Water Footprint of Growing Vegetables in Selected Smallholder Irrigation Schemes in South Africa

By

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A Thesis Submitted in Fulfillment of the Requirements for the Degree of Master of Science in Agriculture (Soil Science)

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June 2014

DECLARATION

I, **Patrick Nyambo,** declare that the thesis hereby submitted for the degree of Master of Science in Agriculture (Soil Science) at the University of Fort Hare is my work and has not been previously submitted to another University.

Signature…………………………….

Date……………………………………

Place: University of Fort Hare, Alice

PREFACE

I thank the Almighty God for his unending and overflowing love and mercies that saw me complete this study. Many thanks to Professor IIC Wakindiki, for the guidance, valuable research insights and opinions he gave me for the whole duration of my study. I acknowledge the Govan Mbeki Research and Development Centre, at the University of Fort Hare, for financial support. Thank you for the bursary and research funds. Furthermore, I acknowledge the South African Weather Services (SAS), Agricultural Research Council (ARC) and Mr X. Mpengesi of the Department of Agriculture and Extension for helping me get some of the data used in the study. To my parents, brothers and sisters I will always be indebted to you for your prayers, love, encouragement, moral support and prayers during my studies. Moreover, I would like to sincerely thank all of my good friends; Dr. Adornis Dakarai Nciizah, Mr. Hupenyu Allan Mupambwa, Mr. Carlos Wyson Tawanda Nantapo, Mr. Tendai L. Kadango, Mr. Wilson Bakasa, Mr. Misheck Musokwa and Mr. Bruce Mutari. Thank you for your ideas, criticisms and moral support. I am grateful to you for encouraging me to keep soldiering on to the end. May the good Lord bless you.

DEDICATION

To my parents, brothers and sisters, thank you for your unreserved moral support, love and patience. To Gogo Mavudzi and Thamsanqa, you left us too early, thank you for the encouragement in life, RIP.

ABSTRACT

Knowledge of water use, through water foot printing (WF) in smallholder agriculture crop production is the key to the global fight against poverty, achievement of food security and sustainability within the world's rural community. Water footprint of a crop can be defined as the volume of fresh water used to produce a certain crop in all the steps in the production line. This study, therefore aimed at contributing towards improvements in rural livelihoods by raising awareness of the increased productive use of green, blue and grey water in smallholder agriculture in South Africa. This was done through determination of water footprints of five vegetable crops, i.e. potatoes *(Solanum tuberosum)*, tomatoes *(Solanum lycopersicum)*, dry beans *(Phaseolus vulgaris)*, cabbage *(Brassica oleracea spp) and spinach (Spinacia oleracea)* in the 2000-2013 period. Quantification of water footprints has been done worldwide but, in South Africa (SA) focus has mostly been on the industrial and domestic sector. Water footprint assessment framework, was used to estimate the full impact of vegetable production on water resources at Zanyokwe, Thabina and Tugela Ferry irrigation schemes as case studies. The CROPWAT$^{@}$ model was used to calculate crop evapotranspiration, differentiating green and blue water. Local climatic data were obtained from SA weather services, while the crop and soil parameters were obtained from the FAO data base. Nitrogen was considered the main pollutant hence its use in the grey water footprint calculation. Generally, Thabina irrigation scheme had the highest water footprint, followed by Tugela Ferry irrigation scheme whilst Zanyokwe irrigation scheme had the lowest. Green beans had the highest water footprint at all the three irrigation schemes with Thabina irrigation scheme having the highest (3535.1 m^3/ton). For Tugela Ferry irrigation scheme, the calculated WF was 2753 m^3/ton whilst the lowest was observed at ZIS i.e. 2407.6 m^3/ton. Cabbage had the lowest water footprint. The highest water footprint for growing cabbage was 254.5 m^3/ton in TFIS, 223.1 m^3/ton in TIS and the lowest was 217.8 m^3/ton in ZIS. The differences observed in the WF of a crop at each scheme maybe attributed to the differences management, weather and environmental characteristics, in the three locations. Moreover, the needs for ET are related to soil type and plant growth, and primarily depend on crop development and climatic factors which are closely related to climatic demands. The grey water footprint was calculated using the recommended fertilizer application rates for all the three sites. Green beans had the highest WF_{grey} i.e. 373 m^3/ton and the lowest was cabbage with 37 m^3/ton. Potato, spinach and tomatoes had 156 m^3/ton, 214 m^3/ton and 132 m^3/ton, respectively. Grey water footprint in this study was higher as compared to other studies, possibly because of the high rates of nitrogen fertilizers used in the calculations and the low yields farmers get. Compared with estimates from other studies, the water footprints of vegetable production within smallholder irrigation schemes was relatively high. There is therefore, a need to focus on crop management and tillage practices that will help in increasing yield while minimizing water usage.

Key words: water scarcity, small holder agriculture, green water foot print, blue water foot print and grey water foot print

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LIST OF ABBREVIATIONS AND ACRONYMS

SHIS	Smallholder irrigation schemes
WF	Water footprint
WF_{green}	Green water footprint
WF_{blue}	Blue water footprint
WF_{grey}	Grey water footprint
ZIS	Zanyokwe irrigation scheme
TFIS	Tugela Ferry irrigation scheme
TIS	Thabina irrigation Scheme
ET	Evapotranspiration
CWU	Crop water use
CWR	Crop Water Requirement

CHAPTER ONE

1.0 INTRODUCTION

Agriculture is under intense pressure to stop damaging the environment; especially by depleting water sources, polluting water systems and contributing to soil infertility and erosion (FAO, 2010). Available fresh water resource is in a constant decline mainly due to increasing demand and climate change (Turral et al., 2008). Furthermore, the decline in the available fresh water resource is exacerbated by ignorance, improper measurement and monitoring of water use in smallholder irrigation schemes (SHIS) (Fanadzo et al., 2010; Mnkeni et al., 2010). Water losses are inherently high due to dilapidated irrigation infrastructure and application of excess water amongst other factors. A study by Fanadzo et al. (2010) found out that irrigation application and system efficiencies in the two SHIS in Eastern Cape province were below the norm and irrigation scheduling did not take crop type and growth stage into account. Therefore, studies in water footprints are vital so as to quantifying water consumption in smallholder agriculture.

Water footprint (WF) (Hoekstra, 2003; Hoekstra & Chapagain, 2008) can be an important tool for considering water conservation impacts from a variety of farm management options (Dourte & Fraisse, 2012). Water Footprint concept was introduced as a tool that expresses the virtual water content of products, organizations, people, and nations in a spatially and temporally explicit way (Hoekstra and Hung 2002). Since the development of the concept in 2002, modifications have been done on how to calculate the water footprints (Hoekstra, 2003). Development and application of the concept has been slowed down by the lack of a generally accepted method of integrating both consumptive water use (CWU) and degradative water use (DWU) impacts into a single stand-alone metric (Ridoutt & Pfister 2012). Currently, the generally accepted and common method of estimating water footprints is according to Hoeskstra et al. (2011). Dourte & Fraisse (2012) defined WF as the comprehensive measure of freshwater consumption that connects consumptive water use to a certain place, time, and type of water resource.

Consumption refers to the loss of water from the available ground - surface water body in a catchment area (Hoekstra et al., 2011). A crop WF is the volume of fresh water used to produce a certain crop in all the steps in the production line. It is a multi-dimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution; all components of a total water footprint are specified geographically and temporally (Hoekstra et al., 2009). The concept includes three types of virtual water which are blue, green and grey. Blue water footprint (WF_{blue}) of a crop refers to the volume of irrigation water that evaporates from a crop field during the growing season while green water footprint (WF_{green}) is the volume of rain water that evaporates from a crop field (Hoekstra, 2009). Grey water footprint (WF_{grey}) refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards (Ercin et al, 2011). Crop WF are dependent on climatic and specific crop parameters collected over time.

Hitherto, studies on crop water foot printing have been done in Europe, where estimation was done for crops such as wheat (Mekonnen & Hoektsra 2010), cotton (Chapagain et al., 2005; Chapagain et al., 2006) and rice (Chapagain & Hoekstra, 2010). In South Africa, WF research is scant. The few available reports concentrate on domestic consumption, power and processing industries. For example, Unilever (2009) quantified the total water for a wide range of its products, while SABMILLER & WWF (2009) focused on the company's WF in beer production. On the other hand, studies on SHIS have focused on assessing their performance (Bembridge 2000, Mnkeni et al., 2010, Crosby et al., 2000). Yokwe (2009) evaluated the performance of Zanyokwe irrigation scheme (ZIS) from an economic point of view, while Shongwe (2007) evaluated water distribution at the Tugela Ferry irrigation scheme (TFIS). Ignorance of irrigated crop production among smallholder farmers was identified as one of the constraints to improved crop productivity (Fanadzo et al., 2010). Machete et al. (2004) and Mnkeni et al. (2010) identified water mismanagement as the main agronomic factor limiting productivity in ZIS. Mnkeni et al. (2010) further noted little control in the usage of water resulting in problems of over application. According to Ntsonto (2005), good irrigation management is a problem in many schemes with ZIS farmers not using water efficiently. A study by Yokwe (2009) highlighted the need to improve water productivity in the smallholder irrigation, while Mnkeni et al. (2010) outlined that priority should be put on the scope of increasing water productivity at irrigation schemes by ensuring its availability and effective distribution within the schemes.

Seventy-five per cent of the worlds' poor population live in rural areas of developing countries, especially sub-Saharan Africa (UN, 2011; IFAD, 2011) and depend on agriculture for livelihood and majority are food insecure. Smallholder agriculture can be a potential area of focus in policy making, rural development, employment creation, income generation, poverty reduction and ultimately food security. To support broad-based poverty reduction and food security in Africa, smallholder agriculture must be a central investment focus (Garvelink et al., 2012).

Ability to quantify and visualize water consumption and pollution in a meaningful way, makes it possible to illustrate the necessity for action and aid in planning for sustainable water use (Lindholm, 2012) and poverty eradication amongst the rural smallholder communities. The problem is not physical scarcity of water, but rather the lack of integrated management approaches to link crop, soil, water, and climate (FAO, 2002). The government of South Africa has prioritised the development of neglected SHIS (Backeberg, 2006) to stimulate small-scale agriculture as a viable poverty reduction and livelihood strategy. Du Plessis et al. (2002), put the smallholder irrigators into four groups viz, farmers on irrigation schemes; independent irrigation farmers; community gardeners; and home gardeners. The largest portion of South Africa's available fresh water is allocated to agriculture, with about 63% going to irrigation (Blaine, 2013).

Focus of this study was on vegetable production in SHIS which, according to Cousins (2013), number up to 317 SHIS in South Africa, mainly growing different vegetables at varying intensities. Majority of SHIS farmers are usually black people residing in the former homelands (Fanadzo, 2012). Many SHIS involve multiple holdings that depend on a shared distribution system for access to irrigation water and, in some cases, on a shared water storage or diversion facility (Van Averbeke at al., 2011). Therefore, SHISs' are multi-farmer irrigation projects larger than 5 ha in size that were established in the former homelands or in the resource poor areas by black people or agencies assisting their development (Van Averbeke, 2008, Fanadzo, 2012). For example, Zanyokwe irrigation scheme located in the Eastern Cape Province (ZIS) is 471 ha. The scheme comprises 6 villages with 61 farming households (Fanadzo et al., 2010). Each farmer has an average of 4.2 ha of irrigated land (Monde et al., 2005). Vegetable production in the SHISs constitutes an important sub-sector of both food security and agricultural economy. This study focused on five vegetable crops: (potatoes *(Solanum tuberosum)*; tomatoes *(Solanum lycopersicum)*, dry beans *(Phaseolus vulgaris)* and cabbage *(Brassica oleracea spp) and spinach (Spinacia oleracea*) produced in three irrigation schemes viz ZIS, Tugela Ferry (TFIS) and Thabina irrigation Scheme (TIS) in the Eastern Cape, Kwazulu Natal and Limpopo provinces respectively.

This study is an attempt to raise awareness of WF of vegetable production in three SHIS. In particular, it focused on green, blue and grey water footprint of different vegetable crop production at these selected irrigation schemes in South Africa. The estimates were done in a spatially-explicit way, from a production perspective using a conceptual framework based on FAO CROPWAT approach (Allen et al., 1998).

1.1 Problem Statement

Irregular seasonal droughts caused by high spatial and temporal rainfall variability have adverse effects on the availability of the already scarce fresh water resource. Water resources in SHIS are being depleted rapidly due to a number of factors with the combination of rising global populations, rapid economic growth in developing countries, and climate change is triggering enormous water availability challenges around the world (Ceres, 2010). Poor land and water management in the SHIS has caused a considerable decline in agricultural production.

Agriculture remains the backbone for food security and income generation for the majority of SHIS farmers. There is a lot of pressure on the already scarce fresh water resources which is negatively affecting crop production, sustainability and ultimately food security in SHIS. The challenge is to eradicate poverty and achieve food security, through increased productive use of water within agriculture. The scarcity of water for most smallholder irrigation schemes caused over or under- utilisation of the resource. The problem is not physical scarcity of water, but rather the lack of integrated management approaches to link crop, soil, water, and climate (FAO, 2002). There are no holistic studies on the amount of water required for vegetable production by the SHIS.

The study has been promoted by the aforementioned situation, and hence the need to give improvements and raise awareness on water management to increase the crop output per drop of water through proper quantification, water foot printing, and monitoring. Focus on water foot-printing in South Africa has hitherto been on the Industrial and domestic sectors.

1.2 Justification

Most people in the communal areas in South Africa are poor and rely on agriculture for survival. Farmers in the SHIS are food insecure due to low crop yields attributable to many factors chief amongst them is poor water use efficiency. Achieving food security through increased productive use of water in agriculture particularly in the SHIS is a challenge.

The research was undertaken to provide insights into the management of water resources, particularly in agriculture, as it consumes large quantity of the available water resource. The current water demand for agricultural activities is very high; irrigation utilises almost 70% of the total available water (FAO, 2012). This study is of utmost importance for calculation and documentation of vegetable crop water footprints for use in development of water management strategies that would help improve water use efficiency thus reducing risk of crop failure. Improvement on the SHIS current efficient use of water will go a long way in increasing crop yield hence food security.

Estimating WF in the SHIS will provide a basis for evaluating water use efficiency, use of the effective rainfall and the significance of irrigation within the schemes and the farmers' livelihoods. Putting attention on SHIS will provide information on water-related impacts such as drought tolerance in their crop production. Furthermore it will provide farmers and policy makers with an estimate of the quantity and quality of water being used in the schemes, an important tool for considering water conservation impacts.

Documenting WF will be helpful in decision making on upgrading existing and/or installing new irrigation infrastructure and ultimately improving crop production through improvement in crop output drop of water. This research was therefore undertaken to generate new knowledge on water foot printing, based on appropriate management approaches linking crop, soil, water, and climate. The generated knowledge will be useful in the drafting and development of important policies and strategies for more efficient and sustainable use of water resources in the SHIS.

1.3 Objectives

Broadly, this study aims to contribute to rural livelihood improvement by documenting productive use of green, blue and grey water in smallholder vegetable production in South Africa.

Specifically to,

1. Estimate the blue, green and grey water footprint of growing vegetables in selected irrigation schemes in South Africa.
2. Assess the variability of rainfall for vegetable crop production in the selected small holder irrigation schemes in South Africa.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Smallholder Irrigation Farming in South Africa

South Africa's economy is founded on agriculture. One of the strategies used in agricultures' development is the expansion of irrigation especially in arid and semiarid areas. Although smallholder irrigation schemes are of secondary importance in terms of land area and farmer participation (Van Averbeke at al., 2011). It presents a great opportunity to increase crop production, incomes, and household food security (Postel, 2001). Today, 40 percent of the world's food comes from the 18 percent of cropland that is irrigated (Schultz, 2001, Ochs & Plusquellec, 2003). Rainfall is unreliable, droughts are common and crop production in most of the country is inherently risky, making irrigation important for a wide range of crops. Irrigation offers a positive supplement and/or alternative to rain fed farming and is central to achieving some of the major Millennium Development Goals and to supports economic growth (Pavelic et al., 2013). Small holder irrigation farming is practiced most commonly by pitchers, porous pipes, and drip lines beneath the soil surface as well as using overhead irrigation systems (Ashrafi, 2002). In South Africa, smallholder irrigation scheme development continues to be regarded as an opportunity to trigger rural and local development. There are around 74 small holder canal schemes left in South Africa of which 67 are still operational (Denison & Manona 2007).

2.2 Challenges Faced by Smallholder Farmer

Small scale farmers constitute about half of world's hungry people and include three quarters of Africa's malnourished children (.These farmers are food insecure and cultivate poor soils under unreliable rainfall conditions (Twomlow & Bruneau, 2000). The major causes of food insecurity as in most other Sub-Saharan countries are frequent crop failures and low crop yield which are a result of low soil fertility, uneven distribution of rainfall, long recurrent intra-seasonal dry spells and improper use of the available water resources. Lack of clearly defined land tenure weakens incentives for long-term investments in land to raise its productivity (Norton, 2004). In the end, small-scale farming in South Africa is practiced to supplement household food supply and only a small proportion of the product is sold because of the class disparities (Cousins, 2013). Land and water management remain the subject of concern to smallholder farmers (Twomlow et al., 2006).

Kirsten & Van Zyl (1998), defined a small-scale farmer as one whose scale of operation is too small to attract the provision of the services he/she needs to be able to significantly increase his/her productivity. Small-scale farming is often related with a rearward, non-productive, non-commercial, subsistence agriculture that is common in parts of the previous homeland areas. It is usually associated with black farmers. While on the other hand, white farmers are generally perceived to be large scale commercial farmers, who are modern and efficient, using advanced technology. These generalisations are a misrepresentation of the facts. For example, almost 25% of all farms in the "white" commercial sector covers a land area smaller than

200 ha and almost 5% less than 10 hectares (Kirsten & Zyl, 1998). This poses a challenge for these farmers as it creates class differentiation.

Smallholder farmers' constraints are inter-linked and cannot be separated. They should therefore be treated as a package. Andrew et al. (2003) identified the following challenges as the most common with the communal agriculture sector; shortages of labour, capital and income to purchase inputs; soil erosion and declining soil fertility. Labour shortages highly affect the production potential of farmers. Woman usually tend to the crops while children help out in both the field and by taking care of the animal. Problems of financing range from a lack of adequate financing for medium and operational purposes, to exceedingly high interest rates where financing is available. Due to unavailability of finance most farmers small scale farmers fail to buy inputs and pay for labour. Difficulties in marketing range from high input costs, low producer prices due to unfair grading by commodity buyers to push down prices, to limited processing capacity which would have added value and reduced transport costs of bulk raw materials. The majority of smallholder farmers live in areas with poor roads which render transport services not only unavailable, but also highly priced.

2.3 Water Productivity in Small-Scale Agriculture

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). Water productivity been defined as the amount of output produced per unit of water involved in the production (Singh 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). Green water is generally considered in assessing water productivity (Senzanje et al., 2005).

Significant water losses occur in the distribution and irrigation systems of SHIS due to a number of factors chief amongst them are dilapidated irrigation infrastructure which causes seepage within the irrigation network canals and lack of proper irrigation water management. A study by Fanadzo et al*.* (2010), reported that irrigation application and system efficiencies were below the norm and irrigation scheduling did not take crop type and growth stage into account hence high water losses and poor average crop yield. Farmers in the SHIS either applied too much water causing waterlogging and heavy nutrient leaching or supplied uneven and too little water for maximum production hence the low yields.

