

Macro-catchment rainwater harvesting systems: challenges and opportunities to access runoff

Mzirai O.B¹ and S.D. Tumbo²,

1Institute of Rural Development Planning, P.O.Box 138,Dodoma, Tanzania:

2Department of Agricultural Engineering, Sokoine University of Agriculture, P.O. Box 3003, Morogoro, Tanzania

Corresponding author email: imzirai@yahoo.com

Keywords: Rainwater harvesting system, macro catchments, runoff, risk of flooding, rainfall, simulation models.

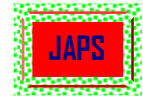
1 SUMMARY

Rainwater harvesting (RWH) is the process of interception and concentration of runoff and its subsequent storage either in soil for direct use by plants or in reservoirs for later application when needed to mitigate dry spells. RWH varies from macro to micro to in-situ systems based on the size of the catchments and runoff transfer distances. Macro RWH systems with or without storage has shown to be more applicable among communities as compared to micro catchments RWH systems. The study aimed at looking on the complexity of biophysical and social economic factors affecting potentiality of the use of runoff harvested from macro catchment. The results of the study identified two broad categories of constraints which are hydro-climatic and management of harvested runoff at the farm level scale. The hydro-climatic challenges are more related to climate while management looks on the transaction cost reflected on the maintenance of the systems, equitable access to runoff and related resources. Results indicated that during the short rain season, the seasonal rainfall amount received does not meet maize water requirements, hence requires supplementary irrigation water to mitigate dry spells. Other biophysical challenge is the change of the runoff conveyance channels due to erosion and deposition. The results showed that fields in close proximity to runoff sources can receive from 70 m³/ha to 300 m³/ha of runoff and the crop yields on these fields that received extra water from external catchments (macro RWH), increased by more than 120% as compared to fields that received rainfall only. The result also showed that the amount received in the field is not the only factor that can contribute to the water use efficiency but also depends on in-field management. The study therefore, recommends that the modeling of macro catchments RWH models should not only deal with hydro-climatic challenges but also looks on the social economic for efficient and equitable distributions of resources runoff from macro-catchment

2 INTRODUCTION

Rainwater harvesting is defined as concentration, collection, storage, and use rainfall via runoff for various purposes such as domestic, livestock and agricultural use (Boers and Ben-Asher, 1982). It is a system which

consists of a catchment area (the surface on which runoff is generated), command area (the area where runoff is utilized), runoff transfer infrastructure (channels, gullies, hard surfaces) diversion method and storage structures.



Water-harvesting (RWH) systems designed for crop production either concentrate water into a storage reservoir or apply water directly to the soil in the cropped area from the catchment area through runoff transfer and diversion infrastructure. Both types of systems can vary in scale from a few square meters benefiting a single household to a few square kilometers serving a larger community. Systems that concentrate water into storage reservoirs can be used for a variety of purposes including: household, irrigation, or livestock consumption. This system is not widely used in resource-constrained farmers, as it is costly to construct the storage structures. However, farmers prefer applying water harvested directly to the cropped field.

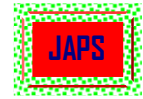
Rainwater harvesting which applies water directly into the field ranges from in-situ techniques such as contour ridging, deep ploughing, terracing, which prevent runoff and promote infiltration where rain falls directly on the crop area. The technique has more benefits in the areas receiving enough high amount of rainfall with good/evenly rainfall distribution throughout the growing season. At the other end of continuum, RWH merges into irrigation, where runoff is tapped from a reliable source (such as seasonal and permanent rivers) and transferred through a network of channels to the cropped fields. However, irrigation is not much applicable in most of semi arid areas these reliable sources of water do not exist.

Recognizing the limitations of techniques at either end of the continuum, there has been growing interest in finding appropriate intermediate RWH techniques. All can be represented as a combination of a runoff producing catchment area and a runoff-receiving crop area (Boers and Ben Asher, 1982; Pacey and Cullis, 1986;). A number of classifications of different types of RWH systems rather than in-situ and irrigation have been attempted (Critchley and Siegert, 1991; Prinz 1995; Barrow, 1999). These includes; micro-catchment RWH systems which comprises a group of techniques for collecting

overland flow (sheet or rill) channeled to a cropped area for supplementing inadequate direct rainfall. Macro-catchment RWH comprises a group or techniques for harvesting runoff from a catchment area (CA) and delivering it to a cropped area (CB). In some areas where large volume of runoff takes a longer time flowing and it is utilized for crop production is referred to as supplementary or spate irrigation. The main distinction micro and macro is the runoff transfer distance and ratio of the catchment to cropped areas.

Several experimental fieldwork have been carried out to test various techniques of micro RWH in different semi-arid areas of the world (Boers and Ben-Asher, 1982, Reij *et al.*, 1988; Rao *et al.*, 1991, Prinz *et al.*, 1994, Oweiss *et al.*, 1999), little has been done in Africa. In Africa, few of the reported work includes Caag system in Somalia (Reij, 1991) soil and water conservation in Mali, Burkina Faso and Niger (Reij *et al.* 1996); in Kenya (Kiome and Stocking, 1993); in Zimbabwe (Thomlov and Hagemann, 1998) and in Tanzania (Rwehumbiza *et al.*, 1999(a), Gowing *et al.*, 1999, Hatibu and Mahoo, 2000). There are only few experiments carried out in macro catchment RWH systems (Gowing *et al.*, 1999; Bakari *et al.*, 1998), and this was typical on-station research which was totally under control of the researchers.

