}e^{yt}+\left(\frac{D}{S_y}\right)$$

5.3 The Cumulative Rainfall Departure model

Bredenkamp *et al.* (1995) note that cumulative rainfall departure (CRD) and groundwater level are correlated and that the relationship between the two series may be derived from first principles. For a specific aquifer, water levels will fluctuate according to the cumulative rainfall departure from the mean with a proportionality coefficient = a/S_y, where a is the fraction of rainfall that constitutes recharge and S_y is the specific yield. The CRD method is analogous to a simple bucket or tank type soil water balance model where the mean rainfall defines the size of a soil water store. For periods when the mean rainfall is exceeded, this store overflows, resulting in drainage and groundwater rise is simulated. When rainfall is below the mean value, groundwater levels fall by an amount related to the difference between rainfall and the mean.

Improved relationships between CRD and groundwater levels may be obtained using the most appropriate short and long-term 'memory' periods for the aquifer in question, rather than calculating the CRD from the long-term mean rainfall (Bredenkamp *et al.*, 1995). The short-term memory accounts for the time-lag in groundwater response to rainfall and can incorporate carry-over of recharge from year to year. The long-term memory represents the period over which the long-term reference rainfall is calculated. The equation used for calculating the CRD at a certain time interval i may therefore be expressed in the form

$$ {}^{m}_{n}CRD_i = \left(\frac{1}{m}\sum_{j=i-(m-1)}^{i} Rf_j\right) - \left(k \times \frac{1}{n}\sum_{j=i-(n-1)}^{i} Rf_j\right) + \left(CRD_{i-1}\right) $$

where m is the short-term memory period, n is the long-term memory period, Rf_j is rainfall at the j^{th} interval and k is a proportional factor which for natural conditions equals one.

Cumulative rainfall departures were calculated using monthly rainfall totals. Calculations were made using various short- and long-term memory periods and the most appropriate averaging periods determined from correlation analysis with observed levels.

5.4 Comparison between measured and simulated groundwater levels

Data collection

Groundwater levels were measured weekly at an un-cased 100 mm diameter observation borehole (piezometer G; Figure 4.1) over four rainy seasons from late 1992 . The piezometer was 10.5 m deep with a gradual progression from soil to weathered material at about 1.5 m. Depth to bedrock in this area is about 12 m. However, the deepest water level recorded at the borehole during this period, which included measurement immediately after the 1991/92 drought, was 8.89 m indicating that levels do not recess into the bedrock at this location.

Measurements of net radiation, wet and dry bulb temperature and wind speed were made at the catchment from February 1994 for calculation of potential evaporation using the Penman (1948) equation. Potential evaporation for the period 1953-94 was calculated from daily maximum and minimum temperatures at Masvingo using the Hargreaves & Samani (1985) equation with a correction factor determined by comparison of results with Penman (1948) calculations over a 22 month period in 1994-95 (Butterworth, 1997).

With the exception of leaf area index, all *ACRU* model parameters were determined from measured or published sources without need to calibrate outputs against measured data. In 1994/95 maize was cultivated in both fields in rows approximately one metre apart. Radiation interception was determined regularly using tube solarimeters positioned above and below the canopy for complete days at five locations within the Red sub-catchment. Leaf area index was determined from the fractional radiation intercepted by the canopy using a modified light extinction coefficient of 0.25, because plant uptake for the sparse crop in widely-spaced rows was overestimated when simulated using coefficients of 0.4-0.7 after Monteith (1969). The same vegetation parameters were used each year of the simulation because maize is the most frequent crop. No attempt was made to vary the vegetation cover to account for differences in crop development due to differences in rainfall between years. The effective rooting depth was assumed to be 1.3 m and the root distribution pattern that suggested by Smithers & Schulze (1995).

Porosity, soil water content and potential that nominally represent permanent wilting point (-1.5 MPa) and field capacity (-0.01 MPa) were calculated from a laboratory derived soil moisture characteristic curve (Butterworth, 1997). Soil water redistribution factors according to texture and streamflow parameters were taken from values given by Smithers & Schulze (1995).

ACRU Model results

The soil water balance model was tested against measured values of runoff, soil water content, drainage and soil evaporation for the 1994/95 season, and runoff during the 1995/96 season. Further details are provided by Butterworth (1997). To incorporate the effects of surface redistribution of rainfall (Chapter 3), *ACRU* runs were repeated using 70, 80, 90, 100, 110, 120 and 130% of measured infiltration. Comparison of measured and simulated values of groundwater level over the period 1992-96 are shown in Figure 5.1. Groundwater levels simulated using *ACRU* to model drainage follow the observed levels closely. Both the timing and magnitude of the groundwater rise and the pattern of recession are well described. The optimised values of specific yield used in the groundwater level simulation were 6.0×10^{-4} at 8 m depth (at the base of the aquifer) and 1.6×10^{-5} at the ground surface, with a linear interpolation between these depths. These figures compare with a measured specific yield of 1.6×10^{-5} determined at a nearby hand-dug well from a short pumping test (Macdonald *et al.*, 1995).

There are two notable deviations between the observed and simulated levels however. Simulated levels rise at the end of December 1992 considerably before the measured rise in mid-February 1993, although a small rise was measured at the time of the simulated rise. The most likely explanation is that up to November 1993 rainfall data were from Chendebvu Dam located 12 km from the catchment. Considerable spatial variation in rainfall over distances of a few kilometres is a common feature due to the convectional nature of rainfall. As the actual rise in the catchment was small it is likely that the catchment rainfall was actually less than at Chendebvu Dam.

The second deviation between observed and simulated water levels occurs in the 1994/95 rainy season. A simulated rise in groundwater level in February 1995 of 0.94 m compares poorly with the observed rise of 2.4 m. Underestimation of drainage from the unsaturated zone may explain this. Simulated drainage for this season amounted to 7 mm compared to an average of 24 mm determined from soil moisture measurements using the ZFP method. When surface redistribution of rainfall is represented in the model, considerably more drainage from the soil profile is simulated in low recharge years. With infiltration represented as 70-130% of the lumped infiltration, simulated drainage increased to 52 mm for the 1994/95 season, resulting in a slight overestimation in groundwater rise rather than underestimation (Figure 5.1 b)

CRD Model results

The best correlation between measured groundwater levels and CRD was obtained using short and long-term memory periods of 1 and 12 months respectively (Butterworth, 1997). Groundwater levels are simulated with less sensitivity than using *ACRU* due to the monthly calculation on which the CRD model is based. However, the annual fluctuations track the observed fluctuations relatively well (Figure 5.1 c). Groundwater rise was also overestimated in the 1994/95 rainy season using this method, due to the well-spaced distribution of rainstorms in this year.

The two models offer different advantages for simulation of groundwater levels in shallow aquifers. The empirical CRD model is a simple and rapid method of predicting groundwater level fluctuations from rainfall, requiring none of the parameters needed by the ACRU model, but observed groundwater levels are required for each site for a reasonable period. Given this simplicity, and the ability to include representation of abstraction, this method has potential for routine use in the management of abstraction from water points. The more physically-based ACRU model has greater data requirements for parameterisation and testing but ultimately has greater capabilities, for example, to simulate the effects of land use changes on groundwater levels.

5.5 Long-term trends in groundwater levels, 1952-96

Monthly groundwater levels for the period 1952-96 simulated using long-term rainfall records and the *ACRU* and CRD models are shown in Figure 5.2.

The simulated groundwater levels highlight large annual fluctuations as the shallow weathered aquifer experiences relatively rapid recharge and discharge. The average annual rise in groundwater levels, defined as the difference between the minimum level prior to recharge and the maximum levels reached during the subsequent wet season, was 3.03 m using the *ACRU* model. However, inter-annual variability is high. The greatest rise was 8.62 m, but for 17 of the 43 seasons zero or negligible recharge was simulated. The mean simulated recharge from the soil water balance model was 100 mm (range 0-417 mm), and this increased to 135 mm (range 0-540 mm) when surface redistribution of rainfall was incorporated. The large variation in rainfall between years is responsible for this temporal variation in recharge and simulated groundwater levels. Little or no recharge is generally simulated in low rainfall years. Comparison between annual total rainfall and simulated recharge suggest that on average, total annual rainfall above a threshold of 507 mm (or 466 mm if surface redistribution of rainfall is included) will result in recharge, although the distribution of rainstorms in the year is important (Chapter 4).

Particularly noticeable is the number and distribution of years when zero or negligible recharge was simulated. Considering the *ACRU* simulation (Figure 5.2 a), groundwater drought is predicted to recur throughout the period 1952-96. However, two periods are particularly noticeable. From 1953-67 groundwater drought is simulated in 7 out of 15 wet seasons with 3 consecutive years of no recharge from 1963-66. Even more extreme is the period from 1981-92 when no recharge is simulated in 9 out of 11 wet seasons. This period of groundwater drought is unprecedented in the period since 1953. The simulation of groundwater drought is slightly less severe when the effects of surface redistribution of rainfall on increased recharge are represented (Figure 5.2 b), when only 10 out 43 seasons show no recharge.

Long-term trends in groundwater level predicted using the two models are shown in Figure 5.3. The end of wet and dry season water levels were taken nominally as the end of March and end of September respectively, and levels were smoothed using a three year average to reduce the degree of annual fluctuation. This highlights the considerable long-term variation since the 1950s and helps to show that this variation reflects cycles of above and below average rainfall. Trends predicted by the *ACRU* and CRD models are similar and there was little difference when the effects of surface redistribution of rainfall were included. Simulated water levels fall during the 1960s and early 1970s during a period of generally low rainfall. They rise during the late 1970s due to a series of higher rainfall years, fall again in the early 1980s, stabilise only slightly in the second half of the 1980s, before falling to the lowest levels in the early 1990s prior to a significant rise with the wet 1995/96 season.

End of wet season levels are shown to vary between about 3 m below ground level in the late 1970s to about 8.5 m depth in the early 1990s. This fall would be expected to have had huge effects on the observed hydrology of the catchment, and in particular the duration of flow of springs and streams. End of dry season water levels are shown to fluctuate less, with a range from about 6 m below ground level in the late 1970s to 9 m in the early 1990s. A fall of almost 3 m in end of dry season regional water levels during the 1980s and early 1990s would be expected to have had a substantial impact on well performance.

