RAINWATER HARVESTING TO ENHANCE WATER PRODUCTIVITY OF RAINFED AGRICULTIRE IN THE SEMI-ARID ZIMBABWE

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ABSTRACT

Zimbabwe's poor are predominantly located in the semi-arid regions (Bird and Shepherd, 2003) and rely on rainfed agriculture for their subsistence. Decline in productivity, scarcity of arable land, irrigation expansion limitations, erratic rainfall and frequent dry spells, among others cause food scarcity. The challenge faced by small-scale farmers is to enhance water productivity of rainfed agriculture by mitigating intra-seasonal dry spells (ISDS) through the adoption of new technologies such as rainwater harvesting (RWH). The paper analyses the agro-hydrological functions of RWH and assesses its impacts (at field scale) on the crop yield gap as well as the Transpirational Water Productivity (WP_T). The survey in six districts of the semi-arid Zimbabwe suggests that three parameters (water source, primary use and storage capacity) can help differentiate storage-type-RWH systems from "conventional dams". The Agricultural Production Simulator Model (APSIM) was used to simulate seven different treatments (Control, RWH, Manure, Manure + RWH, Inorganic Nitrogen and Inorganic Nitrogen + RWH) for 30 years on alfisol deep sand, assuming no fertiliser carry over effect from season to season. The combined use of inorganic fertiliser and RWH is the only treatment that closes the yield gap. Supplemental irrigation alone not only reduces the risks of complete crop failure (from 20% down to 7% on average) for all the treatments but also enhances WP_T (from 1.75 kg m^{-3} up to 2.3 kg m^{-3} on average) by mitigating ISDS.

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Key Words: Rainfed Agriculture, Rainwater harvesting system; Water productivity, yield gap.

1. INTRODUCTION

The majority of the population in sub-Saharan Africa make their living from rainfed agriculture (FAO, 1995), and largely depend on small-scale subsistence agriculture for their livelihood security (Rockström, 2000). In semi-arid regions (SAR) the rainfall has extreme temporal and spatial variability and generally occurs as storms of high rainfall intensity, resulting in agricultural droughts and intra-seasonal dry spells (ISDS) that reduce the yield of rainfed agriculture. Statistically in SAR, severe crop reductions caused by an ISDS occur once to twice out of 5 years, and total crop failure caused by annual droughts once every 10 years (Rockström, 2000). Insufficient, erratic and unreliable rainfall pattern makes supplementary or full irrigation indispensable in SAR. Worldwide, irrigated agriculture is already the largest consumer of runoff water (69% of withdrawn runoff water). Irrigation expansion limitations, high population growth and scarcity of arable land are factors which call for more food production under rainfed agriculture. In semi-arid Africa, average yield of rainfed agriculture oscillate around 1ton/ha for the major cereal crops (maize, millets and sorghum) (Barron, 2004 and Rockström & Falkenmark, 2000), and this is below the 3 to 5 tons/ha that can be produced (Rockström, Barron & Fox 2003 and Rockström, 2002).
To make rainfed agriculture the main source of food and livelihood security for rural communities, the yield gap between the actual yield and the maximum yield must be reduced.

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To close the gap, water productivity of rainfed agriculture has to increase. An option for improving water productivity will be the reduction of non-productive soil evaporation (E_S) in favour of productive plant transpiration (T). Supplemental irrigation of rainfed crops by the use of Rainwater harvesting (RWH) is a likely viable option to increase water productivity at production system level (Oweis et al., 2001; SIWI, 2001). RWH has the potential to provide enough water to supplement rainfall and thereby increase crop yield and reduce the risk of crop failure (Oweis et al., 2001; Critchley et al, 1991). Enhancing and stabilising the crop yield of subsistence farmer will incentivised them to invest in soil nutrient enhancement. Generally, In-field Rainwater harvesting (IRWH) that aim at water conservation (i.e., to maximise soil infiltration and water holding capacity) dominates, while Ex-field Rainwater harvesting (XRWH) with storage systems are less common (SIWI, 2001). Therefore impacts of storage systems used for supplemental irrigation on the water productivity as well as on the yield are not well known. RWH is practised in semi-arid Zimbabwe but, despite its obvious benefits, as claimed by farmers and researchers, there is still a lack of quantitative data on the extent of its use in the country and of scientific information on how the various techniques are performing (FAO, 2005).
This paper, based on Mwenge Kahinda (2004), analyses the agro-hydrological functions of RWH and assesses its impacts (at field scale) on the water balance as well as the Transpirational Water Productivity (WP_T).