Among macro catchment RWH practices, the most practiced system in Tanzania is that of direct application of diverted runoff to the field (Gowing *et al.*, 1999). Farmers prefer the use of runoff that naturally flows in gullies from external catchments. The use of water from external catchments as spate irrigation is also very common in North Africa (e.g. Tunisia, Egypt and Algeria) and Asia (e.g. Yemen and Pakistan) (Cigizogulu, *et al.*, 2002), where water is abstracted from gullies, small streams and diverted to the crop fields. The biophysical constraints facing adoptability of macro-catchment is the risk associated with the design of the systems, as the timing and amount of runoff is still limited and hence risk of dry spells is not well known. Bahi irrigation scheme



was a good example of the macro catchment based on spate irrigation. However, Bahi irrigation scheme was designed as normal flooding irrigation systems and can not be used as a good example on looking on biophysical and social economic used in designing of macro catchment rainwater harvesting systems.

In macro-catchment RWH systems, runoff volumes and flow rates are high as compared to in-situ or micro catchment RWH systems. This gives rise to problems in managing potentially damaging peak flows, which may lead to serious erosion and/or sediment deposition. Substantial channels and runoff control structures may be required. Macro catchment RWH system is a complex function of the characteristics of rainfall amount received at the catchment areas, land surface between runoff producing to runoff utilization, transfer distance and the soil type (Oweis *et al.*, 1999). Macro catchment RWH connects not only pieces of land but also social economic groups like farmers and agropastoralist, where in each group there exist differences along gender, age and wealth dimension (Msangi *et al.*, 2005). Therefore, community behavior towards runoff poses another challenge in the process. Therefore, making a choice of appropriate techniques in terms of suitable design, a significant amount of information is needed and/or measured directly at the desired sites.

3 METHODOLOGY

3.1 The Study area: Bangalala and Makanya villages within the Chome-Makanya catchment in Pangani basin in Tanzania were selected. Chome-Makanya catchment is located between latitudes 4° 25' South, and longitudes 37° 45' and 37° 54' East (Figure 1). The study area lies along the Moshi-Dar es Salaam highway, about 140km from Moshi town, Tanzania. The study area is located on the leeward side of the Pare Block Mountains, at an elevation ranging between 600m and 2500m above mean sea level (amsl). The main seasonal stream flows from the Mwembe and Chome to the village of Makanya where it is utilized for various agricultural enterprises. The experiments for evaluation of the use of runoff generated from macro-catchment were set in Makanya village.

However, most often, the necessary data and information is not readily available when and where it is needed and the cost associated with establishing the required data and information is enormous. Due to high variability in rainfall, soils and topographical characteristics, data available from one area cannot be used in planning and designing of RWH systems in other areas.

Several studies have been carried out to assess the performance of various RWH systems (Bakari *et al.*, 1998; Rwehumbiza *et al.*, 1999(b); Hatibu *et al.*; 1999, Kajiru *et al.*; 1999; and Rockstorm *et al.*, 2002). All of these concluded that the different RWH have potential to increase the crop yield. Some other economical studies haven been carried out on RWH system and reported the benefits, however, were not related directly to extra runoff from external catchments (e.g. Hatibu *et al.*, 2003). However, none of these studies related the extra amount of runoff to the field to crop yield. Therefore, this study evaluated the performance of Macro-catchment RWH system by evaluating the extra-added runoff into a crop field under farmer management. The study underscores the biophysical and management prerequisite for the macro RWH systems design that the input to the macro catchment RWH agro-hydrological simulation model

The physiographic of Chome-Makanya catchments varies from steep slope on higher altitude to gentle slope with gentle rolling plains to flat plains with depressions in the lowlands. The highlands areas (Chome village) on the gentle slope are the main source of the runoff but are prone to soil erosion and are highly degraded for agriculture. As a result, most farmers have their field located lower lands (Makanya village) slopes. The migration of people to lowlands areas of Makanya increased area under cultivation in 20th century following the construction of Tanga – Moshi highway and establishment of sisal estates.