The simulations match community accounts of falling water levels during this period and the concerted efforts they made to maintain their water supply. Between 1980 and 1992 many existing wells were deepened and the number of wells in and around the catchment rose from 9 to 35 (Price, 1993). However, abstraction from even this increased number of wells remains low (Chapter 6). With relatively small changes in land use since the 1950s, the simulations indicate that the main cause of falling groundwater levels in the area in the early 1990s was the long period of relatively low rainfall from 1981 rather than human impacts on catchment hydrology.

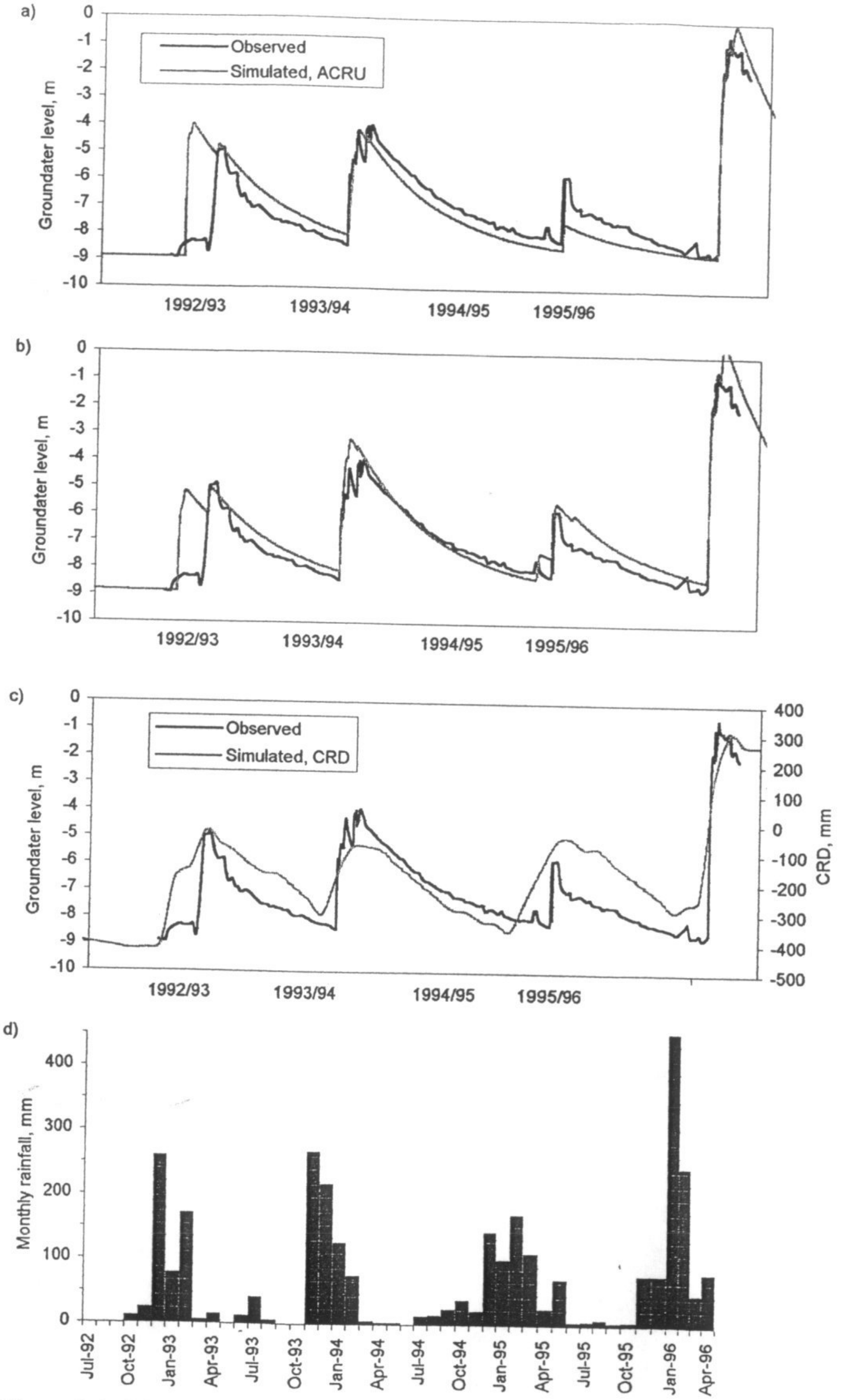


Figure 5.1 Measured and simulated groundwater levels, 1992-96, a)ACRU, b)ACRU with surface redistribution of rainfall, c)CRD 1:12, d)monthly rainfall

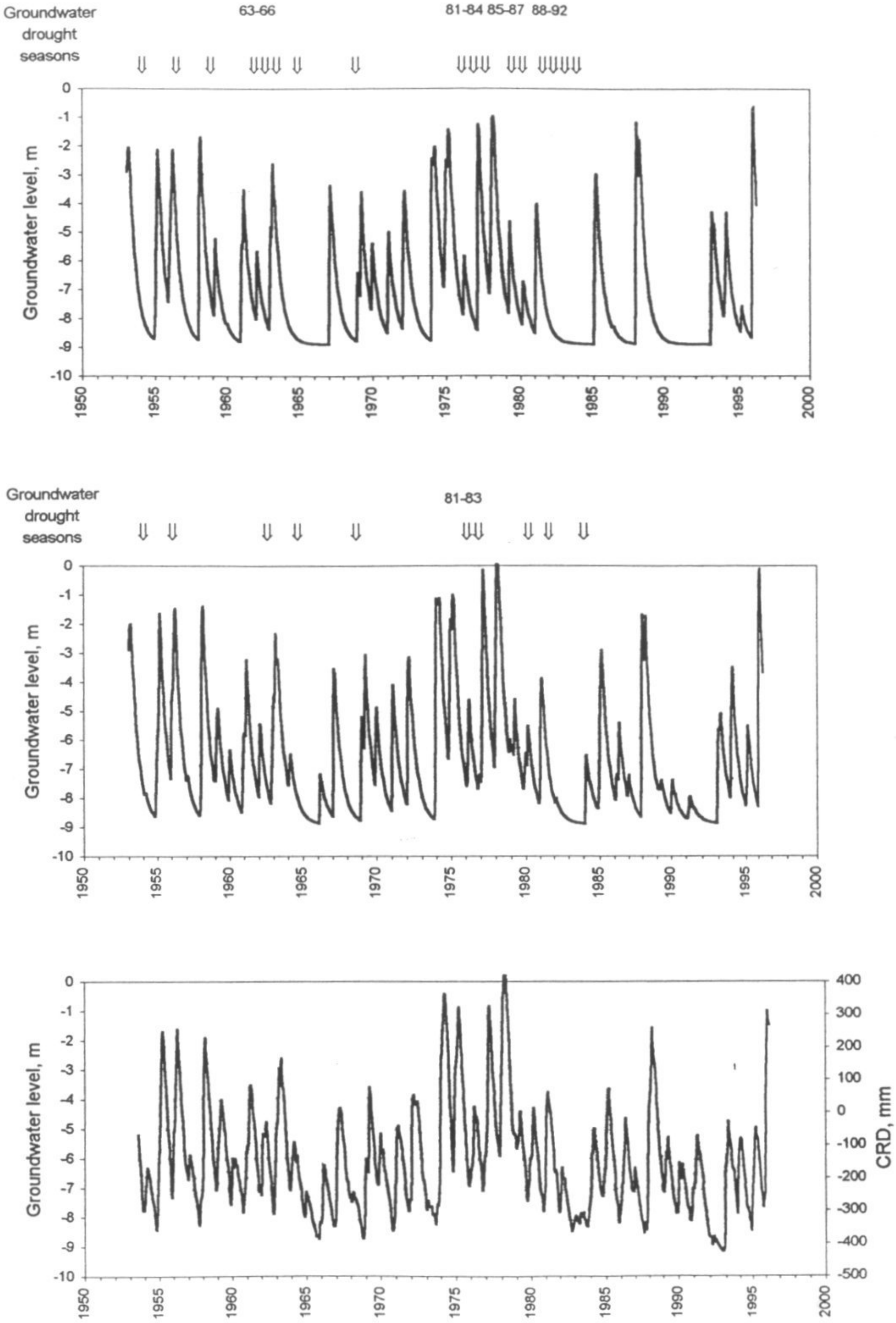


Figure 5.2 Simulated groundwater levels, 1952-96, a) ACRU, b) ACRU including surface redistribution of rainfall, c)CRD 1:12