2. WATER PRODUCTIVITY AND YIELD GAP

WATER PRODUCTIVITY

Productivity is a ratio which reflects the relative magnitude of an output to the input (driver). Water productivity (WP) is used exclusively to denote the amount or value of product over volume or value of water depleted or diverted (Kijne 2003). Molden et al (2003) defines WP as the relative quantity of crop yield per unit of water consumed. The value of the product can be expressed in different terms (biomass, grain, money, etc). WP herein expressed as the ratio between the crop yield (Y) and the water consumed.

Figure 1 gives the general trend expected between WP and crop yield.

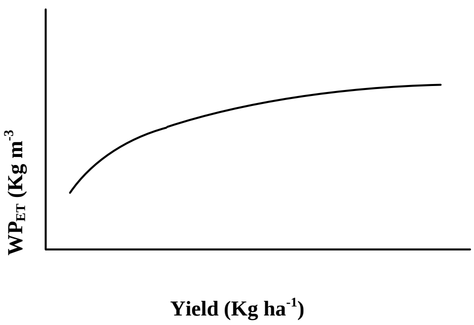

Figure 1. Water Productivity Vs Yield

Since the Crop growth is directly governed by transpiration, it is more appropriate to consider the transpirational WP given by:

$$WP_T = \frac{Y}{T} \qquad (1)$$

However, since it is difficult to separate Evaporation and Transpiration, it is common to assess Evapotranspirational WP.

$$WP_{ET} = \frac{Y}{(E+T)} \qquad (2)$$

WP is a key parameter when assessing the performance of irrigated and rainfed agriculture, that can be raised by either increasing the crop yields and/or decreasing all flows except transpiration. At field scale, this can be done by improving crop, soil and water management. The improvements include: selecting appropriate crops and cultivars; planting methods; minimum tillage; timely irrigation to synchronize water application with the most sensitive crop growth stages; nutrient management; drip irrigation; and improved drainage for water table control. Some field methods used for increasing WP are deficit irrigation and RWH. Both methods require farmer training, proper crop selection as well as proper planning.

YIELD GAP

Yield gap (Y_g) is the difference between the maximum yield (Y_m) and the actual yield (Y_a).

$$Y_g = Y_m - Y_a \qquad (3)$$

The actual yield (Y_a) is the yield of a crop planted in a given soil, under a given climate, with all the factors amenable to management control. The maximum yield (Y_m) is the yield of a crop planted at the optimal plant density for a given soil type and climatic conditions without nutrient limitation, pests, diseases, weeds, soil damage or other factors amenable to management control.

To close the yield gap, there is need to:

- Maximize the plant water availability by maximising infiltration of rainfall, minimising unproductive water losses, increasing soil water holding capacity and maximising root depth;
- Maximize plant water uptake through: crop management and soil fertility management, and;
- Bridge crop water deficits during dry-spells through supplemental irrigation using, as in this study, RWH.

3. RAINWATER HARVESTING IN SEMI-ARID ZIMBABWE

About 70 percent of the population of Zimbabwe depends on agriculture for food and employment but, only 37 percent of the country receives adequate rainfall for agriculture (FAO, 2005). Zimbabwe's poor are predominantly located in the semi-arid regions (Bird and Shepherd, 2003) and rely on rainfed agriculture for their subsistence. A survey of RWH techniques was carried out in Insiza, Gwanda, Umzingwane, Beitbridge, Zvishavane and Chivi; six districts (Figure 2) of the semi-arid Zimbabwe.

Figure 2. District Map of Zimbabwe

Insiza, Gwanda, Umzingwane and Beitbridge are located in the Mzingwane catchment, which is part of the Limpopo river basin. The country is divided into five Natural Regions (Figure 3) relating climate, soils and topography to appropriate farming systems. The six districts lie in Natural Regions IV and V which have low erratic rainfall with high incidence of drought and severe Intra-seasonal dry spells (ISDS), making rainfed agriculture a risky venture. ISDS occurs in dry years (Figure 4) as well as in wet years (Figure 5). July 1991 to July 1992 with an MAR of 109.7 mm is the driest year recorded for Masvingo while July 1999 to July 2000 with an MAR of 1134.8 is the wettest year. In semi-arid Zimbabwe, water is by far a greater constraint than land (FAO, 2005).

