WATER BUDGET, WATER USE EFFICIENCY IN AGRICULTURE IN OLIFANTS CATCHMENT

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfillment of the requirements for the degree of Master of Science in Engineering.

Johannesburg 2007

DECLARATION

I declare that this research report is my own, unaided work. It is submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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Abstract

Eighty percent of the agricultural land worldwide is under rain-fed agriculture that takes place on most soils that are generally low in fertility with attendant high on farm water losses, thereby resulting in low crop yields. This is particularly significant in sub-Saharan African states where a higher percentage of the population is involved in agriculture and the economy is predominantly driven by rural-based rain-fed agriculture. In the Olifants catchment, the challenges in rain-fed agriculture are compounded by erratic, highly variable rainfall patterns in space and time.

The study area (Sekororo, B72A quaternary catchment) is within lower Olifants region. It is located between latitude $24^0$00'00" and $24^0$25'00" South and between longitude $30^0$15'00" and $30^0$45'00" East. The survey sites within the B72A quaternary catchment are Worcester, Enable, Ha-Fanie, and Sofaya. The results on soil nutrients indicate that the soil fertility is very poor, indicative of poor land management which also impacts adversely on water use and crop yields.

The data from Statistics South Africa indicate that average number of people per household dwelling at B72A quaternary catchment is five. Taking into account maize consumption of 100kg per person per annum and average number of persons per household, maize required to achieve food security would be 500kg per household per annum and at current average crop yield of 300kg/ha, food insecurity is very high for rain-fed farmers.

The data on rainfall partitioning indicate that at least 38% of the received rainfall is lost to run-off. The modeled results indicate that crop yield can be improved to 800kg/ha if significant portion of rainfall lost to run-off is harvested, thereby eliminating food insecurity for rain-fed farmers.

ACKNOWLEDGEMENT

I am very much thankful to my MSc supervisor, Professor A.E Taigbenu for his invaluable guidance, inspiration and support throughout the course of my study. I also grateful acknowledge the support of Waternet/CGIAR and NRF whose funding made this research possible.

I am also indebted to Dr D Rollin, Dr W.R Nyabese, Mr. M.S Magombeyi, Mr. E Nyirenda, Mr. T Magagula (from IWMI), Mr. M Ncube, Mrs. M Kgabo and Mr. R Raseona for their useful contributions and support at various stage of this research. This also extends to Mrs. T Booysen, Mr. W Mainganye and Mr. N Alexander who helped me with the execution of laboratory experiments, not forgetting all farmers in Sekororo who provided me with the valuable information and the land to perform pilot study in their farms.

I also wish to thank my parents who were always supportive to me towards the successful completion of this study.

Most importantly, I wish to acknowledge the divine intervention of my Lord Jesus Christ for protection and carrying me this far.

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Chapter one: Introduction

“Food insecurity is an enormous challenge at a global scale, with strong implications both for environmental management and for socio-economic development” (Rockstrom, 2003). This is exaggerated by persistent drought and uneven distribution of rainfall resulting in low crop yield. As the results, millions of lives are threatened with starvation caused by food shortages particularly in the arid and semi arid regions where majority of population still rely on rain-fed agriculture to secure food security (Ntsheme, 2005).

The majority of the affected population threatened with starvation resides in the rural areas with little or no income at all. It is projected that by the year 2010, 33 percent of the population in the Sub-Saharan region will still be without food. This is exacerbated by slow economic growth and poor performance in the agricultural sector. It is likely that the increment of the food gap will occur in the near future intensifying the shortage of food in the region (Kundlande et al, 2004).

The low crop yield and the increasing population result in food insecurity in the semi arid region. The statistics South Africa indicates that there are families who are still staying with more than seven people per household particularly in the rural areas. With the prominent ever-increasing population, the current low crop yield per growing season in the arid and semi-arid region cannot support the increasing population. The current crop yield for rain-fed agriculture in B72A quaternary catchment can only support an average of three persons per year. To secure the food security for seven persons per household, the current crop yields will need to double. While farmers are aware of the average seasonal rainfall of the region, the challenge lies more in improving water use efficiency than increasing the size of the cropping land for the crop production (Mutiro et al, 2006).

“With the majority of poor population making their living from small-holder farming under rain-fed conditions in tropical savannah environments, the challenge is to solve the problem of food insecurity by exploring the impact of rainwater management on improving food security. On average, less than 30% of rainfall in rain-fed agriculture contributes to crop growth, while at least 70% is lost to the crop as evaporation, interception, drainage and surface runoff”. While large proportion of rainfall is lost to run-off, evaporation, and drainage, the inter-seasonal prolonged dry spell causes crop failures. The rainwater management can provide the potential to increase crop yield. Rainwater harvesting can help to improve soil moisture especially during the period of the increased dry spell in the growing season (Rockstrom, 2003).

In Southern Africa, crop production is not limited by shortage of water alone, it is also being limited by poor soil fertility. The poor soil fertility and scarce water resources inhibits farmers to prepare large portions of land to plant crops due to high risk of crop failure associated with arid and semi-arid environment. In most cases, farming in the arid and semi-arid environment is not limited by unavailability of land but due to poor soil fertility and water deficits (Kundhlande et al, 2004).

While water scarcity is the main cause for crop failure in the rain-fed agriculture, irrigation is currently consuming highest quantity of available water resources (both ground and surface water). Where extensive irrigated agriculture is practised 90% of water consumption could be utilised for agriculture alone (Leenhardt et al, 2004). Currently, at Olifants catchment at least 55 % of water resources is being utilised for agriculture (DWAF, 2002). Research results indicate that at current levels of water utilisation, a food shortage is likely to happen in a near future. The solution to this problem lies in improving the water use efficiency in the agricultural sector. Improving crop water use efficiency will save water for environmental flow requirements and industrial consumption (Sally et al, 2003). Taking into account the potential water requirement for crop growth and applying the effective water conservation technology will eventually sustain the agricultural output in the semi-arid environments (Botha et al, 2003).

1.1 Background

The Olifants catchment has been identified by the International Water Management Institute (IWMI) as a reference basin for the long-term study of institutional and management aspects of water resources. With the Consultative Group on International Agricultural Research (CGIAR) and Waternet, a regional research and capacity building body, the principal goal of this research is to improve the rural livelihoods in the Limpopo basin. The three identified catchments in the Limpopo basin include Mzingwane catchment in Zimbabwe, the Olifants catchment in South Africa and Chokwe catchment in Mozambique. Within each catchment, a quaternary catchment was identified, of which B72A was chosen in case of South Africa.

This research seeks to meet the requirements of the global food challenge because it focuses on the smallholder farming communities living in water scarce and ecologically vulnerable landscape such as Sekororo (B72A quaternary catchment) of Olifants catchment. Though the Olifants catchment has developed water resources with 210 dams, the majority of the populations of the basin, mostly in the former homelands, have derived little or no benefit from the considerable developed water resources in the Olifants basin. Redressing this past injustice and ensuring that all citizens have access to water for their basic needs and for productive purposes are key features of the National Water Act (NWA).

Like most of the former homelands, B72A quaternary catchment of Olifants catchment is marginalized and does not benefit from these developed water resources. The agricultural practice in this area largely depends on rainfall and, in some instances, on supplemental irrigation in small irrigation schemes.

This research has been initiated to explore the untapped potential to upgrade rainfed agriculture in the dry tropical environments, through improved soil and water management. Often, the problem is not physical scarcity of water, but rather the lack of integrated management approaches that link crop, soil, water, and climate.

1.2 Location of the study area

The Olifants River Basin is part of three provinces of South Africa, which are Gauteng, Mpumalanga, and Limpopo. The Olifants River Basin is located in the northeastern part of South Africa and southern Mozambique between latitude 24 00' and 26 00' South and between longitude $28^{0}05'00"$ and $31^{0}05'00"$ East and it covers an area of about 54 000 km^{2}.

For the purposes of managing water, the Olifants catchment has been divided into five regions (Figure 1).

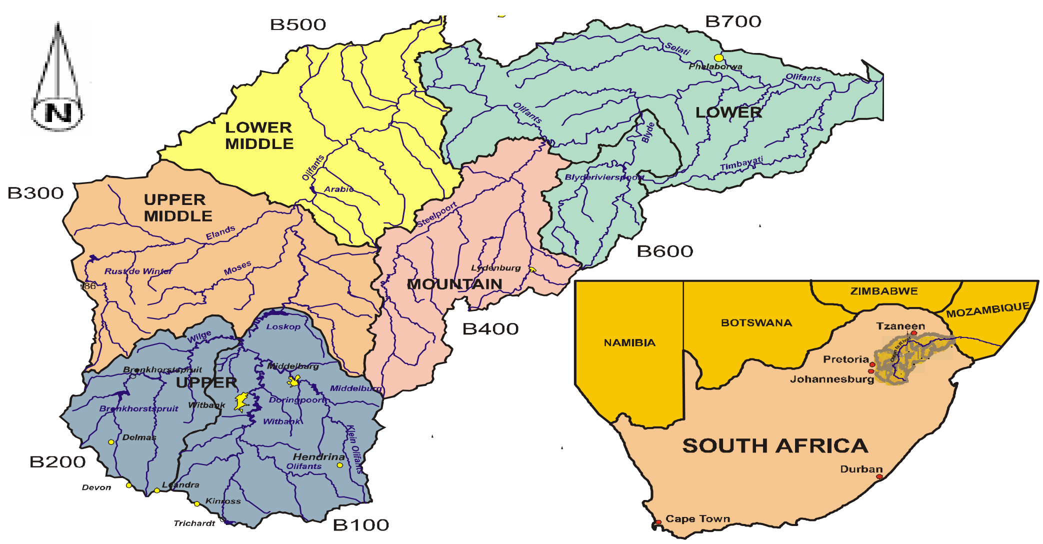

Figure 1.1: Location of the Olifants River Water Management Area and the boundaries of the five water management regions (DWAF, 2002)

Each of these regions consists of a number of quaternary catchments. Quaternary catchments are the principal water management unit in South Africa and were demarcated for the whole country as part of a comprehensive national water resource assessment. The quaternary catchments were delineated to have similar runoff volumes (i.e., the greater the runoff the smaller the catchment area and vice-versa). Quaternary catchments are nested within tertiary, secondary, and primary drainage areas. There are 19 primary drainage regions in South Africa, of which the Olifants River Basin is one of them. The Olifants catchment is divided into five water management areas which are Upper Olifants, Upper middle Olifants, Mountain region, Lower middle Olifants region, and lower Olifants region.

Furthermore, within these five water management areas, there are 7 secondary, 13 tertiary and 114 quaternary catchments of which the study area (B72A quaternary catchment) is one of the 114 quaternary catchment in Olifants basin. The study area (Sekororo, B72A quaternary catchment) is within lower Olifants region (Figure 1). It is located in between latitude $24^0$00' and $24^0$25'00" South and between longitude $30^0$15'00" and $30^0$45'00" East. B72A quaternary catchment covers an area of 535.2 Km^2 and it represents only 1 percent of the whole Olifants catchment.

This quaternary catchment has been chosen because it falls within International Water Management Institute (IWMI) benchmark basin, the need to research at local level, and it is the smallest level of water management for the Department of Water Affairs and Forestry (DWAF) in South Africa.

1.3 Major water use activities in the study area

The most prominent water use activities in the study area are domestic, agricultural, institutional, and the environmental flow requirements. All these activities need to share available water resources equitably. The study area does not have the developed water resources infrastructure like potable water treatment plant, wastewater treatment plant, and household water supply system. The community largely depends on boreholes, and rooftop rainwater harvesting for domestic water use and rivers for both domestic and agricultural purposes. However, there are no major industrial activities in the area, and agricultural activities pose the major threat to the water quality of the river system in the area.

1.4 Statement of the Problem

Water resources in the Olifants basin (Sekororo) region are scarce, and being depleted rapidly with ever increasing demand. The major problem hampering the rural livelihood development in B72A is high population growth coupled with the high rate of unemployment. Due to high unemployment rate, agriculture remains the backbone for food security and income generation for majority of the poor in B72A quaternary catchment (Sekororo).

There is high spatial and temporal rainfall variability resulting in regular seasonal dry spells. The majority of the poor in the study area make their living from smallholder farming under rainfed conditions, that their fortunes in terms of yields are largely dependent on the rainfall distribution. Poor land and water management in the study area has caused considerable erosion and siltation resulting in the decline of land productivity over the years (Ntsheme, 2005).

The scarcity of water for smallholder irrigation schemes increases during winter months for crops grown in winter. This is caused by over utilisation of water to crops grown in summer. These have hampered income generation and caused escalation of food insecurity for majority of the poor in B72A quaternary catchment. The present study has been promoted by the aforementioned situation, and hence the need to proffer improvements in water management practices to increase crop yields and overall profitability.

1.5 Justification of the research

The greatest challenge is to achieve food security, through increased productive use of water used for agriculture, thereby leaving more water available for other users in the basin. The importance of this research on the challenge program on water and food (CPWF) is to develop water management strategies among smallholder farmers that would reduce risk of crop failure, which, together with integrated farm systems management can improve farm income and water productivity.

Rainfed agriculture has been a risky business in B72A (Sekororo) due to recurrent droughts and intra-seasonal dry spells. When droughts occur, huge investment in resources in rainfed agriculture goes down the drain due to crop failures with resultant escalation of food insecurity. Despite these risks, there is a large untapped yield potential in rain-fed agriculture that needs to be explored. The integrated approach to water management can improve rural livelihoods and simultaneously increase water productivity. The improved land and water management will lead to rainwater use efficiency, leaving more water available in the storage dams that can be used beneficially for crops grown in winter.

Smallholder farmers have little or no access to blue water for irrigation in the study area. They cultivate on poor soils and unreliable rainfall is the main source of water. The crop yields are low and failures are frequent. The scarcity of blue water for irrigation puts strong emphasis on the options to improve green water use to save more water resources during wet months that can be utilised later during dry winter months.

The research is undertaken to provide insights into the management of water resources, particularly in agriculture, as it consumes large quantity of water available in the area. The current water demand for agricultural activities is very high; it utilises almost 60% of the total available surface water in the Olifants basin. This research is undertaken therefore to develop strategies for more efficient and sustainable use of water resources in the agricultural sector. The improvement on the current agricultural water use efficiency will go a long way in increasing crop yield and achieving savings of water resources.

This research focuses on adaptive management for risk reduction, crop yield and water productivity improvements. More often, the problem is not physical scarcity of water, but rather the lack of integrated management approaches to link crop, soil, water, and climate. This research is undertaken to generate new knowledge based on appropriate management approaches linking crop, soil, water, and climate.

1.6 Objectives of the research

1.6.1 Overall objective

To contribute to improving rural livelihoods of poor smallholder farmers through increased productive use of green and blue water flows and risk management for drought and dry-spell mitigation in the Olifants catchment (B72A quaternary catchment).

1.6.2 Specific objectives

1.6.2.1 To model the impacts of rainwater harvesting on the crop yield.

1.6.2.2 To improve water use efficiency in the study area (B72A Quaternary catchment) through adoption of effective water management strategy.

Chapter Two: Literature Review

2.1 Challenges facing smallholder farmers in crop production

"The emphasis on improving the livelihoods of smallholder farmers is based on an assessment that of the 850 million people experiencing serious and chronic hunger, approximately 50% are smallholder farmers. It is estimated that at least 25% of the population living in Sub-Saharan Africa will be undernourished. Poverty, food insecurity, and malnutrition remain major challenges in Sub-Saharan Africa. For this reason, the millennium project recommendation on rural development and food security focuses on improving the production and livelihoods". The major cause of food insecurity in most Sub-Saharan countries is low crop yield and frequent crop failures in rain-fed agriculture which supports the majority of population. Low soil fertility, uneven distribution of rainfall, long recurrent intra-seasonal dry spells and poor water resources management are the major cause for crop failures. Land and water management remain the subject of concern to smallholder farmers (Twomlow et al, 2006).

2.2 Climate impact on rain-fed agriculture

The rainfall characteristic in the semi-arid savannah environment is accompanied by high intensity storms which cause less rainfall infiltration and generate high runoff that disappears within short period through various waterways leaving soil with very little soil moisture to sustain crops. The high intensity storm is normally followed by long temporal period of deficit rainfall during cropping season causing crop failure (Ngigi, 2003). Due to unpredictable spatial and temporal rainfall pattern, high risk of agricultural drought and intra-seasonal dry spells that might cause complete crop failure is likely to occur. On average less than 30% rainfall received in semi-arid areas is used for crop growth, and remaining 70% is lost as evaporation, interception, drainage and surface run-off. This suggests that there is significant potential for improvement in crop water productivity if appropriate land and water conservation techniques are implemented. Describing the rainfall pattern in semi-arid areas, Rockstrom et al (2003) stated that seasonal variation in rainfall can typically range from a low of one-third of the long-term average to a high of approximately double the average, meaning that a high rainfall year can be six times higher than a dry year. This makes it difficult to maintain constant crop yield over years. Due to unpredictable seasonal rainfall, the emphasis should be on land and water management so that farmers will be assured of some yield in case the rainfall received is very low or surplus in case of wet seasons. The numbers of rainstorms are normally limited within the short rainy seasons. On average, at B72A quaternary catchment, 80% of the total annual received rainfall is concentrated during summer months between December and March (Ngigi, 2003).

2.3 Water use efficiency or water productivity in the small-scale agriculture

Crop productivity is usually measured in ratio to inputs such as capital, fertilizer, energy and labour. The concept of crop productivity has shifted to water productivity with the idea to manage water resources. The concept of water productivity is a useful water management tool because it provides farmers with an insight into the quantity of water required to acquire minimum, optimal, and maximum crop yield (Bennett, 2003).

Crop yield is a major output in water-productivity frameworks (Bastiaanssen et al, 2003). Water productivity, a concept expressing the value or benefit derived from the use of certain quantity of water, has been defined as the amount of output produced per unit of water involved in the production, or the value added to water in a given circumstance (Singh et al, 2006). Water productivity can be defined with respect to the different sectors of production involving water for example, crop production, fishery, forestry, domestic and industrial water use. Water productivity with respect to crop production is referred to as crop water productivity and is defined as the amount of crop produced per volume of water used (Igbadun et al, 2006). Water consumed includes green water (effective rainfall) for rain-fed agriculture, but for irrigated agriculture, both blue (diverted water from water systems to be used for irrigation) and green water are considered in assessing water productivity (Senzanje et al, 2005). Water productivity is a useful criterion used for decision making on crop production (Tyagi, 2003).

Increasing water productivity is a solution to scarce water resources and it covers several meanings. First it means that the output of a given crop per unit volume (m^3) of water is raised. Secondly, it means that the economic productivity of irrigated agriculture can be increased by shifting to crops with higher benefit per unit volume (m^3) of water applied (Molle, 2003). Improving water productivity will eventually ease the competition for scarce water resources, securing household food security, and preventing environmental degradation. Increasing productivity of water is particularly important in arid and semi-arid environments where water scarcity is very high (Molden et al, 2003). Increased water productivity in the irrigated agriculture provides the baseline for food security with lower water withdrawal leaving more water available to other users within the basin (Randolph et al, 2003).

The unit of crop water productivity (CWP) in terms of seasonal crop consumptive use (Seasonal Water Used (SWU)) can calculated as:

$$CWP_{(\text{Consumptive use})} = \frac{CropYield(Kg)}{SWU(m^3)} \qquad \text{...} 2.1$$

Crop water Productivity can also be expressed in terms of Seasonal Water Applied (SWA), and can be calculated as follows:

$$CWP_{(\text{Water Applied})} = \frac{CropYield(Kg)}{SWA(m^3)} \qquad \text{...} 2.2$$

Crop water productivity can also be defined in monetary terms, expressed in terms of economic return from crop produced per volume of water, with the unit expressed in equivalent of any currency (e.g. $\$/m^3$) (Igbadun et al, 2006), and can be calculated as follows:

$$CWP_{(Economic)} = \frac{Px(CropYield(Kg))}{SWA(m^3)} \quad \ldots 2.3$$

Where P = price of crop (price/Kg crop yield)

Crop water productivity can also be described as the grain yield per unit water evapo-transpired (Tuong et al, 2003; Azevedo et al, 2006).

$$CWP_{(Evapotranspiration)} = \frac{CropYield(Kg)}{Evapotranspiration(mm)} \quad \ldots 2.4$$

The concept of crop water productivity has remained a subject of interest to plant, soil and irrigation scientists for almost 100 years now. The other term used to express the concept of water productivity is water use efficiency. These two words are use interchangeably depending on the preferences of the user (Igbadun et al, 2006).

Studies indicate that yield increases linearly with increasing water supply. Crop yield will increase with each incremental unit of water supplied until it reaches a plateau and eventually maximum yield. This is indicated by figure 2.1.

