The Use of Computer Simulation to Assess the Suitability of RWH Technology Interventions in Semi-arid Tanzania

Gowing, J.W[1]*., M. D. B. Young[1], and F.B.R. Rwehumbiza[2]
[1]Centre for Land Use and Water Resources Research, University of Newcastle upon Tyne, UK
[2]Department of Soil Science, Sokoine University of Agriculture, Tanzania

Abstract

Experimental research into soil water management, whether on a research station or on farmers' fields, is necessarily restricted to specific sites over limited time intervals. Meaningful extrapolation is a problem. With this in mind, the SUA-Newcastle RWH project pursued a twin-track approach in which the experimental effort was linked to the development of a simulation model, which was designed to assess the suitability of RWH technology interventions for any new site. The simulation model is briefly described and typical examples of its use as a tool for agro-technology transfer are presented. The interface is user-friendly and the model itself is designed to work with readily available site data. Long term simulation at a new site can be easily achieved to permit evaluation of average performance and/or variability and risk. The yield-gap under existing practice can be evaluated alongside predicted performance under improved practice. Examples of the application of the model are given for a maize cropping system and for a rain-fed rice cropping system in two different regions of Tanzania.

Keywords: Simulation, RWH, semi-arid, Tanzania

Introduction

Limitations of experimental approach

The objective of improving the livelihoods of the rural population of Tanzania requires the adoption of new ideas, new technologies and better management practices by millions of resource-poor, small-scale farmers. Agricultural support services therefore are required not only to identify useful innovations, but also to make them available to farmers at all locations where they are likely to succeed. In the conventional top-down approach to technology transfer, public-sector researchers develop new technology on research stations, which are then promoted by the extension services. The animal-drawn wheeled tool carrier is a celebrated example of mechanisation innovation developed in this way that was "perfected yet rejected" (Starkey, 1988). Many soil conservation initiatives have been similarly rejected and a noteworthy study by Hudson (1991) for FAO attempted to explain the frequent failures.

Sustainable development depends upon willing adoption rather than coercion, but it is equally undesirable to adopt a 'supermarket strategy' of placing new technology packages on the shelf for the 'buyer' to collect. Rather there is a need for professionals involved in development to reconsider the process. A new 'farmer-first' paradigm is becoming widely accepted (Chambers *et al*, 1989; Scoones and Thompson, 1994). This approach emphasises the participation of farmers at all stages in the process of innovation and is located in the farmers' fields. Both the traditional and the participatory approaches demand time-consuming and costly experimental work in order to arrive at the technology options which seem most likely to work. These experiments are, of necessity, restricted to certain locations over limited time

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* Corresponding author

intervals and extrapolation (spatial and temporal) is always a problem.

Spatial extrapolation

The traditional approach assumed that technologies, which performed well in researcher-managed experiments, would also do well on farmers' fields. This ignored obvious differences in altitude, climate and soils, with research stations in sub-Saharan Africa (SSA) often situated in particularly favourable conditions. Therefore the concern for spatial extrapolation was first tackled by defining agro-ecological zones (AEZ) within which the agri-environment could be considered reasonably homogeneous (FAO, 1978). More recently, it has been recognised that this approach fails to reflect socio-economic differences that influence farmers' technology choice and management. The concept of resource management domains (RMDs) has therefore replaced the AEZ as a basis for spatial extrapolation of research (Syers and Bouma, 1998).

The participatory approach has a major advantage over the traditional approach in this respect as technologies are actually tested out by farmers on their own fields, thus accounting for local soils, topography and management practices. However, most development projects are under pressure to show impact over large areas in a short time. This will not be possible if every potential adopter is expected to carry out experiments on their fields. Therefore, once a technique has been seen to be successful in one area, attempts will be made to transfer it to other areas with different soils, topography and management practices. At this point, the participatory approach faces a similar spatial extrapolation problem as the traditional top-down approach, which may be further complicated by the need to predict performance at a local scale.

Temporal extrapolation

In arid and semi-arid regions, variability in rainfall amount and timing is large and is often the primary determinant of crop performance. This variability is reflected in a wide fluctua tion in annual rainfall and in a wide range o dates for start and end of the growing season Furthermore, there may be great variability i the pattern of rainfall and duration of intra seasonal dry-spells as discussed by Mahoo *e al.*, 1999. It is therefore desirable that an field research programme aimed at quantifyin crop response to management factors (such a RWH) should run for a long period to ensur that results are representative. Even then it i difficult to interpret differences in performanc between years and extrapolation may be base on a crude relationship with seasonal rainfa (Jones, 1987). Generally, experimental work limited to only a few years and cannot captu the variability. Extrapolation to reflect cond tions in other years is difficult (Critchle 1989; Kiome and Stocking, 1993) and ma result in misleading recommendations.