2.4 Water Availability and Its Use

Water is important for food security, which is defined as the regular access of people to enough high-quality food to lead active, healthy lives (FAO, 2012). Seventy percent of the world water resources is frozen in the icecaps, while the remainder is either stored deep in the underground aquifers, lakes or is present as soil moisture. Freshwater is defined as water containing less than 1000 milligrams per litre of dissolved solids, most often salt (USGS, 2013) or simply put is water having a low (less than 1%) salt concentration. Fresh water is becoming a scarce resource mainly due to effects of climate change, increased anthropogenic through ignorance, improper measurement and monitoring of its use (Fanadzo et al., 2010; Mnkeni et al., 2010). Water scarcity concerns the quality of resource available and the quality of the water because degraded water resources become unavailable for more stringent requirements (Pereira et al., 2002). Three major factors causing increasing water demand over the past century are population growth, industrial development and the expansion of irrigated agriculture (UNEP, 2003). Agriculture through irrigation accounts for 70 % (FAO, 2012) of the world fresh water withdrawals, while in high income countries; industry accounts for higher usage of 59% (Figure 1). According to Blaine (2013), 63% of South Africa's fresh water is used in irrigated crop production. World Water Council (2000), estimated that by 2020, water use will increase by 40 per cent, and 17 per cent more water will be required for food production to meet the needs of the growing population.

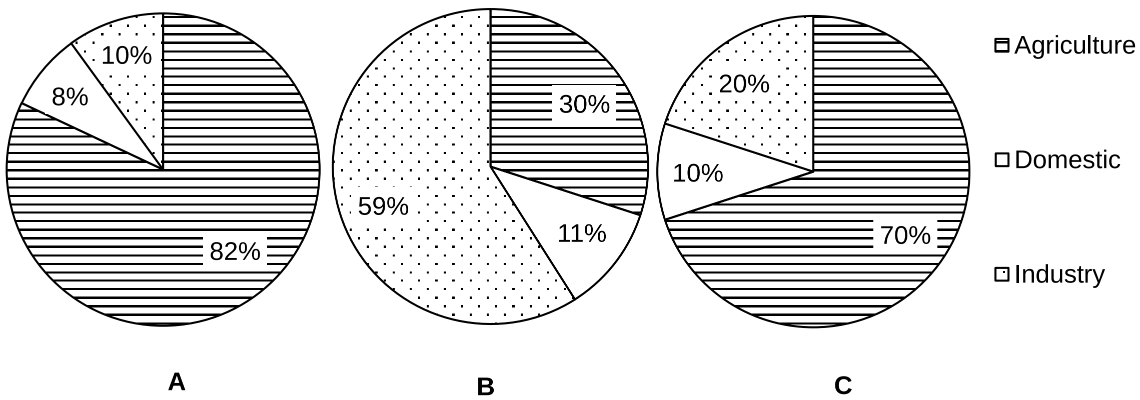

Figure 1: Average Water withdrawal percentages A) developing B) developed and C) world (Data adapted from, world water development report 2012)

2.5 Water movement

The total amount of water on earth is constant but is always moving between different states and sources. A number of processes affect the use, movement, storage and loss of water from the soil medium. Soil water is the water/moisture contained in a given soil.

This water is a major component of the soil in relation to plant growth and the moisture available for plant growth and makes up approximately 0.01 percent of the world's stored water (Ball, 2001). Soil moisture is often the most unreliable and scarce resource, so the challenge is to enhance the availability and productivity of water for biomass production (Van steenbergen & Mehari, 2009). Apart from availability of food nutrients, soil water is one of the major factors affecting crop yields. Precipitation and irrigation are the two primary sources of water for plants use. The rainfall contributes to a greater or lesser extent in satisfying CWR, depending on the location, intensity, time and crop growing period. When there is abundant rainfall, less water from irrigation is used and in dry seasons, irrigation is used to supply water to crops.

Over supply will result in poor soil aeration, inhibition of plant respiration and washing away of food nutrients while little and/or limited supply will starve the plants of the much needed growth medium hence lowering agricultural production. The amount of rainfall, transpiration and soil surface evaporation is linked to the climate of the area, while capillary rise and deep percolation (Figure 2) are mainly influenced by water management on the irrigated and surrounding areas (Van Heerden et al., 2009).

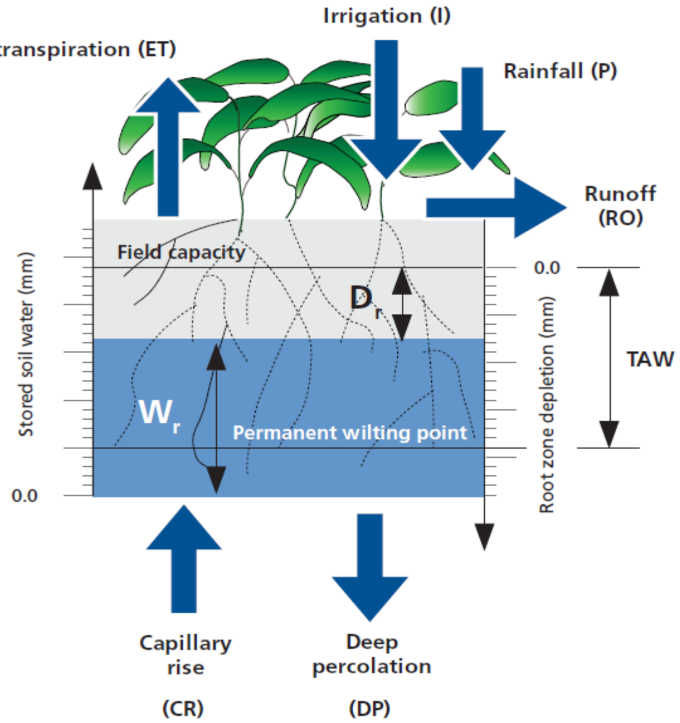

Figure 2: The root zone depicted as a reservoir with indication of the equivalent water depth (Wr) and root zone depletion (Dr). (Steduto et al., 2012)

Irrigation, precipitation and capillary rise are sources of soil water while deep percolation and evaporation form part of soil water loses (Allen et al., 1998) as shown in Figure 2. After irrigation or rainfall, water infiltrates into the soil forming plant available moisture, percolates deep into the soil to recharge groundwater tables, reservoirs and excess becomes runoff into rivers lakes thus replenishing sources of blue water. Loss of water from both the plants and the soil surface into atmosphere as water vapour is termed evapotranspiration and forms a major way of refilling the green water sources.

Moist air cools and condenses forming clouds which then return to the earth surface as precipitation. This movement of water is termed the hydrological cycle (Figure 3). Evapotranspiration (ET) is an essential component of water balance and a major consumptive use of precipitation and irrigation on cropland (Gowda et al., 2007). This Soil water balance can be described mathematically (Allen et al., 1998) as shown by equation 1

$$\Delta D = I + (P - RO) - E - T + CR - DP \qquad (1)$$

Where ΔD represents Change in soil water content

I = Irrigation

P = Precipitation

RO= Run-off

E= Soil Surface evaporation

T=Crop transpiration

CR= Capillary rise

DP= Deep percolation

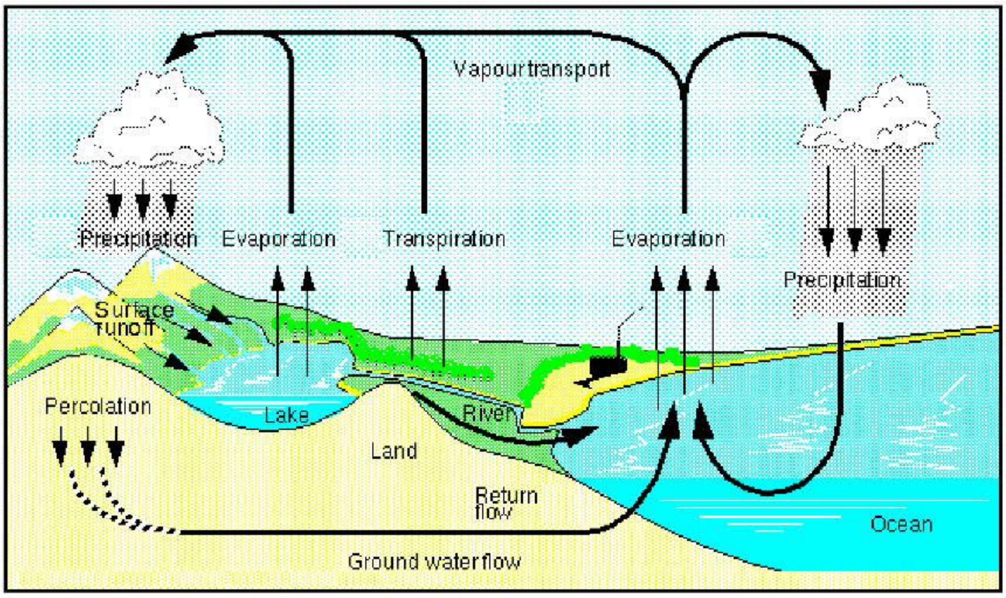

Figure 3: Hydrological Cycle; adapted from (Roeckner, 2010)

2.6 Crop Water Use

Crop water use, also known as evapotranspiration (ET), represents soil evaporation and the water used by a crop for growth and cooling purposes (ICM, 2000). It is a combination of two separate processes whereby water is lost on the one hand from the soil surface through evaporation; and on the other hand from the crop by transpiration (Allen et al., 1998). Plants draw water from the soil through roots and loses it as water vapour through the stomata, a process known as transpiration. Evapotranspiration can be expressed by way of the energy consumed as latent heat energy per unit area or as the equivalent depth of evaporated water with units mm/t where t denotes a time unit (hour, day, month, growing season, or year), (Allen & Robison 2007). Studies have shown that oceans, seas, lakes, and rivers provide nearly 90 percent of the moisture in the atmosphere via evaporation, with the remaining 10 percent being contributed by plant transpiration (USGS, 2013). Evaporation from the land occurs mainly during the early crop development stages; but when the leaves cover the ground, the main form of water loss becomes transpiration. At planting, the main form of water loss is evaporation from the soil surface (Figure 4). As the plant develops, the leaf area index increases thus increasing the rate of transpiration. At full cover, a crop is at the maximum ET rate if soil water is not limited i.e. if the soil root zone is at field capacity (CropWatch, 2008). Up to 95 percent of the water absorbed by roots is lost via transpiration through plant leaves with the remaining 5 percent being used by the plant for growth (natural flow, 2010). Two fifths of a hectare of corn gives off about 11,400-15,100 litres of water each day, and a large oak tree can transpire 151, 000 litres per year (Natural Flow, 2010). Aggarwal et al. (1986) indicated that WUE decreased with increasing evapotranspiration. Among the many uses of evapotranspiration to a plant are evaporative cooling, nutrients and CO_2 uptake. Quantification of ET is required for water resources systems management, design of irrigation system components and for conducting water balances (Allen and Robison, 2007).

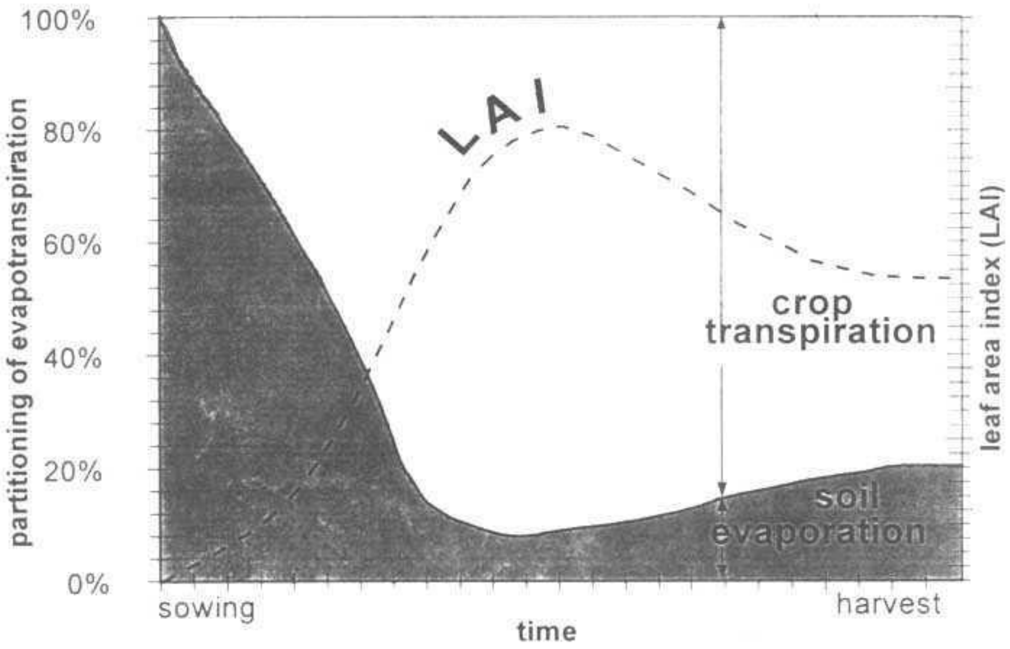

Figure 4: Relationship between evaporation and transpiration over a full growing period of a plant. (Adapted from Allen et al., 1998)

2.7 Factors Affecting Evapotranspiration

Knowledge of a location's weather pattern allows us to predict which crops can be grown successfully where and what production practices need to be followed to reduce the risk of partial or complete crop losses (McMahon et al., 2002). Evapotranspiration depends on climatic parameters, crop characteristics and soil water availability (Allen et al., 1998). Factors that speed up transpiration will also increase the rate of water uptake from the soil.

2.7.1 Climatic parameters

The evaporative power of the atmosphere at a specific location and time of the year is expressed by the reference evapotranspiration (ET_o), (Allen et al., 1998). A combination of factors drives evaporation from a free water surface, namely solar radiation, wind speed, turbulence and humidity (generally expressed as atmospheric vapour pressure deficit (VPD) (Artwell et al., 2010). These factors create a pressure difference between the atmosphere and evaporating surface hence aiding the movement of water out of the plant and from the soil surface.

2.7.1.1 Solar radiation

The evapotranspiration process is determined by the amount of energy available to vaporize water; this energy is provided by the sun in the form of solar energy. Water molecules absorb the solar energy and convert it to latent heat energy; the water vapour thus produced escapes to the atmosphere because of a vapour pressure gradient between the surface and atmosphere (CIMIS, 2009).

Other factors, such as wind, will take up the vapour from the leaf surface and/or plant micro-climate further into the atmosphere. The potential amount of radiation that can reach the evaporating surface is determined by its location and time of the year. Due to differences in the position of the sun, the potential radiation differs at various latitudes and in different seasons (Allen et al., 1998).

2.7.1.2 Wind speed

The process of vapour removal depends to a large extent on wind and air turbulence which transfers large quantities of air over the evaporating surface (Allen et al., 1998). Transpiration is faster in windy conditions because water vapour is removed quickly by air movement, speeding up diffusion of more water vapour out of the leaf and other evaporating surfaces. Wind movement are also dependant on the humidity of the surrounding environment; this is illustrated in Figure 5. Evapotranspiration is higher in hot dry air and is slower in humid and warm air.

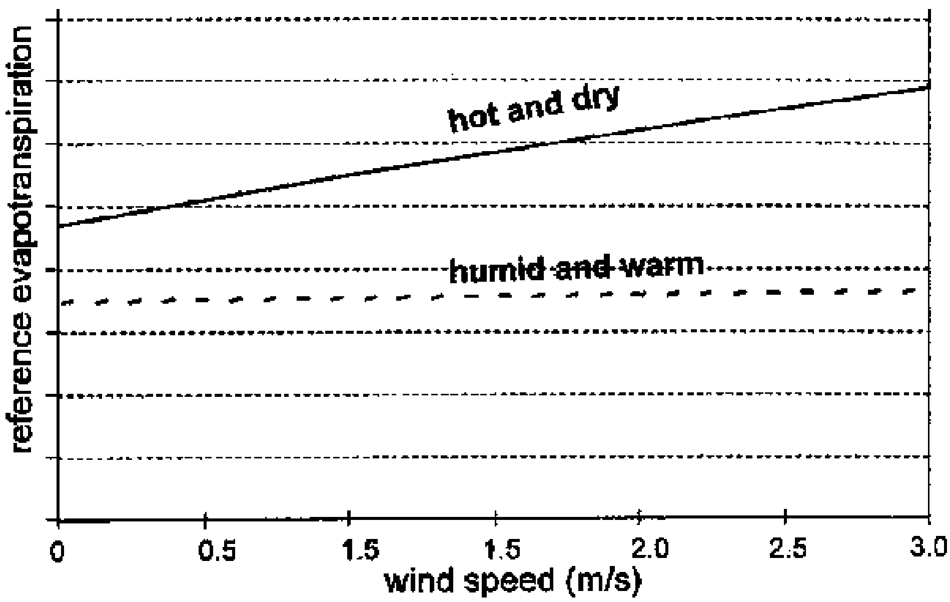

Figure 5: The combined effect of wind and humidity on evapotranspiration

(Source Allen et al., 1998)

2.7.1.3 Humidity

Humidity has a negative correlation with transpiration. As the humidity increases, the rate of transpiration decreases. This is because as the humidity increases, the air around the stomata becomes saturated with water vapor, decreasing the concentration gradient between the air and the leaves. This means less water will evaporate into the air (Allen et al., 1998).

2.8 Water footprint (WF)

Water footprints provide a useful platform about how water is used in a river basin and it offers an opportunity to overlay economic and social considerations onto water consumption trends (Pegasys & Bocma, 2010). The WF concept was coined by Hoekstra (Hoekstra & Hung, 2002). The concept is an indicator of fresh water use that looks at both direct and indirect water use (Hoekstra et al., 2011).

A WF differs from the typical measure of water use, water withdrawals, because a water footprint only accounts for consumptive water use, which is water that becomes unavailable locally in the short term due to evaporation or quality decline (Dourte & Fraisse, 2012). A product's water footprint can be defined by the volume of water required for manufacturing a certain mass of this product at the actual place of manufacture and is given in m^3/kg water/kg product (Schubert, 2011). A crop WF measures the volume of evapotranspiration (ET) or water use of a crop per unit mass of yield, thus making it a ratio of ET volume to crop yield (Dourte & Fraisse, 2012). Consumptive crop water use is the amount of evapotranspiration on cropland stemming from irrigation and precipitation.

Little attention has been given to WF of crop production in South Africa; focus has been on domestic consumption, power and processing industries. SABMILLER and WWF-UK, (2009), calculated the WF of SAB Ltd in South Africa and Czech Republic. The study acknowledged that agricultural crop production accounted for 98.3 percent WF in South Africa; 84.2 percent of this water came from local crop cultivation and 14.1 percent is from cultivation of imported crops. The study showed that 155L of water was used to produce a litre of beer in South Africa as compared to 45L of water used to produce the same quantity of beer in the Czech Republic (Hastings & Pegram, 2012). Unilever, (2009) quantified the total water for a wide range of its products while SABMILLER & WWF, (2009) focused on the company's water footprint in beer production. Other studies done have shown that global WF related to crop production in the period 1996 - 2005 was 7404 billion cubic meters per year (Mekonnen & Hoekstra, 2011).