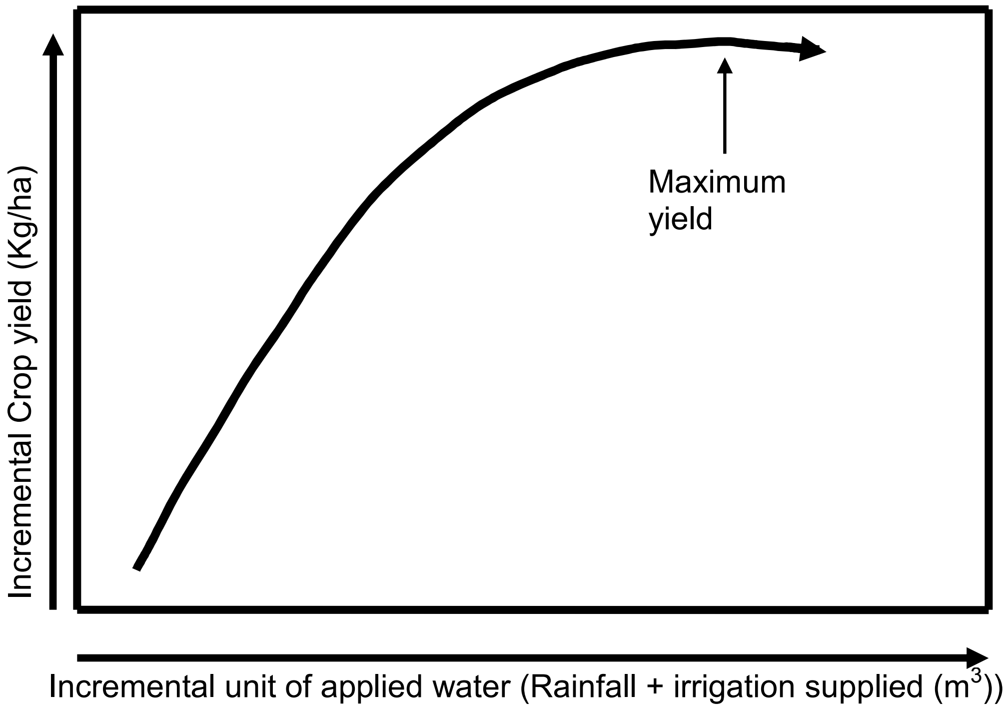

Figure 2.1: Crop yield and applied water relationship (Zhang, 2003)

It is likely that further incremental of water supply above the required water supply units to achieve maximum crop yield might cause decline in crop yield and eventual decrease in water productivity (Zhang, 2003).

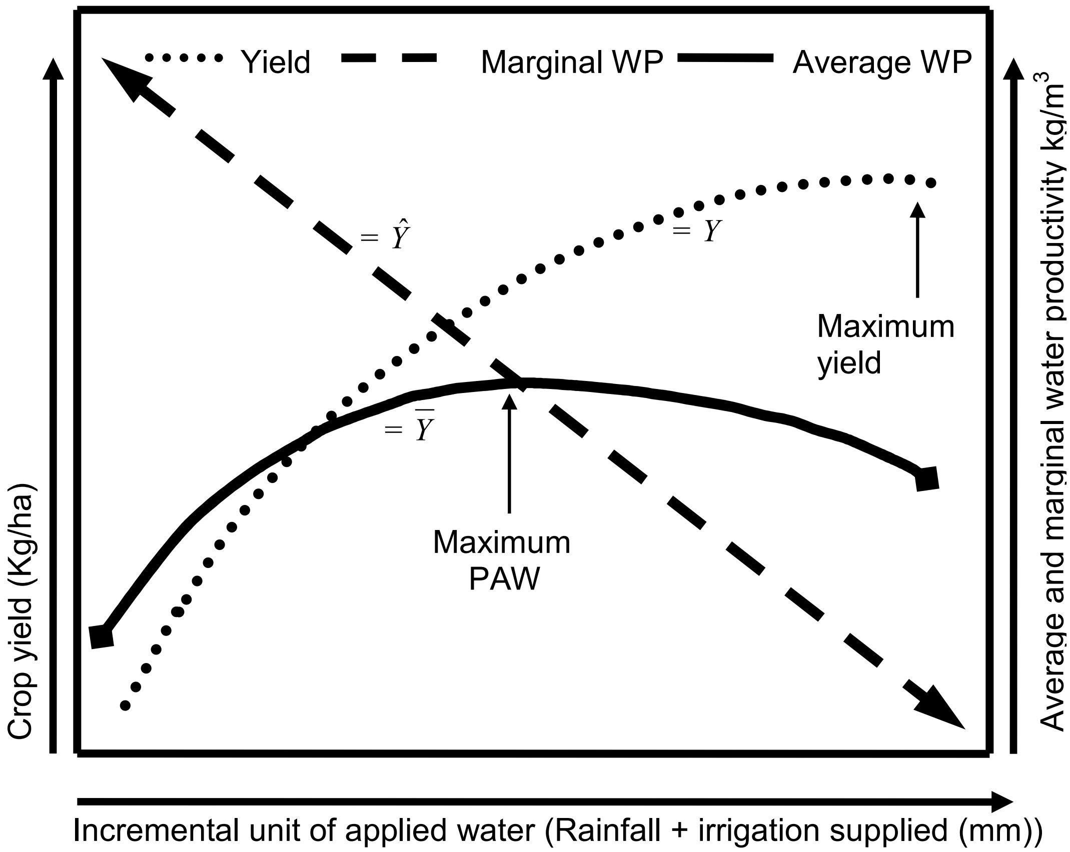

Figure 2.2: Relation of crop production, productivity of applied water (PAW) and marginal productivity to the crop water supply (Zhang, 2003)

Water use efficiency or crop water productivity is a useful tool for exploring potential increase in crop yield that may result from increased water availability. It provides farmers the opportunity to assess whether yield is limited by water supply or by other factors. Water use efficiency reveals the unit increment in yield per unit of water use, from which the impact and worth of additional water supply can be assessed. Information on crop water productivity for the particular area is therefore very crucial for effective planning of irrigation water management strategies (Igbadun et al, 2006).

The maximum yield (figure 2.2) is achieved when the marginal water productivity is equal to zero. When marginal water productivity is equal to zero, it indicates that any incremental water supply will not bring changes to crop yield. The marginal water productivity ($\hat{Y}$) is defined as the change in production associated with the addition of one unit input. It can be written as:

$$\hat{Y} = \frac{\partial Y}{\partial (P + I)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.6$$

Where in $\hat{Y}$ = Marginal water productivity

∂Y = Change in crop yield with increase of productive applied water

P = Precipitation of the growing season

I = Irrigation water applied

The productive applied water and the crop yield relationship gives farmers the insight on how they can manage available water resources. In the case of abundance water, farmers can irrigate crop to the point where marginal water productivity is equal to zero. Any further application of irrigation water beyond point of zero marginal water productivity is a waste of water because no further yield increase can be expected but possibly a yield decrease.

As indicated in figure 2.2, the maximum productivity of applied water (PAW) occurs at a value of applied water lower than that at maximum yield (Zhang, 2003). In a situation of scarce water resource, the goal will be to utilize the resource at about maximum PAW (figure 2.2).

2.4 The impact of rainwater harvesting on the crop yield improvement

"Rainwater harvesting is the process of storing accumulated rainwater for productive use" (Alemaw et al, 2006; Mbilinyi et al, 2005). In arid and semi-arid regions, rain-fed agriculture is not feasible without the use of rainwater harvesting. Long intra-seasonal dry spell and high soil moisture deficit cause frequent crop failures (Abu-awwad, 1998). Rainwater harvesting is widely used throughout the world to improve yields and water use efficiency under rainfed cropping in semi-arid areas, but has thus far received little attention in South Africa and the Southern Africa region, hence crop failures are more frequent (Laker, 2004).

In the dry areas, water, not land, is the limiting factor in improving agricultural production. Shortage of water in dry areas has prompted farmers to plant crops on a very small scale due to high risk of crop failure associated with rain-fed agriculture. Maximizing water productivity, and not yield per unit of land, is therefore a better strategy for on-farm water management (Oweis, et al, 2003).

Poor land and water management has caused high on-farm losses and land degradation. Only small portion of received rainfall is utilized by crops. To minimize these losses, rainwater harvesting will go a long way in increasing water available to crops, thereby increasing crop yield (Rockstrom et al, 2003).

The benefits associated with improving water use efficiency in agriculture have prompted the need for variety of systems to store and conserve water resources in different media for agricultural use to reduce the impacts of water stress on crop growth. Water conservation focused innovation preserves sufficient soil moisture in the root zone for crop uptake during transpiration. This is achieved by encouraging infiltration and reducing soil evaporation (e.g., conservation tillage) and by storing surface runoff for supplemental irrigation during dry spells. The importance of adopting water conservation innovation is that, though the total seasonal rainfall depth is adequate for crop production, its poor temporal distribution causes soil moisture deficits during crucial stages of the crop growth which limits crop yield (Jewitt, 2006).

Rainwater harvesting has been found to be the viable option for improving crop water productivity and food security for smallholder farmers in drought prone areas (Ngigi et al, 2005). It is one of the approaches to integrated land and water management, which could contribute to recovery of agricultural production in dry areas (Ngigi, 2003). When rainwater harvesting is practiced effectively runoff can be harnessed positively and used to enhance agronomic and conservation sustainability (Botha, 2003). Rainwater harvesting systems can be broadly categories into two. The details of these categories are illustrated in figure 2.3.

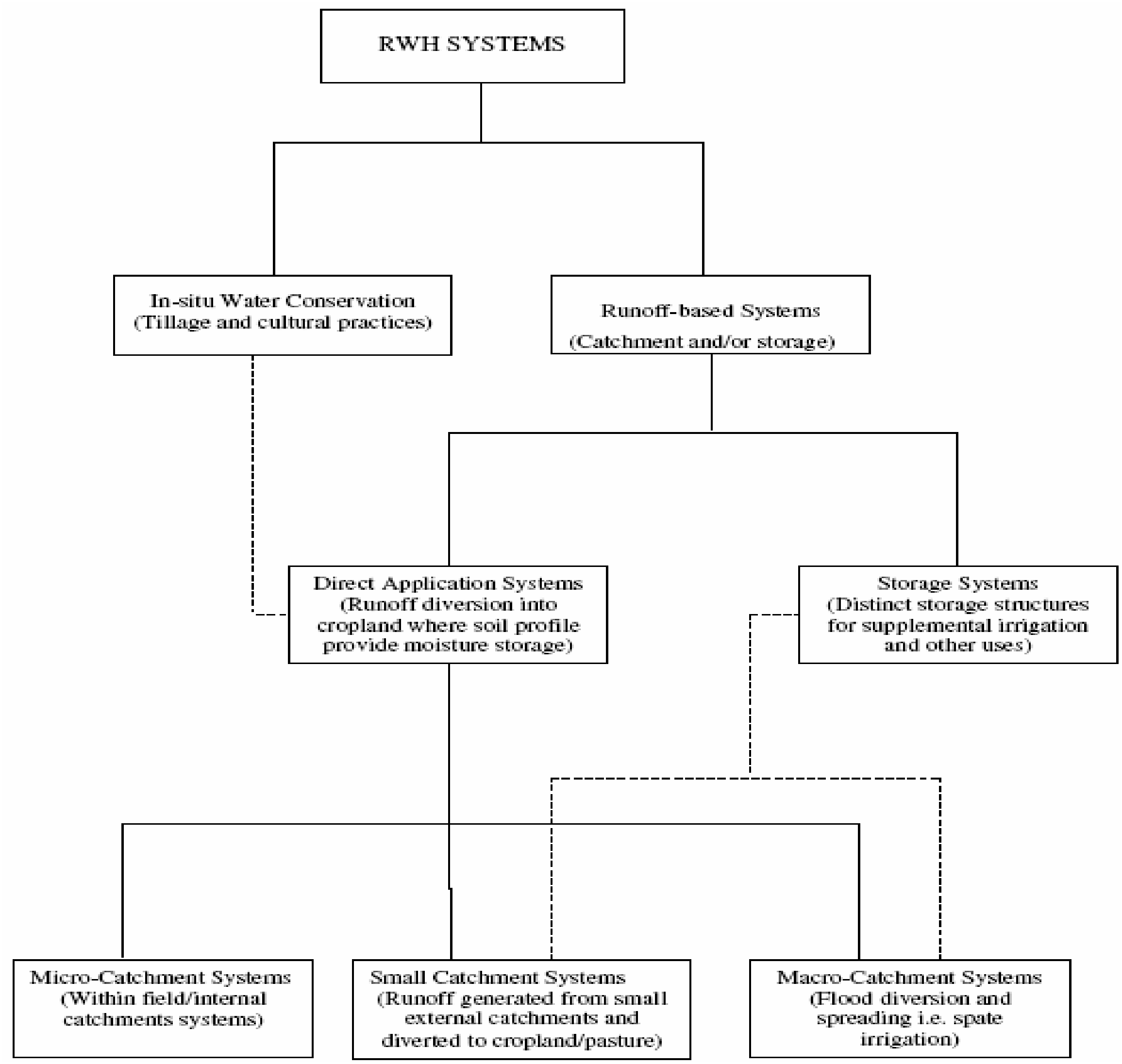

Figure 2.3: Adopted classification of rainwater harvesting technologies and systems in Sub-Saharan Africa (Ngigi, 2003).

Rainwater harvesting is a promising technology for improving the livelihoods of many inhabitants of vast dry regions of the world. Rainwater harvesting can be viable in areas with low annual rainfall. Nevertheless, the technology has been used to sustain food production in the Negev desert of Israel with an average annual rainfall of about 100 mm (Ngigi, 2003). The B72A quaternary catchment received far more annual rainfall than 100mm and this technology can improve crop production if applied effectively.

In addition to rainwater harvesting, adopting a holistic approach to management of rainwater can substantially increase crop productivity. While rainwater harvesting aims at ensuring adequate soil moisture in the soil, mulching prolongs the duration of soil moisture availability by reducing soil evaporation thereby improving crop yield.

The rainwater harvesting technologies and systems that have been tried, experimented, and practiced in different parts of Sub-Saharan Africa include in-situ rainwater conservation and the collection of run-off. In-situ rainwater conservation and run-off collection system outlined in sub-section 2.4.1.1 to 2.4.2.3 proved to be effective on securing food security for rain-fed agriculture farmers (Ngigi, 2003).

2.4.1 In-situ rainwater conservation

In situ water conservation involves conserving rainfall where it falls in the cropped area. The idea to practice in situ rainwater conservation is to enhance infiltration to maximize the amount of soil moisture within the root zone crop uptake during transpiration. In situ rainwater conservation technology is one of the simplest and cheapest rainwater harvesting technologies. The primary objective of this technology has been to conserve soil moisture hence managing the side effects of runoff (Ngigi, 2003).

2.4.1.1 Conservation farming

Conservation farming focuses on abandoning the detrimental practice of conventional soil inversion through ploughing so as to increase use of rainfall, contribute to dry spell mitigation and to increase crop yield. Research results indicate that conventional ploughing with mould board and disc plough on tropical soil contribute to soil degradation and erosion (Rockstrom, 2003). The emphasis is on soil management practices with less tillage and maintenance of more residues on the soil surface (Bowen, 2003). Improved tillage, where soil inversion is abandoned in favour of sub soiling, manual pitting, ripping and zero tillage systems, builds soil biology and improves soil fertility that contributes to immediate productivity benefits (Rockstrom, 2003).

2.4.2 Run-off collection

Run-off occurs after precipitation which is not intercepted or evaporated before it reaches ground saturates soil or when the local rate of rainfall exceeds the local infiltration capacity. The infiltration capacity is the maximum instantaneous rate of absorption of water by the soil (Wetzel et al, 1996). If the rainfall rate is greater than the infiltration rate or when soil is saturated, the excess water starts to collect at the surface and, when the surface storage is exceeded, runoff occurs (Swallow et al, 2003). As run-off occurs, it is then stored for supplement irrigation at a later stage, or applied directly into soil profile to increase soil moisture in the root zone. The run-off can either be collected within the field or from external catchment (Mupangwa et al, 2006).

2.4.2.1 Storage of harvested rainwater

Rainwater harvesting is a useful tool to control water stress and dry spell mitigation. Under normal intra-seasonal droughts which might result in a complete crop failure, storage of harvested rainwater eliminates that scenario and brings about better harvest. Stored harvested rainwater is used for supplement irrigation to control water stress on crops particularly during high soil moisture deficit period (Ngigi, 2003).

2.4.2.2 Flood diversion and spreading (spate irrigation) systems

Flood diversion and spreading (i.e. spate irrigation) involves harvesting rainwater from macro catchment concentrating in gullies and ephemeral streams. Under this practice, the concentrated rainwater is then diverted into cropped area for irrigation. The diverted harvested rainwater is normally distributed through network of canals and retained in the field by bunds and ridges to increase soil moisture within the crop root zone (Ngigi, 2003).

2.4.2.3 Small external catchment systems

These include a form of small-scale flood or run-off conveyed through natural waterways, road drainage or cutoff drains. Under this practice, run-off or flood water from road or footpath drainage is diverted either into storage for supplemental irrigation or into croplands (Ngigi, 2003).

2.5 Water allocation and irrigation efficiency in the smallholder agriculture

If food targets are to be met with less water usage, productivity of water is more meaningful performance parameter than simple yield per hectare (Murray-Rust et al, 2003). Plant water stress and eventual wilting occur when the transpiration demand exceeds the available soil water for the crop growth. For proper water management practice, detecting crop evapo-transpiration demand as early as possible can help in controlling irrigation scheduling and substantial savings of water resources (Klocke et al, 2000).

Smallholder irrigation schemes have a crucial role to play in improving crop yield. Normally water allocation between farmers in the smallholder irrigation scheme is by verbal agreement. The major problem is that smallholder irrigation schemes farmers tend to over utilise water resources. As result, they deprive other farmers within the same irrigation scheme access to water resources leading to conflicts between the farmers. Low irrigation efficiency is normally caused by variety of reasons such as design and the pricing policy (Twomlow et.al, 2006). Additional water can be made available by improving water conservation, increasing water use efficiency of existing water resources and by equitable allocation among the competing users (Chikozho, 2005).

The irrigation method determines to what extent it is possible to reduce evaporation from the soil surface while maintaining adequate soil moisture levels in the root zone to avoid crop stress but they all have the potential to be operated with minimal losses. When the farmers work in a group (e.g. a water users association), the organisational and management skills of the group are also important. Relationships between individuals and between groups strongly affect the way in which water is managed, and hence the losses which occur. As government agencies increasingly follow policies of irrigation management transfer, the capacity of farmer groups to take on new roles becomes ever more critical (Kijne, 2003; Richard, 1999).

The irrigation system in B72A quaternary catchment in all smallholder farmers irrigation scheme is furrow. Furrow irrigation method is generally perceived as less efficient irrigation system. Then more emphasis to manage irrigation water resources should be on improved irrigation design like short furrows and on water pricing policy (Laker, 2004). To improve the standard of irrigation design and irrigation efficiency, enforcement or regulation requiring irrigation technology to be designed to required standard should be implemented (Deng et al, 2006).

Irrigation technology such as low drip kits can help alleviate water scarcity problem. Surface irrigation methods have the application efficiency of about 40%-50% of water applied, but drip irrigation method has the application efficiencies of 70%-90% of supplied water because surface runoff and deep percolation losses are minimal (Maisiri et al, 2005). This allows greater access to irrigation since water demand will be lower than when using the convectional irrigation. Drip irrigation may allow more crops to be grown per unit water supplied and crop cultivation in areas where insufficient water exists to irrigate by surface methods. Drip irrigation on its own increases water use efficiency (Maisiri et al, 2005).

While majority of the farmers in the smallholder irrigation scheme like in B72A quaternary catchment would require some time to adapt and adopt drip irrigation technology due to its operational skills, emphasis should be on correctly designed short furrows that are more efficient. Experience in Kenya and Zimbabwe confirmed that correctly designed and applied short furrow irrigation can be more efficient in water use than the convectional (modern) irrigation methods, and is particularly effective when water is a limiting factor (Laker, 2004).

However, as an alternative to permanent irrigation, crop yields can be improved by deficit irrigation or short-term supplementary irrigation during dry spells (Twomlow et al, 2006). Deficit irrigation has proven to be effective in the management of water resources. The risk with deficit irrigation is low and the considerable amount of water can be saved without a significant yield reduction compared with full irrigation (Zhang, 2003). Limited irrigation means that the soil deficit is controlled at certain stages of crop growth. Studies on the effects of limited irrigation on crop yield and water use efficiency show that crop yield can largely be maintained and product quality can, in some cases, be improved while substantially reducing required irrigation demand (Kang et al, 2002).

In a situation where farmers are not willing to adopt the proposed water saving technologies, water pricing can be used to control water demand for irrigated agricultural sector. Water Pricing is recognised as one of the most important incentive measures for water demand management to achieve the objective of efficiency and sustainability of scarce water resources. The block tariffs can be used to manage available water resources for irrigation. Block tariffs compel farmers to irrigate crops within the allocated water resources boundaries to avoid penalties associated with utilising water resources beyond the allocated boundaries. As a result, farmers will be forced to adopt water saving technologies and all farmers can be assured of adequate water resources within the smallholder irrigation scheme (Savenije et al, 2003).

2.6 Models used for simulation of crop yield and water required for crop growth

Crop simulation models are mathematical representations of plant growth processes as influenced by interactions among genotype, environment, and crop management. They are the useful tool for supporting scientific research, crop management, and policy analysis. Simulation models serve different purposes, and the intended purpose influences the level of detail needed for mechanistic description of key processes, sensitivity to environment and management, data requirements, and model outputs. Cereal crop models need to simulate plant growth and development, biomass partitioning among organs (leaves, stem, root, and reproductive structures), and yield formation (Yang et al, 2003).

The usefulness of using crop models is to answer questions that otherwise could only be answered by carrying out expensive and time consuming experiments. Crop model is particularly imported in developing countries where scarce resources may limit effective agricultural production. Crop models provide insight to the farmers if they can meet the market demand. In addition, crop models help farmers make decisions about the management of their crops (Fodor and Kovacs, 2003).

The limitations of models are that, agricultural systems interaction are complex and are not completely understood. Therefore, models are crude representations of reality. Wherever knowledge is lacking, the modeler usually adopts a simplified equation to describe an extensive subsystem. Models are developed according to model purpose but simplifications are based on the developer's view and therefore constitute some degree of subjectivity. Models that do not result from strong interdisciplinary collaboration are often good in the area of the developer's expertise but are weak in other areas (Cheeroo-Nayamuth, 1999).