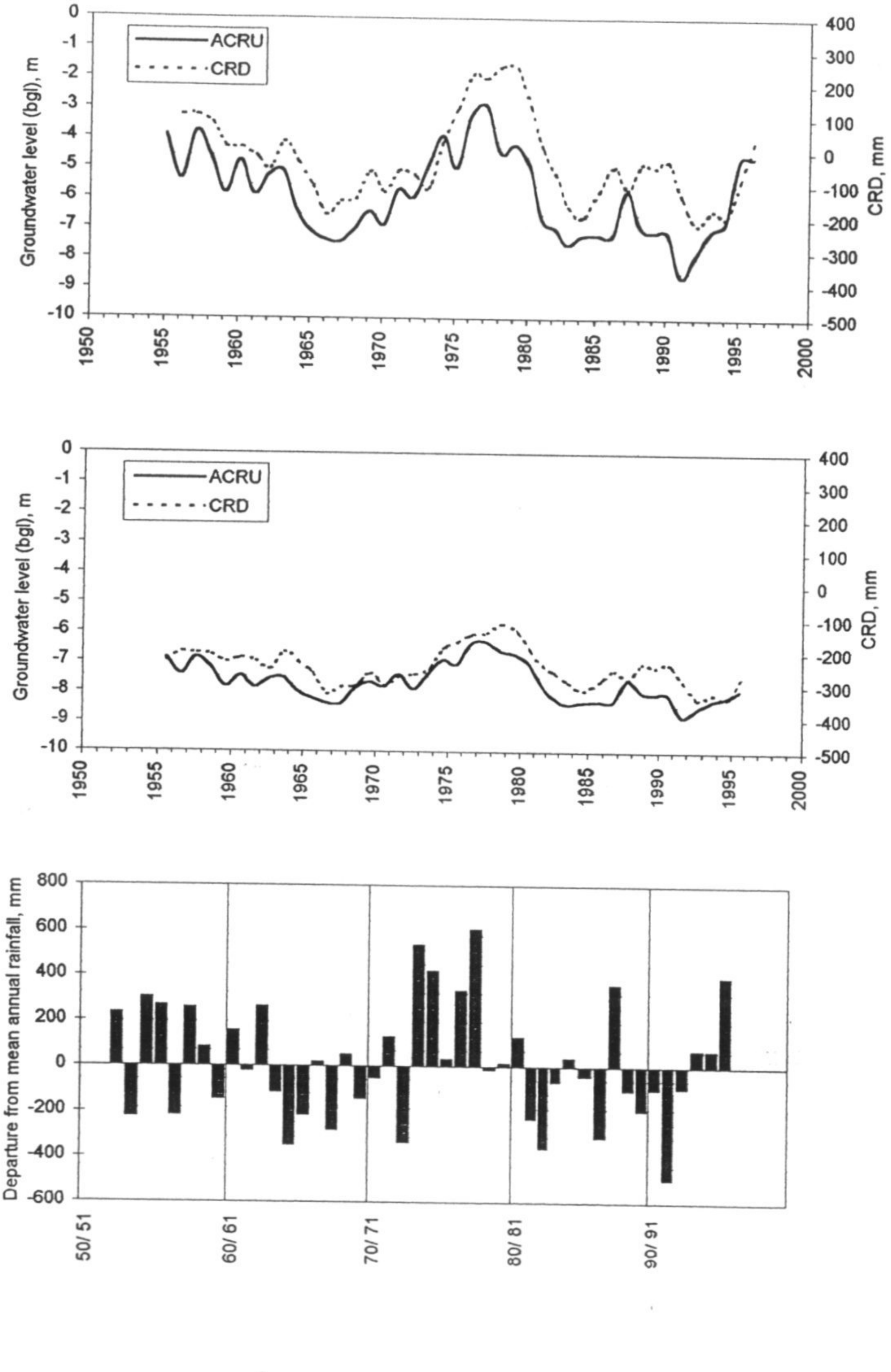


Figure 5.3 Simulated trends in groundwater levels, 1953-96, a) end of wet season, b) end of dry season, c)annual departures of rainfall from the mean

6. A PRELIMINARY WATER BALANCE OF ROMWE CATCHMENT

6.1 Rainfall and potential evaporation

Figures 6.1 a, b and c show cumulative total and daily rainfall and potential evaporation recorded in Romwe catchment during 1994/95, 1995/96 and 1996/97. The meteorological year 1 July to 30 June was assumed. Rainfall was corrected to ground-level measurements. Potential evaporation was calculated using the Penman (1948) equation using meteorological data provided by the automatic weather station in the catchment.

The years 1995/96 and 1996/97 were years of relatively high rainfall in Romwe catchment. They suggest the end of a "dry cycle" of below average rainfall (Figure 2.2a) and the beginning of a "wet cycle" of predominantly above-average rainfall. The problems of farming in this periodically semi-arid environment are clear and flexibility in management is key. In many parts of the valley, crops failed in 1995/96 and 1996/97 when fields became waterlogged, especially on the grey duplex soils. Maize planted in low lying areas remained stunted. Those farmers lucky enough to have better drained land on higher slopes or with fields on the heavier red clay soils fared better, some seeing bumper crops, although often only on the second or third attempt at planting. Those in lower areas and on grey duplex soils who managed to obtain rice seed achieved good yields.

6.2 Runoff and erosion

Figures 6.2 a, b and c show cumulative runoff measured from the different sub-catchments and whole catchment for the same period 1994-97. Table 6.1 summarises the runoff measurements.

In 1994/95, runoff was a relatively small proportion of the water balance, accounting for only 1.2 and 6.5 per cent of total rainfall in the arable sub-catchments with red clay and grey duplex soils respectively. The low runoff was due, in part, to the pattern of rainfall. There were only four significant rainfall events and these were well separated enabling large soil moisture deficits to develop. Runoff from both arable sub-catchments was greater, as a percentage of rainfall, than measured from the miombo woodland sub-catchment and from the whole catchment, which amounted to 0.003 and 0.5 per cent respectively. The presence of a good under storey cover of grasses and shrubs during this wet season was a contributory factor in reducing runoff from these catchment areas. Stocking densities were still low as a result of the 1991/92 drought, and grasses and shrubs were not browsed to any great extent.

In 1995/96, runoff was equivalent to 4.6 and 20.5 per cent of rainfall in the red and grey sub-catchments, and 8.2 and 9.4 per cent from the woodland sub-catchment and whole catchment respectively. This was a year of much higher rainfall, the main stream in the catchment flowed continuously for 87 days, springs that had been dry for a number of years flowed again, and on a less positive note, many pit latrines overflowed and collapsed as a result of the rising groundwater. The contrasting hydrology of the miombo woodland was highlighted by the slower and more prolonged runoff response than recorded from both arable sub-catchments. The fact that woodland runoff is greater than runoff from the deep red clay soils suggests that the rock beneath the woodland is to some extent impermeable, and that lateral subsurface flow from the woodland areas down to the arable fields may be important to recharge in these areas and to sustaining baseflow recorded in the main stream. Further study of miombo woodland hydrology is required.

1996/97 was also a year of relatively high rainfall in Romwe catchment. However, only after 300 mm of rainfall did significant runoff occur with the rainfall events of 11-25 January and 3-15 February. Runoff from the whole catchment this year was equivalent to 7.4 per cent of rainfall.

Comparison of runoff hydrographs

Total runoff calculated by summation of estimates for the red clay soil, grey duplex soil and miombo woodland based on measured sub-catchment runoff and total area assumed for each soil and land use is shown to be consistently greater than actual total runoff measured at the catchment outlet (Table 6.1). In 1994/95, a year of relatively low runoff, the estimate is 2.8 times greater. Although runoff occurred from the arable lands, it appears that most infiltrated probably along ephemeral stream channels before reaching the catchment outlet. Better agreement between estimated and gauged runoff is shown in 1995/96, a year of relatively high runoff, but in 1996/97 the estimated value is again 1.6 times greater than measured. Again this may be due to infiltration of runoff between cropping lands and catchment outlet, or it is because Grey sub-catchment runoff is too high for the soil type as a whole.

Comparison of runoff hydrographs recorded for each soil type and land use (Figure 6.2) suggests that the catchment as a whole is behaving predominantly like the red clay soil. The grey soil area of 85 ha, based on soil colour and surface texture, is therefore too high. It seems likely that not all grey soils in the catchment are in fact duplex in nature or underlain by the impermeable clay horizon present in the Grey soil sub-catchment. Furthermore, it is also likely that some subsurface interflow is entering the Grey soil sub-catchment from the woodland areas up slope, and that some of this extra water is being recorded as "runoff" as it leaves the Grey sub-catchment weir.

Erosion

Only preliminary analysis of erosion and sedimentation rates in Romwe catchment have been undertaken so far. As a guide, in 1995/96 erosion rates of 6.2, 0.4, 0.2 and 1.1 T/ha were recorded from the Grey, Red and Woodland sub-catchments and the whole catchment, respectively. Assuming a bulk density of 1.4 T/m^3, approximately 500 T of suspended sediment left Romwe catchment in the year, which equates to a siltation rate of 3.6 mm/yr if a small dam of area say 2 ha were sited immediately downstream. At the erosion rate of 6.2 T/ha recorded from the Grey sub-catchment, siltation of the same small dam would occur at a rate of 20 mm/yr.

6.3 Estimates of recharge

Groundwater recharge in dryland catchments is generally a small part of the water balance. It can be inferred by difference if other components of the water balance are known, or it can be estimated by various techniques. At the catchment scale, both rainfall and evaporation, the two principal components of the water balance, are difficult to measure accurately. In particular, evaporation varies across different soil and vegetation types and from season to season. Daily estimates based on potential rates (Penman, 1948) often exceed actual rates, and cumulative potential evaporation very quickly exceeds cumulative rainfall (Figure 6.1). Without rigorous measurement of evaporation, groundwater recharge cannot safely be inferred by difference from an annual water balance.

Given these difficulties, it is generally accepted that recharge in dryland areas should be estimated in a number of ways in order to compare results and establish the likely magnitude rather than absolute value (Lerner *et al*, 1990). Table 6.2 shows estimates of recharge and aquifer specific yield S_y for Romwe catchment inferred from the water balance during periods of groundwater rise, and Table 6.4 compares estimates of recharge derived by other techniques. In essence, the various estimates are based either on measured groundwater rise or on deep drainage calculated from the soil profile, and are determined either at point, sub-catchment or whole-catchment scale. Regional estimates provided by Houston (1988) are shown for comparison.

Recharge estimates inferred from the water balance during periods of groundwater rise are up to 15 times higher than historical values for Romwe determined using the chloride balance (Macdonald *et al*, 1995) or previous regional estimates provided by Houston (1988). It appears that the chloride balance may not be a suitable method for estimating recharge in this environment. Recharge estimates based on drainage from the red soil profile are generally similar to estimates based on groundwater rise, especially when aggregate values at sub-catchment scale are considered rather than point values, and when infiltration after surface redistribution of rainfall is considered. In contrast, recharge estimates based on drainage from the grey soil are in all cases higher than estimates based on groundwater rise beneath these soils. This is because deep drainage from the grey soils is severely limited by the impermeable sandy clay B horizon, with most drainage actually flowing laterally over this layer rather than to the water table below.