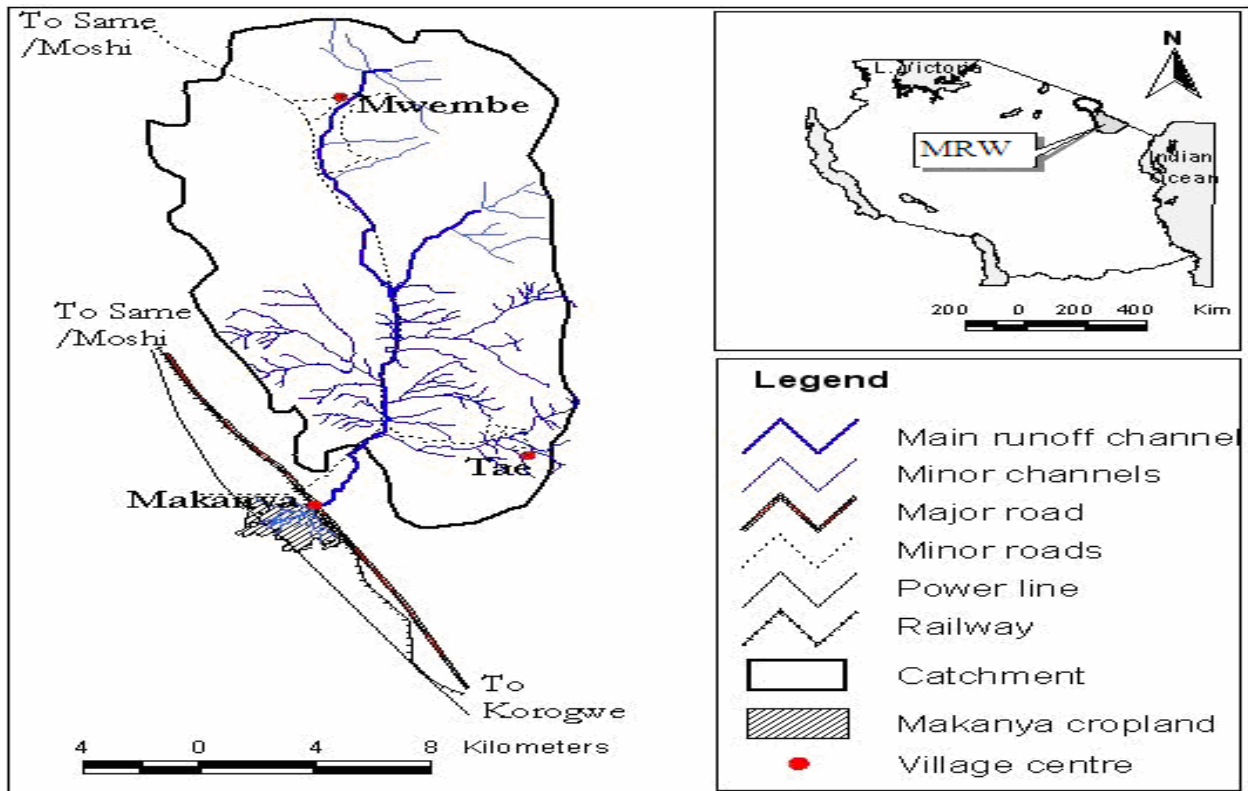


Figure 1: Map of Tanzania showing location of Chome-Makanya catchment (Source SWMRG, 2003)

3.2 Rainfall data: Two meteorological stations exist in the study area. The Hassan Estate meteorological station located at Makanya village and the Gombeleza (Suji) located in Tae village. Rainfall data were collected from both stations for a period of 15 years from 1990 to 2004. The daily rainfall data were analyzed to draw derivatives of daily data including annual total rainfall, long term monthly rainfall, seasonal rainfall amount and occurrence of dry spells. All these parameters are important in determining agro climatic contribution of water management and agricultural planning for macro catchment RWH systems. The analysis was carried out using INSTAT+ software as described by Stern *et al*, (2002) and Stern and Cock (1998). The results of analysis were presented using tables and graphs.

3.3 Vegetation and land uses : The vegetation varies significantly from the Tae village in the mountain where remnants of natural vegetation or forest can still be observed near Shengena Forest Reserve. Makanya village which is on the foot slopes of Pare mountains is dominated by shrub, and some pockets of wooded grassland but do have a relatively large area occupied by small

trees and shrubs most of acacia species. Thickets, scrubland and some wooded grassland, characterize the lowland such as the riparian areas of Pangani River. Makanya village is dominated by agropastoralist land use pattern. Crops commonly grown include maize and legumes and large herds of livestock are kept on free range grazing system. All this depends on the runoff received in the area from the external catchment.

3.4 Runoff management and their effect on access and utilization: Performance of the macro-catchment rainwater harvesting system was carried out to compare the crop yield on different fields located in the cropped area receiving runoff from external catchment. All over the catchment there are intensive RWH practices to support crop growth, as direct rainfall alone cannot supply sufficient moisture. These practices varies from those which capture rainfall directly where it falls to those involving runoff generated far away from where it is to be utilized. The latter technique involves having institutions to distribute runoff, maintain conveyance systems and manage conflicts emanating from struggles to access runoff. These institutions are formed in and only operate within

the area of village jurisdiction. This is a great drawback, as runoff is produced in one village and crosses several others on its way to the ocean. This was carried out in Makanya village valley. In this area the growing season can happen without any drop of rainfall, hence farming depends only on the runoff flowing into this area from external catchment.

Four field plots were used to evaluate the performance of macro-catchment RWH systems. These were located in different parts of the cropped areas on each category of the four crop suitability zones based on its closeness to the water source (Figure 2). One plot was selected in each zone and were classified or named depending on the gully

bringing runoff to the field. The fields are located on different main distribution canals, namely: Suji Kitivo, Salimu Kuku and Wandea. These fields have different field management practices as follows:

- Field I: Located at Suji Kitivo, contained 10 banded plots, deep tilled using hand hoe,
- Field II: Located at Salimu Kuku, was ploughed using hand hoe with no bunds, and
- Field III: Located at Wandea, was deep ploughed using tractors with cut off drain at the end of the field.
- Field IV: Control located in Low zone, receiving only rainfall.