The global wheat production in the period 1996- 2005 required about 108 billion cubic meters of water per year (Mekonnen & Hoekstra, 2011). There is however no research done to determine WF of primary crops in both commercial and SHI farmers in South Africa. Mekonnen & Hoekstra, (2011) calculated the global averages of WF of primary crops and reported that vegetables have roughly 300m^3 per tonne roots and tubers have 400 m^3 per tonne and pulses 4000 m^3 per tonne.

Water footprint quantifies water use by source and pollution, which are blue, green and grey WF. Green" and "blue" water are directly important to crop production in agriculture. As a long-term global average, 65 percent is available as "green" water, while 35 percent is available as "blue" water (Zehnder, 2002 cited by Schubert, 2011).

2.8.1 Green Water Footprint

According to Hoekstra and Chapagain, (2008), "green" WF refers to the total rainwater evaporation from the field during the growing period of the crop, including transpiration by the plants and other forms of evaporation. Gerbens-Leenes et al. (2011), defined it as rainwater consumed. Consumptive green crop water use is evapotranspiration stemming from precipitation on cropland (Stefan & Doll, 2010).

2.8.2 Blue Water Footprint

Schubert, (2011), defines "Blue" water as groundwater and surface water and goes on to state that the utilised share of "blue" water originates from groundwater and/or surface water and is also consumed through evaporation. A blue WF is the volume of total blue water use divided by the quantity of interest (Dourte & Fraisse, 2012) e.g. litres per kg of maize grain. Blue water is mostly water used for irrigation of crops. This water is drawn from rivers, lakes and ground water sources and is either applied directly to the crop or put in reservoirs for a period of time and/or for quality improvement. Losses occur as blue water moves from source to field; these have been reported to be of importance to smallholder farmers as it leads to reduction in yields. Blue water has a higher opportunity cost associated with its use and therefore impacts directly on scarcity (Dabrowski et al., 2008). The main issue with blue water consumption is its potential to contribute to water scarcity, therefore both direct consumption of blue water and the changes in its availability are important considerations (Pindoria, 2010).

Most studies have called for shifting focus to education, improvement and efficiency in water use within the irrigation schemes in South Africa (Yokwe, 2009, Mnkeni et al., 2010). Irrigation water that percolates deep into the soil or is lost through runoff is not included in the WF calculation since it goes back to the water bodies hence is not lost. In a study done by Mekonnen & Hoekstra (2011), it was reported that wheat and rice have the largest blue WF, accounting for 45 percent of the global blue WF. According to Dabrowski et al. (2008), Blue water in maize production is higher in South Africa (117m^3/ton) than in all other SADC countries with the exception of Namibia (211 m^3/ton).

2.8.3 Grey water

Chemicals are used in everyday agriculture since the start of the green revolution. Crops do not use all the chemicals applied during the growing season. Loss of pollutants (agro-chemicals and fertilizers) to water bodies can happen through leaching, runoff or return flow (Dabrowski et al., 2008). The term 'grey water footprint' was introduced for the first time by Hoekstra and Chapagain (2008). The grey water footprint can be defined as the volume of freshwater that is required to incorporate the load of pollutants based on existing ambient water quality standards Hoekstra et al. (2011). However, there has been a disagreement among scholars in that, the calculation method is imperfect as a litre of water extracted directly from a resource is not physically or conceptually the same as a litre of water assimilating an emission (Ridoutt & Pfister, 2010). Pollution generated by the use of agrochemicals has a potential of harming both the world human population and its environment. Crops such as cotton (Franke & Mathews, 2013) and tobacco which are highly dependent on chemical are the major polluters of the environment. In a study done by (Franke & Mathews, 2013), they observed that conventional farming results in large grey water footprints as compared to organic farming.

CHAPTER THREE

3.0 METHODS MATERIALS

3.1 Study Area

A case study of three SHIS namely ZIS, TFIS and TIS were used. The three schemes were selected as because they have been cited as the most productive and exceptionally functional of the remaining SHIS in South Africa and have a wide diversity in production features (Ntsonto, 2005).

ZIS scheme is located in the central part of the Eastern Cape, about 30 km west of King William’s Town towards Fort Beaufort (32°45′S; 27°03′E), and 20 km from the main road (Appendix 1). Climate is semi-arid and relatively mild, with a mean annual rainfall of about 580 mm of which about 445 mm is received in summer. Soils of the Oakleaf and Dundee form (Soil Classification Working Group, 1991) are dominant (Van Averbeke et al., 1998, Fanadzo et al., 2010). The scheme covers approximately 635 hectares of which 434 hectares make the main Zanyokwe and the rest make Kamma-Furrow, these are shared amongst six villages namely: Zingcuka, Kamma-Furrow, Ngqumeya, Zanyokwe, Lenye, and Burnshill, and is served by Sandile Dam (Pundo, 2005).

Tugela Ferry irrigation scheme is located in the Midlands region of KwaZulu-Natal, falls within Msinga local municipality and covers an area of 840 hectares of high-potential soils (Cousins, 2013). It is situated in a dry to semi-arid zone, with a mean rainfall of 600–700 mm per annum and very high summer temperatures of up to 44°C (Cousins, 2013). Water is drawn from a diversion weir across the Thukela River and distributed via a main canal, holding dams and smaller distribution canals (Appendix 2).

Thabina irrigation scheme is in the Limpopo province about 25km from Lydenburg along the R36 close to Tzaneen (Veldwisch, 2006), at the foot of the Rita Mountain. The scheme has four wards where crop production takes place. Annual rainfall averages 790 mm with drastic inter annual variations, recurrent droughts and long dry seasons (Jordaan & Grove, 2012). It consists of 234 plots, which are held under customary land tenure. There are about 160 plot holders, with an average land holding of 1.3 hectares. It covers an area of about 200ha (Appendix 3). Water for agriculture activities is supplied from the Thabina River through a connection of canals.

3.2 Water Footprint for Growing Vegetables

This study was limited to agricultural production, because it is regarded as being responsible for the major part of global water use (Postel et al., 1996 & Kampman, 2007). The focus of the study was on the production stage, that is, the cultivation of the product, from sowing to harvest and study period selected was 2000 to 2012. Crop WF estimates were calculated following the framework by Hoekstra &

Chapagain (2008). The water footprint was calculated for each year distinguishing the green, blue and grey water components. WF_{blue} and WF_{green} of vegetable crops produced at each scheme was quantified by taking into account local climatic and soil conditions in the respective sites. Local nitrogen fertilizer rates applied was used for calculating the grey water. Crop evapotranspiration was calculated using a grid based dynamic water balance model, which computes a daily water balance and calculates crop water use and requirements. Computations of vegetable crop evapotranspiration and yield, was done following the method and assumptions provided by Allen et al. (1998). The CROPWAT model version 8.0$^{@}$ was used to estimate crop water use.

3.3 Evapotranspiration (ET_c)

The actual crop evapotranspiration (ET_c, mm/day) was calculated using equation 2 (Allen et al*.,* 1998, Mekonnen & Hoekstra, 2010):

$$ET_c\left[t\right]=K_c\left[t\right]\times K_s\left[t\right]\times ET_o\left[t\right] \tag{2}$$

Where,

K_c is the crop coefficient,

$K_s[t]$ a dimensionless transpiration reduction factor de-pendent on available soil water and

$ET_O\,[t]$ the reference evapotranspiration (mm/day).

The value of K_s was calculated on a daily basis as a function of the maximum and actual available soil moisture in the root zone.

The amount of rainfall lost through runoff was computed using equation 3, as in the Hydrologiska Bryans Vattenbalansavdelning (HBV) model (Bergstrom, 1995; Lid en & Harlin, 2000; Mekonnen & Hoekstra, 2010).

$$RO\left[t\right]=\left(P\left[t\right]+I\left[t\right]\right)\times\left(\frac{S\left[t-1\right]}{S_{\max}\left[t-1\right]}\right)^{z} \quad (3)$$

In which RO[*t*] is runoff on day *t* [mm];

P [*t*] is precipitation on day *t* [mm];

I [*t*] is net irrigation depth on day *t* that infiltrates the soil [mm].

The value of the parameter *z* was adopted from Siebert & Doll (2010). The irrigation requirement was determined based on the root zone depletion using equation 4. The actual irrigation ***I*** [*t*] depended on the extent to which the irrigation requirement was met:

$$I\left[t\right]=\alpha\times IR\left[t\right] \quad (4)$$

Where α is the fraction of the irrigation requirement that is achieved. Following the method as proposed in Hoekstra et al., (2009) and also applied by Mekonnen & Hoekstra (2010), Siebert & Doll (2010), two scenarios were used, one with α=0 (no application of irrigation, i.e. rain-fed conditions) and the other with α =1 (full irrigation).

3.4 Green Water Footprint (WF_{green})

WF_{green} of vegetable crop production was calculated as a total of the rain water evaporated from the field during the crop growing period. It is calculated as the green component of crop water use (CWU_{green}) divided by the yield t/ha. CWU_{green} (m^3/ha) is calculated using equation 5. The summation of the actual Evapotranspiration (ET_a) was done from the day the vegetable crops were planted until the last day of harvest. In the case of rain-fed vegetable crop production, blue crop water use was zero.

$$CWU_{green} = 10 \times \sum_{d=1}^{\lg p} ET_{c,green} \tag{5}$$

Where:

ET_{green} represents the daily evapotranspiration green (mm/day);

lgp represents the length of growing period in days (*d*);

10 is a factor meant to convert water depths in mm into water volume per hectare (m^3/ha).

Therefore, the WF_{green} was calculated by dividing the CWU_{green} (m^3/ha) by the actual vegetable crop yield (Y) given by equation 6 in t/ha.

$$WF_{green} = \frac{CWU_{green}}{Y} \quad \left(m^3/t\right) \tag{6}$$

3.5 Blue Water Footprint (WF_{blue})

The WF_{blue} of vegetable crop production was calculated as the blue component of crop water use i.e. water from ground or open body surfaces such as rivers and lakes. CWU_{blue}, which was calculated using equation 7, is equal to the total ET_a over the growing period as simulated under the case α=1 (full irrigation) minus the green crop water use. The summation was done from the day the vegetable crops were grown until the last day of harvest.

$$CWU_{blue} = 10 \times \sum_{d=1}^{\lg p} ET_{c,blue} \tag{7}$$

Where

ET_{blue} represents the daily green evapotranspiration (mm/day);

Lgp represents the length of growing period in days (*d*);

10 is a factor meant to convert water depths in millimeters into water volume per hectare (m^3/ha)

WF_{blue} was calculated by dividing the CWU_{blue} (m^3/ha) by the actual vegetable crop yield (Y) given by the equation 8 in t/ha

$$WF_{blue} = \frac{CWU_{blue}}{Y} \quad \left(m^3/t\right) \tag{8}$$

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3.6 Grey Water Footprint (WF_{grey})

The WF_{grey} of vegetable crops production was calculated by quantifying the volume of water needed to assimilate the fertilizers that reach ground or surface water. Nutrients leaching from agricultural fields are the main cause of non-point source pollution of surface and subsurface water bodies. In this study, quantification was done for the grey water footprint related to nitrogen use only. The WF_{grey} m^3/ton was calculated by multiplying the fraction of nitrogen that leached (θ, %) by the local nitrogen application rate (*AR*, kg/ha) and dividing this by the difference between the maximum acceptable concentration of nitrogen (C_{max}, kg/m^3) and the natural concentration of nitrogen in the receiving water body (C_{nat}, kg/m^3) and by the actual individual vegetable crop yields (Y_a) as given in equation 9:

$$WF_{gy} = \left(\frac{\theta \times AR}{C_{\max} - C_{nat}} \right) \times \frac{1}{Y_a} \qquad (9)$$

3.7 Water Footprint (WF_{total})

Total WF per individual crop was calculated using equation 10. It was calculated as the sum of the three components of WF.

$$WF_{total} = WF_{green} + WF_{blue} + WF_{grey} \qquad (10)$$

Where

WF_{total} = the water footprint (litres/product).

WF_{green} = the green water footprint (litres /product).

WF_{blue} = the blue water footprint (litres /product).

WF_{grey} = the grey water footprint (litres /product).

CHAPTER FOUR

4.0 RESULTS

4.1 Assumptions and Yield Data

In this study, the Crop Water Requirement (CWR) component was utilized. This option estimates evapotranspiration under optimal conditions, which means that crop evapotranspiration (ET_c), equals CWR (Hoekstra et al., 2011). Water footprints were calculated using data for the period 2000-2013. According to Hoekstra et al. (2009), average yield data over a period of 5 years is more suitable however, in this study there was not enough yield and planting date data for each of the three SHIS for the period from 2000-2013. Resultantly, an assumption was made that farmers in the three SHIS get the same average yield and use the nationally recommended planting dates for each crop (Table 1). Yield averages and planting dates for the five vegetable crops used in the study were obtained from the extension officers' in the Department of Agriculture. Crop coefficients of different vegetable crops were taken from Allen et al. (1998).

Table 1: Average yields of vegetable crops grown in SHIS in South Africa

Crop	Yield (t/ha)	Planting months
Cabbage	30.0	August
Tomato	19.0	September
Spinach	7.0	February
Potato	9.0	April
Green beans	1.5	October

4.2 Annual and Monthly Rainfall Analysis

4.2.1 Meteorological Data

Climatic data was obtained from the South African Weather services. Missing data from any of the parameters for all stations was obtained from the nearest weather station. For TFIS, there was no climatic data for the year 2000, so calculations were made using data for the period 2001 to 2013 and radiation data were estimated using CROPWAT. Humidity data for ZIS were estimated using CROPWAT. There was no rainfall data for the year 2013 for ZIS, an average of the available data was used in the calculations by averaging rainfall data from the 2000-2012. Meteorological data from the SHIS in the three provinces was obtained from weather stations nearest to each scheme. The CROPWAT programme was used to calculate the evapotranspiration (ET_O) per site following the Penman-Monteith formula, while rainfall data from the respective stations were used to calculate effective rainfall (P_{eff}) by applying the USDA Soil Conservation Service formula following guidelines by Hoekstra et al., (2011). Based on total rainfall and monthly consumptive use, effective rainfall values were computed (Table 2). TIS had the highest average annual rainfall (890.2 mm), with an annual average effective rainfall of 79 percent of the total rainfall. The TFIS had an annual average rainfall of 766.8 mm and 84 percent an average effective rainfall of the total rainfall. ZIS had the lowest average rainfall i.e. 692.3 mm and an 89 effective rainfall average of the total rainfall received in the study period.

Table 2: Average effective rainfall at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation scheme (TIS) for the period 2000-2013. (Data imported from CROPWAT 8.0©)

Month	**Zanyokwe Irrigation Scheme**		**Tugela Ferry Irrigation Scheme**		**Thabina Irrigation Scheme**	
	Rainfall	Effective rainfall	Rainfall	Effective rainfall	Rainfall	Effective rainfall
			mm			
January	92.0	78.5	138.7	107.9	179.4	127.9
February	65.0	58.2	32.1	31.3	122.6	98.5
March	69.0	61.4	62.1	56.0	101.2	84.8
April	58.0	52.6	46.8	43.3	68.1	60.7
May	34.0	32.2	13.9	13.6	3.5	3.5
June	29.0	27.7	12.9	12.6	5.5	5.5
July	32.0	30.4	14.1	13.8	5.8	5.8
August	46.0	42.6	21.8	21.0	3.1	3.1
September	42.0	39.2	38.4	36.0	26.9	25.8
October	64.0	57.4	72.9	64.4	48.4	44.6
November	79.6	69.5	117.1	95.2	168.3	123.0
December	82.3	71.4	145.8	111.8	157.5	117.8
Total	692.3	621.0	766.8	647.0	890.2	700.9

4.2.2 Annual Average Rainfall

The annual average rainfall distribution showed high variability for the three SHISs (Figure 6). Generally, Thabina received more rain per year compared to the other two SHIS. Annual average rainfall within the three irrigation schemes varied with geographical location and from year to year as depicted in Figure 6. The average annual rainfall recorded for all the 3 stations between 2000 and 2013 is 767 mm. Thabina SHIS received the highest average rainfall per year in 2004 recording 1677.6 mm with Tugela Ferry SHIS receiving the second highest of 1324 mm in 2006 while Zanyokwe SHIS received the least highest of 1017 mm in 2011. The lowest averages of 289 mm in 2002, 302.5 mm in 2012 and 416.7 mm in 2008 were recorded at Thabina, Tugela Ferry and Zanyokwe SHISs respectively. The data showed that in high rainfall years in all the Schemes total annual rainfall increased; conversely, low average rainfall years are common to all the SHISs. The results show that for ZIS, 10 out of the recorded 13 annual rainfall amounts surpassed the all-time normal average rainfall of 580 mm. Relatively high recordings were observed in 2011, 2006 and 2000 i.e. 1117 mm, 806 mm and 818.2 mm respectively. Of the 11 years that received rainfall which was above the normal average of 600 mm at TFIS, the highest amount was observed in 2006 (1324 mm), 2004 (903.7 mm) and 2010 (934.5 mm). Eight out of 14 years recorded for TIS had rainfall amounts above the normal average of 790 mm. Highest deviancies were observed in 2000, 2004, 2006, and 2011 i.e. 1607.6 mm, 1677.6 mm, 1276 mm, 1108.72 mm respectively.

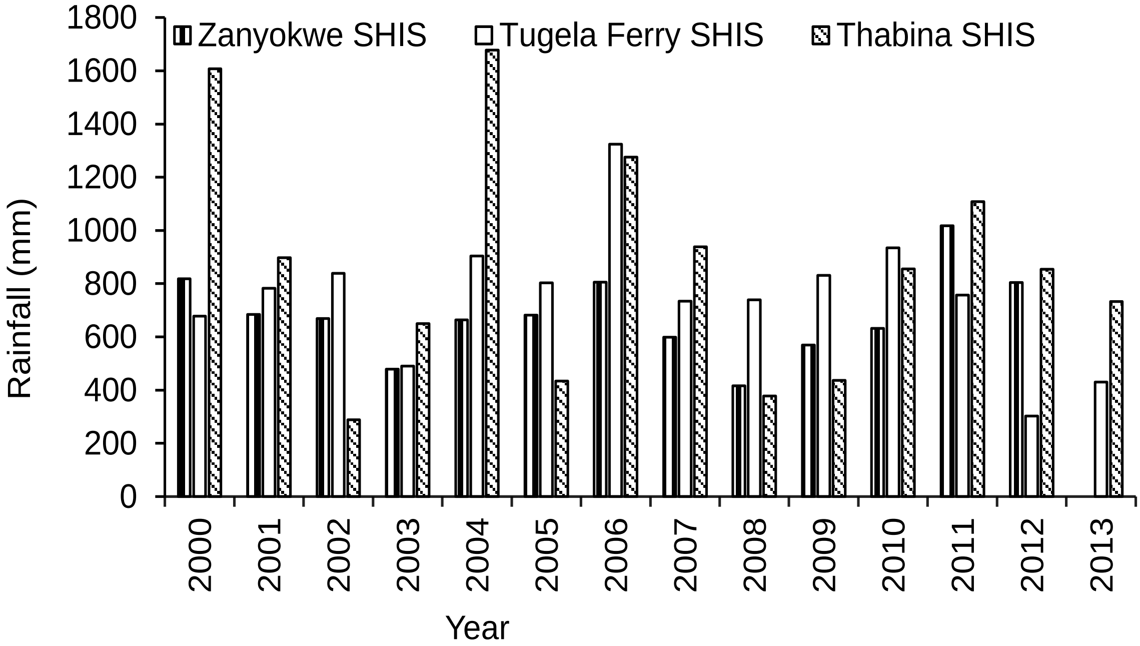

Figure 6: Average annual rainfall at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation scheme (TIS) in South Africa, for the period 2000-2013.

