# NATURAL RESOURCES SYSTEMS PROGRAMME
## *FINAL TECHNICAL REPORT*

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Evaluation and promotion of rainwater harvesting in semi-arid areas.

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# Evaluation & Promotion of Rainwater Harvesting in Semi-Arid Areas

UNIVERSITY OF
NEWCASTLE

# Final Technical Report

October 1996

J.W Gowing and M.D.B Young

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# ACKNOWLEDGEMENTS

The work described in this report has been funded by the UK Overseas Development Administration (ODA) through research programmes managed by the Natural Resources Institute (NRI). Their support is gratefully acknowledged.

Throughout the project close collaboration has been maintained between the research team at the University of Newcastle upon Tyne and their counterparts at Sokoine University of Agriculture in Tanzania, whose contribution is gratefully acknowledged.

Special mention should go to Dr Guido Wyseure who was an invaluable member of the Newcastle team before his departure from the University.

While acknowledging the important contributions of many others to the work reported in this document, the authors accept full responsibility for the information and views contained herein. They should not be attributed to ODA or to NRI.

## EXECUTIVE SUMMARY

The project falls within the NRSP Semi-Arid portfolio of research and has the following goal:

> *Commodity production increased through improved conservation and use of water resources.*

Its purpose is as follows:

> Improved techniques for rainwater harvesting and conservation tillage developed and promoted.

The geographic focus for the project is the semi-arid lowlands in North of Tanzania lying in the western foothills of the Pare mountains. This area has been settled relatively recently as a result of migration from the over-populated highlands. Similar patterns of population pressure in the high-potential uplands causing migration into semi-arid areas have been noted throughout East Africa.

The project seeks, through a combination of fieldwork and computer modelling, to fulfil two aims:

1) to demonstrate viable cropping systems based upon rainwater harvesting techniques;

2) to develop a model of the RWH process as an aid to identifying best-bet options.

The project has been closely integrated with the activities of a research team at Sokoine University (SUA) in Tanzania, who have primary responsibility for all fieldwork.

Experimental fieldwork has been executed at three sites, which are representative of different land resource zones within the semi-arid part of Tanzania. The experiments established on these sites were:

- runoff measurement experiment designed to provide data on runoff response from small plots representing within-field RWH systems

- runoff farming experiment designed to provide data on crop response to varying levels of enhanced water supply

- conservation tillage experiment designed to investigate improved soil-water management without water harvesting.

Data from runoff measurement experiments at two sites have been used in validating the model (PARCHED-THIRST).

PARCHED-THIRST is a physically-based model which simulates the key processes influencing the performance of RWH systems. It uses input data that are readily available or can be easily obtained. It incorporates pre-processors to assist in assembling the necessary climate data and soils data. The rainfall-runoff process is simulated as an infiltration excess using a Green-Ampt infiltration estimator. It is designed for within-field RWH systems and therefore does not deal explicitly with the overland process, since transfer distances are short. It uses daily rainfall data as input which are then converted to intensity values by the rainfall disaggregator model.

The PARCHED-THIRST model is a tool that can extend and add-value to field experiments which are themselves costly, time-consuming and laborious. It is seen as a tool for technology transfer in that it allows the user to conduct computational experiments (i.e. what-if analysis) and hence determine 'best-bet' options. Long-term simulation can be readily achieved to permit evaluation of sustainability in terms of average performance as well as seasonal and annual variability.

Results of 30year simulations are reported for conditions typical of the project's main geographic focus. There is found to be little overall increase in Masika yield due to RWH, but a marked improvement occurs in four years thus resulting in reduced variance. In contrast, it is seen that the introduction of RWH causes increased variance in Vuli season yields and a significant overall increase.

The limitations of the existing model are acknowledged and further work is proposed to allow for its refinement and for testing its transferability. There is a need also for further development of the model as an extension tool based upon participative research both with farmers and extension agents.

# 1. BACKGROUND

## 1.1 Context and Origins

The project began in April 1992 under the auspices of the ODA financed *Resource Assessment and Farming Systems* (RAFS) research programme. As a result of the review of ODA's Renewable Natural Resources Research Strategy (RNRRS) in 1993/4, RAFS was revised and extended to create the new Natural Resources Systems Programme (NRSP). The project then fell within the NRSP Semi-Arid Production Systems portfolio.

Recent ODA involvement in dryland farming research in semi-arid Africa can be traced back to the Dryland Farming Research Scheme (1971-85), which was succeeded by the Land & Water Management Project (1987-92). These major projects which were supported by strategic research funds were both based in Botswana.

As a component of the RNRRS strategy review, extensive consultations in Southern and Eastern Africa (Pound *et al*, 1991) led to the conclusion that high priority should be given to land and water management research. It was resolved to build upon earlier experience, particularly in Botswana, with a view to:

- elaborating processes influencing soil fertility and moisture availability
- developing appropriate technologies to assist resource-poor farmers
- strengthening national and regional capacity to carry out relevant research.

Given the increasing concern over impact and uptake of research, it was decided to shift the emphasis to other countries within the region.

At about this time, following a World Bank assisted review of agricultural research strategy within Tanzania, a National Agricultural Research Master Plan was prepared (MoA, 1991). This plan identifies 'soil and water management' as top priority and accordingly Sokoine University of Agriculture (SUA) was invited to provide leadership in establishing a programme of research in soil and water management. The current project was therefore formulated as a collaborative venture between SUA and University of Newcastle.

The project seeks to address the critical researchable constraint of improved management of soil-water in dryland crop production. It is therefore concerned with Purpose 1 of NRSP Semi-Arid Production System:

> *Commodity production increased through improved conservation and use of water resources.*

and in particular, it is concerned with Output 1:

*Improved techniques for rainwater harvesting and conservation tillage developed and promoted.*

The economy of Tanzania remains dominated by agriculture but production is severely constrained by a combination of low soil fertility with inadequate and unreliable rainfall in addition to tsetse infestation. Lateral expansion into more marginal areas offers little prospect of acceptable returns and carries a high risk of environmental degradation (BDDEA, 1994). There is therefore a clear need to intensify production on existing land, where soil-water availability is often a limiting constraint.

Scope for improving dryland crop production through rainwater harvesting probably exists throughout the semi-arid regions of Tanzania (rainfall 400 - 800 mm pa), but seems most promising within two of the main farming systems: maize/legumes and livestock/sorghum/millet/cotton/rice. These cover respectively 30% and 12% of the mainland area of Tanzania (BDDEA, 1994).

The initial focus for the project was chosen to be the semi-arid lowlands in the south of Kilimanjaro region, particularly in the foothills of the Pare mountains. This area has been settled relatively recently as a result of migration from the overpopulated highlands. The preferred cropping system is maize/legumes and previous attempts by the government extension service to promote sorghum as an alternative have been largely unsuccessful. A development opportunity was therefore clearly identified which requires evaluation and promotion of suitable cropping systems based upon rainwater harvesting/conservation.

Previous work by ODA Land & Water Management Project in Botswana (Miller, 1992) concluded that external catchment systems appeared to offer more advantage than within-field systems. This conclusion was to be tested under conditions prevailing in Tanzania, particularly in relation to concern over possible induced damage due to floods and soil erosion arising from external catchment systems.

Although the work is concentrated in Tanzania, and is focused particularly on the target area mentioned above, its wider relevance should not be ignored. A critical look at the environmental situation throughout East Africa (Tanzania, Uganda, Kenya, Ethiopia) reveals similar patterns of population pressure in the high-potential uplands causing migration into semi-arid areas (Stahl, 1993).

## 1.2 Overview of related work

The links between poverty and environmental degradation pose a real challenge to any attempts to promote sustainable development in semi-arid Africa. It is therefore recognised that soil/water management is a key element of any strategy for sustainable development in that it offers the means to reverse both processes. Yet it is a research topic that until recently received little attention, as is illustrated by the fact that of the 170 sources cited by Boers and Ben Asher (1982) in their review of water harvesting, only one dealt with SSA.

More recently, interest in water harvesting within SSA has increased, possibly as a result of the World Bank supported study (Reij *et al.*, 1988). Since then other significant publications have included reviews of soil and water conservation (Hudson, 1987; Reij, 1991; IFAD, 1992; Prinz, 1995) and manuals for technicians and extension workers (Critchley & Siegert, 1991; Critchley, 1991). These sources represent a significant advance in that they attempt to assemble and systematise indigenous knowledge, but they do not attempt any scientific analysis of the processes involved.

Different approaches to classifying water harvesting methods have been proposed by a number of authors. Generally, these are based on the characteristics of the runoff producing and storage elements of the system as represented in Figure 1.1. At the simplest level, the various methods can be considered in two groups:

(i) *within-field methods* in which the transfer of water takes place over a short distance (maximum 50-100 m) usually by sheet flow. This category includes microcatchments, contour ridges, furrow dyking, contour benches, strip planting etc.

(ii) *external catchment methods* in which runoff is collected from a catchment area at a considerable distance from the receiving area and is transferred by channel flow. This category includes terraced wadi systems, hillside conduit systems, dams used for recession planting etc.

At one extreme, the limit between within-field water harvesting and *in-situ* moisture conservation is indistinct. The former makes use of and even induces surface runoff, while the latter aims at preventing runoff and conserving water where it falls. However, if the runoff producing area is small and is surrounded by the runoff receiving area, then the distinction may not be clear. At the other extreme, the limit between external catchment methods of water harvesting and irrigation is also indistinct. In this case it is the degree of uncertainty and lack of control over water supply which allows for differentiation.

Considering the micro-scale end of the continuum, there is an extensive literature on work in Tanzania (as elsewhere in SSA) on soil conservation, which can often be traced back to colonial initiatives (Berry & Townsend, 1972). The poor scientific basis for these early policy initiatives has been cited as a reason for their lack of success (Temple 1972, Watson 1972). A considerable research effort followed through the 1970's and 1980's, but with limited impact due to reluctance amongst resource-poor farmers to adopt new practices (Hudson, 1991).

In spite of this considerable interest in soil conservation, there has been little systematic research within SSA into within-field (i.e. micro-scale) methods of water harvesting. Efforts to analyse the processes governing the performance of such systems have been concentrated in the Middle East (Evenari *et al*, 1971, Ben-Asher & Warrick, 1987, Boers *et al*, 1986, Oron &Enthoven 1987) and to a lesser extent in India and USA (Sharma 1986, Hari Krishna 1989, Sharma *et al* 1986, Namde 1987).

At the macro-scale end of the continuum, external catchment methods (runoff irrigation) have attracted greater interest within SSA (Ben-Asher & Berliner 1994, Tauer & Humborg, 1992) and some progress has been made in understanding the hydrological processes involved (Carter & Miller 1991). There is also an earlier literature on catchment-scale hydrology in East Africa (Pereira *et al* 1962, Blackie *et al* 1979) but this is not immediately applicable in designing meso-scale rainwater harvesting systems.

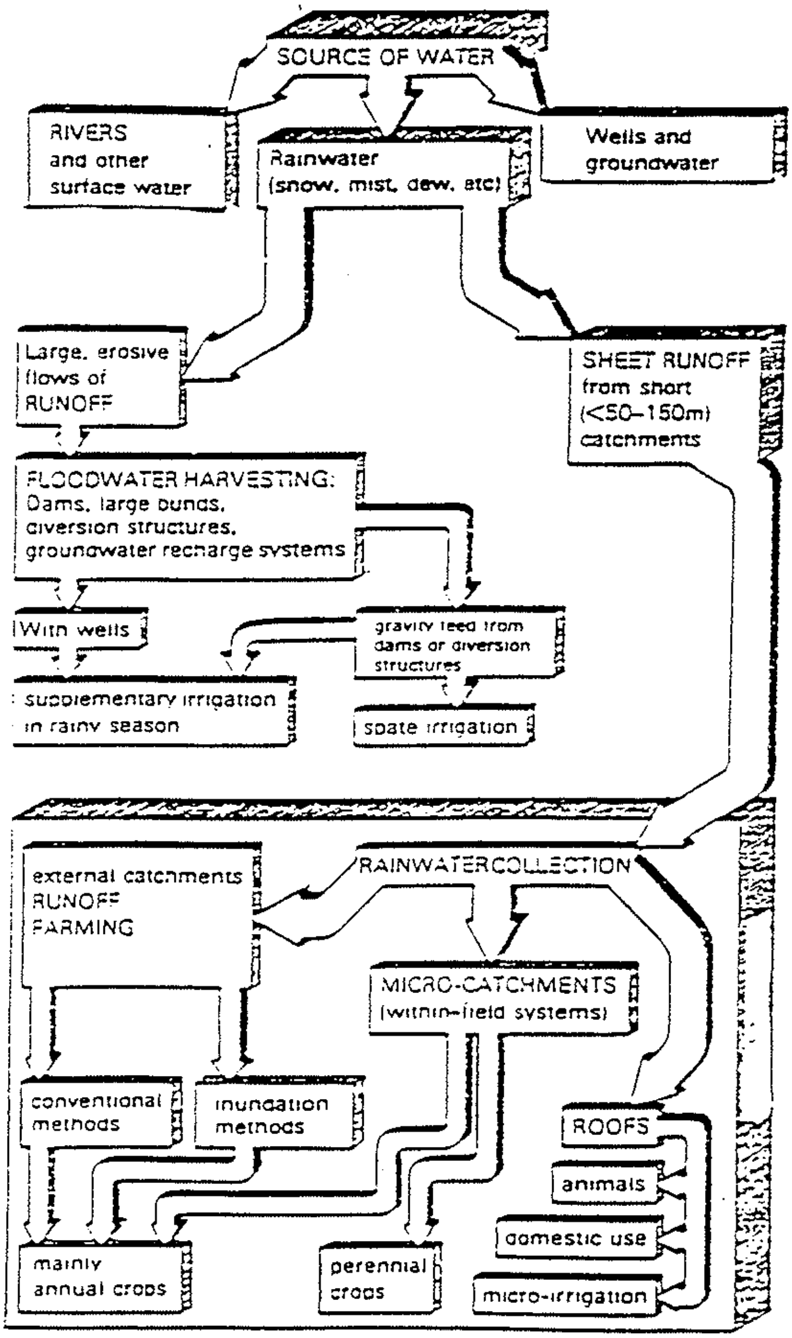


**Figure 1.1** Water harvesting in relation to other water sources
*(Source: Pacey and Cullis, 1986)*

# 2. PURPOSE

## 2.1 Objectives of the project

A successful water harvesting system must be:

- technically sound (i.e. designed to suit physical conditions)
- socially acceptable (i.e. adapted to social/farming systems)
- economically feasible (i.e. relevant to perceived economic need)

The project has sought to address these problems through a combination of experimental work in Tanzania and modelling studies based in Newcastle, which aimed to:

a) evaluate agro-ecological constraints on cropping (of maize in particular) in selected pilot project areas in Tanzania;

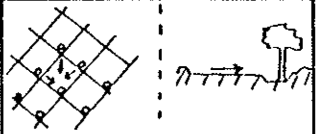
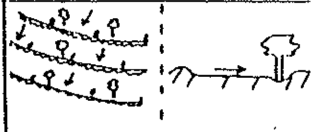
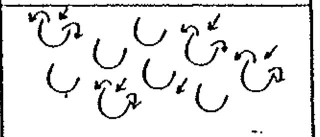
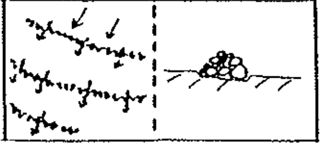
b) evaluate existing farmer-knowledge of soil-water management practices in Tanzania;

c) develop and test an agro-hydrological model based on water harvesting trials in the selected pilot project areas;

d) use the model to simulate performance of various water harvesting systems with a view to developing it as a tool for technology transfer.

The project involves close collaboration with a research team at Sokoine University of Agriculture (SUA) in Tanzania, who have primary responsibility for all fieldwork including operating the three experimental sites (Kisangara, Hombolo, Morogoro). These activities are reported separately by SUA and are covered here only in so far as they impinge on the primary concern of this project, which is modelling the performance of within-field RWH systems. A summary of the systems considered is presented in Table 2.1.

Table 2.1 Summary of within-field water harvesting techniques

| | Classification | Main Uses | Description | Where Appropriate | Limitations | |
|---|---|---|---|---|---|---|
| negarim microcatchments | microcatchment (short slope catchment) technique | trees & grass | Closed grid of diamond shapes or open-ended "V"s formed by small earth ridges, with infiltration pits | For tree planting in situations where land is uneven or only a few tree are planted | Not easily mechanised therefore limited to small scale. Not easy to cultivate between tree lines |  |
| contour bunds | microcatchment ( short slope catchment) technique | trees & grass | Earth bunds on contour spaced at 5-10 metres apart with furrow upslope and cross-ties | For tree planting on a large scale especially when mechanised | Not suitable for uneven terrain |  |
| semi circular bunds | microcatchment (short slope catchment) technique | rangeland & fodder (also trees) | Semi-circular shaped earth bunds with tips on contour. In a series with bunds in staggered formation | Useful for grass reseeding, fodder or tree planting in degraded rangeland | Cannot be mechanised therefore limited to areas with available hand labour |  |
| contour ridges | microcatchment (short slope catchment) technique | crops | Small earth ridges on contour at 1.5m -3m apart with furrow upslope and cross-ties Uncultivated catchment between ridges | For crop production in semi-arid areas especially where soil fertile and easy to work | Requires new technique of land preparation and planting, therefore may be problem with acceptance |  |
| trapezoidal bunds | external catchment (long slope catchment) technique | crops | Trapezoidal shaped earth bunds capturing runoff from external catchment and over-flowing around wingtips | Widely suitable (in a variety of designs) for crop production in arid and semi-arid areas | Labour-intensive and uneven depth of runoff within plot. |  |
| contour stone bunds | external catchment (long slope catchment) technique | crops | Small stone bunds constructed on the contour at spacing of 15-35 metres apart slowing and filtering runoff | Versatile system for crop production in a wide variety of situations. Easily constructed by resouce-poor farmers | Only possible where abundant loose stone available |  |

Source: Critchley and Siegert, 1991

Whether or not any specific water conservation intervention will be adopted by farmers is influenced by many factors. These barriers to adoption have received greater attention in recent years (Hudson 1991, Baum *et al* 1993) and have resulted in a paradigm shift. Previous top-down approaches which attempted to impose 'improved' technology packages are being replaced by more facilitating/participative approaches to extension (FAO 1995). The resulting shifts in emphasis are summarised in Table 2.2.

**Table 2.2:** Some Shifts in Emphasis Regarding Water and Soil Conservation

| FOCUS THEN | FOCUS NOW |
|---|---|
| Loss of soil and water | Loss of productivity |
| Physical conservation works on the surface | Improvements in soil conditions at and below the surface |
| How much soil and water lost | How much water and soil retained |
| Uni-disciplinary approach, distinct from normal agricultural practice | Multi-disciplinary approach, based on and strengthening normal agricultural practice |
| Runoff control | Water absorption |
| Add-on conservation technologies | Techniques interwoven in conservation-effective farming systems |
| Farmers as labour for implementing works | Farmers as managers of conservation-effective systems |
| Doing soil and water conservation by decree | Achieving conservation of soil and water as a by-product of improved productivity |
| Works costing money | Exploiting free actions by soil meso- and micro-organisms |
| Assumption that specialists' perceptions of degradation problems and their solutions are correct - outsiders judge what is best | Awareness that other views of the reality may require different types of approaches - farm families decide what fits best |
| Small farmers are considered ignorant, irrational and reactionary | Small farmers are knowledgeable about their local circumstances, but also constrained and understandably cautious in adopting new ideas |

In adopting such an approach, it is acknowledged that any new technology must accord with the experience of the user. Accordingly, IFAD (1992) states "*the first step in the design process of a new soil and water conservation programme should be the identification of indigenous farming systems and their conservation techniques.*" For this reason, items (a) and (b) above have been included within the scope of the project, but are covered in the separate SUA report.

While examples of good practice can be anticipated, the project is predicated on the belief that a key constraint is lack of access to information about potential improvements to the indigenous cropping system. Farmers require technical advice and continue to rely on extension agents, who face greater difficulties in their new facilitating role than was previously the case. For the target group (resource-poor farmers) risks are unacceptable, therefore in order to promote innovation it is inappropriate to adopt a 'suck-it-and-see' approach. What is needed is an alternative approach which enables the adviser to screen options and identify the 'best bet' location-specific option.

The project therefore seeks through a combination of fieldwork and computer modelling to fulfil two aims:

1) to demonstrate viable cropping systems based upon rainwater harvesting techniques;

2) to develop a model of the RWH process as an aid to identifying best-bet options.

## 2.2 Relationship to PARCH project

The acronym adopted for the RWH model is PARCHED-THIRST, which is abbreviated from:

> Predicting Arable Resource Capture in Hostile Environments During The Harvesting of Incident Rainfall in the Semi-arid Tropics.

Most of the routines of the original PARCH model (Bradley & Crout, 1994) are incorporated and new components have been designed to maximise their compatibility with PARCH.

Development of the PARCH model was funded by ODA at the University of Nottingham. The model is intended as a tool to examine the factors important in determining the effectiveness of semi-arid agriculture (Bradley & Crout, 1994). It has been tested extensively on sorghum, but treatment of maize is at a more rudimentary level. PARCH program source code is written mainly in MS Quick BASIC on the premise that this language is widely available, widely understood and therefore 'transparent' to would-be users. The intention is that this will encourage adoption by NARS researchers.

The same principles have been adopted in developing THIRST modules, but the language adopted is Visual BASIC, which has now largely superseded Quick BASIC. While being compatible with this language, it has significant advantages due to greater memory and improved graphical capabilities.

# 3. RESEARCH ACTIVITIES : EXPERIMENTAL WORK

## 3.1 Fieldwork Sites

Experimental fieldwork has been executed at three sites in Tanzania at the following locations:

| | | | | |
|---|---|---|---|---|
| (i) | Kisangara (Mwanga) | 3°45' S | 37°35' E | 870 m elevation. |
| (ii) | SUA campus (Morogoro) | 6°50' S | 37°42' E | 520 m elevation. |
| (iii) | Hombolo (Dodoma) | 5°45' S | 35°57' E | 102 m elevation. |

These sites which are shown in Figure 3.1 are representative of three different land resource zones within Tanzania (NRI, 1987). Dodoma lies within the central semi-arid zone which represents 15% of the total land area. Rainfall is described as low and unreliable; topography is gently undulating and soils are generally well-drained sands with low fertility. Mwanga lies within the Masai steppe zone (8% area). Rainfall is generally 400-600 mm, bimodal in the North of the zone. Topography is rolling plains and soils are reddish sandy clays with low fertility and susceptible to surface sealing. Morogoro lies within the South-East semi-arid zone (8%). Rainfall is described as unreliable but may reach 800 mm. Topography is generally flat or gently undulating. Soils are moderately fertile loams and clays.