2.6.1 Types of crop models

2.6.1.1 Deterministic and stochastic models

A deterministic model is one that makes definite predictions for quantities (for example crop yield) from a simulation with one set of inputs and parameter values. Inaccuracies in the recorded input data may produce unsatisfactory results because deterministic model only permit one outcomes. Stochastic models allow randomness in possible outcomes due to uncertainty in the input variables but cannot predict with exactness (Cheeroo-Nayamuth, 1999).

2.6.1.2 Optimizing and simulation models

Optimising models have the specific objective of devising the best option in terms of management inputs for practical operation of the system. For deriving solutions, they use decision rules that are consistent with some optimising algorithm. This forces some rigidity into their structure resulting in restrictions in representing stochastic and dynamic aspects of agricultural systems. Simulation models form a group of models that is designed for the purpose of imitating the behaviour of a system. They are designed to imitate the system at short time intervals (for example, daily time-step) and the aspect of variability related to daily change in weather and soil conditions is integrated. The short simulation time-step demands that a large amount of input data (climate parameters, soil characteristics and crop parameters) be available for the model to run. These types of models can be used to investigate a wide range of management strategies. Most crop models that are used to estimate crop yield fall within this category (Cheeroo-Nayamuth, 1999). Crop models outlined in sub-section 2.6.1.2.1 and 2.6.1.2.2 fall within this category.

2.6.1.2.1 Generic crop model

Generic crop models describe the processes of assimilation, respiration, development and growth without regard to crop species, and are then fine-tuned to simulate the phenological and physiological traits of specific crops such as maize, rice, or potatoes. An example of generic crop model is WOFOST (Yang et al, 2003).

2.6.1.2.2 Crop specific simulation model

In contrast to generic models, specific crop model is developed to simulate growth and development of a specific crop species. Specific crop model differ considerably from generic models in both theoretical framework and treatment process that give growth and development (Yang et al, 2003).

2.6.2 Review of the selected models

2.6.2.1 APSIM

The Agricultural Production Systems Simulator (APSIM) software system has been developed in Australia to facilitate analysis of complex production and sustainability issues of agricultural systems. APSIM simulates cropping systems at the point-scale, accounting for soil chemical, physical and crop physiological growth processes on a daily time step. The model has been developed using a modular software structure so that different modules can be easily linked to adapt to different applications.

2.6.2.2 Ceres-maize

Ceres maize is one of the crop models embedded into DSSAT (Decision Support System for Agro technology Transfer). The embedded crop models under

DSSAT are the Ceres model for cereals (barley, maize, sorghum, millet, rice and wheat); the CROGRO models for legumes (dry bean, soybean, peanut and chickpea) and other models for root crops (cassava, potato) and other crops such as (sugarcane, tomato, and sunflower). Ceres maize is a process-based model that can be used to predict growth, development, and yield of a maize crop as affected by environment, genotypes, and management.

2.6.2.3 Hybrid Maize

Hybrid-Maize is a crop simulation model that uses mathematical formulations to describe the processes of maize (Zea Mays) growth and development in relation to weather, soil properties, and management factors. It has been evaluated primarily in rain-fed and irrigated maize systems of US corn belt conditions based on daily weather data. It allows the user to assess the overall site yield potential and its variability; evaluate changes in attainable yield using different choices of planting date, maize hybrid, and plant density; analyze maize growth in specific years; explore options for irrigation water management, and conduct in-season simulations to evaluate actual growth and forecast final yield starting at different growth stages. Hybrid-Maize does not allow assessment of different options for nutrient management nor does it account for yield losses due to weeds, insects, diseases, lodging, and other stresses.

2.6.2.4 Parched-Thirst

Predicting Arable Resource Capture in Hostile Environments During the Harvesting of Incident Rainfall in the Semi-arid Tropics (PARCHED-THIRST) is a process based model which combines the simulation of hydrology with growth and yield of a crop. It is a model which simulates the rainfall-runoff processes, soil moisture movement and crop growth to daily climate data.

2.6.2.5 SAPWAT

One of the important aspects in irrigation system management is the estimation of the crop water requirements grown in the system. To achieve this, SAPWAT can be used. SAPWAT is not a crop growth model but it is used to estimate crop water requirement only for areas within South Africa. It uses irrigation systems and planting dates which represent the general production patterns found in the area to estimate crop water requirement. The methodology employed in this program is based on atmospheric demand utilising the Penman-Monteith method that calculates evapo-transpiration from a sward of short grass as the reference evaporation and is similar in principle to the use of A-pan.

Chapter Three: Materials and Methods

The methodology employed in this project involved, among others included, data collection, analysis, and modelling. Both primary and secondary data collection methods have been used. Primary data collection method is the research methodology that involves direct data collection in the field. Secondary data collection involves the collection of data using relevant books, journals, magazines, historical records and the internet.

3.1 Primary data collection

The study was conducted on two consecutive summer seasons on four sites in the first season and three sites in the second season. The size of the maize plot in each site is 1 hectare. On both seasons, only one site was smallholder irrigated agriculture scheme and the remaining sites were rain-fed agriculture.

3.1.1 Gauging rainfall depth

The maize field experiments were conducted over the period of four months on four plots which are far apart within the same quaternary catchment. The trials were conducted during summer season from December 2005 to April 2006 and from December 2006 to April 2007. The rainfall data was recorded daily within the experimental plots using a manual plastic standard rain gauge.

3.1.2 Measurement of irrigation water supplied to the farm

The measurement of water supplied to the farm was done using a container. For very small channelled flows, this method involves diverting the whole flow from raised channel into a container such as bucket or barrel while recording the time taken for the container to fill. The water discharge was determined by dividing the volume of the water in the container by the filling time (Canren, 2004). The measurement was latter recorded using stage-discharge relationship of a V-notch weir. The weir was calibrated in the laboratory.

3.1.3 Runoff measurement

Runoff measurements from the fields resulting from the rainfall events were difficult to carry out. The most direct method would have been to take measurements as rain occurred, but this was not feasible because one would have had to be in the field during the rainfall event. It was particularly impracticable when it rained during the night. To overcome this problem, runoff gauging devices with data logger can be used, but the cost of these devices for four sites prevented this option to be pursued. The procedure followed was based on runoff from part of the field site that was collected in a container. In a first season, a test plot of 0.6m x 0.6m was used. Figure 3.1 illustrates this.

Figure 3.1: Runoff collection system

An improvement in the runoff collection system was made in the second summer cropping season. The runoff collection test plot of 2mx2m was used. Figure 3.2 and 3.3 illustrate this.

Figure 3.2: Modified runoff collection system

Figure 3.3: Series of runoff collection containers

3.1.4 Soil moisture content measurement

The moisture content of the soil was measured with a Hydrosense soil moisture probe manufactured by Campbell Scientific, Inc instrument. The Hydrosense system combines a compact, handheld display and sophisticated soil water sensing probe in a portable package to provide quick and reliable soil water content measurements. Soil moisture content was obtained by inserting probe rods into the soil to a depth of probe rods length (20cm) and the soil moisture reading was then displayed on the instrument screen. Soil moisture content measurement value was recorded at three points within the cropped area. This was done to assess the variation of soil moisture within the cropped area. Although soil moisture content recorded from three sites did not vary significantly, the values from three points were averaged to determine the representative soil moisture for the entire cropped area. The data was collected daily for the entire maize-cropping season.

3.1.5 Soil grain –analysis for each site

The information on grain size is crucial because it can be used to predict soil water movement (Timlin et al, 2001). The soil particle distribution analysis was done at the School of Civil and Environmental Engineering laboratory. Only one soil sample from each maize plot has been used to assess particle distribution analysis. The soil analysis data are one of the inputs into the Parched-Thirst model. Two methods have been used to compute grain size (i.e. mechanical and hydrometer grain analysis methods) and are presented in appendix B.

3.1.6 Soil nutrient analysis at each study site

Soil nutrients have been evaluated to assess the soil fertility in the study area. Only one sample was used to assess soil fertility for each parameter analysed. The soil nutrients status was analysed only at the beginning of the growing season for the two consecutive seasons of this study. The rate of soil nutrients up taking for crop growth occurs slowly and as the results nutrients depletion in the soil is slow. It is more likely that the soil nutrients status will remain unchanged for at least three consecutive years if fertilisers have not been added into the soil (Hanlon, 2001). For this reason, soil nutrients status has been assessed only once in two consecutive seasons of this study. The methods used in analysing soil nutrients are outlined in appendix C.

3.2 Secondary data collection

Secondary data collection involves data obtained from relevant books, journals, magazines, historical records and the internet.

3.2.1 Historical data collection

The historical data were collected because they are the major input data required to run the model Parched-Thirst model used to simulate crop yield. The Parched-Thirst model uses data like rainfall (mm), evaporation (mm), temperature (^{0}C), relative humidity (%), wind speed (Km/day), Saturation deficit (kPa), and Solar radiation (MJM^{-2}day^{-1}). However, only data on evaporation (mm), temperature (^{0}C), relative humidity (%), and wind speed (Km/day) were collected from the nearby meteorological station, and the data on Saturation deficit and Solar radiation were not available.

The meteorological station in B72A quaternary catchment which collects all the meteorological data has only been operating for the past eight months. Previously, only rainfall data were recorded in the B72A quaternary catchment. The model required annual long meteorological historical data and as the results, only rainfall (mm) data from meteorological station within the study area were used, and the rest of data were collected from the nearby station.

Some of the required meteorological data not recorded in the study area were obtained from tours meteorological station located at 24^0 05' 55" East latitude and 30^0 15' 30" South longitudes. The Tours meteorological station is within Olifants catchment and it is the same water management area with the study area (B72A quaternary catchment). Tours meteorological station was found to be the nearest station with the adequate meteorological data required to run the Parched-Thirst model.

Though the data on saturation deficit (kPa) was also not available at the nearby meteorological station, the relationship between temperature and humidity has been used to calculate saturation deficit (kPa).

Saturation deficit is defined as the difference between the actual vapour pressure of the moist air sample at a given temperature and the saturation vapour pressure corresponding to that temperature. It may be called dryness of the air. It is one of the important climatic variables which determined the potential growth of plant. It is the difference between the pressure exerted by the water vapour actually present in the atmosphere at a given time and given temperature and the pressure that would be exerted if the atmosphere were saturated with water vapour at the same temperature. Temperature is the major environmental factor affecting shoot growth and photosynthesis, hence closely linked to the influence of temperature is the influence of large saturation deficit (Uddin et al, 2005).

The saturation deficit was calculated by using the following equation:

Saturation deficit (SD) = ea – (RH x ea) ……………………………………..... 3.3

Wherein,

ea = Saturation vapour pressure at t °C (dry bulb)

RH = Relative humidity

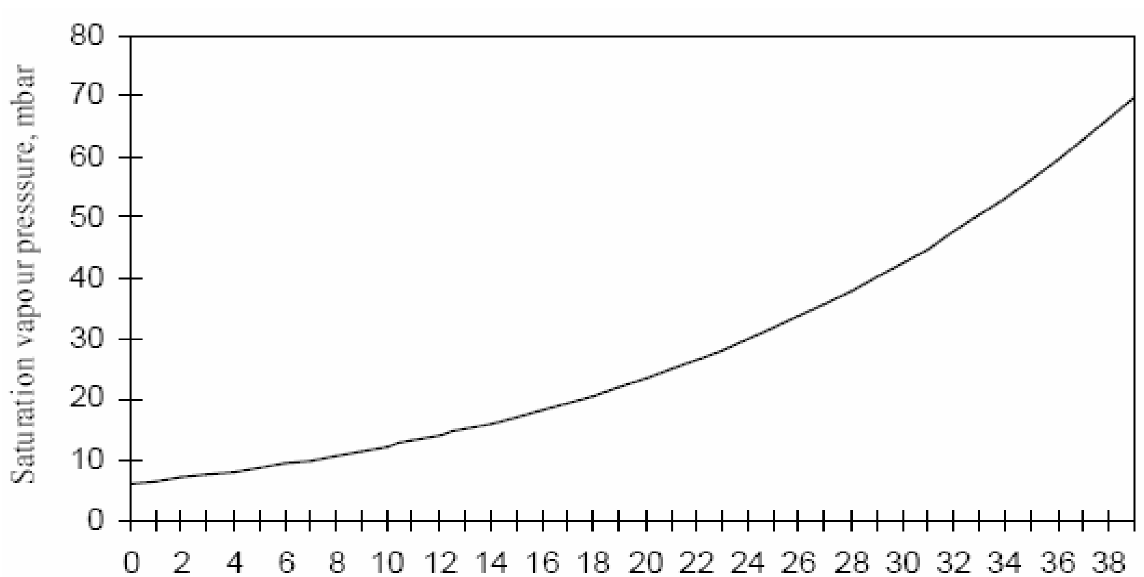

Figure 3.4: Saturation vapour pressure in mbar as function of mean air temperature (Uddin et al, 2005).

The measurement of solar radiation from Tours meteorological station were unavailable, however daily sunshine data were available. Solar radiation can be calculated using its relation to the radiation received at the top of the atmosphere (extraterrestrial radiation, R_A) and the value of actual sunshine duration hours data divided by the maximum sunshine duration hours.

The formula developed by Angstrom corrects the extraterrestrial radiation value for ratio of actual and maximum possible number of sunshine hours. This method is based on the linear relationship between the variables and assumes certain physical meaning of the coefficients (Trnka et al, 2005). This is illustrated by the equation below:

$$R_s = \left(a_A + b_A \frac{n}{D} \right) R_A \quad \text{......} 3.3$$

= $MJm^{-2}day^{-1}$

Wherein;

R_s = Solar radiation
R_A = Extraterrestrial radiation; i.e. solar radiation received on horizontal plane at the top of the atmosphere
n = Actual sunshine duration
D = Maximum sunshine duration (hours). The maximum sunshine duration hours varies with the latitude and the time of the year.

The a_A and b_A are are empirical coefficients determined for the particular site. These constants vary with the season, and region of the earth and to some extent, they depend on the time scale (i.e. daily, weekly, or monthly). The general values for South Africa are 0.24 for a_A and 0.53 for b_A.

Depending on the geographical location, extraterrestrial radiation and maximum sunshine hours values in Appendix A.1 and A.2 can be used in calculating solar radiation. The study area is located in between $24^0 00'$ and $24^0 25'00''$ South latitude, and by interpolation, actual values of maximum sunshine hours and extraterrestrial radiation were obtained. These values are summarised in table 3.6.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Extraterrestrial radiation	975.74	1008.3	802.07	691.49	595.50	556.40	565.25	658.65	784.74	876.63	987.64	989.23
Maximum sunshine hours	13.446	12.964	12.3	11.618	10.954	10.654	10.754	11.34	12.00	12.682	13.264	13.628

Table 3.6: Actual values of extraterrestrial radiation and maximum sunshine hours values for B72A quaternary catchment

Chapter Four: Modelling crop yield and crop water requirement

Two computerised programme, namely SAPWAT and PARCHED-THIRST, were used to model crop water requirements and crop yield.

4.1 Modelling crop water requirement with SAPWAT

Understanding the relationship between applied water and consumptively used water by the crop is critical in achieving optimal water use allocation. In order to optimize agricultural water use one needs to relate applied water to some measure of crop water consumption since consumptively used water is directly related to crop yield. To estimate crop water requirement, SAPWAT program has been used (Grove, 2006).

SAPWAT links to and is a development of the Food and agriculture Organization (FAO) planning model, CROPWAT, which, in turn, leans strongly on several FAO irrigation and drainage papers on irrigation management that have been published since 1979, the latest being Crop Evapotranspiration published in 1998. It is supported by extensive South African climate and crop database (van Heerden et al, 2002).

The reliable indication of seasonal crop water requirement is estimated with the program SAPWAT. SAPWAT estimates crop water requirements based on irrigation systems used in the area and the crop planting dates. The irrigation water requirement acquired using this program represents the fixed amount of water required for crop growth.

4.2 Modelling crop yield with PARCHED-THIRST

Predicting Arable Resource Capture in Hostile Environments During the Harvesting of Incident Rainfall in the Semi-arid Tropics (PARCHED-THIRST) is a process based model which combines the simulation of hydrology with growth and yield of a crop. It is a model which simulates the rainfall-runoff processes, soil moisture movement and crop growth to daily climate data. Long-term climatic data series can be used as the input data in the Parched-Thirst model to generate probable future climatic data.

Among other crop yield models outlined in subsection 2.6.1 to 2.6.4 of this report, PARCHED-THIRST simulation model has been chosen because it provides fast and reliable crop yield data. The data requirements to run this program are minimal compared to other programs which require for more data sets to run them. In addition, this program is free of charge and has been used previously in some Sub-Saharan countries like Tanzania to simulate crop yield under similar rain-fed conditions (Tumbo et al, 2004).

4.2.1 Data requirements

PARCHED-THIRST requires daily data. Its main input data are rainfall (mm), evaporation (mm), temperature (^{0}C), relative humidity (%), wind speed (Km/day), Saturation deficit (kPa), and Solar radiation (MJM^{-2}day^{-1}). To simulate crop yield, PARCHED-THIRST model uses the above mentioned data on an annual basis.

In addition, an empirical input data set consisting of specific leaf area (m^2/kg), maximum leaf area of a single plant in sparse canopy (m^2), maximum daily root extension rate (mm/d), maximum rooting depth (mm), grain number, maximum grain weight (g), soil types, bulk density of the soil (g/cm^3) and soil nutrients (fertility) are also required to simulate crop yield accurately.

4.2.2 Validation and calibration of the PARCHED-THIRST model for B72A quaternary catchment

Crop growth models simulate crop growth on the basis of parameters that affect the way crop responds to the environment. PARCHED-THIRST has been developed for arid and semi-arid environments and has shown to reliably predict crop growth and yield (Young et al, 1997). However, to use PARCHED-THIRST for B72A quaternary catchment, it must be calibrated. The calibration of PARCHED-THIRST parameters was done to correctly simulate the growth of local cultivar. To achieve this, results from field and laboratory experiments provided guidance in adjusting parameters in the model.

To calibrate this model, empirical input data measured from the laboratory and from the cultivars field observation were used in the simulations to replace default values so that simulated results closely match field observations. Though not all parameters need to be calibrated, those that were calibrated include; growth degree days (^{o}C), specific leaf area, (m^2/kg), maximum leaf area of a single plant in sparse canopy (m^2), maximum daily root extension rate (mm/d), maximum rooting depth (mm), grain number, maximum grain weight (g), soil types, bulk density of the soil (g/cm^3) and soil nutrients (fertility).

In a situation where input data are not available due to lack of time and laboratory equipment to execute experiments, trial and error was used. To validate this model, the model outputs results had been compared with the observed yield to assess whether the two results can adequately match.

Chapter Five: Results and Discussions

5.1 Soil classification in the study sites

After both mechanical and hydrometer grain-size analysis methods outlined in chapter 3 were carried out, the soil distribution graph at each agricultural site was produced and are presented in figure 5.1 to figure 5.4.

Sieve size (mm)	Type
6.7000	Gravel
4.7500	
2.3600	
1.1800	Sand
0.6000	
0.4250	
0.3000	
0.1500	
0.0750	
0.0730	Silt
0.0460	
0.0330	
0.0210	
0.0125	
0.0090	
0.0063	
0.0031	
0.0013	
0.0010	Clay

Table 5.1: Soil particle size classification (Means and Parcher, 1963; Jumikis, 1967)

Table 5.1 has been used to categorise the soils sampled from the experimented field site. The information on table 5.1 together with the information on soil distribution from figure 5.1 to figure 5.4 were used simultaneously to provide the insight on soil particle size composition for the each of the surveyed fields.