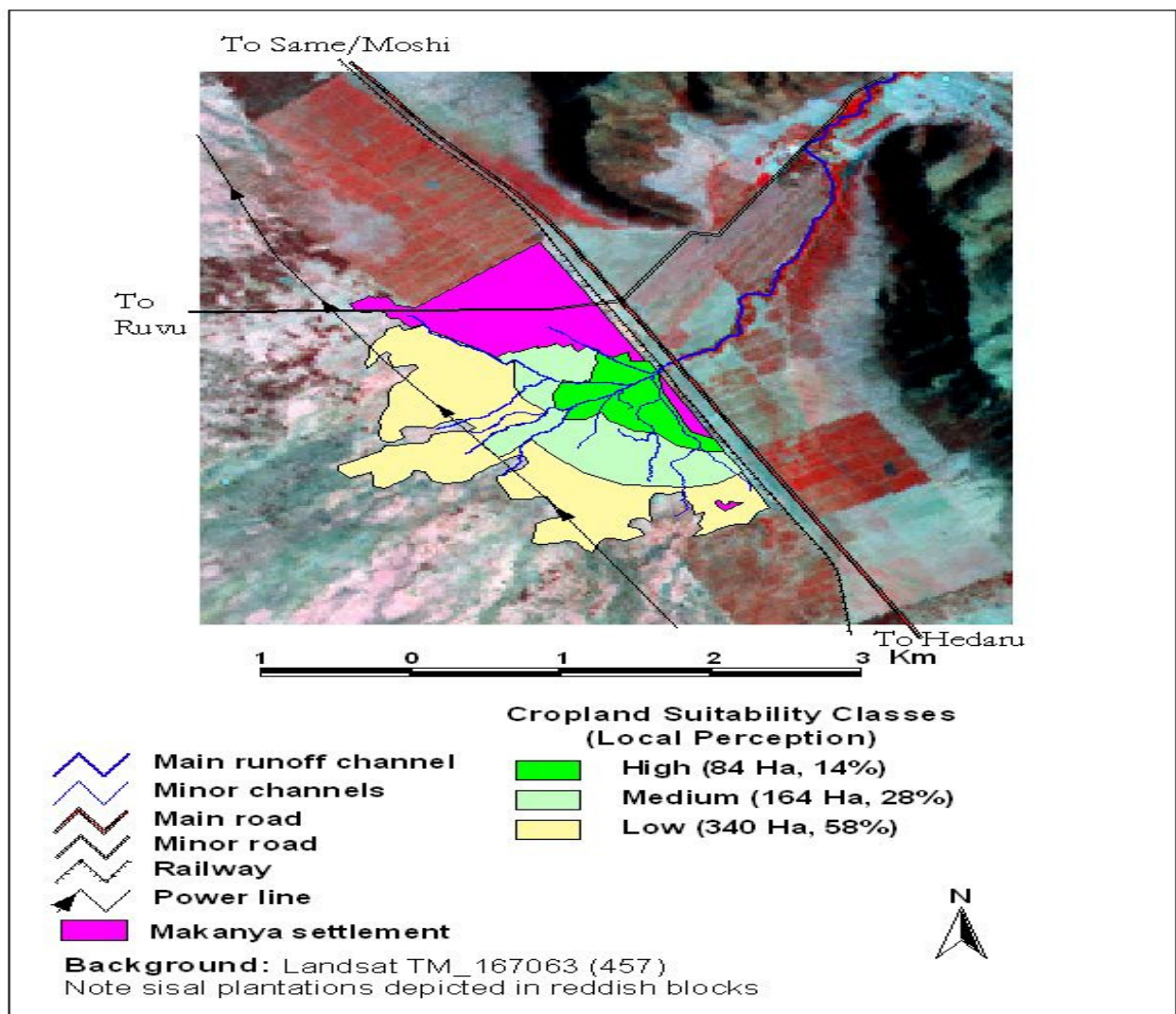
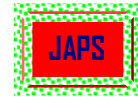


Figure 2: A map of part of Makanya village showing distribution and acreage of cropland suitability classes (source: SWMRG, 2003)



Data collected in this study-included amount of runoff diverted to the crop field, which was measured to each field except field IV, using a triangular weir, and the stage was measured by flood gauge and converted to discharge using an empirical stage – discharge relationship. Timing (start and end) and duration of the each runoff event was recorded. Soil-moisture for each plot was monitored during the entire growing season; maize was the test crop for each field. With exception of the land preparation and sowing dates, other agronomical activities such as planting, thinning,

weeding dates were based on the farmers’ practices. Soil properties measured and monitored included, bulk density, soil physical properties. Crop yield was observed for each plot after harvesting. Data were collected for three seasons Masika 2004, Vuli 2004/05 and Masika 2005. Farmers’ interview was carried out using simple questionnaire on their perception of adequate runoff. Field visits were made to evaluate constraints as raised by farmers on the effects of erosion and human activities on the gully, which in return reduces the command area.

4 RESULTS AND DISCUSSIONS

4.1 Long term rainfall characteristics: The long term analysis was based on two synoptic stations, namely Suji and Makanya sisal Estate. Suji station is located in the highlands, which are the source of runoff while Makanya station is located in the lowlands, and it is the runoff receiving area. Data used for this study were of 1990 to 2004. Figure 3 shows annual rainfall records and 15 years average annual rainfall for both stations. The highlands receive more rainfall than the lowlands. Figure 4 gives the mean monthly rainfall received

and recorded for Makanya and Suji Stations. The results show that Suji station which is located on the highland area received high annual rainfall in 14 out of 15 years as compared to Makanya stations. The 15 years average annual rainfall received was 650mm and 400 mm for Suji and Makanya stations, respectively. Both areas receive rainfall in two seasons. The short rainy season locally called vuli, starts in October and ends in January. The long rainy season, locally called masika starts in March and ends in May.

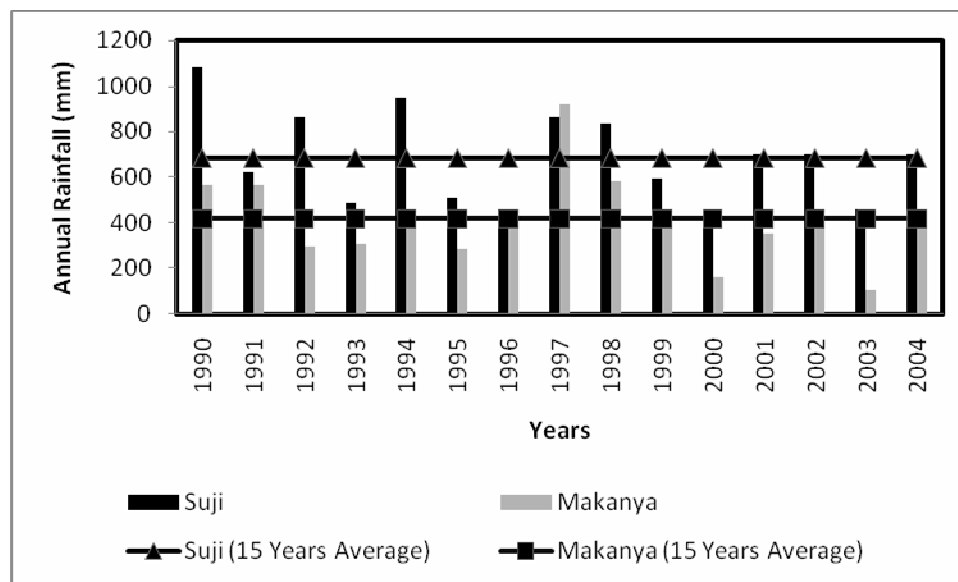


Figure 3: Annual rainfall and 13 years annual average for Makanya and Suji stations