4.2.3 Monthly Average Rainfall

A similar trend in the rainfall pattern was observed in the three irrigation schemes, where highest monthly rainfall averages where recorded between and including November and April. The lowest rainfall was between May and August (Figure 7). Thabina irrigation scheme had the highest recorded monthly rainfall amongst the three irrigation schemes (168 mm) and the lowest i.e. 3 mm in November and August respectively. Both ZIS and TFIS received lowest and highest monthly rainfall averages in the same months, i.e. June and December respectively. The lowest monthly average rainfall for ZIS is 29 mm and the highest being 92 mm. Tugela Ferry irrigation scheme had the lowest monthly rainfall of 12 mm and a highest of 146 mm in December respectively. TIS had the highest total rainfall (867 mm). It was observed that ZIS had the lowest total of 680 mm and TFIS had 754 mm.

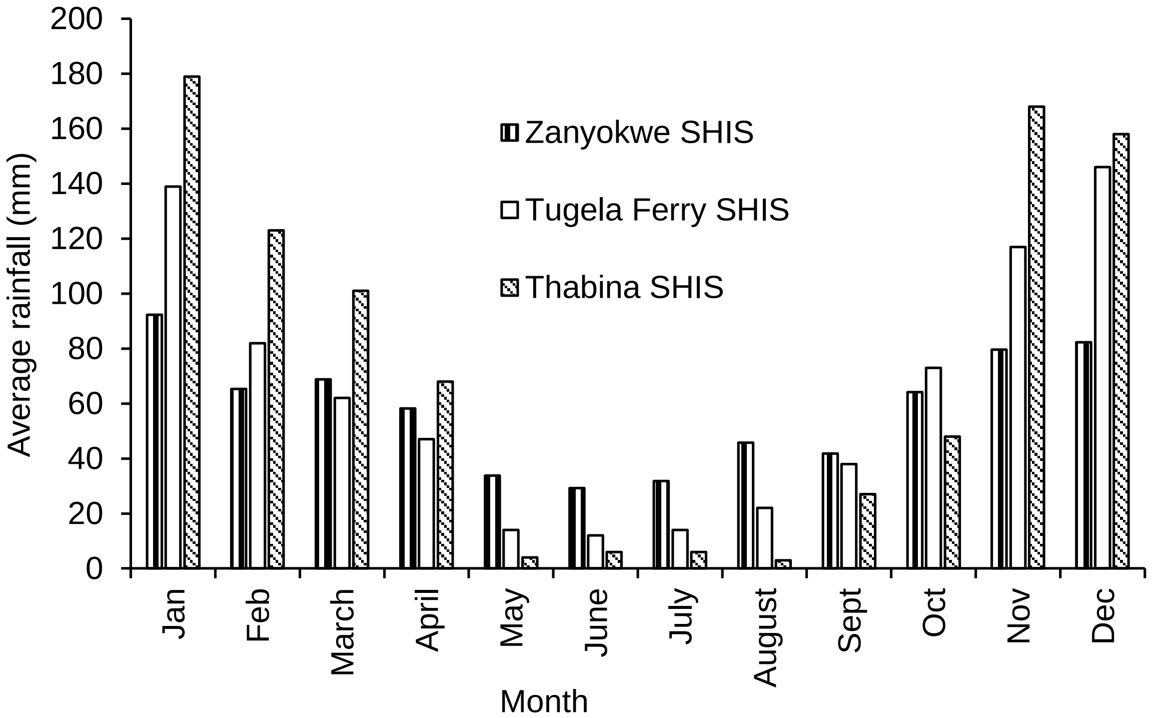

Figure 7: Average monthly rainfall at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation scheme (TIS) in South Africa for the period 2000- 2013

4.2.3 Variability of Annual Rainfall

The statistical parameters for the annual rainfall data are summarised in Table 3, where the mean, standard deviation, coefficient of variation, skewness and kurtosis values are given. These parameters show the variability in the annual rainfall at the three irrigation schemes. TIS received the highest mean annual rainfall of 866.9 mm, TFIS received 753 mm and ZIS received the least amount of rainfall, i.e. 680.3 mm. Rainfall range indicated the difference between the maximum and minimum annual rainfall. High ranges were observed at all the schemes i.e. 1388.3 mm for TIS, 1021.5 mm for TFIS and 600.3 mm for ZIS. TIS had a standard deviation of 433.9, ZFIS has 245.1 and ZIS with the lowest standard deviation of 156.9. All the three schemes had very high standard deviations, which can be correlated with high rainfall ranges. The skewness values for the three irrigation schemes are all in the positive ranges. Both ZFIS and ZIS are approximately symmetric while TIS data was moderately skewed**.** ZFIS has a skewness value of 0.59 while ZIS and TIS had 0.42 and 0.32 respectively. The CV for annual rainfall was high in the SHISs. There was more annual rainfall variability at TIS, where the CV was 50.05. TFIS had a CV of 32.5 and ZIS the least variability at 23.07.

Table 3: Descriptive statistics of annual rainfall data for rainfall data received at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation scheme (TIS) (2000-2013).

Parameter	Zanyokwe Irrigation Scheme	Tugela Ferry Irrigation Scheme	Thabina Irrigation Scheme
Mean	680.3	753.7	866.9
Range	600.3	1021.5	1388.5
Minimum	416.7	302.5	289.1
Maximum	1017	1324	1677.6
Standard Deviation	156.9	245.1	433.9
kurtosis coefficient	0.72	1.74	-0.37
Skewness coefficient	0.42	0.32	0.59
Coefficient of variation (CV)	0.23	0.33	0.50

4.2.4 Probability Exceedance of Yearly Rainfall

The relationship between yearly rainfall and exceedance probability at ZIS, TFIS and TIS was approximated by the straight line as shown by the Figure 8. For TIS, the straight line accounts for about 94 percent (r^2 = 0.94) of the variability of yearly rainfall depending on probability of exceedance. The probability of exceedance for a certain amount of annual rainfall increased the threshold rainfall amount decreased. For instance, for TIS, the exceedance probability of receiving 1314 mm was 20 percent (P20); the average for a wet year (Figure 8A). Similarly exceedance probability for 865 mm is 50 percent, and for P80 its 417 mm. For TFIS, the straight line accounts for about 83 percent (r^2 = 0.83) of the variability of yearly rainfall depending on probability of exceedance. In 20 percent of the time, yearly average rainfall was equal to 993 mm, P (50) was observed to be 753 mm and P (80) was 513 mm (Figure 8B). Lastly, for TIS, the straight line accounts for about 91 percent (r^2 = 0.91) of the variability of annual rainfall depending on probability of exceedance (Figure 8C). The calculated P (20), P (50) and P (80) values for ZIS are 843 mm, 680 mm and 519 mm respectively. TIS received more rainfall in both the wet, dry seasons as compared to the other two irrigation schemes.

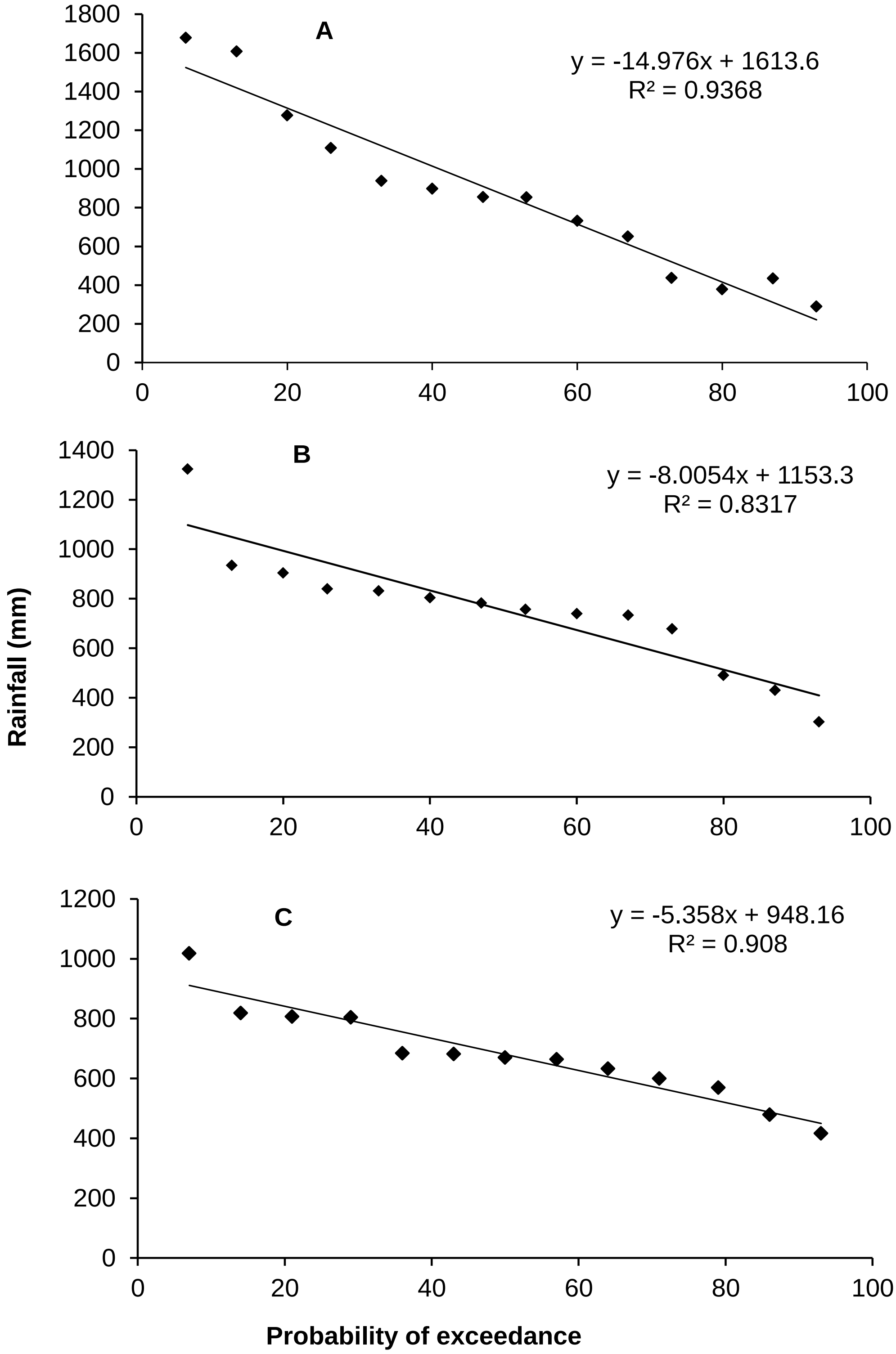

Figure 8: Probability of exceedance for yearly rainfall at A) Thabina (TIS) B) Tugela Ferry (TFIS) and C) Zanyokwe Irrigation (ZIS) scheme for a period (2000-2013).

4.3 Blue Water Evapotranspiration (ET_{blue})

4.3.1 ET_{Blue} for Cabbage Production

The growing season generally starts in August to January (Figure 9). Generally, for all schemes, there is a general increase of ET_{blue} from August to December then decreases in January. The highest average ET_{blue} is 66.2 mm was observed at ZIS in December with the same scheme having its lowest ET_{blue} of 3.7 mm in August. The total average ET_{blue} for ZIS for the entire growing season was 214.1 mm. At TFIS the highest amount of average ET_{blue} for cabbage was 47.2 mm and occurred in December, the lowest was 21.8 mm in August. The total average ET_{blue} for ZFIS in the whole cabbage growing season was 237.5 mm and was the highest among the three schemes. TIS had lowest total average ET_{blue} of 145.3 mm. The highest monthly ET_{blue} (51.2 mm) occurred in October whilst the lowest volume, i.e. 2.5 mm occurred in January.

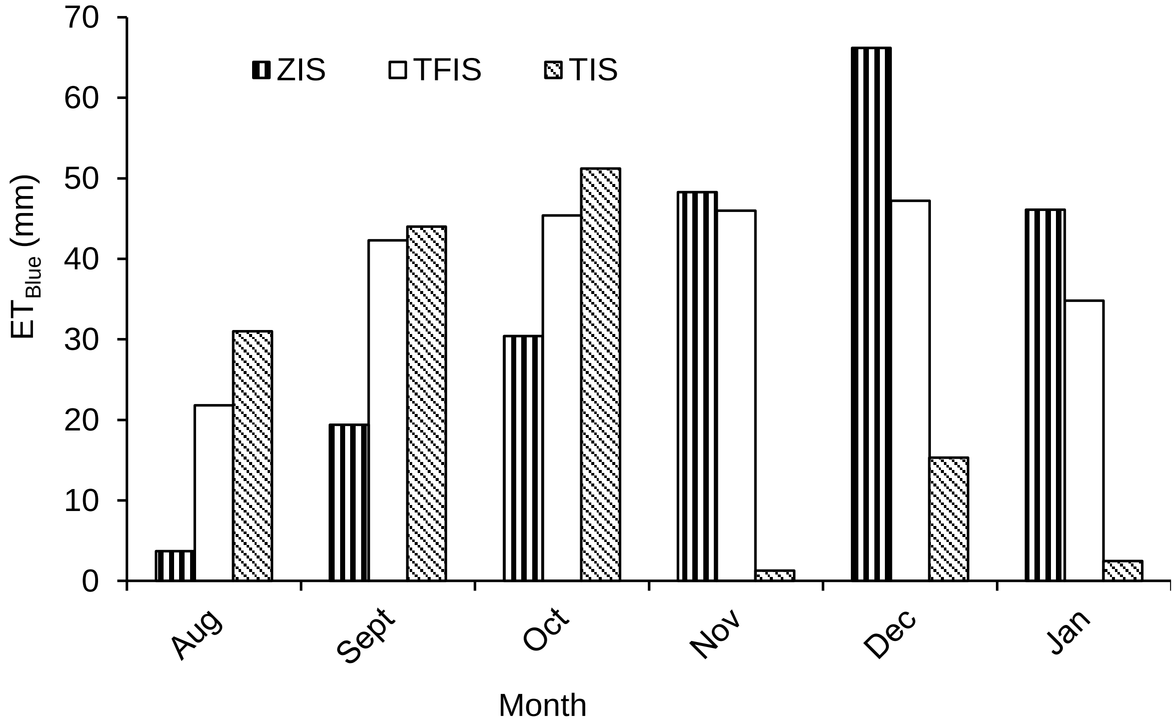

Figure 9: Blue water evapotranspiration (ET_{blue}) in mm of cabbage production at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation scheme (TIS) (Period 2000–2013).

4.3.2 ET_{Blue} for Potato Production

Monthly ET_{blue} was low at the start of the potato growing season in April and gradually increased until July where the highest amounts were observed, before dropping slightly in August (Figure 10). ZIS had the lowest total average ET_{blue} for the growing season i.e. 69.9 mm; TFIS had 184.5 mm while TIS had the highest amount of 226.5 mm. Both TIS and ZIS had no ET_{blue} in the month of April while TFIS had 1.7 mm and is the lowest monthly ET_{blue} in the whole potato production season. The highest monthly ET_{blue} can be observed in July; ZIS had the least amount of 28 mm, TFIS had 58.2 mm and TIS had 68.1 mm the highest of the three schemes.

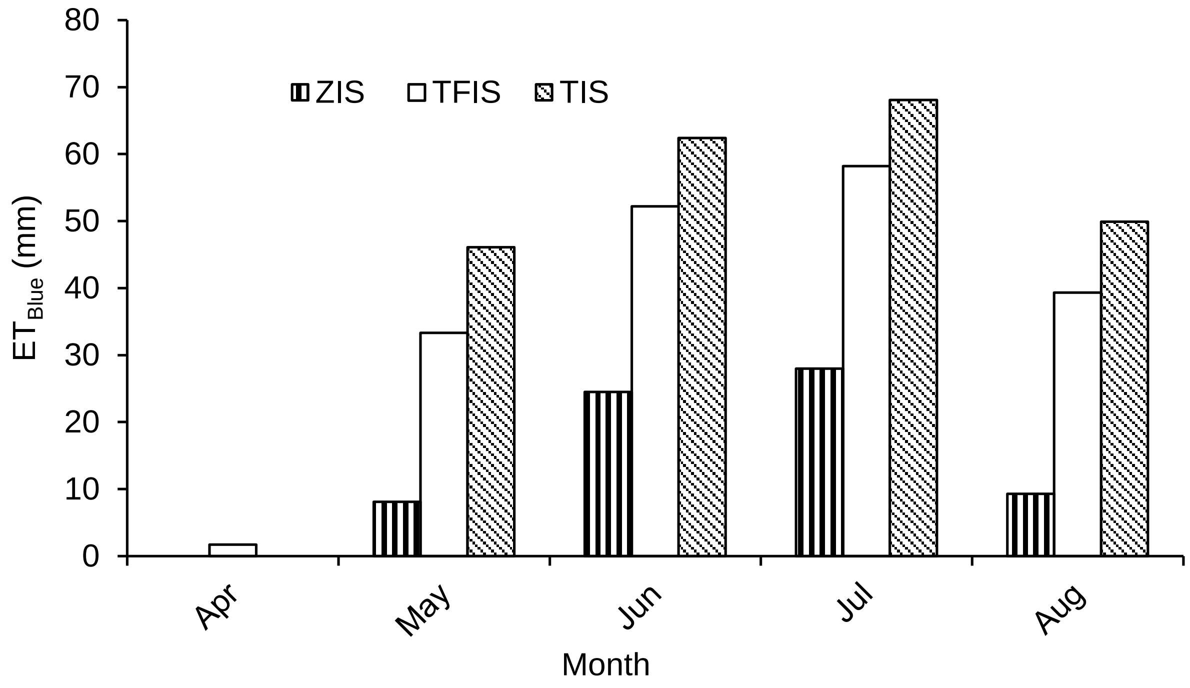

Figure 10: Blue water evapotranspiration (ET_{blue}) in mm of potato production at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation schemes (TIS) (Period 2000–2013).

4.3.3 ET_{Blue} for Green Beans Production

Of the five crops, green beans had the shortest growing period (Figure 11). Average monthly ET_{blue} generally increased from October, peaks in December then drops in January. TIS had 0 mm ET_{blue} twice in November and January. The highest ET_{blue} for TIS were recorded in December, having 15 mm, though this was the lowest when compared to the other two schemes where the highest amount of average monthly ET_{blue} were 66 mm and 46.5 mm at ZIS and TFIS respectively; all observed in the same month of December. Generally for TFIS the lowest ET_{blue} (0.1 mm) was recorded in the month of October having the same trend as observed at ZIS, where the lowest amounts of ET_{blue} were in October and the highest in December before the amounts dropped in January to 18.7 mm. The average total ET_{blue} for the whole green bean growing season varied amongst the schemes. ZIS had the highest amount of ET_{blue} at 103.3 mm; TFIS had 69.9 mm and the lowest was for TIS with an average of 19.2 mm.

