Comparing Water Allocation Quotas with Irrigation Requirements as Estimated by SAPWAT4 in South Africa

by

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DECLARATION STATEMENT

I assert that:

The work presented in this thesis is the result of my independent research and investigation, except where otherwise acknowledged in the text. Any assistance received in preparing this thesis and sources of information has been acknowledged appropriately. All secondary sources used in this thesis have been duly cited and referenced. The content of this thesis has not been submitted for any other degree or qualification in any other university or institution. Any material previously published or written by other authors used in this thesis has been properly attributed, cited, and referenced. I grant the University of the Free State a non-exclusive license to use this thesis for academic purposes, archiving and online dissemination.

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ABSTRACT

South Africa is generally considered a water-scarce country due to its varying climatic conditions and increased demand for water resources. The irrigation estimation tool was used to estimate the effective rainfall and irrigation water requirement for different cropping patterns under various soils and irrigation systems in three distinct irrigation schemes. The study also compared two improved management practice scenarios, revealing the benefits of these practices in increasing productivity and water use efficiency. The findings highlight the regional variations in both water allocation quotas and irrigation requirements, which are crucial for developing region-specific water management strategies.

The findings reveal that the current water quota is sufficient for the existing cropping pattern in semi-arid cold climates, like the Sand-Vet irrigation scheme. While applying a slight water stress approach could reduce the irrigation water requirement. The conservation (CONS) scenarios could be an option to reduce irrigation requirements, but the high costs associated with implementation adaptation have limited its adoption. The study also highlights the significant role of irrigation in semi-arid cold climates, particularly in the centre pivot and linear irrigation systems, which are energy-saving and water-efficient methods for irrigating large fields. In semi-arid hot climates, like Hartbeespoort schemes, the finding reveals that irrigation is a more significant factor than effective rainfall, particularly under a slight water stress (STRESS) scenario. Due to their water retention capabilities, the study finds that clay and loam soils require nearly identical amounts of irrigation as sandy loam. Clay soils, favored by farmers due to their superior fertility and water retention capabilities, showed a higher relative change compared to loam, silt loam, and sandy soils. It also found that the flood irrigation system requires almost double the total amount of water compared to the more efficient drip irrigation system. The study further reveals a significant difference between the micro-spray and sprinkler irrigation systems, with the micro-spray system being more efficient for both the CONS and STRESS approaches.

In an arid-hot climate, like the Orange-Vaal irrigation scheme, using a centre pivot irrigation system under sandy loam soil, the STRESS approach requires significantly more water than the CONS approach. These findings underscore the importance of careful consideration in irrigation planning to ensure sustainable and efficient use of water resources. The study provides valuable insights that can guide future research and policymaking in irrigation and water management. The study presents a comprehensive overview of irrigation requirements under various climatic conditions and management practices using SAPWAT4 simulation. It reveals that the size of the cultivated area in different schemes adjusts according to water availability and other factors. The study found that different irrigation systems and approaches retain varying amounts of water, suggesting the need for revisiting quotas to ensure adequate water allocation. Notably, the CONS and STRESS management strategies in different irrigation systems showed potential for water conservation and saving compared to the conventional approach.

The findings underscore the importance of understanding different regions' and crops' specific water needs for efficient water management, particularly in light of changing climate conditions. The study shared its findings with Water User Associations (WUAs) during the visitation. It showed the SAPWAT4 program as a tool to assist farmers in managing their water quotas and distribution systems. Feedback from the WUAs revealed various strategies for managing water resources, such as transferring water from adjoining areas and using borehole water. However, challenges such as poor water quality and insufficient canal water supply during peak demand periods were also identified. The study concluded that continuous engagement with the farming community and innovative tools like SAPWAT4 is crucial for ensuring sustainable and efficient use of water resources.

Keywords: Arid hot climate, Conservation and Slight water-stress strategies, Conventional approach, Semi-arid cold and Semi-arid hot climates, Water User Association.

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LIST OF ACRONYMS

ARC	Agriculture Research Council
CA	Conservation Agriculture
CDS	Centre for Development and Support
CEO	Chief Executive Officer
CON	Conventional Tillage
CONS	Conservation strategy
CR	Capillary Rise
DAFF	Department of Agriculture, Forestry and Fisheries
DP	Deep Percolation
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
e_a	Actual Water Vapour Pressure (kPa)
ERF	Effective Rainwater (mm)
ER_m	Monthly Effective Rainfall (mm)
e_s	Saturation Water Vapour pressure (kPa)
E_s	Soil Evaporation
ET	Evapotranspiration
ET_c	Crop Evapotranspiration (mm d^{-1})
ET_o	Reference Evapotranspiration (mm d^{-1})
FAO	Food and Agriculture Organization of the United Nations
G	Soil heat flux density (MJ m^{-2} d^{-1})
I	Irrigation (mm)
IRR	Irrigation Water Requirement (mm)
K_c	Dual Crop Coefficient
K_{cb}	Basal crop coefficient
K_e	Soil evaporation coefficient
K_f	Adsorption coefficient
MAP	Mean Annual Precipitation (mm)
NWDACE	North West Department of Agriculture Conservation and Environment
OECD	Organization for Economic Co-operation and Development
P	Precipitation (mm)
RAW	Readily Available Water (mm)
Rn	Net irradiance (MJ m^{-2} d^{-1})
R_o	Runoff (mm)
SF	Subsurface flow
STRESS	Slight water stress
SWB	Soil Water Balance
T	Mean daily air temperature (°C)
Tr	Transpiration
u_2	Mean daily wind speed at 2 m height (m s^{-1})
USDA-SCS	United States Department of Agriculture's Soil Conservation Service

USGS	United States Geological Survey
WHO	World Health Organization
WMA	Water Management Areas
WRC	Water Research Commission
WRI	World Resources Institute
WUA	Water User Associations
WUA-Sub	Water User Associations subsidiary
γ	Psychrometric Constant ($\approx$ 66 kPa $°C^{-1}$)

CHAPTER 1: INTRODUCTION

1.1 Background and motivation

South Africa is generally considered a water-scarce country due to its varying climatic conditions and increased demand for water resources. Water scarcity is driven by recurrent droughts intensified by climatic variation. Irrigation must be done as effectively as possible since it uses 62% of ground- and surface-water resources (Tlou and Joubert, 2013). A systematic analysis of water allocation for irrigation needs to be conducted based on existing cropping patterns. This allocation depends on the type of soil, amount of irrigation water available, upgrading of new irrigation systems, shorter growing crop varieties and economic considerations (van Heerden, 2015). Several methods of irrigation are used in South Africa. According to the Water Research Commission (Matthews, 2017), this includes sprinkler, flood and drip irrigation systems, which cover around 53%, 28.5 % and 18.5% of the total irrigated area, respectively. Irrigated agriculture contributes about 25% to 30% to the gross agricultural production of South Africa (SA Water Bulletin, 2001).

The initial estimates of irrigation water allocations for different regions have not been altered or slightly adjusted. These estimates were based on research findings and the intrinsic experience of the farmers (van Heerden, 2015). Besides measurement, procedures for determining plant irrigation water requirements were only accessible to a limited extent. However, during the early and middle 20th century, van Heerden and De Kock (1980) research findings led to recommendations on irrigation water management practices. One example was lucerne production in the Great Fish River Valley, where two irrigations of 75 mm per cutting were required (van Heerden and De Kock, 1980).