4.2 Long term mean monthly rainfall: In Figure 4 the long term mean monthly rainfall received during the long rainy seasons (*Masika*) at Makanya ranges from 30 to 80mm while in short rainy season (*Vuli*) it ranges from 20 to 70mm. As

from the results of annual total rainfall, the highlands receive higher rainfall than the lowlands. The highest recorded monthly rainfall was 160 mm in December at Suji Station during Vuli season. While in *Masika* season the highly monthly rainfall

was 118 mm recorded on April at Suji station. During *Masika*, this rainfall can support micro-catchment RWH system. Similar results were observed in India with the Khaldin RWH system where a rainfall amount of 75-100 mm was observed to be sufficient to recharge the soils with sufficient soil moisture to raise a successful local crop (Agarwal and Narain, 1977). The amount of rainfall received during *Vuli* is too low to support a micro catchment RWH system. Therefore, for the

case of Makanya, the most viable option is to use macro catchment RWH systems. Farmers were already practicing this option but major improvements are required. However, based on the amount of mean monthly rainfall recorded its not easy for planners to make informed decision for weather RWH is required. Hence seasonal analysis was done for both seasons in Makanya where agricultural production to a large extent is based on RWH.

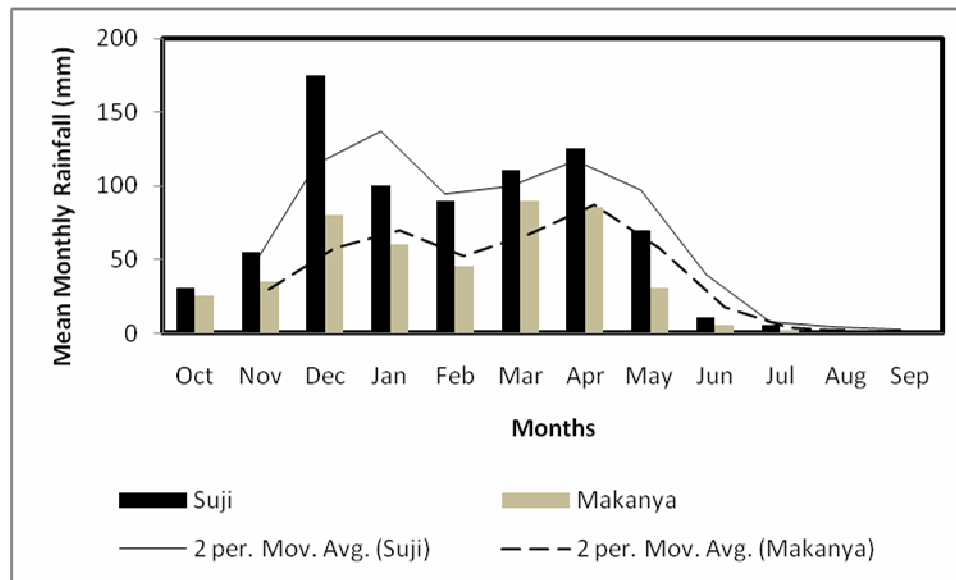


Figure 4: An average of 15 years mean monthly rainfall (mm) for Makanya and Suji stations

4.3 Seasonal Rainfall: Analysis of the seasonal rainfall for both seasons in Makanya station for the duration of 15 years on available records was carried out. The results show that 15 years average seasonal rainfall received was 119 mm and 227 mm during *Masika* and *Vuli*, respectively (Figure 5). In general, these results show that the average seasonal rainfall in both seasons can not support the production of a crop like maize whose crop water requirements is 750mm for the entire season. These results therefore support the fact that for maize production in the lowlands, RWH is necessary. The result shows that for *Masika* season, four (4) out of 15

years received rainfall above 15 years long term average rainfall. However, that was not more than 300 mm, which again is low than crop water requirement for maize. Further, the result indicates that it's only *Vuli* 1997 (one year out of 15 years) where seasonal rainfall was around 700 mm, and this was the year when El nino occurred and floods was observed in Makanya. It is now evident that crop production in Makanya is not possible without RWH. However, analysis is further required to understand the severity of dry spells during growing season.