Aquifer specific yield S_y

To convert groundwater rise measured in the network of catchment piezometers (Figure 4.1) to a volume of water requires knowledge of aquifer specific yield S_y. Data on specific yield is scarce (Wright, 1992) but in a typical weathering profile developed upon crystalline basement rocks, values may be expected to range from 0.25-0.4 (25-40%) in the upper soil horizons of high porosity, from 0.05-0.25 (5-25%) in the weathered regolith, and from 0.01 to 0.05 (1-5%) in the fractured and fissured rock of low porosity (Acworth, 1987).

Table 6.2 shows values of S_y for pyroxene and leucocratic gneisses (red clay and grey duplex soils) and the whole catchment, inferred from the water balance during the wet seasons of 1994/95, 1995/96 and 1996/97. Three piezometers on the red soil (K4, G, N6) and three on the grey soil (K2d, P, S) spaced along the length of the catchment were considered. The start date for each period was the date of rainfall event which triggered the first major rise in groundwater level. The end date for deriving the water balance was the date on which the water level peaked. The balance of rainfall less potential evaporation and runoff during each period was assumed to be available for recharge (rather than to storage in the unsaturated zone or to lateral flow). Linking this maximum value of recharge to measured groundwater rise gives average values for S_y of 3.4, 2.2 and 4.5 per cent for pyroxene and leucocratic gneisses and the whole catchment, respectively.

These values of S_y fall within the expected range for crystalline basement aquifers and show reasonable inter-annual agreement suggesting that the assumptions made in their derivation are reasonable. A value of 0.5 per cent was determined for the grey soil in Romwe catchment using neutron probe measurements of soil moisture change (Butterworth, 1997). Alternative values of S_y for the whole catchment inferred by considering the annual water balance but assuming ratios of actual to potential evaporation provided by Farquharson and Bullock (1992) for different annual rainfalls are shown in Table 6.3. The method does not work well for 1994/95, a year of relatively low rainfall and runoff, but the average value for S_y of 0.061 determined for the whole catchment for the years 1995/96 and 1996/97 is similar to the average value of 0.045 determined above.

6.4 The annual water balance

Table 6.5 summarises the annual water balance of Romwe catchment for 1994/95, 1995/96 and 1996/97. The figures shown are not absolute, but they are estimates which are considered to be of the correct order of magnitude. The values of groundwater recharge are taken from Table 6.2 inferred from the water balance during periods of groundwater rise. Changes in groundwater storage are determined using average values for S_y of 3.4, 2.2 and 4.5 per cent for pyroxene and leucocratic gneisses and whole catchment, respectively, and average changes in groundwater level measured across the network of piezometers from 1 July to 30 June each year. Natural groundwater recession is calculated as the difference between recharge and change in groundwater storage. Human abstraction is calculated as the sum of estimated abstraction (2.0 Ml/year) from the 26 traditional dug wells in the catchment (Macdonald *et al*, 1995) plus average abstraction (1.6 Ml/year) from the collector well measured from 1991-97 (see Section 7.3). Evaporation from soil and vegetation, plus change in soil moisture storage, plus any other unaccounted losses, comprise the remaining balance.

The preliminary water balance for Romwe catchment highlights a number of important points:

- present human abstraction of groundwater for domestic use and small scale irrigation is trivial, equivalent to less than 1 mm across the catchment;

- in contrast, natural loss of groundwater is a major process up to 230 times greater than present human abstraction. Initial inspection suggests that most of this natural loss is probably through abstraction by deep rooted evergreen vegetation that covers about 21 ha of the valley floor rather than through lateral flow or leakage into the fractured bedrock;

- recharge in any one year can be up to 12 times higher than previous regional or long-term estimates. However, the net gain in groundwater storage after natural recession is always far less, and of the order 60-100 mm/year in two years of good recharge;

- recharge through the red soils is consistently 4-5 times greater than through the grey duplex soils, and in Romwe contributes up to 60 per cent of recharge to the whole catchment.

It will be important to substantiate these preliminary findings with more rigorous analysis and modelling of the groundwater data now collected.

Table 6.1 Runoff from Romwe catchment in 1994/95, 1995/96 and 1996/97

1994/95 **rainfall 738mm**	Sub-catchment runoff (mm)	Percentage of rainfall	Total area in catchment (ha)	Total runoff (Ml)	Percentage of total runoff
Red clay soil	9	1.2	84	7.6	15.7
Grey duplex soil	48	6.5	85	40.8	84.1
Miombo woodland	0.02	0.003	255	0.05	0.1
Total catchment (by extrapolation)	—	—	424	48.5	100.0
Total catchment (measured at outlet)	4	0.5	424	17.0	35.1

1995/96 **rainfall 990mm**	Sub-catchment runoff (mm)	Percentage of rainfall	Total area in catchment (ha)	Total runoff (Ml)	Percentage of total runoff
Red clay soil	46	4.6	84	38.6	9.2
Grey duplex soil	203	20.5	85	172.6	41.3
Miombo woodland	81	8.2	255	206.6	49.5
Total catchment (by extrapolation)	—	—	424	417.8	100.0
Total catchment (measured at outlet)	93	9.4	424	394.3	94.4

1996/97 **rainfall 1140mm**	Sub-catchment runoff (mm)	Percentage of rainfall	Total area in catchment (ha)	Total runoff (Ml)	Percentage of total runoff
Red clay soil	64	5.6	84	53.8	9.1
Grey duplex soil	335	29.4	85	284.8	48.4
Miombo woodland	98	8.6	255	249.9	42.5
Total catchment (by extrapolation)	—	—	424	588.5	100.0
Total catchment (measured at outlet)	84	7.4	424	356.2	60.5

* Total catchment assumed to comprise 84 ha red clay soil, 85 ha grey duplex soil, and 255 ha miombo woodland.

Table 6.2 **Groundwater recharge and aquifer specific yield S_y inferred from the water balance during periods of rising groundwater**

1994/95	Rainfall (mm)	Potential evaporation (mm)	Runoff (mm)	Balance available for recharge (mm)	Average rise in groundwater level (m)	Maximum value of specific yield S_y
Red clay soil 17/2/95 - 6/3/95	149	88	9	51	2.5	0.020
Grey duplex soil 17/2/95 - 20/3/95	168	148	46	-26	1.3	na
Catchment 17/2/95 - 13/3/95	160	118	4	38	1.7	0.022

1995/96	Rainfall (mm)	Potential evaporation (mm)	Runoff (mm)	Balance available for recharge (mm)	Average rise in groundwater level (m)	Maximum value of specific yield S_y
Red clay soil 14/1/96 - 15/2/96	452	98	46	308	7.5	0.041
Grey duplex soil 14/1/96 - 27/2/96	485	153	194	138	4.6	0.03
Catchment 14/1/96 - 21/2/96	466	124	80	262	5.5	0.048

1996/97	Rainfall (mm)	Potential evaporation (mm)	Runoff (mm)	Balance available for recharge (mm)	Average rise in groundwater level (m)	Maximum value of specific yield S_y
Red clay soil 5/12/96 - 29/1/97	527	221	25	281	7.1	0.040
Grey duplex soil 5/12/96 - 3/3/97	713	360	303	50	3.6	0.014
Catchment 5/12/96 - 15/2/97	645	286	63	296	4.6	0.064

Table 6.3 **Values of aquifer specific yield S_y inferred from the annual water balance**

Year (July 1 - June 30)	Rainfall (mm)	Potential evaporation (mm)	Ratio*	Actual evaporation (mm)	Runoff (mm)	Balance for recharge (mm)	Av. rise in water level (m)	Specific yield S_y
1994/95	738	1071	0.35	375	4	359	1.7	0.211
1995/96	990	1417	0.45	638	93	259	5.5	0.047
1996/97	1140	1423	0.5	712	84	344	4.6	0.075

* Ratio of actual to potential evaporation after Farquharson and Bullock (1992).

Table 6.4 Comparison of groundwater recharge estimates in Romwe catchment

Method	Red soil (mm)	Grey soil (mm)	Miombo woodland (mm)	Whole catchment (mm)
Based on Soil Water Measurements				
ACRU soil water balance applied to piezometer 'G' (Butterworth, 1997)				
simulated recharge 1994/95: without surface redistribution of rain	7			
with surface redistribution of rain	52			
mean recharge 1952-96: without surface redistribution of rain	100			
with surface redistribution of rain	135			
Zero Flux Plane (Butterworth, 1997)				
mean drainage at 16 sites in Red sub-catchment 1994/95	24			
drainage at 6 sites in inselberg hillslope profile 1994/95	0-300			
Change in moisture content at base of soil profile (Butterworth, 1997)				
mean of 3 sites in Grey sub-catchment 1994/95: without surface redistribution		51		
mean of 4 sites in Grey sub-catchment 1994/95: with surface redistribution		91		
ACRU soil water balance applied to sub-catchments (Butterworth,1997)				
1994/95	6	89	0	48 (s)
1995/96	327	264	36	295 (s)
mean simulated recharge 1952-96: well managed ground cover	87		2	
poorly managed ground cover	121		21	
Based on water balance				
Balance available during periods of recharge 1994/95	51	-26	na	38
1995/96	308	138	na	262
1996/97	281	50	na	296
Based on chloride balance (Macdonald *et al*, 1995)				
mean recharge historically (exact period unknown)	24	8		16 (s)
Previous Studies				
Regional value 2-5 % of annual rainfall (Houston, 1988)				
1993/94 (rainfall 740 mm)				15-37
1994/95 (rainfall 738 mm)				15-37
1995/96 (rainfall 990 mm)				20-50
1996/97 (rainfall 1140 mm)				23-57

s = summation of recharge estimates for the red clay and grey duplex soils assuming 84 ha red clay soil and 85 ha grey duplex soil and 169 ha total aquifer area.