One of the recommendations was to use soil water requirement monitoring equipment such as resistance blocks, tensiometers, neutron probes, and capacitance probes to assess the required irrigation water allocations. However, it was shown that 81% of farmers in South Africa irrigated by intuition, limiting the use of such findings as a reference to crop irrigation needs (Stevens et al., 2005). Experimental findings from lysimeters might also be used to estimate irrigation demand

(Zerizghy et al., 2013), but unfortunately, these are not widely available nationwide. Additional crop evapotranspiration (ET_c) sources can also be used, including remote sensing, scintillometer, and other micrometeorological methods (Allen et al., 1998). Evaporimeter techniques such as evaporation pans can be used as indirect indications are among the scheduling aids that may be used to allocate the irrigation water requirements for a particular crop, soil and climate (Allen et al., 1998).

Data from automatic weather stations linked to crop growth and development models, such as the Soil Water Balance (SWB) computer model (Jarmain et al., 2014), are examples of alternative ways of estimating irrigation water requirements for different crops. Measuring water use by crops can improve the accuracy of anticipated irrigation water usage. On the contrary irrigation water usage can only be measured in terms of crops and geographic distribution. The problem is exacerbated in regions where irrigation water usage is not recorded or is measured in a restricted way. This dilemma prompted the creation of computerized programs that could estimate crop irrigation needs based on meteorological data.

Various tools of irrigation estimation have been developed with reasonable success in terms of reliability of results and implementation, such as CROPWAT (Smith, 1992) and SAPWAT4 (van Heerden and Walker, 2016). These tools consider all the factors that are deemed important in determining crop irrigation requirements at a given location. The output provides reliable irrigation estimations, as was shown by Jarmain et al. (2014) in the case of maize using the SAPWAT4 program. This software also estimates irrigation requirements for crops growing in various Köppen-Geiger climatic zones (Strahler and Strahler, 2002; van Heerden and Walker, 2016).

The climatic conditions of an area play a major role in the crop water use. A crop grown in a humid, cooler climate needs less water than one grown in a dry and hot climate (Brouwer and Heibloem, 1986). Wind speed, radiation, and rainfall can influence crop water requirements in a specific region (Brouwer and Heibloem, 1986; Allen et al., 1998). Crop water requirements are much higher in dry climates than in humid ones, while in windy conditions, the crops will use more water than in calm conditions (Allen et al.,1998). More water is required in areas which are hot, dry and sunny, the least amount of water is needed in areas that are cool, humid, and cloudy with little or no wind. There are studies in South Africa to estimate the irrigation water requirements for different crops based on climatic factors (Brouwer and Heibloem, 1986; Woyessa et al., 2004; van Heerden and van Heerden, 2020).

1.2 Problem statement

Despite the National Water Act (NWA) (Act No. 36 of 1998) calling for efficient and sustainable water use, traditional irrigation practices in South Africa have often led to water being used inefficiently. While there have been improvements in irrigation systems, some do not incorporate best management practices, such as leaching requirements to minimize soil salinity or mulching practices to reduce water loss, particularly under stressed conditions. Applying the SAPWAT4 planning tool for irrigation could help improve that only the necessary amount of water is allocated, preventing potential crop yield losses and inefficient water use. However, applying incorrect quantities of water to soils prone to problems (e.g. high evaporation or salinity problems) could exacerbate these issues and shorten the economic lifespan of an irrigation area. Furthermore, the possibility of cultivating two crops in one season in the same irrigated area, thanks to the development of shorter-growing varieties and various adaptation strategies, raises questions about water allocation. In some irrigation schemes, water allocation has not been reviewed since the original use of the first allocation, and there are limited studies on different irrigation management practices.

1.3 Objectives of the study

The research question was, how do the allocated water quotas compare to the crop irrigation requirements as simulated by SAPWAT4. Therefore, through this study, it is expected to test whether the water allocation quotas of three selected irrigation schemes are comparable to irrigation water requirements as estimated by the SAPWAT4 program. Hence, this research provides insight into the interplay between crop type, soil type and irrigation method that affect crop water use under different climatic conditions (including arid hot, semi-arid hot, and semi-arid cold) as presented in selected irrigation schemes.

The overall aim of this study was to estimate general irrigation requirements in selected water-stressed irrigation schemes in South Africa by using the SAPWAT4 program. Specific objectives included:

a) To conduct a survey (using questionnaires) to collect information from Water User Associations (WUAs) on the crop, soil and irrigation system combinations in selected irrigation schemes;
b) To estimate the general irrigation requirements in selected irrigation schemes for different cropping systems, including different soil-crop combinations and irrigation systems under a conventional irrigation practice;
c) To determine the influence of a deficit irrigation practice, alternate irrigation practices employed by farmers, and stubble mulch cover management on the general irrigation requirements; and
d) To compare the estimated irrigation requirement with the actual water allocation quotas in each selected irrigation scheme.

The irrigation areas that will be focused on this study are:

- Sand-Vet irrigation scheme (Semi-arid cold)
- Hartbeespoort irrigation scheme (Semi-arid hot)
- Orange-Vaal irrigation scheme (Arid hot)

These areas will be described in more detail in section 3.1

CHAPTER 2: LITERATURE REVIEW

2.1 South African climate

The South African climate is largely determined by its location between 22°S and 35°S in the southern subtropical zone. This country is between the Indian Ocean's warm Agulhas current and the Atlantic Ocean's cold Benguela current (Frenken, 2005). South Africa has an average rainfall of 495 mm, which is about half of the global average, with the mean annual precipitation (MAP) ranging from less than 100 mm along the west coast to about 2 000 mm on the eastern escarpment (Schulze, 2016). As depicted in Figure 2.1, the MAP over the eastern parts (sub-tropical) of the county is much higher over the eastern parts of the country than the western parts and with semi-desert regions in the north-west. While the Western Cape has a Mediterranean climate with winter rainfall, most of the country experiences summer rain.

Precipitation of at least 500 mm is received by only 35% of the country, while 44% has precipitation that ranges between 200 to 500 mm. On average, the remaining 21% receives less than 200 mm of rain per year. It is evident that in about 65% of the country, there is a deficit of rainfall to accommodate rainfed crop production (Schulze, 2016). Low and erratic distribution of rainfall results in water scarcity in arid and semi-arid locations, making rainfed agriculture an unreliable business (Christian-Smith, et al., 2012). Semi-arid conditions dominate South Africa. It is therefore there is a huge advantage when crops are grown under irrigation, especially in semi-arid and arid areas (Frenken, 2005).