The objective of this paper is to explore alte native approach of using computer models overcome the limitations of experimental a proach.

Simulation Approach

Simulation approaches must be considered relation to the available models, which attem to simulate the biophysical processes in each the RWH sub-systems:

- The catchment sub-system generates ru off, which is harvested and conveyed the cropped area;
- The cropped area sub-system receives a stores both rainfall and runoff, whi contribute to the soil-moisture reservoir.

For the crop area sub-system, mechanistic cr models are useful, in that they offer the c portunity for researchers to evaluate expec yield under the range of weather conditi experienced over many years. There are number of models which simulate maize mo crops under semi-arid conditions includ SODCOM (O'Callaghan *et al.*, 1994), CER (Tsuji *et al.*, 1994) and PARCH (Bradley Crout, 1996). These models represent the portant biophysical processes using parameters that represent the conditions for a specific site. In the context of RWH, proper simulation of the soil-water dynamics and crop response to moisture regime is particularly important. Stephens and Hess (1999) demonstrate how the PARCH model was used to extrapolate experimental data for maize in semi-arid Kenya under different soil-water management scenarios.

For the catchment area sub-system, the requirement is to simulate runoff response to rainfall at appropriate temporal and spatial scales. Proper modelling of the soil-water reservoir in the cropped area determines the requirement for a daily time-step. The selection of spatial scale however depends upon the type of RWH system. For a micro-catchment system this will be typically 100 m^2 to 1 ha, whereas for a macro-catchment system it will be 1 ha to 100 ha (Gowing *at al.*, 1999). As with mechanistic crop models, a deterministic (physically-based) approach is preferred, since in general the data required to calibrate a stochastic model will not be available.

Boers (1994) discusses alternative approaches to modelling micro-catchments in which the slope-length is limited to a few tens of metres. He concludes that a two-parameter (i.e. slope and threshold) linear regression model fits the data very well. He found a small improvement by including a kinematic wave model, but this requires six parameters. Tauer and Humborg (1992) review approaches relevant to macro-catchments and evaluate them using data from a 114 ha experimental catchment in Mali. A single lumped-parameter model based on the Soil Conservation Service (SCS) curve number method (USDA, 1972) performed quite well. Pathak *et al.*, (1989) also report good prediction performance using a similar model in India. An alternative approach in dealing with macro-catchments is to use a distributed parameter approach to model the spatially varying processes on an event basis. Models of this type have been developed primarily for use in small ungauged watersheds (typically 1 km^2 to 100 km^2) to predict the influence of land-use and management on runoff, sediment yield and water quality. Some such models are over-parameterised, but pragmatic approaches, which take full account of the problem of parameterisation, are available. Ben Asher and Humborg (1992) used a model, which is similar to the curve number approach, to obtain grid-scale runoff yield. Silburn and Connolly (1995) developed the ANSWERS model based on a Green-Ampt grid-scale infiltration model. They demonstrated that parameter estimation could be successfully accomplished using a 1m^2 portable rainfall simulator.

Simulating RWH technology interventions in Tanzania

Recognising the inherent limitations of the experimental approach and in order to add value to the costly and time-consuming field experiments, the SUA-Newcastle project pursued a twin-track approach. This involved linking the experimental effort to the development of a simulation model designed to permit easy spatial and temporal extrapolation. The model aims to represent the important biophysical processes using parameters that can be measured or estimated to represent crop, soil, site and rainfall. It comprises various sub-models, which are linked together as shown in Figure 1. It incorporates the PARCH crop model (Bradley and Crout, 1996) to simulate maize growth and the ORYZA crop model (Wopereis *et al.*, 1996) to simulate rice growth, but in principle can also incorporate other crop models.