The Dodoma site is located at the Ministry of Agriculture Hombolo Research Station, which is situated about 38 km north-east of Dodoma town. The site was originally used by SUA for soil-water management research funded by IDRC (Canada). The general slope is 3-5%. Soils are reddish silty sandy loam. The natural vegetation consists of scattered baobab and acacia trees with grassland.

The Morogoro site is located within SUA farm close to the main gate to the campus. Slopes vary from 3-4% on the upper part of the site to 6-8% on the lower part. Soils are reddish brown sandy clay loam underlain at variable depth with sandy clay subsoil. The site was under fallow following maize cultivation prior to the experiment.

The main experimental site for the project is Kisangara which is located within the Karimjee Agriculture Sisal Estate close to Mwanga township. The land had been under sisal since 1975 and was cleared for the experiment. Slopes vary from 7-10% on the upper part of the site to 2-3% on the lower part. Soils are well-drained sandy clay loams over clay loams.

## 3.2 Experiment Design

The experiments established on these sites were as follows:

Runoff Measurement (Kisangara, Morogoro)
Runoff Farming (Kisangara, Morogoro, Hombolo)
Soil/Water Conservation (Kisangara, Hombolo)

The Runoff Measurement experiment was designed to provide data on runoff response from a small catchment area representative of within-field RWH systems. This was a plot experiment involving combinations of three factors (not replicated):

(i) Plot size : 10 x 5 m and 10 x 10 m
(ii) Plot slope: gentle and steep depending on natural slope
(iii) Surface Condition: four treatments applied were

(B) bare surface (i.e. kept clear of weeds)
(BC) bare and compacted (compaction by roller)
(V) natural vegetation
(LMC) low management crop.

The Runoff Farming experiment was designed to provide data on crop response to varying levels of enhanced water supply. The crop was maize in a pure stand in 50 $m^2$ plots. This was a similar experiment also involving three factors (replicated):

| | | |
|---|---|---|
| (i) | Catchment size: | 0, 50 $m^2$, 100 $m^2$, 200 $m^2$ |
| (ii) | Plot slope: | as above |
| (iii) | Tillage treatment: | staggered ridge or flat cultivation. |

The design at Hombolo differed slightly from the other two sites and consisted of five treatments (plot sizes) with three replicates. This was part of the IDRC funded project.

The soil/water conservation at Hombolo was also part of the IDRC funded project and consisted of 28 treatments in 3 replicates. This was repeated on a smaller scale at Kisangara with 5 treatment in 3 replicates. The treatments were:

(ZT) zero tillage (locally known as Kitang'ang'a)
(FC) flat cultivation with hand hoe to a depth of 10-15 cm
(CR) contour ridging at 5 m spacing with hand hoe cultivation
(SB) stone bunds at 5 m spacing with hand hoe cultivation
(LB) live barriers (as above) of vetiver grass and local alternative.

The layout of the sites at Morogoro and Kisangara is shown in Figures 3.2 and 3.3. It can be seen that the Kisangara site also included two additional demonstration plots in which runoff was collected from external catchments under natural vegetation.

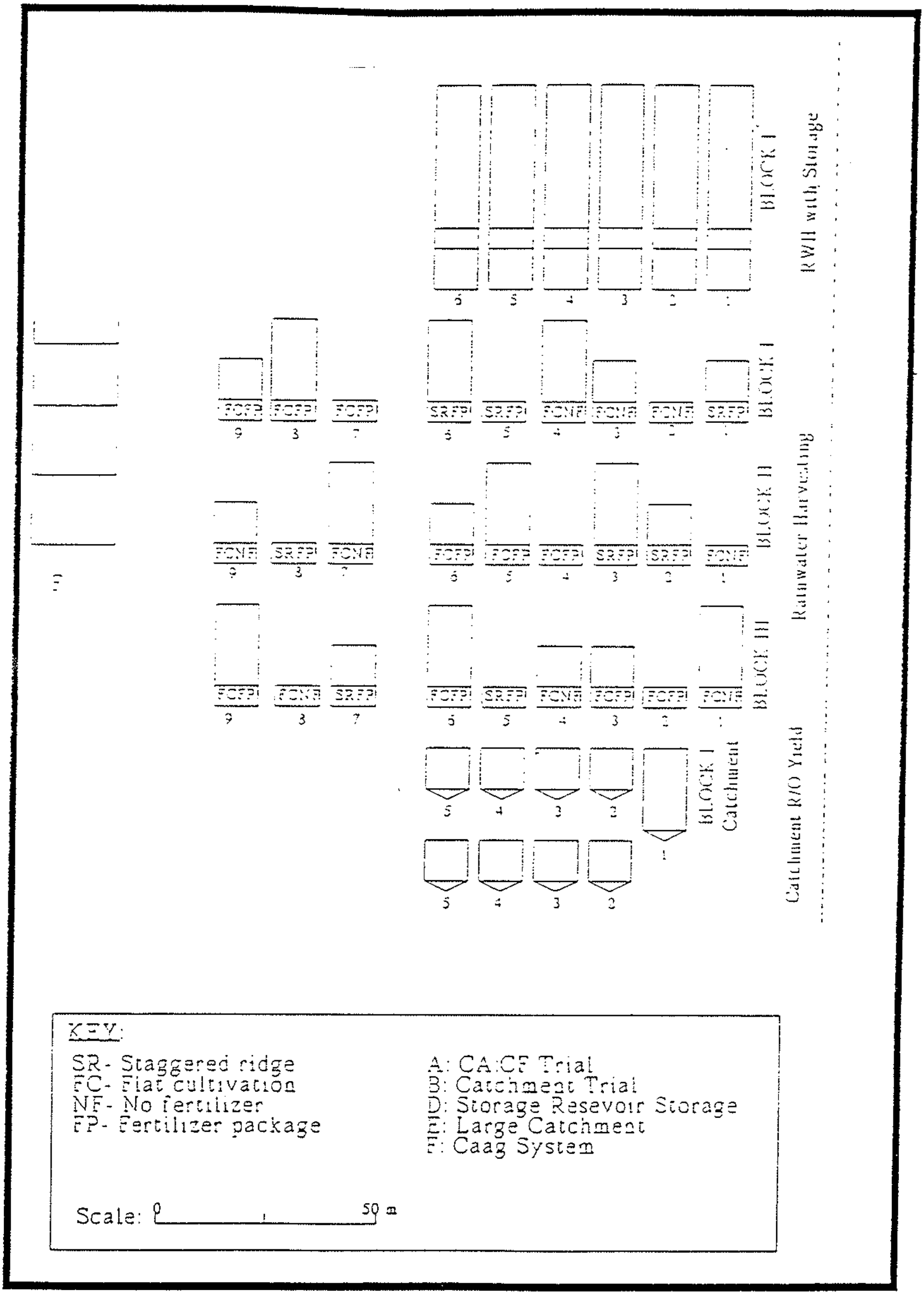


Figure 3.1(a): Layout of the experiments in 3% slope Kisangara

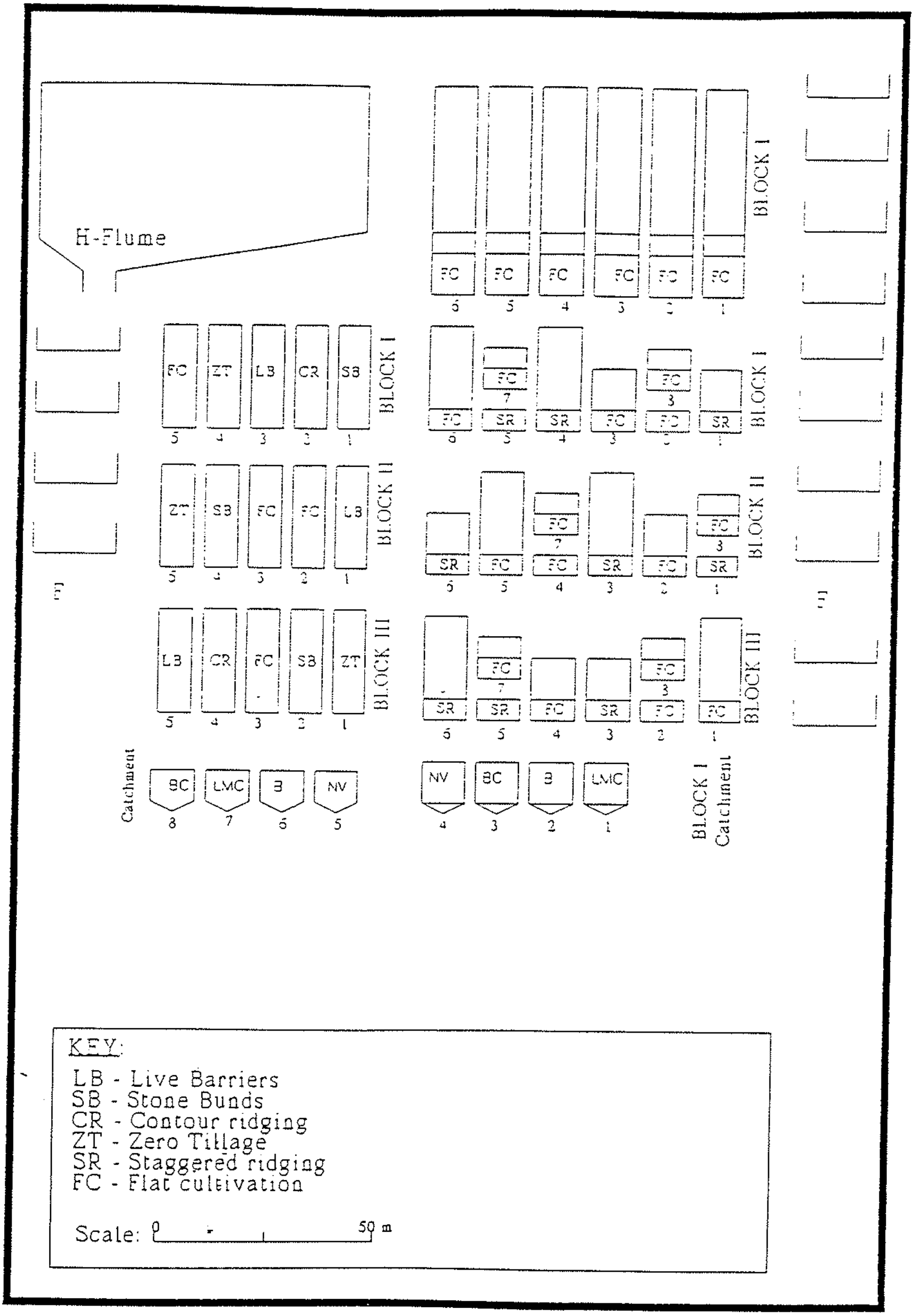


**Figure 3.1(b):** Layout of the experiments in 8% slope Kisangara

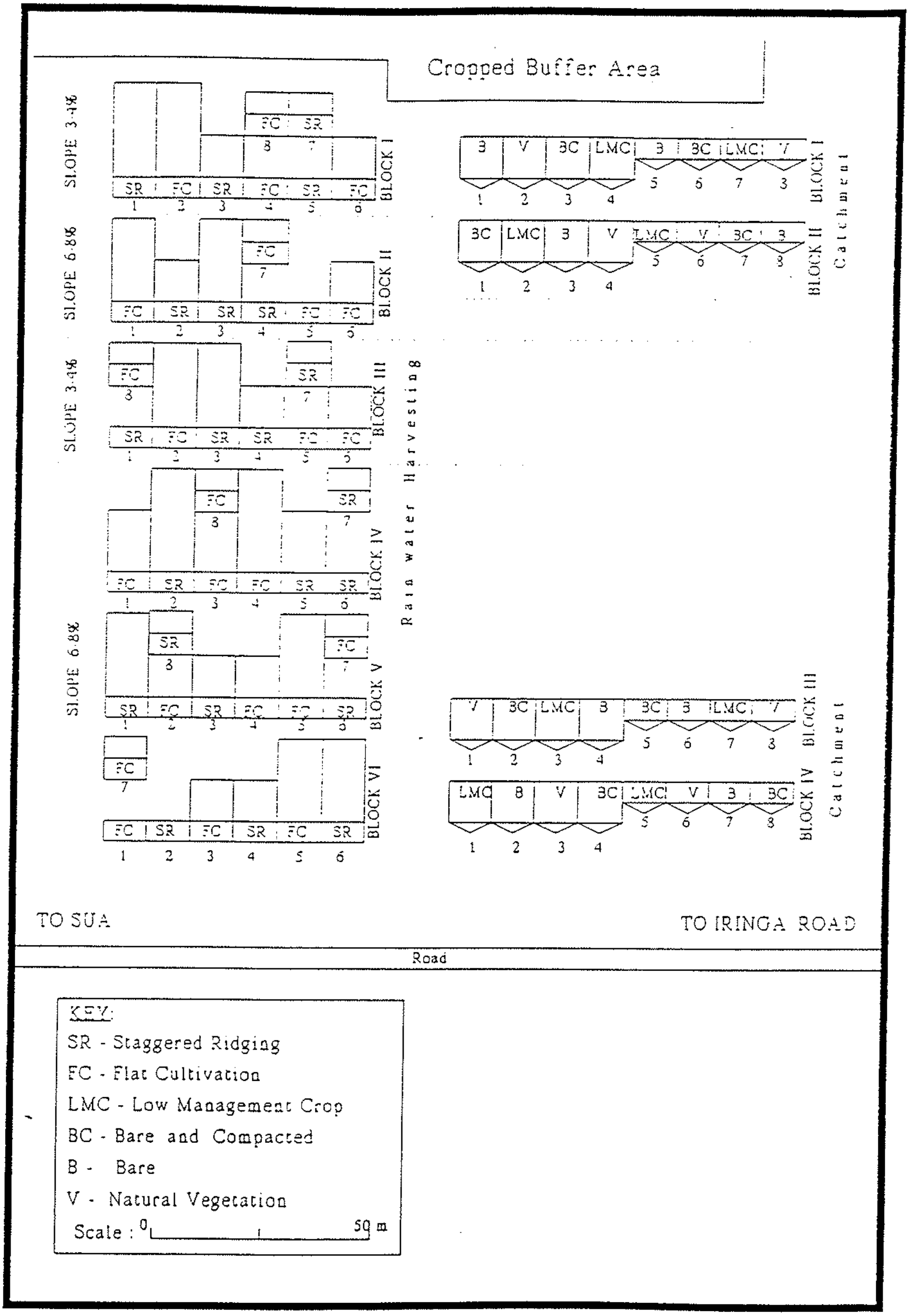


**Figure 3.2:** Experimental layout of Morogoro site

Detailed design of these experiments, together with their instrumentation requirements and data collection procedures, were determined in close collaboration with the SUA team. Full descriptions of these procedures and experimental results are presented in the SUA project report. This report is concerned only with the results of the Runoff Measurement experiment.

## 3.3 Site Characterisation

*Hombolo*

The soils are classified as Typic Ustorthent in the US Soil Taxonomy and as Dystric Regosol in the FAO-UNESCO system. The soil profile is fairly deep (> 100 cm) with texture ranging from sandy to sandy clay on the surface to sand clay loam in the subsoil. The structure of the surface horizon is weakly developed. The profile is characterised by an ochric epipedon and no other diagnostic horizon is recognised. The sand fraction in the profile is dominated by quartz minerals. The moisture and temperature regimes of the soil are ustic and thermic, respectively.

The structure of the surface and subsurface horizons (0-30 and 30-150 cm depths, is weakly developed whereas that of the deep soil is strongly developed with course sub-angular blocky quartz gravel, (at 150-184 cm depth). The bulk density of surface soils is 1.4-1.5 Mg $cm^{-3}$, increasing with depth. Total porosity of surface soils is 42%, that of subsoils is 35% and 30% deep for soils. The surface soils are also characterised by hard setting and crusting phenomena, rendering them relatively impermeable to water. The chemical properties of the soils are characterised by soil reaction of pH 5.1-6.0, low levels of organic carbon (C), total nitrogen (N), and exchangeable bases ($Ca^{2+}$, $Na^{+}$, K), and therefore, generally of poor fertility (Table 3.1). Independent measurements of saturated hydraulic conductivity using laboratory cores and *in-situ* measurements are in close agreement with values of 0.5-0.7 m $day^{-1}$ at the surface and around 0.2 m $day^{-1}$ in subsoil.

The typical profile description is as follows:

**Ap 0-12 cm:** Brown (7.5 YR 5/4) moist and light brown (7.5 YR 6/4) dry, sandy loam; moderately weak medium crumb; slightly sticky, slightly plastic (wet), very friable (moist) and slightly hard (dry); many very find to fine random pores; porosity 42.7%; common very fine roots; abrupt, smooth boundary.

**AB 12-28 cm:** Brown to dark brown (7.5 YR 4/4) moist and brown (7.5 YR 5/4) dry, sandy loam; strong coarse granular; slightly sticky, slightly plastic (wet), very friable (moist) and hard (dry); very few medium and common fine and very fine random pores; porosity 36.5%; few very fine roots; clear; smooth boundary.

**Bu1 28-46 cm:** Strong brown (7.5 YR 5/8) moist and reddish yellow (7.5 YR 6/6) dry, sandy clay loam; moderately weak medium sub-angular blocky, nonsticky, nonplastic (wet), very friable (moist) and hard (dry); common fine and very fine random pores; porosity 38.5%; gradual smooth boundary.

**Bu2 46-102 cm:** Reddish yellow (5 YR 6/8) moist and reddish yellow (5 YR 7/8) dry, sandy clay loam; moderately weak medium sub-angular blocky; nonsticky nonplastic (wet); very friable (moist) and hard (dry); common fine and very fine random pores; porosity 42.3%; gradual smooth boundary.

**Bu3 102-158 cm:** Reddish yellow (5 YR 6/8) moist and reddish yellow (5 YR 7/8) dry, sandy clay loam; moderately weak fine and medium sub-angular blocky; slightly stick slightly plastic (wet), very friable (moist) and hard (dry) common fine and very fine random pores; porosity 40.4%; clear smooth boundary.

**Bgcs 158-178 cm:** Light brown (7.5 YR 6/4) moist and pink (7.5 YR 7/4) dry, common fine faint clear strong brown (7.5 YR 5/6 and 7.5 YR 5/8) mottles; slightly gravelly sandy clay loam; moderate coarse sub-angular blocky sticky and plastic (wet), firm (moist) and very hard (dry); few fine to medium pores; porosity 35%; very few angular quartz gravels (2-4 mm) very few large (1.0-1.5 cm) slightly soft irregular dark red ironstone nodules; abrupt smooth boundary.

**Ccs 178-184 cm:** Pinkish grey (7.5 YR 6/2) moist and pinkish grey (7.5 YR 7/2) dry; common medium distinct clear strong brown mottles, slightly gravelly sandy clay loam; massive; sticky and plastic (wet), firm (moist) and extremely hard (dry); few fine pores; porosity 30.7%; very few large (1.0-1.5 cm) slightly soft irregular dark red ironstone nodules.

**Table 3.1** Analytical data of the soil profile at Hombolo

| **Horizon** | | **Ap** | **AB** | **Bu1** | **Bu2** | **Bu3** | **Bgcs** | **Ccs** |
|---|---|---|---|---|---|---|---|---|
| Depth (cm) | | 0-12 | 12-28 | 28-46 | 46-102 | 102-158 | 158-178 | 178-184+ |
| Clay (%) | | 16.0 | 17.0 | 22.0 | 23.0 | 32.0 | 27.0 | 24.0 |
| Silt (%) | | 5.0 | 5.0 | 4.0 | 5.0 | 2.0 | 4.0 | 2.0 |
| Sand (%) | | 79.0 | 78.0 | 74.0 | 72.0 | 66.0 | 69.0 | 74.0 |
| Textural Class | | SL | SL | SCL | SCL | SCL | SCL | SCL |
| pH | (1:2.5 water) | 5.4 | 5.1 | 5.2 | 6.0 | 5.5 | 5.4 | 5.3 |
| | (1:2.5 KCl) | 4.2 | 4.0 | 3.8 | 3.8 | 3.8 | 3.7 | 5.8 |
| Organic C (%) | | 0.60 | 0.36 | 0.33 | 0.16 | 0.16 | 0.20 | 0.11 |
| Organic matter (%) | | 1.03 | 0.62 | 0.57 | 0.28 | 0.28 | 0.34 | 0.19 |
| Total N (%) | | 0.05 | 0.03 | 0.04 | 0.02 | 0.03 | 0.03 | 0.02 |
| Available P (mg/kg) | | 11.6 | 5.6 | 2.8 | 2.8 | 2.8 | 2.5 | 2.8 |
| Exchangeable Cations (cmol (+) kg$^{-1}$ | Ca2+ | 2.0 | 5.2 | 2.8 | 2.0 | 2.4 | 4.2 | 4.4 |
| | Mg2+ | 0.6 | 0.4 | 0.3 | 0.2 | 0.6 | 1.1 | 2.3 |
| | Na+ | 1.4 | 0.9 | 1.5 | 1.1 | 4.0 | 1.6 | 1.5 |
| | K+ | 0.9 | 0.3 | 0.3 | 0.3 | 0.2 | 0.3 | 0.6 |
| Total Exch. bases | | 6.8 | 4.9 | 3.6 | 7.2 | 7.2 | 8.8 | |
| Exchangeable Al | | 0.8 | 1.4 | 2.4 | 3.0 | 2.9 | 2.0 | 1.0 |
| Cation Exchange capacity | | 12.6 | 9.6 | 11.6 | 14.0 | 13.6 | 15.6 | 9.0 |
| % Base saturation | | 38.9 | 70.8 | 42.2 | 25.7 | 52.9 | 46.2 | 97.8 |

### *Morogoro*

The soils of the SUA experimental farm at Morogoro are described by Kaaya (1989). They are derived from quartz-rich meta-sediments from the Uluguru mountain range and are characterised by red sandy clay loam overlying sandy clay subsoil. Typical physico-chemical characteristics are summarised in Table 3.2.