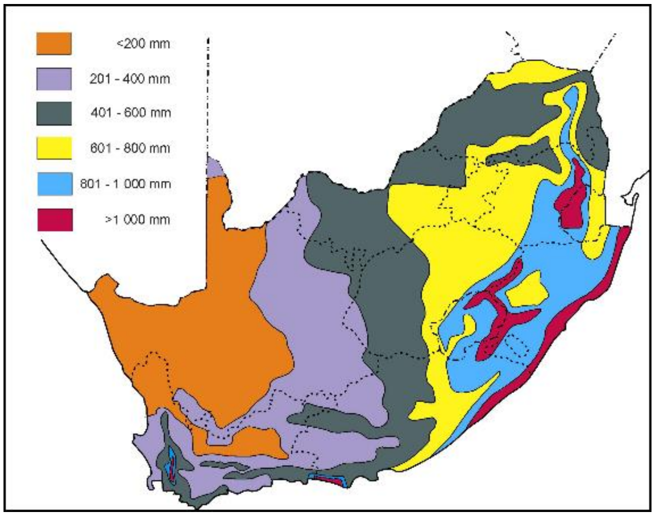


Figure 2.1 Mean annual precipitation of South Africa (Chuene, 2016).

Frost is very common over the South African interior, and it has proven to have a detrimental impact on crops. On the great central plateau, there is normally an occurrence of mid to severe frost, which limits the crop choices, therefore resulting in strong seasonal crop patterns. The Western Cape Province experiences winter rainfall (Mediterranean climate), while the rest of the country receives summer rainfall. On average, temperatures in winter range from 0°C at night time to approximately 18°C at noon, while in the summer time the range of temperatures is approximately 15°C at night time to about 30°C at noon. On the interior plateau winter temperatures often drop below 0°C thus making the occurrence of frost probable which is around June and expected to last towards the beginning of August (Frenken, 2005).

2.2 Thornthwaite and Köppen-Geiger climate regions

Thornthwaite (1948) established a climate categorization system in 1931 and refined it in 1948. The vegetation of climates is defined by precipitation effectiveness, which separates climates into groups based on their vegetation characteristics. In 1948, there was an update in the method to incorporate a moisture index, which connects plant water demand to available precipitation using a potential evapotranspiration (PE) index generated from air temperature and day length readings (Allaby, 2008). The study's title focuses on Thornthwaite moisture zones as a climatic indicator (Schulze, 1958). In South Africa, these terms apply to humid, sub-humid, semi-arid, and arid climates (Figure 2.2).

The Köppen-Geiger climate regions are based on a combination of rainfall and temperature. In South Africa, they are established on the differences between dry and mesothermal (mild, humid) climate regions (Figure 2.3). There are similarities between the Köppen-Geiger and Thornthwaite climate regions in South Africa. The Thornthwaite humid and sub-humid climates generally coincides with the Köppen-Geiger mesothermal climates. Similarly, the Thornthwaite semi-arid and arid climates coincide largely with the Köppen-Geiger dry steppe and desert climates (Figure 2.2, Figure 2.3).

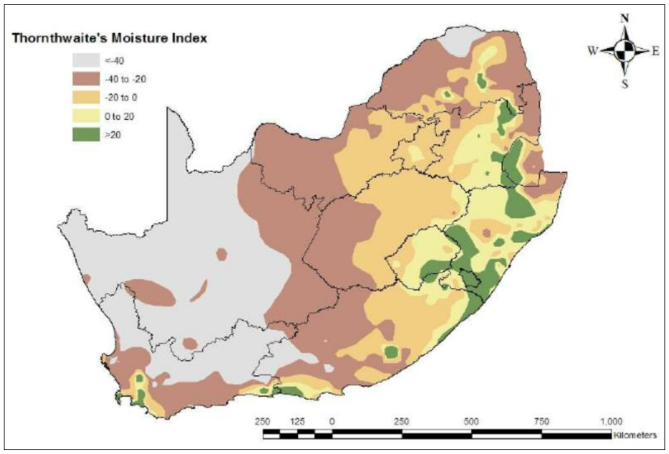


Figure 2.2 Moisture regions of South Africa based on Thornthwaite (Paige-Green, 2009).

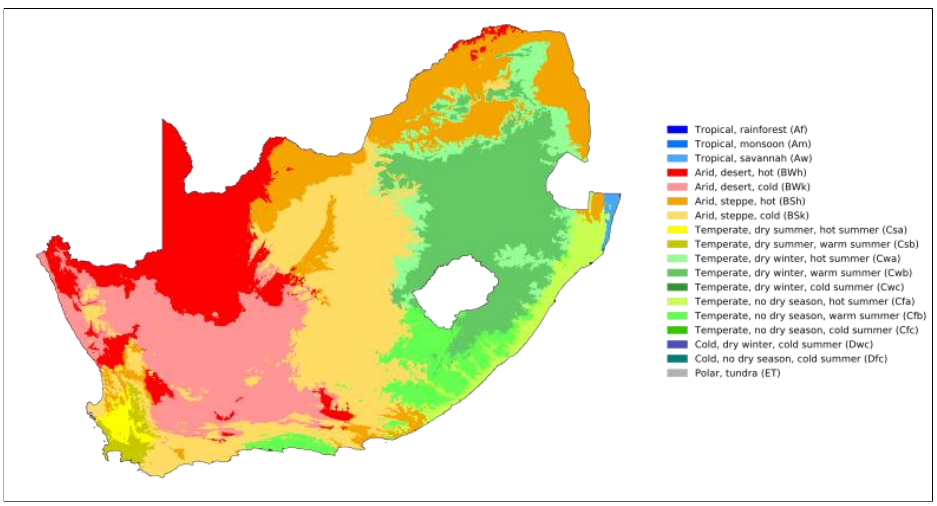


Figure 2.3 Köppen-Geiger climate classification of South Africa (Hylke et al., 2018).

The use of distinct moisture zones suggests that each moisture region’s irrigation requirements differ. A crop cultivated in a drier environment would require more irrigation water than a crop grown in a more humid climate. Temperature differences between climatic zones have a crucial effect on crop growth and development (van Heerden and Walker, 2016).

2.3 SAPWAT4 program

SAPWAT4 was designed to be an interactive program, allowing to simulate large numbers of conditions to find an irrigation management approach or optimised design. The intent of making this program interactive is to help people understand some of the fundamental elements that can impact on irrigation efficiency and management and the irrigation system design. It also allows the user to manage the data fully, and this approach motivates the user to have full control over the data of the program (van Heerden et al., 2001; van Heerden et al., 2008).

Evaporation and transpiration are two simultaneous processes featured in SAPWAT4 program that cause water loss from the soil surface. The combination of these two processes is called evapotranspiration (ET) (Zotarelli et al., 2013; Labędzki et al., 2014). Figure 2.4 shows the soil water balance and how ET is affected by weather parameters (relative humidity, wind speed, air temperature and solar radiation), crop features, management of the crop and surroundings, and environmental variables.

