Methodologies and case studies for investigating upstream-downstream interactions of rainwater water harvesting in the Limpopo Basin

Bongani Ncube[1✉], *Manuel Magombeyi*[2], *Paiva Munguambe*[3],

Walter Mupangwa[4], *David Love*[1,4]

[1]WaterNet, PO Box MP 600, Mt Pleasant, Harare, Zimbabwe
[2]School of Civil and Environmental Engineering Witwatersrand University, RSA
[3] Faculty of Agronomy and Forest Engineering-University Eduardo Mondlane, Maputo, Mozambique
[4]ICRISAT- Matopos Research Station Bulawayo, Zimbabwe
✉Corresponding author: bncube@waternetonline.org, bongisto@yahoo.com

Abstract

Rainwater harvesting (RWH) is a promising technology for increasing water availability for crop production of smallholder farmers in the semi-arid regions of the Limpopo Basin. A few studies on rainwater harvesting have been conducted in the basin at small plot and farmer field scales. Results from Mozambique, Zimbabwe and South Africa indicate substantial benefits to crops grown using a range of rainwater harvesting techniques. However, there have been no catchment and basin level studies to investigate the impacts of wide scale adoption at these levels. A methodology flow chart is proposed for systematically investigating the impacts of out-scaling of these in-field and ex-field rainwater harvesting techniques. The method proposes an analysis of levels of adoption to help identify optimum levels that will maximize land and water productivity while minimizing negative hydrological and ecological impacts at catchment or basin scales.

Key words

hydrological model, methodology flow chart, smallholder farmers, technology, out-scaling

Background and Introduction

Introduction

The Limpopo Basin is one of the benchmark sites of the Consultative Group of International Agricultural Research (CGIAR) Challenge Program on Water and Food Crop (CPWF). The basin has low annual rainfall (530 mm) and it covers most semi-arid regions of Southern Africa (Harrington *et al.* 2004). Crop production is one of the major activities in the basin, but farmers face many challenges, especially smallholder farmers. The low rainfall and frequent droughts that are experienced during the growing season make rain-fed farming a risky business (Butterworth *et al.* 1999; Twomlow and Bruneau 2000; Unganai and Mason 2002). There is competition for water among countries and communities within the region (Basson and Rossouw 2003; Mazvimavi 2004; Mugabe *et al.* 2007; Nyabeze 2004; Vörösmarty *et al.* 2000). The CPWF program in the Limpopo Basin is therefore addressing issues of improving the productivity of rainfed cropping systems by introducing drought resistant varieties, suitable crop and soil management practices, appropriate water policies and governance, and adopting a basin approach to water management (Harrington *et al.* 2004). Smallholder rainfed farming remains the dominant economic activity for a large part of the southern African population. Given the constraints on availability of blue water for full-scale irrigation, which are likely to remain the case for the medium term future, the improvement of smallholder rainfed farming must be a priority (Love *et al.* 2006). Green water use efficiency (that proportion of rainwater that is converted to transpiration) is very low in sub-Saharan Africa (15 %, Stroosnijder 2008). The need for technologies that increase the efficiency of use of the limited water in both crop production and domestic use is therefore very clear (Ngigi 2003). Rainwater harvesting (RWH) is one of these technologies.

Rainwater harvesting is broadly defined as the collection and concentration of runoff for productive purposes (crop, fodder, pasture or tree production, livestock and domestic water supply etc.) (Ngigi 2003) or the process of concentrating rainfall as runoff for use in a smaller target area (Botha *et al.* 2003). The rainfall harvested can either be in-field (tillage techniques, pits etc.) or off-field (micro-catchment or runoff farming and supplementary irrigation). The advantages of RWH include increases in infiltration and groundwater recharge, and the potential to harvest water from small rainfall events that do not always produce increased stored water for irrigation (Li 2008). Field scale studies in the Limpopo basin have so far looked at some of the RWH technologies (Woltering 2005; Magombeyi and Taigbenu 2008, Mupangwa *et al.* 2007 and 2008; Mwenge-Kahinda *et al.* 2007), but the impacts of up-scaling the techniques are not known and are not easy to quantify.