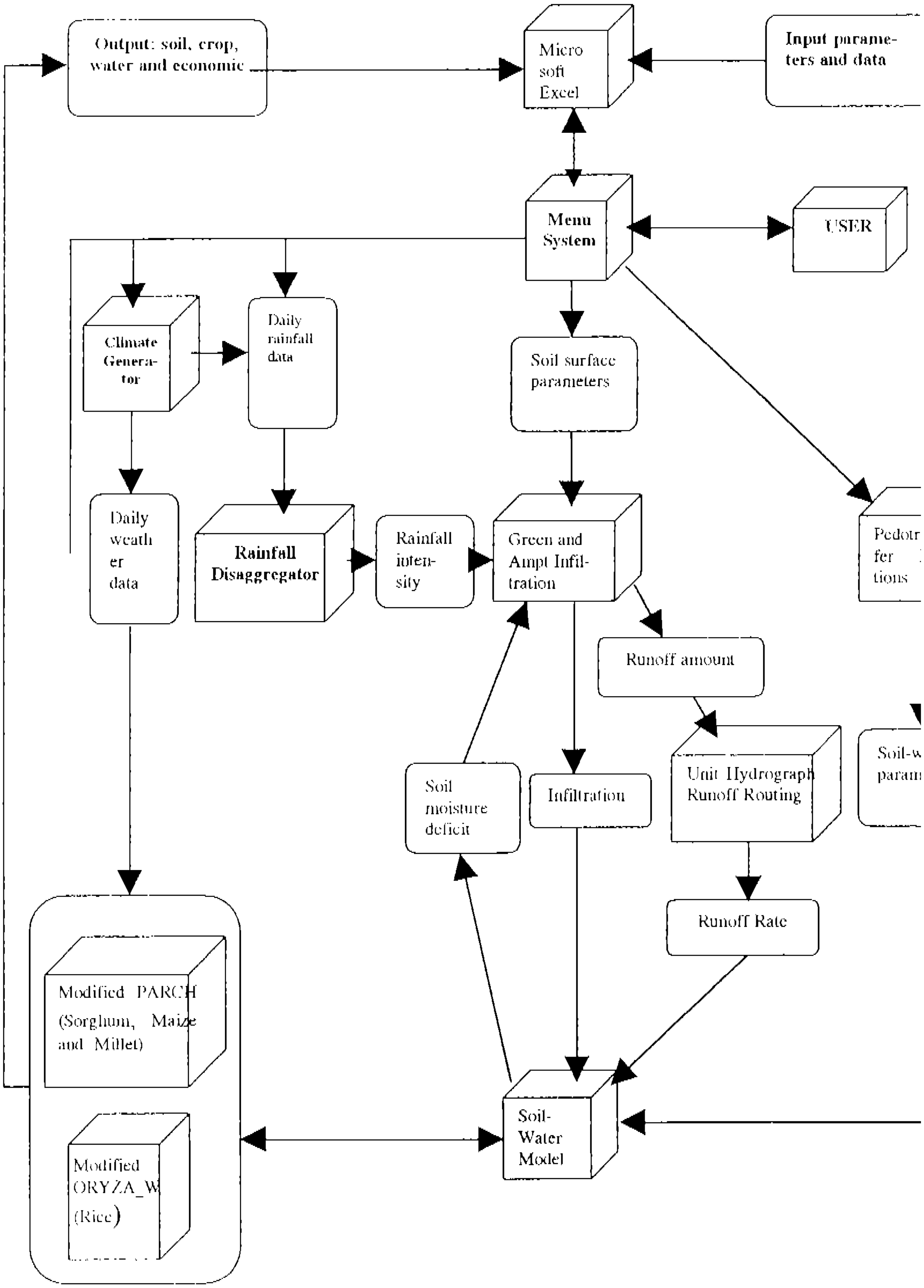


Figure 1: Structure of the PARCHED-THIRST Decision Support System (DSS)

The model is driven by daily values of rainfall and other agro-meteorological variables. The rainfall-runoff process is simulated using the Green-Ampt method. By varying the surface treatment parameters, a wide variety of rainwater harvesting/conservation practices can be simulated. The first version of the model (Young and Gowing, 1996) was designed for in-field micro-catchment systems, but this has since been extended by incorporating a runoff routing module to allow simulation of external macro-catchment systems.

Validation data have been provided by a seven-year programme of experimental work at four sites located in different agro-ecological zones of Tanzania. Over 300 small plot experiments on experimental sites and farmers' fields have been monitored for a variety of soil-plant-water data. In addition, the runoff from five larger catchments has been measured. Using the model, computational experiments can be easily completed for a range of site conditions over an extended period.