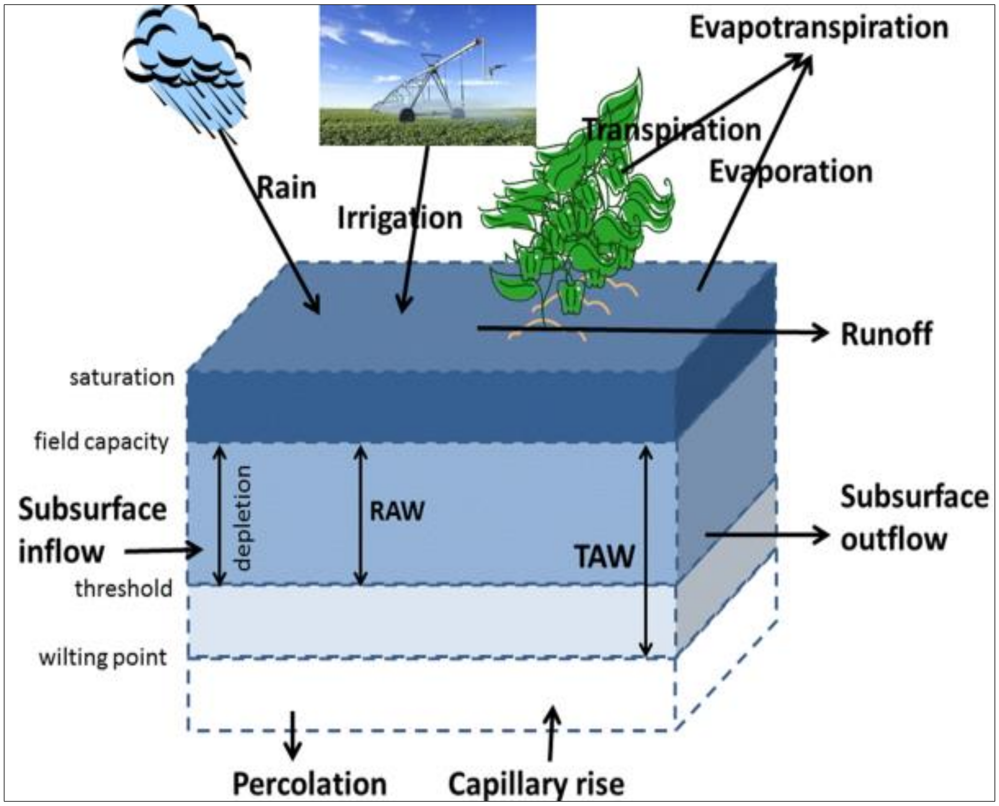


Figure 2.4 Soil water balance components in the root zone and interactions with the atmosphere (Allen et al., 1998).

Irrigation, capillary rise, and rainfall add water to a profile, whereas evapotranspiration and deep percolation extract it. Runoff is normally deducted from surface rainfall since it does not add to the soil water content in the block of soil volume. The area's climate influences evapotranspiration and rainfall, whereas soil characteristics and water management on irrigated and neighbouring lands influence deep percolation capillary rise (Allen et al., 1998).

The structural design of SAPWAT4 is shown in Figure 2.5. The calculator is placed at the centre of the design and provides a link between the weather data and crop data through the reference evapotranspiration (ET_o) and the dual crop approach ($K_{cb} + K_e$) to calculate the amount of water required by a crop (ET_c), then [$ET_c = (K_{cb} + K_e) \times ET_o$] (Allen et al., 1998). This provides the influence of rainfall, irrigation amount, soil water holding capacity and irrigation system efficiency, in order to provide monthly, weekly and daily estimates of required irrigation (van Heerden et al., 2008).

The reference evapotranspiration (ET_o) is one of the key components of agrometeorology, since it may be utilized for irrigation and management planning, as well as estimating atmospheric demand. To calculate the amount of water consumed by a crop, the coefficient of the crop's reference evapotranspiration (K_c) may be used (Allen, 2000). ET_o differs from ET_c in that ET_o is based on observable weather data, whereas ET_c is an estimate of the water balance input and output of a specific crop. According to Allen (2000) during the growing season of the crop, the evapotranspiration was calculated to be 9 % and 14% under solo cotton and mixed cropping, respectively. In some of the studies by Tesfuhuney (2012) and Chuene (2016), the calculations of ET were done as a residual of the soil water balance.

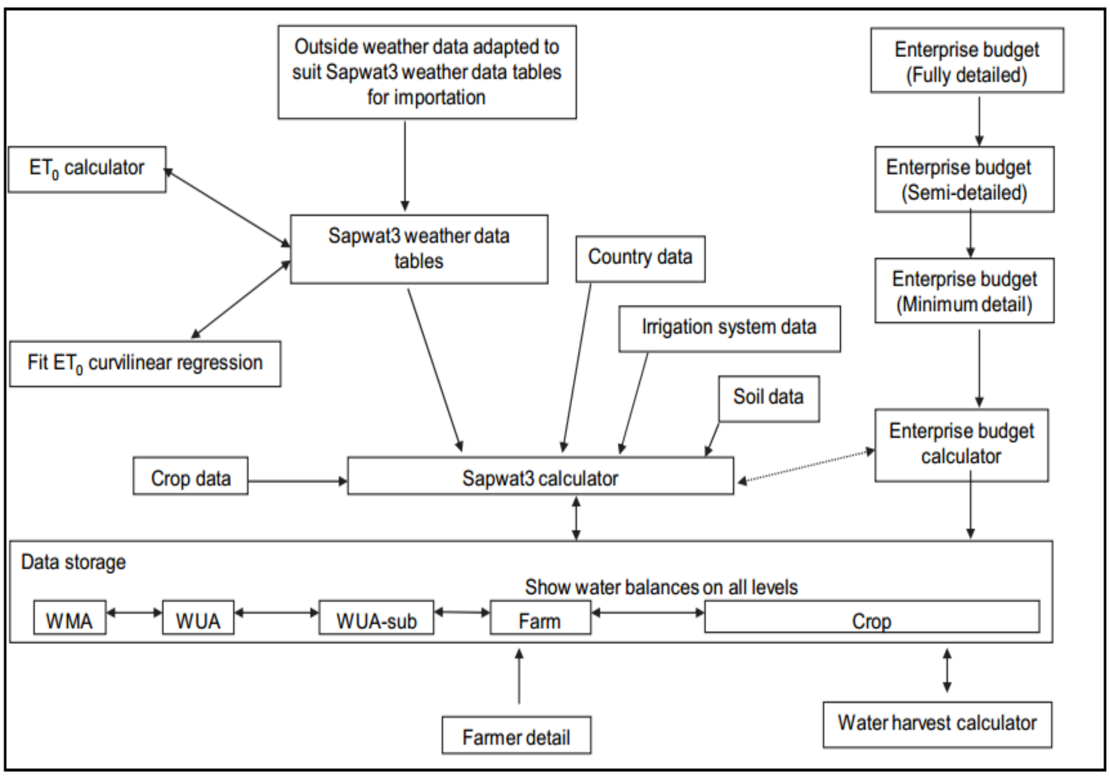


Figure 2.5 Schematic diagram layout of SAPWAT3 structure showing water; water user's association area (WUA), water user's association sub-area (WUA-sub) and management area (WMA) (van Heerden and Walker, 2016).