Table 6.5 Annual water balance of Romwe catchment (calendar year 1 July - 30 June)

1994/95 rainfall 738mm	Runoff (mm)	Recharge (mm)	Change in groundwater storage (mm)	Natural recession (mm)	Human abstraction (mm)	Balance (evaporation + change in soil moisture + other losses) (mm)
Red clay soil	9	51	-19	70	1	677
Grey duplex soil	48	0	-19	19	0	690
Woodland	0	0	0	0	0	738
Total catchment	4	38	-34	72	1	695

1995/96 rainfall 990mm	Runoff (mm)	Recharge (mm)	Change in groundwater storage (mm)	Natural recession (mm)	Human abstraction (mm)	Balance (evaporation + change in soil moisture + other losses) (mm)
Red clay soil	46	308	+58	250	1	635
Grey duplex soil	203	138	+46	92	0	649
Woodland	81	36	na	na	0	873
Total catchment	93	262	+100	162	1	634

1996/97 rainfall 1140mm	Runoff (mm)	Recharge (mm)	Change in groundwater storage (mm)	Natural recession (mm)	Human abstraction (mm)	Balance (evaporation + change in soil moisture + other losses) (mm)
Red clay soil	64	281	+50	231	1	794
Grey duplex soil	335	50	+24	26	0	755
Woodland	98	na	na	na	0	1042
Total catchment	84	296	+62	234	1	759

* Change in groundwater storage calculated using average change in groundwater level measured across the network of piezometers, and assuming average values of specific yield $S_y = 0.034$, 0.022 and 0.045 for red clay and grey duplex soils and whole catchment, respectively. Groundwater recession calculated as the difference between recharge and change in groundwater storage. Balance calculated as rainfall - runoff - recharge - human abstraction

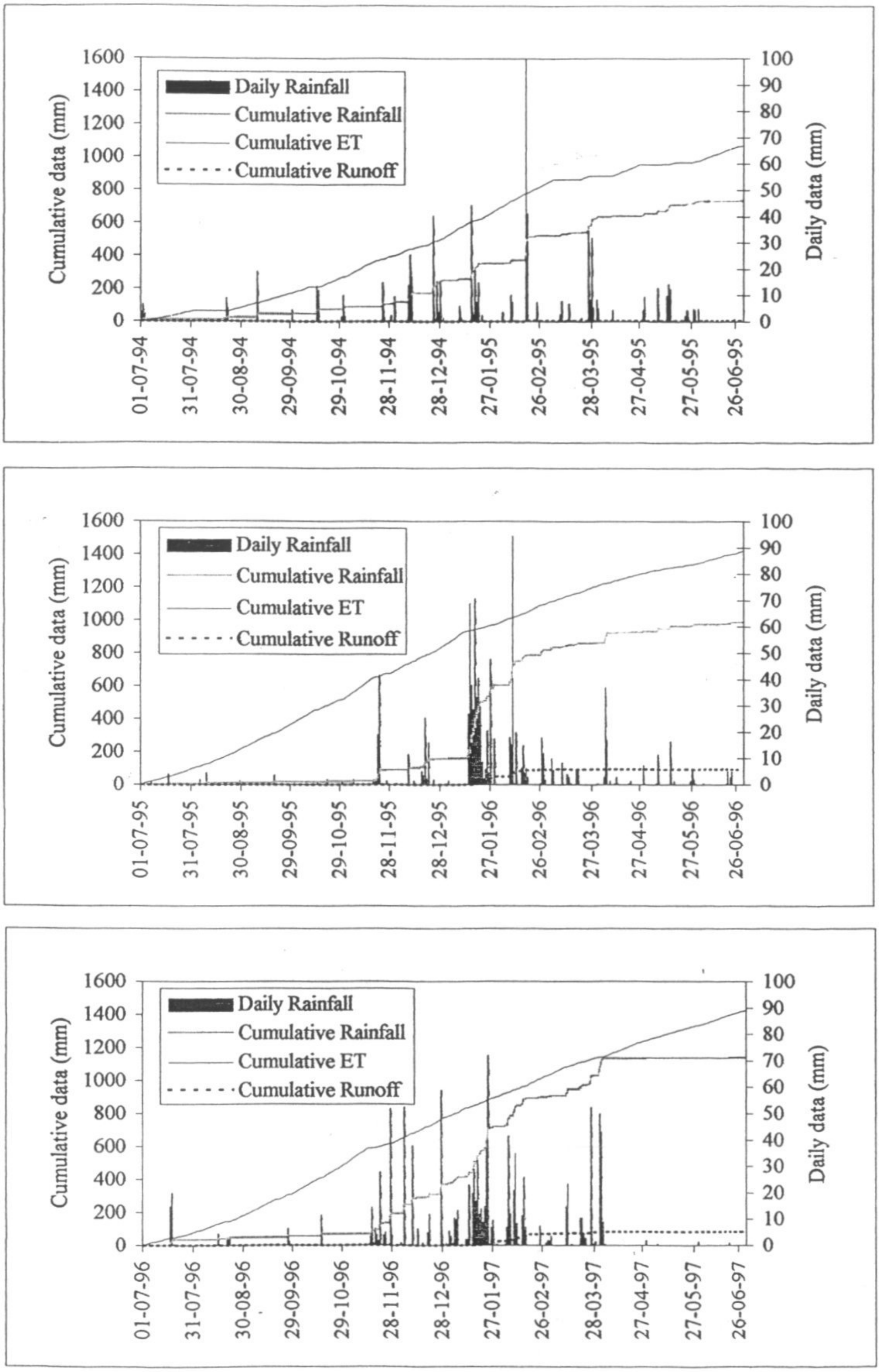


Figure 6.1 Total and daily rainfall, potential evaporation (Penman, 1948) and catchment runoff a) 1994/95, b) 1995/96, c) 1996/97

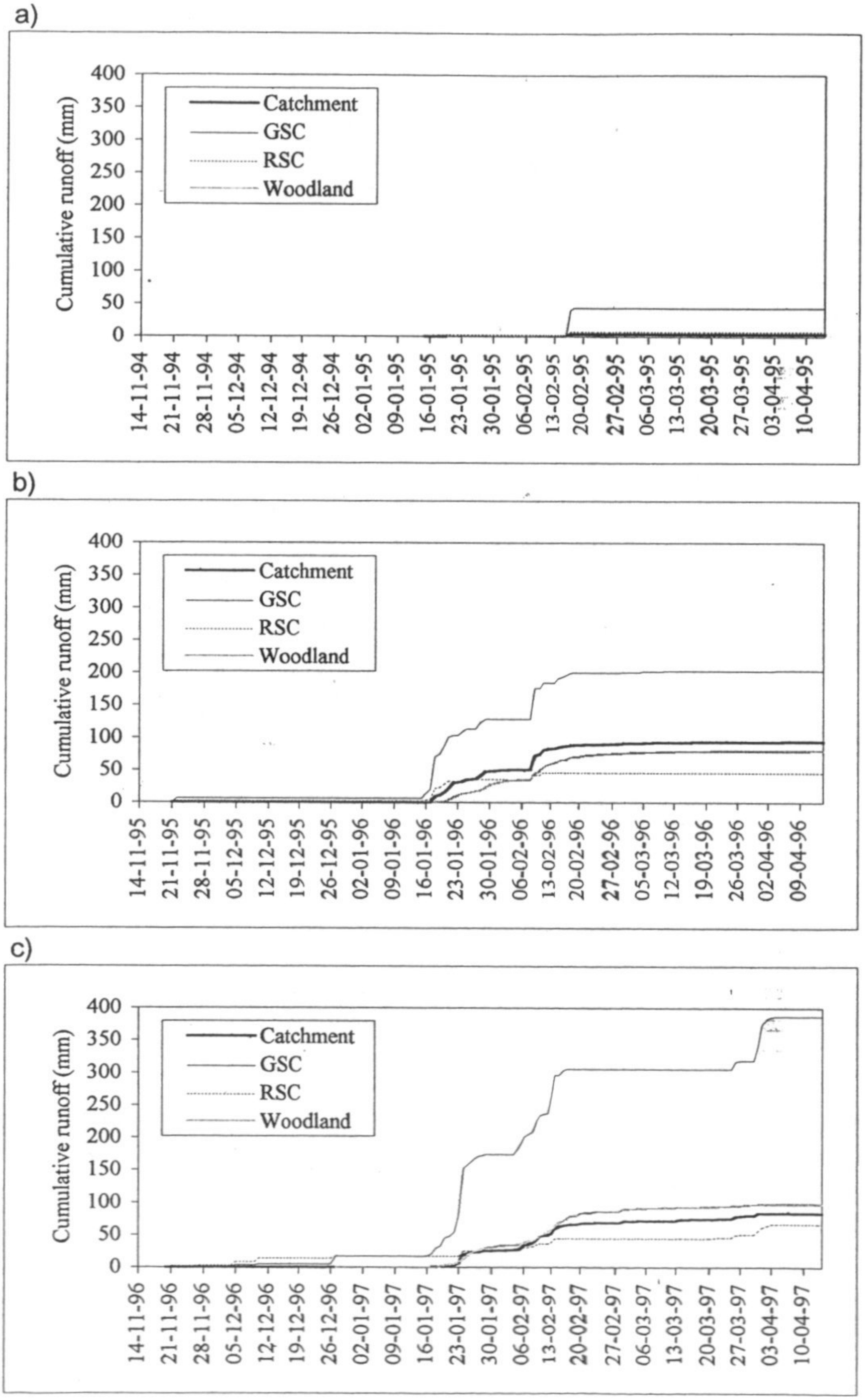


Figure 6.2 Cumulative runoff for sub-catchments and main catchment a) 1994/95, b) 1995/96, c) 1996/97

7. DISCUSSION

7.1 Surface water management

At the catchment scale, runoff from dryland catchments is generally a small part of the water balance. Hence, efficiency of capture is often already high. In Romwe catchment, runoff in 1994/95, 1995/96 and 1996/97 was only 4, 93 and 84 mm, respectively. However, in volume this represented 5, 109 and 99 times the total groundwater abstracted per year by the community for domestic use and small-scale irrigation. Although a small part of the water balance, runoff nonetheless still represents a major volume of water that could potentially be harvested.

Importantly, runoff from Romwe catchment is lower than reported from larger catchments in the same physical setting. 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 (Butterworth, pers.comm.). Further work is needed to assess if this difference is due to poorer land management within units of the larger catchments and, if the results of Romwe remain valid, how they can best be scaled up to achieve water resource management in this setting at sub-catchment and river-catchment scale.