**Table 3.2** Some Physico-Chemical Characteristics of Morogoro Site (Kaaya, 1989)

| Soil Property | **HORIZONS** | | |
|---|---|---|---|
| | 0 - 12 | 12 51 | 51 - 60 |
| Bulk density (g/cm$^3$) | 1.43 | 1.40 | 1.63 |
| Water holding capacity (%) | | | |
| 0.3 bars | 23.6 | 27.0 | 19.1 |
| 15 bars | 13.0 | 17.1 | 12.3 |
| Available water capacity (%) | 10.6 | 9.9 | 6.8 |
| Particle size distribution (%) | | | |
| Sand (0.5-2 cm) | 58.2 | 51.1 | 47.2 |
| Silt (0.002-0.05 cm) | 7.2 | 8.7 | 7.4 |
| Clay (< 0.002) | 34.4 | 40.2 | 45.4 |
| Textural class | SCL | SC | SC |
| pH | | | |
| 1:2.5 $H_2O$ | 7.8 | 7.8 | 7.9 |
| 1:2.5 $CaCl_2$ | 6.8 | 6.9 | 7.0 |
| Exchangeable Cations (cmol(+)/kg of soil) | | | |
| $Na^+$ | 0.1 | 0.16 | 0.18 |
| $K^+$ | 0.48 | 0.21 | 0.21 |
| $Mg^{2+}$ | 0.99 | 1.32 | 2.06 |
| $Ca^{2+}$ | 34.18 | 36.69 | 39.56 |
| Sum of bases | 35.75 | 38.38 | 42.01 |
| CEC (cmol/kg of soil) | | | |
| Soil | 44.59 | 39.38 | 42.14 |
| Clay | 122.25 | 94.75 | 90.87 |
| % base saturation | 80.2 | 97.9 | 99.7 |
| Organic carbon (%) | 0.98 | 0.43 | 0.34 |
| Total N (%) | 0.18 | 0.10 | 0.09 |
| Available P (mg/kg) | 3.51 | 1.75 | 1.75 |

SCL = Sandy clay Loam, SC = Sandy clay.

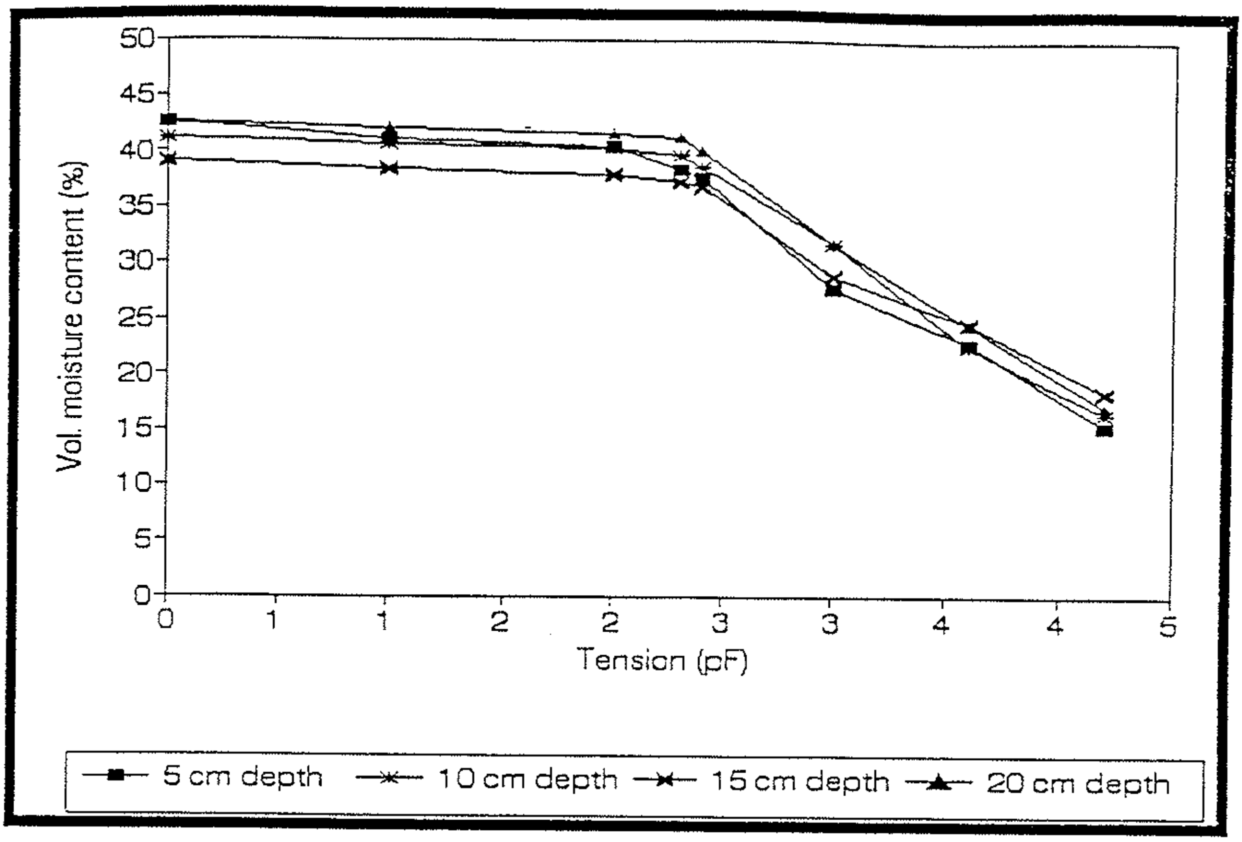


**Figure 3.4** Effects of soil depth on Moisture release characteristics at Morogoro site

**Table 3.3** Temporal variation of bulk density

| Site | Depth | Before treatments | Immediately after tillage | At harvest |
|---|---|---|---|---|
| Morogoro | 0-5 | 1.40 | 1.35 | 1.51 |
| | 5-10 | 1.59 | 1.40 | 1.51 |
| | 10-15 | 1.55 | 1.42 | 1.54 |
| | 15-20 | 1.48 | 1.53 | 1.62 |
| Kisangara | 0-5 | 1.39 | 1.38 | 1.40 |
| | 5-10 | 1.37 | 1.37 | 1.41 |
| | 10-15 | 1.50 | | |
| | 15-20 | 1.50 | 1.51 | 1.49 |

*Kisangara*

Prior information on the soils at the site were not available and a survey was commissioned from Selian Agricultural Research Institute (Ngatoluwa *et al*, 1995). The fieldwork was conducted in October and November 1994. Seven soil pits were described and sampled for laboratory analysis. Locations were chosen to reflect the observed soil variations.

Soils are developed from weathered acid granulite and gneiss and are generally reddish sandy clay loams and sandy clays. Soil classification according to FAO-UNESCO soil taxonomy system indicates that the description is Ferric Luvisol. Fertility status is generally low and is influenced by topography with lowest nutrient levels in upper slopes.

Bulk density values vary from about 1.4 $mg.m^{-3}$ in topsoil to 1.6-1.7 $mg.m^{-3}$ in subsoil. Hydraulic conductivity values are 0.7-0.9 $m.day^{-1}$. Soil texture analyses are presented in Table 3.4. Detailed profile descriptions are as follows:-

**Pit A**
Soil classification
FAO: Niti Ferralic Cambisol
USDA: Oxic Ustropept

These soils have developed on weathered acid granulite gneiss bed rock materials that have been deposited at the base of escarpment. Such materials have been moved down slope by forces of gravity and surface runoff. These soils lack clay accumulation and exhibit little variation in clay content in the sub surface horizons and are classified as Cambisols.

The soils have generally the most coarse texture when in comparison with soils on lower slope positions (pit C & D). The soils are well to rapidly drained, fairly deep yellowish red in colour. Soil texture is sandy clay loam on the surface as well as on the underlying horizons. Soil fertility is low, the soils are acid in reaction with low base status and are likely to be deficient in phosphorous and nitrogen.

**Pit B**
Soil Classification
FAO: Acri Plinthic Luvisol
USDA: Oxic Rhodustalf

Acri Plinthic Luvisol are most extensive on the Northern part of the study area, covering nearly 10-15% of the whole area. They have developed on acid granulite gneiss bedrock with a thick plinthic layer. The soils are well drained, and moderately deep. They are uniformly coloured red to strongly brown, with very little colour horizonation. Soil texture at greater depths is clay loam with a sandy clay loam at the surface. The soils are somewhat coarse in texture with up to 49% sand content. As a consequence moisture holding capacity would also be expected to be relatively lower. The dark organic rich surface horizon is less than 25 cm thick.

**Pits C and D**

Soil classification
FAO: Acri Ferric Luvisol
USDA: Typic Plinthustalf

Acri Ferric Luvisols occur intensively on the middle and lower slope position (3-5%) and they account for nearly 75% of the surveyed area. Pits C and D are located on a 3% zone. Pit C is situated approximately 85 m south of pit A while pit D is located approximately 45 m west of the site's office. The development of these soils is associated with the accumulation of clay in the subsurface horizons (Bt) and exhibit little colour horizonation. These soils are virtually similar to those described for pits: F and G. However, it was noted that in pit F and G clay content tended to increase with depth while the opposite was true for pits C and D. The major difference between this order and that described for pit A is the level of soil development. In pit A there was no clear horizon formation as it was the case in pits C and D. On the other hand pit B is more or less similar to pits C & D except that pit B is associated with the presence of plinthite layer at a depth of approximately 50 cm.

The soil texture is typically Sandy Loam at the surface with Sandy Clay Loam texture at lower depths. These soils are associated with low organic matter content. The low organic matter content and high sand content cause a low water holding capacity of these soils.

**Pit E**

Classification
FAO: Rudi Chromic Luvisol
USDA: Oxic Haplustalf

Pit E is located on the middle slope position (3-5%) on the abandoned sisal field. These soils have developed on acid granulite gneiss parent material and they occupy less than 2% of the experimental site. The soils are lithic to shallow, well drained, reddish brown, stony, and Sandy Clay Loam in texture.

Severe erosion has resulted in shallow soil (depth to bed rock) as well as in some parts, the exposure of the underlying bedrock. Moisture holding capacity is a major limiting factor on these soils.

**Pits F and G**

Classification
FAO: Acri Ferric Luvisol
USDA: Oxic Rhodustalf

Pits F and G are located on the lower slope position (3%) of the site. Pit F is situated on the Southeast portion of the study area while pig G is located on the Southwest part approximately 100 m south of pit D. Soils in these two pits are more or less similar in their morphological and chemical properties. These soils have an accumulation of clay in the subsurface horizon and are classified as Luvisol (F.A.O.) or Alfisol (U.S.D.A.). Clay movements and accumulation are evident and are marked by a variation of clay content in the subsurface horizons. Clay content tended to increase substantially with increasing depth. Although the whole experimental site is rated as having low natural fertility, it appears that the lower part (3%) has relatively high natural fertility. Secondary minerals such as quartz were common throughout the profile.

**Table 3.4** Particle size analyses of Kisangara Rain Water Harvesting experimental site (without and with dispersing agent)

| PHYSICAL ANALYSIS | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | PARTICLE SIZE DISTRIBUTION WITHOUT DISPERSING AGENT | | | PARTICLE SIZE DISTRIBUTION WITH DISPERSING AGENT (CALGON) | | |
| Identification | Depth(Cm) | Sand % | Silt % | Clay % | Sand % | Silt % | Clay % |
| Pit A | 0-10 | 56.5 | 17.4 | 26.1 | 54.2 | 16.6 | 29.2 |
| | 10-30 | 57.4 | 25.6 | 17.0 | 55.1 | 24.5 | 20.4 |
| | 50-75 | 57.2 | 25.7 | 17.1 | 54.8 | 24.6 | 20.5 |
| | 75-100 | 61.6 | 21.3 | 17.1 | 61.6 | 17.1 | 21.3 |
| | 100-135 | 62.0 | 16.9 | 21.1 | 62.0 | 16.9 | 21.1 |
| Pit B | 0-10 | 49.1 | 21.2 | 29.7 | 49.1 | 21.2 | 29.7 |
| | 10.30 | 49.4 | 21.1 | 29.5 | 49.4 | 16.9 | 33.7 |
| | 50-75 | 40.1 | 29.9 | 29.9 | 38.5 | 20.5 | 41.0 |
| | 75-100 | 54.2 | 18.3 | 27.5 | 49.6 | 16.8 | 33.6 |
| | 100-120 | 44.0 | 25.8 | 30.1 | 42.2 | 24.8 | 33.0 |
| Pit C | 0-10 | 65.7 | 17.1 | 17.1 | 63.0 | 20.6 | 16.4 |
| | 10-30 | 64.1 | 13.5 | 22.4 | 61.4 | 12.9 | 25.7 |
| | 50-75 | 48.6 | 38.6 | 12.8 | 48.6 | 21.4 | 30.0 |
| | 75-100 | 45.8 | 25.0 | 29.2 | 45.8 | 20.8 | 33.4 |
| | 100-150 | 45.5 | 33.5 | 21.0 | 47.5 | 17.5 | 35.0 |
| Pit D | 0-10 | 48.9 | 17.0 | 34.1 | 46.9 | 20.4 | 32.7 |
| | 10-30 | 45.0 | 21.2 | 33.8 | 43.1 | 16.2 | 40.6 |
| | 50-75 | 40.1 | 38.5 | 21.4 | 38.5 | 28.7 | 32.8 |
| | 75-100 | 36.0 | 38.4 | 25.6 | 36.0 | 25.6 | 38.4 |
| | 100-150 | 49:3 | 32.3 | 18.4 | 47.1 | 35.2 | 17.6 |
| Pit E | 0-10 | 58.3 | 25.0 | 16.7 | 60.9 | 17.4 | 21.7 |
| | 10-30 | 51.1 | 17.8 | 31.1 | 51.1 | 13.3 | 35.6 |
| | 50-75 | 51.1 | 17.8 | 31.1 | 46.9 | 16.4 | 36.7 |
| | 75-100 | 49.8 | 29.3 | 20.9 | 52.0 | 21.8 | 26.2 |
| | 100-135 | 66.1 | 21.2 | 12.7 | 66.2 | 16.9 | 16.9 |
| Pit F | 0-10 | 63.1 | 20.5 | 16.4 | 65.8 | 8.5 | 25.7 |
| | 10-30 | 56.3 | 17.5 | 26.2 | 56.3 | 17.5 | 26.2 |
| | 50-75 | 43.0 | 39.4 | 17.5 | 41.2 | 25.2 | 35.6 |
| | 75-100 | 40.5 | 34.0 | 25.5 | 40.5 | 25.5 | 34.0 |
| | 100-150 | 39.8 | 43.0 | 17.2 | 41.6 | 31.4 | 27.0 |
| Pit G | 0-10 | 53.2 | 21.3 | 25.5 | 53.2 | 17.0 | 29.8 |
| | 10-30 | 48.2 | 21.6 | 30.2 | 48.2 | 8.6 | 43.2 |
| | 50-75 | 39.1 | 32.5 | 28.4 | 39.1 | 16.2 | 44.7 |
| | 75-100 | 49.0 | 29.7 | 21.2 | 49.0 | 25.5 | 25.5 |
| | 100-150 | 38.6 | 45.0 | 16.4 | 40.2 | 34.2 | 25.6 |

## 3.4 Soil Monolith Tests

Modelling the performance of RWH systems requires knowledge of soil hydraulic properties. The approach adopted is to use pedotransfer functions to predict these properties from easily measurable soil parameters as described in Section 4 following. In order to test their reliability, it was necessary to obtain experimental data by a combination of tests on core samples and *in-situ* soil monolith tests.

SMTs were installed at Morogoro and Kisangara with the help of SUA staff. Klute (1986) recommends a 3.6 m x 3.6 m plot, but because of the problems of water availability and the high infiltration rates of the soils, the size of the plot was reduced to 2.5 m x 2.5 m. The methodology which follows is based upon that of Klute (1986).

Equipment

4 x 2.5 m x 30 cm Wooden Boards
4 x 1.2 m x 20 cm Metal Sheets
5 x Tensiometers (10, 20, 30, 60 and 90 cm)
Manometer stand and mercury reservoir
Neutron Probe and Access Tube
Silicone Sealant
Waterproof Tape
2 x 200l Oil Drums - one equipped with an outlet at the base, the other equipped with an inlet controlled by a ball-cock, and an outlet just below the maximum water level (see figure 3.5).
Plastic sheeting (1.5 m x 1.5 m) for covering inner area.
Waterproof Structure (3 m x 3 m) for covering plot.
(5 x 200l oil drums for water transport)

Procedure

A suitable site was chosen which was level and representative of the surrounding area. NOTE: From this point on trampling on the plot area was kept to a minimum. The outer square was delineated (see Figure 3.5) and a 15 cm deep trench was dug. The side of the trench towards the plot was kept vertical as far as possible. Wooden Boards (250 x 30 cm) were then joined to form a square and the corners sealed. This square was lowered into the trench and any gaps were filled with soil and compacted to form the outer boundary of the buffer zone.

Metal sheets (120 x 25 cm) were then installed to form the central square. Ideally, these should be steel of a thickness which allows them to be hammered into the soil, thereby causing minimal disturbance to the soil surface. However, in this case, only aluminium sheeting was available. A narrow trench was carefully excavated to a depth of c.10 cm using a ‘panga’. The sheeting was then joined to form a square using waterproof tape and pushed into the trench.

Any remaining gaps were then carefully filled with soil. From this point on walking boards were used to minimise compaction of the soil surface.
The level at which water in the control tank closes the valve allowing water in from the supply tank having already been established, the control tank was installed in a pit such that water ponded at a depth of c.5 cm in the inner area. The supply tank was raised on a platform of soil to ensure sufficient pressure head (see figure 3.5).

A neutron probe access tube was installed in the centre of the inner area to a depth of 1.3 m (soil depth allowing). Tensiometers were then installed in a semi-circle around the tube, at a distance of 30 cm to prevent water in the tensiometer bodies being recorded by the neutron probe.

Wetting was achieved by filling the supply tank with water. The control tank then maintained the pond in the inner area at c.5 cm depth. The buffer area was wetted using buckets. However, because of the high infiltration rates of the soils at Kisangara and Morogoro, and because of an inadequate supply of water, it was not always possible to maintain the pond in the outer area at this level.

When the soil-water tension registered by all five tensiometers became steady, the infiltration rate in the inner area was measured by recording changes in the level of water in the supply tank over time.

The supply of water was cut off and the pond was allowed to drain. At the moment when ponding stopped, the second reading was taken. Readings were then taken every two hours for the first few hours. The interval between readings was gradually increased to daily, then every other day and finally weekly. The rate at which the interval is increased depends upon the rate of changes of soil moisture in the monolith. Neutron probe standard (water) counts were taken every day before measurement. In order to ensure that the accuracy of neutron probe calibration did not affect the results obtained, every other reading, samples of moisture content were taken at 10 cm intervals using a screw auger and analysed gravimetrically. These were taken from just inside the inner area on the side away from the tensiometers (see figure 3.5). After sampling, the holes were refilled with soil from the outer area.

Once ponding had ceased, the whole plot was covered to prevent rainfall from reaching the surface and, to reduce evaporation, plastic sheeting was laid on the surface of the inner area. Readings were then taken until the mercury column in (usually the shallowest) the tensiometers broke.

### Results

Two tests were completed at Kisangara at locations considered to be representative of the upper and lower parts of the site. These tests were continued over a period of 90 days. One test was completed at Morogoro at a location on 7% slope. This test was continued for 40 days. Analysis of data obtained is presented in Section 4.2.

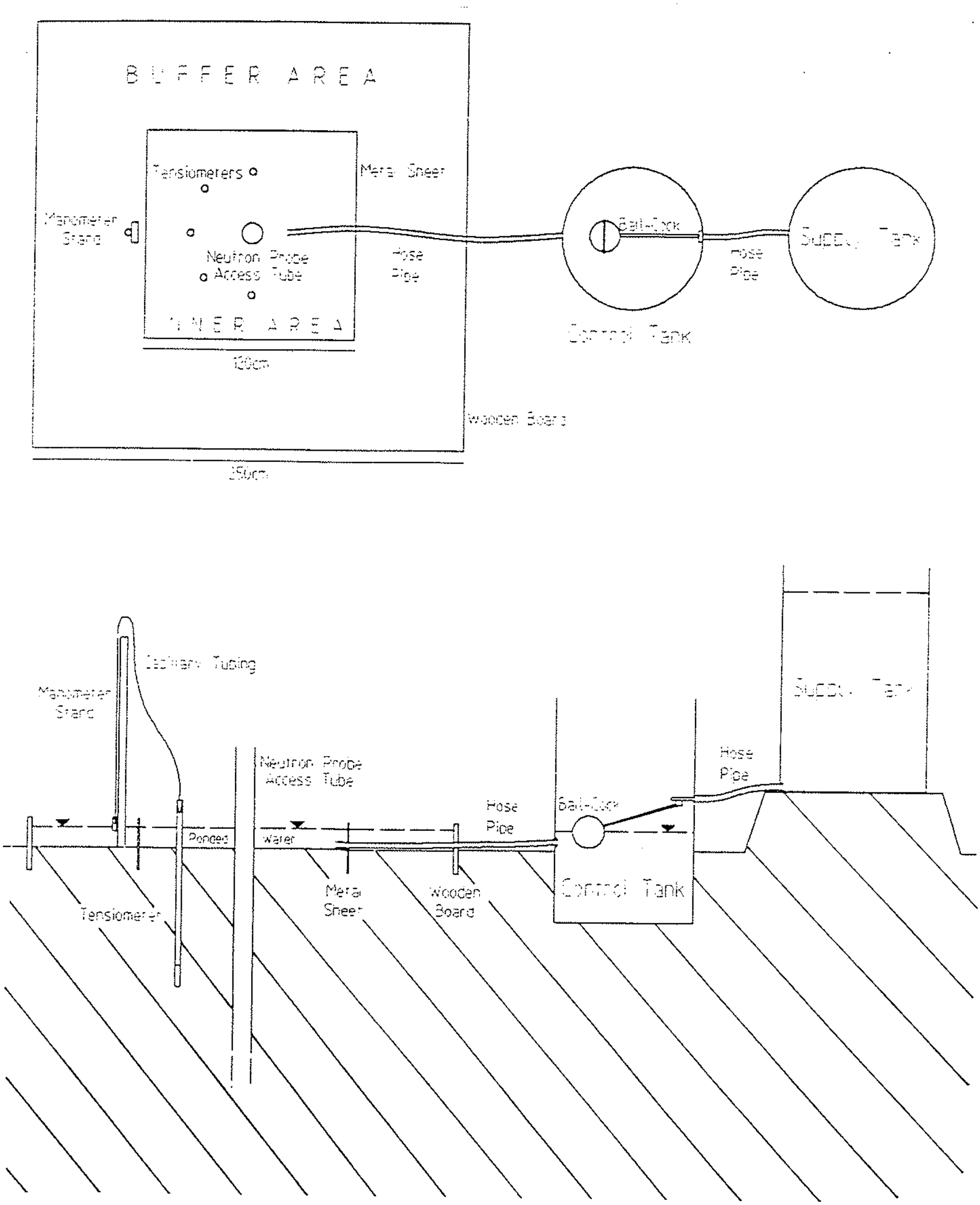


**Figure 3.5.** The Soil Monolith Drainage Test

# 4. RESEARCH ACTIVITIES : MODELLING WORK

## 4.1 Model Development

### *4.1.1 Model Overview*

The PARCHED-THIRST model aims to represent the important hydrological processes using physical parameters that can be measured or estimated in order to discriminate differences in soil, relief, rainfall etc. It comprises various component sub-models which are linked together as shown in Figure 4.1. It incorporates the original PARCH model (Bradley & Crout, 1994).

The model is driven by daily values of rainfall and other agrometeorological variables. In order to provide for simulation of long-term performance a Climate Generator can be used to extend the available historical data. Daily rainfall values are then converted by the Rainfall Disaggregator into intensity data which are required for the infiltration model.

