Hydrological impacts of field interventions in smallholder farming systems: a case study of Makanya catchment in semi-arid northern Tanzania

HODSON MAKURIRA[1,2]**, STEFAN UHLENBROOK**[2] **& HUBERT H. G. SAVENIJE**[2,3]

1 *Department of Civil Engineering, University of Zimbabwe. PO Box MP 167, Mt Pleasant, Harare, Zimbabwe*
makurira@eng.uz.ac.zw

2 *UNESCO-IHE, Institute for Water Education, PO Box 3015, 2601 DA Delft, The Netherlands*

3 *Delft University of Technology, PO Box 5048, 2600 GA Delft, The Netherlands*

Abstract The challenge of achieving the Millennium Development Goals (MDGs) on food security is, to a large extent, achievable through balancing water, nutrients and farm management practices. For sub-Saharan Africa, water is believed to be the limiting factor to crop productivity, yet the majority of the population relies entirely on rainfed agriculture. The region has of late been experiencing climate extremes with more dry spells and, a few times, destructive wet spell conditions. This paper presents results from a study being conducted in the semi-arid Makanya catchment, northern Tanzania, where the average rainfall is 400–600 mm year^{-1} and is split over two seasons per annum. Combinations of water harvesting and soil moisture retention techniques were studied at five different sites. A comprehensive on-site measuring network was set up to measure the water partitioning processes. The parameters measured include rainfall, run-on and runoff from measured catchment areas, soil evaporation, and transpiration and soil moisture using geophysical measurement techniques. The results from the research showed significant changes to the water balance mainly through improvement in soil moisture retention; hence more crop productivity resulted from a combination of interventions and not a single technique. Soil moisture increased by between 30% and 50% where interventions such as deep tillage, runoff diversion or infiltration trenches were introduced. The study also showed that the zone of greatest soil moisture retention was at around 40–60 cm depth, which also coincides with maximum rooting depths for maize crops under subsistence farming in the study area. As a result, yields for maize increased by up to 235%, depending on techniques applied and water availability to support crop growth at each site.

Key words on-farm hydrology; rainfed agriculture; water partitioning; water productivity

INTRODUCTION

One critical challenge towards water resources management in the coming generations will be how to secure food demands for a rapidly expanding world population, while, at the same time sustaining other critical ecological functions in regions with highly unreliable and scarce water resources (Bhatt *et al.*, 2006). Sub-Saharan Africa hosts the largest proportion of water-scarcity-prone areas as well as the highest levels of malnutrition (Rockström *et al*., 2003). Water scarcity therefore presents a challenge to the attainment of the Millennium Development Goal on food security and hunger which aims to attain food security by 2015. Water scarcity should not be viewed as just a shortage of water for drinking or basic household requirements; equally challenging, is the lack of sufficient water to produce food for basic human survival (Savenije, 1998). How then is this possible with average rainfall of generally less than 600 mm per season and high potential evaporation rates of more than 1500 mm/year?

While irrigation is perceived to be the solution to bridging the impacts of dry spells during growing seasons, it is also accepted that irrigation schemes have only benefited a small percentage of the population in sub-Saharan Africa and, in most cases, the viability of developed public irrigation schemes have been generally unsatisfactory (World Bank, 2006). While efforts towards improving smallholder agriculture are strategic in achieving food security, there is less momentum in this respect. Samakande *et al*. (2004) note that smallholder farming is generally viewed as economically unviable, particularly in relation to supplementary irrigation. Ngigi *et al*. (2005) argue that the uptake of more efficient techniques is hampered by lack of resources, especially financial, to achieve this at smallholder scales. This is despite the fact that low productivity in the region is attributed more towards sub-optimal management rather than physical potential (Rockström & Falkenmark, 2000).

It is therefore necessary to consider more efficient and affordable field interventions which, if taken up by smallholder farmers, help to guarantee safe yields in areas prone to frequent dry spell occurrences. These interventions include any physical structures which may be introduced within the field to promote infiltration and retention of soil moisture within the root zone. Inevitably, these "improved techniques" result in alterations to the water partitioning process. The water partitioning processes involve the paths taken by water as it becomes available at field scale either after rainfall events or as added runoff. At field scale and from an agricultural point of view, this implies the transformation of water flows so that green water flows are promoted at the expense of unproductive blue and white water processes. This is more important for rainfed farming systems where the majority of sub-Saharan populations derive their livelihood (Rockström, 2003).

The challenge is to understand in more detail the hydrological processes at play due to these interventions especially given that, in general, estimations for the parameters contributing to water partitioning processes are based on empirical equations and not direct on site observations.