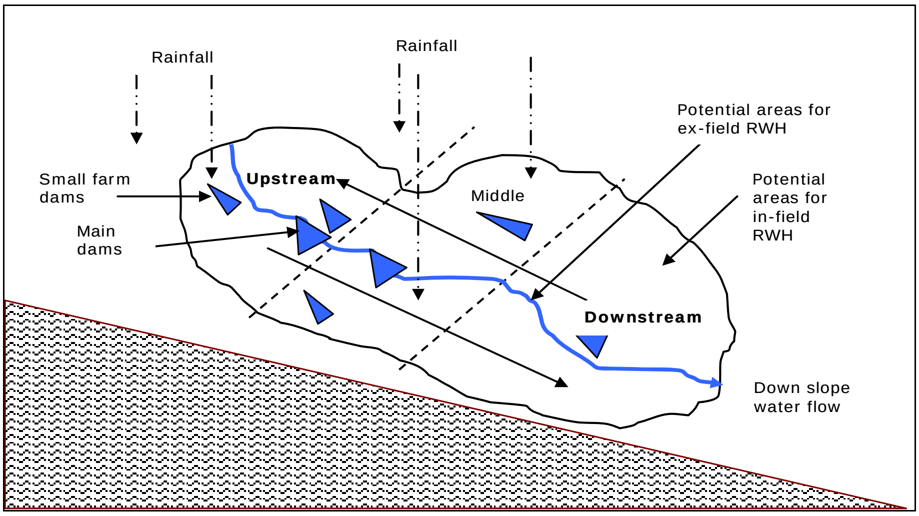
Rainwater harvesting may have a substantial downstream impact if it results in: (i) diverting significant amounts of rainwater or soil moisture from recharge, overland flow or stream runoff into transpiration, (ii) diverting rainwater from one micro-catchment to another micro-catchment, or (iii) both. Where RWH diverts incoming rainwater that would otherwise have been lost through interception or soil evaporation it does not exert a demand on the terrestrial water balance and can be said to have minimal downstream impact.

Water regulations governing the management of upstream-downstream impacts

Water tends to build asymmetrical relationships between people and communities within river basins because of water flow down slope (Figure 1). The activities of upstream users impact on the downstream users but not vice versa. To equitably share blue and green water resources in a catchment implies that upstream users have to forego some potential water benefits (van der Zaag 2007). Under the international water laws (Thompson 2006) that deal with equitable and reasonable allocation of water in trans-boundary river basins (in this study the Limpopo River Basin), upstream states support rules that give them control of the waters that originate in their territory, in line with the absolute territorial sovereignty doctrine, while downstream states/communities on the other hand appeal to the doctrines of prior appropriation and absolute territorial sovereignty that would provide them with unaltered flow quantity of the waters that enter their states/ catchments.

Helsinki Rules would consider the water that falls on the drainage basin and used before flowing into a common river as beneficial water use (e.g., rainfed agriculture, in-field RWH, natural forest and groundwater use) for the state/user having benefit of the water, whereas the UN Convention (United Nations 1997) would not consider any water use from outside the watercourse as part of the water to be equitably used (Thompson 2006). In the future the water to be shared in Southern Africa will change from actual water flowing in the river (SADC Revised Protocol on Shared Watercourses Systems), as required by UN Convention, to rainfall over the basin (Thompson 2006). Under such circumstances the impacts of in-field RWH would need to be assessed to avoid tensions and conflicts between upstream and downstream users at local or basin level.

Figure 1. Upstream-downstream catchment relationship with water flux (partly adapted from van der Zaag 2007)



Different RWH techniques influence hydrological processes at different spatial scales in a non-linear mode. Processes governing rainfall and runoff partitioning operate at a variety of scales (Blöschl and Sivapalan 1995). At the micro-catchment and field scales (approximately 10^{-3} to 10^{1} km^2), factors such as infiltration (which is spatially variable) and the length of the slope (distance of overland flow before entry of runoff into a stream) control the proportion of site runoff that is discharged from that scale as runoff and the proportion that is redistributed to become soil moisture (van de Giesen *et al.* 2000). At the meso-catchment scale (approximately 10^{1} to 10^{3} km^2), processes after runoff generation operate upon streams, for example the transfer of water between streams and groundwater or redistribution and re-infiltration in wetlands. This has been shown to sometimes lead to the estimation of (apparently) less conversion of rainfall into runoff at larger scales. Flow monitoring in a semi-arid area at different spatial scales showed that the runoff coefficient varied from 46 % at field scale to 12 % at basin scale in Kenya (Ngigi *et al.* 2005) and from 6.3 % for a 41 km^2 catchment to 0.7 % for a 1,386 km^2 catchment in Zimbabwe (Love *et al.* 2007). Due to this scale dependent complexity, the estimation of (apparent) diversion of rainwater from runoff generation to transpiration can be affected by the scale at which water balance measurements are made. These complex scale relationships and the potential for changes to downstream stream and groundwater flow make it important to assess the hydrological and socio-economic impacts (positive and negative) of out-scaling of RWH.

Despite the anticipated socio-economic impacts related to farm decision-making and farmer actions, out-scaling of RWH techniques, beyond a certain limit, may lead to hydrological and environmental impacts (Ngigi *et al.* 2005; Woyessa *et al.* 2006). Therefore, it is important to know the impacts of in-field and ex-field RWH techniques at catchment and basin scales. Furthermore, an understanding of the optimum level of adoption at catchment or basin scale that maximizes land and water productivity while minimizing negative hydrological and ecological impacts is important for sustainability of RWH technologies. This paper seeks to present small plot and farmer field scale case studies of RWH technologies conducted in the

Limpopo River Basin, and to propose an approach for systematically investigating the impacts of out-scaling such technologies to catchment and basin levels.