Sieve size (mm)	Soil Particle Percentage Passing (%)	Soil Particle Percentage retained (%)
6.7000	100.00	0.00
4.7500	98.50	1.50
2.3600	89.80	8.70
1.1800	76.20	13.60
0.6000	64.20	12.00
0.4250	58.40	5.80
0.3000	52.90	5.50
0.1500	41.30	11.60
0.0750	30.80	10.50
0.0730	30.25	0.55
0.0460	24.01	6.24
0.0330	16.81	7.20
0.0210	13.70	3.11
0.0125	10.90	2.80
0.0090	8.41	2.49
0.0063	8.18	0.23
0.0031	6.25	1.93
0.0013	4.41	1.84

Table 5.2: Worcester soil particle size distribution

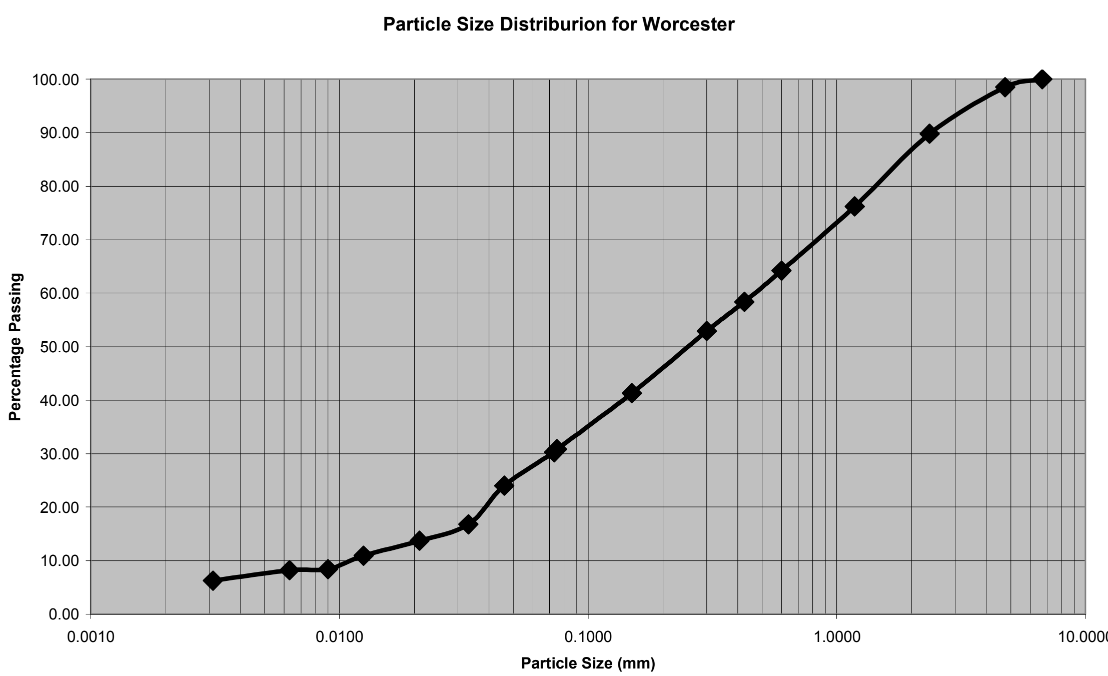

Figure 5.1: Worcester soil particle size distribution curve

Sieve size (mm)	Soil Particle Percentage Passing (%)	Soil Particle Percentage Passing (%)
6.7000	100.00	0.00
4.7500	97.40	2.60
2.3600	82.70	14.70
1.1800	65.50	17.20
0.6000	51.70	13.80
0.4250	45.06	6.64
0.3000	38.78	6.28
0.1500	27.37	11.41
0.0750	19.00	8.37
0.0720	18.00	1.00
0.0460	7.36	10.64
0.0370	4.45	2.91
0.0240	2.92	1.53
0.0140	1.81	1.11
0.0085	0.55	1.26
0.0057	0.29	0.26
0.0025	0.12	0.17
0.0009	0.01	0.11

Table 5.3: Enable soil particle size distribution

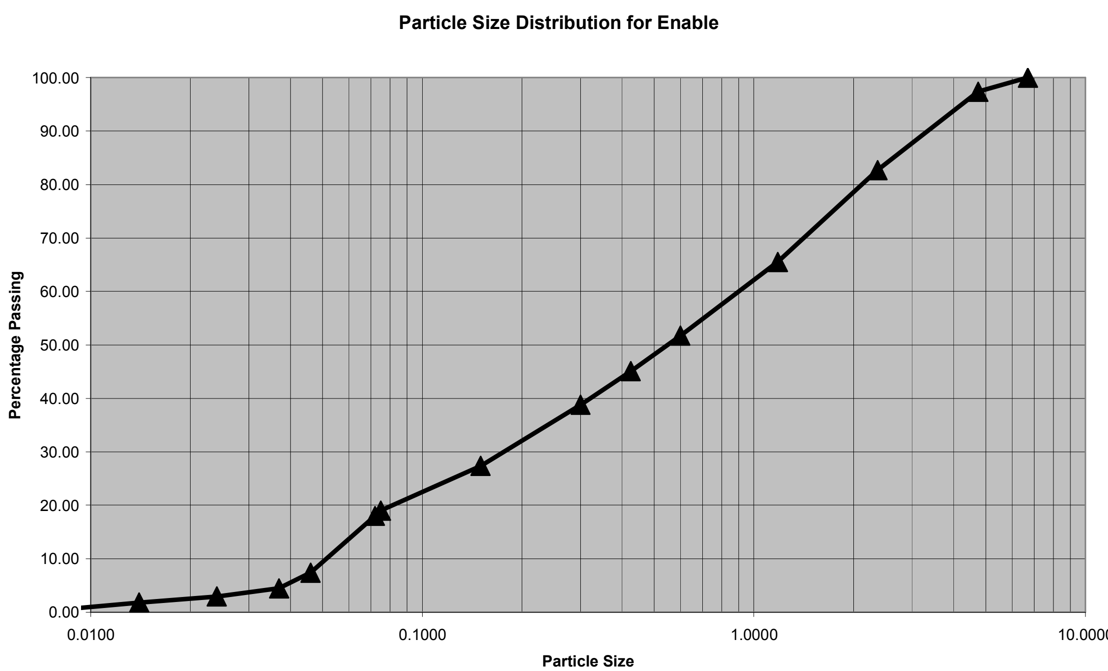

Figure 5.2: Enable soil particle size distribution curve

Sieve size (mm)	Soil Particle Percentage Passing (%)	Soil Particle Percentage Retained (%)
6.7000	100.0000	0.0000
4.7500	99.9000	0.1000
2.3600	94.0000	5.9000
1.1800	77.4000	16.6000
0.6000	62.1000	15.3000
0.4250	55.2000	6.9000
0.3000	48.3000	6.9000
0.1500	31.5000	16.8000
0.0750	20.6000	10.9000
0.0720	18.5300	2.0700
0.0480	8.0300	10.5000
0.0370	4.3000	3.7300
0.0230	1.1300	3.1700
0.0140	0.6100	0.5200
0.0096	0.1100	0.5000
0.0069	0.0200	0.0900
0.0034	0.0016	0.0184
0.0014	0.0016	0.0000

Table 5.4: Ha-Fanie soil particle size distribution

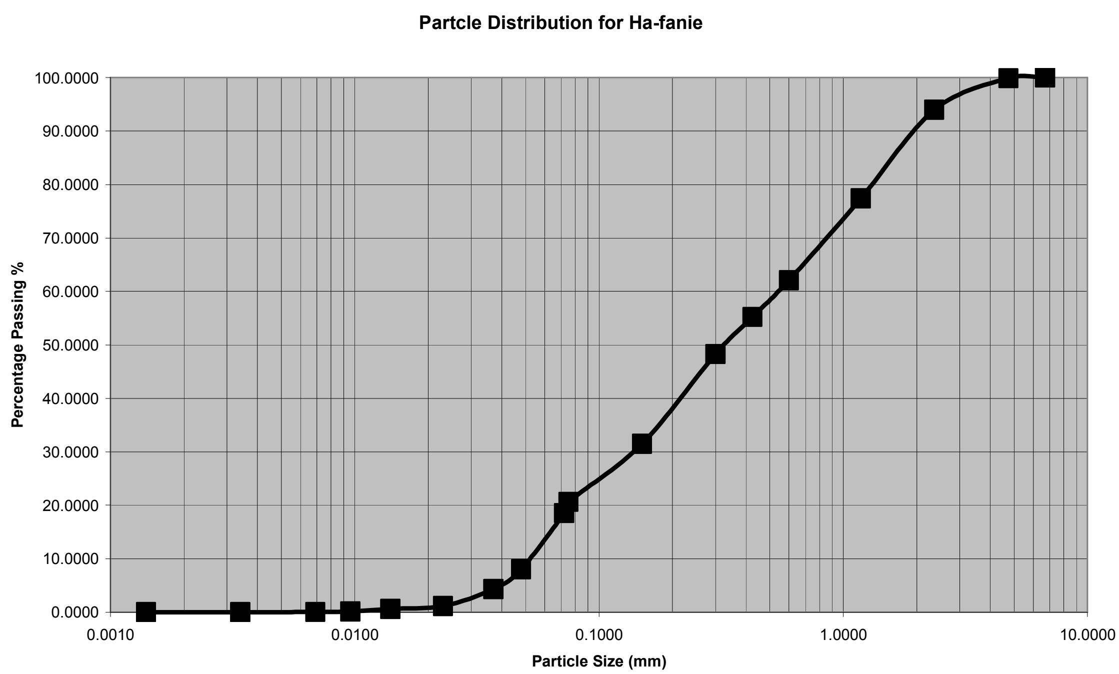

Figure 5.3: Ha-Fanie soil particle size distribution curve

Sieve size (mm)	Soil Particle Percentage Passing (%)	Soil Particle Percentage Retained (%)
6.7000	100.00	0.00
4.7500	99.70	0.30
2.3600	98.80	0.90
1.1800	93.80	5.00
0.6000	83.70	10.10
0.4250	77.20	6.50
0.3000	70.10	7.10
0.1500	54.90	15.90
0.0750	45.40	9.50
0.0750	44.44	0.96
0.0500	34.46	9.98
0.0310	30.17	4.29
0.0190	24.00	6.17
0.0125	21.87	2.13
0.0084	18.31	3.56
0.0060	16.64	1.67
0.0030	15.37	1.27
0.0013	10.14	5.23

Table 5.5: Sofaya soil particle size distribution

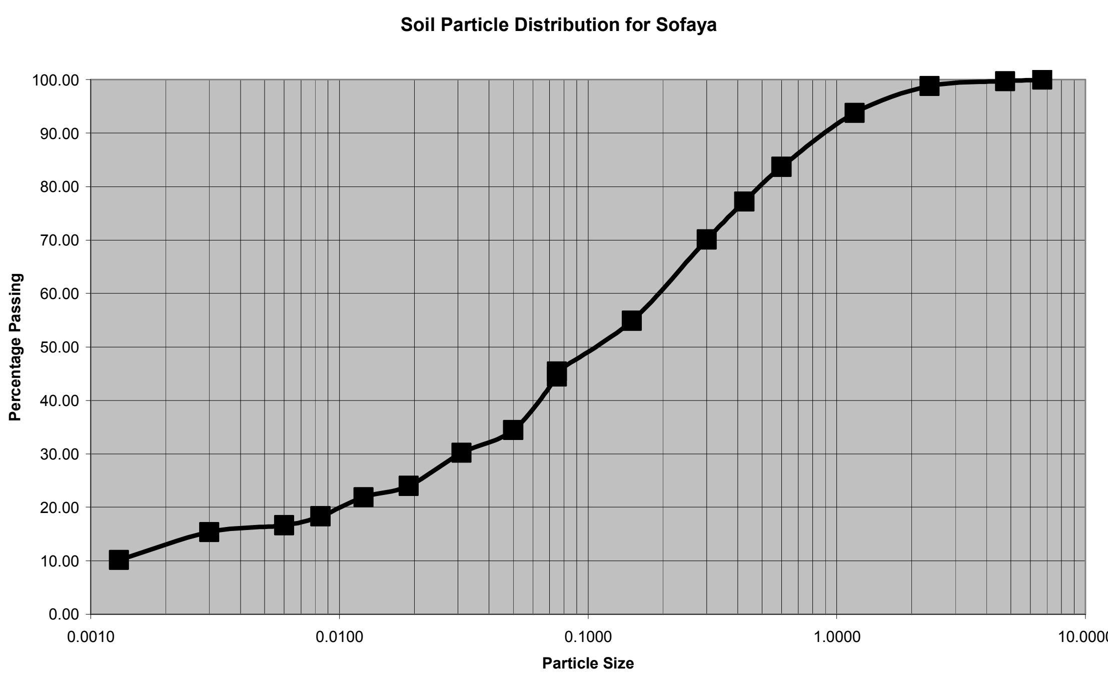

Figure 5.4: Sofaya soil particle size distribution curve

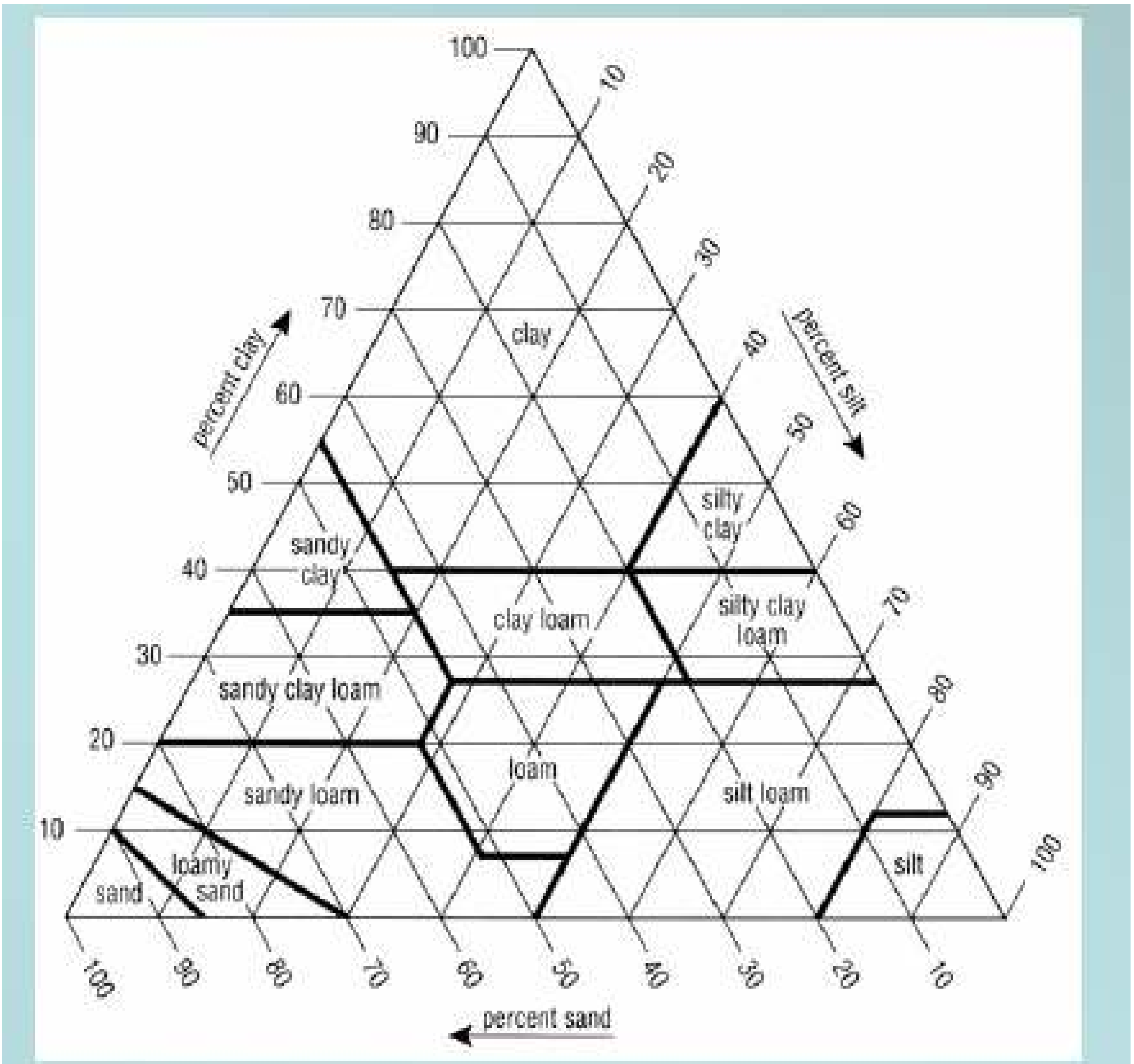

Figure 5.5 USDA Soil textural classifications (UWYO, 2007)

Place	Soil particles percentage (%)			Soil type
	Sand	Silt	Clay	
Enable	81	18.9	0.1	Loamy sand
Sofaya	55	35	10	Sandy loam
Ha-Fanie	79.4	20.6	0	Loamy sand
Worcester	69	26	5	Sandy loam

Table 5.6: Soil type on each study site

5.2 Irrigation water requirement results modelled with SAPWAT in B72A quaternary catchment

The reliable indication of seasonal crop water requirement is estimated with the program SAPWAT by using irrigation systems and planting dates that represent the general production patterns found in the B72A quaternary catchment. Considering that the irrigation furrows in B72A quaternary catchment are long, the water application efficiency is likely to be between 40% - 50% of the applied water (Maisiri, et al, 2005). Long furrow irrigation has low water application efficiency compared to short furrow irrigation (Laker, 2004).

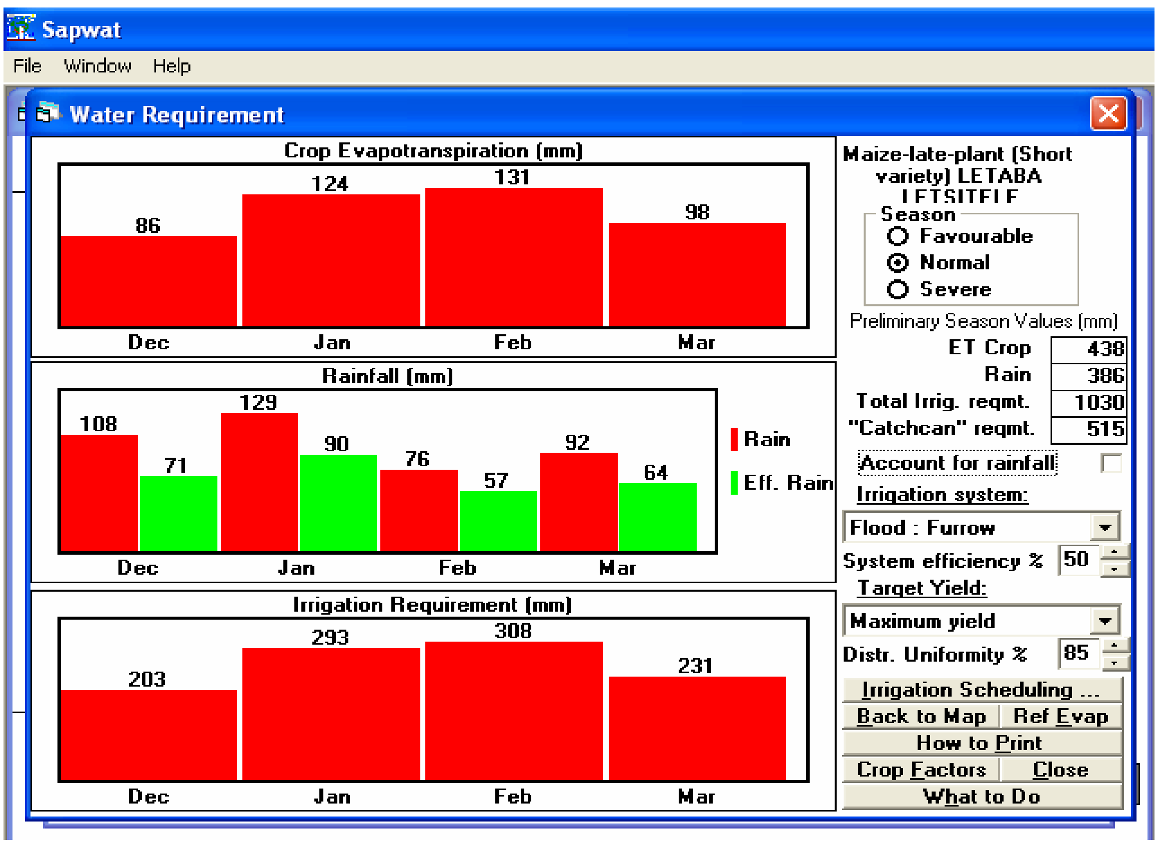

Figure 5.6: Seasonal irrigation water requirement estimation for maize crop grown in B72A quaternary catchment modelled with SAPWAT

After running the SAPWAT model, the results indicate that, at the current water application efficiency of 50% of the irrigation water supplied, water requirement to achieve maximum yield for maize crops grown in the study area is 1030mm as shown by figure 5.6. However, the results also indicate that if water application efficiency of the supplied water is improved to 75% by making use of short furrows and by increasing the retention of rainwater in the soil within the root zone, the irrigation water requirement can be reduced to 330mm while maintaining the maximum crop yield and this fulfills specific objective 1.6.2.2. This then becomes an efficient water management strategy as irrigation demand is reduced by 68%. Improving rainwater use efficiency and water application efficiency will definitely provide saving in the available water resources to irrigate winter crops where water stress is very high.

5.3 Soil nutrients status in the study sites

Soil nutrient test results are used to evaluate fertility and provide a measure of the soil nutrients that are expected to become plant-available. Measurements of total nutrients content are not useful indicators of sufficiency for plant growth, because only a small portion of the nutrients are plant available. To assess the soil nutrients status in the study area, some form of rating scale has been adopted (Marx et al, 1999).

According to Hanlon (2001) classification, the terminologies outlined below are used to provide an insight on the level of soil nutrients and the probable crop yield.

Low	Less than 50% of crop yield potential is expected without addition of the nutrient in question. Yield increase to the added nutrient is always expected. A large portion of the crop nutrient requirement must come from fertilization.

Medium	50 to 75% of the crop yield potential is expected without addition of the nutrient. Yield increase to added nutrient is expected. A portion of the crop nutrient requirement must come from fertilization.
High	75 to 100% of the crop yield potential is expected without addition of the nutrient. Yield increase to added nutrient is expected. A small portion of the crop nutrient requirement must come from fertilization.
Extremely high	Yield increase to the added nutrient is not expected. The soil can supply the entire crop nutrient requirement. No additional fertilizer is needed. Very high yield increase to the added nutrient is not expected. The soil can supply much more than the entire crop nutrient requirement. Additional fertilizer should not be added to avoid nutritional problems and adverse environmental consequences.

The guideline presented in table 5.7 is used to interpret soil test results. These guidelines are an important element to be used in the soil nutrient management (Marx et al, 1999).

Interpretation	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Phosphorus (P)	Nitrogen (NH_4^+-N)	Nitrogen (NO_3^--N)	PH
Low	< 150 ppm	< 1000 ppm	< 60 ppm	< 20 ppm	< 2 ppm	< 10 ppm	6.6-1
Medium	150-250 ppm	1000-2000 ppm	60-180 ppm	20-40 ppm	2-10 ppm	10-20 ppm	6.6-7.3
High	250-800 ppm	> 2000 ppm	>180 ppm	40-100 ppm	> 10 ppm	20-30 ppm	7.3-14
Extremely high	> 800 ppm	None	None	> 100 ppm	None	> 100 ppm	None

Table 5.7: The guideline table to interpret soil test results (Marx et al, 1999)

The data presented in table 5.8 are the results from the soil nutrients test analysis in the sites of the study area (Sekororo B72A), during the 2005/2006 cropping season. The figures related to table 5.8 are outlined in appendix C. These data are compared to the guideline values presented in table 5.7 to determine whether the soil nutrients in the study sites meet the standard soil nutrient requirements for growing maize.