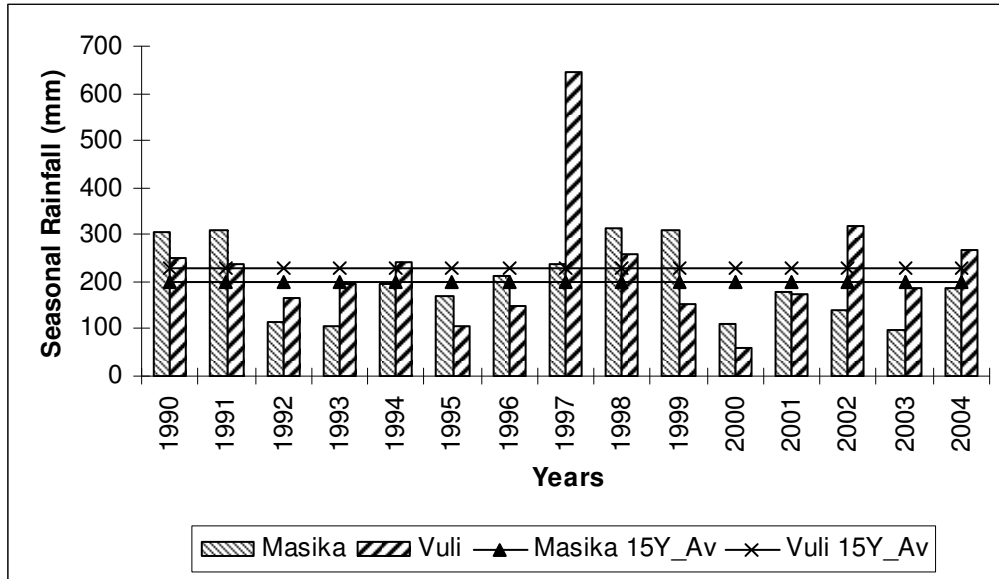


Figure 5: Seasonal rainfall at Makanya as compared to 15 years mean

4.4 Occurrence of dry spells: Crop failure is not necessarily associated with the total amount of rainfall received. In most cases the risk of crop failure is dependent on the distribution of rainfall. Crop failure is therefore related to the periods of occurrence of dry spells. Therefore, another important rainfall parameter is the occurrence of dry spells during the growing season. Figures 6a and 6b, show the probability of occurrence of dry spells

during Masika and *Vuli* seasons respectively. There are high chances of occurrences of dry spells of more than 10 days during the start of *Vuli* seasons with a probability of occurrence of more than 80% as compared to *Masika* season. Therefore, chances of total crop failure are higher during the *Vuli* seasons than in *Masika*. Hence rainwater harvesting is required more during the *Vuli* seasons so as to mitigate effects of dry spells.

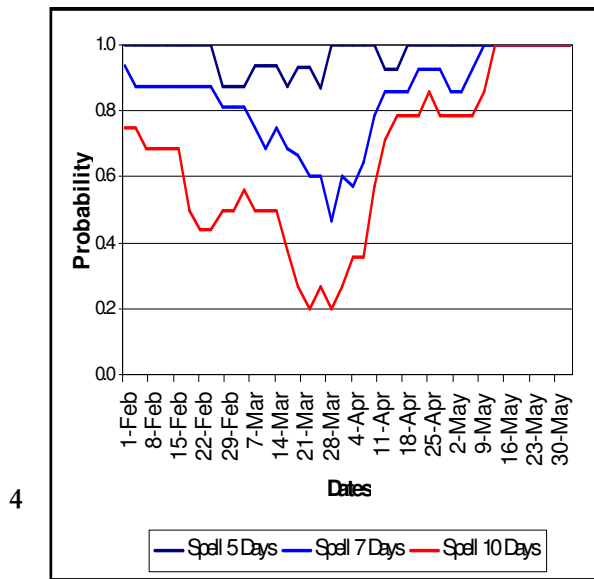


Figure 6a: Probability of occurrence of dry spell - Masika season

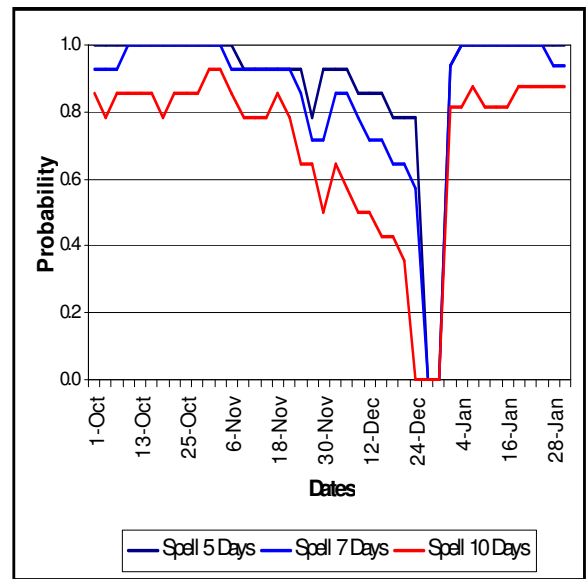
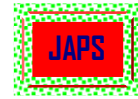


Figure 6b: Probability of occurrence of dry spell - Vuli season



The results of runoff diverted and received on different fields are as shown in Table 1. Generally, the amount of runoff received during *Vuli* season was higher than that received during the *Masika* season. This is due to the fact that most of the runoff received in *Makanya* is generated from the catchment located on the highlands, which receives higher rainfall during the *Vuli* season. The rainfall received during *Vuli* in the highlands in most cases is enough to raise crops in those areas. Therefore, it can be argued that during *Vuli* the abstraction of runoff in the highlands is less hence, more runoff is released for downstream users. Variation of the runoff received in different fields is mainly due to

the position of the field with relation to the source (Gully). The fields, which are located near the main outlet of the catchment normally, receive higher runoff. In the lowlands, some fields do not get runoff even if there is substantial amount of runoff or flood. The major reason is the existing low command where by the water level in the gully is far below the ground level where the crop fields are located. Msangi *et al.*, 2005 observed the similar results where by there is differential access to runoff between farmers of different categories where 67% of those getting enough water was close to the source.

Table 1: Amount of runoff received in different fields (mm) during the shown growing season

	Masika 2004	Vuli 04/05	Masika 2005
Field I	0	0	0
Field II	79	320	136
Field III	209	345	180
Field IV	312	251	127

The higher amount of runoff received on farmers fields are directly related to the harvested maize yield. Table 2 gives the results of maize yield recorded on the different farmers' fields at *Makanya*

during three seasons. These fields are located at different positions along a gully, and one of the fields does not receive runoff from the gully.