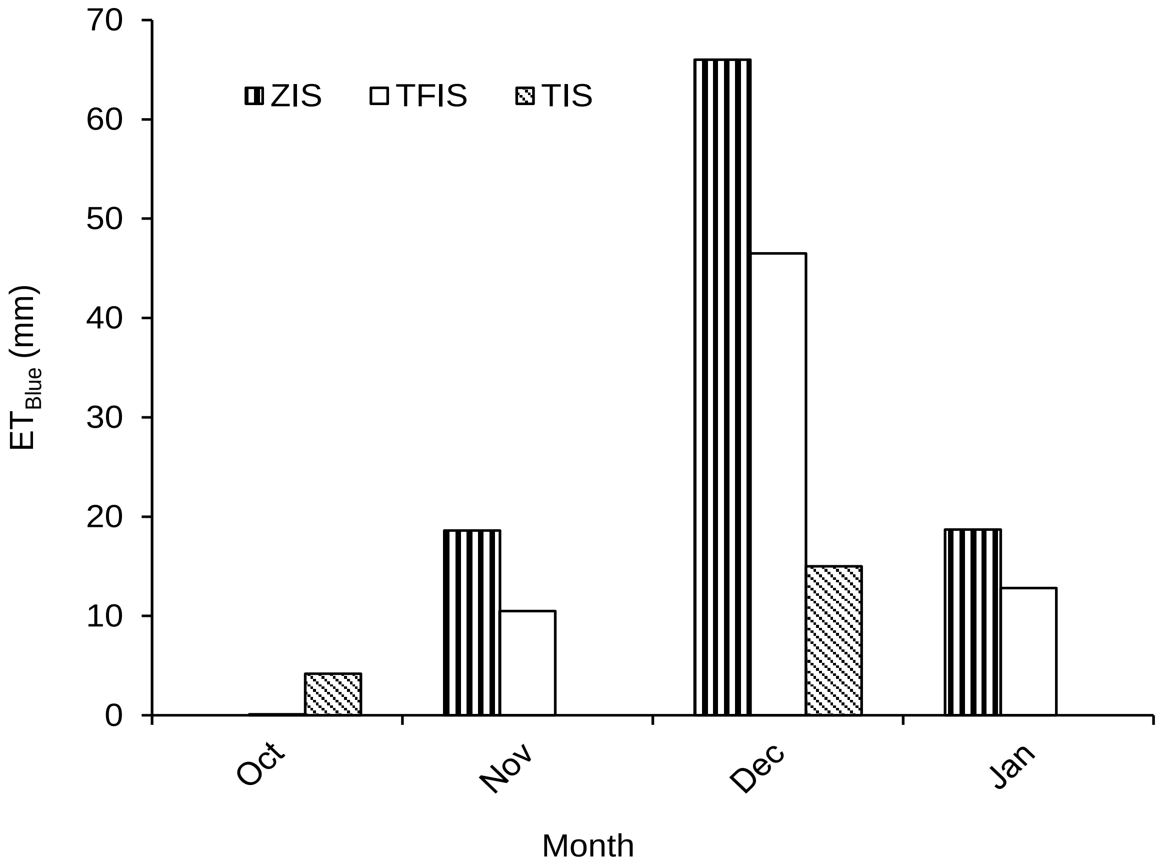

Figure 11: Blue water evapotranspiration (ET_{blue}) in mm of green beans production at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation schemes (TIS) (Period 2000–2013).

4.3.4 ET_{Blue} for Tomato Production

The tomato season was much longer than most vegetable crops grown in small holder irrigation schemes. Generally, it ran from September to February (Figure 12). A general trend can be observed where in September ET_{blue} is at its lowest; peaks in December then gradually decreases between January and February. ZIS had the highest average total ET_{blue} of 217.3 mm followed by TFIS, which had 202 mm (Figure 4.7). TIS had lowest total average ET_{blue} of 84.7 mm. The lowest monthly ET_{blue} observed was 0 mm in February for TIS. The lowest monthly ET_{blue} for ZIS and TFIS are 6.3 mm in September and 6.9 mm in February respectively. Both ZIS and TFIS had their highest average monthly ET_{blue} in December with ZIS having 79.2 mm and TFIS having 62.1 mm.

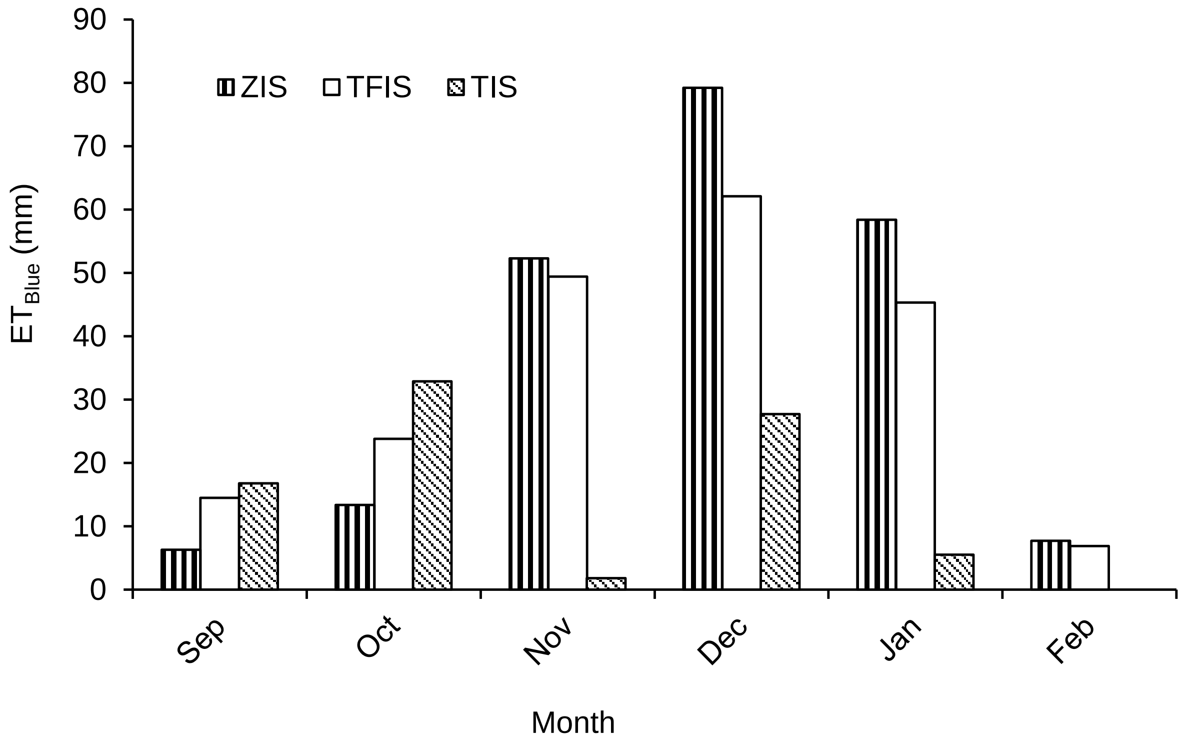

Figure 12: Blue water evapotranspiration (ET_{blue}) in mm of tomatoes production at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation schemes (TIS) (Period 2000–2013).

4.3.5 ET $_{Blue}$ for Spinach Production

February had the lowest amount of monthly ET_{blue} at all the irrigation schemes (Figure 13). There was a general increase in ET_{blue} at all the schemes from February till the end of the growing season. The lowest amount of monthly ET_{blue} observed for ZIS was 9.3 mm in February. For TFIS the lowest monthly ET_{blue} at the scheme is 7.7 mm also observed in February. The highest monthly ET_{blue} was observed in April for both ZIS and TFIS; the schemes had 23.6 mm and 45 mm respectively. For TIS the highest monthly ET_{blue} was 46 mm in May. Of the three schemes; TFIS had the highest average total ET_{blue} of 128.8 mm while ZIS had the least at 71.1 mm and TIS had 83.4 mm.

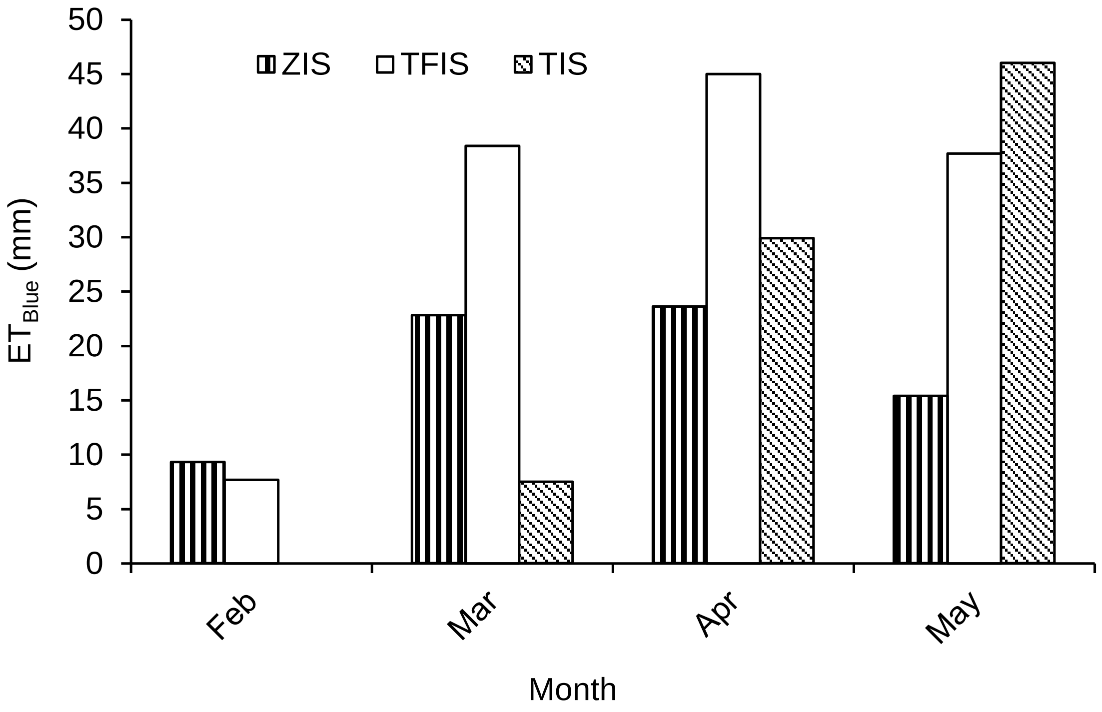

Figure 13: Blue water evapotranspiration (ET_{blue}) in mm of spinach production at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation schemes (TIS) (Period 2000–2013).

4.4 Blue Water Footprint of Selected Vegetable Crops.

The overall blue water footprint (WF_{blue}) for vegetable production at ZIS, TFIS and TIS is shown in Table 4. The total ET_{blue} in mm were converted to crop water use (CWU_{blue}) in m^3/ha by a factor of ten following Hoekstra, (2011). The final WF_{blue} is calculated by dividing the CWU_{blue} by the respective crop yield. The WF_{blue} for cabbage production was found to be highest at TFIS where 79.2 m^3 is used to produce a ton of the crop. At ZIS the WF_{blue} was 71.4 m^3/ton while the lowest amount water was being used at TIS at 48.4 m^3/ton. Green beans had the highest WF_{blue} of all the crops in the three SHISs. More blue water was used at both TIS and ZIS in the production of green bean with averages of 1280 m^3/ton and 688.6 m^3/ton respectively. The average blue water used in green bean production at TFIS is 64 m^3/ton water was used in green beans production at ZIS than any other crops. At TFIS potato production used more blue water with an average of 205.2 m^3/ton over the growing period from 2000 to 2013; the lowest blue water user in the scheme is cabbage. Green beans, potato and tomato all used relatively more water at TFIS than the other two schemes. At TIS an average of 251.7 m^3/ton blue water was used to produce potatoes in the research period. The least amount of blue water used at TIS was in the production of tomato with an average of 44.6 m^3/ton. Generally it can be observed from the table that the average total blue water footprint for production of the five vegetable crops at ZIS is 655.2 m^3/ton; at TFIS its 709.6 m^3/ton while the TIS had the lowest total average blue water of 464.3 m^3/ton.

Table 4: Blue water footprint of five vegetable crops grown Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation schemes (TIS) (Period 2000–13)

Crop	**ET_{blue} (mm/dec)**	**CWU_{blue} (m^3/ha)**	**Yield (ton/ha)**	**WF_{blue} m^3/ton**
	Zanyokwe Smallholder Irrigation Scheme			
Cabbage	214.1	2141	30	71.4
Green beans	103.3	1033	1.5	688.6
Potato	69.9	699	9	77.7
Spinach	71.1	711	7	101.6
Tomato	217.3	2173	19	114.4
	Tugela Ferry Smallholder Irrigation Scheme			
Cabbage	237.5	2375	30	79.2
Green beans	69.9	699	1.5	466
Potato	184.7	1847	9	205.2
Spinach	128.8	1288	7	184
Tomato	202	2020	19	106.3
	Thabina Smallholder irrigation Scheme			
Cabbage	145.3	1453	30	48.4
Green beans	19.2	192	1.5	1280
Potato	226.5	2265	9	251.7
Spinach	83.4	834	7	119.1
Tomato	84.7	847	19	44.6

4.5 Green Water Evapotranspiration (ET_{Green})

The measures of green water evapotranspiration are derived from the minimum values between total crop ET and effective precipitation (Hoekstra et al., 2011).

4.5.1 ET_{green} for Cabbage Production

There was general increase in ET_{green} from the start of the cabbage growing season in August until the end in January (Figure 14). Early in the production of cabbage ZIS had the highest ET_{green} usage but as the season progresses TIS becomes the scheme with the highest evapotranspiration. The average of total $ET_{green\ of}$ the whole growing season differed among the three irrigation schemes. TIS had the highest average of total ET_{green} and ZIS had the lowest total, i.e. ZIS had 328.1 mm, TFIS had 414.8 mm and TIS had 413.1 mm. The highest monthly ET_{green} was in December at all the three irrigation schemes; ZIS, TIS and TFIS having 71.6 mm, 117.9 mm and 111.7 mm respectively. The lowest average monthly ET_{green} for all the three sites were in the same month of August; where ZIS had an average of 23.2 mm compared to TIS and TFIS which had 2.6 mm an 11.7 mm respectively.

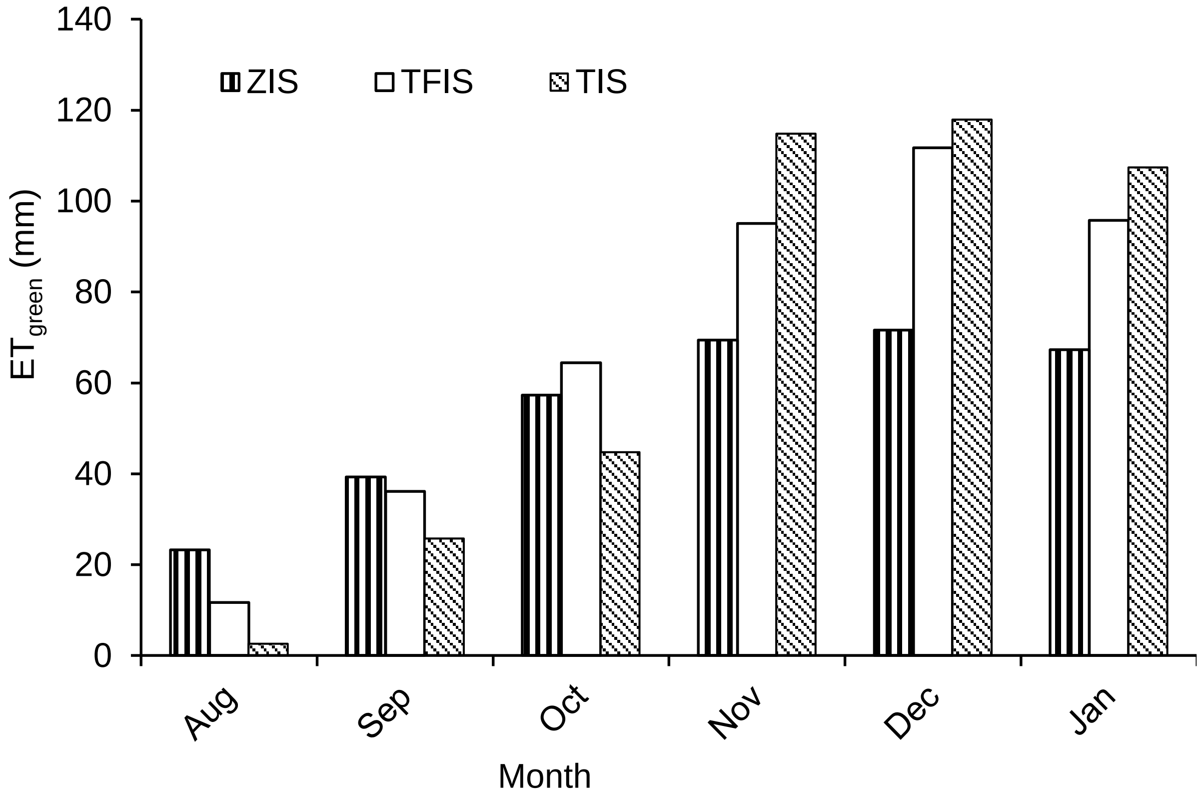

Figure 14: Green water evapotranspiration for cabbage production (mm) at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation schemes (TIS). Period 2000–2013

4.5.2 ET_{green} for Potato Production

Generally, ZIS had the highest total ET_{green} for the full period of the potato growing season (137 mm). TFIS had 74.1 mm while the TIS had the lowest evapotranspiration at 36.1 mm. The highest monthly ET_{green} for both TFIS and TIS was in April (Figure 15). Of the two schemes TIS had a highest evapotranspiration of 22.8 mm and TFIS had 18.7 mm. The highest monthly ET_{green} for ZIS was observed in August i.e. 30.6 mm. ZIS unlike the other two schemes had its lowest ET_{green} in April (18.5 mm). TISs' lowest ET_{green} was 1.1 mm in August and 12.8 mm for TFIS in June.