Place	K (ppm)	Ca (ppm)	Mg (ppm)	P (ppm)	NH_4^+-N (ppm)	NO_3^--N (ppm)	OM (C) g/100g	PH
Enable	117	3489	343	3	2.73	0.834	0.0121	7.2
Worcester	145	3505	428	0	1.98	0.615	0.0132	5
Ha-Fanie	54	239	354	2.4	3.9	0.517	0.0061	4
Sofaya	100	1927	284	2.4	8.47	0.556	0.0126	5.1

Table 5.8: Soil nutrients status in the study sites for summer cropping season 2005 to 2006

The soils in the study sites are deficiency in Nitrogen, the most important macronutrient required for growing maize. The soils are also lacking other important nutrients, like phosphorus and potassium. According to rating guidelines in table 5.7, the three most important macronutrients (Nitrogen, Phosphorus, Potassium) in the study sites are low (Table 5.8).

Soil nutrient is an important factor for crop growth. Farmers need to first improve soil fertility in their farms before attempting to improve other variables like water and weeding. Fertile soil conserves soil moisture and improves crop water use efficiency.

Nitrogen is important in improving water use efficiency and soil water use, while Phosphorus plays an important role in increasing not only total soil water use but also water extraction from deep soil layer (Deng et al, 2006). Lack of macronutrients in the soil results in poor extraction of water by crops causing irrigated or rainwater being lost to deep percolation or evaporation. It is crucial that farmers in B72A quaternary catchment do enhance soil fertility at the same time with efficient water application.

On average, maize is capable of yielding 12 t/ha under well nourished conditions (Wadsworth, 2003). At current level of soil nutrient in B72A quaternary catchment, crop yield is expected to be less than 50% (i.e. 6t/ha) of the maximum crop yield under well nourished conditions regardless of improving water supply.

5.4 Water allocation to achieve maximum crop yield in B72A quaternary catchment

A water pricing policy for the allocation water in B72A quaternary catchment irrigation scheme does not currently exist. This has given farmers in the area no incentives to utilised water efficiently. Currently the farmers do not pay for water. The water allocation between the farmers is not always equitable or efficient, and this problem is even worse during drought winter months when there is little rainfall or during drought years when water resource is very scarce. Conflicts between the farmers arise when they have to start competing to get limited water resource for irrigation. The water allocation between the farmers in B72A irrigation schemes is based on verbal agreements and not on pricing policy or economic instruments (Ntsheme, 2005). That same study revealed that despite the existence of a water distribution mechanism, some individuals use various means to get water without following the laid down procedures especially during dry conditions. This is because there is no enough water and farmers are not sure whether irrigation crop water requirements will be met for the entire cropping season. As a result, competition for water between the farmers is intensified, giving rise to conflicts between them. The solution to this problem can be achieved if rainwater use efficiency is increased for summer crops, thereby making available water supplement irrigation during summer and full irrigation for winter crops.

In areas where there are no irrigation schemes in B72A quaternary catchment, small underground rainwater harvesting reservoirs funded by World Vision organisation are constructed to collect summer rains to irrigate winter crops. The major challenge facing small scale and backyard farmers in B72A quaternary catchment is the shortage of water during winter months due to lack of adequate reservoir facilities to store harvested rainwater . The constructed reservoirs are relatively small, but if used efficiently, food security during summer and winter seasons can be assured.

To ensure that water is available for winter crops, the harvested early summer rainfall can be used to bridge intra-seasonal dry spell to improve crop water use efficiency for summer crops, and the harvested late summer rainfall can be reserved for winter crops. The major cause for crop failure in maize production is related to moisture deficit at the critical growth stage of the crops. Bridging moisture deficit with early harvested rainfall during critical growth stage of maize crops will assure farmers with higher yields. The late summer rainfall would then be stored to irrigate winter crops.

Though the constructed rainwater harvesting reservoirs are relatively small, they can provide at least some food security during winter months compared to what farmers are currently getting. Some farmers indicated that due to shortage of water during winter months they use household generated grey water to irrigate only $6m^2$ of planted winter crops to reap some harvest.

The harvested rainwater is allocated to winter crops like tomatoes, cabbage, and spinach. Table 5.9 outlines the rainwater harvesting reservoir capacity, possible irrigation area and allocated water to each site. In allocating water resources to each planted crop type, the crop water requirements for winter crops were estimated using SAPWAT, and the quantity of harvested water is equivalent to reservoir size at the commencement of the cropping season. Estimating crop water requirement with SAPWAT and the quantity of water harvested determines the size of the land that can be irrigated so that crop water demand is fully met. The table 5.9 illustrates this.

Place	Crop water requirements (ET, mm) (From SAPWAT)			Reservoir Storage (m^3)		Volume of water to be supplied per crop type (m^3)			Area size to be planted per crop type (m^2)	Total area to be planted (m^2)
	Tomato	Cabbage	Spinach	Tank 1	Tank 2	Tomato	Cabbage	Spinach		
Enable	514	251	581	57	25	31.3	15.3	35.4	60.9	183
Ha-Fanie	514	251	581	25	0	9.6	4.7	10.8	18.6	56
Sofaya	514	251	581	25	0	9.6	4.7	10.8	18.6	56
Worcester	514	251	581	57	0	21.7	10.6	24.6	42.3	127

Table 5.9: Harvested water allocation to different crop types per cropping winter season

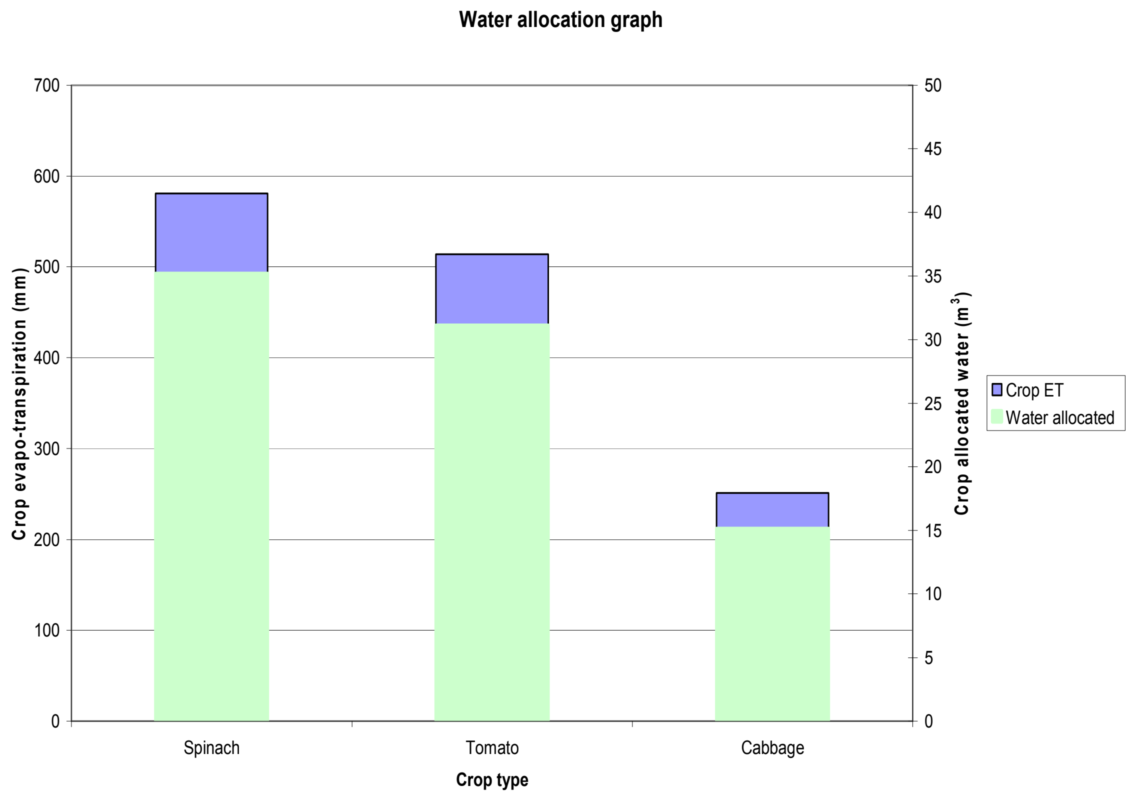

Figure 5.7: Enable water allocation graph for each planted crop type per 60.6 m^2

The graphs for the remaining three sites are presented in appendix D. The graphs indicate that for the study site with rainwater harvesting reservoir of given capacity outlined in table 5.9, the reservoir is only able to supply irrigation water to a land size that depends on the crop type or the crop water demand. For example, from the m^3 reservoir in Enable water allocation to tomatoes, cabbage, and spinach will be done according to the relative magnitude of their evapo-transpiration demand of 514mm, 251mm, and 581mm, respectively. In other words, tomatoes, cabbage, and spinach will be allocated 31.3 m^3, 15.3 m^3 and 35.4 m^3 of water. Due to small rainwater harvesting reservoirs, only small portion of the land can be cropped. On average each cultivar will need to be cropped over a maximum area of 61 m^2 in order not to have any water deficit. The total area that would be cropped for all three crop cultivars mentioned above at Enable site would be 183 m^2. The detailed results are outlined in table 5.9. Crop evapo-transpiration demand has been modelled with SAPWAT. Farmers in some areas of B72A quaternary catchment like Enable use grey water to irrigate winter crops on a very small scale of 6 m^2, so 183 m^2 is an improved area that farmers can irrigate using harvested rainwater at Enable to reap some yield.

5.5 Volume of irrigation water supplied to grow crops in the irrigation schemes in the study area

The volume of water supplied to the farm per irrigation schedule was measured as explained in 3.1.2. The discharge measured was 9 litres per seconds. To calculate the actual volume of water supplied to the farm per schedule, the measured discharge is multiplied by average duration for irrigation. With an average estimated time of 4 hours taken to irrigate the one hectare field at supply rate of 9 litres per second, the volume of water supplied to the farm per irrigation schedule is 129.6 m^3.

The irrigation depth of water supplied, was estimated by the equation 5.1.

$$V = A \times D \qquad (5.1)$$

Where in V = Volume of water supplied

A = Area of the crop field

D = Depth of the water supplied

The size of agricultural plot for crop production for the smallholder farmers in the study sites is 1 hectare, then irrigation depth was calculated to be 12.96 mm per irrigation schedule.

5.6 The on-farm water budget assessment in the study area

The soil water budget has been assessed by collecting seasonal agro-meteorological data on a daily basis. The water balance relationship for crop production was adopted in the computation of soil water balance components (Walker et al, 2003). The water balance relationship for crop production has been assessed for the entire seasonal, but the data were collected on a daily basis in order to identify any significant change in the water balance within short period of time. To assess the water balance data for the whole seasonal, collected daily parameters data for the whole season are summed to obtain the seasonal data. Equation 5.2 has been used to assess seasonal water balance.

$$T = (P + \Delta S) - (E_S + RO + D) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 5.2$$

Where in;

P is the precipitation during the growing season (mm)

T is the seasonal water uptake by the plant roots (mm), essentially the transpiration from crop canopy

RO is the run-off from the field during the growing season (mm)

D is deep drainage beyond the root zone of the crop during the cropping season (mm)

E_S is the amount of seasonal soil evaporation (mm)

ΔS is the seasonal change in soil water content (mm) of the root zone (i.e. difference between the sowing time soil water and final harvest soil water).

However equation 5.2 has been rearranged and used as follows for the rain-fed agriculture.

$$ET = (P + \Delta S) - (RO + D) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 5.3$$

Where in ET = Evapo-transpiration

In the irrigated agriculture, soil water budget has been calculated as follows;

$$ET = (P + irr + \Delta S) - (RO + D) \quad \text{……} 5.4$$

Wherein irr = Seasonal irrigation water to the farm

The table 5.10 indicates the measured and the calculated water balance values for 2005/2006 cropping season for the four sites.

Place	P (mm)	Irrigation (mm)	∆S (mm)	RO (mm)	D (mm)	ET (mm)	Run-off percentage (%)
Worcester	1072	0	-44	436	0	592	41
Enable	1112	0	-22	411	0	677	37
Ha-Fanie	1234	0	-42	406	0	786	33
Sofaya	1422	120	-40	630	0	872	44
Average							39

Table 5.10: Water Budget table for the maize crops during 2005/2006 cropping season

The root zone for maize crop considered in this study is 1500mm (du Plessis, 2003). The deep drainage beyond root zone was considered minimal and therefore neglected during the growing seasons. This may be a good assumption due to the high run-off that occurred during the growing season. On average 39% of the received rainfall during 2005/2006 cropping season has been lost to run-off.

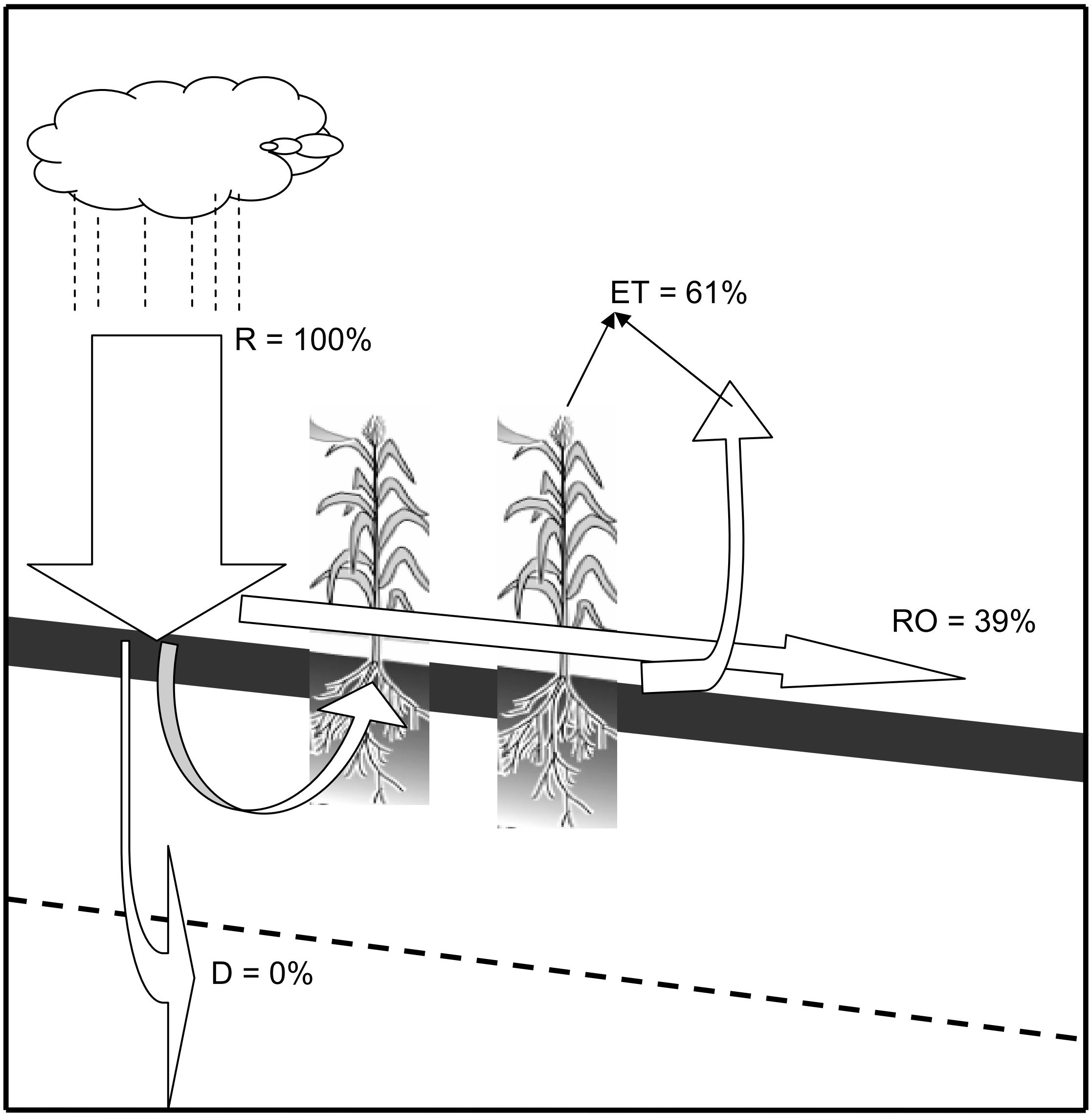

Figure 5.8: Rainfall partition for agricultural use at B72A quaternary catchment

Table 5.10 and figure 5.8 clearly indicate that current rainfall partitioning for agricultural use in B72A quaternary catchment contributes to low yields and crop failures. On average, collected data for 2005/2006 cropping season in B72A quaternary catchment indicate that 39% of the received rainfall has been lost to run-off while 61% has been used for evapo-transpiration demand. Similar study by Walker et al (2003) reported that, 38% of the evapo-transpired water is lost to soil evaporation which is not beneficial for crop growth and only 71% of evapo-transpired water is used for crop growth. By considering all rainwater and soil evaporation loss that occurs in crop agriculture in the studied sites for 2005/2006 cropping season, it can be deduced that only 39% of received rainfall has been used for crop growth. The results indicate that poor utilizing of rainwater for agriculture in B72A quaternary catchment is the major contributing factor for low crop yield and crop failures. While only 39% of the received rainfall is been used for crop growth, there is a window for crop yield improvement if green water use can be improved to at least 70% of the received rainfall. Improved land and water management like rainwater harvesting, mulching and improving soil fertility can drastically increase green water use for rain-fed agriculture.

5.7 Crop water use efficiency in the study area

The water use efficiency is defined as the ratio of crop output to water input, as outlined in chapter two of this study. It is a measure which relates the water use of plants to their growth or production (van Der Zel et al, 1993). Depending on the type of water considered, water use efficiency can be expressed in terms of seasonal water used, seasonal water applied, seasonal water evapo-transpired or seasonal water transpired.

In this study, water use efficiency has been calculated in terms of seasonal water evapo-transpired (mm). To calculate water use efficiency, equation 2.4 is used. Evapo-transpiration is preferred as a measure of crop consumptive water although it does include evaporation from the soil. The reason is that there is a linear relationship between ET (mm) and crop yield (Grove, 2006). In addition, because of the difficulty of separating soil evaporation losses from plant transpired water, it is easier to express water use efficiency in terms of the evapo-transpiration.

$$WUE_{(Evapotranspiration)} = \frac{CropYield(Kg)}{Evapotranspiration(mm)}$$

Place	Rainfall (mm)	Irrigation (mm)	Evapo-transpiration (mm)	Crop Yield (t/ha)	Water Productivity (Kg/mm)
Worcester	1072	0	592	0.6	1.01
Enable	1112	0	677	0.8	1.20
Ha-Fanie	1234	0	786	0.9	1.15
Sofaya	1422	120	872	2	2.30

Table 5.11: Observed maize yield and calculated water use efficiency in B72A quaternary catchment for 2005/2006 cropping season

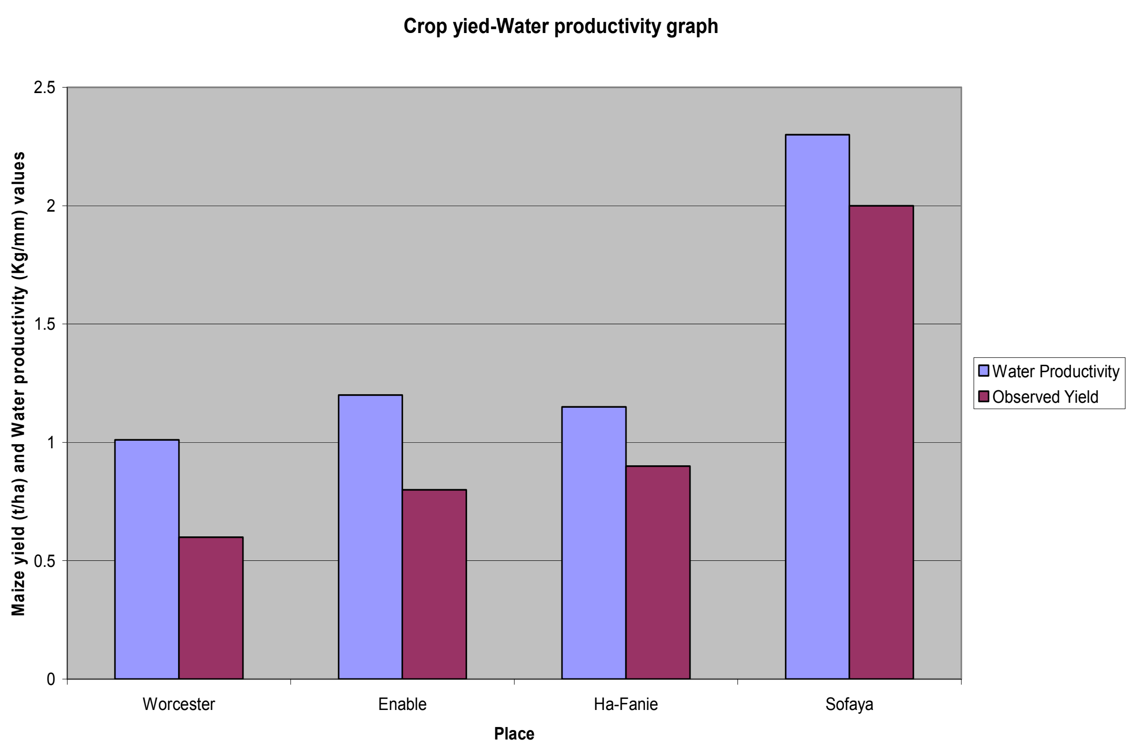

Figure 5.9: Actual maize yield measured and calculated water productivity for the 2005/2006 summer season in B72A quaternary catchment

Under average rainfall of 500 mm, the average crop yield in B72A Quaternary catchment is about 0.3 t/ha for rain-fed agriculture. The improved crop yield presented on table 5.11 under 2005/2006 summer cropping season is linked to above average seasonal rainfall which increased crop evapo-transpired water. During the 2005/2006 summer cropping season, the rainfall doubled, providing more water to sustain crop.