Rainwater harvesting case studies within the Limpopo Basin

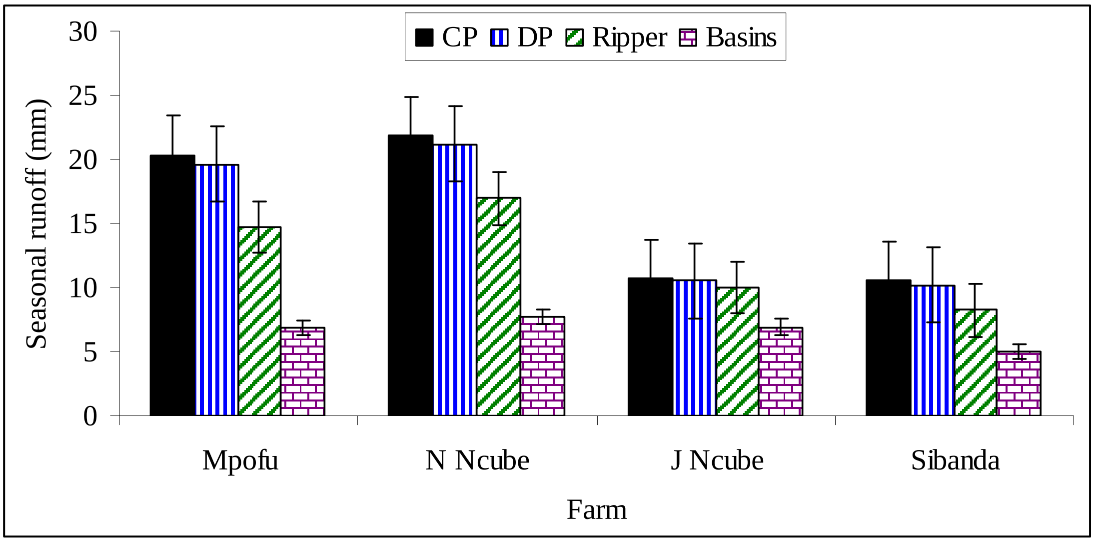
In-field RWH field experiments were conducted at several locations in Zimbabwe, Mozambique and South Africa. All experiments included treatments with 'Planting Basins'. Planting basins systems, with a variety of basin size and spacing, are practised in various part of Africa under a variety of names such as the Z*ai* system in Mozambique, Mali and Burkina Faso, the Chololo system in Tanzania (Mati 2005), the *Trus* system in Sudan, and the *Tassa* system in Niger. Crops are planted in the basins, often with small amounts of organic and/or inorganic fertilizers. The objectives of the basins are to reduce runoff and increase infiltration through breaking the surface crust and creation of a depression/pit/hole, and to increase soil fertility through reduction in erosion. Modelling studies were also conducted to evaluate RWH options. Some of the rainwater management techniques increase demand for labour, and their suitability for adoption will depend on economic viability and other factors such as acceptability to farmers. Another relevant issue is the required land versus land availability for these practices, as well as the need to coexist with other farming techniques such as inter cropping.

In-field rainwater management techniques: Mzingwane Catchment, Zimbabwe

The effect of planting basins and ripping on surface runoff and soil water storage in cropped fields was assessed over two cropping seasons in the semi-arid Mzingwane Catchment in Zimbabwe (Mupangwa 2009). The planting basins were dug using a hand hoe and each basin measured 0.15 m (length) × 0.15 m (width) × 0.15 m (depth). The basins were dug at 0.9 m × 0.6 m spacing. The rip lines were created at 0.9 m inter-row spacing using a commercially available ripper tine (ZimPlow) attached to the beam of a donkey-drawn mouldboard plough. The planting basins gave the lowest seasonal runoff losses regardless of soil type and field slope (Figure 2). Despite the below average rainfall of 328-353 mm during the period of experimentation (2006/07 and 2007/08 seasons), planting basins consistently gave the highest soil water content particularly during the first half of the cropping period. Despite the higher soil water content and lower surface runoff in the planting basin system, there were no significant ($P > 0.05$) maize yield differences between the four tillage systems regardless of the different rainfall distribution each season.

The results from the two year study indicate that planting basins have the potential to: i) promote infiltration of rainwater, ii) minimize soil, water and nutrient losses from the field, iii) reduce siltation and pollution (by agrochemicals) downstream of the fields, and iv) increase groundwater recharge as soil water is lost through deep drainage especially on sandy soils. However, during high rainfall seasons water logging (the severity depending on the soil type) can occur and affect yield. High surface runoff from each tillage system is likely during seasons with above-normal rainfall on the predominantly sandy soils of Gwanda and Insiza districts.

Figure 2. Seasonal runoff measured under each tillage treatment at Mpofu, N Ncube, J Ncube and Sibanda farms in Insiza and Gwanda Districts (adapted from Mupangwa, 2009). Data are means of 11 rainfall events that generated measurable runoff from each tillage treatment during the 2007/08 cropping period. Vertical bars indicate standard error of means. CP = conventional practice; DP = double ploughing.