Table 2: Maize grain yield from different fields (t/ha)

	Masika 2004	Vuli 04/05	Masika 2005
Field I	0.20	0.50	0.30
Field II	1.50	3.50	1.70
Field III	2.20	5.25	3.00
Field IV	3.80	3.44	2.50

The importance of extra runoff received from the macro catchment RWH can be assessed by the adequacy of runoff received in the fields to produce crop yields higher than those fields, which are not receiving extra runoff. In an attempt to show the importance of extra water added to a cropped field, Rockstorm *et al.*, (2002) used water use efficiency. Table 3 present results of water use efficiency in kg ha⁻¹ mm⁻¹ from extra water received from a macro catchment. However, higher yields were observed during *Masika* 2005 for Field IV, its water use

efficiency was less than that of field III on the same season. This can be associated with using too much water than what is required for crop production, ending up in water losses. This may also be due to having fewer dry spells during the critical stages of crop growth as shown in Figure 6b during *Masika* season. Similar results were observed by Barron *et al.*, (2003) in the semi arid areas of Machakos in Kenya, where water productivity improvement was only achieved during rainy season with higher dry spells.

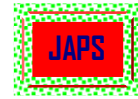


Table 3: Water Use efficiency different fields (kg ha⁻¹ mm⁻¹) during the shown growing

	Masika 2004	Vuli 04/05	Masika 2005
Field I	1.1	1.9	1.5
Field II	16.5	9.4	10.3
Field III	9.6	13.8	15.0
Field IV	11.5	11.7	17.3

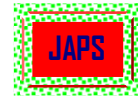
5 CONCLUSION

The study has shown that crop production in semi-arid areas can be increased by using appropriate water management techniques, this is supporting many other studies in relation to the performance of various rainwater harvesting systems. What is peculiar with this study as compared to others is the association of the runoff amount diverted from the gully under the farmers' management into the water use efficiency. With macro-catchment RWH systems, water use efficiency can be increased up to

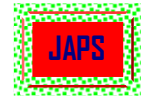
more than 20 kg ha⁻¹ mm⁻¹ compared to rain-fed system where water use efficiency can hardly reach 3 kg ha⁻¹ mm⁻¹. Though some challenges has been observed in macro-catchment rainwater harvesting system, its has also proved that by receiving more than 70 mm of extra runoff, farmers can manage the water and invest on higher value crop. This is one way of reducing poverty not by being involved in self-sufficiency at household level but rather on the market for food security.

6 REFERENCES

- Agarwal and S. Narain, 1997. Dying Wisdom. Centre for Science and Environment. , Thomson press Ltd, Faridabad . 215pp
- Bakari, A.H., Mahoo. H.F., and Hatibu, N. 1998. Perormance of maize under gully flow supplementary irrigation. In a proceedings of Tanzania Society of Agricultural Engineers (Edited by Makungu, P.J., Mahoo, H.F., Silayo, V.C.K and Mdemu,, M). Vol.8: 20 -42
- Barron, J., Rockstrom, J., Gichuki, F., Hatibu, N. 2003.. Dry spell analysis and maize yield for two semi-arid locations in East Africa. *Agricultural and Forestry Meteorology* 117: 23 - 37
- Barrow, C.J. 1999. Alternative Irrigation: the promise of runoff agriculture. Earthscan Publications, London.
- Boers, T.M. & Ben-Asher, J. 1982. A review of rainwater harvesting. *Agric. Water Management* 5: 145-158.
- Cigizogulu, H.K. Adamson, P.T and Metcalfe, A.V. 2002. Bivariate stochastic modeling of ephemeral streamflow. *Hydrol. Process* 16: 1452 – 1465.
- Critchley, W. & Siegert, K. 1991. Water harvesting: a manual for the design and construction of water harvesting schemes for plant production. Report ACL/MISC/17/91, FAO, Rome.
- Gowing, J. 2002. Food security for West Africa: does water scarcity limit the options? Paper to be presented in WASAE International Water Conference on Food Security and Poverty Alleviation ink West Africa, October 29 – 31, 2002.
- Gowing, J.W and G.C.L Wyseure 2000. Agrohydrological Modeling: A Tool for Sustainable Development of Land Resources Pg 132-144
- Gowing, J.W, Mahoo, H.F, Mzirai O.B and Hatibu N. 1999. Review of water harvesting techniques and evidence for their use in semi-arid Tanzania. *Tanzania Journal of Agricultural Science* 2(2): 171-180
- Hatibu, N and Mahoo, H.F. (eds), 2000. Rainwater harvesting for Natural Resources Management. A planning Guide for Tanzania, RELMA/Sida, ICRAF House, Gigiri, Kenya 14400
- Hatibu, N, M.D.B. Young, H. Mahoo, J.W. Gowing, O.B. Mzirai 2003. Developing improved dryland cropping systems in semi-arid Tanzania: Part 1: Experimental Evidence for the Benefits of Rainwater Harvesting. *Experimental Agriculture*, 39:279-292
- Hatibu, N. Gowing J.W, Mzirai O.B and Mahoo, H.F 1999. Perfomance of maize under micro catchment rainwater harvesting in