5.8 Crop yield results modelled with Parched-Thirst

The model simulates crop yield by incorporating scenarios with and without rainwater harvesting. Simulating crop yield under rainwater harvesting scenario provides an insight into the benefits that are likely to be derived from this practice. Farmers in B72A quaternary catchment do not currently practise rainwater harvesting to grow their crops, so it is important to simulate crop yield under rainwater harvesting to have an insight on how much crop yield can be harvested if rainwater harvesting is practised.

To simulate crop yield under rainwater harvesting condition, climatic data for 1998/1999 cropping season has been used. The climatic data from this season has been used because its data is complete and has seasonal rainfall amount of 530mm, closer to average seasonal rainfall of the catchment. The simulated crop yield indicates that maize yield of 0.8t/ha can be harvested if rainwater harvesting is practised.

5.9 Comparison between the simulated maize yield and the measured maize yield at B72A quaternary catchment for 2005/2006 cropping summer season

The 1998/1999 climatic data was used to simulate crop yield under conditions wherein rainwater harvesting is practised, while 2005/2006 climatic data was used to simulate crop yield under conditions wherein rainwater harvesting is not practised. The reason why two seasonal climatic data instead of one has been used to simulate these scenarios is because each climatic data partially meets the need for modelling these scenarios.

The 1998/1999 seasonal data has been used for modelling the scenario with rainwater harvesting because they present normal rainfall season for the catchment. Modelling with normal climatic conditions provides realistic insight into how much crop yield farmers can get when harvesting is practised unlike modelling with extreme climatic conditions (i.e. very dry or very wet conditions). The 2005/2006 climatic data was not used in this scenario for this reason because the season was too wet, with an average rainfall of 1139mm or twice the rainfall which is received under normal rainfall season.

The actual field observation data measured from previous years indicate that average crop yield is 0.3t/ha for rain-fed agriculture in B72A Quaternary catchment under average rainfall of 500 mm. The simulated data with PARCHED-THIRST indicate that the crop yield could be improved to 0.8 t/ha under average rainfall of 530mm if rainwater harvesting is practiced. Maize yield of 0.8 t/ha is a much more improved yield compared to 0.3 t/ha which farmers are currently getting under the same rainfall amount. It can be observed from the modelled results that rainfall amount which produces crop yield of 0.3 t/ha in B72A quaternary catchment can be doubled or even quadrupled crop yield if rainwater harvesting is practiced and this fulfills specific objective 1.6.2.1.

The rainfall deficit aggravated by poor partition is the major factor contributing to crop failures due to poor seasonal soil moisture to meet crop evapo-transpiration demand. Maize is an efficient user of water in terms of total dry matter production and among cereals it is potentially the highest yielding grain crop. For maximum production a medium maturity grain crop requires between 500 and 800 mm of water depending on climate (FAO, 2002). On average, maize is capable of yielding 12 t/ha under well nourished conditions (Wadsworth, 2003).

The 2005/2006 climatic data has been used to simulate crop yield under conditions wherein rainwater harvesting is not practised to assess the level of variation between simulated yield and observed yield. The 2005/2006 climatic data has been used only for this scenario because both crop yield and rainfall data were collected on four sites within the catchment making it easy to assess the level of variation between the simulated yield and actual measured crop yield The reason not to use 1998/1999 climatic data for this scenario is that only one set of climatic data is available simulate crop yield for whole catchment. The simulated crop yield and observed crop yield data are presented in table 5.12.

Place	Rainfall (mm)	Irrigation (mm)	Measured Crop Yield (t/ha)	Simulated crop yield (t/ha)
Worcester	1072	0	0.6	0.5
Enable	1112	0	0.8	0.9
Ha-Fanie	1234	0	0.9	1
Sofaya	1422	120	2	1.2

Table 5.12: Simulated-measured crop yield

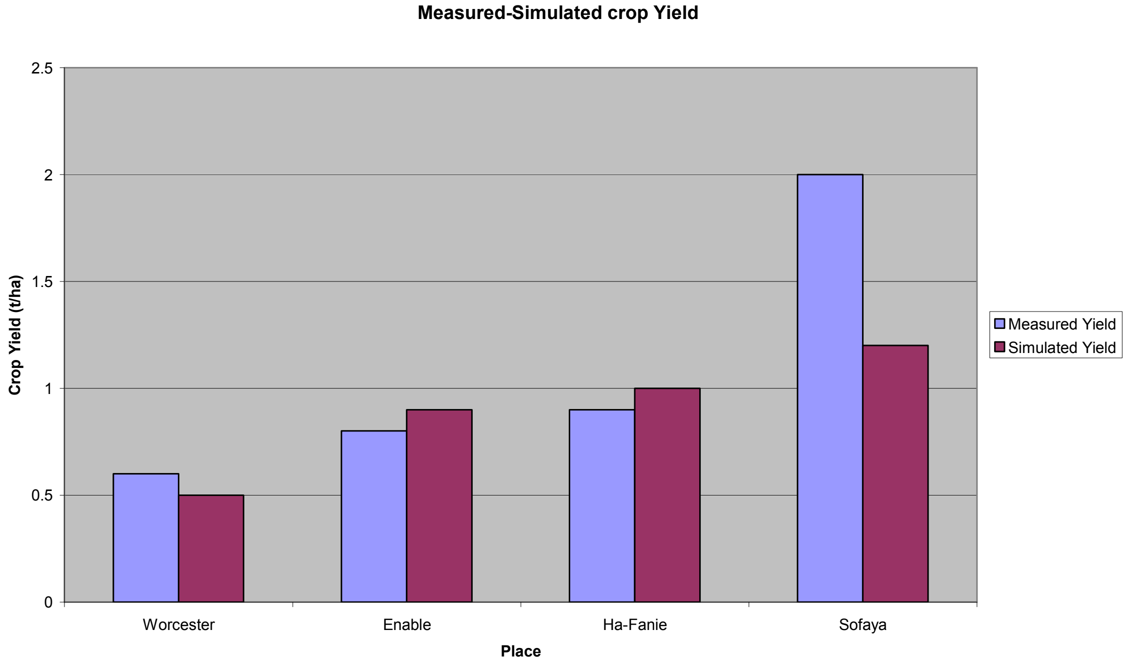

Figure 5.10 Measured-Simulated crop yields

The crop yield variation between measured yield and simulated yield has shown to be very high for Sofaya study site. The reason might that; Sofaya farmers irrigate their crops particularly during extended dry spell within cropping season. PARCHED-THIRST does not capture moisture added due to irrigation.

Though the recorded rainfall in B72A quaternary catchment was above 1000mm for 2005/2006 summer season, adequate to sustain crop to produce maximum yield, the maize yield was still very low, recording as low as 0.6 t/ha in some areas. The data collected indicate that rainfall was poorly distributed, coupled with increased run off and was concentrated on one part of the season with the prolonged intra-seasonal dry spell early in the season. Figure 5.8 indicates that seasonal runoff made 39 % of the total rainfall occurred. As a result, soil did not have adequate moisture to sustain crop growth throughout the entire season. The crops were affected by the prolonged intra-seasonal dry spell causing moisture deficit during the moisture sensitive growth stage of the crop.

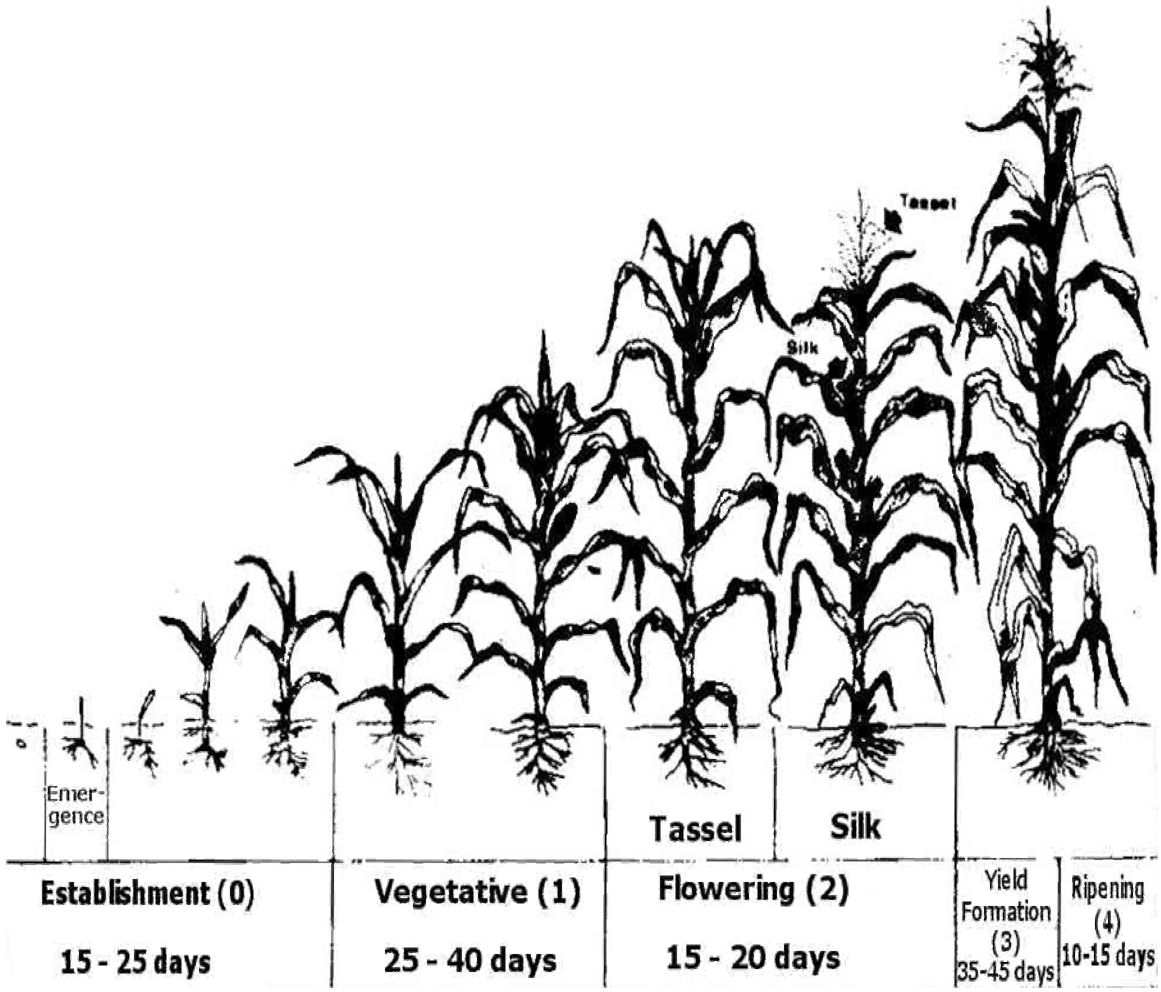

Figure 5.11: The growth stages of the maize crop (FAO, 2002).

Greatest decrease in grain yields is caused by water deficits during the flowering period including tasselling, silking and pollination, due mainly to a reduction in grain number per cob. This effect is less pronounced in the preceding vegetative period. Severe water deficits during the flowering period particularly at the time of silking and pollination may result in little or no grain yield due to silk drying. Water deficits during the yield formation period may lead to reduced yield due to a reduction in grain size. Water deficit during the ripening period has little effect on grain yield (FAO, 2002).

Where rainfall is low and irrigation water supply is restricted, irrigation scheduling should be done to avoid water deficits during the flowering period, followed by the yield formation period. When a severe water deficit during the flowering period is unavoidable, water may be saved by reducing supply during the vegetative period as well as during the yield formation period without incurring additional yield losses (FAO, 2002).

The data collected indicate that intra-seasonal dry spell in 2005/2006 cropping season in B72A quaternary catchment was severe, causing moisture deficits especially during flowering stage, which is the moisture sensitive stage for maize growth resulting in yield decrease. If rainwater is harvested, it can be reserved for use during the moisture most sensitive stage. Figure 5.6 indicates moisture trend for the 2005/2006 cropping in B72A quaternary catchment study sites. Thompson et al (1981) indicates that as soon as the maximum soil moisture available is depleted by 40%, evapo-transpiration starts to decline from its maximum value (ET_{max}). Figure 5.12 indicates that available soil moisture was depleted by as much as 80% in some study sites during the moisture most sensitive stage like flowering, leading to low crop yield during 2005/2006 cropping season. It is at crop growth stage like this wherein harvested rainwater can be utilized.

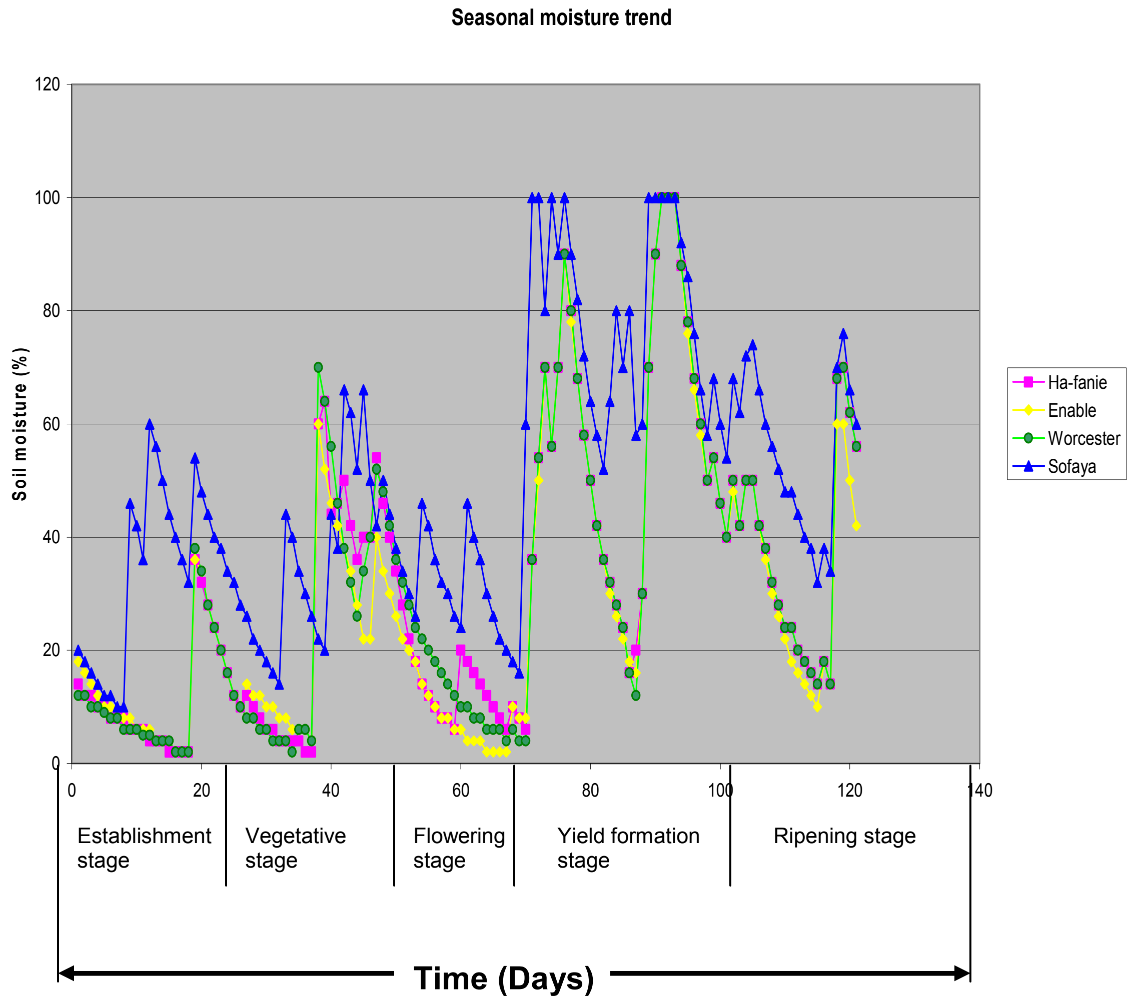

Figure 5.12: Measured soil moisture trend for 2005/2006 cropping season at B72A quaternary catchment

Chapter Six: Conclusions and Recommendation

Development is a type of social change in which new ideas are introduced into a social system in order to produce higher per capita incomes and enhance livelihoods through more improved production methods (Botha et al, 2003). Implementation of rainwater harvesting technologies will benefit rain-fed farmers in B72A quaternary catchment by assuring food security. The results with SAPWAT in section 5.2 indicate that increasing rainwater use efficiency and water application efficiency in the irrigated agriculture by making use of short furrows can drastically reduce irrigation water requirement by 68%. As a result, substantial water savings will allow farmers to plant more cash crops other than maize, thereby improving their livelihoods through income generation. The above-mentioned benefits associated with increased rainwater use efficiency for rain-fed agriculture and improved water application in the irrigated agriculture fulfills overall objectives 1.6.1.

6.1 Implementation of rainwater-harvesting to improve water productivity in B72A quaternary catchment

The modelled results with PARCHED-THIRST indicate that implementing rainwater harvesting could drastically improve crop yield in the study area. This is due to the fact that soil moisture will be enhanced thereby reducing the effects of intra-seasonal dry spell.

The study area has an average of 500 mm annual rainfall, but in the very wet season like 2005/2006 summer season rainfall exceeded 1000 mm. Though the rainfall exceeded 1000 mm, crop failure did not occur but crop yields were still low, measuring about 0.6 t/ha. This was caused by the prolonged period of intra-seasonal dry spell that occurred during the most sensitive crop growth stages resulting in low yields.

Considering that 39% of the received rainfall constitutes runoff, in-situ rainwater harvesting can be used to improve infiltration and hence soil moisture. In addition, collected run-off can be used as the supplement irrigation to bridge the prolonged period of intra-seasonal dry spell. The higher yield in Sofaya outlined in table 5.11 strongly suggests that with supplementary irrigation, which can be adopted at all sites through strategies like rainwater harvesting, crop yield can be enhanced.

Under normal intra-seasonal droughts which might result in complete crop failure, storing the harvested rainwater, farmer can be assured of a better harvest (Ngigi, 2003). With all the benefits that can be achieved with implementation of rainwater harvesting techniques, it is therefore important that the trial of rainwater harvesting techniques and new agricultural practices and techniques should be carried out with full understanding of the socio-economic status of the community and agro-climatic conditions under which the target farmers operate.

The modeled results with Parched-Thirst indicate that the crop yield for rainfed agriculture in B72A quaternary catchment can be improved to 0.8t/ha under average seasonal rainfall of 500mm if rainwater harvesting is implemented. This is a much more improved yield compared to 0.3t/ha which farmers are currently harvesting. Eicher et al (1997) reported that current maize consumption in the Southern African Development Community (SADC) is 100kg per person per annum. Statistics South Africa indicates that the average number of household occupants in B72A quaternary catchment is five (Lehohla, 2005). If the number of people in a household is matched with the maize consumption per person per annum, the required maize to secure food security per household would be 500kg per annum. Food insecurity is very high in B72A quaternary catchment for rural population that rely on rain-fed agriculture to support their families at the current crop yield of 0.3t/ha. If rainwater harvesting is implemented, crop yield will be improved to 0.8t/ha.

It is acknowledged that other measures apart from increased crop yield are required to achieve food security. These include having adequate storage facilities for harvested crops. This will go a long in ensuring that farmers have adequate food till next cropping season, thereby eradicating food insecurity. It is recommended that farmers should seek funding from NGO's and government to build centralized storage facilities where all farmers in the area can preserve their harvest.

6.2 Improving the level of soil fertility in the study area

Besides drought, another factor constraining productivity in dry land farming areas is soil infertility. Nitrogen is important in improving water use efficiency and soil water use, while Phosphorus plays an important role in increasing not only total soil water use but also water extraction from deep soil layer (Deng et al, 2006).

The studies done by Ntsheme 2005 indicate that poor land management in B72A quaternary catchment prevailed for years, causing soil erosion, and loss of soil nutrients. As a result, crop production has been declining over the years.

The tested soil nutrients data in this research on B72A study sites indicate that the soil nutrients status is very low. Considering that majority of poor population in B72A quaternary catchment rely on agriculture to improve their livelihoods, soil fertility should be improved to increase crop yield. Because most of the farmers cannot purchase their own fertilizers, recommendation is that these farmers should be subsidized or provided with free fertilizers by government and Non Governmental Organization to improve soil fertility in their fields.

6.3 Improving water allocation in the study area

The study by Ntsheme indicates that the current water allocation in the study area at the smallholder irrigation scheme is based on verbal agreement between the farmers, in which the individual farmers will irrigate their crops only on the agreed time and day of the week. However, poor irrigation efficiency has promoted many farmers to over utilize water, resulting breaking the agreement leading to few farmers getting access water resources.

Currently the government is making efforts to rehabilitate the irrigation system at B72A quaternary catchment, trying to ensure that there is equitable allocation of water resources amongst all farmers. The future water allocation will need to be based on the economic instruments. Farmers will need to pay, with respect to the quantity of water used.