Rainwater harvesting in Chokwe, Mozambique

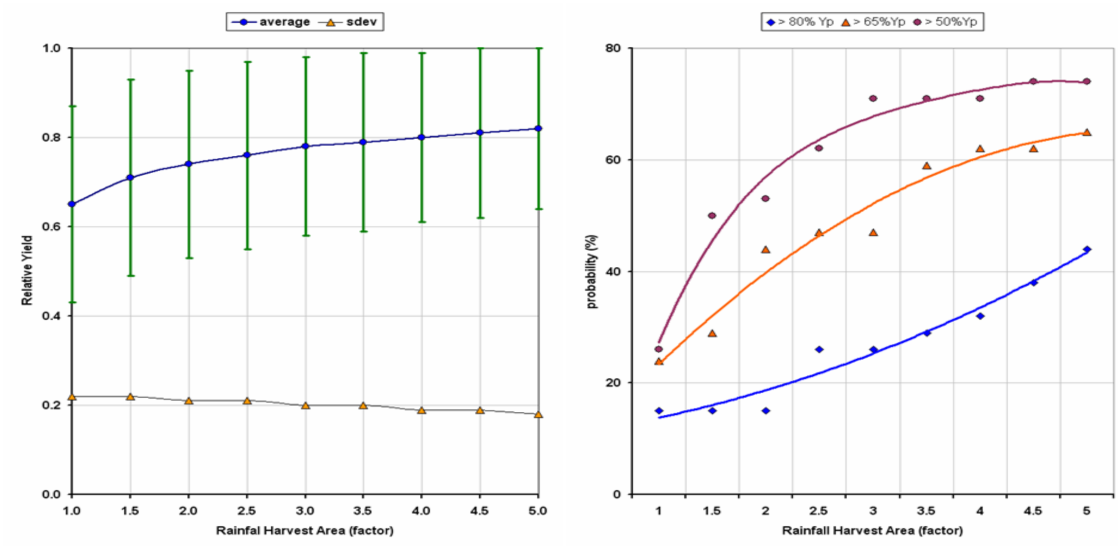
Modelling rainwater harvesting

Modelling studies were carried out to assess the potential for in-field RWH in the semi-arid region of Chókwè in Mozambique (Niquice 2006). The studies examined planting date, RWH, and storage of water in the root zone for rainfed maize. The main objective of these modelling studies was to maximise the use of rainwater captured by plants by looking at the effects of catchment area (through changing planting density) on final grain yield. Other effects such as soil texture and type, different RWH techniques, agronomic management and varieties were not considered. There were some limitations in the models in that they simply estimated the runoff to the plants with the assumption that no runoff from the field is generated.

The results indicated that total seasonal evaporation always exceeds rainfall in this part of the Limpopo River Basin near the coast, despite the relatively large rainfall here. Figure 3 shows the effect of “rainfall harvest area” factor (horizontal axis) on relative grain yield. The “rainfall harvest area” factor is the ratio of the area of runoff collection per plant to the runoff area per plant for the recommended planting density. A factor of 1.0 means using the recommended planting density, and a factor of 3.0, for example, means that the area per plant is three times larger than with the recommended density, increasing the area (three-fold in this case) of for runoff collection per plant (Niquice 2006).

Moving from the recommended plant density with a “rainfall harvest area” factor of 1.0 to lower planting densities with a factor of 5.0, the expected relative yields increased from 65 to 82% of potential yield (with water non-limiting), as shown on the left hand graph in Figure 3. The standard deviation tends to decline slightly due to limited increment of yield as the factor increases, determined by the soil water storage capacity within the root zone. The right hand graph shows that as the runoff area for RWH increases, the chances of getting certain threshold of relative yields increases (Niquice 2006).

Figure 3 Effect of "rainfall harvest area" factor (the ratio of the area of runoff collection per plant to the runoff area per plant for the recommended planting density) on predicted relative potential yield for maize in Chókwè (adapted from Niquice 2006). A factor of 1 means recommended planting density. (left) Average and standard deviation (sdev) of yields. (right) Probability of potential yield (Yp) for different factors



Rainwater harvesting trials using zai pits

Studies were carried out in three locations within Chókwè District to assess maize and cowpea yields grown using Zai Pits (planting basins), in comparison with the same crops produced under farmers' practice (control), i.e. mixed cropping systems (maize intercropped with cowpea, cassava etc.) using conventional tillage. The dimensions of the Zai pits were about 0.6 m diameter and 0.3 m in depth. Four to eight seeds of maize or cowpea were sown in each pit, and the seeds were evenly distributed within the pit. The planting density in the Zai treatment was half that of the control.

The maize grain yield was 14 and 111 kg ha^{-1} for the control and pits respectively. Although the yields were very low in both treatments due to low rainfall, the pits increased yield 8-fold. Grain yield of cowpeas was increased from 92 kg ha^{-1} to 131 kg ha^{-1} by the pits.

The Zai pits tended to increase water availability in the root zone, especially in loam-clay soils . On sandy soils, the technique has some limitations due to poor soil structure (low water holding capacity). Although the study has shown a potential for increased RWH, its effectiveness depends on rainfall patterns, soil type, crops and other agricultural practices like planting date and density, and mulching. Further work is required to identify situations where Zai pits are likely to be beneficial and to develop associated crop management guidelines. The surprising result from these studies was that 21% of farmers (including those who were already implementing Zai pits before these studies) in the study area have adopted the pits despite the need for further study (Momade 2006).