Weather data may be manually entered or imported on a daily or monthly basis. The ET_o calculator creates ET_o values for monthly or daily results, as well as fitting a cosine curvilinear regression to the ET_o data (Snedecor and Cochran, 1989) to give the software authorization to execute water balance calculations daily, even when weather data is only provided in monthly averages (van Heerden et al., 2008). Reference to different moisture regions implies that irrigation requirements are not the same for the various moisture regions. SAPWAT4 uses weather station data to estimate the irrigation requirements for crops for the area represented by the weather station, it does not use the climate classification for that purpose. However, temperature differences between the climate regions play an important role in the crop growth and development. These differences are reflected in the crop coefficients used by SAPWAT4 generated by the FAO (where data is available). For those crops that do not have specific data (i.e. from literature and personal communications), the crop coefficient have been generalized to the Köppen-Geiger climate regions (van Heerden and Walker, 2016).

The physiology of crops has changed over time by developing of new and shorter growing crop varieties, cultivars with a shorter life span, generally use less water per growing season, and usually produce higher yields (McMahon et al., 2002). Included in SAPWAT4 are tables representing crop growth and development characteristics, expressed as growing periods per crop growth cycle as well as a factor that represents the ratio between ET_o and ET_c, referred to as crop coefficients (K_c). Crop coefficients used in SAPWAT4 are linked to climate regime (van Heerden and Walker, 2016) and are largely based on data published in FAO 56 (Allen et al., 1998) and in FAO 66 (Steduto et al., 2012). The user has access to the crop coefficient tables and can alter the values to reflect the results of newer and more accurate research results (van Heerden and Walker, 2016).

2.4 Effective rainfall

In the case of SAPWAT4, "effective rain" is based on the soil water storage capacity. The amount of rain required to fill up the soil profile to soil capacity is taken as effective. If rainfall occurs, the profile will only be filled to the level that the rain adds to the profile available water. In this case effective rainfall forms 100% of precipitation.When determining the water allocation of an area, the potential contribution of rainfall is considered. The allocation for irrigation at an area is just a supplementary water supply to the rainfall received in an area and its aim is to allow optimal crop production (van Heerden and Walker, 2016). This can be done by managing strategies for irrigation, in a way that there is maintenance of space in the profile for rainwater storage, a portion of irrigation requirements can therefore be supplied by rainwater (van Heerden and Walker, 2016).

2.5 Influence of climate on agriculture

There are many drivers in the agricultural sector, each of which may have a huge variety of repercussions not only on foreign exchange earnings and employment, but also on forests, fiber, and food production. Climate varies from one year to another. The agricultural field in South Africa has become vulnerable due to the ever-changing climate, this is because the productivity of farming is directly affected by the extreme weather events (Schulze, 2016).

Poor farming communities with little to no equipment to conduct their farming practice are affected by climate change and variability because most of these communities are directly dependent on ecosystem services and the natural environment for their livelihood and survival. Therefore, they suffer most from climate related impacts, because of lack of resilience due to knowledge, poverty, poor infrastructure and financial constraints, there is small probability of poverty-stricken farmers switching to other income sources (Schulze, 2016).

Climate change is expected to bring reduced rainfall and greater temperatures in South Africa. Variations in crop productivity will impact global trade patterns and food supply as a result of variations in soil moisture content and regional water endowments. The burden on South Africa's natural resources and food security will increase due to rapid population expansion in Asia and Africa. It would be necessary to achieve yield increases in agricultural research and development of more than 20% over baseline levels in order to mitigate the negative effects of climate change putting a strain on South Africa's food security and natural resources (Calzadilla, 2014).

2.5.1 Temperature related climate issues

It is evident that due to climate change there have been more extreme weather events, and climate change expectations are now conditioning farmers. There are questions on where, when, what impacts to expect, how much and how to adapt. Some of these severe weather conditions which might impact farming include (Schulze, 2016):

- Threshold temperatures: due to more frequent hot days (above 32°C), farmers are vulnerable to reduced yields, the consequence of which could be significant;
- Increased connectivity: if crops are exposed to more frequent severe thunderstorm activity, erosion and surface runoff could increase, which will have negative consequences on productivity;
- Winter temperatures: winter days are perceived to have become warmer, and winter to be arriving later, affecting disease incidence and quality of deciduous fruits;
- Frost days: the same applies to frost days, with the perception of fewer days with frost than in the past, and a possibility of fewer shade cloths having to be used in future to minimize frost damage;
- Snowmelt: if / when snow falls, it now melts more rapidly than before, according to farmers in areas where snowfalls occur;
- Chill units: chill units are no longer recorded in May in many regions of the Western Cape, according to farmers; they instead begin in June. Farmers are switching from apples to pears in some locations (e.g., Grabouw), which require fewer chill units;
- Enhanced variability: variability, e.g., in frost occurrences per annum, appears higher; and
- Heat island effect: with urban expansion, the urban heat island effect is expanding outwards into agricultural lands – already to the detriment of farmers.

2.5.2 Rainfall related issues

- Amount of rain at planting time: farmers believe they nowadays get too little rain at planting time, especially in the case of summer crops, with this rendering them more vulnerable to crop failures (Schulze, 2016);
- Enhanced rainfall variability: this will add to the vagaries of sustainable crop production;
- Long cycle crops and drought: when farming with multi-year crops with 20-30 years plant cycles, such as commercial production forestry or deciduous fruit, farmers are vulnerable to 2-3 successive droughts years, which do considerable long term and sometimes permanent damage to the trees;
- Persistence of rain days: long duration, multiple light showers of rain in winter rainfall region are observed, according to farmers;

- Rainfall intensity: rainfalls are nowadays perceived to be more intense in the winter rainfall region than previously, resulting in mudslides / landslides as well as soil erosion;
- Number of rain days: there are now fewer days with rain in winter rainfall region, according to farmers; and
- Onset of rains: the onset of winter rains is now perceived to be later, and the rains extend into November.

2.6 Conventional tillage (CT)

Subsistence and commercial smallholder farmers with varied input consumption and land preparation in South Africa, typically use conventional tillage (CON). The mouldboard plough is commonly used in this approach in order to bury the residues from other crops deep in the soil and prepare the land. This is in contrast to conservation agriculture, where the turning of the soil does not take place, some of the residues from the previous crop are normally left on the field for the reduction of water loss through evaporation, to combat erosion and to retain the nutrients of the soil (Oisat, 2005). As climate elements such as temperatures and rainfall an impact on soil properties, cropping and management strategies can also have an impact on the biological, physical, and chemical soil qualities. The conservation tillage strategy utilized for a particular field can either enhance or harm the chemical and biological qualities of the soil (Larsbo et al., 2009). Moreover, the physical qualities of the soil, such as porosity, bulk density and infiltration rate of the soil, can be affected due to the CON tillage strategy used.

When employing CON, farmers may encounter a number of potential negative impacts. According to Hobbs et al. (2008), CON leaves the soil exposed to severe weather conditions such as heavy rainfall and strong winds, allowing the fertile topsoil to be swept away. CON also frequently loses soils because of water and wind erosion. Macrospores are frequently killed in soils under CON (Mapa et al., 1986). Okada et al. (2016) investigated the mobility and adsorption of glyphosate in various soils under conventional tillage and no-till conditions. The adsorption was found to be extremely high in all of the soils studied, thus the adsorption coefficient (K_f) was higher in all CON tillage treatments. When this treatment is used it exposes the soil to a high rate of chemical adsorption, which can cause some damage to the soil. To prevent soil deterioration and water loss through runoff, agricultural communities have implemented conservation agriculture methods such as infield rainwater harvesting.