The rainfall runoff process is simulated as an infiltration excess with infiltration being determined by the Green-Ampt Infiltration Calculator. Because of the cost and difficulty of measuring soil hydraulic parameters in the field, a Pedotransfer Function option is included to allow for their prediction from readily available soils data.

The model is a tool that will extend and add-value to field experiments, which are themselves costly, time-consuming and laborious. It is seen also as a tool for technology transfer in that it can be used to predict performance of RWH systems at new sites. It is designed to use readily available input data and can quickly produce simulated output over a timescale that allows for assessment of risk and sustainability.

Further details of the underlying theory and structure of the model are given in the companion report (Young & Gowing, 1996).

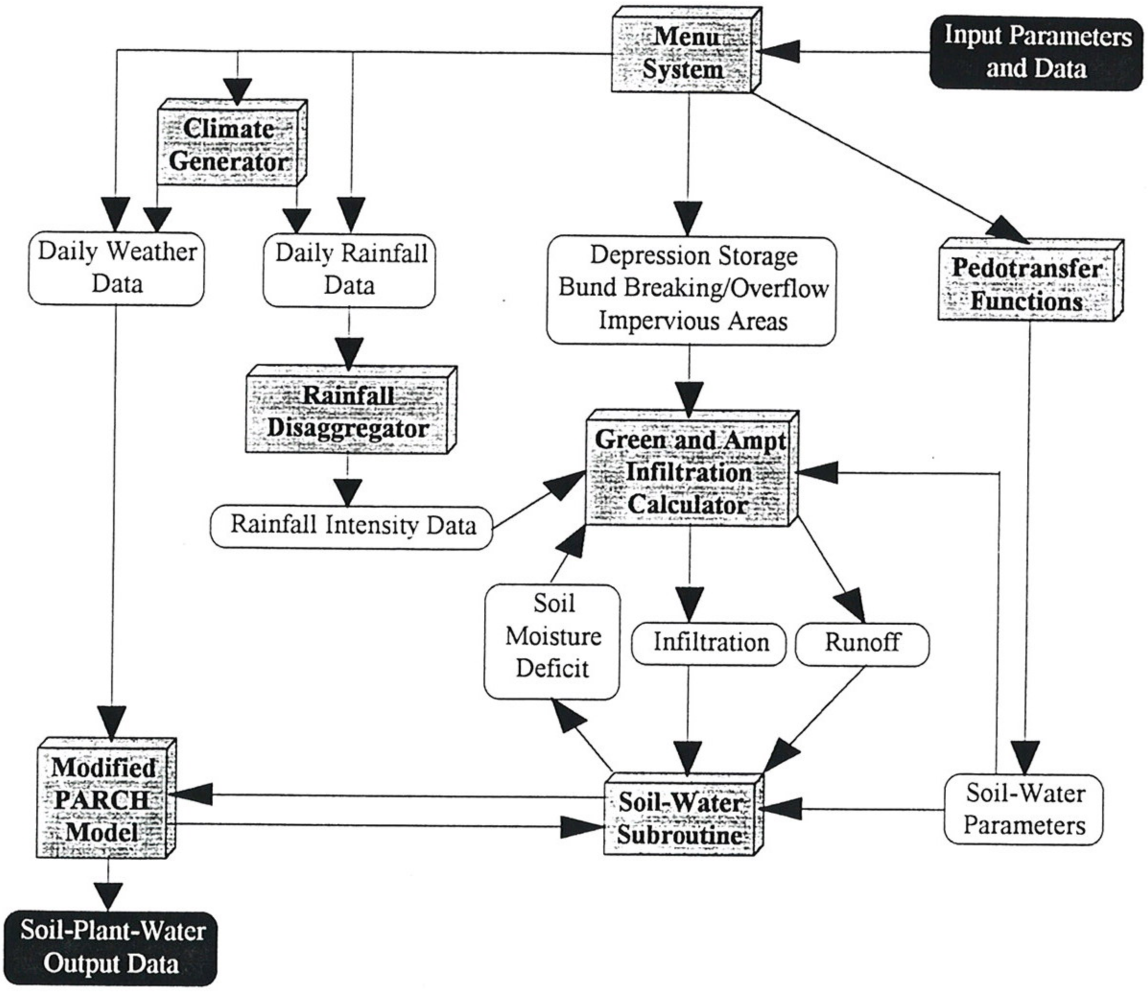


**Figure 4.1** The runoff-infiltration sub-model - interactions with other components of the PARCHED-THIRST Model

### *4.1.2 Climate Generator*

Availability of climatic data of the high temporal resolution needed in physically-based runoff and soil-water models is a major constraint in developing countries. The climate generator will therefore fulfil two purposes:

- The provision of data for areas which have none and;
- The infilling and extrapolation of data for areas which have little.

The **PARCHED-THIRST Climate Generator** works by extracting the statistical properties of historical weather data and using these, in combination with random number generators to produce novel series of weather data with the same statistical properties as that which was input. It is important to realise that it is in no way a weather forecasting tool and that the weather it generates takes no account of long-term climatic change.

Rainfall is the controlling variable, with all other variables (except wind speed) dependent upon whether a simulated day is wet or dry. Overall, seven weather variables are considered by the model. These are:

- **Rainfall** - Rainfall generation is a two-stage process whereby rainfall occurrence (i.e. wet or dry day) is based upon a first-order Markov chain and rainfall amount is sampled from the gamma distribution.
- **Maximum Temperature, Minimum Temperature and Radiation** - These are generated by a multivariate process which involves the generation of residuals about long-term means. The means used and the residuals generated depend upon the wet or dry status of the day.
- **Relative Humidity** - Relative humidity is sampled from one of two gamma distributions depending upon the wet or dry status of the day.
- **Wind Speed** - Wind speed (or run) is sampled from a gamma distribution but is not dependent upon the wet or dry status of the day.
- **Evaporation** - Evaporation is not strictly generated. Rather, it is calculated from the other variables using an approach based upon the Penman-Monteith method.

### *4.1.3 Rainfall Disaggregator*

The approach adopted for the Runoff Model (§ 4.1.4) requires that daily rainfall values must be further decomposed into instantaneous values which represent the storm profile. Whilst the network of daily raingauges within SSA is sparse, it is very much better than the coverage provided by automatic recording raingauges which provide continuous intensity data. The Rainfall Disaggregator therefore serves two purposes:

(i) prediction of peak intensity and rainfall duration from total daily rainfall amount;

(ii) fitting the storm profile to the daily data.

If rainfall intensity data are available, then these can be used as input data. The minimum dataset requirement is then:-

- total daily rainfall amount
- duration of that rainfall
- maximum 30 minute intensity (I30) during that day.

If the minimum dataset is not available for a given location, then it is generated from daily rainfall values. This is implemented as a regional relation based upon regression analysis of available continuous data. To date this has been attempted for Kisangara and Morogoro.

The Newton-Raphson iterative numerical technique is used to fit an assumed rainfall distribution to this minimum data set. The chosen distribution assumes that each storm is composed of three distinct periods (Figure 4.2):

- Rainfall intensity rises linearly to a maximum over a period of 30 minutes.

- For the next 15 minutes, rainfall intensity falls linearly.

- Rainfall intensity then falls exponentially.

The rainfall intensities at a user-defined interval can then be 'read' from this distribution and passed to the runoff model.

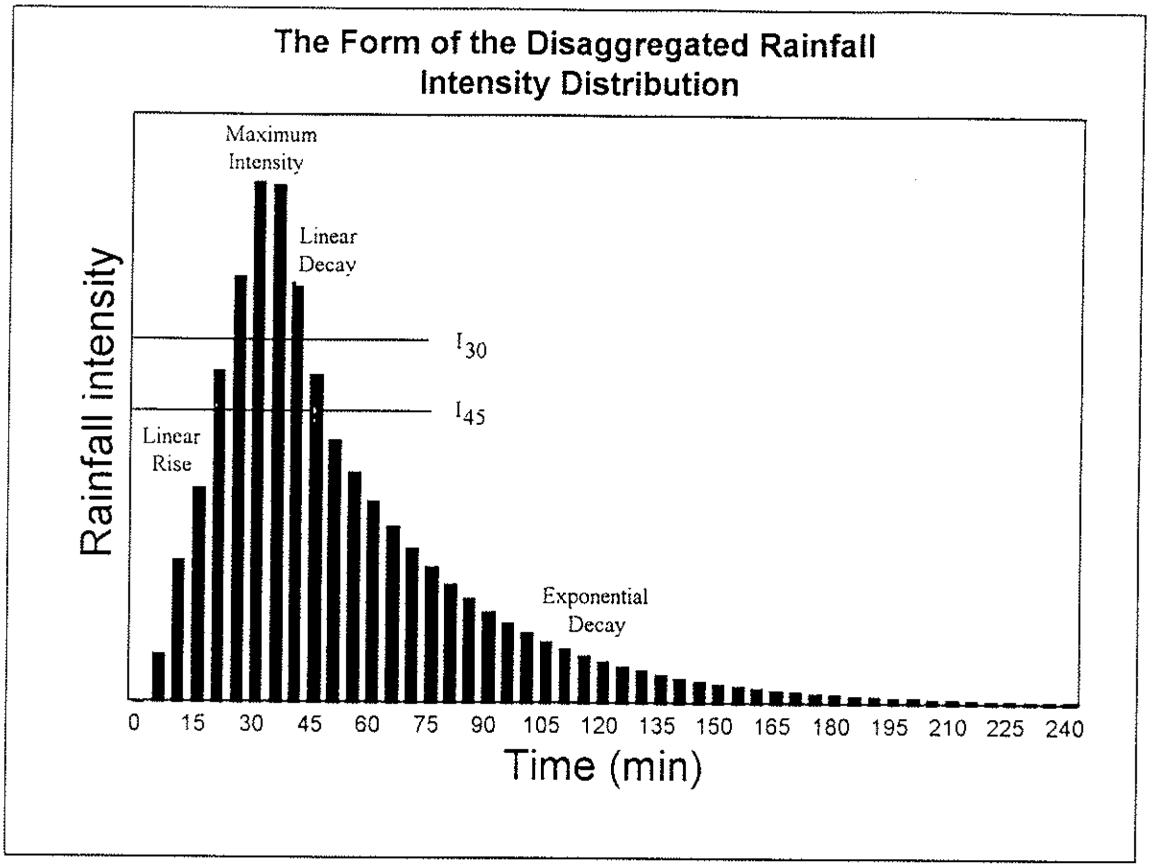


**Figure 4.2.** Schematic representation of the pattern of rainfall intensity with time which is assumed in the PARCHED-THIRST rainfall disaggregator.

### 4.1.4 Runoff Model

There are two main approaches to runoff modelling. These are:

- Simple empirical models such as the Rational Method or the Curve Number approach (with or without antecedent precipitation index);
- Physically-based infiltration excess models based upon either the Green-Ampt model or numerical approximations of Richards equation.

The approach adopted is based upon Hortonian infiltration-excess and no attempt is made to represent the processes of overland flow or sub-surface flow. Infiltration is modelled by the quasi-physical Green and Ampt approach, which uses measurable physical parameters to represent soil behaviour, but does not demand excessive computational effort.

The Green and Ampt (1911) infiltration equation is given by:

$$fp(t) = K_{fs}\left(1 + \frac{S_{av} D_i}{F(t)}\right)$$

| Where: | | | |
|---|---|---|---|
| | $K_{fs}$ | = | Hydraulic Conductivity at field saturation |
| | $S_{av}$ | = | Wetting Front Suction |
| | $D_i$ | = | Initial moisture deficit ($\theta_s$ - $\theta$) |
| | fp(t) | = | Potential infiltration rate at time, t |
| | F(t) | = | Cumulative infiltration at time, t |

It was formulated for infiltration under ponded conditions into an homogeneous soil profile with uniform initial soil moisture. As this is rarely the case in real soils, the runoff-infiltration model takes its parameters from the top four layers of the user-defined soil profile. This reflects the fact that these layers are, subjectively, the most important with respect to infiltration and that they will commonly be of the same soil type. The three soil-dependent parameters ($K_{fs}$, $S_{av}$ and $\theta_s$) are estimated from soils data using the pedotransfer functions developed by Rawls and Brakensiek (1989) which are discussed in section 4.2.

The movement of infiltrated water is assumed to occur as an advancing wetting front, the depth of which controls the rate of infiltration. Potential infiltration rate is calculated at the beginning of a time-step. Rainfall at less than this rate is assumed to infiltrate during the time-step and a new theoretical potential infiltration rate is calculated for the end of the time-step based upon this assumed infiltration. If this theoretical potential infiltration rate is less than the rainfall rate during the whole of the time-step, then ponding has occurred and the process is repeated using progressively smaller timesteps, otherwise, all the incident rainfall is assumed to infiltrate.

When rainfall intensity exceeds infiltration rate, the excess water begins to fill micro-depressions at the soil surface. These depressions are of various sizes and are both interconnected and superimposed. In a situation where rainfall intensity exceeds infiltration rate for a prolonged period, the smallest depressions are quickly filled and overland flow begins. Some of this flow will move downhill to fill larger depressions, and some will continue unobstructed. Eventually, all the depression storage will be filled. Water in depressions is either infiltrated during or after rainfall or evaporated.

Therefore, in order to successfully simulate infiltration and thus runoff, determination of the volume of depression storage is important. Depression storage can be measured directly but it is both difficult and costly. A number of authors (e.g. Moore and Larson, 1979; Gayle and Skaggs, 1978, etc.) have attempted to relate depression storage to more easily measured surface characteristics. However, the system is complex and the amount of data required to fully characterise it is prohibitive. Therefore, because of the need for a minimal data set, a simple, empirical approach has been adopted in the PARCHED-THIRST Model.

The basis for this is Random Roughness ($R_r$) which is a measure of the variability of the height of the soil when the effects of slope and tillage have been removed. There are a number of methods for quantifying this (Currence and Lovely, 1970; Onstad, 1984, etc.) but the most common is a microrelief meter which simply uses grids of pins to measure surface height. This is still a fairly involved method and therefore suggested values for a number of tillage practices are given in the **PARCHED-THIRST** User Guide. Further work needs to be done to develop pedotransfer type relationships with soil texture and tillage methods.

The development of a soil crust or surface seal can dramatically reduce the hydraulic conductivity of a soil. Rawls and Brakensiek (1989) present a relatively simple 'Crust Factor' for determining the level of this reduction in an equilibrium crust. They suggest that ignoring the development of the crust with time is allowable as crusts reach a stable state very rapidly and usually after c.5cm of rainfall. Rawls and Brakensiek's (1989) macroporosity factor has been developed to quantify the increase in potential infiltration caused by surface rocks, litter and residue and the resultant floral and faunal action.

### 4.1.5 Crop Growth Model

Although a simple soil water status output would give an idea of the effects of RWH, in order to quantify these effects in terms of what the farmer is interested in (the yield), some idea of the implications for crop growth is necessary. A crop model fulfils this role and also allows investigation of the possible risks of waterlogging and drought.

Crop systems are extremely complex and are generally modelled by a combination of empirical and physical techniques. Penning de Vries *et al.*

(1989) suggest that there are four levels of crop growth models. Level 1 models consider only climatic variables; those in Level 2 model the effects of soil water availability as well; Level 3 models include an account of soil fertility; and those in Level 4 attempt to include all other possible stress factors.

The Tropical Crops Unit at the University of Nottingham has developed the PARCH model (Bradley and Crout, 1994) for sorghum which has been adapted for maize. Older versions simplistically modelled weeds and nutrient stress, but focused on water stress and thus fell into Level 2. The most recent version (Version 3.0) models nutrient stress in a more comprehensive manner and thus falls into Level 3.

The PARCH model is embedded within the current version of PARCHED-THIRST, but linkages to other crop growth models could be developed for future versions.

### 4.1.6 Pedotransfer Functions

In order to minimise the amount of data collection required for the application of physically-based runoff and soil water movement models, there has been a great deal of interest in pedotransfer functions (PTF). These are equations relating easily measurable soil properties (usually soil texture, organic matter content and bulk density) to the hydraulic properties of the soil (moisture retention function (MRF), and saturated and unsaturated hydraulic conductivity (SHC and UHC). Being empirically derived, their reliability as predictive tools depends upon the similarity between the soils with which they were calibrated and those to which they are to be applied. Those PTFs used in the various components of the model are summarised in Table 4.1.

Moisture Retention Functions (MRF)

There are basically three methods for predicting the MRF:

- Point Regression Method - These methods attempt to predict water content at certain discrete matric potentials by means of (mainly non-linear) regression analysis. Work in this field includes Gupta and Larson (1979) and Rawls *et al.* (1982). Some of the problems associated with these methods are: (i) the discrete nature of the water content vs matric potential points generated requires interpolation and even extrapolation for tensions/water contents not estimated; (ii) restrictions in the range of soils on which they were calibrated and thus to which they are applicable.

- Physical Model Method - Arya and Paris (1981) present a three-stage process which first calculates the pore-size distribution from the particle size distribution. The water content is then predicted from the pore-size distribution according to conservation of mass and finally the matric potential is predicted from the water content according to the equation of capillarity. Although this is called a physical model method, one parameter must be derived empirically to estimate the water content from the pore-size distribution - however, in most cases, its value can be assumed constant. Both this and the majority of methods under this heading (e.g. Haverkamp and Parlange (1986) and Tyler and Wheatcraft (1989)) also require an estimate of the saturated water content - usually derived from the porosity.

- Functional Parameter Regression Method - This is by far the most reliable and therefore, widely used of the three approaches. It involves estimating the parameters of certain closed-form functions assumed to represent the relationship between matric potential and water content (e.g. van Genuchten (1980), Brooks and Corey (1964). Methods have been developed by, amongst others, Cosby *et al* (1984), Rawls and Brakensiek (1985, 1989) and Vereecken *et al.* (1989a).

Vereecken *et al.* (1989a) determined the MRFs for 182 horizons in 40 important Belgian soils with textures ranging from sand to heavy clay. They attempted to fit van Genuchten's (1980) model and four, reduced parameter forms of the same model to the data, arguing that "fewer parameters would be more appropriate in describing the MRC [Moisture Release Characteristic] data." Of the five, the original model matched the observed data best. However, because of the efficiency gains, a four-parameter model was recommended.

From the early '80s onwards, Rawls and Brakensiek, with various co-authors, produced a string of papers on various aspects of pedotransfer functions. In one of their more recent articles, Rawls and Brakensiek (1989) present pedotransfer functions (based upon analysis of up to 1323 soils from around the USA) for the estimation of the parameters of MRFs, hydraulic conductivity functions (HCF), infiltration equations and for the effects of crusting, macroporosity and plant canopies upon these.

Tietje and Tapkenhinrichs (1993) compared measured soil water retention curves and those estimated by PTFs of all three types using 1079 German soils covering the majority of possible soil textures. They found the method proposed by Vereecken *et al.* (1989a) not only to be applicable to all of these soils, but also to yield very low errors in prediction. The Rawls and Brakensiek (1985) method was also applicable to all the soils and, although it has a tendency to underestimate soil water, it is used in a number of models where its performance has been acceptable and, in some cases, better than the Vereecken *et al.* (1989a) method. However, as it was already included (and validated) in the original PARCH model, the Campbell (1985) method with the Campbell (1985) MRF is currently used within the PARCHED-THIRST model. Comparisons with other PTFs are presented in Young (1995).

Hydraulic Conductivity Functions (HCF)

Vereecken *et al.* (1989b) recognised three distinct approaches to estimating the hydraulic conductivity function (HCF) from basic soil parameters.

- The first is rather similar to the point regression method of determining the soil water retention of a soil in that discrete points of the HCF are estimated. However, most authors (e.g. Rawls *et al.* 1982; Puckett *et al.* 1985) have restricted themselves to determining only saturated hydraulic conductivity (SHC) as validation data is more readily available. However, because of the high variability of SHC, these attempts have had limited success.

- The second involves using parameters of the MRF (often estimated using the functional parameter regression method in theoretically derived models). In most cases (Brooks and Corey, 1964; Mualem, 1976; Van Genuchten, 1980), a value of $K_s$ is also needed.

- The third approach involves direct estimation of the parameters of theoretical functions developed using experimental $K(\theta)$ or $K(h)$ data without a priori knowledge of the MRF. Vereecken *et al.* (1989b) tested five such models on the same 40 soils as above and found Gardner's (1958) three parameter model to be the best.

As it has already been validated within the PARCH model, the PARCHED-THIRST model uses the Campbell (1985) HCF with parameters estimated using Campbell's (1985) method.

### Wetting Front Suction

The wetting front suction parameter of the Green and Ampt infiltration equation has been the subject of much debate in the literature. Although originally thought to have little physical significance (Philip, 1958), a number of authors (Bouwer, 1964; Mein and Larson, 1971; Slack, 1980) have since related it to the relative conductivity suction curve as well as other measureable properties (Brakensiek, 1977; Campbell, 1974). The PTF used in its estimation in the PARCHED-THIRST model is that presented by Rawls and Brakensiek (1989).

However, Brakensiek and Onstad (1977) demonstrated that, of all the parameters of the Green and Ampt equation it is least sensitive to wetting front suction.

Table 4.1 - Model parameters and the pedotransfer functions used in their estimation.

| **Model Component** | | **Infiltration** | **Moisture Retention Function** | **Hydraulic Conductivity Function** |
|---|---|---|---|---|
| **Function Source** | | Green & Ampt (1911) | Campbell (1985) | Campbell (1985) |
| **Pedotransfer Function (by Parameter)** | fs | Rawls and Brakensiek (1989) | Rawls and Brakensiek (1989) | Rawls and Brakensiek (1989) |
| | $K_{fs}$ | Rawls and Brakensiek (1989) | | Rawls and Brakensiek (1989) |
| | $S_{av}$ | Rawls and Brakensiek (1989) | | |
| | b | | Campbell (1985) | |
| | m | | | Campbell (1985) |

## 4.2 Model Validation

### *4.2.1 Validation Tests*

Model validation can be defined as the process of substantiating that a model, within its domain of applicability, behaves with satisfactory accuracy consistent with the study of objectives (Balci, 1987). There is no accepted standard approach for validating models that simulate hydrological processes, but there is a general consensus that validation should be based on both graphical displays and quantitative techniques.

Graphical analysis can be used to identify anomalies in both observed and predicted data. Quantitative techniques provide an objective assessment of model performance by measuring differences between job served and predicted values. Such techniques fall into three general categories:

- comparison of summary statistics
- hypothesis testing
- measures of goodness and fit

It was not the intent of this exercise to re-examine those PARCH components of the model which have already been extensively validated (Bradley and Crout, 1995) i.e. the soil water and crop growth components. Rather, validation tests have concentrated on the THIRST components, namely:

- The climate generator;
- the rainfall disaggregator;
- the pedotransfer functions and;
- the runoff model.