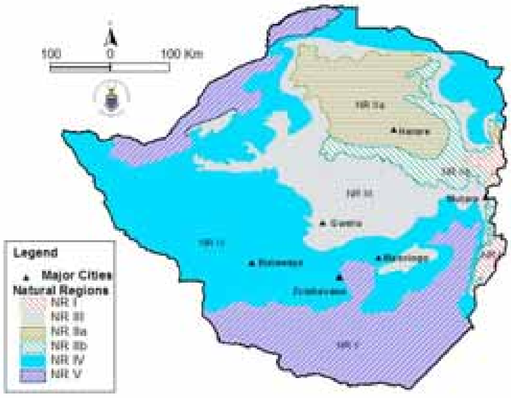

Figure 3. Zimbabwe Natural Region Map

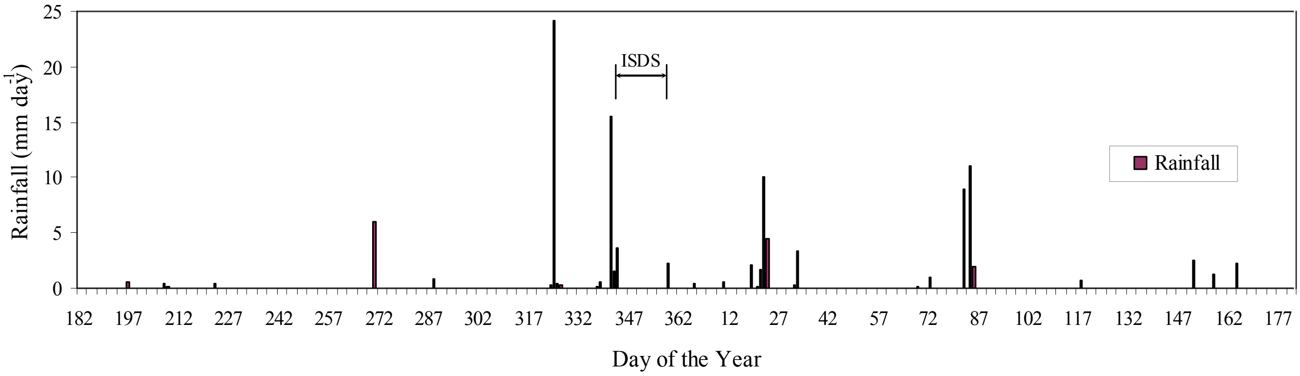

Figure 4. Rainfall and ISDS from July 91 to July 92

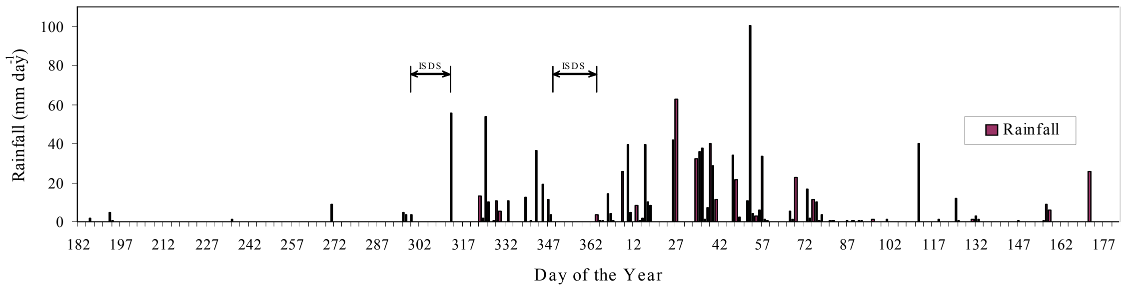

Figure 5. Rainfall and ISDS from July 99 to July 2000

In the past, the government invested in human and financial resources for agricultural research. The top down approach used did not take account of the farmers' priority needs and socio-economic situation (IIRR, 1998). Traditionally, drought-tolerant crops were seen as the solution to erratic rainfall in the drought-prone areas (Mutekwa & Kusangaya, 2006). In recent years, to mitigate the effects of ISDS and stabilise the crop yield, RWH techniques have been introduced and promoted by non-governmental organisations (NGOs). Despite the obvious benefits of water harvesting in the country, as claimed by farmers and researchers, there is still a lack of quantitative data on the extent of its use in the country and lack of scientific information on how the various techniques are performing (FAO, 2005).
The survey indicated that IRWH is dominant in the six districts. This finding is in line with those of FAO (2005) who lists infiltration pits, tied furrows, dead level contours, potholing and fanya juus as the most common IRWH techniques. Rock Catchments, an XRWH, are also common since, the granite areas of Zimbabwe that cover over 50% of the country are well supplied with domes (ruware), often of sufficient size to be utilised as water catchment areas (Dry Land Farming, 2006).

2.1. Conventional dams and XRWH with Storage system

The term "dam" is often preferred by the technical staff of Zimbabwe and FAO in their documentation to signify small water bodies or reservoirs, and in many cases the terms "dams", "small water bodies" and "reservoirs" are used interchangeably (Sugunan, 1997). This inconsistency in the nomenclature makes it difficult to differentiate between conventional dams and XRWH with Storage system. In Zimbabwe there are quit a number of small water bodies which have been constructed to mitigate local and temporary water shortages. This is illustrated in Table 1 for the six districts of the semi-arid Zimbabwe.

Table 1. Distribution of dams in the six districts (Sugunan, 1997)

District	Number	Capacity (m^3)
Beitridge	63	46,993
Chivi	78	135,943
Gwanda	265	77,241
Insiza	856	318,145
Umzingwane	214	210,514
Zvishavane	58	9,534

To differentiate between conventional dam and XRWH with Storage System, one should consider the water source and the primary intended use of the water collected (Table 2).