The Romwe catchment study highlights that water harvesting to improve crop production is not the same as water harvesting to improve groundwater recharge. Surface management practices such as tied ridge and furrow, which harvest rain where it falls, can benefit rainfed crops and can mean the difference between a farmer achieving some yield or no yield (Nyamudeza and Nyakatawa,1995; Nyakatawa, 1996). However, the same practice, by preventing surface redistribution and concentration of rainfall behind conservation structures, may actually prevent groundwater recharge through the soil matrix. In years of low or evenly distributed rainfall, there will be a trade-off between the benefits to individual farmers of improved crop production through in-field water harvesting, and the benefits to the wider community of enhanced groundwater recharge through water harvesting at a larger scale. A "whole catchment" approach to water resource management is needed, and modelling the outcome of various management scenarios is likely to be critical to achieve the optimum balance (Butterworth, 1997).

Another practical implication for surface water management concerns the type of structure needed to meaningfully enhance groundwater recharge. Studies in Romwe catchment of a recharge trench comprising of three screened boreholes drilled to bedrock and sited in a trench to collect runoff from the base of a large inselberg (Macdonald *et al*, 1998) showed recharge enhancement to be severely limited by the volume of water stored in the trench. With infrequent but high intensity storms, only numerous low-cost structures such as contour channels, or more substantial structures such as small dams, may be expected to store sufficient runoff to enhance recharge. Indeed, in the driest parts of Zimbabwe, the most reliable wells and boreholes are invariably those located downstream of small dams. With enhanced recharge, these provide water after the dam has dried and other water points have failed. The second major advantage of adopting this conjunctive use or "belt and braces" approach to reliable water supply in difficult areas is that local communities can more readily see the need to protect the local catchment to protect the dam (reduce siltation) than to enhance recharge to protect the groundwater (Waughray *et al*, 1997).

A final practical implication concerns the design of contour channels that exist in most communal areas of Zimbabwe today. Ironically, these channels were constructed in the 1950s to carry water away in a controlled manner and thereby reduce soil erosion. In most areas they have not been maintained and presently contribute little to either controlling soil erosion (now recognised to depend more on in-field management) or to conserving water. Adaptation of these contour channels so that they hold rather than transport significant quantities of water would be a cost-effective measure that would immediately enhance recharge, particularly in areas of red clay soil.

7.2 Groundwater management

The study has highlighted that natural recession in groundwater is a major hydrological process and an important part of the catchment water balance. The recession recorded in Romwe is typically exponential, as Bredenkamp *et al* (1995) also observed for various aquifers in South Africa. Initial inspection suggests that this natural loss occurs through abstraction by deep rooted vegetation that covers about 21 ha of the valley floor, and through lateral flow. Although permeability in crystalline basement aquifers is generally low, a relatively transmissive layer occurs at the base of the regolith (Wright, 1992). Within the catchment this results in a large east-west gradient in groundwater levels. At the end of the dry season in November 1993, the gradient in levels was in excess of 60 m over a distance of 2.75 km, a slope of 2.2 per cent (Butterworth, 1997).

The practical consequence of this natural recession in groundwater is that recharge in a particular location may have little lasting benefit in that location, and carry-over from year to year will be limited by the natural recession. In these environments, groundwater should therefore be managed to make full use of the resource, firstly by enhancing recharge to ensure some replenishment every year (Section 7.1) and secondly, by using the water while it is there. In particular, there is considerable potential to increase abstraction while water tables are high. The number of seasonal wells in Romwe catchment, for example, could safely be increased tenfold or more and still have negligible impact on the natural recession of groundwater.

The belief amongst rural communities that abstraction should be limited to "save" the groundwater is to a large extent a fallacy. Natural recession will occur irrespective of any local reductions in use, and in fact will predominate. In other words, if the groundwater resource is not used while it is there, the opportunity will be lost.

The belief that groundwater can be "saved" is understandable, but is caused by a misunderstanding of why wells and boreholes fail. In Romwe, some traditional wells, particularly in the southern part of the catchment, typically run dry towards the end of the dry season. This is due in part to the natural recession in groundwater catching up with the limited depth of wells in the area. It is also due to low aquifer permeability. This can cause steep cones of depression to develop in the water table in the vicinity of pumping wells and boreholes, which on its own, or combined with extended periods of low recharge, can cause a serious decline in yield (Macdonald *et al.*, 1995). When local people reduce abstraction to "save" groundwater, they reduce the cone of depression around the well, thereby maintaining a low but consistent yield until natural recession causes well failure. As discussed in the next section, there is considerable potential to significantly increase abstraction without accelerating the natural recession by careful siting and design of water points.

7.3 Water point siting and design

Although implemented in 1991 at the time of maximum perceived groundwater stress, the Romwe collector well (sited by exploratory drilling to identify favourable aquifer properties and designed with lateral boreholes to overcome the permeability constraint) has successfully sustained an average yield of 1.6 Ml per year, just less than the sum of the abstraction (2 Ml per year) from all other 26 traditional dug wells in the catchment (Macdonald *et al*, 1995). Monitoring of the collector well since 1991 (Figure 7.1) shows that this relatively high abstraction from a single well has been achieved despite natural groundwater recession (indicated by piezometer G) and without any adverse effects upon the groundwater resource. In fact, groundwater levels show a complete recovery to pre-drought levels and above during the period 1993-97.

In low permeability aquifers, the siting and design of a water point are clearly critical to the amount of water that can be abstracted. Of the two, siting appears to be of paramount importance. To avoid well failure through natural recession of groundwater levels, particularly during extended periods of low recharge or drought, siting must locate the maximum depth of saturated aquifer. To avoid failure through the formation of a cone of depression around the well, siting must locate an aquifer of reasonable transmissivity or permeability. Well design can help, but the key is proper initial siting. Figure 7.2 shows data from the pilot project: Small-scale irrigation using collector wells (Lovell *et al*, 1996) which suggests that the improvement in yield achieved by drilling lateral boreholes to overcome the permeability constraint decreases with decreasing aquifer transmissivity, and is minimal if initial siting puts the well in an aquifer of transmissivity less than 1 m^2/day, unless one of the laterals intercepts a major water bearing fissure as in the case of site 1 (Figure 7.2).

In the pilot project: Small scale irrigation using collector wells (Lovell *et al*, 1996), exploratory drilling was found to be vital to locate optimum well sites because neither water divining nor present geophysical methods have sufficient resolution in terrain of such high spatial variability. The findings from Romwe catchment reinforce the need for, and the value of, improved well siting methods, and it will be important to investigate the cost-effectiveness of exploratory drilling and to quantify by how much the yield and reliability of simple dug wells can be improved when sited by this new approach. The policy implications for rural water supply and drought mitigation are discussed in the next section.

7.4 Policy implications for rural water supply and drought mitigation

Monitor groundwater

Groundwater provides a buffer against individual dry years. The massive failure of wells and boreholes that occurred throughout southern Africa in the early 1990s need not have come as a surprise. Long-term trends in groundwater levels are apparent and reflect cycles in rainfall. If groundwater levels and rainfall are monitored, groundwater drought can be predicted well in advance. This can allow planned and more sustainable long-term drought mitigation programmes to be implemented, and avoid the need for "emergency" drought-relief projects which have often been put in place only after the event and which have rarely been cost-effective (Waterkeyn 1997).

Develop family wells and communal water points

The cause of low groundwater levels in the early 1990s is shown to be the extended period of low rainfall from 1981 rather than human impacts on catchment hydrology. Above average rainfall since 1993 has completely restored groundwater to pre-drought levels and above. Boreholes and wells successfully sited during the low groundwater period are likely to be sustainable through future periods of drought. However, many being constructed now during a period of generally high water levels will probably not be sustainable. In particular, the current trend to implement traditional family wells (Morgan *et al*, 1996; Mtakwa and Chimbunde, 1997; Morgan, 1997) is worrying if this is to be at the expense of siting reliable, relatively high yielding communal water points in a coordinated programme.

Family wells are often low yielding because siting with respect to the homestead rather than aquifer properties is not optimum for water supply. Average abstraction from family wells in Romwe is only 210 litres per day (Macdonald *et al*, 1995). Moreover, they are prone to failure because if sited where permeability is low, they fail prematurely due to localised dewatering around the well, and if sited where saturated weathering is shallow, they fail due to natural recession in the groundwater, especially during drought. With increasing population, and increasing reliance on groundwater for domestic use and production, the section of population at risk during low rainfall cycles is growing. Areas of best groundwater potential are frequently under land already "owned" by individual families. It will become increasingly important in water resource development to ensure equity of access to these water resources. This can best be achieved by development of reliable, relatively high yielding communal water points in these locations.

Although development of traditional family wells offers important advantages of simplicity, individual ownership and low cost, and undoubtedly adds to general security and wellbeing in times of plentiful rain, there is equal need to develop reliable communal schemes as a backstop for times of low rainfall and for those families without land suited to a family well. Given the nature of crystalline basement aquifers and the cyclical pattern of rainfall, a policy to develop a mix of both individual family wells and more reliable communal water points with irrigation schemes is recommended (Moriarty and Lovell, 1997).

Rehabilitation of existing water points offers the most cost-effective way to provide reliable communal water points in many areas. Rehabilitation in this context is not the same as repair. The pilot project "Small scale irrigation using collector wells" (Lovell *et al*, 1996) highlighted that many existing water points are under-utilised at present because pump capacity is far less than potential safe yield. By increasing pump capacity, these water points can be turned into "productive water points" and support income generating activities such as small scale irrigation. Giving water an economic value in this way creates the incentive to maintain and repair, and helps to ensure that this water point at least is always maintained by the local community (Waughray *et al*, 1997).

During the rehabilitation process, pumping test analysis is required to determine the maximum sustainable yield. The Romwe study reinforces the need to model the abstraction that can safely be sustained during prolonged periods of natural groundwater recession. Suitable modelling approaches are described by Thompson and Lovell (1996) and MacDonald and Macdonald (1997). This appraisal should form an integral part of rural water supply programmes but can provide the basis for an immediate increase in water supply and development of small scale irrigation with the respective communities.