2.7 Conservation Agriculture (CA)

Traditional tillage techniques are a major source of concern for agricultural communities. This is due to the negative effects on soil production and environmental degradation (Knower and Bradshaw, 2007). As a result, farmers and the government must look at various techniques that might increase soil fertility. Conservation agriculture is a system in which agricultural resources are better used by managing available soil, water and biological resources (Garc'a-Torres et al., 2003). According to the WMO (2002), CA is any tillage method in which 30 percent of the crop residues cover the land during the fallow season. Soil and water conservation methods are vital in decreasing water loss due to evapotranspiration (ET) and runoff (R_o), improving soil water availability, crop yield. Some advantages of CA, include increased water infiltration and intensification of the water holding capacity owing to crop residues left on the soil surface.

2.8 Overview of the water situation in South Africa

2.8.1 Water sources

River flows reflect the country's rainfall patterns. Rivers that originating in the higher rainfall regions of the eastern escarpment's humid highlands and the mountains of the Western Cape usually have perennial flows. Rivers that have their origin in dry, sub-humid neighboring areas flow in a predictable pattern, but rivers that start on the dry, western great plateau have episodic flows (Frenken, 2005). Total annual surface runoff is estimated to be 49 km^3 a^{-1}, or around 9% of yearly rainfall. Lesotho and Swaziland provide around 5 km^3 a^{-1} (rivers travelling through South Africa). However, because most of the total runoff volume is lost due to flood spillage and evaporation, the usable yield in the year 2000 was estimated to be 13.2 km^3 a^{-1}. The entire capacity of dams/reservoirs in 2025 is projected to be 32.4 km^3 by the department of water affairs and forestry. The dams can hold almost all of the plateau's runoff, but undiscovered resources of water are concentrated along the country's east and south coasts (Tlou and Joubert, 2013). The ecological reserve is expected to require 9.5 km^3 a^{-1} of water. In the year 2000, total water extraction was projected to be 12.5 km^3 a^{-1}, or 26% of total runoff (Tlou and Joubert, 2013).

The most suitable estimate of South Africa's groundwater storage is 17 400 km^3 (MacDonald et al., 2012). Annually, about 4.8 km^3 a^{-1} of ground water is provided via fountains, springs, and boreholes, of which approximately 3 km^3 a^{-1} is drained by rivers (Frenken, 2005). Despite the fact that ground water supply is restricted, and borehole productivity is typically regarded as low to moderate due to the country's geology, it is widely used in rural and dry areas. Only a few regions have large, permeable aquifers. In the year 2000, available outputs from these resources for irrigation and household were projected to be 1 km^3 a^{-1}; however, current extraction is not thoroughly monitored. Ground water extraction for human use is expected to rise, particularly in the country's western areas which lacks perennial rivers (Tlou and Joubert, 2013). There is a possibility of future ground water development, but on a lower scale. The Department of Water Affairs and Forestry's projections for 2025 estimated that the total annual water withdrawals will increase from 12.5 km^3 a^{-1} to 14.5 km^3 a^{-1} (Tlou and Joubert, 2013).

2.8.2 Water use

Ferner (2017) published a Huffington post based on Water Resources Institute (WRI) research on water-stressed countries. Floods, drought, and rivalry for limited resources can affect the agricultural sector, the lives of people and the economy according to Paul Reig, the associate for WRI's Aqueduct project. He described the ratio of yearly water withdrawals to total available annual renewable supply as baseline water stress. As seen in WRI's map (Figure 2.6), a higher percentage suggests more people are competing for increasingly scarce water supplies (World Resources Institute, 1997).

It is vital for a country to assess its risk of water scarcity that extremely high water stress levels do not always suggest a country would experience water shortage if appropriate conservation measures and water management tools are implemented. According to World Resources Institute (1997) South Africa is already under extreme stress, with 40 to 60% of its renewable water resources being depleted. The ratio of total withdrawals to total renewable supply in a specific area is depicted on this map, which displays the average exposure of water consumers in each country. A larger proportion indicates that more people are competing for the limited supply of water. WRI Aqueduct, Gassert et al., 2013.

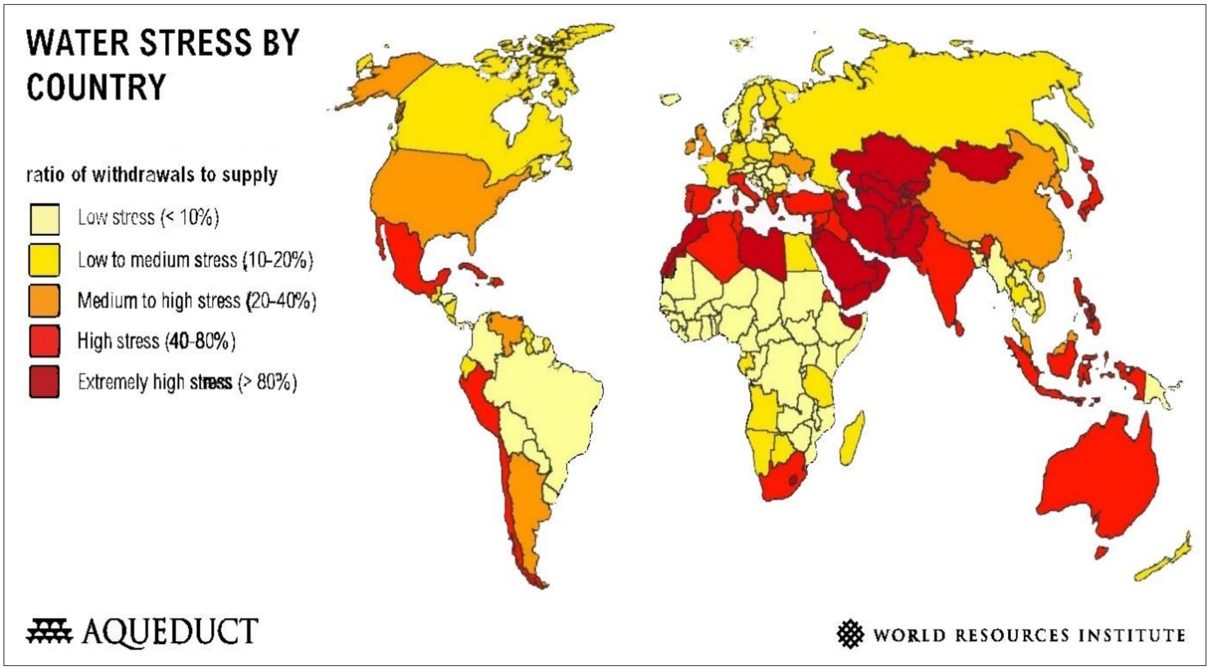


Figure 2.6 Water stress of different countries (Ferner, 2017).

South Africa's ground and surface water resources are largely depleted and consumed in the country's northern regions (Gauteng, Mpumalanga, and Limpopo). Considerable undeveloped and little-used resources remain in the country's southeastern regions where most rainfall is received such as Eastern Cape, coastal areas of the Western Cape and KwaZulu-Natal (Basson and Van Niekerk, 1997; Tlou and Joubert, 2013).