Rainwater harvesting in the Olifants Catchment, South Africa

Rainwater harvesting studies were also conducted at the field level in the Olifants Catchment, South Africa. In-field RWH techniques (Chololo pits or ridges) were compared with conventional tillage at 2 locations. The potential benefits of ex-field RWH for supplementary irrigation were also studied in separate experiments.

In-field rainwater harvesting experiments

The dimensions of the Chololo pits were 0.22 m in diameter and 0.3 m in depth. The pits were spaced 0.6 m apart within rows and 0.9 m between the rows, which ran along the contour. Conventional tillage involved ploughing then levelling and sowing in lines 0.9 m apart with 0.40 m between plants within rows. Three maize seeds were sown per pit, and plant density was 4 plants m^{-2} in both treatments. There were two replicates of each treatment at each site, and plot dimensions were 6 m x 13 m. Deep drainage *(D) was* determined from volumetric soil water content (θ, measured) and soil hydraulic conductivity, using Darcy's equation (Stephens, 2000; Reshmidevi et al. 2008). Van Genuchten's (1980) equation was used to estimate soil hydraulic conductivity, $K(\theta)$, and crop evapotranspiration (E_c) was calculated as the residual term in the water balance equation:

$$E_c = P - (R + D + \Delta S)$$

where P is precipitation, R is runoff (measured), D is deep drainage below root zone and ΔS is change in soil water content (harvest soil moisture minus sowing soil moisture).

Table 1 shows the maize crop water balance components, yield and cost of each technique from the two sites. Precipitation during the crop season was very low at both sites, and the RWH treatments made the difference between no yield and yields of 585 or 335 kg ha^{-1} at Worcester and Enable, respectively. Yields with Chololo pits at Worcester were higher than yields with tied ridges at Enable, despite the lower rainfall at Worcester. Good results (yield tripling) under Chololo pits have also been reported in East Africa (Mati 2005). The water harvesting treatments reduced runoff, and increased deep drainage slightly. There was much greater soil drying in the Chololo pits at Worcester than in the other treatments, reflecting the better crop growth at that site. However, during high rainfall seasons, leaching and water logging could adversely affect crop yield.

The Chololo pits required much more labour than conventional tillage, and they cost almost 5 times as much to implement (Table 1), but the technique produced grain yield in a low rainfall year when conventional methods produced no grain yield. Farmers have shown enthusiasm for the technique, with a number of them adopting the pits in their small vegetable gardens. The pits also reduced runoff by 100% in small to moderate rainfall events (Magombeyi *et al.*, 2008; Botha *et al.*, 2003). The ridges required about one third of the labour of the Chololo pits, and at about one third the cost, but were also more labour demanding and expensive than conventional tillage. However, they also made the difference between no yield and some yield during this low rainfall year.

Table 1 Maize water balance components, grain yield and water productivity at the 2 study sites in 2007/8, and the cost of preparing Chololo pits compared to other techniques, in Olifants catchment.

	Worcester		Enable	
	Chololo pits	Conventional tillage	Ridges	Conventional tillage
Precipitation (P, mm)	268	268	361	361
Change in soil moisture between harvest and sowing (ΔS, mm)	-111	-36	-24	-17
Runoff (R, mm)	21	69	46	129
Drainage[a] (*D*, mm)	22	11	19	8
Crop evapotranspiration[b] (*Ec*, mm)	336	224	320	241
Maize crop grain yield (kg/ha)	585	0	335	0
Grain water productivity (kg grain/ha/mm of *Ec*)	1.74	0	1.05	0
Labour requirement (person days)	43	10	15	10
Cost (ZAR* ha^{-1})	1,512	316	521	316

*ZAR = South Africa Rand (1 US$ = ZAR 10)