*The Climate Generator*

The objective of the climate generator is that it generates climate with the same long-term statistical properties as the climatic data with which it is calibrated for the range of climates likely to be encountered in the target area.

Validation datasets are as follows:

| | |
|---|---|
| Morogoro | - 1971-1987 and 1993-1995 |
| Same | - 1958-1992 |
| Hombolo | - 1992-1994 |

Assessment of model validity was based upon the comparison of the long-term statistical properties of model-generated and meteorological station observed climatic data.

The statistical properties compared were as follows:

- annual totals/averages
- monthly totals/averages
- inter- and intra-annual variability
- inter- and intra-monthly variability

*The Rainfall Disaggregator*

The objective of the rainfall disaggregator is that it decomposes daily rainfall into a series of five-minute intensities such that, when used as input to the runoff model, it leads to the same daily runoff totals as if observed continuous rainfall data were used.

Validation data consists of those rainfall events at Kisangara and Morogoro given in Table 4.1 where daily meteorological station rainfall data is within 15% of the total continuous meteorological station rainfall data. This corresponds to 100 events at Morogoro and 54 events at Kisangara.

The validity of the rainfall disaggregator was assessed by comparing daily runoff predicted using observed continuous data with that predicted using disaggregated rainfall data.

*Pedotransfer Functions*

The objective of the pedotransfer functions is to accurately predict soil moisture retention and hydraulic conductivity functions from readily available soil data for the range of soils likely to be encountered in the target area.

Validation data were restricted to soil monolith drainage tests at two sites (§3.4).

The validation undertaken attempts to quantify the degree to which the observed moisture retention functions (MRFs), hydraulic conductivity functions (HCFs) and values of $K_{fs}$ and $\theta_{fs}$ match those predicted by the pedotransfer functions.

The Campbell (1985) PTFs, and a wide range of other PTFs are analysed in greater detail for their ability to predict the data observed in these monolith tests in Young & Wyseure (1995).

*The Runoff Model*

The objective of the runoff model is that it accurately predicts daily runoff from the full range of storms likely to be encountered in the target area and from the full range of surfaces likely to be used for microcatchment RWH.

Validation data, as described in §4.2.2, were restricted to three seasons of rainfall-runoff data from three surface treatments at two sites.

Model validity was assessed by comparing model-predicted with experimentally-observed runoff data at two time-scales:

- daily and;
- seasonal.

The approach adopted was formal testing of the hypothesis of equality between observed and predicted values, which are treated as pairs.

### 4.2.2 Validation Data

*Climate*

The PARCHED-THIRST model requires daily values of rainfall, evaporation, maximum and minimum temperature, saturation deficit, and radiation. With the exception of a few missing data, these were available at Morogoro from the SUA campus meteorological station. The PARCHED-THIRST Climate Generator was used to generate likely values of any variable which was missing based upon the statistical characteristics of historical climate and conditioned on the wet/dry status of the day. At Kisangara, only a partial data set was available from the meteorological station. The rest of the climatic data was again generated in the same way using the statistical properties of historical data from the Same meteorological station which is located approximately 40km from the site.

Runoff is a rate-dependent process controlled by the relative magnitude of rainfall and infiltration rates. Continuous rainfall data is therefore important for proper validation of the runoff model. Continuously-recording rainfall gauges were available close to each site and in the majority of cases rainfall totals agreed fairly well with those measured by standard raingauges at the Kisangara and SUA campus meteorological stations (Figures 4.1 and 4.2). In those cases where agreement was poor, the most likely reasons are errors recording of the daily data, malfunctioning of the continuous recorders and/or errors in digitising the continuous rainfall charts.

There was a much lesser degree of agreement between the continuously recording rainguages and those at the experimental sites. Semi-arid rainfall is typified by spatial and temporal variability but the degree of variation over distances of a few hundred metres was greater than anticipated. It is likely that the location of the Kisangara and Morogoro sites at the foot of mountain ranges in both cases may explain this effect which is shown in Figures 4.1 and 4.2.

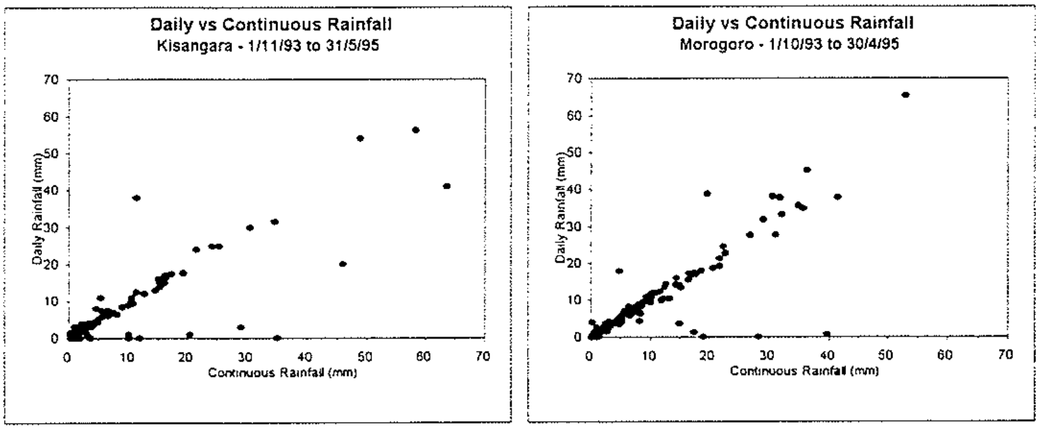


**Figure 4.1** Daily rainfall against daily totals of continuous rainfall measured at the two meteorological stations.

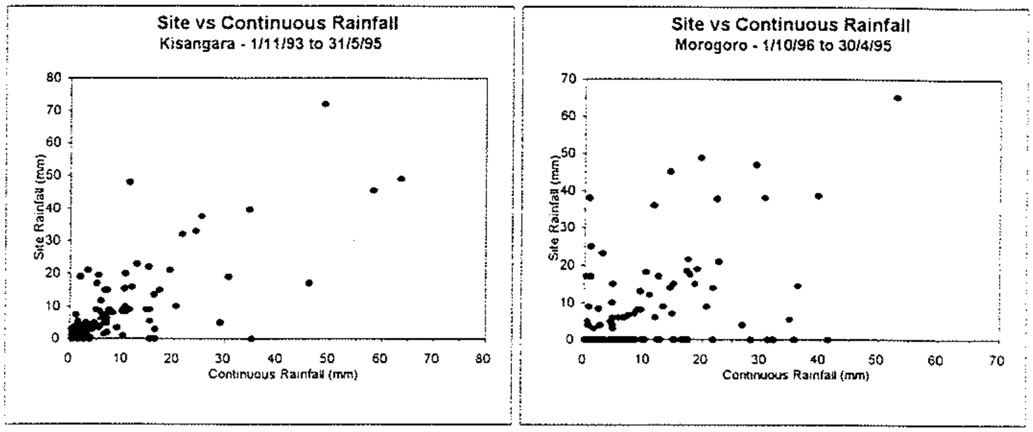


**Figure 4.2** - Daily rainfall measured at the two sites against daily totals of continuous rainfall measured at the two meteorological stations.

To try and isolate the effects of these errors, two different sets of climatic data were used in validation at each site. The first (referred to as station rainfall) consists of daily rainfall as measured at the Kisangara or SUA campus meteorological stations with continuous rainfall used where daily totals were within 15%. The second (referred to as site rainfall) uses daily rainfall totals from on-site raingauges again with continuous rainfall used where daily totals were within 15%. Table 4.2 summarises the two data sets. In those cases where reliable continuous data were not available, the rainfall disaggregator was used to disaggregate daily rainfall data into five minute intensities.

**Table 4.2** - A summary of the two climatic data sets used in validation.

| | Kisangara | | Morogoro | |
|---|---|---|---|---|
| | Site Rainfall | Station Rainfall | Site Rainfall | Station Rainfall |
| Total Rainfall Events | 124 | 128 | 78 | 219 |
| Reliable Continuous Data | 15 | 54 | 15 | 100 |

*Runoff*

At each site runoff data were available from plots with two different catchment areas, two different slopes and four different surface treatments. The PARCHED-THIRST model, because it was designed to deal only with microcatchment RWH, only accounts for catchment area relative to the cropped area with a simple multiplier. The validity of this assumption (for small catchment areas) was shown by analysis of runoff data from Morogoro (Mahoo et al, 1994) which showed that catchment length had no significant influence on runoff amount in 90% of events tested.

Runoff was collected from each plot via a cement-sealed apron into a storage tank made from an oil drum sunk into a pit. During large runoff events, overflow was collected in a second tank connected to the first by a flow divider such that it collected only part of the flow. These dividers were recalibrated after every runoff event but were designed to deliver approximately 1/15 of the total flow. The collector tanks were emptied after every runoff event.

There were more runoff-producing storms during Vuli than during Masika seasons. Surface treatment influenced runoff such that runoff events and runoff amounts increased in magnitude from Low Management Crop (LMC) plots to Bare (B) plots and from B plots to Bare and Compacted (BC) plots. In total, 76 runoff events were available for use in validation at both sites.

### *Soil Hydraulic Properties*

The PARCHED-THIRST model, while it can be run with measured values of soil hydraulic properties, can also use pedotransfer functions which estimate hydraulic properties from easily available data such as soil texture and bulk density. Reliable values of unsaturated hydraulic conductivity, moisture release characteristics, etc. were not available and therefore pedotransfer functions were used. The soil water model uses functions developed by Campbell (1985) while the runoff model uses those developed by Rawls and Brakensiek (1989).

**Table 4.3** - SHC (mm/s) of surface samples at the two sites (*no observed value was available. Therefore the SHC is assumed equal to that of the same surface treatment on the other slope).

| Surface Treatment | Kisangara | | Morogoro | |
|---|---|---|---|---|
| | 3% Slope | 8% Slope | 3% Slope | 7% Slope |
| Bare | 0.0077* | 0.0077 | 0.0054 | 0.0031 |
| Bare and Compacted | 0.0032 | 0.0039 | 0.0026 | 0.0008 |
| Low Management Crop | 0.0064 | 0.0174 | 0.0085 | 0.0021 |

Observed values of saturated hydraulic conductivity (SHC) were available from site characterisation work carried out by SUA. These are summarised in Table 4.3 (above).

The PARCHED-THIRST Model considers four characteristics of the soil surface:

- Random roughness/surface storage - equations by Zobeck and Onstad (1991) relate the amount (and changes with time) of surface storage to the random roughness of the soil. As random roughness data were not available on the soils at the site, estimates were made based upon figures suggested by Zobeck and Onstad (1991). These were:

| | |
|---|---|
| Bare and compacted | 0.6 |
| Bare | 1.0 |
| Low management crop | 1.5 |

- Impervious areas - The soils at both sites are, when devoid of vegetation, characterised by the development of "concreted" areas over time. These areas are effectively impervious to water and therefore produce nearly 100% runoff from anything but the smallest rainfall events. The PARCHED-THIRST runoff model, because it considers only within-field RWH, makes no attempt to model the movement of water across the soil surface. However, it is inevitable that there is some saturation of the soil at the lower end of the plot during prolonged rainfall. Again, this will cause a localised increase in runoff which can become significant on plots whose total length is only 10m. To account for both of these effects, the user can specify a percentage of the plot which is considered as impervious. In this case, 5% was considered reasonable for the vegetation-free plots while 1% was assumed for the low management crop plots.

- Soil crusting - It is a recognised characteristic of many semi-arid soils that, after rainfall, a surface crust or seal can develop, becoming the most important determinant of infiltration rate. Within the PARCHED-THIRST Model, this is accounted for by a *Crust Factor*, developed by Rawls and Brakensiek (1989), which simply reduces the value of the SHC parameter of the Green-Ampt infiltration equation. The inclusion of this crust factor has to depend upon a priori knowledge of whether a soil will crust as it is not currently possible to predict it from soil texture alone. Because crusting has not been observed at either site, the crust factor was not used in model validation.

- Macropore flow - Macropores allow water to enter the soil profile through lines of weakness without passing through the soil matrix. This is included in the PARCHED-THIRST model by two means; a macropore factor, developed by Rawls and Brakensiek (1989); and a macropore flow rate and crack distribution based upon Jarvis et al. (1991). The former, which merely increases the SHC based upon soil texture was not used. Without any field observations of the two parameters of the latter method, they were assigned estimated values as shown:

| Surface Treatment | Macropore Flow Rate | Macropore Distribution |
|---|---|---|
| Bare | 0.1 | 10 |
| Bare and Compacted | 0.01 | 10 |
| Low Management Crop | 0.9 | 10 |

*Soil Texture, bulk density and cation exchange capacity*

The texture of the soil affects a number of processes simulated by the PARCHED-THIRST Model and is the basis of the pedotransfer functions. For the purpose of validation, the soil profile at both sites was divided three layers with the physical properties of each layer being determined from data collated from a number of sources including those given in section 3.3. In all, four different soil profiles were defined, two for each site. These are given in tables 4.6 and 4.7 (below). Table 4.5 shows the position of the soil types within the soil profile at each site.

**Table 4.4** - Distribution of soil types with depth at the two sites.

| Depth(mm) | Kisangara | Morogoro |
|---|---|---|
| 0-10 | 1 | 1 |
| 11-30 | 1 | 1 |
| 31-60 | 1 | 1 |
| 61-100 | 1 | 1 |
| 101-200 | 2 | 1 |
| 201-300 | 2 | 2 |
| 301-500 | 3 | 2 |
| 501-700 | 3 | 3 |
| 701-900 | 3 | 3 |
| 901-1100 | 3 | 3 |

**Table 4.5** - Soil texture and CEC parameters for the three soil types at each site

| Soil Type | Soil Property | Kisangara | | Morogoro | |
|---|---|---|---|---|---|
| | | 3% Slope | 8% Slope | 3% Slope | 7% Slope |
| 1 | Sand (%) | 30 | 32 | 35 | 33 |
| | Silt (%) | 17 | 20 | 17 | 8 |
| | Clay (%) | 52 | 46 | 47 | 58 |
| | Org.Matt. (%) | 2.3 | 2.7 | 1.7 | 1.7 |
| | CEC Parameter | 0.58 | 0.51 | 0.9 | 0.9 |
| 2 | Sand (%) | 43 | 40 | 33 | 33 |
| | Silt (%) | 9 | 16 | 16 | 16 |
| | Clay (%) | 48 | 43 | 51 | 51 |
| | Org.Matt. (%) | 0.9 | 1.7 | 0.7 | 0.7 |
| | CEC Parameter | 0.91 | 0.89 | 0.97 | 0.97 |
| 3 | Sand (%) | 35 | 36 | 39 | 39 |
| | Silt (%) | 20 | 27 | 17 | 17 |
| | Clay (%) | 45 | 37 | 44 | 44 |
| | Org.Matt. (%) | 0.5 | 0.7 | 0.6 | 0.6 |
| | CEC Parameter | 0.94 | 0.94 | 0.98 | 0.98 |

**Table 4.6** - Bulk densities of soil layers (g/cm3) at each site.

| Soil Type | Surface Treatment | Kisangara | | Morogoro | |
|---|---|---|---|---|---|
| | | 3% Slope | 8% Slope | 3% Slope | 7% Slope |
| 1 | Bare | 1.45 | 1.30 | 1.53 | 1.53 |
| | Bare and Compacted | 1.36 | 1.36 | 1.54 | 1.54 |
| | Low Management Crop | 1.32 | 1.22 | 1.51 | 1.51 |
| 2 | Bare | 1.39 | 1.32 | 1.60 | 1.60 |
| | Bare and Compacted | 1.42 | 1.41 | 1.60 | 1.60 |
| | Low Management Crop | 1.36 | 1.31 | 1.60 | 1.60 |
| 3 | Bare | 1.65 | 1.65 | 1.66 | 1.66 |
| | Bare and Compacted | 1.65 | 1.65 | 1.66 | 1.66 |
| | Low Management Crop | 1.65 | 1.65 | 1.66 | 1.66 |

*Soil Water*

An initial value of soil moisture is required by the PARCHED-THIRST model for each simulation.

Soil moisture was measured weekly on the majority of plots at both sites with some plots monitored on a daily basis. However, because of the enormity of the task of instrumenting over 300 plots at three sites, many of the neutron probe access tubes were installed one or two seasons into the life of the project. Therefore soil moisture data from many plots were not available until mid 1994. Initial soil moisture conditions for the validation runs are given in table 4.7. For those runs where observed data were not available (Vuli 1993/94 and Masika 1994), a figure of 15% vol/vol moisture content was assumed as this reflected average values of available data.

**Table 4.7** - Initial soil moisture data for the Vuli 1994/95 validation simulation

| Surface Treatment | Depth (cm) | Kisangara | | Morogoro | |
|---|---|---|---|---|---|
| | | 3% Slope | 8% Slope | 3% Slope | 7% Slope |
| B | 0-10 | 0.13 | 0.12 | 0.13 | 0.13 |
| | >10 | 0.21 | 0.22 | 0.26 | 0.26 |
| BC | 0-10 | 0.09 | 0.10 | 0.14 | 0.14 |
| | >10 | 0.19 | 0.20 | 0.24 | 0.24 |
| LMC | 0-10 | 0.14 | 0.13 | 0.11 | 0.11 |
| | >10 | 0.19 | 0.18 | 0.22 | 0.22 |

### 4.2.3 *Validation Results*

*The Climate Generator*

While a detailed description of the climate generator validation is given in Young (1996), figures 4.3, 4.4, 4.5 & 4.6 give an idea of the effectiveness of the climate generator by comparing historical and generated daily averages of rainfall, temperature, radiation, relative humidity and saturation deficit for Same. The model generates climatic data whose statistical properties are nearly identical to those of the input historical climatic data.

*Rainfall Disaggregator*

The aim of the disaggregator is not to mimic the actual pattern of rainfall during the day, but to generate accurate runoff volumes. The test therefore involved comparison of infiltration and runoff obtained by running the runoff model with actual and generated rainfall intensities.

Results are presented in Table 4.8 for 15 rainy days at Morogoro in 1989. In almost all cases, the resulting infiltration and runoff volumes are the same for the two datasets. Where these is disagreement, this can be attributed to the difficulty of dealing with multiple showers within a single day.

### *Pedotransfer Functions*

### *MRFs*

The soil monolith drainage test was used to test the performance of a variety of pedotransfer functions in matching observed moisture release characteristics and full results are presented in a separate report (Young, 1995).

Each monolith test produced a series of moisture content-matric potential data. Using a spreadsheet optimiser, the widely accepted van Genuchten moisture retention function was fitted to these data as an approximation of the observed moisture release characteristic. The Campbell (1985) MRF, with parameters estimated from pedotransfer functions (using soil texture, organic matter content and bulk density), was compared with the observed data with results shown in figures 4.7, 4.8 & 4.9 and summarised in table 4.9 for Kisangara and Morogoro.

The CODET values indicate the degree of agreement between the observed data and the MRFs, with a value of 1 indicating perfect agreement and values of less than 1 indicating progressively worse agreement. It is effectively a comparison between the differences between observed and predicted data and the variance of the observed data. As such, the greater the variance of the observed data, the less well the predicted data need fit to obtain good CODET values.

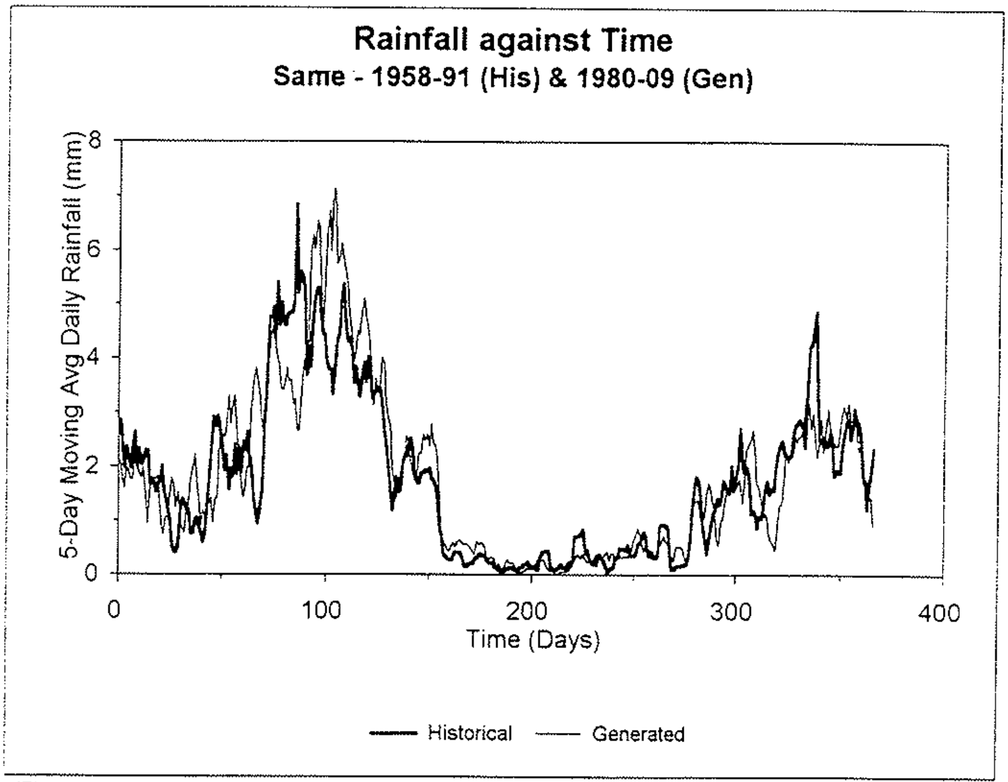


**Figure 4.3** - 5-day moving averaged average daily rainfall against time for 34 years of historical and 30 years of generated rainfall at Same.