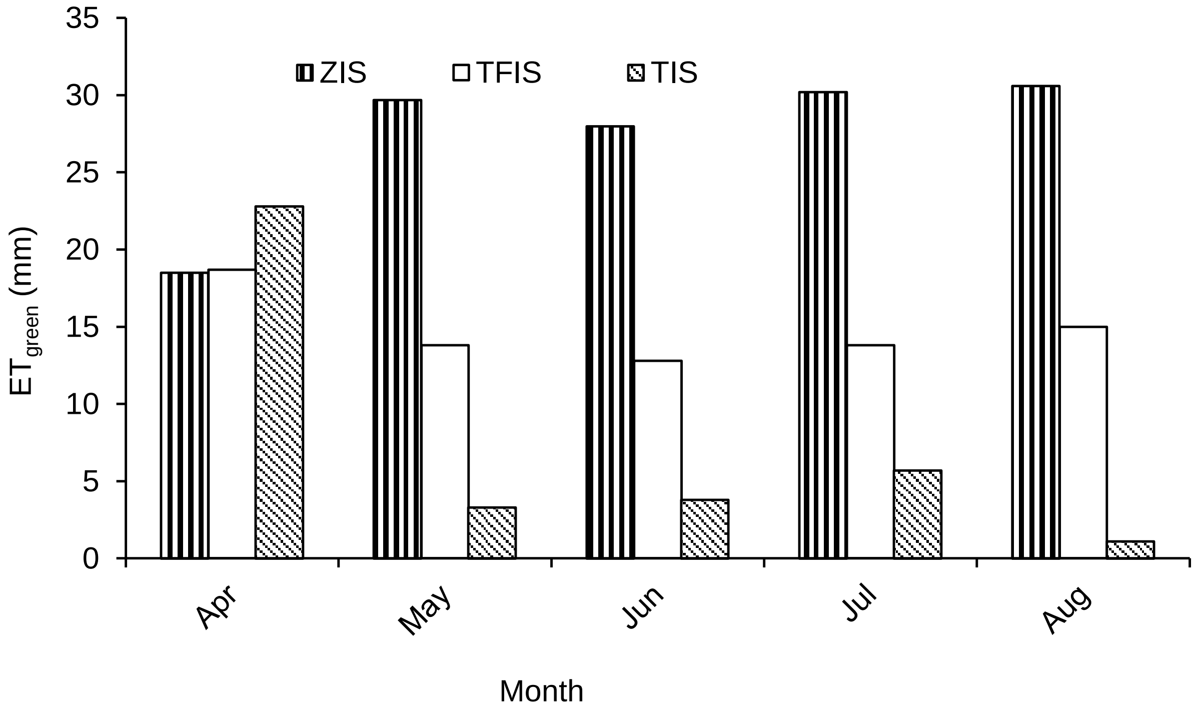

Figure 15: Green water evapotranspiration for potato production (mm) at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation schemes (TIS). Period 2000–2013

4.5.3 ET_{green} for Tomato Production

A raise was noted in ET_{green} from the tomato growing season starting from September to January and a decrease was greatly noted in the month of February (Figure 16). Early in the production of tomato TIS had the lowest evapotranspiration of 16mm but it ended up with the highest evapotranspiration. The average of total ET_{green} of the whole season growing tomatoes TIS had highest average of 443.2mm followed by TFIS having 418.5mm and ZIS had the lowest average of 311.1mm. The highest monthly ET_{green} was in November for TIS it had 118mm, TFIS had 111.7mm in December. ZIS had the highest monthly ET_{green} in January having 78.6mm. The lowest monthly ET_{green} for TIS was 16mm, TFIS had 19mm and ZIS had 12.6mm.

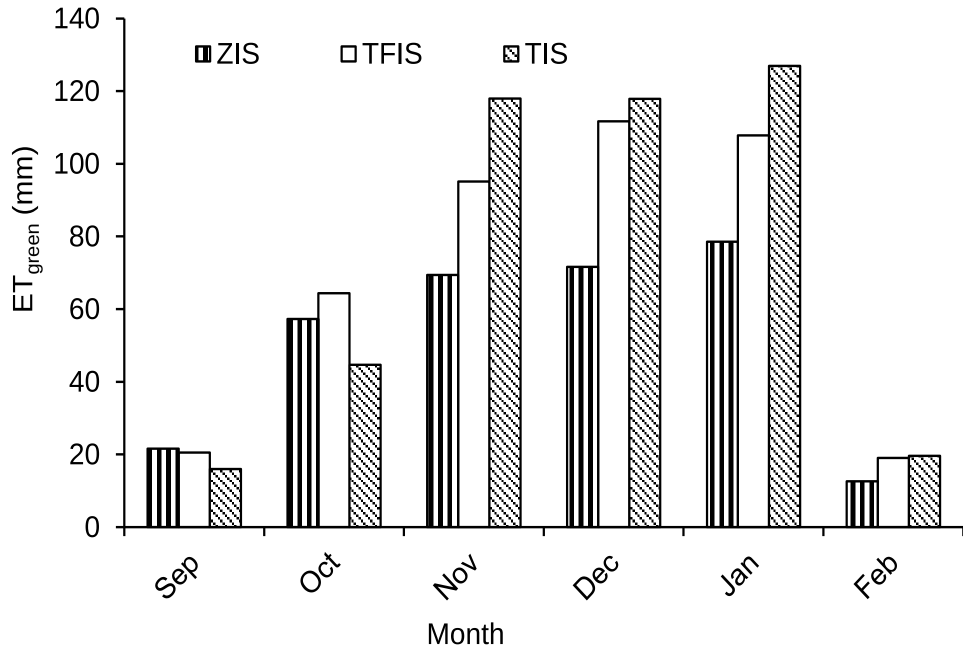

Figure 16: Green water evapotranspiration for tomato production (mm) at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation schemes (TIS). Period 2000–2013

4.5.4 ET_{green} for green beans Production

Tugela Ferry Small holder irrigation scheme had the highest ET_{green} for the full period of green beans growing season with an average of 287.1 mm, TIS had 282.4 mm, while ZIS had the lowest evapotranspiration of 201.9 mm (Figure 17). The highest monthly ET_{green} for both TFS and TIS were in December. Of the two schemes, TIS had the highest evapotranspiration of 117.9 mm and TFIS had 111.7 mm. The highest monthly ET_{green} for ZIS was observed in December, it had 71.6 mm. ZIS had its lowest ET_{green} in October it was 30.2 mm. TIS had its lowest evapotranspiration in October, i.e. 28.5 mm. TFS also had its lowest in October (35.4 mm).

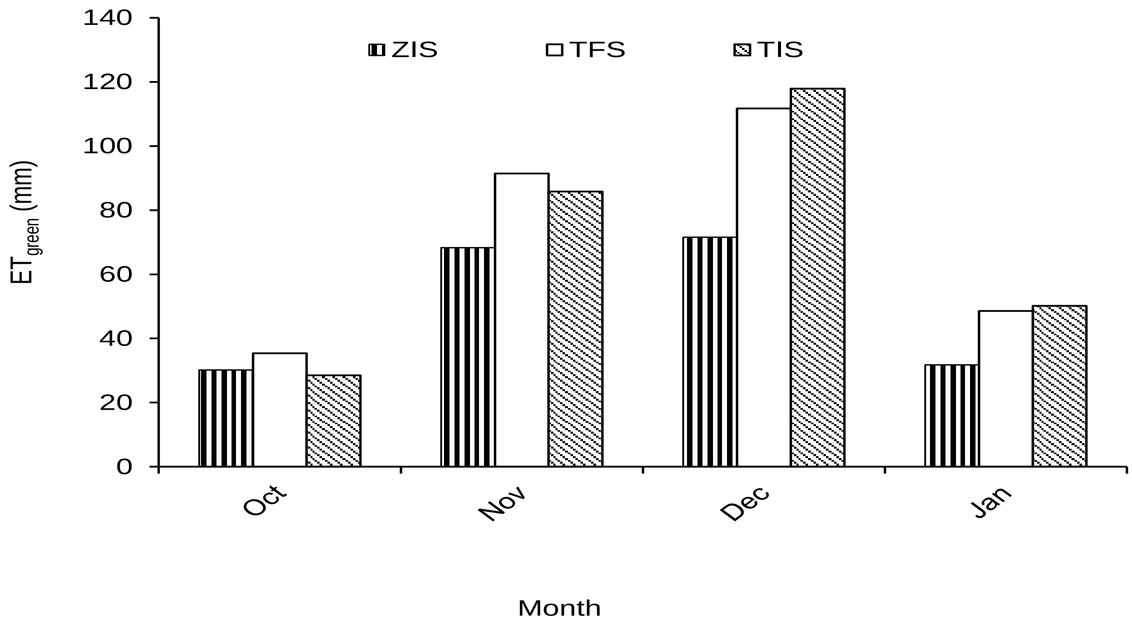

Figure 17: Green water evapotranspiration for green beans production (mm) at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation schemes (TIS). Period 2000–2013

4.5.5 ET_{green} for Spinach Production

There was a general increase in ET_{green} from the start of the spinach growing season in February until end April and it started to decrease in May (Figure 18). As the season started, TIS had the highest ET_{green} evapotranspiration of 39 mm but as the season progressed to the end it ended up with the highest average of ET_{green} of 183.5 mm. ZIS followed with an average ET_{green} of 166.4 mm and TFS had 144.5 mm. The highest monthly ET_{green} for all the three irrigation schemes were in March; TIS, ZIS, and TFIS having 80.6 mm, 61.4 mm and 56.1 mm respectively. The lowest average monthly ET_{green} for all the three sites were in the same month of May: ZIS, TFIS, TIS having 22.5 mm, 10.2mm and 3.3 mm respectively.

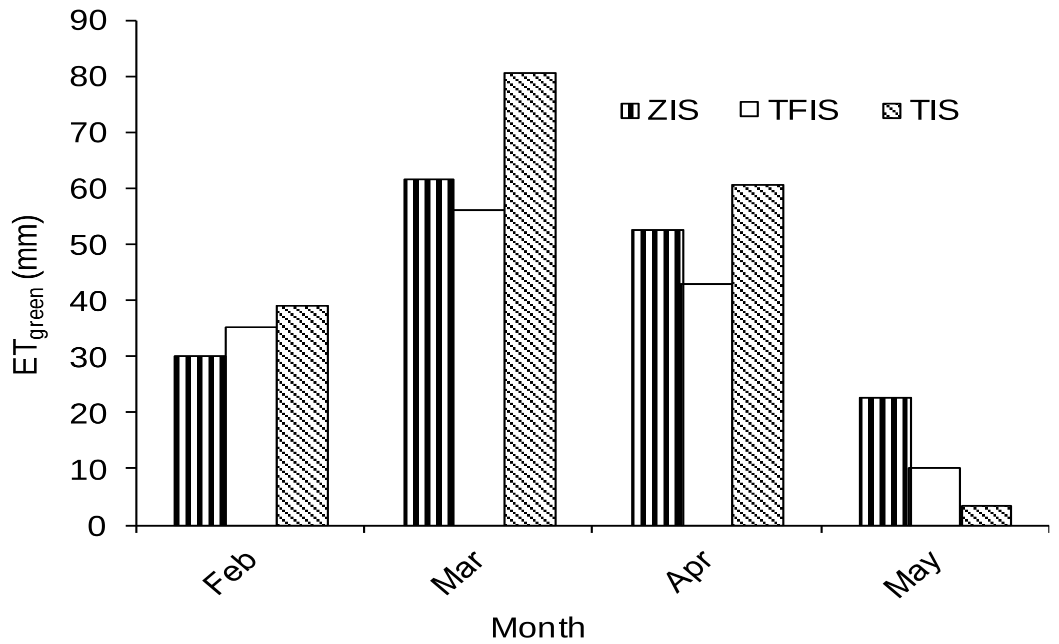

Figure 18: Green water evapotranspiration for spinach production (mm) at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation schemes (TIS). Period 2000–2013

4.6 Green Water Footprint of Selected Vegetable Crops

Green beans were observed to have the highest WF_{blue} of all the crops in the three SHISs. It was observed that WF_{green} for green beans at TFIS was the highest (1914 m^3/ton), TIS was 1882.7 m^3/ton while the lowest was at ZIS (1346 m^3/ton). used more blue water with an average of 205.2 m^3/ton over the 2000- 2013 growing period; the lowest blue water user in the scheme was cabbage. Within ZIS, potatoes had the lowest WF_{green} (152.2 m^3/ton) and the highest being green beans. The same scenario was observed at both TFIS and TIS where potato had the lowest WF_{green} and green beans had the highest (Table 5). There was not much difference in WF_{green} for cabbage production at TFIS and TIS. The study showed that TIS's WF_{green} for cabbage production was 137.7 m^3/ton, while TFIS had 138.3 m^3/ton. The sum of the WF_{green} at the three SHIS revealed that TFIS and TIS used almost the same green water in the production of the named five vegetable crops. WF_{green} of the crops grown at each SHIS revealed that TIS had 2556.6 m^3/ton and TFIS had 2561.3 m^3/ton, ZIS having the lowest total i.e. 2009 m^3/ton.

Table 5: Green water footprint of five vegetable crops grown at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation schemes (TIS) (Period 2000–13)

Crop	**ET_{green} (mm/dec)**	**CWU_{green} (m^3/ha)**	**Yield (ton/ha)**	**WF_{green} m^3/ton**
	Zanyokwe Smallholder Irrigation Scheme			
Cabbage	328.1	3281	30	109.4
Green beans	201.9	2019	1.5	1346
Potato	137	1370	9	152.2
Spinach	166.4	1664	7	237.7
Tomato	311.1	3111	19	163.7
	Tugela Ferry Smallholder Irrigation Scheme			
Cabbage	414.8	4148	30	138.3
Green beans	287.1	2871	1.5	1914
Potato	74.1	741	9	82.3
Spinach	144.5	1445	7	206.4
Tomato	418.5	4185	19	220.3
	Thabina Smallholder irrigation Scheme			
Cabbage	413.1	4131	30	137.7
Green beans	282.4	2824	1.5	1882.7
Potato	36.7	367	9	40.8
Spinach	183.5	1835	7	262.1
Tomato	443.2	4432	19	233.3

4.7 Grey Water Footprint of Selected Vegetable Crops

The grey water component was calculated based on the application of nitrogen (N) fertilizer only to the vegetable crop field. The average N fertilizer rates applied to the vegetables were obtained from the agricultural extension officers in the Department of Agriculture. The rates applied were taken from Tredoux et al. (2009). The nitrate leaching fraction was assumed to be 10% of the applied fertilizer rate. The natural concentration of N in the receiving water body was assumed to be zero. Only the nitrogen fertilizer use was incorporated in the calculations of the WF_{grey}, as it was described as the most critical pollutant with the greatest application rate (Hoekstra, 2009). Due to unavailability of data, only the recommended fertilizer application rates were used for grey water footprint estimation at all the three SHIS (Table 6). It was observed that green beans had the highest WF_{grey} i.e.373 m^3/ton and the lowest was cabbage with 37 m^3/ton. Potato, spinach and tomatoes had 156 m^3/ton, 214 m^3/ton and 132 m^3/ton respectively.

Table 6: Data and calculation of the grey water footprint of growing vegetable crops in smallholder irrigation schemes in South Africa.

Crop	***Average Fertilizer Application Rate (kgN/ha)**	***Water Quality Standard (mg/L)**	**Yield (t/ha)**	**Total WF_{grey} (m^3/ton)**
Cabbage	112	10	30	37
Potato	140	10	9	156
Tomato	250	10	19	132
Spinach	150	10	7	214
Green beans	56	10	1.5	373

*Source: department of agriculture forestry and fisheries. Directorate Plant Production- http://www.nda.agric.za and Tredoux et al. (2009)

4.8 Total Water Foot Print of Vegetable Crops

The highest total water foot print was observed in green beans in the current study (Figure 19). TIS had the highest WF in the production of green beans (3535.1 m^3/ton), for TFIS the calculated WF was 2753 m^3/ton, whilst the lowest was observed at ZIS i.e. 2407.6 m^3/ton. Cabbage had the lowest WF compared to all the crops in this study. Of the three schemes, the highest WF for cabbage was 254.5 m^3/ton observed at TFIS and the lowest was 217.8 m^3/ton observed at ZIS. Spinach was the second highest water user in production. At TFIS, the calculated WF for spinach was 604.4 m^3/ton, which is the highest amongst the three SHIS. For TIS, the calculated WF was 595.2 m^3/ton and the lowest WF in spinach production was observed at ZIS i.e. 553.3 m^3/ton. Total WF for potato production was highest at TIS and lowest at ZIS having 448.5 m^3/ton and 385.9 m^3/ton, respectively. Tugela Ferry irrigation scheme had a WF of 443.5 m^3/ton in the production of potato. Following potato in the hierarchy of water use in the current study was tomato, with TFIS having the highest WF i.e. 458.6 m^3/ton, TIS had 409.9 m^3/ton and the lowest was at ZIS with 310.1 m^3/ton.

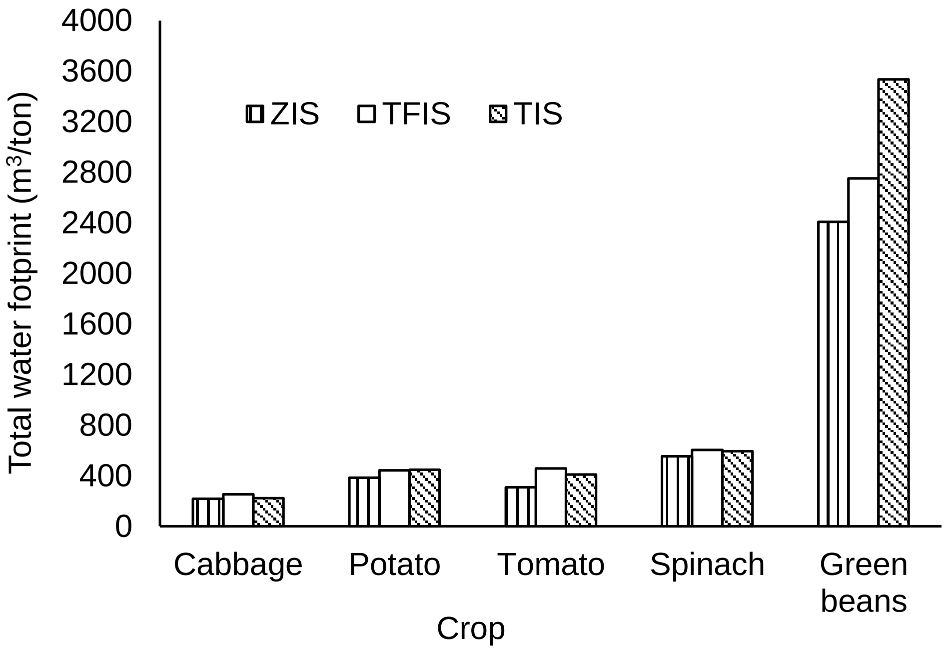

Figure 19: Total water footprint for vegetable crop production (mm) at Zanyokwe irrigation scheme (ZIS), Tugela Ferry irrigation scheme (TFIS) and Thabina irrigation schemes (TIS). Period 2000–2013.

CHAPTER FIVE

5.0 DISCUSSION

5.1 Annual and monthly Average Rainfall

Rainfall characteristics in South Africa are the prime reason behind its variation in the three case studies. Rainfall variability is a major factor affecting subsistence farming in southern Africa (Scholes & Biggs, 2004). The start, duration and variability of the rainy season (Figure 7) are consistent with the expectations and was similar to other studies. There is a distinct summer period where rainfall was high, and a winter period, which is cold and relatively dry. Lynch et al. (2001) observed that on average, the rainy season, starts in November and ends towards the latter part of April with an approximate period of 6 months. In addition, Mzezewa et al. (2010) observed that in Limpopo province, about 80% of annual rainfall is received during the months of October to March while Orne-Gliemann (2008) observed that 90 percent of the rain occurs between October and February. Therefore, variability in the monthly and annual cumulative rainfall among the three irrigation schemes studied is possibly due to the differences in the geography and location of the Provinces within the country. The vast and greatly varied geographical landscape of South Africa significantly influences the different climates experienced in the different parts of the country. According to Hanssen-Bauer et al. (1997), precipitation amount and variability may differ due to orographic effects, which are sensitive to small differences in circulation patterns. For instance, the high annual rainfall in the year 2000 (Figure 6) could be attributed to the cyclone Eline, which caused flooding in the whole of southern Africa. To this effect, Reason & Keibel (2004) noted that the increase in rainfall observed during the 1999/2000 season was associated with the floods that occurred in southern Africa which were associated with Tropical Cyclone Eline.