The model parameters have been kept as simple as possible and, where they are difficult or time-consuming to measure, parameter estimation methods have been included. One of these pre-processors provides pedotransfer functions which are used to estimate complex soil hydraulic properties, such as moisture retention and hydraulic conductivity, from more easily obtained soil properties (i.e. soil texture, organic matter and bulk density). Although there are long rainfall records for a number of sites in Southern and Eastern Africa, in many areas climatic data tend to have been collected for only a few years or have large numbers of missing data. For this reason, another pre-processor is the climate generator, which can generate long series of synthetic weather data with the same stochastic properties (variability and means) as the available historical data and fill in one or more missing meteorological variables.

The PARCHED-THIRST climatic 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. The climatic generator is supplied with weather parameter files for a number of sites in Tanzania. The historical data used in the model was for a period of 20 to 30 years in each case. As with any statistical method the larger the sample of historical data (the number of years of weather data at a site), the better will it represent the population from which it is taken.

Depending upon the data available, the climatic generator can generate two types of weather data:

(a) Full agrometeorological weather files - this is the generation of the full range of variables required by the PARCHED-THIRST model.

(b) Rainfall dependent weather files - in many areas, rainfall data have been collected for long periods of time while other agrometeorological data have only been recorded in recent years. To allow the full potential of these long-term rainfall records to be realised, the climatic generator can use the statistical properties of the rest of agrometeorological data to realistically generate the rest of the weather variables in the years for which only rainfall data are available.

Simulation results and discussion

Micro-catchment systems

Experimental results for maize grown with micro-catchment RWH were obtained for a site in the Western Pare lowlands (Kisangara) for five seasons and for four different catchment sizes (Hatibu *et al.*, 1999). In view of the pronounced variability in rainfall amount and timing, these results cannot easily be interpreted in a longer-term perspective. Therefore, the longer term variability and average performance was evaluated with the aid of scenario simulation based on a 30-year simulation period with synthetic weather data representative of the Kisangara site. The resulting average rainfall values were 338 mm in *Vuli* and 502 mm in *Masika*.

Results are presented in Figure 2 for both seasons for one catchment size (i.e. twice size of cropped area with Catchment Basin Area Ra (CBAR) of 2:1). Average yields over the year period are increased by 10% in *Mas* and by 75% in *Vuli*. This extended analy provides a clearer context for the interpretati