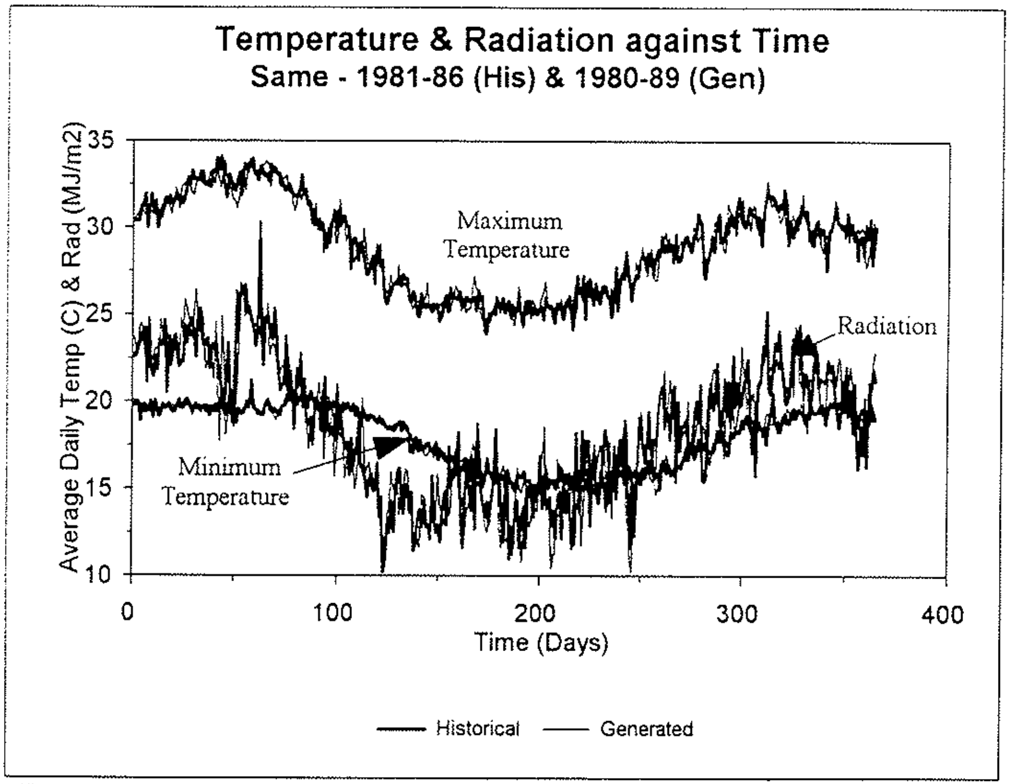


**Figure 4.4** - Maximum & minimum temperature and radiation against time for 7 years of historical and 10 years of generated data at Same.

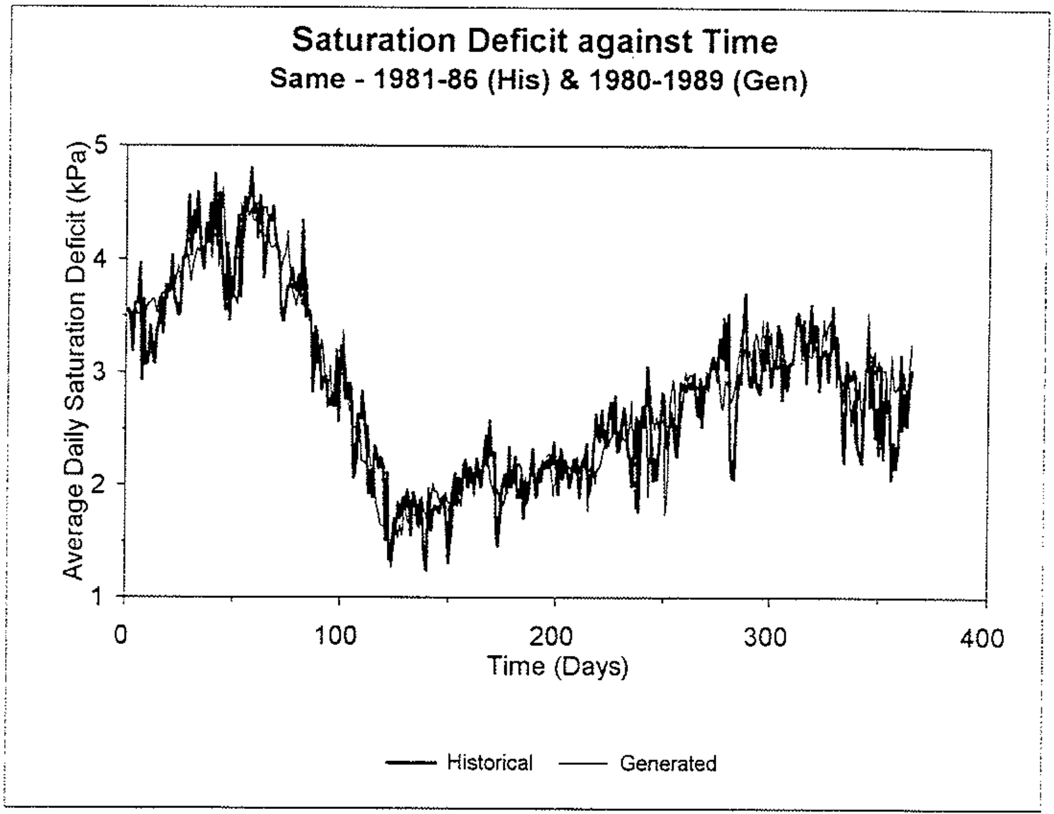


**Figure 4.5** - Historical and generated saturation deficit against time at Same.

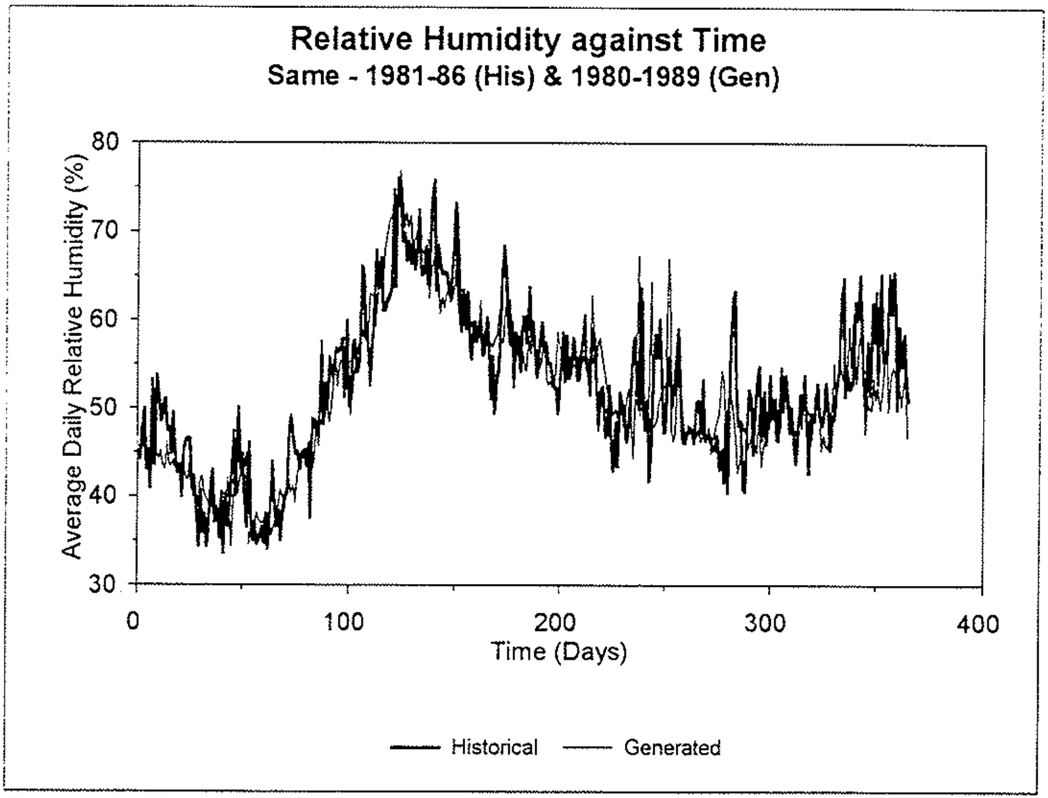


**Figure 4.6** - Historical and generated relative humidity against time at Same.

**Table 4.8** Comparison of Actual vs Simulated Rainfall Intensity Data

| Date | Rainfall Source | Rainfall Duration | $I_{30}$ | Total Measured Rainfall | Rainfall as Input | Infiltration | Runoff |
|---|---|---|---|---|---|---|---|
| 15/4/89 | Actual | 8 | 8.4 | 10.2 | 10.2 | 4.35 | 5.84 |
| | Simulated | 2 | | | 10.2 | 3.44 | 6.81 |
| 16/4/89 | Actual | 20 | 5.2 | 9.3 | 9.3 | 5.75 | 3.54 |
| | Simulated | 2.5 | | | 9.3 | 4.68 | 4.65 |
| 17/4/89 | Actual | 14 | 3 | 7.2 | 7.2 | 7 | 0.193 |
| | Simulated | 4.5 | | | 7.2 | 6.23 | 0.98 |
| 18/4/89 | Actual | 23 | 7.2 | 12.7 | 12.7 | 7.57 | 5.12 |
| | Simulated | 4.5 | | | 12.7 | 6.52 | 6.22 |
| 19/4/89 | Actual | 24 | 4.4 | 8.6 | 8.6 | 7.51 | 1.08 |
| | Simulated | 6 | | | 8.6 | 6.49 | 2.13 |
| 20/4/89 | Actual | 24 | 8.4 | 10.4 | 10.4 | 7.11 | 3.28 |
| | Simulated | 3 | | | 10.4 | 4.6 | 5.85 |
| 21/4/89 | Actual | 13 | 3.2 | 8.1 | 8.1 | 7.22 | 0.871 |
| | Simulated | 5.5 | | | 8.1 | 7.07 | 1.04 |
| 3/5/89 | Actual | 13 | 23 | 12.6 | 12.6 | 2.8 | 9.79 |
| | Simulated | N/A | | | N/A | N/A | N/A |
| 14/5/89 | Actual | 15.5 | 9 | 10.5 | 10.5 | 3.74 | 6.75 |
| | Simulated | 2 | | | 10.5 | 3.87 | 6.69 |
| 15/5/89 | Actual | 23.5 | 18.6 | 17.5 | 17.5 | 6.68 | 10.8 |
| | Simulated | 5.5 | | | 17.6 | 4.14 | 13.4 |
| 17/5/89 | Actual | 20.5 | 6 | 13.4 | 13.4 | 7.19 | 6.2 |
| | Simulated | 6.5 | | | 13.4 | 8.19 | 5.24 |
| 18/5/89 | Actual | 12 | 4 | 4.6 | 4.6 | 3.46 | 1.13 |
| | Simulated | 3 | | | 4.6 | 3.57 | 1.05 |
| 19/5/89 | Actual | 15.5 | 3.4 | 3.8 | 3.8 | 3.27 | 0.52 |
| | Simulated | 3 | | | 3.8 | 3.21 | 0.603 |
| 21/5/89 | Actual | 21 | 10.4 | 11.5 | 11.5 | 6.77 | 4.72 |
| | Simulated | 6 | | | 11.5 | 4.54 | 7.02 |
| 25/5/89 | Actual | 11.5 | 19.4 | 11 | 11 | 3.41 | 8.38 |
| | Simulated | N/A | | | N/A | N/A | N/A |

**Table 4.9** - CODETs for the Campbell (1985) MRFs at each test site. †indicates unreliable observed data.

| Depth (cm) | Morogoro | Kisangara (3%) | Kisangara (8%) |
|---|---|---|---|
| 10 | -42.74 | -42.5 | -6.40 |
| 20 | 0.89 | -66 | -0.22 |
| 30 | 0.60 | -48.1 | -0.90 |
| 40 | 0.69 | -11.8 | -0.37 |
| 50 | 0.09 | 0.77 | -0.96 |
| 60 | 0.27 | 0.08 | 0.57 |
| 70 | -53.0† | -1.45 | -0.52 |
| 80 | -255† | -0.58 | -1.04 |
| 90 |  | -0.13 | -0.30 |

From the data in Table 4.9 and Figure 4.9, it is apparent that at Morogoro the Campbell (1985) MRF fits the observed soil moisture release characteristic at five depths fairly well. The exceptions are the MRFs at the surface and at depth where experimental errors both in collecting the observed data (neutron probes do not work well near the surface) and in measuring data (surface bulk density is highly variable and difficult to measure) used in the PTFs are the most likely causes.

Table 4.9 and Figures 4.7 & 4.8 show that Campbell's MRF is much less successful at Kisangara than at Morogoro. Only in three cases do the MRFs approach a good fit to the observed data. As well as experimental errors, this is most probably due to an unusual property of many heavily-weathered tropical soils which is the tendency for clay particles to aggregate, forming particles whose hydraulic behaviour is closer to that of sand than of clay. This results in a bimodal pore size distribution which leads to large discontinuities in the moisture release characteristic firstly as the larger pores empty and then as the pores within these aggregated clays begin to empty. The majority of PTFs (including Campbell's) have been developed in Europe or the USA and have not attempted to model this phenomenon. As a result, they tend to predict MRFs whose nature is more "clayey" than the sandy moisture release characteristics observed in the these soils.

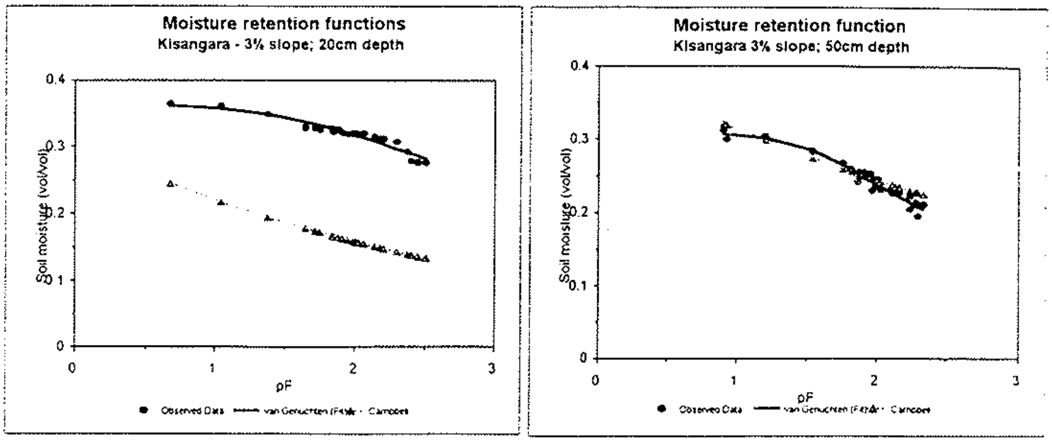


**Figure 4.7** - MRFs from Kisangara (3% slope) at 20 and 50cm depths.

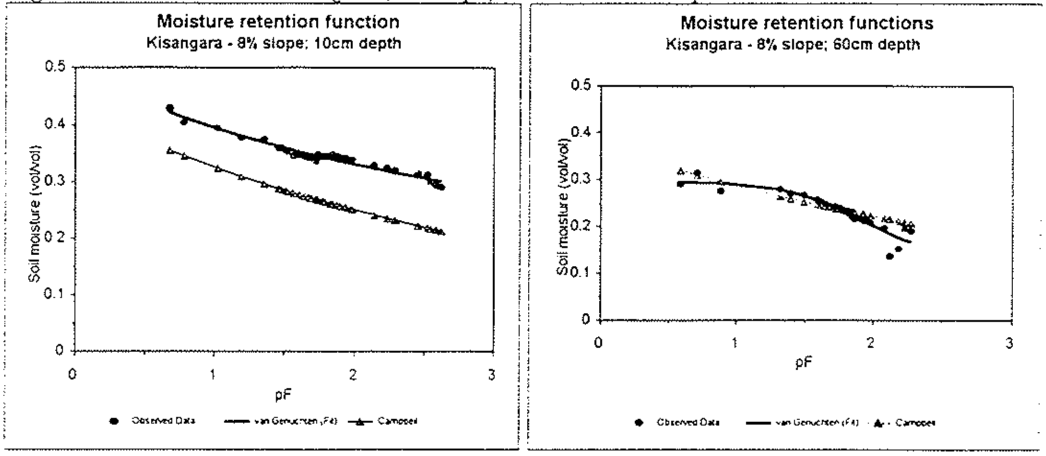


**Figure 4.8** - MRFs from Kisangara (8% slope) at 10 and 60cm depths.

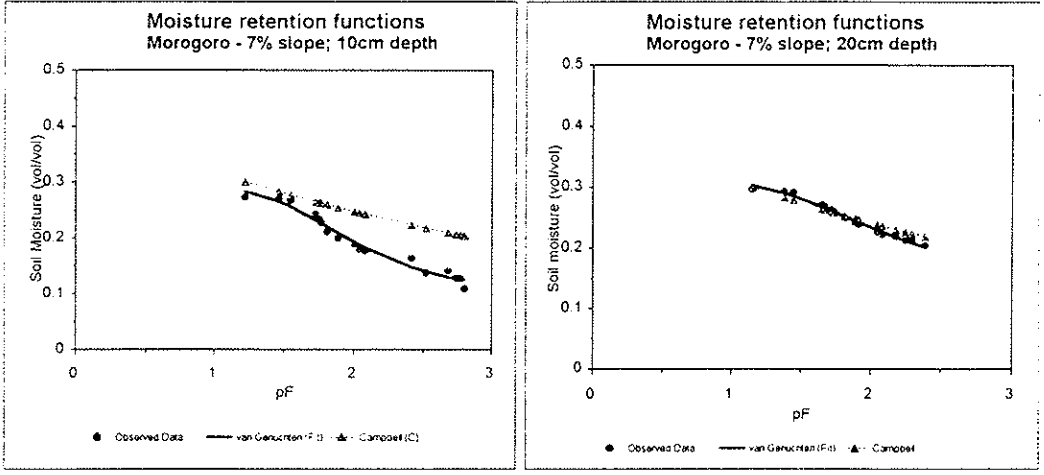


**Figure 4.9** - MRFs from Morogoro at 10 and 60cm depths.

### *HCFs*

Each monolith test produced a series of moisture content-hydraulic conductivity data. Using a spreadsheet optimiser, the widely accepted van Genuchten hydraulic conductivity function was fitted to these data as an approximation of the observed unsaturated hydraulic conductivity. The Campbell (1985) HCF, with parameters estimated from pedotransfer functions (using soil texture, organic matter content and bulk density), was compared with the observed data with results shown in Figures 4.10, 4.11 & 4.12 and table 4.10 and for Kisangara and Morogoro.

Because of the poor performance of the pedotransfer functions using estimated $K_{sat}$ in a number of cases, the observed data were also compared with the Campbell (1985) HCF calibrated with the observed infiltration rate just before drainage of the monolith.

Again, the CODET values indicate the degree of agreement between the observed data and the HCFs.

Figure 4.10 and Table 4.10 clearly show a very poor agreement between the observed and predicted moisture release characteristics at Morogoro, although the relationship does improve with depth. The calibration of the PTFs with the ponded infiltration rate does improve the situation slightly even though the observed and predicted values are an order of magnitude different in most cases (Table 4.12). The radical underestimation of hydraulic conductivity at all depths suggests that a large part of the disagreement may be due to the aggregation of clay particles as described above (under MRFs).

At Kisangara, agreement is slightly better, although the high CODETs at depth on the 3% slope is more due to the high variance of the observed data than the accuracy of the PTFs. While the inclusion of observed infiltration rate reduces agreement on the 8% slope it has a less clear effect on the 3% slope predictions. With no clear pattern in the data, it is difficult to explain these variations except in terms of experimental error and possibly the same clay aggregation phenomenon as was evident in the MRFs.

### $K_{sat}$ *and* $\theta_s$

Values of $K_{sat}$ and $\theta_s$ are required by both the soil-water movement and infiltration components of the model. Unfortunately, it was not possible to saturate the whole monolith during the test and therefore, $K_{sat}$ could not be calculated. The best approximation possible was therefore the steady-state infiltration rate attained just prior to ceasing ponding. Although $\theta_s$ was similarly not observed, an approximation can also be made using the van Genuchten MRF fitted to the observed data. Comparisons of (approximate) observed and PTF-estimated values of both these parameters are given in tables 4.11 and 4.12.

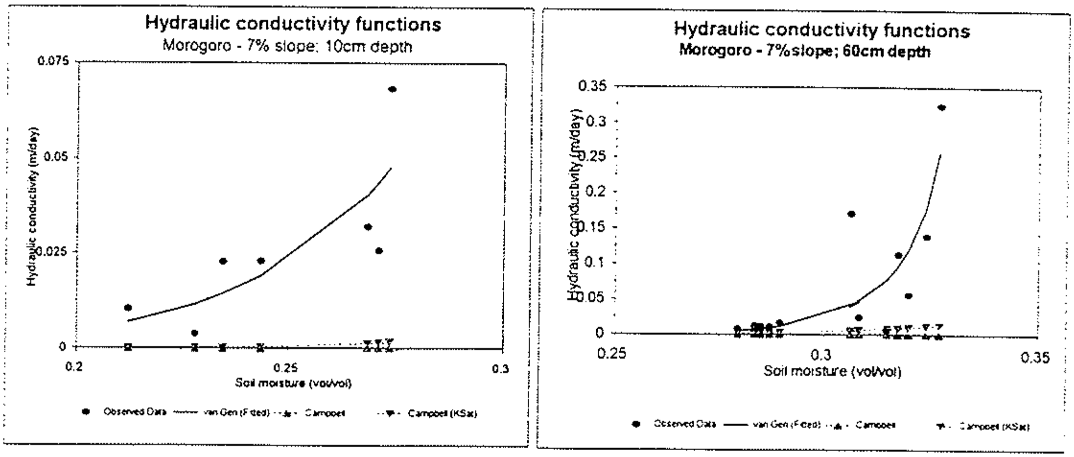


**Figure 4.10** - HCFs from Morogoro at 10 and 60cm depths.

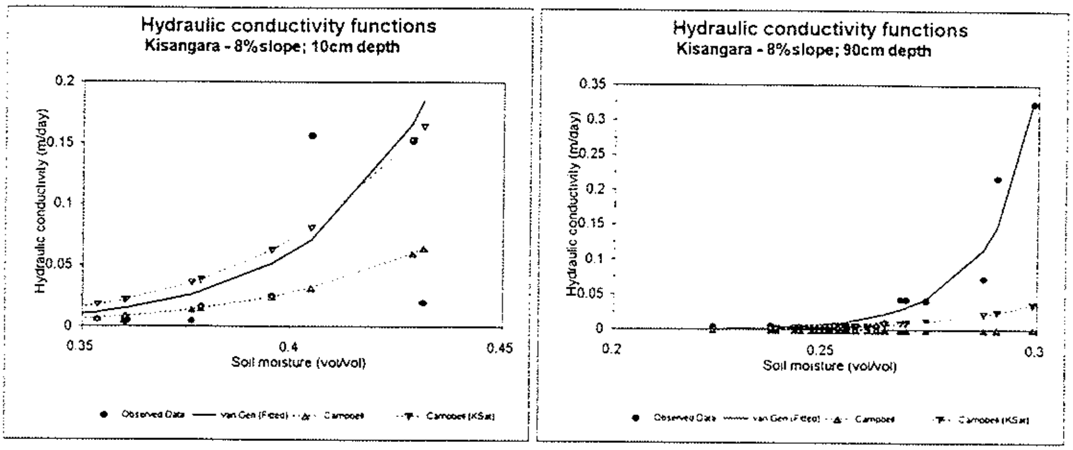


**Figure 4.11** - HCFs from Kisangara (8% slope) at 10 and 90cm depths.

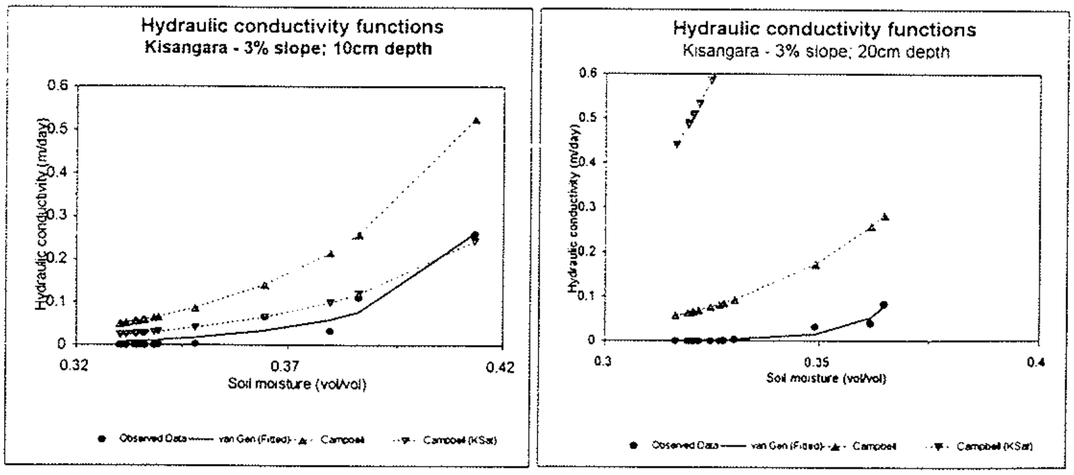


**Figure 4.12** - HCFs from Kisangara (3% slope) at 10 and 20cm depths.

**Table 4.10** - CODETs for the Campbell (1985) HCFs at each test site.

| Depth (cm) | Morogoro | | Kisangara (3%) | | Kisangara (8%) | |
|---|---|---|---|---|---|---|
| $K_{sat}$ source | Pedo | Obs | Pedo | Obs | Pedo | Obs |
| 10 | -3.36 | -3.14 | -1.86 | 0.77 | 0.28 | 0.13 |
| 20 | -3.51 | -2.80 | -24.8 | -2009 | -0.30 | 0.19 |
| 30 | -2.00 | -1.83 | 0.53 | -396 | -0.30 | -0.07 |
| 40 | | | 0.26 | -3.12 | -0.20 | 0.02 |
| 50 | | | -0.32 | 0.19 | -0.28 | 0.01 |
| 60 | -1.03 | -0.85 | -0.33 | -0.15 | -0.29 | 0.14 |
| 70 | -0.89 | -0.82 | -0.28 | -0.26 | -0.33 | -0.07 |
| 80 | -0.84 | -0.71 | -0.23 | -0.18 | -0.34 | -0.11 |
| 90 | | | 0.85 | 0.87 | -0.82 | -0.41 |