Ex-field rainwater harvesting for supplementary irrigation

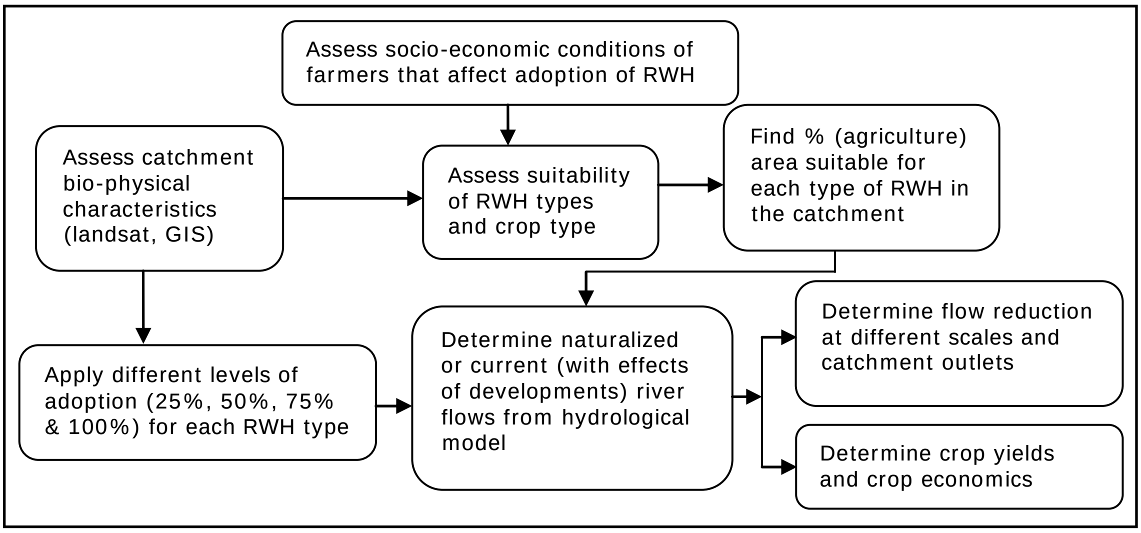
Components of the water balance and yield were compared in rainfed plots and plots receiving supplementary irrigation over 3 seasons (2005-2008) at 2 sites in the Olifants catchment (Magombeyi et al. 2008). Ex-field RWH by means of a weir across a stream was used to create the water supply for supplementary irrigation to 1 ha plots in farmers' fields. Plant density was 3 plants m^{-2} in all plots. Supplementary irrigation increased water productivity with respect to evapotranspiration from an average of 2 kg mm^{-1} ha^{-1} under rainfed conditions to 4 kg mm^{-1} ha^{-1} with supplementary irrigation. This was associated with an increase in average maize grain yield from 0.7 t ha^{-1} under rainfed to 1.7 t ha^{-1} under supplementary irrigation, an average increase of 143 % when compared to exclusive rainfed maize farming. Huge benefits of supplementary irrigation were realised when the crop growing period rainfall was below average and unevenly distributed throughout the season, as in the 2006/7 and 2007/8 seasons, when supplementary irrigation increased yields more than 4-fold. The study concluded that timely and adequate supplementary irrigation could be fundamental in ensuring farming families' food security and improved livelihoods by bridging the frequent intra-seasonal dry spells characteristic of semi-arid areas. However, extraction of water for supplementary irrigation reduces downstream flows. Hence, there is need for hydrological studies to estimate the crop area that can be brought under supplementary irrigation in the catchment without causing adverse impacts on downstream users and the environment.

Proposed approach for up-scaling the impacts of adoption of RWH technologies to catchment level

Model structure

The few small plot and farmer field studies presented above indicate that there is considerable potential for RWH technologies to increase yield and water productivity within the Limpopo River Basin. However, there are no studies showing what impacts these technologies will have upstream or downstream, both at catchment and basin levels. There is a need to find ways of up-scaling these techniques to catchment level and to understand what impacts these technologies will have. We want to answer questions such as: at catchment or basin scale what is the impact of these in-field and ex-field RWH techniques?; what level of adoption will maximize land and water productivity while avoiding unacceptably adverse hydrological and ecological impacts at these scales?; how to define "unacceptably adverse" impacts? A methodology model (flow chart) (Figure 4) is proposed for a systematic approach to assessing the biophysical and economic impacts of RWH to inform policy formulation and institutional reform processes regarding adoption of RWH practices that may promote integrated water resources management (IWRM).

Figure 4 Proposed flow chart for assessment of the impacts of up-scaling rainwater harvesting technologies in the Limpopo River Basin. RWH is rain water harvesting.



Indicators that could be used to assess the environmental impacts of increased RWH include relative reduction of runoff and river flows for average, high and low flows; irrigation water demands due to adoption of RWH systems (if more water is captured in the soil profile under in-field RWH, less irrigation water is required); and increased crop yields and income from crop sales.

The RWH techniques could be classified according to factors such as: agronomic productivity, riskiness, economic viability, and attractiveness of the technology to farmers. Social acceptability of the technology is also important for up-scaling to catchment level, and the socio-economic aspects which shape the water demand and ability to adopt the RWH technology by the farmers need to be included.

Use of a hydrological model to assess the hydrological impacts of rainwater harvesting

A spatial hydrological model is needed to answer questions such as:

- What are the potential areas where RWH technologies could be applied in the catchment?
- If you implement RWH what is the impact on flows downstream and sediment yields?
- What is the limit of out-scaling a particular RWH technology in the catchment?

Scenarios on the different levels of adoption for different RWH techniques such as: in-field soil storage systems (in situ water conservation: conservation tillage, bunds, micro-basins, mulching), micro-catchment (overland flows) and macro-catchment (diversion of an ephemeral stream by a weir into cropland e.g. in Olifants)

- What percentage of the area is suitable for RWH in the catchment? Studies on the suitability of RWH using land slope, rainfall, land cover, soil type and depth/texture structures are needed in Mozambique and Zimbabwe to complement work done in South Africa (Mwenge-Kahinda 2008).
- What percentage of land can be put under RWH so that the water requirements for downstream users and environment are still met (the level of adoption that is sustainable).
- Do the farmers accept the RWH techniques (acceptability)? Work on modelling farmer adoption of RWH and supplementary irrigation adoption was reported in He et al. (2007). Is there a need for it? What's the current level of water supply in the catchment? Do they have money to build the RWH facilities or structures (affordability of the RWH techniques)?