Generally, the annual rainfall averages in the three irrigation schemes were higher than the respective general provincial averages. One possibility could be the effects of climate change, which are causing higher than normal rainfall in wet years and extreme droughts in dry years. These changes account for the variation in both the total and average rainfall per year (Davis, 2011). Gbetibouo & Ringler (2009) also noted that climate change is expected to cause broad summer rainfall reductions of 5 to 10 percent, and an increase in the incidence of both droughts and floods. The high coefficients of variation observed in this study are also in line with those observed by other researchers, for example 40 percent in the Limpopo River basin (FAO, 2009) and 26 percent in Potchefstroom (Lynch et al., 2001).

It is difficult to predict with certainty the exact amount of rainfall an area will receive in the coming season. This is due to the fact that the weather changes and varies from place to place. Use of past records is done to estimate the probability that certain rainfall amounts will occur at a location. At TIS, the probability of rainfall exceeding 800 mm was 53 percent, which was close to 47 percent probability reported in Limpopo by Mzezewa et al. (2010). High intensities of rainfall normally reduce the effective rainfall this is seen by a trend where the effective rainfall is higher at ZIS (89 percent) as compared to the other sites. Higher intensities increase the run-off and reduce infiltration, uneven distribution decreases the extent of effective rainfall while an even spread enhances it.

5.2 Blue and Green Water Evapotranspiration (ET_{blue})

According to Hoekstra et al. (2011), the measure of blue water evapotranspiration (ET_{blue}) is estimated as the difference between total evapotranspiration (ET_c) and the total effective rainfall (P_{eff}). However, if the P_{eff} is greater than total ET_c then ET_{blue} is equal to zero. An output from CROPWAT for the blue water estimation is shown in Appendix 4 to 18. The ET demand of a crop is a measure of how much water can be consumed via soil evaporation and plant transpiration assuming that plant available water is adequate (Andales, 2014). ET_{blue} is mostly irrigation water, which is often used to offset the impact of rainfall variability on crop yield and to reduce the risk associated with weather variability (Guerra et al., 2005). Generally, ET_{blue} was lower than ET_{green} at all the three sites (Table 4 and 5), possibly because the vegetable crops were produced using more rain water. Irrigation is usually used as a supplement to deficiencies during the growing season.

Different vegetable crops have different blue and green ET at the three sites; this may be attributed to the differences in weather and environmental characteristics in the three locations. According to Dukes et al. (2012), the needs for ET are related to soil type and plant growth, and primarily depend on crop development and climatic factors which are closely related to climatic demands. The ET demand varies from day to day depending on crop growth stage and weather variables (Andales et al., 2014)

Vegetable crops have a high requirement for water during the growth season, which could be the reason for the high ET in the three SHISs. The differences in ET of crops at the same SHIS could be due to the physiology and biology of the crops; for example, some crops have inherently high transpiration than others. Evapotranspiration and crop coefficient varies in the course of the season because morphological and eco-physiological characteristics of the crop do change over time.

5.4 Water footprint of growing vegetable crops

Jordaan & Grove (2012) noted that a number of vegetables are produced particularly at ZIS and TIS. The farmers sell their produce to local markets and use some for home consumption. Water mismanagement was identified as one of the main agronomic factors limiting productivity in SHISs (Machete et al., 2004 & Mnkeni et al., 2010). Therefore, water mismanagement makes water foot printing of vegetable crop production in SHISs very significant. However, there is no documented work on water footprints of producing vegetable crops in smallholder irrigation schemes in South Africa, particularly in the selected locations. Therefore, the results of this study were compared to the global averages and specific averages of the five crops used. An observation by Mekonnen & Hoekstra (2010b), that the average WF per tonne of primary crops differ significantly among crops and across production regions can be a possible explanation of the differences in both the WF_{blue} and WF_{green} of the vegetable crops within and among the schemes in SA.

According to a study by Mekonnen & Hoekstra (2010b), the global WF_{blue} and WF_{green} of production cabbage was 181 m^3/ton and 26 m^3/ton, respectively. Results observed by Mekonnen & Hoesktra (2010b) and other studies are very low as compared to the results observed in this study (Tables 4, 5 and 6). One possible reason could be the low yields and the difference in planting dates (Table 1), which are attained by smallholder farmers; the lower the yields the higher the water footprint. Jordaan & Grove (2012) observed that blue water required to produce cabbages and carrots at ZIS was 763 m^3/ton and 273 m^3/ton respectively. This result is however very different from the WF_{blue} observed in this study. The difference can possibly be attributed to the difference in the period of the data used in the calculations. The SAPWAT (Van Heerden et al., 2009) programme used in the above study uses climatic data from 1957 to 1999. Another important factor is the change in, for example, the length of the growing period may notably vary the crop water use and thereafter the green and blue water footprint obtained (Chico et al., 2010). The differences indicate that the methodology applied is sensitive to input of climatic data and assumptions concerning the start of the growing season (Gerbens-Leenes et al., 2008).

The results for the average WF_{blue} and WF_{green} obtained in the current study were not in the same range as those from other studies. Chapagain & Orr (2009) found the national virtual water contents of Spanish tomatoes were, 60.5 m^3/ton WF_{blue} and 13.6 m^3/ton WF_{green}. Mekonnen & Hoekstra (2010b) calculated the global average WF of tomatoes to be 63 m^3/ton for WF_{blue} and 108 m^3/ton for WF_{green}. Aldaya and Hoekstra (2010), calculated values for Italian tomato production to be about 35

m^3/ton WF_{green}, 60 m^3/ton WF_{blue}. Contrary to the above results, the results of this study can possibly be attributed to the differences in production and weather characteristics as alluded to by Gerbens-Leenes et al. (2008). Ridoutt and Pfister (2013), highlighted that the potential environmental impacts related to water use are different from one location to another.

CHAPTER SIX

6.1 SUMMARY AND CONCLUSIONS

1. Generally, TIS had the highest WF followed by TFIS whilst ZIS had the lowest. There are large differences in WF among SHIS that are caused by a number of factors, chief among them are weather and production practices. More water is used in crop production within SHISs in SA compared to other countries as evidenced by the high WF observed in this study. This can be an indicator that the yield is not proportional to the drop of water hence a need to increase crop output.

2. The general observation was that ZIS had the lowest total WF in the vegetable crop category and TIS had the highest total WF.

3. Thabina Irrigation Scheme had the highest $WF_{blue\ in}$ green beans and potato and the least in tomatoes. Green beans WF_{blue} at observed TIS was 1280 m^3/ton, and ZIS had 688.6 m^3/ton while the lowest was observed at TFIS (466 m^3/ton). TFIS had the highest WF_{blue} in cabbage, spinach and tomatoes. However, it can be shown from the results of the study that there is more WF_{green} in vegetable production at all the three sites except for potato at both TFIS and TIS.

4. WF_{green} is highest in green beans compared to the other crops in all the SHISs. The results also show that in potato production more blue water was used with the highest WF_{green} recorded at ZIS. Spinach and tomatoes had the highest WF_{green} at TIS. An improvement in the production practices and

ultimate yield is a must in order to reduce the WF thus improving water use efficiency.

5. Rainfall is highly variable, thus affecting crop production differently amongst the schemes. The study has shown that more rain falls in the Thabina SHIS, hence the high effective rainfall and he least was at ZIS.

6. The grey water footprint was relatively low for all the vegetable crops and was assumed to be the same at the three sites. Green beans had the highest WF_{grey} i.e.373 m^3/ton and the lowest was cabbage with 37 m^3/ton (table 3). Potato, spinach and tomatoes had 156 m^3/ton, 214 m^3/ton and 132 m^3/ton respectively.

6.2 Recommendations

1. This particular study focused on five vegetable crops only. Further studies can be carried out which will include more vegetable crops and other crops grown within SHIS.

2. The study focused on general planting dates as advised by the extension agents. There is need to calculate WF within the SHIS differentiating summer and winter crops as some crops are grown twice a year.

3. There is need to collect data from the field on aspects like the crop parameters and water quality standards from water bodies which supply the SHIS. Having site and field specific data will greatly impact the grey water out-put at each irrigation scheme.

4. There is need to carry out further studies in areas which focus on the management aspects like tillage system and/ crop rotations which have a potential of increasing green water use and reduce blue water use.

5. The focus of this study was on the production stage only, therefore there is need to estimate the water foot prints of the processing and end products.

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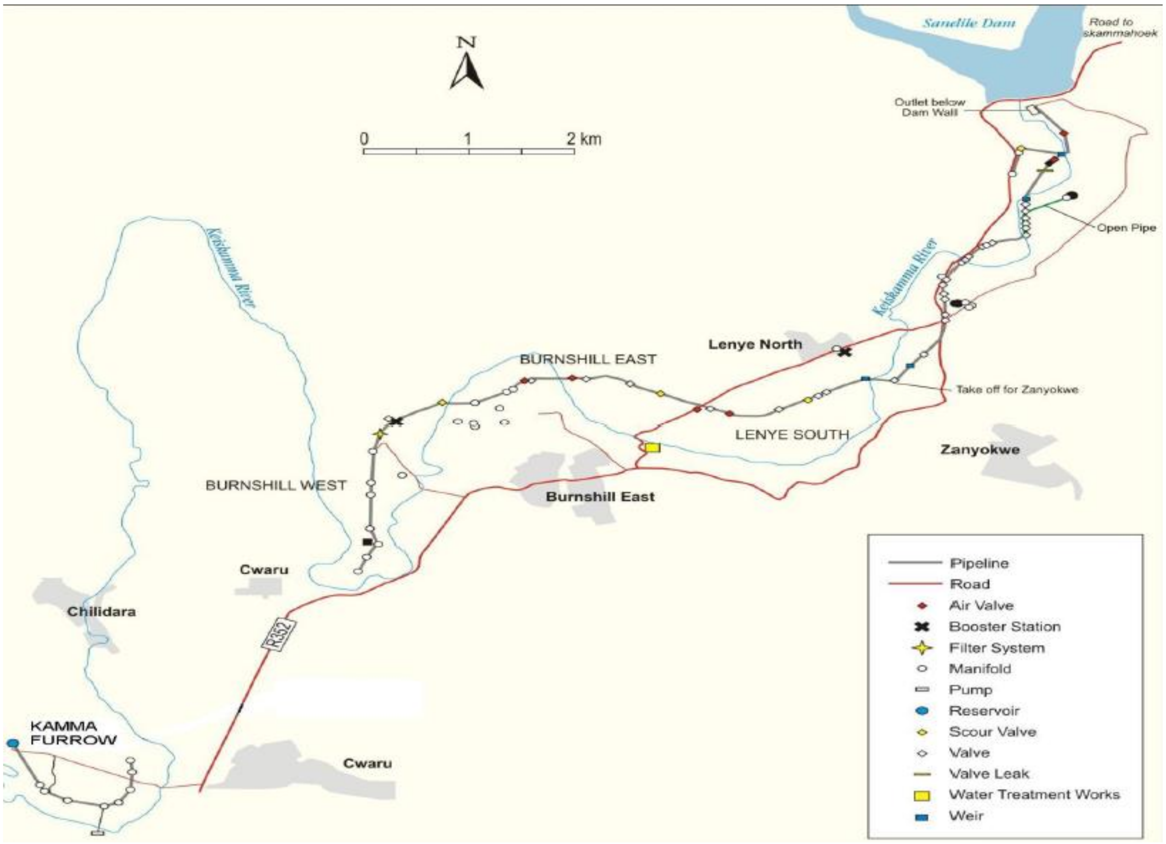
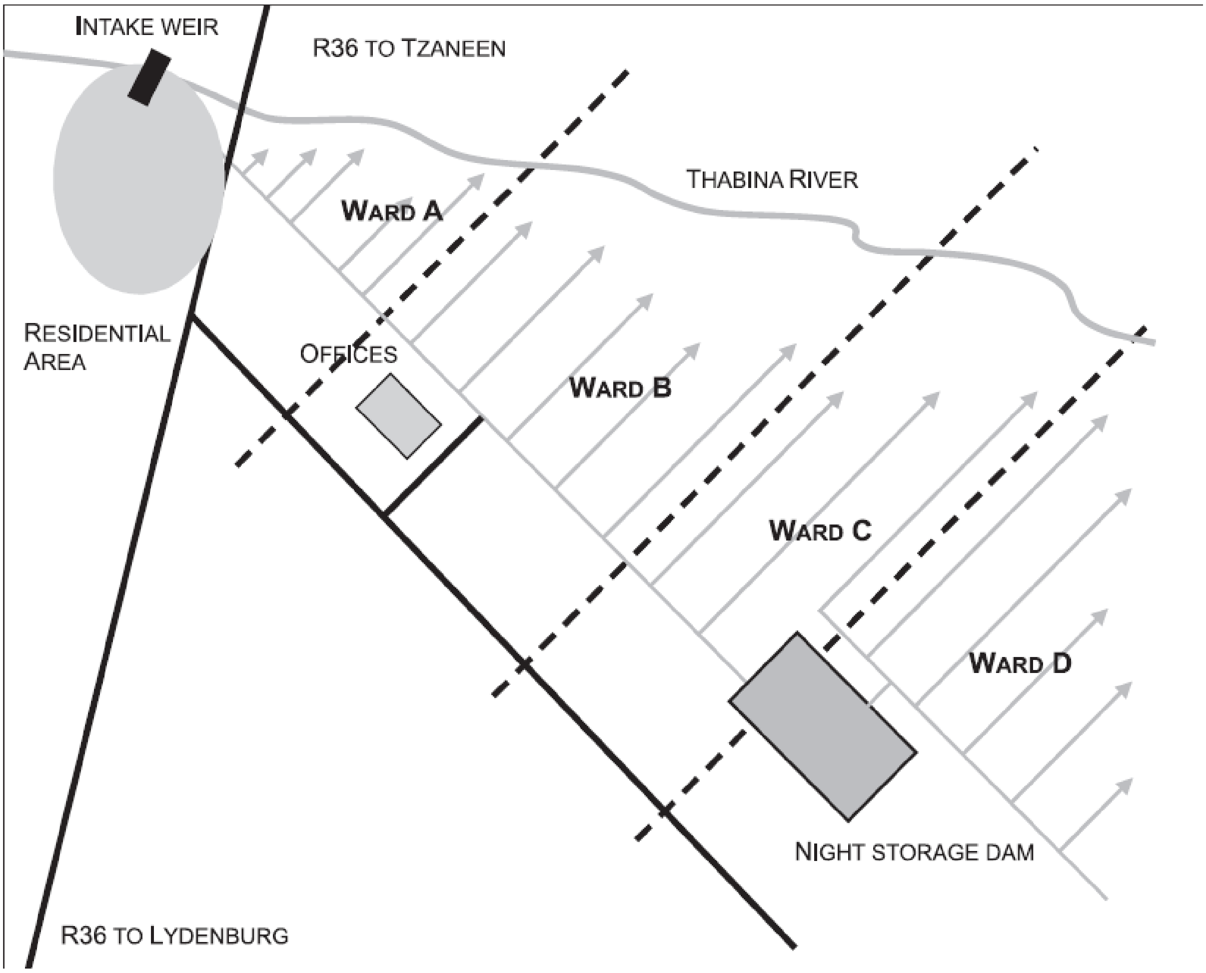
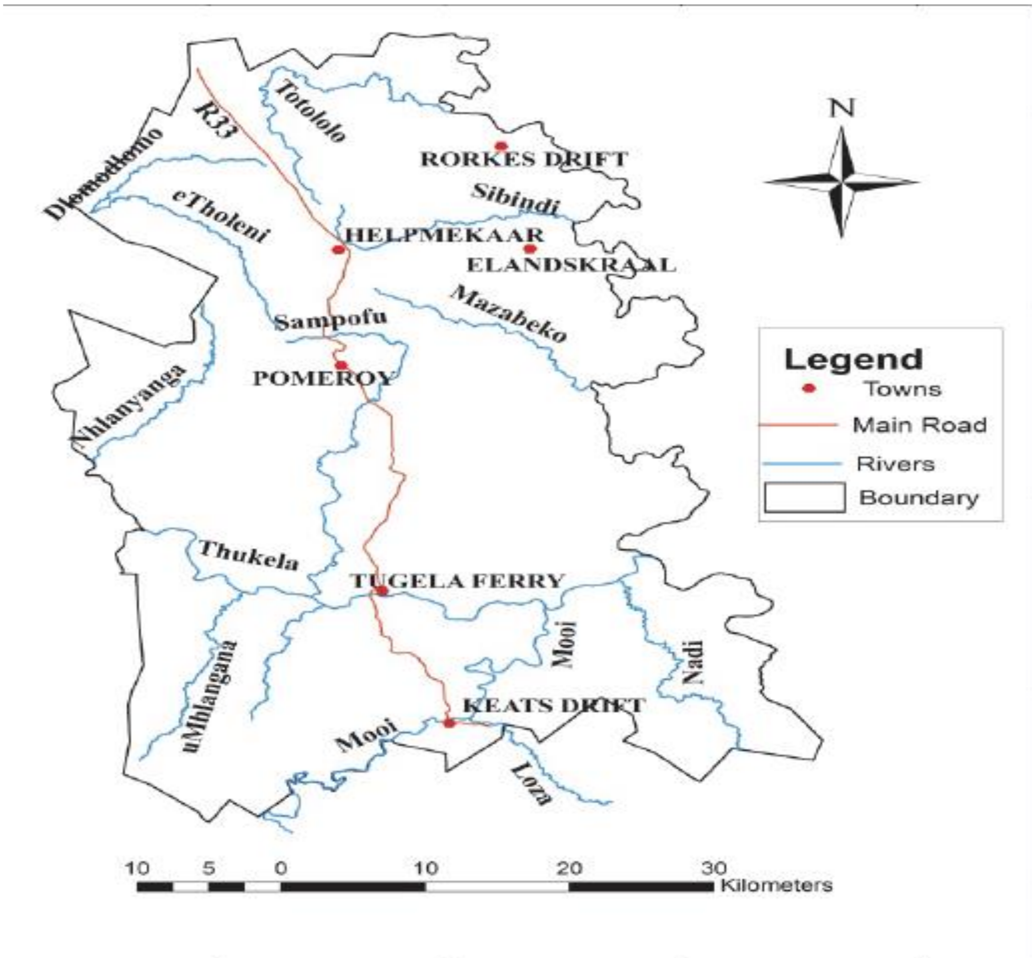


Appendix 1: Map of Zanyokwe irrigation scheme showing all the participating areas in the scheme (Source Yokwe, 2005)



Appendix 2: Map of Thabina irrigation scheme showing all the participating areas in the scheme (Source Veldwisch G.J. 2006)



Appendix 3: Map of Tugela Ferry irrigation scheme showing all the participating areas in the scheme (Source Sinyolo et al., 2014).