**Table 4.11** - A comparison of the PTF-estimated value of $_s$ and of that obtained by fitting the van Genuchten MRF to the observed data (vol/vol).

| Depth | Morogoro | | Kisangara (3%) | | Kisangara (8%) | |
|---|---|---|---|---|---|---|
| | Obs (Fit) | PTF | Obs (Fit) | PTF | Obs (Fit) | PTF |
| 10 | 0.30 | 0.43 | 0.45 | 0.46 | 0.52 | 0.49 |
| 20 | 0.32 | 0.43 | 0.36 | 0.33 | 0.36 | 0.41 |
| 30 | 0.30 | 0.43 | 0.34 | 0.33 | 0.33 | 0.41 |
| 40 | 0.32 | 0.43 | 0.32 | 0.37 | 0.29 | 0.39 |
| 50 | 0.33 | 0.43 | 0.31 | 0.40 | 0.28 | 0.36 |
| 60 | 0.33 | 0.43 | 0.30 | 0.40 | 0.30 | 0.36 |
| 70 | 0.34 | 0.43 | 0.28 | 0.40 | 0.30 | 0.36 |
| 80 | 0.33 | 0.43 | 0.26 | 0.34 | 0.31 | 0.38 |
| 90 | | | 0.27 | 0.34 | 0.31 | 0.38 |

**Table 4.12** - A comparison of the steady-sate infiltration rate and the PTF-estimated value of$K_{sat}$ (m/day).

| Site | Morogoro | | Kisangara (3%) | | Kisangara (8%) | |
|---|---|---|---|---|---|---|
| $K_{sat}$ source | Obs | PTF | Obs | PTF | Obs | PTF |
| 10 cm | 0.670 | 0.063 | 0.754 | 1.629 | 0.708 | 0.278 |
| 20 cm | 0.670 | 0.067 | 0.754 | 0.099 | 0.708 | 0.012 |
| 30 cm | 0.670 | 0.137 | 0.754 | 0.031 | 0.708 | 0.012 |
| 40 cm | 0.670 | 0.114 | 0.754 | 0.079 | 0.708 | 0.010 |
| 50 cm | 0.670 | 0.042 | 0.754 | 0.014 | 0.708 | 0.005 |
| 60 cm | 0.670 | 0.030 | 0.754 | 0.014 | 0.708 | 0.005 |
| 70 cm | 0.670 | 0.002 | 0.754 | 0.016 | 0.708 | 0.005 |
| 80 cm | 0.670 | 0.002 | 0.754 | 0.003 | 0.708 | 0.008 |
| 90 cm | | | 0.754 | 0.003 | 0.708 | 0.008 |

Apart from a couple of surface measurements (where both the neutron probe and bulk density measurement can be unreliable), the PTF-estimated values of $\theta s$ were all significantly lower than the values obtained from the observed data. This again supports the theory of the aggregation of clay particles to form soil which behaves hydraulically as if it were sandier than its texture alone would suggest.

In Table 4.12, a similar problem is evident. In all but one case, the observed infiltration rate (approximating to $K_{sat}$) is between one and two orders of magnitude higher than the PTF-estimated value. While part of this difference may well be due to the influence of macropores, cracks, roots and other means of water entry which bypasses the soil matrix, the clay aggregation phenomenon is likely to be a major factor.

*Runoff Model*

The level of agreement between observed and predicted daily and monthly runoff was assessed in two ways:

- Graphical analysis through scatter plots of predicted against observed runoff
- Regression analysis of the two series (predicted and observed) to give values of:

\- $R^2$. This is a measure of the strength of the relationship between the two series with 0 indicating no relationship and 1 indicating a perfect relationship. A perfect model would thus produce an $R^2$ value of 1.

- the regression coefficient. This is an indication of the type of relationship between the two series. A value of 1 indicates that there is a 1:1 relationship between the two series and thus, a perfect model would produce a regression coefficient of 1. Associated with the regression coefficient is a measure of the significance of the coefficient.

Tables 4.13 and 4.14 summarise the results of the regression analyses for all 24 validation scenarios tested at Morogoro and Kisangara respectively. Each scenario uses one of the two climatic data sets on one of the two slopes with one of the three surface treatments. Each test carried out once with an observed and once with a pedotransfer function predicted value of SHC.

Figures 4.13, 4.14, 4.15 & 4.16 are plots of predicted runoff against observed runoff at seasonal and daily time-scales using site rainfall data for BC and LMC treatments. Each graph shows the results of validation on both slopes.

Overall, the model performs well in predicting daily runoff, with almost all $R^2$ values above 0.5 and most above 0.6. On a seasonal basis, over half the scenarios produced $R^2$ values in excess of 0.85. A number of clear patterns are apparent in the tables and figures:

- The effects of the source of rainfall data on model performance are dependent upon the site. While at Morogoro the predictive capability is better with meteorological station data, at Kisangara, on-site rainfall data leads to better results. The relative importance of accurate rainfall totals as opposed to accurate rainfall intensities is probably the reason for this. At Kisangara, it would appear that the level of discrepancy between rainfall totals from the meteorological station and those from the site is such that, although over 85% of the events have no corresponding reliable continuous data and thus must be disaggregated, this data is a more reliable predictor of runoff than the observed continuous data. At Morogoro, on the other hand, the availability of continuous rainfall data for nearly 50% of events overshadows the greater reliability of the rainfall totals from the on-site gauges.

- Contrary to what might be expected as a result of the pedotransfer function validation experiments, in almost every case, the use of pedotransfer functions to estimate SHC provided more reliable predictions than the use of observed values of SHC. The most obvious explanation is that the observed values were measured incorrectly or at locations not representative of the plot as a whole.

- While the model appears to represent B and BC treatments satisfactorily, its performance in simulating the LMC treatment is poor in a number of cases. This could be due to any of several factors:

    - The PARCHED-THIRST Model makes no attempt to model the flow of runoff over the soil surface, rather all the infiltration excess which exceeds the simple depression storage factor is assumed to reach the bottom of the slope. The B and BC treatments have relatively smooth surfaces which produce little resistance to flow. The LMC treatment, because of the effects of tillage, weeds, plant stems and litter, however, produces a surface which may have a significant effect on the movement of water, especially over long distances. While this is accounted for, to a certain extent by the increased random roughness, the complexity of the situation in the field cannot, at present, be simulated by the model.

- Macropore flow was represented during validation by a crack distribution and a macropore flow factor. In the absence of any measurements, values of these factors were estimated. Again, while the B and BC treatments are likely to have relatively few macropores, the LMC treatment, because of the effects of plant roots, increased soil faunal activity, etc., is likely to display marked effects of macroporosity.

- As well as its effects on depression storage and the flow of runoff, tillage has a profound effect on the bulk density of the tilled layers of the soil. This, in turn effects the hydraulic conductivity and thus the infiltration capacity of the soil. The B and BC treatments remain virtually undisturbed from season to season and thus measurements of infiltration rate/bulk density are likely to be representative over long periods. The necessary tillage involved in the preparation, planting, weeding and harvesting of the crop on the LMC plots creates a wide range of conditions that will change with the time of year. Therefore, measurements at the soil surface are likely to be unreliable indicators of conditions at any other time.

- Interception and subsequent evaporation of rainfall by plant leaves is not currently simulated by the model. This can lead to a significant reduction in the amount of rainfall reaching the ground during low-intensity rainfall events. This may, in turn, lead to overprediction of runoff from these events.

**Table 4.13** - Summary of regression analysis of predicted on observed runoff for 24 validation scenarios atMorogoro. (“ indicates significance at the 1% level; ‘ at the 5% level and , at the 10% level)

| Rain Source | Slope (%) | Surface Treatment | Daily Data | | | | Seasonal Data | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Pedo | | Obs SHC | | Pedo | | Obs SHC | |
| | | | $R^2$ | Coeff. | $R^2$ | Coeff. | $R^2$ | Coeff. | $R^2$ | Coeff. |
| Station | 3 | B | 0.72 | 1.092” | 0.25 | 0.177” | 0.99 | 1. 183” | 0.99 | 0.234 |
| | | BC | 0.70 | 1.029” | 0.47 | 0.414” | 0.99 | 1.100” | 0.99 | 0.428” |
| | | LMC | 0.55 | 0.04” | 0.23 | 0.417” | 0.37 | 1.770’ | 0.27 | 0.092’ |
| | 7 | B | 0.69 | 1.060” | 0.51 | 0.410” | 0.90 | 1.105” | 0.87 | 0.395” |
| | | BC | 0.70 | 1.080” | 0.68 | 0.963” | 0.97 | 1.135” | 0.97 | 0.995” |
| | | LMC | 0.66 | 2.149” | 0.59 | 1.173” | -1.85 | 1.767 | 0.73 | 0.859’ |
| Site | 3 | B | 0.52 | 0.962” | 0.3 | 0.124” | 0.99 | 0.967” | 0.94 | 0.155” |
| | | BC | 0.62 | 0.952” | 0.37 | 0.264” | 0.99 | 0.910” | 0.98 | 0.269” |
| | | LMC | 0.61 | 1.29” | 0.15 | 0.04” | 0.78 | 1.187’ | 0.85 | 0.082” |
| | 7 | B | 0.64 | 0.973” | 0.32 | 0.307” | 0.82 | 0.968” | 0.35 | 0.295’ |
| | | BC | 0.58 | 0.966” | 0.54 | 0.822” | 0.89 | 0.982” | 0.89 | 0.834” |
| | | LMC | 0.60 | 1.707” | 0.29 | 0.573” | 0.73 | 2.307’ | 0.62 | 0.867’ |

**Table 4.14** - Summary of regression analysis of predicted on observed runoff for 24 validation scenarios atKisangara. (‘’ indicates significance at the 1% level; ‘ at the 5% level and , at the 10% level)

| Rain Source | Slope (%) | Surface Treatment | Daily Data | | | | Seasonal Data | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Pedo | | Obs SHC | | Pedo | | Obs SHC | |
| | | | $R^2$ | Coeff. | $R^2$ | Coeff. | $R^2$ | Coeff. | $R^2$ | Coeff. |
| Station | 3 | B | 0.37 | 1.134" | 0.18 | 0.246" | 0.79 | 1.354' | 0.92 | 0.357" |
| | | BC | 0.6 | 0.510" | 0.55 | 0.373" | 0.80 | 0.573' | 0.81 | 0.410' |
| | | LMC | 0.39 | 0.294" | 0.43 | 0.120" | 0.44 | 0.355 | 0.5 | 0.133 |
| | 8 | B | 0.57 | 0.899" | 0.61 | 0.315" | 0.84 | 0.901" | 0.93 | 0.330" |
| | | BC | 0.51 | 0.833" | 0.44 | 0.489" | 0.86 | 0.859" | 0.87 | 0.491" |
| | | LMC | 0.14 | 0.485" | 0.03 | 0.049" | -0.15 | 0.632 | -7.75 | 0.122' |
| Site | 3 | B | 0.65 | 1.46" | 0.58 | 0.237" | 0.96 | 1.402" | 0.91 | 0.329" |
| | | BC | 0.83 | 0.758" | 0.77 | 0.527" | 0.95 | 0.675" | 0.91 | 0.485" |
| | | LMC | 0.77 | 0.351" | 0.08 | 0.028" | 0.96 | 0.325" | -2.48 | 0.076, |
| | 8 | B | 0.59 | 0.886" | 0.65 | 0.246" | 0.88 | 0.900" | 0.77 | 0.306" |
| | | BC | 0.5 | 0.951" | 0.47 | 0.422" | 0.94 | 0.933" | 0.94 | 0.432" |
| | | LMC | 0.28 | 0.772" | 0.08 | 0.065" | -0.05 | 1.014 | -0.02 | 0.168' |

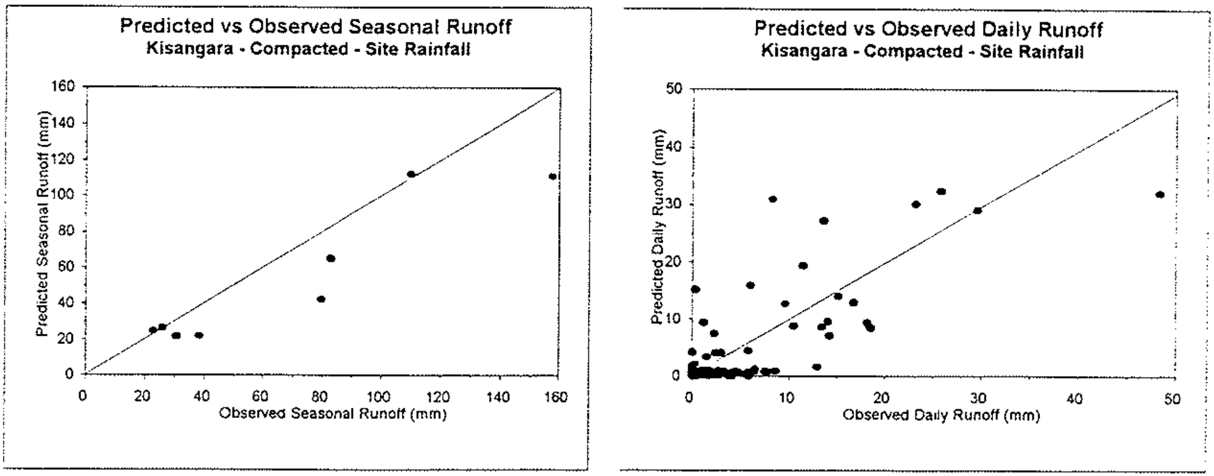


**Figure 4.13** - showing predicted runoff against observed runoff at seasonal and daily time-scales using site rainfall data for the BC treatment on both slopes at Kisangara.

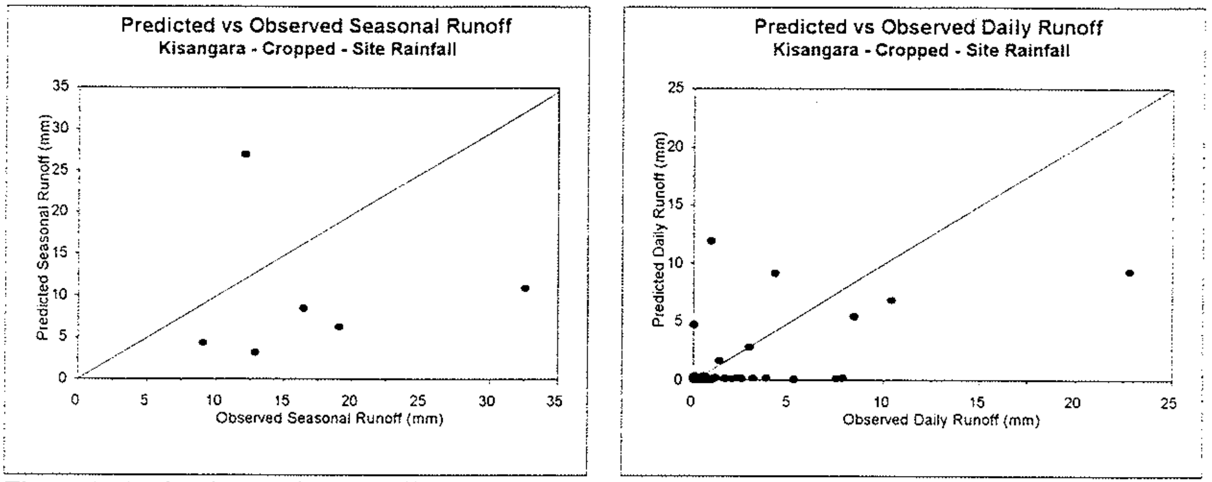


**Figure 4.14** - showing predicted runoff against observed runoff at seasonal and daily time-scales using site rainfall data for the LMC treatment on both slopes at Kisangara.

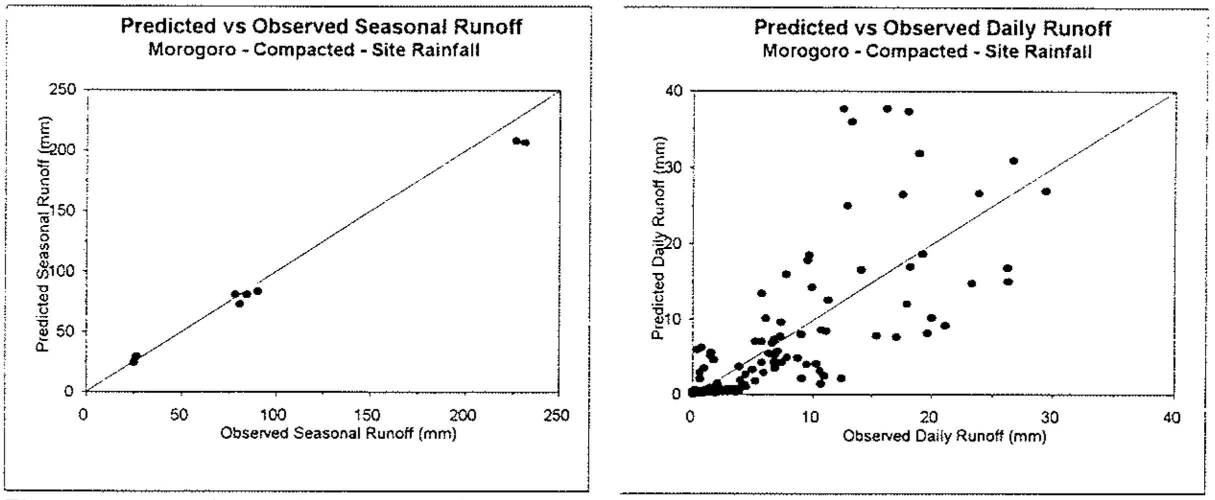


**Figure 4.15** - showing predicted runoff against observed runoff at seasonal and daily time-scales using site rainfall data for the LMC treatment on both slopes at Morogoro.

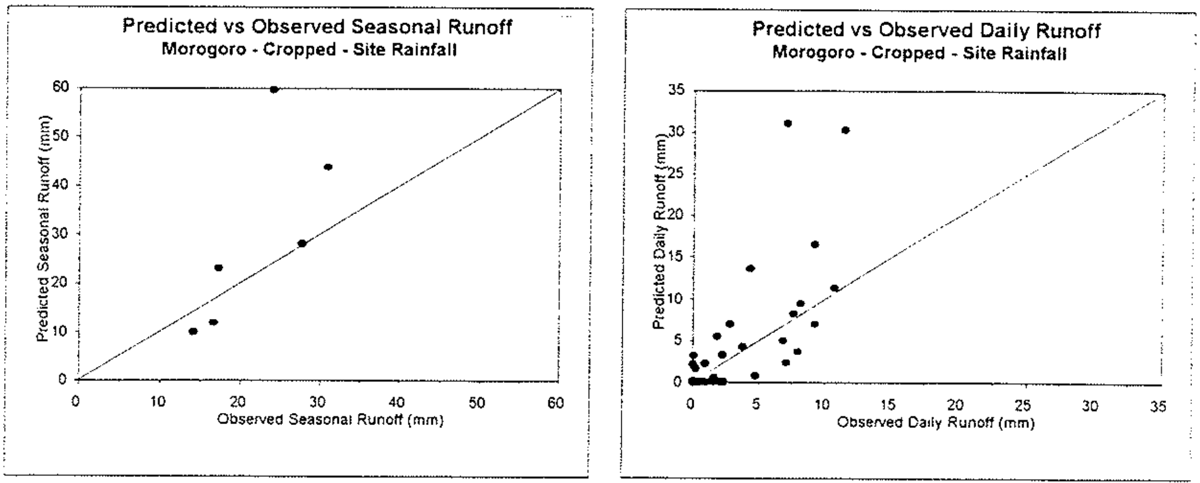


**Figure 4.16** - showing predicted runoff against observed runoff at seasonal and daily time-scales using site rainfall data for theLMC treatment on both slopes at Morogoro.

# 5. RESEARCH OUTPUTS

## 5.1 Status of RWH Model

### *5.1.1 Achievements*

The PARCHED-THIRST model of RWH processes has been developed and tested for within-field systems using data from field sites at Kisangara and Morogoro.

Considerable effort has gone into developing a user-interface in order to make the model accessible to users with only limited computing expertise. A comprehensive user-guide has been published (Young & Gowing, 1996) as a companion document.