Table 2. Difference between Conventional Dam and XRWH with Storage System

	Rainwater harvesting	**Conventional Dam**
Water source	Undefined drainage network.	Defined drainage network (Rivers, etc)
Primary Use	1. Supplemental irrigation 2. Off season irrigation	1. Full irrigation 2. Supplemental irrigation
Storage capacity m^3 (Oweis et al., 2001)	≤500000 m^3	>500000 m^3

4. RESULTS OF SIMULATIONS WITH THE APSIM MODEL

The Agricultural Production Systems SIMulator (APSIM) is a modelling environment that uses various component modules to simulate cropping systems (Keating et al., 2003). Modules can be biological, environmental, managerial or economic and are linked via the APSIM "engine", which passes information between modules according to a standard protocol. APSIM was used to model the RWH system of Mr. Phiri Maseko, a pioneer of RWH in Zimbabwe, located some 20 km from Zvishavane. He combined a rock catchment with dead level contours and infiltration pits. His cattle produce about 3 tonnes yr^{-1} of organic manure. For more details on Mr. Phiri's RWH technique and achievements, refer to Witoshynsky (2000).
During the modelling exercise, 30 years of climatic from Masvingo were incorporated into the model. Masvingo falls under the same natural region as Zvishavane (Figure 3). Zvishavane data being unreliable. SC401, a very early maturing white dent hybrid maize cultivar was planted with at a density of 3 plants m^{-2}, in an Alfisol deep sand of plant available water content 87mm, depth 1.8m and organic content 1.1. For the seven run (Table 3), no over year carry over where allowed. The 15 october of each year, the available soil water is fixed at 10 percent of the total soil available water content

Table 3. APSIM Runs

Name	Treatment
Maximum yield	Non limiting nitrogen
Control	No fertiliser, no Supplemental Irrigation (SI)
RWH	SI from RWH
Manure	3t manure/ha each season
Manure + RWH	3t manure each season+ SI
Nitrogen	10kg/ha of inorganic Nitrogen
Nitrogen + RWH	10kg/ha of inorganic Nitrogen + SI

For more details on the different runs, read Mwenge Kahinda (2004)

RWH has a positive effect on WP_T. Results indicate a significant increase in WP_T for all the treatments with supplemental irrigation (Table 4). Supplemental irrigation alone improved WP_T (RWH treatment) by 22% on average (from 1.75 kg m^{-3} to 2.13 kg m^{-3}) compared with the control (farmer practice). The highest improvement in both yield and WP_T was achieved by a combination of supplemental irrigation and inorganic nitrogen (Nitrogen + RWH treatment), which gives a better synergy between soil nutrients, water and crop than the other treatments.