The objectives of the study were therefore to determine if there is scope for improved yields through alterations to the hydrological cycle at smallholder field scale. This would be achieved by carrying out detailed in-field water balance measurements at field scale.

MATERIALS AND METHODS

Study area

The research area lies within the Makanya catchment, which is part of the Pangani Basin of northern Tanzania (Fig. 1). The research area receives an average rainfall of

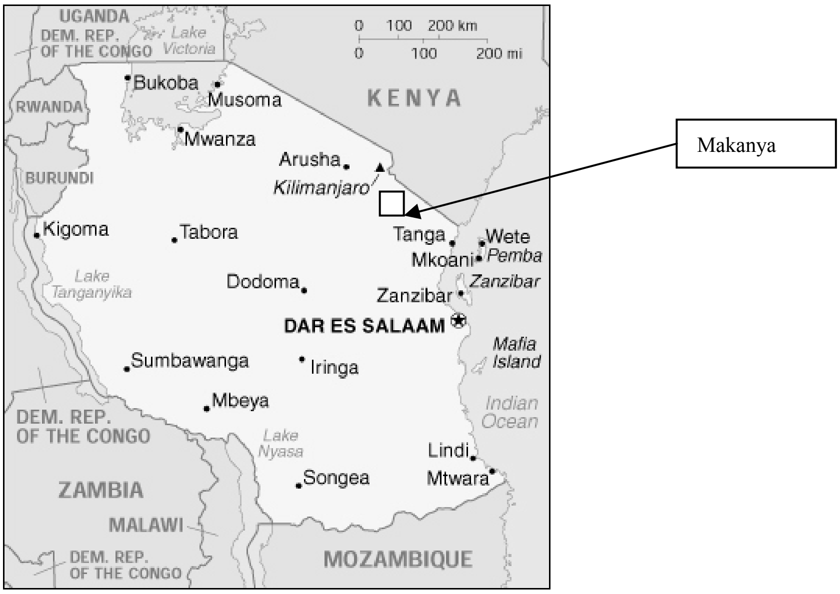

Fig. 1 Location of the research site within Tanzania.

400–600 mm/year over two distinct seasons in a year. This means that this average annual rainfall is shared between two seasons, thus making the challenge of attaining food security through rainfed agriculture even more complex due to insufficient direct rainfall. Maize is the staple food crop and an average maize variety requires between 500 and 800 mm of water per season (depending on climate) (Wahaj *et al.*, 2006). High potential evaporation rates of more than 1500 mm year^{-1} means that more rainfall would be required to satisfy crop water requirements.

Research approach

Participatory field research was conducted at five separate sites (sites A–E) operated by different farmers located within a radius of 10 km. Typical farming plots in the research area do not exceed 2500 m^2. The typical agricultural system is that of hand-hoeing with maize, the staple food crop, being the most common crop. This traditional hand hoe tillage technique was studied against perceived more efficient soil and water conservation tillage techniques such as runoff diversions into infiltration trenches (*fanya juus*), soil bunds and the use of the ripper as a substitute for the traditional hand hoe or plough. The effectiveness of the different soil and water use techniques on water productivity for the maize crop was studied with the standard of measure being crop yield (t/ha) and water productivity (t/ha/mm). For water partitioning analysis, rainfall, runoff, evaporation and soil moisture measurements were conducted at each site. Rainfall was measured using 125 mm diameter raingauges placed at each site. Runoff was measured both at inlet and outlet points (where appropriate) using tipping buckets equipped with data loggers. Daily evaporation was measured using an on-site fabricated lysimeter which operates on the system of counter-weights. Soil moisture was monitored twice weekly at 10 cm depth intervals using a combination of Time Domain Refractory (TDR) and Electrical Resistivity Tomography (ERT) methods.

RESULTS AND DISCUSSION

Rainfall

The cumulative rainfall received at each site was generally less than 400 mm which is less than the 500 mm/season estimated to be the minimum crop water requirement for an average maize variety (Wahaj *et al.*, 2006). The results also highlight the high seasonal variability of rainfall received at the different sites, even though the sites are located within a small radius of 10 km. The seasonal rainfall at each site ranged between 186 mm/season and 407 mm/season.

Runoff

The applied techniques resulted in more runoff being diverted and retained in the study plots. Site B benefited from diversion from its relatively larger runoff generating area and had a gully diversion structure constructed to divert runoff from the gully onto the field plot. Consequently, despite this site receiving the least rainfall (186 mm/season), the contribution from runoff was estimated to be 150% of the actual rainfall received, hence the site experienced the largest water availability. Site D had the least interventions and the resultant incremental water availability was estimated at 0.5%. For the other sites, the incremental water availability as a result of the improved techniques ranged between 10% and 40% of received direct rainfall. Figure 2 shows typical hydrographs from harvested runoff onto field plots. The figure shows that the duration of runoff from rainfall events is short and barely exceeds one hour.