Water allocation based on the economic instruments will change farmer's perception on water utilization, and will stimulate the desire to improve water use efficiency by farmers in the irrigated agriculture. If economic instruments are implemented effectively to manage scarce water resource, all farmers can be assured of having access to the irrigation water resources, drastically decrease conflicts between the farmers.

6.4 Enhance farmer's capacity building

Capacity building refers to the potential and capacity of the people of a particular community and to the process of assisting them in developing skills at various levels in order to become masters of their own development and thus acquire the capability to manage their own future (Botha et al, 2003). The main disadvantage with the rainwater harvesting storage techniques is that it requires some knowledge on water management (Ngigi, 2003). When farmers are introduced to the new farming technologies, training is of paramount importance to ensure that the proposed project is sustainable and flexible to the farmers. Among other things, knowledge on crop population or spacing, weeding, and fertilizer application should be infrared to the farmers. It is therefore should be a learning process characterized by flexibility, sustainability and a total capacity-building approach.

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Appendix A

Tables used in Calculating Solar Radiation

Table A.1: Angot's values of short-wave radiation flux R_A at the outer limit of the atmosphere in g cal/cm^2/day* as a function of the month of the year and the latitude.

Lat (deg)	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*July*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*
N 90	0	0	55	518	903	1077	944	605	136	0	0	0
80	0	3	143	518	875	1060	930	600	219	17	0	0
60	86	234	424	687	866	983	892	714	494	258	113	55
40	358	538	663	847	930	1001	941	843	719	528	397	318
20	631	795	821	914	912	947	912	887	856	740	666	599
Equator	844	963	878	876	803	803	792	820	891	866	873	829
20	970	1020	832	737	608	580	588	680	820	892	986	978
40	998	963	686	515	358	308	333	453	648	817	994	1033
60	947	802	459	240	95	50	77	187	403	648	920	1013
80	981	649	181	9	0	0	0	0	113	459	917	1094
S 90	995	656	92	0	0	0	0	0	30	447	932	1110

* 1 g cal/m^2 = 41.9 kJ/m^2

Source: Wilson E.M., (1990), *Engineering Hydrology, 2nd Edition*. The MacMillan Press

Table A.2: Mean daily maximum hours of sunshine for different months and latitudes.

Latitude (° South)	*July*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*
50	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.5	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.	12.1	12.1	12.1

Source: Wilson E.M., (1990), *Engineering Hydrology, 2nd Edition*. The MacMillan Press

Appendix B

B.1 Mechanical grain-size analysis method

In this method, the relative proportions of different grain sizes which make up a given soil profile are determined. The soil particles pass through sieve sizes between 0.075mm and 6.7mm. For particles below 0.075mm, the hydrometer method was used. The procedure for grain size analysis using mechanical method is outlined below.

The sampled soil measured 500g from the experimented agricultural field was placed into a bowel with water and washed to rid it off organic matter and dust particles. The process was considered adequate when a clear effluent was obtained. The much clear effluent was poured off and the remaining settled soil particles placed in the oven for drying for 24 hours.

After 24 hours, soil sample was taken out and weighed the oven-dry residue, and then passes it through the stack of sieves. The stack of sieves was then placed in the mechanical sieve shaker and sieve up to 10 minutes.

The stack of sieves was then removed from the shaker and the weight of material remaining in the sieve was obtained. The weight obtained from each sieve was summed and compared it with initial mass to detect any loss of soil in the mechanical sieving operation because any loss by 2 percent is considered unsatisfactory and the test should be repeated. Then the percentage of particle passing was computed.

B.2 Hydrometer grain-size analysis method

This procedure utilises the relationship between the velocity of fall of spheres in a fluid, the diameter of the sphere, the unit weight of the sphere and of the fluid, and the viscosity of the fluid. This procedure uses stoke's equation.

$$\upsilon = \frac{2}{9}\frac{\gamma_s - \gamma_w}{\eta}\left(\frac{D}{2}\right)^2 \quad \text{...3.1}$$

Wherein υ = Velocity of fall of the spheres, cm/sec

γ_s = Unit weight of the sphere, g/cm^3

γ_w = Unit weight of the fluid, g/cm^3, usually water

η = Absolute viscosity of the fluid, dyne-sec/cm^2

D = Diameter of the sphere, cm

Equation 3.1 can be rearranged to obtain D:

$$D = \sqrt{\frac{18\eta\upsilon}{\gamma_s - \gamma_w}} \text{ cm} \quad \text{..3.2}$$

The range of soil-particle diameters D for the equation 3.2 to be valid is approximately 0.0002 mm $\leq$ D $\leq$ 0.2 mm since larger grains cause excessive fluid turbulence.

The procedures outlined below have been followed for hydrometer readings.

The soil sample of 50 g of oven-dry well pulverised soil was mixed with metaphosphate solution (dispersing agent). The mixture was allowed to stand for 16 hours, and was transferred to the malt mixer cup and mixed with tap water for three minutes. Then all the contents of the cup were transferred to the sedimentation cylinder. Then the tap water was added to fill the cylinder to 1000 cm^3 mark. The sedimentation cylinder was then closed with the rubber stopper and agitated for at least one minute.

After agitation, stopper is removed, and hydrometer readings are taken at the elapsed times of 18 sec, 40 sec, 2 min, 5 min, 15 min, 30 min, 60 min, 250 min and 1440 min. The mixture temperature was also taken as well. The temperature of the fluid is very important because temperature above 20^0C or below 20^0C affects the settling velocity of the particles in the fluid (Means and Parcher, 1963; Jumikis, 1967).

The dispersing agent (Calgon) was added to neutralise the charges on the smaller soil grains, often have plus or minus charges. With proper orientation, these charged soil grains, which often have plus and minus charges will be attracted to each other with sufficient force to remain stuck together, thus creating larger particles. According to stoke's law, these larger particles settle faster through the fluid than the small particles, resulting in providing wrong values (Means and Parcher, 1963; Jumikis, 1967).

The following equipments have been used for the experiment.

(I) Sedimentation cylinder (1000 cm^3 cylinder), also termed a hydrometer jar
(II) Hydrometer (152H model)
(III) Dispersion agent (Calgon) and thermometer

Appendix C

C.1 Extractable cations: Ammonium Acetate (1 mol dm^{-3}, pH 7)

This method is used to determine extractable cations Ca^{2+}, Mg^{2+}, K^+, and Na^+, soils, reflecting the nutrients status. In implementing this method, the air dry soil sample with less than 2mm diameter weighing 5 $\pm$ 0.05 g is placed in a 100 cm^3 extraction bottle. Then 50 cm^3 of Ammonium Acetate solution is added to the soil in the extraction bottle, cooled to 20 $\pm$ 2^0C and shaken horizontally on a reciprocating shaker at 180 oscillations per minute for 30 minutes. Then Whatman no 40 filter paper was placed into suction Buchner funnel to filter the extract. The filtered extract was then collected and elements K, Ca, Mg, and Na concentrations were determined from the extract by flame spectrophotometer.

Place	Calcium (Ca), (ppm)
Enable	3489
Worcester	3505
Ha-Fanie	1239
Sofaya	1928

Table C.1.1: Calcium (Ca) nutrient value in the study sites

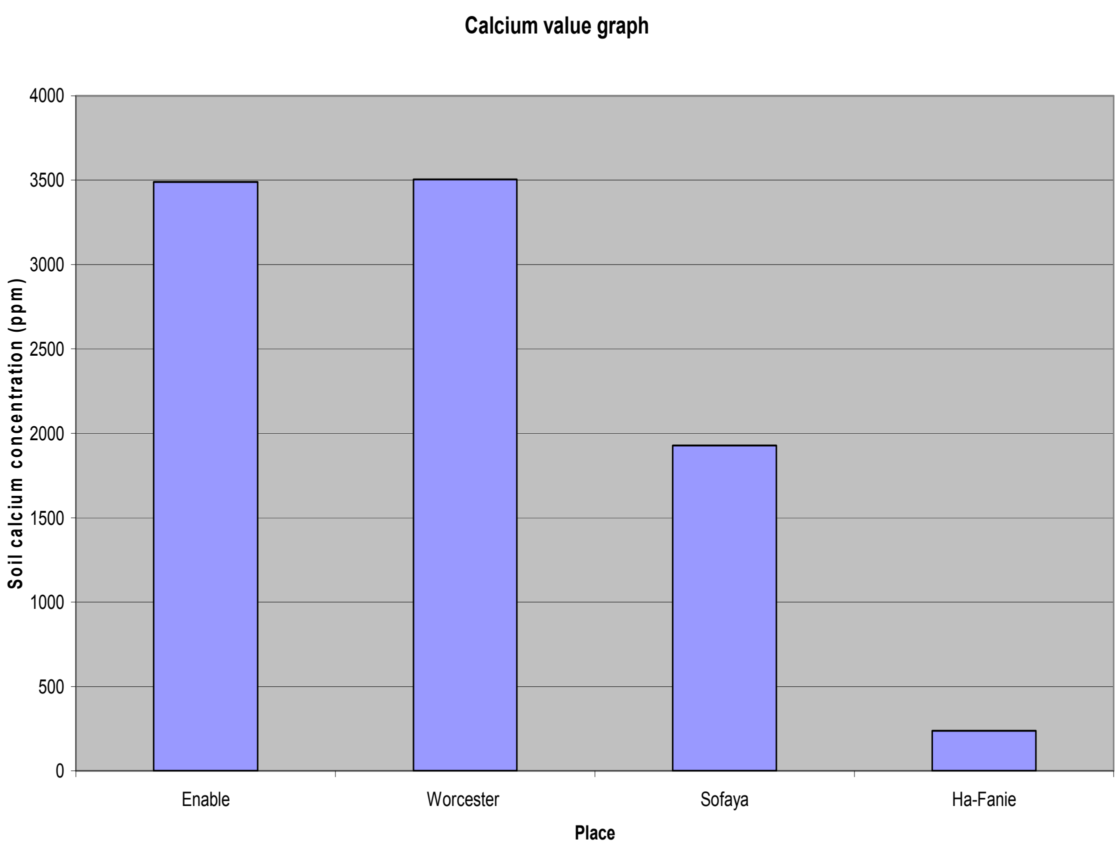

Figure C.1.1: Calcium (Ca) nutrient value graph for the study sites

Place	Potassium (K), (ppm)
Enable	117
Worcester	145
Ha-Fanie	54
Sofaya	100

Table C.1.2: Potassium (K) nutrient value in the study sites

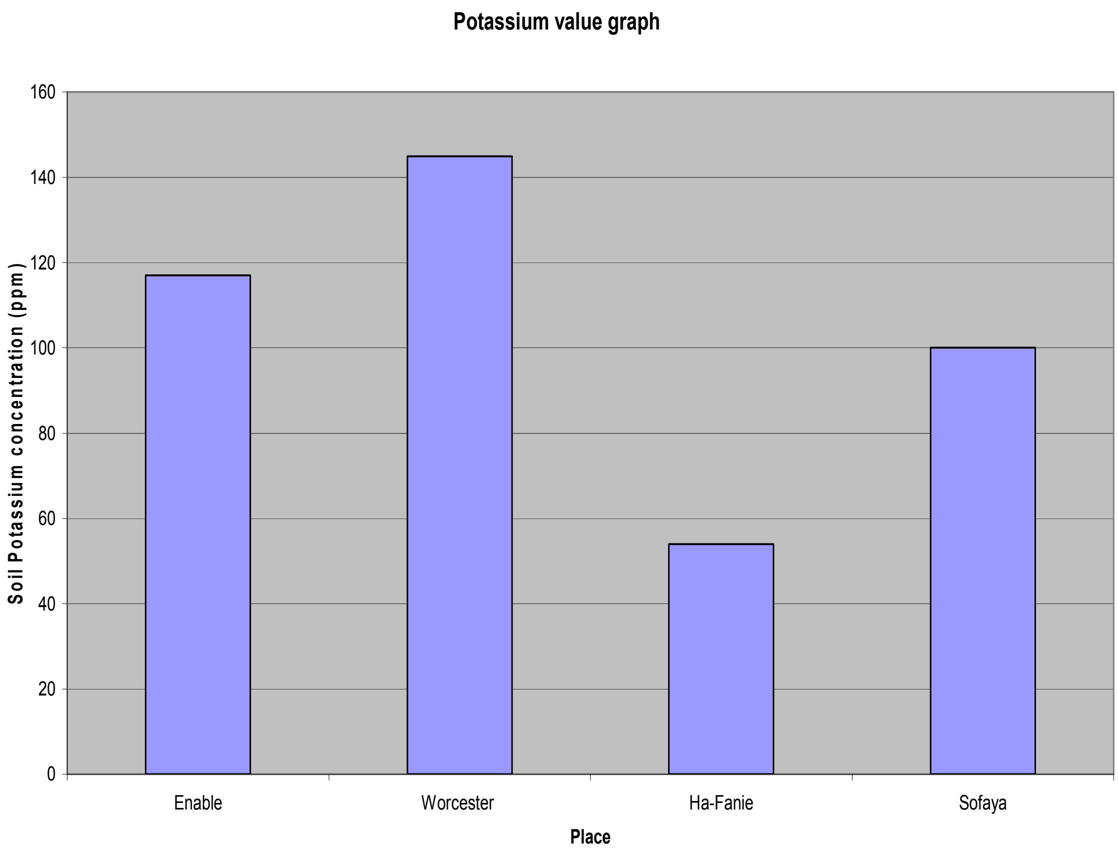

Figure C.1.2.: Potassium (K) nutrient value graph for the study sites

Place	Magnesium (Mg), (ppm)
Enable	343
Worcester	428
Ha-Fanie	354
Sofaya	284

Table C.1.3: Magnesium (Mg) nutrient value in the study sites

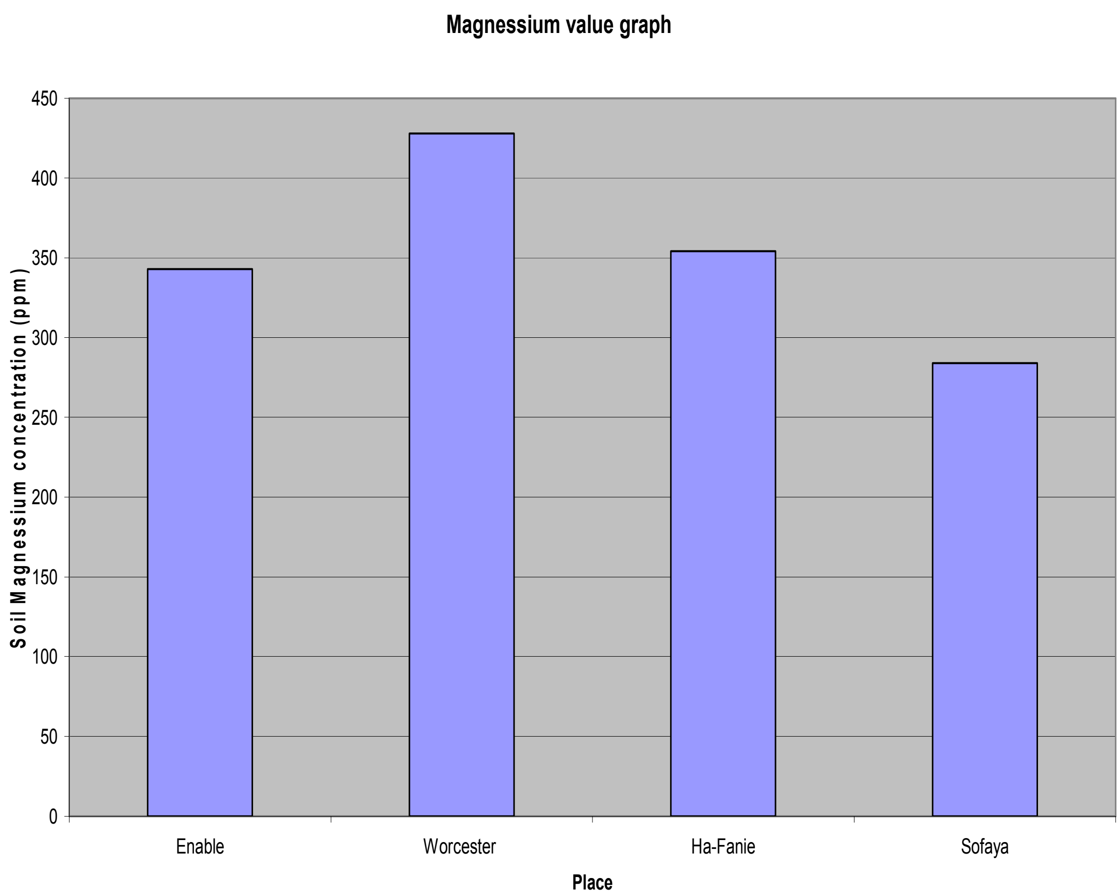

Figure C.1.3: Magnesium (Mg) nutrient value graph for the study sites

C.2 Organic Carbon: Walkey-Black

This method proposes that organic material in soil may be oxidised by treatment with a hot mixture of $K_2Cr_2O_7$ and sulphuric acid. To perform this soil test, soil is grinded to pass a 0.35 mm sieve using a porcelain mortar and pestle. Then transfer 1 g of air-dried sampled soil into 500cm^3 Erlenmeyer flask. Add 10cm^3 $K_2Cr_2O_7$ solution by pipette to the soil sample. Swirl the flask to mix the soil and the solution. After mixing then rapidly add 20 cm^3 of concentrated sulphuric acid. Swirl again flask gently until soil and reagents are mixed, then more vigorously for a total time of 1 minute. Allow the flask to cool on a sheet of asbestos for 30 minutes. Add 150 cm^3 de-ionised water and 10 cm^3 concentrated ortho-phosphoric acid. Add 1 cm^3 indicator and titrate excess dichromate with iron (II) ammonium sulphate solution. As the end point is approached, the solution colour changes to dark violet brown. Add iron (II) ammonium sulphate drop by drop until the colour changes sharply to green.

Then carbon content is calculated according to the following formula, using a recovery factor of 1.3.

Concentration of Fe $(NH_4)_2$ $(SO_4)_2$ mol.dm^{-3} = $\frac{10cm^3 K_2Cr_2O_7 x0.167x6}{cm^3 Fe(NH_4)_2(SO_4)_2}$

Organic C % = $\frac{(cm^3 Fe(NH_4)_2(SO_4)_2 blank - cm^3 Fe(NH_4)_2(SO_4)_2 sample)xMx0.3xf}{SoilMass(g)}$

Where M = Concentration of the Fe $(NH_4)_2(SO_4)_2$ in mol dm^{-3}

Place	Organic Matter (C), (g/100g)
Enable	0.0121
Worcester	0.0132
Ha-Fanie	0.0061
Sofaya	0.0126

Table C.2.1: Organic matter (C) value in the study sites

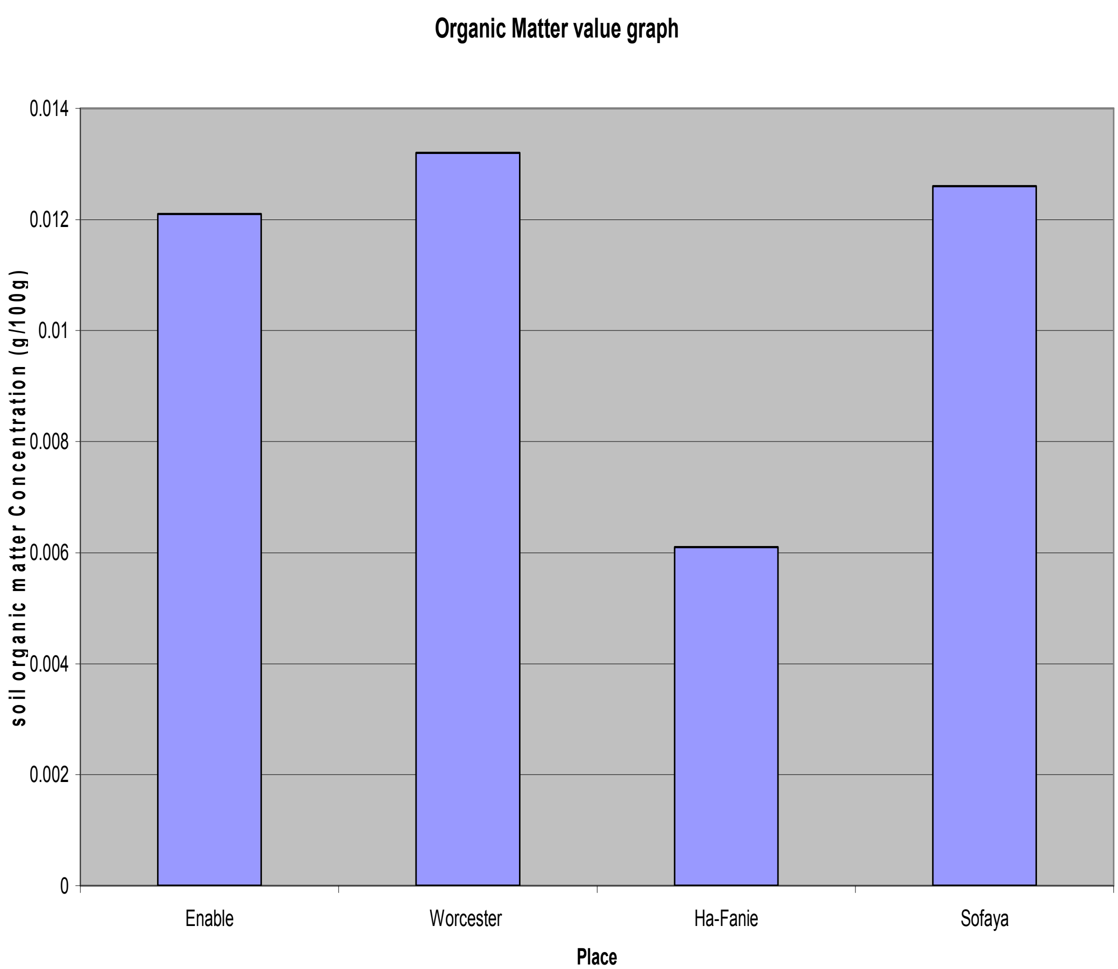

Figure C.2.1: Organic matter (C) value graph for the study sites

C.3 Extractable Phosphorus: Bray-1

Weigh 4g ± 0.05 g of the soil sample into a 250 ml Erlenmeyer flask. Add about 1g of the phosphate-free charcoal to each flask. Add 60 ml of the Bray extracting solution, stopper and shake for 40 ± 1 second. Immediately after shaking, add 2 drops of flocculent solution and swirl. Filter through a Whatman No.30 paper into a 500 ml volumetric flask. Dilute to a volume with distilled water. Determine ortho-phosphate on the auto-analyser. The absorbance of one set of standards was read prior to samples and one set after samples.