Hydrological implications of up-scaling RWH in a river basin

It will be important to know what amount of runoff (overland flow) is retained by farmers. This is important because cumulative effects of hydrological processes at the field scale influence and regulate what happens at the larger catchment scale. The level of reduction in river flow that results from overland flow retention upstream will also be important. The impacts of reduced surface land flow could become significant as the RWH is adopted by a larger population in the catchment. Possible sources of data for up-scaling would include Landsat and remote sense images.

Possible Challenges

Hydrological models are only as good as the available input data. Hence, it is paramount to validate and verify input data. There is an increasing degree of uncertainty and complexity in water fluxes when moving from field scale to catchment scale hydrology, meaning that it is not valid to directly extrapolate or interpolate results from one spatial scale to another. The dynamic socio-economic conditions (family annual income and labour) of the farmers also pose challenges in setting up the integrated impact model (Figure 4).

Conclusions

In-field and ex-field rainwater harvesting technologies are promising technologies for the semi-arid regions such as the Limpopo River Basin. Field scale studies have shown substantial crop yield benefits to smallholder farmers. However, RWH technologies often require more labour and additional cost to implement than normal farmer practice, and the magnitude of the yield gains varies depending on seasonal and site conditions. There is a need to systematically identify under which situations RWH technologies are likely to increase productivity and profitability. There is also a need to find ways of out-scaling the technologies for a greater impact on the livelihoods and food security of the very large numbers of poor farming families in the Basin. However, as we find ways of out-scaling, there is also need to understand the up-stream and down-stream impacts of out-scaling in-field and ex-field RWH at catchment and basin levels. Development of a decision support tool in the form of an integrated model presented in this paper could answer several questions on the impacts and sustainable levels of RWH adoption and aid policy makers.

Acknowledgments

This paper is an output of the CGIAR Challenge Program on Water and Food Project 17 ''Integrated Water Resource Management for Improved Rural Livelihoods: Managing risk, mitigating drought and improving water productivity in the water scarce Limpopo Basin''. The opinions and results presented in this paper are those of the authors and do not necessarily represent the donors or participating institutions.

References

Basson, M.S. and J.D. Rossouw. 2003. *Olifants Water Management Area: overview of water resources availability and utilization*. Report P WMA 04/000/00/0203, Department of Water Affairs and Forestry, Pretoria, South Africa, 55p.

Blöschl, G. and M. Sivapalan. 1995. Scale issues in hydrological modelling: a review. *Hydrological Processes, **9**, 251-290.*

Botha, J.J., van Rensburg, L.D., Anderson, J.J., Hensley, M., Macheli, M.S., van Staden., Kundhlande, G., Groenewald, D.G., and M.N. Baiphethi. 2003. Water conservation techniques on small plots in semi-arid areas `to enhance rainfall use efficiency, food security, and sustainable crop production. Water Research Commission of South Africa, Pretoria, Report No: 1176/1/03, ISBN No: 1-77005-149-X.

Butterworth, J.A., Mugabe, F., Simmonds, L.P., and M.G. Hodnett. 1999. Hydrological processes and water resources management in a dryland environment II: surface redistribution of rainfall within fields. *Hydrology and Earth Systems Sciences, **3**, 333-343.*

Harrington et al 2004. Baseline 2004. Challenge Program on Water and Food, Colombo, Sri Lanka.

He, X., Cao, H and F. Li. 2007. Econometric analysis of the determinants of adoption of rainwater harvesting and supplementary irrigation technology (RHSIT) in the semi-arid Loess Plateau of China. *Agricultural Water Management, **89** (3), 243-250.*

Love, D., Uhlenbrook, S., van der Zaag, P., and S. Twomlow. 2007. Response of semi-arid meso-catchments to rainfall at daily and monthly time steps. 8th *WaterNet/WARFSA/GWP-SA Symposium*, Lusaka, Zambia.

Magombeyi, M.S. and A.E. Taigbenu. 2008. Crop yield risk analysis and mitigation of smallholder farmers at quaternary catchment level: Case study of B72A in Olifants river basin, South Africa. *Physics and Chemistry of the Earth, **33**, 744-756.*

Magombeyi, M.S., Rasiuba, T., and A.E. Taigbenu. 2009. Maize yields under supplementary irrigation in the Olifants River Basin, South Africa. In: Humphreys, E. and R.S. Bayot (eds.) Proceedings of the CPWF Workshop 'Increasing the Productivity and Sustainability of Rainfed Cropping Systems of Poor Smallholder Farmers', Tamale, Ghana, 22-25 September 2008. CGIAR Challenge Program on Water and Food, www.waterandfood.org

Mati, B. M. 2005. Overview of Water and Soil Nutrient management under Smallholder Rainfed Agriculture in East Africa. Working Paper 105. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Mazvimavi, D. 2004. *Estimation of Flow Characteristics of Ungauged Catchments: Case study in Zimbabwe*. Ph.D. dissertation. Wageningen University and International Institute for Geo-Information Science and Earth Observation, Delft.