Evaporation

Lysimeter data showed daily soil evaporation averaging 1.7 mm/day.

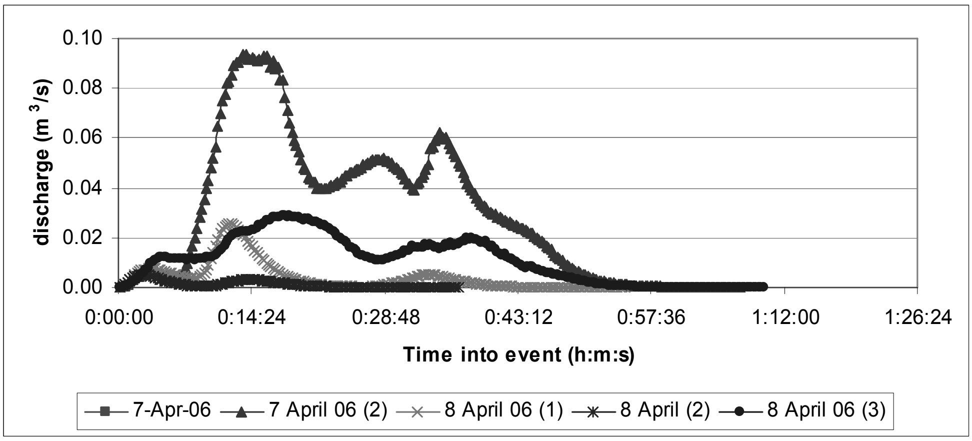

Fig. 2 Typical hydrographs for harvested runoff.

Soil moisture measurements

Continuous soil moisture measurements throughout the season showed that soil moisture increased from about 12% at all sites at the beginning of the season up to about 30% immediately after good rainfall events at some sites where interventions had the biggest impact. However, soil moisture could not exceed 20% at any time during the season at sites with minimum interventions. The study also showed that the zone of greatest soil moisture retention was at 40–60 cm depth, which also coincides with maximum rooting depths for maize crops under subsistence farming in the study area. Figure 3 shows a typical picture from a ERT longitudinal survey on a field where infiltration pits were installed at chainages 10 m, 20 m, 30 m and 41 m. The picture shows areas of less resistivity (suggesting higher moisture content) at the location of these interventions. Comparison with TDR readings yielded similar results with tubes nearer to *fanya-juus* recording higher soil moisture than those further away from the readings.

It is clear that the interventions play a dual role of reducing soil and nutrient loss and, at the same time, promote soil moisture retention at upper horizons for easier uptake by plant roots.

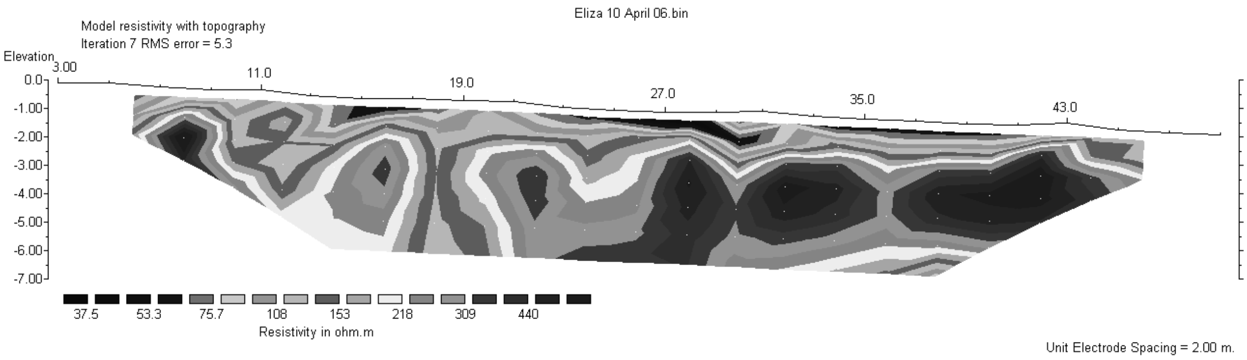

Fig. 3 Resistivity values along section with infiltration pit interventions

Table 1 Yields obtained from different treatments at each site.