Basson and Van Niekerk (1997) examined South Africa's water balance, comparing 1996 values with projections for 2030 and it was discovered that seven drainage basins were over-utilized in 1996. This number was anticipated to rise to eight by 2030. Limpopo/Crocodile, Great Fish, Olifants, Buffels, Sundays, Orange, and the Vaal Basin are among the over-utilized basins. By 2030, it was predicted that the Berg basin will have joined them. Because of this, ground water failure is frequent in more densely inhabited areas, such as the North West, Limpopo, and Mpumalanga provinces. As a result, the average mean ground water level dropped, similar to what happens internationally when there is an occurrence of an overuse (Basson and Van Niekerk, 1997).

Reinders et al. (2010) reported irrigation water losses to range between 43 % and 57 % while the efficiency of irrigation systems ranged from 38% to 77%. Extreme situations exist within the aforementioned rivers, but they represent the inefficiency that may be expected in worst-case conditions. Steep topography, extensive shallow, eroded soils and slope lengths define most areas in South Africa. The over exploitation of natural resources is frequently the cause of eroded soils. Large catchments can produce up to 1000 t km^{-2} a^{-1} of sediment. More than 120 million tonnes of sediments are projected to enter South African rivers annually. This has major ramifications for the downstream water environment and causes dam siltation. According to the Department of Water Affairs (1986), the average loss capacity of big dams is less than 10% per decade in South Africa, while there are signs that this problem is improving recently due to conservation farming strategies.

Floods are common in South Africa, they supply the majority of the inflow to most of South Africa's dams, rather than base flows. Severe floods are a reason because they might cause some structural damage. If no records are available, the scale of a flood with a certain likelihood of occurrence can be calculated by analyzing the historical record at a river location, or by applying one or more of numerous other approaches, this is mostly done in the costal regions of South Africa such as Kwa-Zulu Natal and Eastern Cape where floods are frequent. Flood management by dams is often only successful for minimizing damage to irrigated fields along rivers during mild floods, while excessive flood regulation by dams is usually ineffective (Department of Water Affairs, 1986).

More advanced drought management measures are necessary when the basic flow controlling benefits of dam storage in a river system become insufficient because of increased demand. In recent years, improved systems and hydrological analysis approaches have been developed for this purpose (De Waal and Verster, 2012; Ghile and Schulze, 2008). Modeling techniques for spillway management from major dams are among them (De Waal and Verster, 2009). As a result, the Department of Water Affairs and Forestry is working on improving previous management approaches based on basic storage capacity/yield relationships and sufficient for prior usage levels and assurance needs. As the drought intensifies, recent drought management approaches include imposing continually changing, progressive rises in the degree of water restrictions, followed by a progressive relaxation of restrictions as the condition improves (Tlou and Joubert, 2013). Relationships between, yield, economic optimization, storage capacity and risk, are all considered in current management techniques. Financing needs, development and operational rules, and collaboration with customers and water distributors can all be considered (Tlou and Joubert, 2013).

Once the economic limitations of water resource exploitation and inter-basin water transfer are reached, restrictions of water on a scheduled and more frequent basis will be necessary. Many user groups have proved their capacity to significantly reduce their use due to restrictions. If curtailed use becomes a permanent feature, consumers will be limited in adjusting to future limits. To minimize the impact of limitations, close collaboration between the customers and the Department of Water Affairs is required (Department of Water Affairs, 1986).

2.9 Irrigation in South Africa

Irrigated agriculture is important to livelihoods around the world. Irrigated agriculture is South Africa's main consumer of runoff water, the government has heightened expectations that the industry improves efficiency and cut consumption in order to increase the quantity of water available for other purposes, particularly household consumption. Irrigation is being done on 1.6 x 10^6 hectares in South Africa. It consumed 62% of runoff water used by all sectors in the year 2000, or 39.5 % of the accessible runoff water (Stevens and Buys, 2012). Research and studies for over 40 years, on mobile, micro and flood irrigation techniques contributed to the knowledge base of the correct application of the irrigation system. Irrigation systems vary in terms of cost and performance, and individual components and they can be divided into three groups (Stevens and Buys, 2012):

Flood-irrigation systems

This is the type of irrigation system where water flows across the surface by gravity while infiltrating the soil examples of these are border, basin and furrow (Stevens and Buys, 2012). The gradient of the water surface itself is what actually drives the water to flow over level surfaces, even though the soil gradient is important in starting the irrigation water flow. Gradient formation is therefore essential to the efficiency of the water movement. Given that surface irrigation covers

80% of all irrigated land, it is by far the most popular type of irrigation (Reinder, 2021). Although flood irrigation is a low-tech and inexpensive irrigation technique, it is not the most efficient. Most water is lost to evaporation and runoff near the field's boundaries, therefore it requires more water to irrigate crops when compared to other irrigation systems (United States Geological Survey, 2016).

Mobile irrigation systems

These irrigation systems irrigate the farmland, while moving across it under their own power, examples of these are linear and centre pivot (Stevens and Buys, 2012). A centre pivot irrigation system is a self-propelled continuously moving machine that revolves around a central point, while a linear irrigation system is normally described as a centre pivot adaptation. However, the linear system moves across the field in a straight line, usually at an angle to the row direction, as opposed to a circle. The centre pivot and linear systems provide the producer with an energy and water-efficient system on big fields, therefore they require large supply of crop water. Since there is a uniform distribution of water, less water is wasted they also need the least amount of labor (Sneed and Evans, 1996).

Static systems

Which include all stationary systems while water is applied. There are two types of namely:

a) Micro-irrigation system, which include mini-sprinklers, micro-sprayers and drip systems are irrigators with low pressure that mist, spray, sprinkle, or drip and are normally installed below ground (Stevens and Buys, 2012). Emission of these devices are made for specific applications according to agronomic or horticultural needs, which results in different water discharge patterns. Pipes, tubing, water emitting devices, flow control equipment, installation tools, fittings, and accessories are some of the parts used in micro-irrigation. These systems have minimal conveyance loss, no water loss, less evaporation, runoff, and deep percolation as water is irrigated straight to the roots. It saves a lot of energy and can reduce weed and diseases, they are also perfect in irrigating row crops (Hla and Scherer, 1998).

b) Sprinkler irrigation system water supplied above ground through permanent or portable systems like quick-coupling, drag-line, hop along, big-gun, side-roll and boom irrigation (Stevens and Buys, 2012). Irrigation water is sprayed into the air, breaking into tiny water droplets falling to the earth. Water must be applied uniformly, hence the pump supply system, and they use more water, energy and has high evaporation and runoff compared to micro-irrigation system (Hla and Scherer, 1998).

The national water resources strategy of the Department of Water Affairs (2013a) notes that water demands effect South Africa's rising economic and social development, will result in an increase in demand for water. Given the limited water supplies available, this is unlikely to be simple or cost-effective. Many sectors are rapidly nearing the point where all commercially exploitable fresh water resources have been depleted, necessitating the development of innovative techniques to balance demand and supply, particularly in places where the majority of South Africa's economic growth occurs. It's also critical to meet demand in rural regions in order to boost the economy.