- Western Pare Lowlands. *Tanzania Journal of Agricultural Science* 2(2): 193-205
- Hatibu, N., Mahoo, H.F, Lazaro E. Rwehumbiza, F.B. Okubal, P., and M.Makumbi 2000. The contribution of soil and water conservation to sustainable livelihoods in semi-arid areas of sub-Saharan Africa (In Boyd, C and C.Turton (eds) AgREN Network paper No. 102, 16p.
- Kiome, R. and Stocking, M. 1993 Soil and Water Conservation in Semi-Arid Kenya, Bulletin 61 Natural Resources Institute, Chatham.
- Msangi A.S.K., E.M.M. Senkondo, K.D. Mutabazi, E.Lazaro and N. Hatibu 2005.Transaction costs of Rainwater Harvesting Systems Management and their Effects on Access to Runoff. Proceedings of the Eastern Africa Integrated River Basin Management Conference, 7th – 9th March, 2005. Sokoine University of Agriculture, Morogoro, Tanzania. Edited by B. A. Lankford and H.F. Mahoo.pp 409 - 419
- Mzirai, O.B.M, Gowing J.W, Hatibu N, Rwehumbiza, F.B and Young, M.D.B 2001. Investigating the feasibility of rainwater harvesting (RWH) under semi-arid conditions: benefits of computer simulation in adding value to field experiments. Poster presentation at the 10th International Conference on Rainwater Catchment System, Mannheim Germany, 10 – 14 September 2001.
- Oweiss, T, Hachum, A, and Kijne, J 1999. Water harvesting and supplementary irrigation of improved water use efficiency in dry areas. SWIM paper 7. International Water Management Institute, Colombo, Sri Lanka.
- Oweiss, T.Y. and Taimeh, 1996. Evaluation of small basin water harvesting system in the arid region of Jordan. *Water Resources Management* 10 (1): 21-34.
- Pacey, A and Cullis, A 1986. Rainwater harvesting: the collection of rainfall and runoff in rural areas. Report LR 14, Natural Resources Institute, Chatham.
- Pacey, A. and Cullis, A. 1986. Rainwater Harvesting: the collection of rainfall and runoff in rural areas. Intermediate Technology Publications, London.
- Pathak, P., Larya, K.B and Sudi, R 1989. Runoff management for watersheds in the semi-arid tropics. *Transactions of ASAE*.32:1619 – 1624
- Prinz, D. 1995.Water harvesting techniques in the Mediterranean region. In: Rainwater harvesting and management of small reservoirs in arid and semi-arid areas. (Edited by Berndtson, R.). Lund University, Sweden. 32 – 45pp
- Prinz, D. 1998. Water harvesting techniques in the Mediterranean region. In : Berndtson, R. (Ed) Rainwater harvesting and management of small reservoirs in arid and semi-arid areas. Proceedings of an expert seminar, Lund University, Sweden.
- Prinz, D and Singh, A. 2003. Technological Potential for Improvements of Water-Harvesting. Prepared for Thematic Review IV.2: Assessment of Irrigation Options. *World Commission of Dams*. As download from <http://www.damsreport.org/docs/kbase/c ontgrib/opt158.pdf on 29.04.2004>
- Prinz, D., Tauer, W. and Vögtle, T. 1994. Application of remote sensing and geographic information systems for determining potential sites for water harvesting. In: Water harvesting for improved agricultural production. Proceedings of FAO Experts Consultation. Cairo, Egypt, Nov 1993, FAO, Rome. P 135 - 144
- Rao, K.P.C., Cogle, A.L. and Srivastava, K.L. 1991. Conservation effects of porous and vegetative barriers. Resource Management Program, International Crops Research Institute for Semi-Arid Tropics (ICRISAT), Annual Report 1991. Pantacheru, Andhra Pradesh, India.
- Reij, C. 1991. Indigenous soil and water conservation in Africa IIED, GATEKEEPER Series No. 27. 35pp
- Reij, C.; Scoones, I. and. Toulmin, C 1996. Sustaining the soil : indigenous soil and water conservation in Africa. Earthscan Publications, London.
- Reij. C., Mulder, P and.Begermann L. 1988. Water harvesting for plant production. World Bank Technical paper No. 91, World Bank, Washington D.C, 123pp
- Rockstrom J., 1997. On farm agro hydrological analysis of the Sahelian yield crisis:rainfall portioning, soil nutrient and water use



- efficiency of pear millet. Natural Resources Management, Department of System Ecology, Stockholm University, Sweden.
- Rockstrom, J. 2000. Water resources management in smallholder farmers in Eastern and Southern Africa. *Phys. Chem. Earth*(B). 25(3):275-283
- Rockstrom, J. Barron J., and Fox P. 2002. Rainwater management for increased productivity among smallholder farmers in drought prone environments, *Phys. Chem. Earth* 27:949 –959.
- Rockström, J., Jansson, P.E. and Barron, J. 1998, Seasonal rainfall partitioning under runoff and runoff conditions on sandy soil in Niger. On-farm measurements and water balance modelling. *J. Hydrol.* 210: 68–92.
- Rwehumbiza F.B., Hatibu ,N., and Kishebuka, S.R. 1999a. Performance of contour barriers for conservation of soil and water. *Tanzania Journal of Agric. Sci.* Vol. 2(2): 179 - 189
- Rwehumbiza, F.B.R., Hatibu, N. and Machibya, M.1999 b. Land characteristics, run-off and erosion in semi-arid area of Tanzania .*Tanzania Journal of Agric. Sci.*, Vol. 2(2): 141 - 149.
- Soil Conservation Service 1972. National Engineering Handbook USDA_SCS. US Government Printing Office, Washington DC.
- Stern, R and Knock, J. 1998. INSTAT Climatic Guide. Statistical Service Centre, University of Reading, UK, 285 pp.
- Stern, R. Knock, J., Rijks D. and Dale, I. 2002. Instat + Climatic Guide. University of Readings, UK.
- Tauer, W and G.Humborg 1992. Runoff harvesting in the Sahel zone. CTA, Wagenigen, The Netherlands
- Twomlow, S. and Hagmann, J. 1998. A Bibliography of References on Soil and Water Management for Semi Arid Zimbabwe, Report IDG/98/19. Silsoe Research Institute, UK.
- Wallace, J.S 2000. Increasing agricultural water use efficiency to meet future food production. *Agriculture, Ecosystems and Environment.* 82:105-119
- World Water Council 2000. World Water Vision: making water everybody's business. London, Earthscan Publications.
- Young M.D.B, Gowing,J.W, Wyseure, G.C.L., and Hatibu, N. 2002. Parched Thirst: Development and validation of a process-based model of rainwater harvesting. *Agricultural Water Management*, 55: 121-140