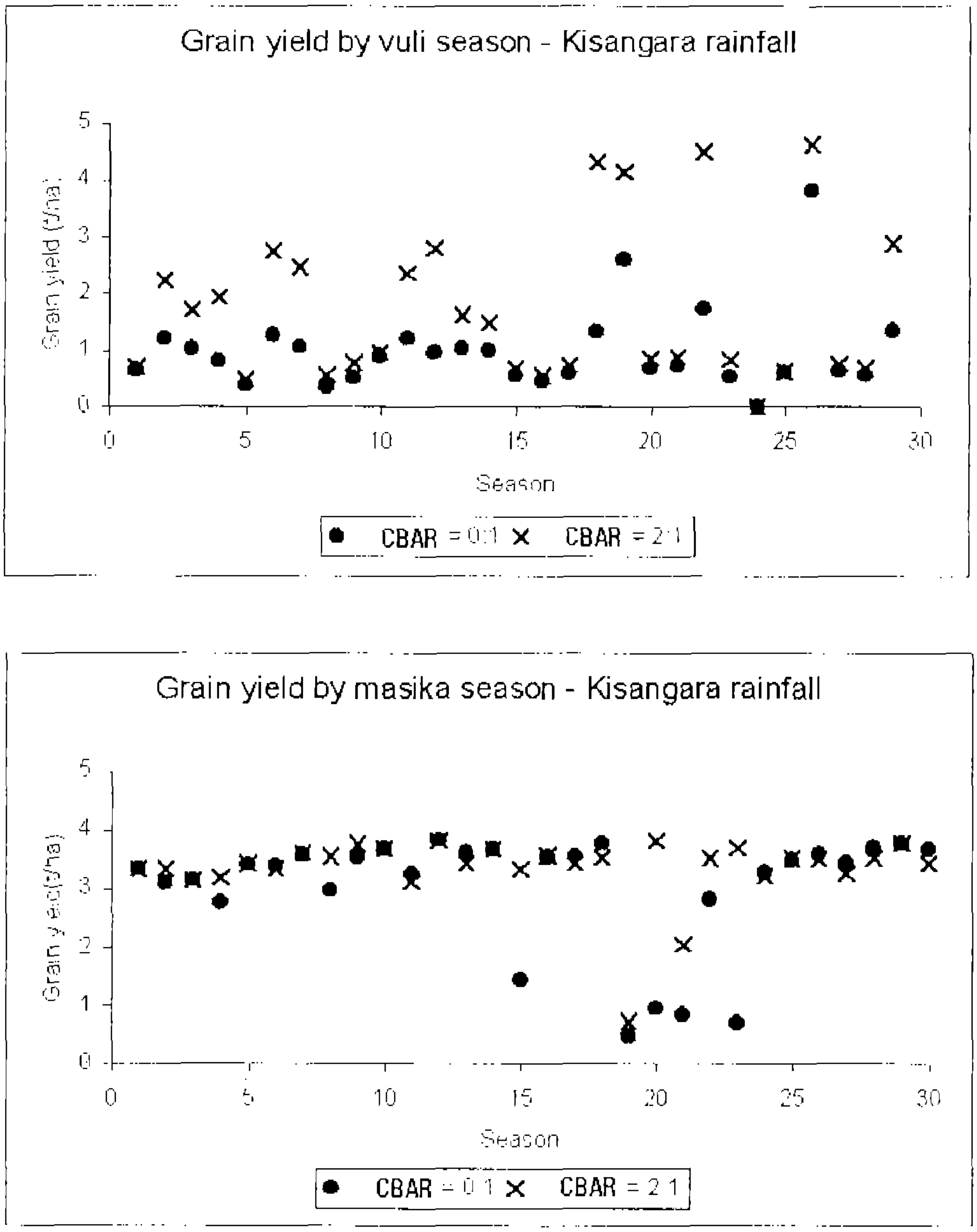


Figure 2: Simulated grain yield by season for 30 years at Kisangara.

of relatively short-term experiments, which may occur during a wet period or a dry period. However, the value of the simulation lies not only in the evaluation of long-term average response, but even more so in the year-to-year variability. It can be seen that there is little improvement in most *Masika* seasons, but a clear response is apparent in approximately half of the *Vuli* seasons. This provides a sound basis for evaluating variability and risk, which may be at least as important as mean response in determining technology adoption, but cannot otherwise be analysed except by very long-term experiments.

A second scenario simulation was conducted to examine the way in which the same RWH system could be expected to perform under conditions of decreased rainfall. This was achieved by repeating the simulation using different data sets, which are representative of Kisangara, Same and a drier site. Average rainfall totals for each case are given in Table 1 together with summarised data on yield increments obtained from comparing the RWH system with a rainfed crop in each case given in Figure 3.

In *Masika* season, the benefit obtained from RWH is minimal under all three scenarios. It can therefore be concluded that the experimental results obtained at Kisangara can be assumed to apply for all sites in the Western Pare lowlands, since the simulation scenarios reflect the full range of conditions to be expected. In *Vuli* season, however, it is apparent that the response varies with rainfall regime. An average yield increment of 24% was obtained under the driest case, but this increased to 43% under the wettest. This indicates that the experimental results obtained for Kisangara cannot reliably be extrapolated to drier sites within the Western Pare lowlands.

Table 1: 30 year mean *Vuli* and *Masika* seasonal rainfall totals (mm) for three rainfall regime

Rainfall regime	Mean seasonal rainfall (mm)	
	Vuli	*Masika*
Kisangara	338	502
Same	238	405
Decreased	215	315