7.5 Hydrogeological zones of different groundwater potential

Development of small-scale irrigation using groundwater in semi-arid areas underlain by crystalline basement rocks has the potential to be of very considerable benefit both to local people and to the local environment (Lovell *et al*, 1996; Waughray *et al*, 1997). This potential extends far beyond Zimbabwe and includes many countries in southern, central and western Africa (Wright, 1992).

In zones where hydrogeology is similar to that of Romwe catchment, the present study indicates enormous potential to safely and significantly increase groundwater abstraction to support small-scale irrigation and other income generating activities through the development of low-cost seasonal wells and relatively high-yielding perennial wells. However, not all areas will hold the same potential or require the same mix of well types. The potential to develop productive water points across the region is linked to rainfall, parent rock mineralogy and surface morphology as the three principal factors affecting recharge and chemical weathering, permeability and hydraulic gradient, respectively. These factors combine to determine the weathering profile and relative position of the water table, which in turn determine the most appropriate exploration and development strategy. A plot of parent rock type against rainfall becomes a valid projection upon which the various groundwater provinces can be plotted and provides a useful means of classifying the various occurrences of groundwater (Acworth, 1987). Applying this approach, zones of different groundwater potential in southern Zimbabwe are mapped in Figure 7.3 and described in Table 7.1 in terms of the relative numbers of productive water points and most appropriate development strategies anticipated.

The findings and recommendations from Romwe catchment are relevant wherever communally-managed catchments are located in areas of younger undifferentiated gneisses with Agricultural Rainfall Index (ARI) greater than 40 (Bernardi and Madzudzo, 1990). In Zimbabwe, this hydrogeological zone covers a total area of about 30,000 km^2 in the south-east of the country (zone 2b in Figure 7.3). The findings are directly relevant to parts of Bikita, Chivi, Masvingo and Zaka Districts, and to a lesser extent in drier zone 2a to parts of Beitbridge, Gwanda, Mberengwa and Mwenezi Districts. The findings are also relevant to dambo management in wetter areas to the north (McCartney *et al*, 1998), and the study has answered many of the questions posed in recent dambo reports concerning the effects of climatic variation and land use change on dambo resilience and appropriate water resource development strategies (NRI, 1997).

7.6 Catchment management in communally-managed dryland areas

In catchments similar to Romwe, recharge through red clay soils will generally be 4-5 times greater than through grey duplex soils, and will contribute significantly to recharge of the whole catchment. Although preliminary, these findings suggest that areas of red clay soil should be the focus for development of wells, and should be managed to enhance recharge using modified contour channels (*Fanya juu*) rather than in-field water harvesting. In contrast, areas of grey-duplex soil contribute little to groundwater recharge but are the major source of runoff and interflow. This could be harvested in small dams and used to water livestock and perhaps irrigate pastures. In-field water harvesting would be more appropriate on the grey duplex soils, probably as a system of broad ridges and furrows across the contour which can provide flexibility in this periodically semi-arid, periodically waterlogged environment (Mharapara, pers.comm.). In dry years, staple crops such as maize can be grown in the furrows and benefit from localised rainfall concentration. In wet years, when a perched water table forms on top of the impermeable B horizon, maize can be grown on the ridges and rice grown in the waterlogged furrows, the excess water from the furrows flowing to the small dams.

Many catchment management programmes in dryland areas are being implemented on the basis of scant and often inappropriate information. The Romwe Catchment Study is an example of the type of study needed to obtain the fundamental hydrological, agricultural and socio-economic information needed to ensure that these programmes do not end in disappointment. Instrumented small catchment studies similar to Romwe are required in other principal physical and social settings throughout the region. In Zimbabwe, small catchment studies are particularly required to quantify water resource potential and identify appropriate agricultural development strategies in the driest and most degraded catchments that typify Communal and Resettlement Areas in hydrogeological zones 1a, 3a, 4 and 5 (Figure 7.3; Table 7.1) and to identify the principles and local organisational structures best suited for water resource management in these different settings.

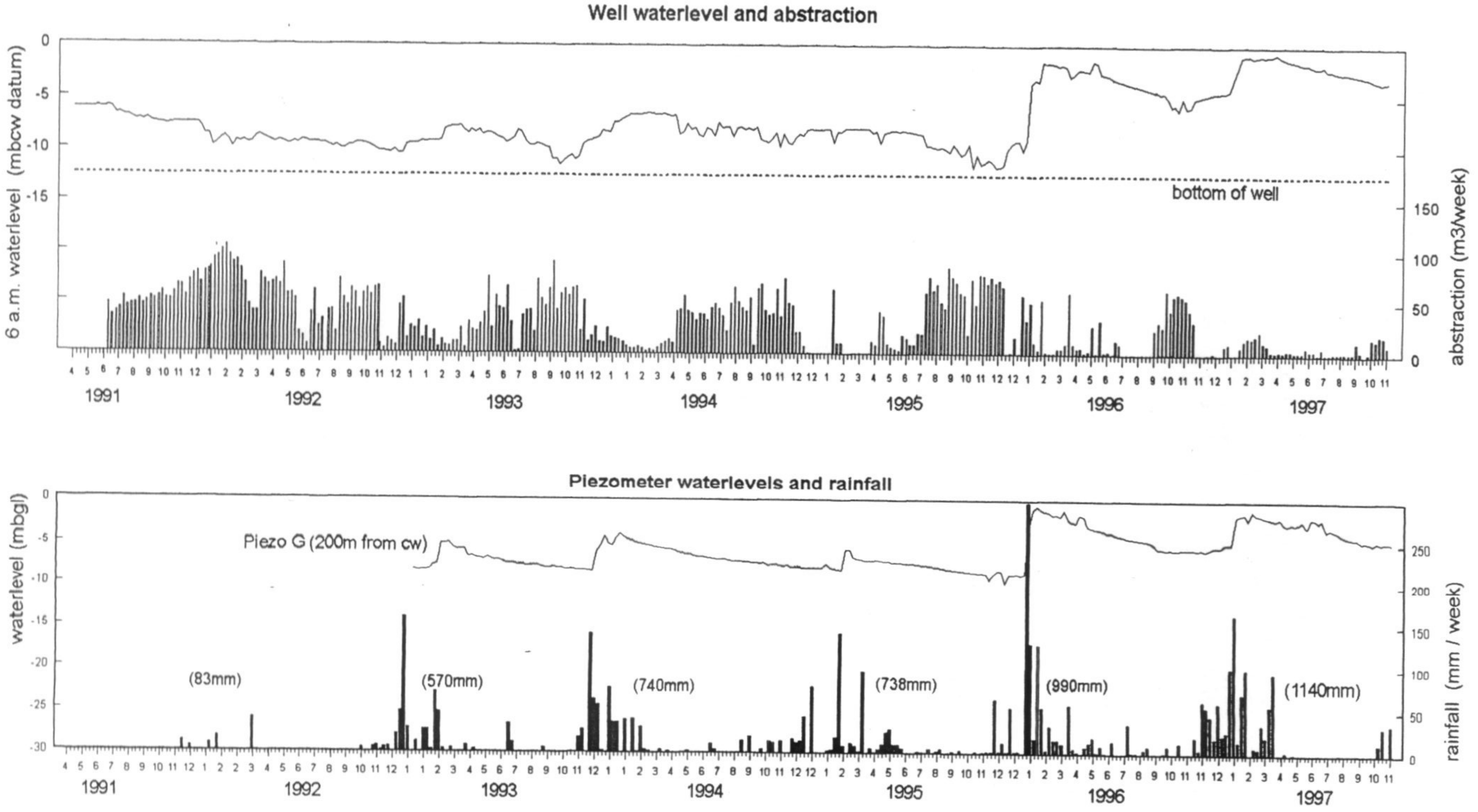
An objective of the Romwe catchment study was to provide a long-term research facility for the region. The problems of natural resource management in communally-managed dryland areas are long-term, and the solutions may not be rapid. A research facility to enable continued work was considered important. Excellent relations have been maintained with the Romwe community since initial development of their collector well and irrigation scheme in 1991. The catchment is fully instrumented to measure all components of the water balance, and sub-catchments provide detail on the two major arable soils and miombo woodland. Hydrological, social and economic baseline information has been assembled with the participation of the local people, and a comprehensive database is established. The study offers an ideal opportunity for Zimbabwean students.

It is hoped that the study can be expanded to become a long-term assessment of the physical and socio-economic benefits of taking an integrated approach to community-based management of natural resources in semi-arid areas. For the people and environment of Romwe and areas like it, the present project will be a success if the local participation and infrastructure developed since 1991 can now be used to introduce and quantify the impact of some of the identified management options, and the research facility can become the first in a number of demonstration catchments for visiting extension staff and communities from similar environments elsewhere in the region.