Appendix 4: Total green and blue water evapotranspiration of cabbage at Zanyokwe SHIS based on the CWR output table of CROPWAT 8.0

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
August	2	Init	0.7	1.48	8.9	8.9	1.4	8.9	0
August	3	Init	0.7	1.64	18	14.3	3.7	14.3	3.7
September	1	Init	0.7	1.79	17.9	12.8	5.1	12.8	5.1
September	2	Init	0.7	1.94	19.4	12.1	7.4	12.1	7.3
September	3	Deve	0.72	2.14	21.4	14.4	7	14.4	7
October	1	Deve	0.77	2.46	24.6	17.3	7.3	17.3	7.3
October	2	Deve	0.82	2.81	28.1	19.4	8.7	19.4	8.7
October	3	Deve	0.88	3.18	35	20.6	14.3	20.6	14.4
November	1	Deve	0.94	3.58	35.5	22.1	13.6	22.1	13.4
November	2	Deve	0.99	3.98	39.8	23.6	16.2	23.6	16.2
November	3	Mid	1.03	4.24	42.4	23.7	18.7	23.7	18.7
December	1	Mid	1.03	4.36	43.6	23.5	20.1	23.5	20.1
December	2	Mid	1.03	4.48	44.8	23.6	21.2	23.6	21.2
December	3	Mid	1.03	4.5	49.4	24.5	25	24.5	24.9
January	1	Mid	1.03	4.51	45.1	26.3	18.9	26.3	18.8
January	2	Late	0.99	4.39	43.9	27.5	16.4	27.5	16.4
January	3	Late	0.94	4.06	24.4	13.5	12	13.5	10.9
Total over entire period					542.2	328.1	217	328.1	214.1

Appendix 5: Total green and blue water evapotranspiration of cabbage at Tugela Ferry small holder irrigation scheme based on the CWR output table of CROPWAT 8.0 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
August	2	Init	0.7	1.93	9.7	3.3	6.3	3.3	6.4
August	3	Init	0.7	2.16	23.8	8.4	15.4	8.4	15.4
September	1	Init	0.7	2.4	24	9.9	14	9.9	14.1
September	2	Init	0.7	2.63	26.3	11.4	14.9	11.4	14.9
September	3	Deve	0.71	2.81	28.1	14.8	13.3	14.8	13.3
October	1	Deve	0.76	3.15	31.5	18.2	13.2	18.2	13.3
October	2	Deve	0.82	3.52	35.2	21.4	13.8	21.4	13.8
October	3	Deve	0.87	3.92	43.1	24.8	18.3	24.8	18.3
November	1	Deve	0.93	4.33	43.3	28.7	14.6	28.7	14.6
November	2	Deve	0.98	4.76	47.6	32.4	15.2	32.4	15.2
November	3	Mid	1.02	5.02	50.2	34	16.2	34	16.2
December	1	Mid	1.02	5.1	51	36	14.9	36	15
December	2	Mid	1.02	5.17	51.7	38.2	13.4	38.2	13.5
December	3	Mid	1.02	5.11	56.2	37.5	18.7	37.5	18.7
January	1	Mid	1.02	5.05	50.5	37.4	13.1	37.4	13.1
January	2	Late	1	4.88	48.8	37.5	11.3	37.5	11.3
January	3	Late	0.94	4.47	31.3	20.9	0	20.9	10.4
Total over entire period					652.3	414.8	226.8	414.8	237.5

Appendix 6 Total green and blue water evapotranspiration of cabbage at Thabina smallholder irrigation scheme based on the CWR output table of CROPWAT 8 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
August	2	Init	0.7	1.88	11.3	0.0	11.3	0	11.3
August	3	Init	0.7	2.03	22.3	2.6	19.7	2.6	19.7
September	1	Init	0.7	2.17	21.7	6.2	15.6	6.2	15.5
September	2	Init	0.7	2.32	23.2	8.7	14.5	8.7	14.5
September	3	Deve	0.71	2.48	24.8	10.8	14.1	10.8	14
October	1	Deve	0.76	2.78	27.8	10.9	16.9	10.9	16.9
October	2	Deve	0.82	3.11	31.1	12.1	19.0	12.1	19
October	3	Deve	0.87	3.36	37.0	21.7	15.3	21.7	15.3
November	1	Deve	0.92	3.62	36.2	34.9	1.3	34.9	1.3
November	2	Deve	0.98	3.88	38.8	44.9	0.0	38.8	0.0
November	3	Mid	1.01	4.11	41.1	43.1	0.0	41.1	0.0
December	1	Mid	1.01	4.22	42.2	39.4	2.8	39.4	2.8
December	2	Mid	1.01	4.32	43.2	38.6	4.6	38.6	4.6
December	3	Mid	1.01	4.34	47.8	39.9	7.8	39.9	7.9
January	1	Mid	1.01	4.37	43.7	42.7	0.9	42.7	1.0
January	2	Late	0.98	4.26	42.6	44.5	0.0	42.6	0.0
January	3	Late	0.92	3.94	23.6	22.1	3.3	22.1	1.5
Total over entire period					558.4	423.1	147.1	413.1	145.3

Appendix 7: Total green and blue water evapotranspiration of Potatoes at Zanyokwe smallholder irrigation scheme based on the CWR output table of CROPWAT 8 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
April	2	Init	0.5	1.22	7.3	10.3	0	7.3	0
April	3	Init	0.5	1.12	11.2	15.6	0	11.2	0
May	1	Deve	0.5	1.01	10.1	12.5	0	10.1	0
May	2	Deve	0.64	1.15	11.5	9.9	1.7	9.9	1.6
May	3	Deve	0.86	1.48	16.2	9.7	6.6	9.7	6.5
June	1	Mid	1.08	1.75	17.5	9.6	7.9	9.6	7.9
June	2	Mid	1.14	1.73	17.3	9	8.3	9	8.3
June	3	Mid	1.14	1.77	17.7	9.4	8.4	9.4	8.3
July	1	Mid	1.14	1.81	18.1	9.5	8.6	9.5	8.6
July	2	Mid	1.14	1.85	18.5	9.6	8.9	9.6	8.9
July	3	Late	1.1	1.96	21.6	11.1	10.5	11.1	10.5
August	1	Late	0.96	1.88	18.8	13.2	5.5	13.2	5.6
August	2	Late	0.83	1.76	17.6	14.8	2.8	14.8	2.8
August	3	Late	0.75	1.76	3.5	2.6	3.5	2.6	0.9
Total over entire period					206.9	146.8	72.6	137	69.9

Appendix 8: Total green and blue water evapotranspiration of Potatoes at Tugela Ferry smallholder irrigation scheme based on the CWR output table of CROPWAT 8 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
April	2	Init	0.5	1.41	7.1	7.6	0	7.1	0
April	3	Init	0.5	1.33	13.3	11.6	1.7	11.6	1.7
May	1	Deve	0.5	1.25	12.5	7	5.6	7	5.5
May	2	Deve	0.62	1.44	14.4	3.2	11.2	3.2	11.2
May	3	Deve	0.84	1.84	20.2	3.6	16.6	3.6	16.6
June	1	Mid	1.05	2.16	21.6	4.3	17.3	4.3	17.3
June	2	Mid	1.13	2.15	21.5	4.2	17.3	4.2	17.3
June	3	Mid	1.13	2.19	21.9	4.3	17.6	4.3	17.6
July	1	Mid	1.13	2.22	22.2	4.3	17.9	4.3	17.9
July	2	Mid	1.13	2.26	22.6	4.3	18.3	4.3	18.3
July	3	Late	1.1	2.47	27.2	5.2	22	5.2	22
August	1	Late	0.97	2.42	24.2	6	18.2	6	18.2
August	2	Late	0.84	2.31	23.1	6.7	16.4	6.7	16.4
August	3	Late	0.75	2.32	7	2.3	2.7	2.3	4.7
Total over entire period					258.8	74.6	182.9	74.1	184.7

Appendix 9: Total green and blue water evapotranspiration of potatoes at Thabina small holder irrigation scheme based on the CWR output table of CROPWAT 8.0 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
April	2	Init	0.5	1.48	8.9	13.1	0	8.9	0
April	3	Init	0.5	1.39	13.9	14.9	0	13.9	0
May	1	Deve	0.5	1.3	13	3.3	9.7	3.3	9.7
May	2	Deve	0.64	1.53	15.3	0	15.3	0	15.3
May	3	Deve	0.87	1.94	21.4	0.3	21.1	0.3	21.1
June	1	Mid	1.09	2.27	22.7	1.6	21.1	1.6	21.1
June	2	Mid	1.15	2.23	22.3	1.9	20.4	1.9	20.4
June	3	Mid	1.15	2.28	22.8	1.9	20.9	1.9	20.9
july	1	Mid	1.15	2.33	22.3	2	21.3	2	20.3
July	2	Mid	1.15	2.38	23.8	2	21.7	2	21.8
July	3	Late	1.1	2.51	27.7	1.7	26	1.7	26
August	1	Late	0.97	2.41	24.1	0.6	23.5	0.6	23.5
August	2	Late	0.84	2.25	22.5	0	22.5	0	22.5
August	3	Late	0.76	2.19	4.4	0.5	4.4	0.5	3.9
Total over entire period					265.1	43.8	227.8	38.6	221.3

Appendix 10: Total green and blue water evapotranspiration of green beans at Zanyokwe small holder irrigation scheme based on the CWR output table of CROPWAT 8.0 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
October	2	Init	0.5	1.71	10.3	11.7	0.6	10.3	0
October	3	Init	0.5	1.81	19.9	20.6	0	19.9	0
November	1	Deve	0.55	2.1	21	22.1	0	21	0
November	2	Deve	0.72	2.89	28.9	23.6	5.3	23.6	5.3
November	3	Deve	0.89	3.7	37	23.7	13.3	23.7	13.3
December	1	Mid	1.02	4.34	43.4	23.5	19.9	23.5	19.9
December	2	Mid	1.03	4.48	44.8	23.6	21.2	23.6	21.2
December	3	Mid	1.03	4.5	49.4	24.5	25	24.5	24.9
January	1	Late	0.97	4.27	42.7	26.3	16.4	26.3	16.4
January	2	Late	0.88	3.88	7.8	5.5	7.8	5.5	2.3
Total over entire period					305.2	205.1	109.3	201.9	103.3

Appendix 11: Total green and blue water evapotranspiration of green beans at Tugela Ferry small holder irrigation scheme based on the CWR output table of CROPWAT 8.0 (2000- 2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
October	2	Init	0.5	2.15	10.8	10.7	0.1	10.7	0.1
October	3	Init	0.5	2.24	24.7	24.8	0	24.7	0
November	1	Deve	0.54	2.5	25	28.7	0	25	0
November	2	Deve	0.7	3.39	33.9	32.4	1.5	32.4	1.5
November	3	Deve	0.88	4.3	43	34	9	34	9
December	1	Mid	1.02	5.04	50.4	36	14.4	36	14.4
December	2	Mid	1.02	5.16	51.6	38.2	13.4	38.2	13.4
December	3	Mid	1.02	5.11	56.2	37.5	18.7	37.5	18.7
January	1	Late	0.98	4.84	48.4	37.4	11	37.4	11
January	2	Late	0.88	4.32	13	11.2	0	11.2	1.8
Total over entire period					357	290.9	68.1	287.1	69.9

Appendix 12: Total green and blue water evapotranspiration of green beans at Thabina small holder irrigation scheme based on the CWR output table of CROPWAT 8.0 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
October	2	Init	0.5	1.9	11.4	7.2	5.4	7.2	4.2
October	3	Init	0.5	1.93	21.3	21.7	0	21.3	0
November	1	Deve	0.55	2.15	21.5	34.9	0	21.5	0
November	2	Deve	71	2.83	28.3	44.9	0	28.3	0
November	3	Deve	0.88	3.6	36	43.1	0	36	0
December	1	Mid	1	4.19	41.9	39.4	2.6	39.4	2.5
December	2	Mid	1.01	4.32	43.2	38.6	4.6	38.6	4.6
December	3	Mid	1.01	4.34	47.8	39.9	7.8	39.9	7.9
January	1	Late	0.95	4.13	41.3	42.7	0	41.3	0
January	2	Late	0.86	3.75	7.5	8.9	7.5	8.9	0
Total over entire period					300.2	321.3	27.9	282.4	19.2

Appendix 13: Total green and blue water evapotranspiration of Tomato at Zanyokwe small holder irrigation scheme based on the CWR output table of CROPWAT 8.0 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
September	2	Init	0.6	1.67	10	7.2	4	7.2	2.8
September	3	Init	0.6	1.79	17.9	14.4	3.5	14.4	3.5
October	1	Init	0.6	1.92	19.2	17.3	1.9	17.3	1.9
October	2	Deve	0.63	2.14	21.4	19.4	2	19.4	2
October	3	Deve	0.76	2.74	30.1	20.6	9.5	20.6	9.5
November	1	Deve	0.89	3.42	34.2	22.1	12	22.1	12.1
November	2	Deve	1.03	4.12	41.2	23.6	17.6	23.6	17.6
November	3	Mid	1.12	4.63	46.3	23.7	22.6	23.7	22.6
December	1	Mid	1.12	4.77	47.7	23.5	24.3	23.5	24.2
December	2	Mid	1.12	4.9	49	23.6	25.4	23.6	25.4
December	3	Mid	1.12	4.92	54.1	24.5	29.7	24.5	29.6
January	1	Late	1.12	4.91	49.1	26.3	22.8	26.3	22.8
January	2	Late	1.02	4.52	45.2	27.5	17.6	27.5	17.7
January	3	Late	0.9	3.88	42.7	24.8	17.9	24.8	17.9
February	1	Late	0.8	3.38	20.3	12.6	9.8	12.6	7.7
Total over entire period					528.5	311.1	220.7	311.1	217.3

Appendix 14: Total green and blue water evapotranspiration of Tomato at Tugela Ferry small holder irrigation scheme based on the CWR output table of CROPWAT 8.0 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
September	2	Init	0.6	2.26	11.3	5.7	5.6	5.7	5.6
September	3	Init	0.6	2.37	23.7	14.8	8.9	14.8	8.9
October	1	Init	0.6	2.48	24.8	18.2	6.5	18.2	6.6
October	2	Deve	0.62	2.67	26.7	21.4	5.3	21.4	5.3
October	3	Deve	0.74	3.33	36.7	24.8	11.9	24.8	11.9
November	1	Deve	0.88	4.1	41	28.7	12.3	28.7	12.3
November	2	Deve	1.01	4.89	48.9	32.4	16.5	32.4	16.5
November	3	Mid	1.11	5.46	54.6	34	20.6	34	20.6
December	1	Mid	1.12	5.58	55.8	36	19.7	36	19.8
December	2	Mid	1.12	5.65	56.5	38.2	18.3	38.2	18.3
December	3	Mid	1.12	5.59	61.5	37.5	24.1	37.5	24
January	1	Late	1.12	5.52	55.2	37.4	17.8	37.4	17.8
January	2	Late	1.03	5.04	50.4	37.5	12.9	37.5	12.9
January	3	Late	0.91	4.32	47.5	32.9	14.6	32.9	14.6
February	1	Late	0.8	3.71	25.9	19	0	19	6.9
Total over entire period					620.5	418	195	418.5	202

Appendix 15: Total green and blue water evapotranspiration of Tomato at Thabina small holder irrigation scheme based on the CWR output table of CROPWAT 8.0 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
September	2	Init	0.6	1.99	11.9	5.2	7.6	5.2	6.7
September	3	Init	0.6	2.09	20.9	10.8	10.1	10.8	10.1
October	1	Init	0.6	2.19	21.9	10.9	10.9	10.9	11
October	2	Deve	0.63	2.38	23.8	12.1	11.8	12.1	11.7
October	3	Deve	0.75	2.9	31.9	21.7	10.2	21.7	10.2
November	1	Deve	0.88	3.47	34.7	34.9	0	34.7	0
November	2	Deve	1.01	4.02	40.2	44.9	0	40.2	0
November	3	Mid	1.1	4.49	44.9	43.1	1.8	43.1	1.8
December	1	Mid	1.1	4.61	46.1	39.4	6.8	39.4	6.7
December	2	Mid	1.1	4.72	47.2	38.6	8.7	38.6	8.6
December	3	Mid	1.1	4.75	52.3	39.9	12.3	39.9	12.4
January	1	Late	1.1	4.75	47.5	42.7	4.7	42.7	4.8
January	2	Late	1	4.37	43.7	44.5	0	43.7	0
January	3	Late	0.88	3.75	41.3	40.6	0.7	40.6	0.7
February	1	Late	0.78	3.26	19.6	21.4	1.7	19.6	0
Total over entire period					527.8	450.7	87.3	443.2	84.7

Appendix 16: Total green and blue water evapotranspiration of spinach at Zanyokwe small holder irrigation scheme based on the CWR output table of CROPWAT 8.0 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
February	2	Init	0.7	2.91	17.5	11.1	8.3	11.1	6.4
February	3	Init	0.7	2.73	21.9	19	2.8	19	2.9
March	1	Deve	0.71	2.59	25.9	20.5	5.5	20.5	5.4
March	2	Deve	0.8	2.73	27.3	21	6.3	21	6.3
March	3	Deve	0.92	2.82	31	19.9	11.2	19.9	11.1
April	1	Mid	1.01	2.8	28	18.8	9.2	18.8	9.2
April	2	Mid	1.02	2.51	25.1	18	7	18	7.1
April	3	Mid	1.02	2.29	22.9	15.6	7.3	15.6	7.3
May	1	Late	1.02	2.05	20.5	12.5	8	12.5	8
May	2	Late	0.96	1.74	17.4	10	7.4	10	7.4
Total over entire period					237.5	166.4	73	166.4	71.1

Appendix 17: Total green and blue water evapotranspiration of spinach at Tugela Ferry small holder irrigation scheme based on the CWR output table of CROPWAT 8.0 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
February	2	Init	0.7	3.15	18.9	13.7	7.5	13.7	5.2
February	3	Init	0.7	2.99	23.9	21.4	2.5	21.4	2.5
March	1	Deve	0.71	2.88	28.8	20.3	8.4	20.3	8.5
March	2	Deve	0.8	3.06	30.6	18.6	12	18.6	12
March	3	Deve	0.92	3.19	35.1	17.2	17.9	17.2	17.9
April	1	Mid	1.01	3.19	31.9	16.3	15.6	16.3	15.6
April	2	Mid	1.02	2.89	28.9	15.2	13.7	15.2	13.7
April	3	Mid	1.02	2.73	27.3	11.6	15.6	11.6	15.7
May	1	Late	1.01	2.54	25.4	7	18.4	7	18.4
May	2	Late	0.96	2.25	22.5	3.2	19.2	3.2	19.3
Total over entire period					273.3	144.5	131	144.5	128.8

Appendix 18: Total green and blue water evapotranspiration of spinach at Thabina small holder irrigation scheme based on the CWR output table of CROPWAT 8.0 (2000-2013).

Month	Decade	Stage	K_c	ET_c (mm/day)	ET_c (mm/dec)	P_{eff} (mm/dec)	Irr.req. (mm/dec)	ET_{green} (mm/dec)	ET_{blue} (mm/dec)
February	2	Init	0.7	2.87	17.2	19.3	1.1	17.2	0
February	3	Init	0.7	2.73	21.8	30.9	0	21.8	0
March	1	Deve	0.71	2.53	26.6	30.1	0	26.6	0
March	2	Deve	0.8	2.01	28.1	28.7	0	28.1	0
March	3	Deve	0.92	3.04	33.4	25.9	7.5	25.9	7.5
April	1	Mid	1.01	3.18	31.8	23.9	7.9	23.9	7.9
April	2	Mid	1.02	3.03	30.3	21.8	8.5	21.8	8.5
April	3	Mid	1.02	2.84	28.4	14.9	13.5	14.9	13.5
May	1	Late	1.01	2.62	26.2	3.3	22.9	3.3	22.9
May	2	Late	0.96	2.31	23.1	0	23.1	0	23.1
Total over entire period					266.6	198.7	84.6	183.5	83.4