Site	Total water received (mm)**	Water productivity (kg mm^{-1} ha^{-1})							
		Treatment number							
		1	2	3	4	5	6	7	8
A	372				8			7	10
B	465	10		10		6	8		3
C	477	7	10			5	6		7
D	416	4	5			4	4		4
E	312	2	3			3	4		2

** sum of rainfall and runoff contribution.

Where: treatment 1, ripping, runoff diversion, infiltration pits; treatment 2, ripping, runoff diversion, infiltration pits, manure; treatment 3, ripping, runoff diversion, infiltration pits, manure, cover crop; treatment 4: ripping, manure; treatment 5, hand hoe, runoff diversion, infiltration pits; treatment 6, hand hoe, runoff diversion, infiltration pits, manure; treatment 7: hand hoe, manure; treatment 8, Control (hand hoe, entirely rainfed).

Crop yield and water productivity

The water productivity from the different treatments is summarized in Table 1.

Maize yields obtained ranged from 0.6 t ha^{-1} to 4.8 t ha^{-1}. This was a remarkable improvement from the average less than 1 t ha^{-1} traditionally obtained even though the rainfall season was perceived to be better.

For rainfed semiarid maize farming systems, yields above 2 t ha^{-1} are considered to be reasonable for rainfed smallholder systems depending on soil type and the prevailing climate.

CONCLUSIONS

The conclusions from this research are that water is the limiting factor to improved yields within the study area. The differences in yield obtained are not so much as a result of farm management practices such as cover cropping or application of manure, but more to do with altering the water partitioning processes towards green water flows.

The rainfall experienced during normal seasons is insufficient to support crop growth. With improved water harvesting and conservation agriculture techniques, there is scope to increase water availability at field scale by as much as 150% and, hence, improve crop yields. The introduction of more efficient soil and water conservation techniques can alter the flow patterns at field scale to divert more water into the root zone where it can be used as productive green water.

The interventions tested in this research proved to be successful as evidenced by increased water productivity at farm scale. Geophysical methods support this finding by showing higher moisture concentrations around the areas where these techniques are located.

If these interesting interventions were to be out-scaled for increased food security at smallholder levels, it could well be possible that the hydrological impact at larger spatial scales could be negative due to less resultant runoff downstream.

Acknowledgements The work reported here was undertaken as part of the Smallholder System Innovations in Integrated Watershed Management (SSI) Programme comprising of the following partner institutions: the International Water Management Institute (IWMI), UNESCO-IHE Institute for Water Education, Stockholm University, University of KwaZulu Natal, and Sokoine University of Agriculture, Tanzania.

REFERENCES

Bhatt, Y., Bossio, D., Enfors, E., Gordon, L., Kongo, V., Kosgei, J. R., Makurira, H., Masuki, K., Mul, M. & Tumbo, S. D. (2006) Smallholder System Innovations in Integrated Watershed Management (SSI): Strategies of water for food and environmental security in drought-prone tropical agro-ecosystems. Colombo, Sri Lanka: International Water Management Institute. IWMI working paper 1009; SSI Working Paper 1.

Ngigi, S. N., Savenije, H. H. G., Thome, J. N., Rockström, J. & Penning de Vries, F. W. T. (2005) Agro-hydrological evaluation of on-farm rainwater storage systems for supplemental irrigation in Laikipia district, Kenya. *Agric. Water Manage.* **73**, 21–41.

Rockström, J., (2003) Water for food and nature in drought-prone tropics: vapour shift in rain-fed agriculture. The Royal Society pp 1997–2009.

Rockström, J. & Falkenmark, M. (2003) Semi-arid crop production from a hydrological perspective: gap between potential and actual yields. *Crit. Rev. Plant Sci*. **19**(4), 319–346.

Rockström, J., Kaumbutho, P., Mwalley, P. & Temesgen, M. (2001) Conservation farming among smallholder farmers in E.Africa: Adapting and adopting innovative land management options. In: *1st World Congress on Conservation Agriculture*, 363–373.

Samakande, I., Senzanje, A. & Manzungu, E. (2004) Sustainable water management in smallholder irrigation schemes: Understanding the impact of field water management on maize productivity on two irrigation schemes in Zimbabwe. *Physics & Chemistry of the Earth* **29**, 1075–1081.

Savenije, H. H. G. (1998) How do we feed a growing world population in a situation of water scarcity? Keynote paper. In: *Water–The Key to Socio-economic Development and Quality of Life* (8th Stockholm Symposium, 10–13 August, SIWI, Stockholm), 49–58.

Wahaj, R. Maraux, F. & Munoz, G. (2006) Actual crop water use in project countries: A synthesis at the regional level. CEEPA Discussion paper No. 38, CEEPA, University of Pretoria, South Africa.

World Bank (2006) Directions in Development. Re-engaging in Agricultural Water Management. Challenges and Options. Washington, DC, USA.