Miyazaki, T. 2006. Water Flow is Soils. Edition: 2, illustrated. CRC Press. 418pp.

Momade, A. 2006. Levantamento das Técnicas de Recolha e Conservação de Água da Chuva na Produção Agrícola no Distrito de Chókwè. Tese de Licenciatura em Engenharia Agronómica. Faculdade de Agronomia e Engenaharia Florestal, Universidade Eduardo Mondlane, Maputo, Moçambique.

Mugabe, F.T., Hodnett, M., and A. Senzanje. 2007. Comparative hydrological behaviour of two small catchments in semi-arid Zimbabwe. *Journal of Arid Environments*, ***69***, *599-616*.

Mupangwa, W, Twomlow, S, Hove, L, and S. Walker. 2007. Effect of mulching and minimum tillage on maize (*Zea mays* L.) yield and water content of clayey and sandy soils. *Physics and Chemistry of the Earth*, ***32***, *1127-1134*.

Mupangwa, W, Twomlow, S, Hove, L, and S. Walker. 2008. The influence of conservation tillage methods on soil water regimes in semi-arid southern Zimbabwe. *Physics and Chemistry of the Earth*, ***33***, *762-767*.

Mupangwa, W. 2009. Water and nitrogen management for risk mitigation in semi-arid cropping systems. PhD Thesis (unpublished). University of Free State, South Africa. 357pp.

Mwenge-Kahinda, J.-M., Lillie, E.S.B., Taigbenu, A.E., Taute, M. and R.J. Boroto. 2008. Developing suitability maps for rainwater harvesting in South Africa. *Physics and Chemistry of the Earth*, ***33***, *788-799*.

Mwenge-Kahinda, J.-M., Rockström, J., Taigbenu, A.E., and J. Dimes. 2007. Rainwater harvesting to enhance water productivity of rainfed agriculture in the semi-arid Zimbabwe. *Physics and Chemistry of the Earth*, ***32***, *1068-1073*.

Ngigi, S. N., Savenije, H.G., and F.N. Gichuki. 2005. Land use changes and hydrological impacts related to up-scaling of rainwater harvesting and management in upper Ewaso Ng'iro river basin, Kenya. *Land Use Policy*, ***24***, *129-140*.

Ngigi, S.N. 2003. What is the limit of up-scaling rainwater harvesting in a river basin? *Physics and Chemistry of the Earth*, ***28***, *943–956*.

Niquice C.A. 2006. Efeito "Multiplicativo" de Água da Chuva para a Produção e Milho em Regime de Sequeiro – Distrito do Chókwè. Tese de Licenciatura em Engenharia Agronómica. Faculdade de Agronomia e Engenaharia Florestal, UEM, Maputo, Moçambique.

Nyabeze, W.R. 2004. Estimating and interpreting hydrological drought indices using a selected catchment in Zimbabwe. *Physics and Chemistry of the Earth*, ***29***, *1173-1180*.

Reshmidevi, T.V., Jana, R., and T.I. Eldho. 2008. Geospatial estimation of soil moisture in rainfed paddy fields using SCS-CN-based model. *Agricultural Water Management* ***95***, *447-457*.

Stephens, D.B. 2000. Vadose Zone Hydrology. Lewis Publishers, Boca Raton Florida.

Thompson, H 2006. Water Law, A practical approach to resource management and the provision of services. JUTA and Co Ltd, South Africa.

Twomlow, S. and P. Bruneau. 2000. Semi-arid soil water regimes in Zimbabwe. *Geoderma,* ***95****,33-51*.

Unganai, L.S. and Mason, S.J. 2002. Long-range predictability of Zimbabwe summer rainfall. *International Journal of Climatology,* ***22****, 1091 – 1103*.

United Nations. 1997. Convention on the Law of the non-navigational uses of international watercourses. Adopted by the United Nations General Assembly in resolution 51/2 of 21 May 1997. United Nations, New York.

Van de Giesen, N.C., Stomph, T.J., and N. de Ridder. 2000. Scale effects of Hortonian overland flow and rainfall-runoff dynamics in a West African catena landscape. *Hydrological Processes,* ***14****, 165-175*.

van der Zaag, P. 2007. Asymmetry and equity in water resources management; Critical institutional issues for Southern Africa. *Water Resource Management* ***21****, 1993-2004*.

Van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* ***44*** *(5), 892-898*.

Vörösmarty, C.J., Green, P., Salisbury, J., and R.B. Lammers. 2000. Global water resources: vunerability from climate change and population growth. *Science,* ***289****, 284-288*.

Woltering, L. 2005. Estimating the influence of on-farm Conservation Practices on the Water Balance: Case of the Mzinyathini Catchment in Zimbabwe. M.Sc. thesis (unpublished), Delft University of Technology, the Netherlands.

Woyessa, Y.E., Pretorius, E., Hensley, M., van Resnburg, L.D., and P.S. van Heerden. 2006. Up-scaling of rain-water harvesting for crop production in the communal lands of the Modder River basin in South Africa: Comparing upstream and downstream scenarios. *Water SA,* ***32****, 223-228*.