PARCHED-THIRST is a physically based model which simulates the key processes influencing the performance of RWH systems using input data that are readily available or can be easily obtained:

- daily agrometeorological variables
- soil physical characteristics.

The model incorporates a Climate Generator which extends the agrometeorological record as necessary and disaggregates daily rainfall totals into intensity values. It also incorporates a component which uses pedotransfer functions to obtain soil hydraulic parameters from readily available soil properties.

The PARCHED-THIRST model allows the user to conduct computational experiments (what-if analysis) at any site where the basic input data are available. Long-term simulation (e.g. 30 years) can be readily achieved in this way to permit evaluation of average performance of any RWH system as well as seasonal and annual variability.

### *5.1.2 Limitations*

*Soil Properties*

The pedotransfer functions which are included in the model were not developed for tropical soils. On the basis of the limited testing which has been completed, it appears that clay aggregation in some soils leads to errors. Further work is proposed to refine the pedotransfer functions.

Soil capping/sealing may occur in some circumstances and is included in the model because of its influence on infiltration and runoff. Further work is needed to test and refine this component of the model.

Soil fertility is included by the model in only a very simple manner under the assumption that water, and not fertility will be limiting in semi-arid environments. Further work on fertility may be necessary. This could include adaptation of the fertility routines included in the latest version of PARCH.

### *Spatial Variability*

Both rainfall and soil properties are subject to spatial variability. The influence of rainfall variability on validation experiments has already been noted. Soils are also inherently variable, but thus far no account has been taken of the influence of their heterogeneity.

Generally it can be expected that soil properties are spatially correlated. Therefore it can be expected that within the scale adopted for the plot experiment, soil properties will be clearly related. However, plots separated by a larger distance may not markedly show differing properties.

Further work is needed to examine the influence of spatial variability in both soils and rainfall.

### *Management*

Crop management decisions will influence performance of any RWH system, but farmer behaviour is not well understood in some important respects. Firstly, the planting decision has been shown to influence RWH response, but considerations determining the time of planting have not been investigated. Secondly, the decision on storing or draining water collected in the crop area can have an effect, given the poor tolerance of maize to waterlogging. This requires more investigation in the field and also further development of the crop growth model (PARCH).

The work to-date has concentrated on pure stands of maize, but the farmers' stated preference is for mixed cropping of maize-beans. The water-use efficiency of such mixed stands merits investigation in both modelling studies and further field experiments. Farmers are sceptical about the practice of leaving bare-fallow areas to act as the rainwater catchment. Further work is needed to examine the desirability of a response-farming approach utilising a low-management crop (possibly sorghum) in the catchment area. This may require adaptation of the model to include consideration of interception losses.

### *External Catchments*

Work has concentrated on within-field systems, but there is some evidence that farmers are more likely to adopt external catchment systems. In order to accommodate such systems, there is a need to extend and modify the way in which runoff processes are modelled. There is a need also to examine the risk of induced soil erosion.

Adoption of such systems on any scale could lead to problems over access to common property resources, which are currently used for grazing.

## 5.2 RWH Simulation

### *5.2.1 Simulation conditions*

Computational experiments have been completed for conditions representative of the main project target area over a 30 year simulation period for both Masika and Vuli seasons. The 20 simulations presented here provide an indication of what can be done with the model and also allow for an assessment of RWH in the target area.

The Same climate dataset was used, but in order to examine sensitivity to rainfall amount, values were varied using the Climate Generator to achieve long-term average increase of c.30% or decrease of c.15%. The resulting average rainfall values were as follows:

| | Vuli | Masika | Total |
|---|---|---|---|
| Same-nor | 238 | 405 | 643 mm |
| Same-inc | 338 | 502 | 841 mm |
| Same-dec | 215 | 315 | 530 mm |

All simulations were run for the same catchment treatment (i.e. Bare), but with four different sizes (i.e. C:C Ratio). Most runs were for a standard set of Maize cultivar parameters, but two tests were also done on Katumani maize. PARCH routines for response to waterlogging are not fully developed and were therefore disabled for most tests.

The planting time was based upon standard decision criteria, as follows:

- Available Soil Water exceeds 63 mm
- Rainfall occurs in 3 of last 6 days.

In two tests, the second condition was not invoked.

An additional crop management decision was also included to allow for avoidance of waterlogging. This allows for all harvested runoff to be retained within the cropped area provided that ponded conditions do not persist beyond three days. After this time it is assumed that bund-breaking by the farmer will release the excess. This condition was invoked in all except two simulation runs.

### 5.2.2 *Simulation results*

Results of the long-term simulation for each set of conditions are summarised in Table 5.2. in terms of grain yield for Vuli and Masika seasons.

It appears that for conditions typical of Same (i.e. Same-nor), Vuli yield increases from 0.57 t/ha to 0.80 t/ha while Masika yield increases only marginally (3.03 to 3.09 t/ha) if a 2:1 CC Ratio RWH system is adopted. Comparison with lower rainfall tests (i.e. Same dec) shows a similar response in Vuli and greater response in Masika (2.60 t/ha to 3.00 t/ha).

Examination of tests with higher rainfall (i.e. Same-inc) are of particular interest, since these correspond closely to conditions prevailing at the Kisangara experimental site. Results are reproduced for comparison in Table 5.1.

***Table 5.1*** Summary of Same-inc Tests

| C:C Area Ratio | 0:1 | 1:1 | 2:1 | 4:1 |
|---|---|---|---|---|
| Vuli Yield | 0.98 | 1.33 | 1.72 | 2.28 |
| Masika Yield | 3.01 | 3.57 | 3.35 | 3.57 |
| Vuli Variance | 0.54 | 1.21 | 1.83 | 2.66 |
| Masika Variance | 1.03 | 0.04 | 0.35 | 0.04 |

It can be seen that there is some increase in Masika yield if RWH is introduced, which appears to be associated with reduced variance. However, there is no benefit from increasing the CC Ratio beyond 1:1 (i.e. 50% area cropped). The increase in Vuli yield is greater and improves at higher CC Ratios but in this case is associated with increased variance.

The response of the 2:1 CC ratio RWH system can be clearly seen in Figure 5.1. Full results for the 30 year simulation, as presented in Figure 5.2. It can be seen that there is little improvement in most Masika seasons but four dry seasons do show a marked response. In contrast, it is apparent that there is a clear response in approximately half of the Vuli seasons.

The limited testing with Katumani maize provided encouraging results. These show improved performance compared with the variety in current use both with and without RWH in Vuli season.

**Table 5.2** Summary of various long-term simulation results

| Climate | C:C Ratio | Waterlogging | Bund Breaking | Cultivar | Planting | Average Grain Yield (t/ha) | | Variance | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Vuli | Masika | Vuli | Masika |
| Same - inc | 0:1 | No | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 0.98 | 3.01 | 0.54 | 1.03 |
| Same - inc | 0:1 | No | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 0.98 | 2.89 | 0.54 | 0.66 |
| Same - inc | 1:1 | No | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 1.33 | 3.57 | 1.21 | 0.04 |
| Same - inc | 1:1 | No | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 1.35 | 3.60 | 1.19 | 0.05 |
| Same - inc | 2:1 | No | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 1.72 | 3.35 | 1.83 | 0.35 |
| Same - inc | 2:1 | No | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 1.72 | 3.33 | 1.83 | 0.53 |
| Same - inc | 4:1 | No | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 2.28 | 3.57 | 2.66 | 0.04 |
| Same - inc | 4:1 | No | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 2.12 | 3.67 | 2.51 | 0.04 |
| Same - inc | 2:1 | No | Yes | KARI Maize | ASW>63mm;Rain 3/6 days | 2.37 | 3.17 | 1.66 | 0.06 |
| Same - inc | 0:1 | No | Yes | KARI Maize | ASW>63mm;Rain 3/6 days | 1.57 | 2.95 | 0.69 | 0.53 |
| Same - nor | 2:1 | No | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 0.80 | 3.09 | 0.24 | 081 |
| Same - nor | 0:1 | No | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 0.57 | 3.03 | 0.18 | 0.91 |
| Same - dec | 2:1 | No | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 0.63 | 3.00 | 0.16 | 0.65 |
| Same - dec | 0:1 | No | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 0.48 | 2.60 | 0.07 | 1.11 |
| Same - inc | 2:1 | Yes | No | Std Maize | ASW>63mm;Rain 3/6 days | 0.66 | 0.03 | 1.19 | 0.01 |
| Same - inc | 0:1 | Yes | No | Std Maize | ASW>63mm;Rain 3/6 days | 0.68 | 0.16 | 0.56 | 0.21 |
| Same - inc | 2:1 | Yes | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 0.66 | 0.03 | 1.19 | 0.01 |
| Same - inc | 0:1 | Yes | Yes | Std Maize | ASW>63mm;Rain 3/6 days | 0.68 | 0.16 | 0.56 | 0.21 |
| Same - inc | 2:1 | No | Yes | Std Maize | ASW>63mm | 1.72 | 3.05 | 1.83 | 0.95 |
| Same - inc | 0:1 | No | Yes | Std Maize | ASW>63mm | 0.98 | 2.75 | 0.54 | 1.65 |

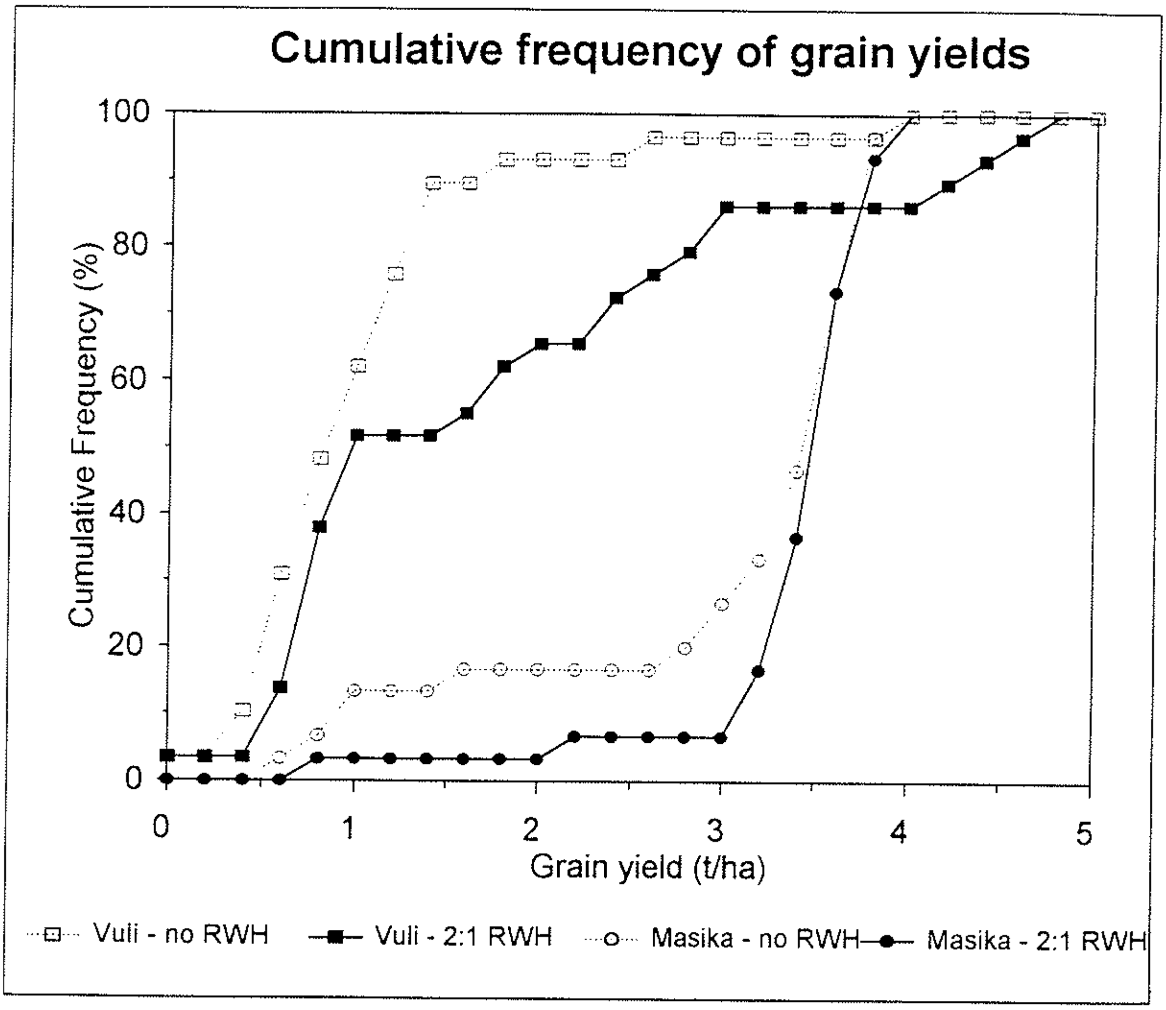
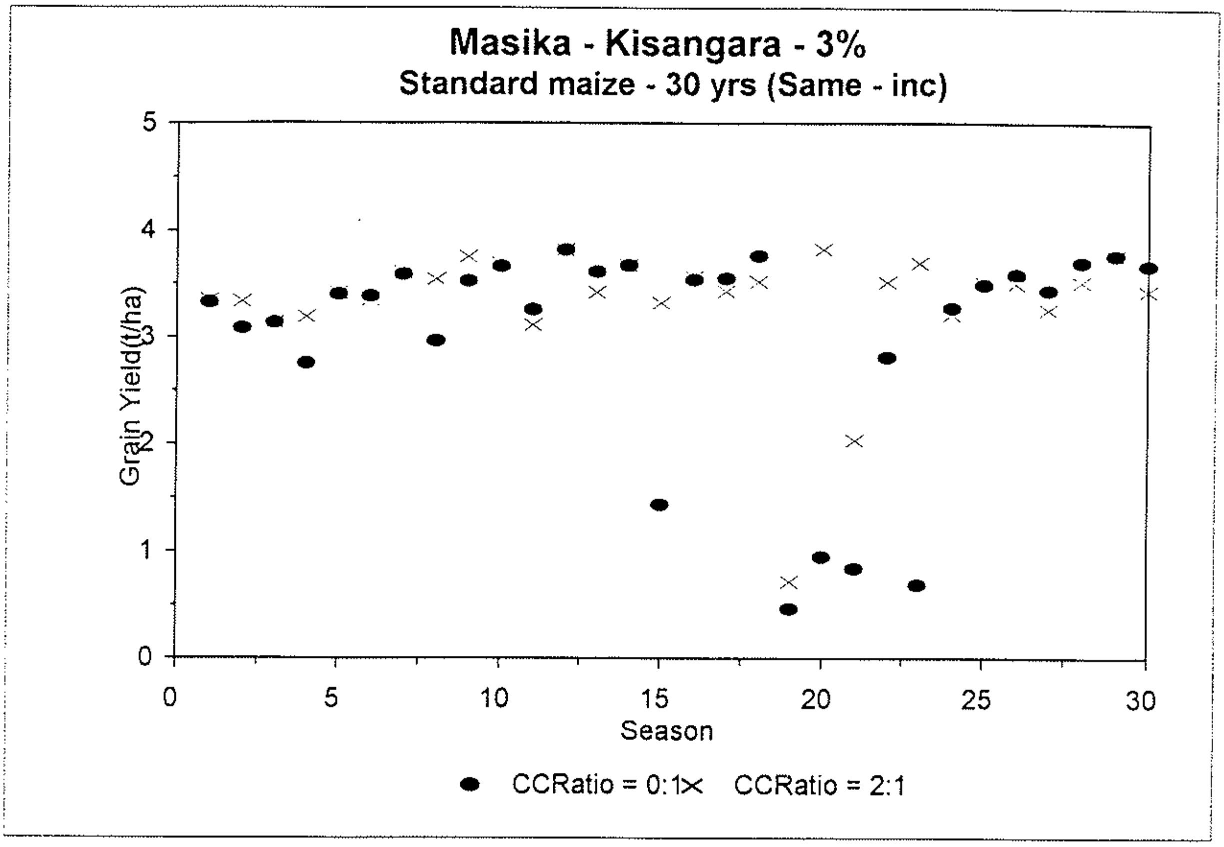


**Figure 5.1** Cumulative frequency of simulated yields of maize in the vuli and masika seasons using same-inc climate data, both with and without 2:1 RWH



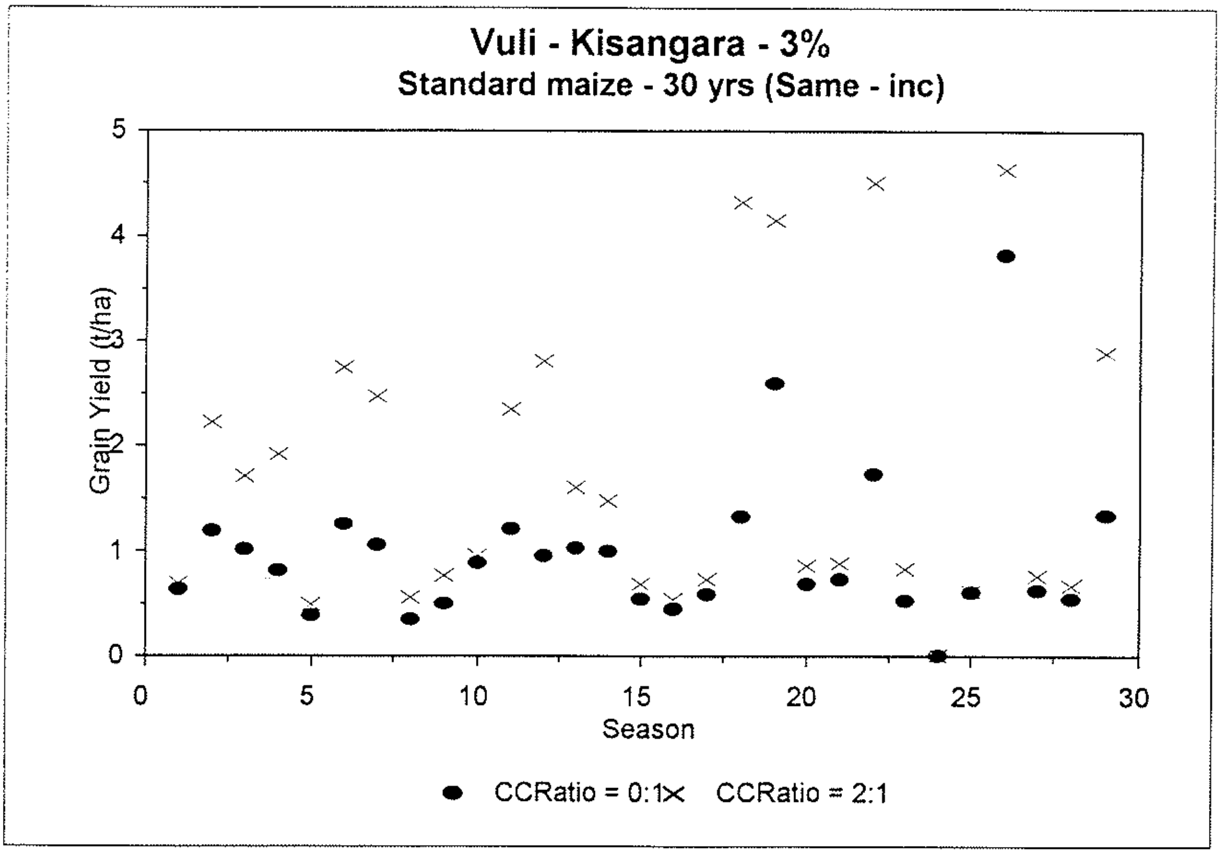


**Figure 5.2** Typical results for 30 years simulation

# 6. CONCLUSIONS

## 6.1 Contribution to Science

Through a programme of field research and modelling based upon close collaboration with the SUA research team, this project has achieved its aims:

- to demonstrate viability of cropping systems based upon rainwater harvesting techniques
- to develop a computer model of the RWH process as an aid to identifying best-bet options.

Close attention to detailed site characterisation and data quality control have provided for model validation and also ensured reliability and transferability of experimental results. The model is a tool which can extend and add value to the field experiments, which are themselves costly, time-consuming and laborious.

PARCHED-THIRST is a physically-based model which represents the important hydrological processes affecting runoff and soil-water availability. Likely constraints on availability of appropriate climatic and soils data have been addressed by incorporating pre-processors within the model, which will:

a) generate or extrapolate climatic data
b) predict soil physical properties by means of pedotransfer functions.

## 6.2 Contribution to Development

The project seeks to address the problem which arises from population pressure in high-potential uplands causing migration into semi-arid lowlands. Although the work has focused on one particular target area in Tanzania, the problem is known to occur throughout East Africa. Proper soil/water management is a key element of any strategy for sustainable crop production.

The project has contributed to the goal of improving commodity production in such circumstances. This has been achieved by demonstrating improved techniques adapted to the preferred cropping system (maize/legumes) based on rainwater harvesting. Farmers in target villages have responded positively and are already adopting new practices. Whereas previously rainwater runoff was seen as a threat, it is now recognised as a potentially valuable resource.

The project has been seen to have potential impact at two levels and efforts have been made to promote uptake in each. The first level concerns the direct beneficiaries (i.e. farmers) who depend upon extension services for advice. Extension agents accustomed to working in a top-down T & V mode face great difficulties in adapting to a new facilitating role which recognises the importance of participation. The project has worked with extension agents in demonstrating new techniques and in devising a means of screening best-bed options through the use of the model.

The second level concerns NARS researchers who need to adopt up-to-date practice with IT tools to improve quality and impact of their field research. The project has worked with scientists at SUA in developing the model. Many NARS scientists and SUA students have visited the project sites and participated in workshop discussions. The link with SUA and thence to NARS scientists within Tanzania and more widely within SADC countries represents the most appropriate uptake pathway.

Publications to-date (see Appendix) have mainly been targeted at dissemination to the SADC scientific community. This effort will continue with distribution of the model and user guide. However, the work has now reached an appropriate stage for publication in the international scientific literature.

### 6.3 Recommendations for further work

The limitations of the existing PARCHED-THIRST model are acknowledged (see § 5.1.2) and further work is needed, including:

- refinement of pedotransfer functions
- better treatment of soil capping/sealing
- up-scaling to accommodate external catchments
- explicit treatment of spatial variability
- inclusion of mixed cropping (maize/bean).

Barriers to adoption of improved soil/water conservation practices have received considerable attention in recent years and it is recognised that any new technology must accord with the experience of the user. Previous top-down approaches are being replaced by more facilitating/participative approaches to extension. Therefore, a need for a means of systematising and understanding indigenous knowledge becomes apparent.

A new Newcastle/SUA project with EU funding will aim to extend the work further in this direction, particularly in relation to soil properties and management. There is a need also for further work on crop management and on the wider livelihood system of beneficiaries. This becomes particularly important in relation to concern over access to common property resources in the case of external catchment RWH systems.

# APPENDIX A

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