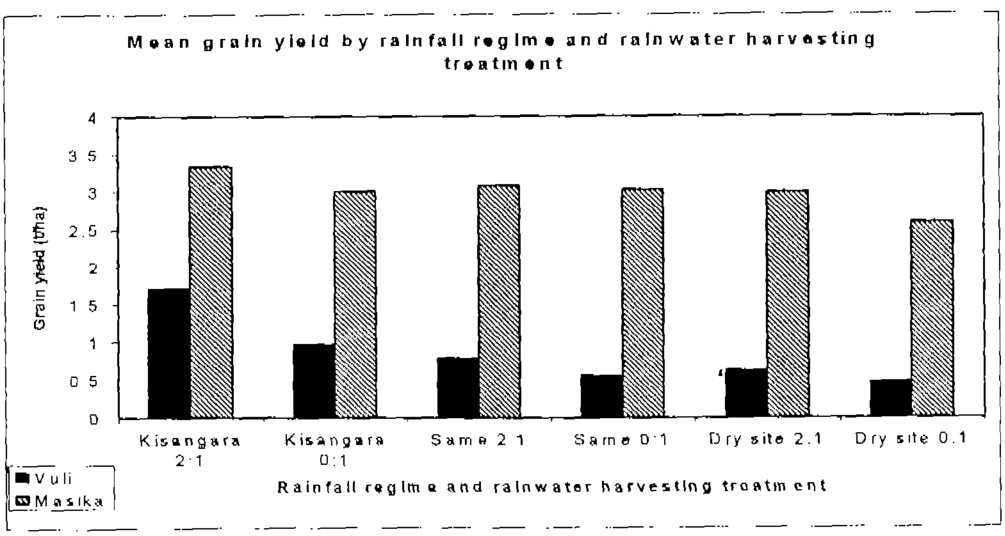


Figure 3: Mean grain yield by rainfall regime and catchment: cropped area ratio.

Macro-catchment systems

Experimental results for maize grown with macro-catchment RWH were obtained for Kifaru site for three seasons (Kajiru *et al.*, 1999). To extrapolate and add value to these results, a scenario simulation was completed using a 20-year simulation period with weather data representative of the site. The simulation was then extended to examine three water-sharing scenarios. The first reflects the actual experimental conditions; in the second scenario the same volume of runoff is spread over a cropped area of twice the size; in the third scenario, the cropped area is three times the size of the first. The actual volume of runoff harvested by the system and number of runoff events varies from season-to-season, but is the same for all three scenarios.

The initial simulation indicates that no improvement over rainfed production was achieved in the *Masika* season. However, in *Vuli* season it can be seen from Figure 4 and Table 2 that a clear response is apparent in approximately half of the seasons simulated. As a result average grain yield was more than doubled and the overall average performance achieved was more than 70% of the *Masika* yield. When the simulation was extended to include consideration of water-sharing, it showed that in most years the incremental yield per hectare compared with rainfed conditions was greatly reduced by spreading runoff over a larger area, but total production was increased. This indicates that simulation studies provide an important aid to optimising the size command area for a macro-catchment syste A second scenario simulation was conducte simulate performance of the majaluba sys for rainfed rice production. Weather data Ngudu in Maswa district for a 20-year pe provided the basis for the simulation. The vestigation included three different ratios catchment to cropped area and two diffe methods of water distribution within cropped area. The cropped area in each was kept at 3 ha, but the catchment areas set as 3 ha, 10 ha and 20 ha. Water distribu alternatives were a serial (cascade) system a parallel (equal division) system as illustr in Figure 5. In each case yield was predic for the top third, middle third and bottom t of the cropped area.

The results indicate that a 3ha catchment is inadequate, but that there is little differe between 10 ha and 20 ha catchment sizes. sults also clearly show that the parallel sys (i.e. equal water division) is much better the middle and bottom plots. Overall perfo ance is increased by 80% over the crop area taken as a whole, but the trade-off is the yield from the top plot is reduced by 3 Clearly, if all three plots down the slope long to a single farmer, the optimal strat must be to spread the water equally. In prac there may be different farmers involved the simulation result may therefore provic basis for discussion and agreement over w sharing.

Table 2: Simulated grain yield (t/ha) of maize under different water managemen strategies at Kifaru.

Rainwater harvesting practice	Mean grain yield (t/ha)	
	Vuli	*Masika*
Rainfed	**0.98**	**3.38**
All water for one field	**2.48**	**3.39**
Shared between 2	**1.74**	**3.40**
Shared between 3	**1.48**	**3.40**