Table 4. Average Yield Gap, Transpirational Water Productivity & Risks of complete Crop failure

	Maximum	Control	RWH	Manure	Manure + RWH	Nitrogen	Nitrogen + RWH
WP_T (kg m^{-3})	1.75	1.75	2.13	1.76	2.15	1.83	2.31
Risk of Crop Failure (%)	20	20	7	20	7	20	7
Yield Gap (kg ha^{-1})		907	422	887	381	651	-64

Supplemental irrigation alone achieved a higher reduction of the yield gap (422 kg ha^{-1}) than the Fertiliser alone (651 kg ha^{-1}). The yield gap is only completely closed (-64 kg ha^{-1}) when supplemental irrigation and inorganic nitrogen are combined.

For seasons with intense ISDS, there was a total crop failure of all the treatments without supplemental irrigation, independent of nature and level of fertiliser. During the years with intense ISDS inorganic nitrogen application exacerbate water stress thereby resulting in total crop failure. The bridging of ISDS through supplemental irrigation increases and stabilises the crop yield, assuring a minimum reliable yield (when no fertiliser is applied). The study indicates a 13 % reduction of the risks of total crop failure that occurs once out of 5 years because of ISDS (Figure 6) when RWH is used for supplemental irrigation. This is also valid when there is no addition of either organic or inorganic nitrogen, suggesting that water is a major limitation to crop production in the area. An added advantage of XRWH with storage system is the possibility for the farmer to grow winter crops. Crop yield stabilisation coupled with winter cropping should be an incentive for the farmers to invest in fertilisers. The level of investments in fertilisers is lower than 20 kg ha^{-1} year^{-1} in sub-saharan Africa (Rockstrom et al, 2003).

It takes more than a season for manure to release nitrogen in the soil. As a result, the cumulative crop yields of the control and RWH treatments are very similar to those of the Manure and Manure + RWH treatments respectively (Figure 6). Inorganic fertiliser increases the crop yield especially when combined with RWH for supplemental irrigation.

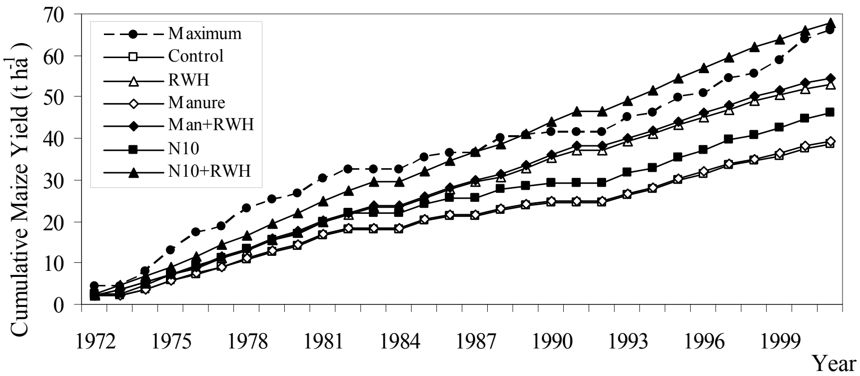

Figure 6. Cumulative Crop Yield

CONCLUSION AND RECOMMENDATIONS

This paper analyses from a modelling perspective the impacts of RWH on the WP_T and the yield gap of a maize crop in rural semi-arid Zimbabwe. As shown in the paper, the use of RWH for supplemental irrigation increases WP_T and stabilises the crop yield. It can be concluded that water is not the only limiting factor to crop growth. To close the yield gap, small-scale farmers will have to simultaneously invest in RWH and nutrient enhancement. For an efficient use of the water harvested, farmers should be trained to identify critical growing stages during which water shortages considerably affect yields, and apply water with drip kits instead of the traditional bucket.

Successful implementation of RWH in Zimbabwe requires an integrated approach where not only the technical aspect is considered but also the socio-economic and the institutional aspects. An involvement of the government and the local water authorities who are the decision makers and the implementers of the national water resources plan is key to the widespread of RWH. The upscaling of RWH should also consider its impacts on the hydrological cycle.

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