Table 7.1 Hydrogeological zones of different groundwater potential in southern Zimbabwe and likely development methods

Zone	Description	Groundwater potential	District (fraction of)	Development method (%)
1a	Older gneiss complex Agricultural rainfall index < 40	Low to Moderate (1-2 schemes per ward)	Gwanda: 40% Mberengwa: 30% Shurugwi: 10% Zvishavane: 30% Chivi: 30% Bikita: 10%	Boreholes 50 Coll.Wells 25 Small dams 25
1b	Older gneiss complex Agricultural rainfall index > 40	Moderate to High (3-4 schemes per ward)	Shurugwi: 80% Zvishavane: 10% Masvingo: 20% Zaka: 30% Bikita: 20% Gutu: 10%	Boreholes 50 Coll.Wells 50
2a	Younger undifferentiated gneisses Agricultural rainfall index < 40	Low to Moderate (1-2 schemes per ward)	Beitbridge: 5% Gwanda: 30% Mberengwa: 30% Mwenezi: 30% Bikita: 10% Chivi: 20%	Boreholes 60 Coll.Wells 40
2b	Younger undifferentiated gneisses Agricultural rainfall index > 40	Moderate to High (3-4 schemes per ward)	Zaka: 50% Bikita: 20% Masvingo: 30% Chivi: 30%	Boreholes 40 Coll.Wells 60
3a	Younger intrusive granites Agricultural rainfall index < 40	Very low (0-1 scheme per ward)	Gwanda: 20% Mberengwa: 30% Zvishavane: 10% Chivi: 20% Bikita: 10%	Boreholes 40 Coll.Wells 10 Small dams 50
3b	Younger intrusive granites Agricultural rainfall index > 40	Low to Moderate (1-2 schemes per ward)	Zaka: 20% Bikita: 30% Masvingo: 20% Gutu: 90%	Boreholes 50 Coll. Wells 50
4	Beitbridge paragneiss	Moderate (2-3 schemes per ward)	Beitbridge: 50% Mwenezi: 40% Chiredzi: 30%	Boreholes 80 Coll.Wells 20
5	Karoo basalt	High (4-5 schemes per ward)	Beitbridge: 50% Gwanda: 10% Mwenezi: 30% Chiredzi: 60%	Boreholes 50 Coll.Wells 50

Agricultural Rainfall Index (ARI): 100 x (80% EDR / ET) %
EDR: Estimated dependable rainfall (mm)
ET: Potential evaporation (mm)
(Source: Bernardi and Madzudzo, 1990)



Well waterlevel and abstraction

Piezometer waterlevels and rainfall

Figure 7.1 Romwe collector well performance, 1991-97

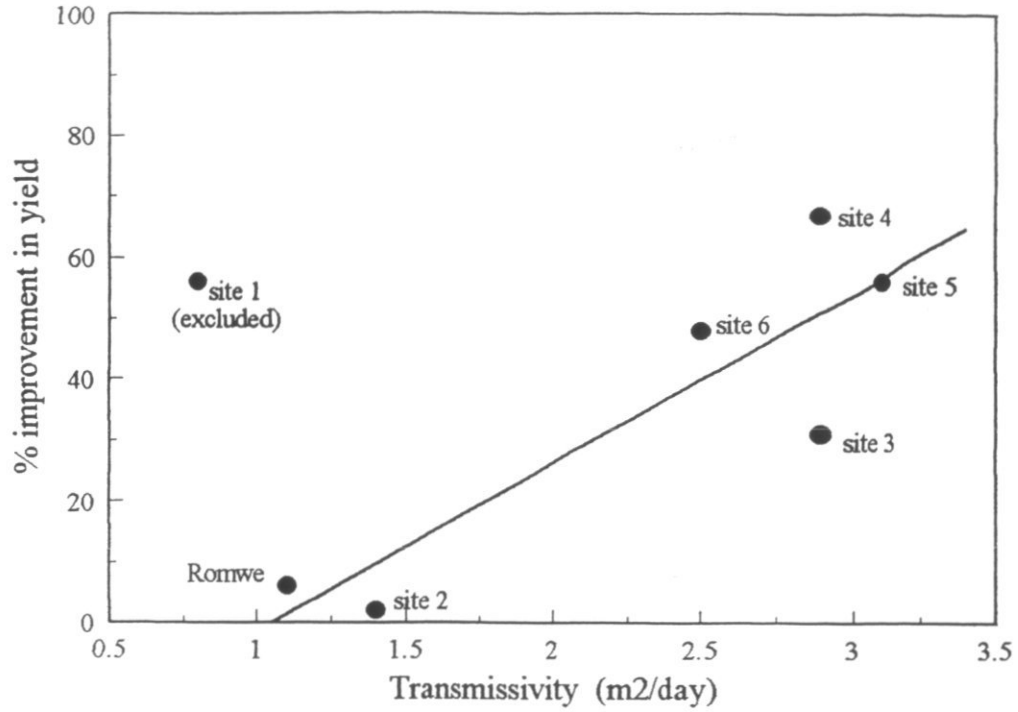


Figure 7.2 **Improvement in yield due to lateral drilling in crystalline basement aquifers of different transmissivity (source: Lovell et al, 1996)**

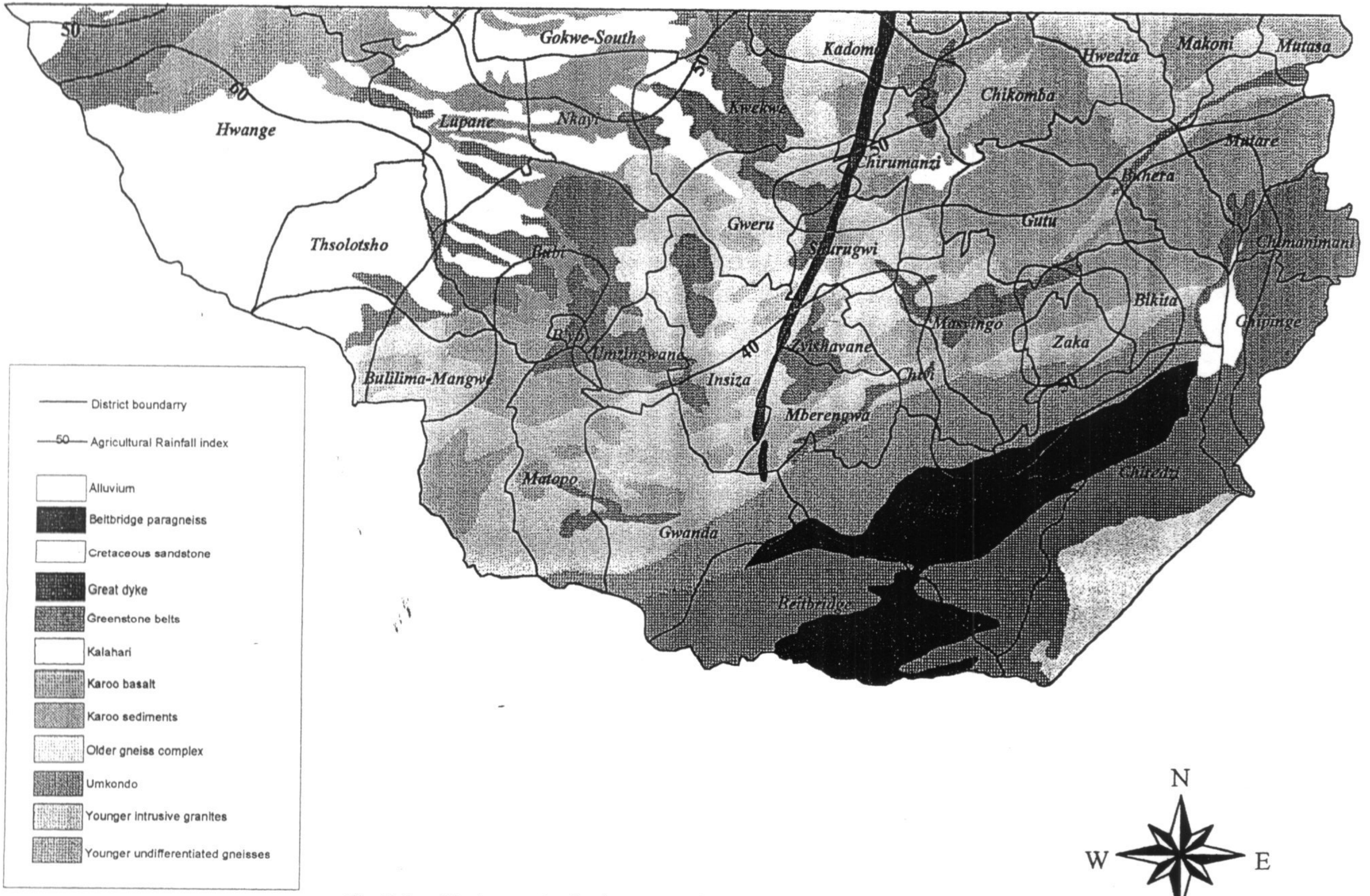


Fig 7.3 Hydrogeological zones of different groundwater potential in southern Zimbabwe based on geology and agricultural rainfall index

8. RECOMMENDATIONS

Education:

- There is need to prepare extension materials and popular articles to put communities, extension staff, local authorities and NGOs in touch with the findings of this study, particularly regarding the fallacy of "saving" groundwater and the potential to safely use more groundwater for income generating projects, especially while water tables are high.

Productive groundwater development:

- Governments and Donors to consider developing programmes to convert existing, under-utilised communal water points into productive water points that support income generating activities such as small scale irrigation. Appraisal should include pumping tests and modelling of groundwater recession to determine yields sustainable during drought, and selection of appropriate pump technology matched to these yields, but can provide the basis for immediate increase in water supply and development of small-scale irrigation with respective communities

- Agencies involved in water resource development in dryland areas underlain by crystalline basement rocks to investigate the improvement in yield and reliability of simple dug wells sited by low-cost exploratory drilling.

Catchment Management:

- Governments and Donors to consider instrumenting small catchments as an integral part of larger water resource development programmes. Sited in principal physical and social settings, these studies can provide the fundamental hydrological, agricultural and socio-economic information needed to underpin development. In Zimbabwe, small catchment studies are particularly needed to quantify water resource potential and identify appropriate agricultural development strategies in dry, degraded Communal and Resettlement Areas on basalt, granite and gneiss in areas with mean annual rainfall less than 600 mm.

- Further work is needed to assess if management strategies for micro-catchments such as Romwe can provide the building blocks for catchment management. Research is required to identify the principles and organisational structures best suited for catchment management in the different physical and social settings, and to investigate and test the institutional relations and bio-physical links between micro-catchments needed to scale up to management at sub-catchment and river-catchment scale. In Zimbabwe, this information is needed to help develop the national Water Resources Management Strategy (WRMS).

- Study of miombo woodland hydrology is required to quantify the importance to overall catchment hydrology. Study of natural groundwater recession is required to partition the process to abstraction by deep rooted vegetation, lateral flow and leakage into the fractured bedrock, and to determine the importance to downstream water supplies.

- As more information becomes available, trade-offs between resource management options become clearer. It will be important for researchers to develop user-friendly decision support systems such as Bayesian belief networks that integrate the available information, and help policy makers, catchment planners and extension staff to reach sound management decisions.

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