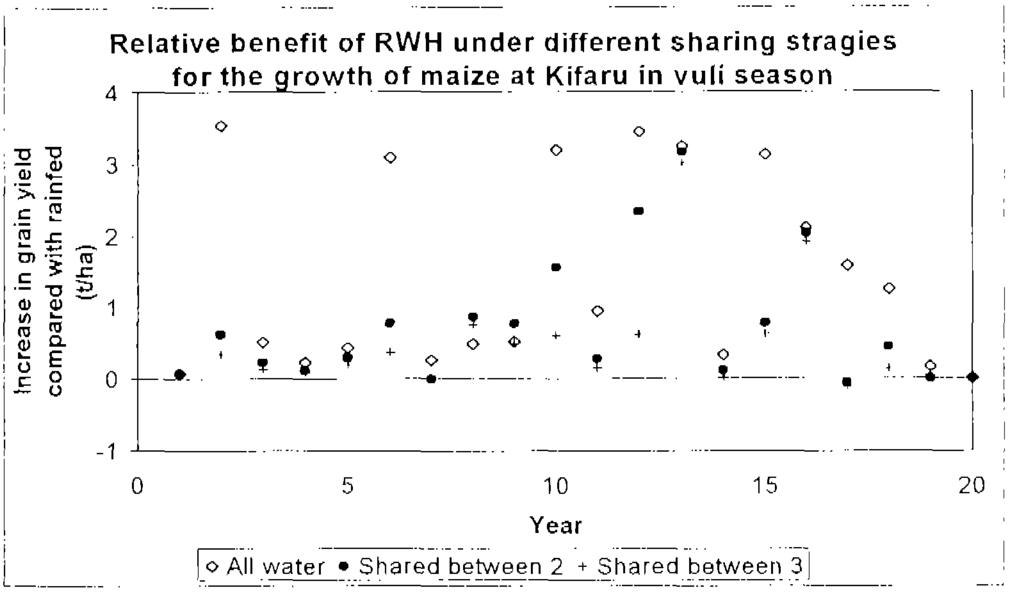
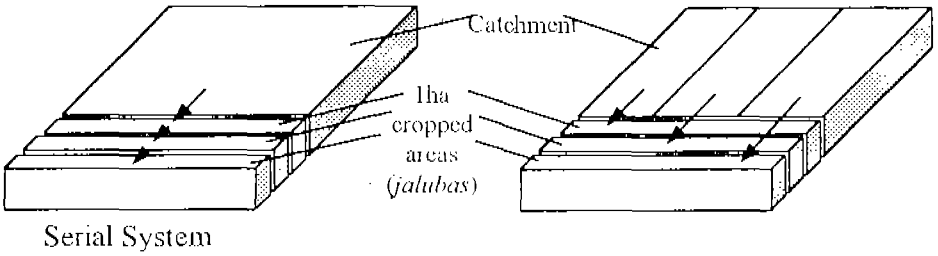


Figure 4: Simulated benefit (t/ha grain yield) of rainwater harvesting with different sharing strategies over rainfed maize production during *Vuli* season at Kifaru.



	Jaluba position	Serial system yield (t/ha)	Parallel system yield (t/ha)
3 ha	Top	0.71	0.84
	Middle	0.20	0.83
	Bottom	0.07	0.83

	Jaluba position	Serial system yield (t/ha)	Parallel system yield (t/ha)
10 ha	Top	1.22	0.85
	Middle	0.80	0.85
	Bottom	0.71	0.85

	Jaluba position	Serial system yield (t/ha)	Parallel system yield (t/ha)
20 ha	Top	1.25	1.01
	Middle	1.33	1.01
	Bottom	0.84	1.01

Figure 5: The two majaluba systems simulated (serial and parallel) with grain yields for different catchment sizes (3, 10 and 20 ha) feeding three 1ha *jalubas*.

Conclusions

Experimental research into soil-water management, whether on a research station or on farmers' fields, is necessarily restricted to specific sites over limited time intervals and meaningful extrapolation is a problem. Recognising the inherent limitations of the experimental approach, the SUA-Newcastle project pursued a twin-track approach. This involved linking the experimental effort to the development of a simulation model designed to permit easy spatial and temporal extrapolation. The model aims to represent the important biophysical processes using parameters that can be measured or estimated to represent crop, soil, site and rainfall. This paper has demonstrated only a few of the scenario simulations that can be conducted using input data that can be obtained relatively easily for any site in semi-arid Tanzania.

The twin-track approach introduced additional requirements into the experimental effort in order to provide all data necessary for validating the model, but it is concluded that this burden was worthwhile because of the added value, which accrued from the work. This can be judged on the basis of two key questions:

- Does it make the research better?
- Does it make the research more efficient?

In both cases the answer is positive, since the twin-track approach provides more complete understanding and more accurate predictions than would be the case for field research alone unless it was continued over a much longer period and replicated on a number of sites.

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