Place	Phosphorus (P), (ppm)
Enable	3.0
Worcester	0
Ha-Fanie	2.4
Sofaya	2.4

Table C.3.1: Phosphorus (P) nutrient value in the study sites

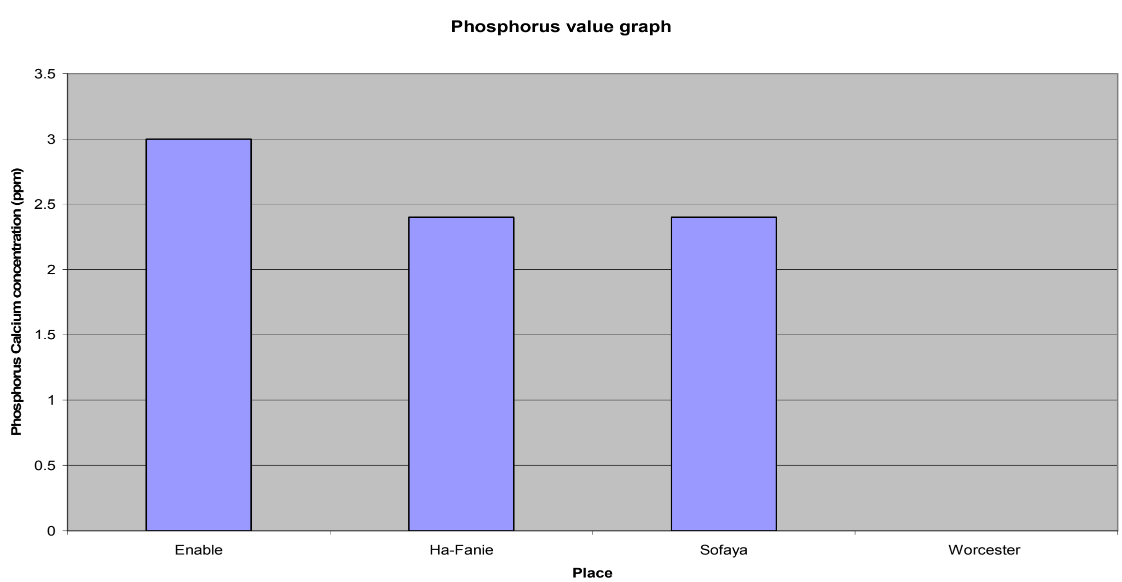

Figure C.3.1: Phosphorus (P) nutrient value graph for the study sites

C.4 Soil pH

Weigh 20g of the soil sample, transfer it to the 100 ml beaker. Add 50 ml distilled water, stir the mixture well with a solid glass rod, and stir again after 50 minutes. Allow to stand for further 10 minutes, stir the suspension vigorously. Remove the stirring rod, measure the PH immediately, and record the reading units of PH as soon as a steady value is obtained. The beaker was kept agitated to avoid sedimentation of soil until the equilibrium value is reached.

Place	**PH**
Enable	7.2
Worcester	5
Ha-Fanie	4
Sofaya	5.1

Table C.4.1: Soil PH value in the study sites

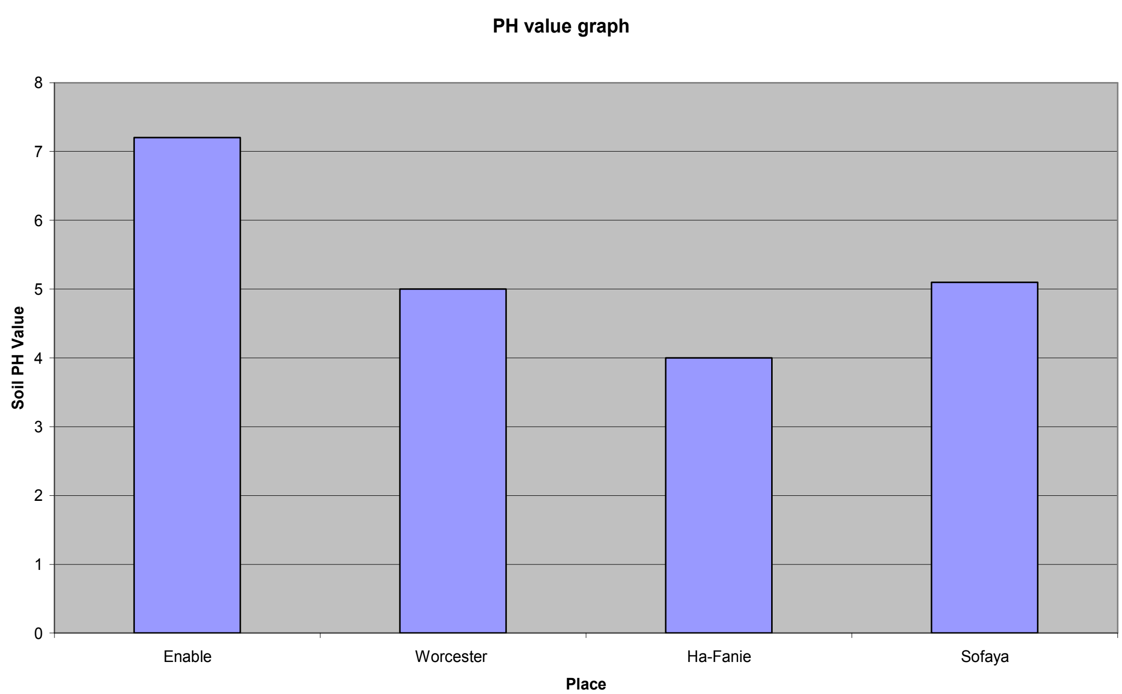

Figure C.4.1: Soil PH value graph for the study sites

C.5 Extractable Inorganic Nitrogen: KCl (1 mol dm^{-3})

To obtain extract solution for analysis in the soil sample, place 10.0 $\pm$ 0.05g $\leq$ 2.0 mm air-dry soil into a 250 cm^3 wide mouth extraction bottle. Add 100 cm^3 1.0 mol dm^{-3} KCl, stopper and shake for at least 30 minutes on a shaker. Then filter with 110 mm Whatman no 2V filter paper, to obtain clear extract.

The plant available forms of nitrogen are nitrate ($NO_3^- - N$) and ammonium ($NH_4^+ - N$) (Marx et al, 1999). To obtain the plant available nitrogen in the soil sample, the following method has been used.

C.5.1 Phenate method (Nitrogen ammonia, $NH_4^+ - N$)

To a 25 ml sample in a 50 ml Erlenmeyer flask, add, with through mixing after each addition, 1 ml phenol solution, 1 ml sodium nitroprusside solution, and 2.5 ml oxidixing solution. Cover samples with plastic wrap. Let the colour develop at room temperature (22 to 27^{0}C) in subdued light for at least one hour. Use spectrophotometer to measure absorbance at 640 nm. The absorbance of one set of standards was read prior to samples and one set after samples.

Place	Nitrogen Ammonium (NH_4^--N), (ppm)
Enable	2.73
Worcester	1.98
Ha-Fanie	3.9
Sofaya	8.47

Table C.5.1.1: Nitrogen Ammonium (NH_4^--N) nutrient value in the study sites

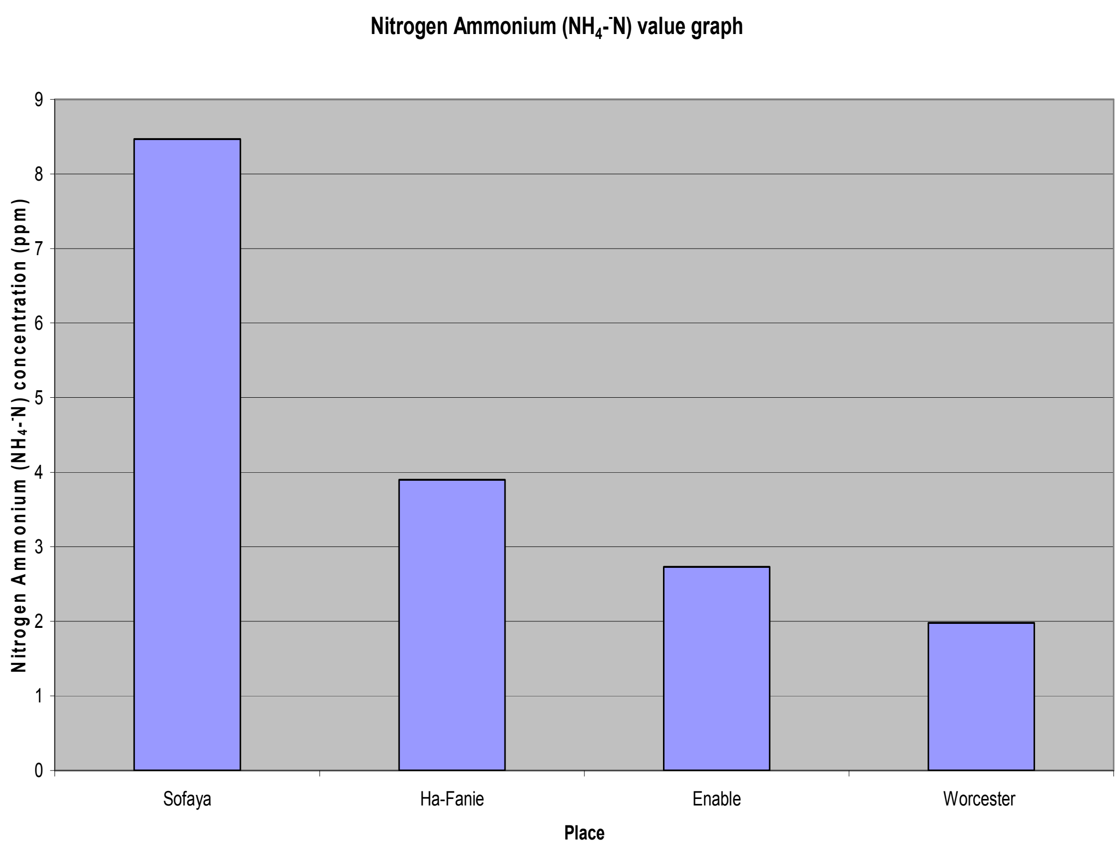

Figure C.5.1.1: Nitrogen Ammonium (NH_4^--N) nutrient value graph for the study sites

C.5.2 Nitrogen nitrate, $NO_3^- - N$ (Method after Kamphake)

Place 50 ml sample in a 125 ml rubber capped Erlenmeyer flask, into water bath at 37 ^{0}C ± 1 ^{0}C, and bring the sample to the water bath temperature. Simultaneously add 1ml reducing solution, 2ml phenate buffer and mix. Allow reaction to proceed at 37 ^{0}C for 30 minutes. Remove sample from the water bath. Simultaneously add 1 ml sulphanilamide and 1 ml N-(1-naphthyl)-ethylenediamine dihydrochloride(NED), and mix. Cool the sample to the room temperature. Read absorbance at 543 nm in a 5 cm cell. The absorbance of one set of standards was read prior to samples and one set after samples.

Place	**Nitrogen Nitrate (NO_3^--N), (ppm)**
Enable	0.834
Worcester	0.615
Ha-Fanie	0.517
Sofaya	0.556

Table C.5.2.1: Nitrogen Nitrate (NO_3^--N) nutrient value in the study sites

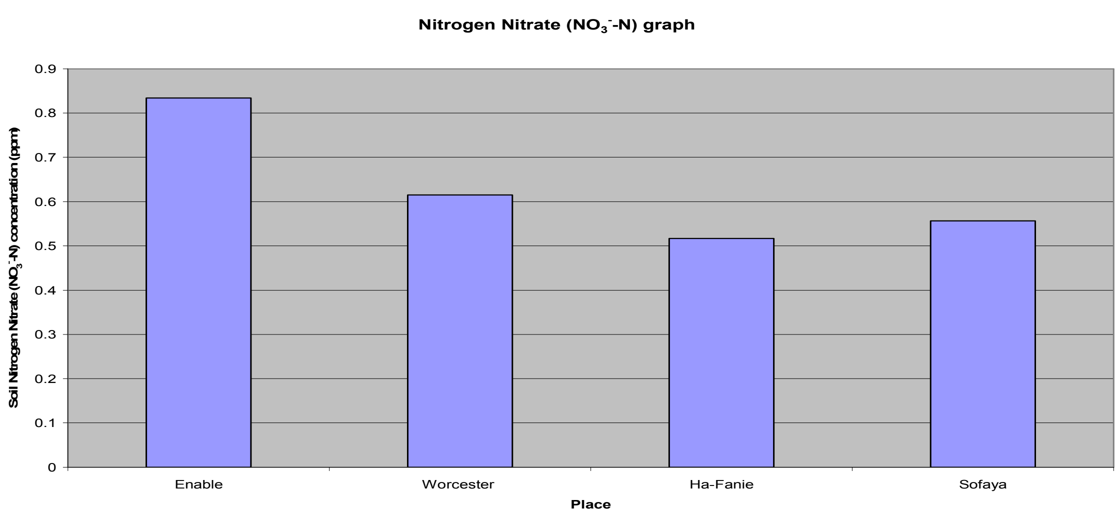

Figure C.5.2.2: Nitrogen Nitrate (NO_3^--N) nutrient value graph for the study sites

Appendix D

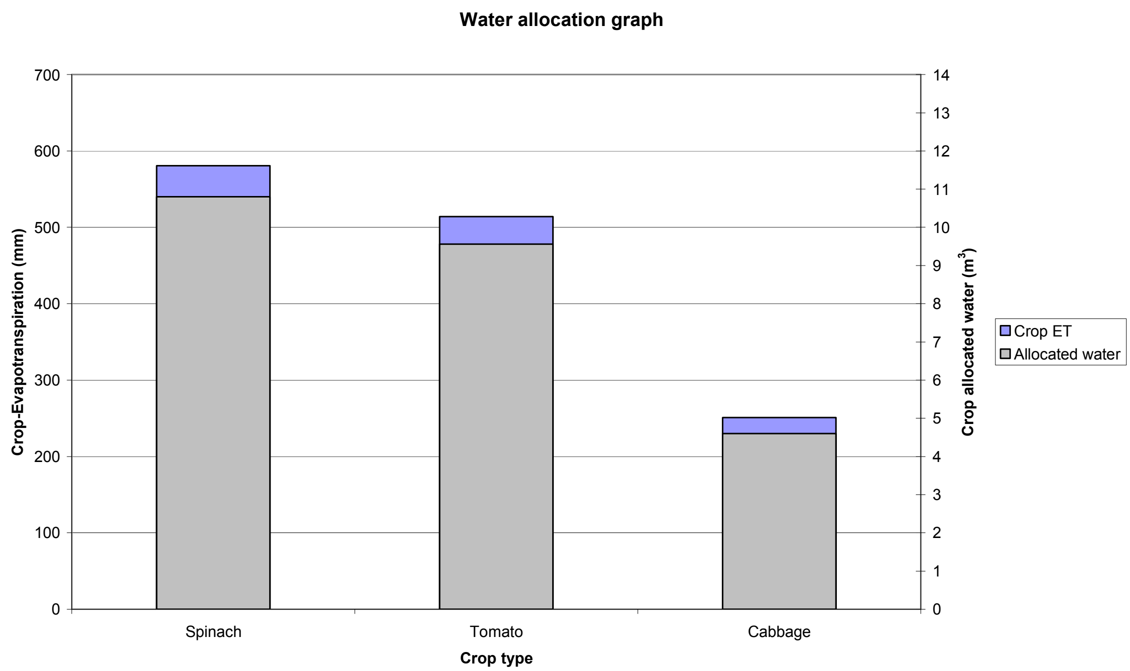

Figure D1: Ha-fanie water allocation graph for each planted crop type per 18.6 m^2

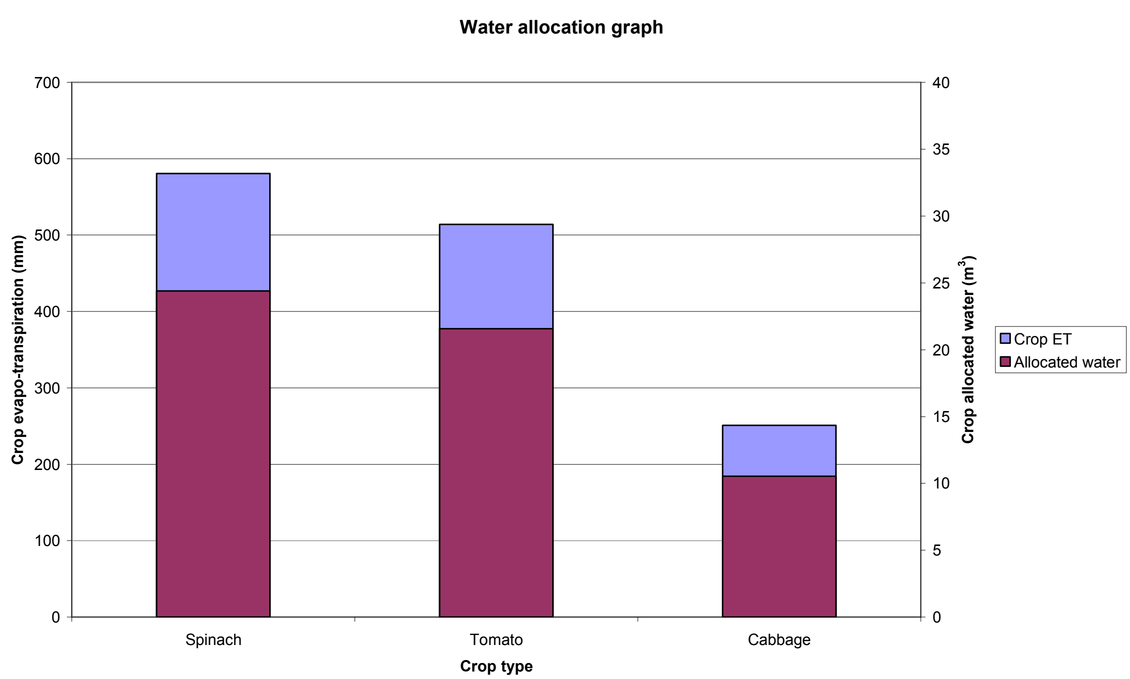

Figure D2: Worcester water allocation graph for each planted crop type per 42 m^2

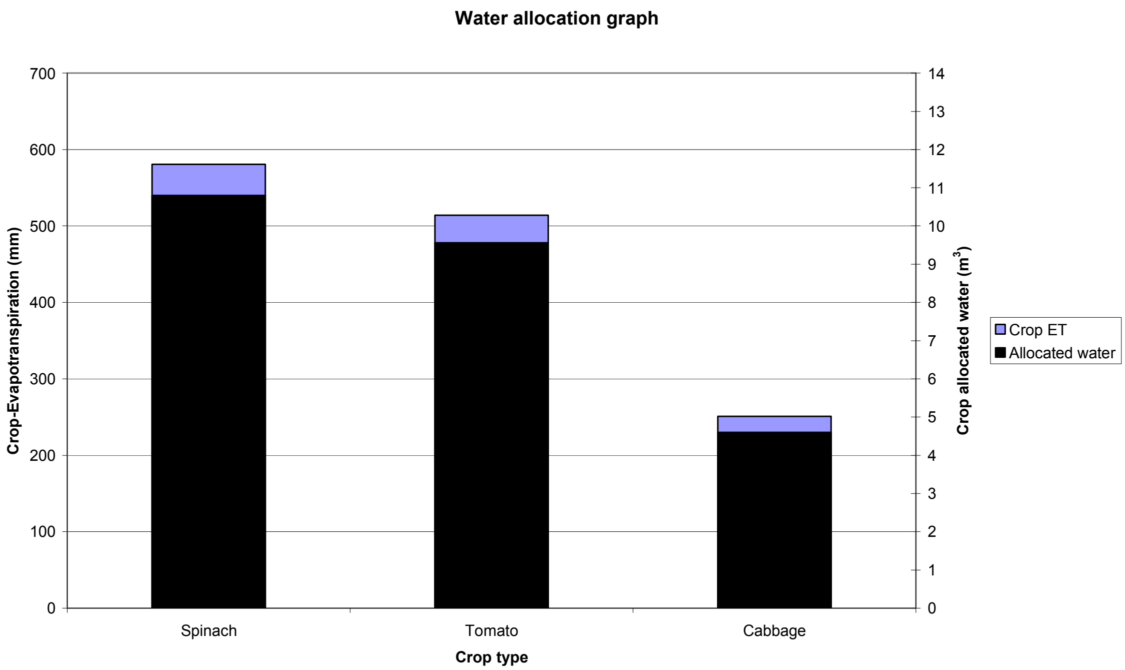

Figure D3: Sofaya water allocation graph for each planted crop type per 18.6 m^2