The cost of transporting water to places where it is needed is increasing. Developing new water resources infrastructure is a complicated and time-consuming process that normally takes more than a decade from conception to completion, particularly for large projects with environmental and political sensitivity. This emphasizes the importance of meticulous planning with lengthy time horizons. The ecological reserve is expected to require 9.5 $km^3\ a^{-1}$ of water. The overall water extraction was calculated to be 12.5 $km^3\ a^{-1}$, or 26% of total runoff, Figure 2.7 depicts several criteria (Department of Water Affairs, 2013).

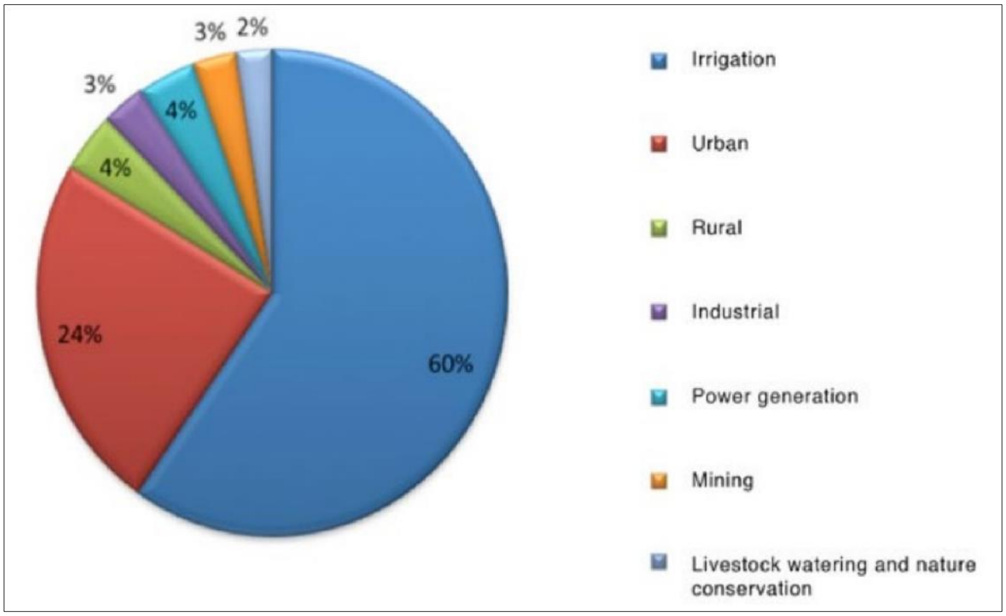


Figure 2.7 Water use by public, industrial, environmental, and irrigation (Department of Water Affairs, 2013).

According to the water balance outlined in the first water resources plan (Department of Water Affairs, 2013), a mix of water resources would be necessary to reconcile supply and demand, the surface water resources will also be exhausted during the medium term. Reconciliation strategies, which have been designed to assist water resource investment and management decisions for big systems feeding areas of substantial economic importance and individual towns and cities. This includes improving international resource collaboration in the areas of technology and development, trading, engineering, and scientific interests of the country by assisting partners that South Africa can support in increasing their capabilities. Furthermore to make use of global resources to the water industry's advantage and lastly to utilize the experience gained from global partnerships to assist RSA institutions in putting the Water and Sanitation masterplan into practice. (Department of Water Affairs, 2013).

All water resources in the water mix should be studied and exploited to guarantee adequate water of acceptable quality is provided for the country's socioeconomic demands while also assuring sufficient water for conserving aquatic ecosystems. Surface water supply and its remaining growth potential, according to water Reconciliation strategy analyses, will not be adequate to fully sustain the expanding economy and related requirements. South Africa will have to use alternate resources to fulfil rising demand (Department of Water Affairs, 2013).

Agriculture

The goal of the Irrigation Strategy is to increase irrigated areas by more than 50%. The Department of Water and Sanitation anticipates that the amount of water given to agriculture will stay unchanged. This means that all land reform programs and smallholder irrigation scheme revitalization will utilize the same amount of water as previously. A rise in irrigation will be accompanied by a rise in water-use efficiency (Department of Water Affairs, 2013).

Mining

South Africa has many abandoned or disused mines. New mining activities, notably for platinum and coal, are in the pipeline. Some of these new mines are located in water-scarce locations, putting additional strain on the water supply. Water contamination is a concern for both abandoned and new mines (Department of Water Affairs, 2013).

Forestry

Forestry development is limited to high-rainfall areas, such as Mpumalanga, Limpopo, Eastern Cape and Kwazulu-Natal. More forestry areas are required for the industry to develop, although downstream processing industries such as sawmills, pulping, and paper manufacturing can also help. However, downstream operations may consume significant water and contaminate water resources. On the other hand, forestation will restrict stream flow while protecting biodiversity (Department of Water Affairs, 2013).

2.10 Farmers’ engagement and knowledge uptake

Rural populations in arid and semi-arid environments suffer several problems, including food insecurity and poverty. However, the issues might be exacerbated due to socio-economic constraints, such as a lack of funds and awareness. Environmental constraints, such as inadequate soil fertility, climate variability, inconsistent rainfall, and socio-economic constraints. Farmers who rely on subsistence agriculture are more vulnerable to crop failure as a result of climate change and environmental degradation (Meijer et al., 2014). When the farmers are not advised appropriately by extension officers, they are more likely to abandon agricultural technologies, making the adoption process extremely difficult.

Technological advancements in the agriculture industry are critical for developing ways to enhance labor productivity, generate revenue, eliminate food insecurity and support economic growth in the long run (Martens and Barrett, 2012). Community-beneficial innovations are not always immediately embraced (Martens and Barrett, 2012). The choice to adopt new technology is critical (Abera, 2008). In the agriculture industry, adoption is determined by the farmer's view and attitude toward the new technology. However, factors such as farmers' capacity to comprehend new knowledge and their ability to put new abilities into practice play a part in the adoption process. Other important considerations include location, societal, and economic issues. Geographic problems are linked to climate and water crises; social concerns are linked to gender issues and language barriers; and financial constraints are linked to poverty and uneven land distribution. The capacity of the adoption process is determined by comparing the costs and benefits of old and new technology (Meijer et al., 2014).

As a result, adoption cannot be a one-time choice, but rather a step-by-step process of analyzing the costs and advantages of the new technology. A broad range of stakeholders should participate in implementing of technology for sustainable agriculture (Shikur and Beshah, 2013). With the goal of preserving sustainable agriculture practices, stakeholders should include agricultural markets, non-government and governmental institutions, researchers and farmers.

CHAPTER 3: METHODOLOGY

3.1 Study area selection and description

In South Africa, the number of irrigation schemes was indicated to be 302 in 2010 with a command area of 47 667 hectares (Van Averbeke et al., 2011). The population of the farmers in these irrigation schemes was estimated to be 34,158 (Van Averbeke et al., 2011). Although most of the agricultural practices in South Africa rely on rainfed production, irrigation still plays a major role in crop production. Figure 3.1 indicates actively irrigated areas for the year 2015/16 depicted in blue, while red shaded rainfed production (Matthews, 2017).

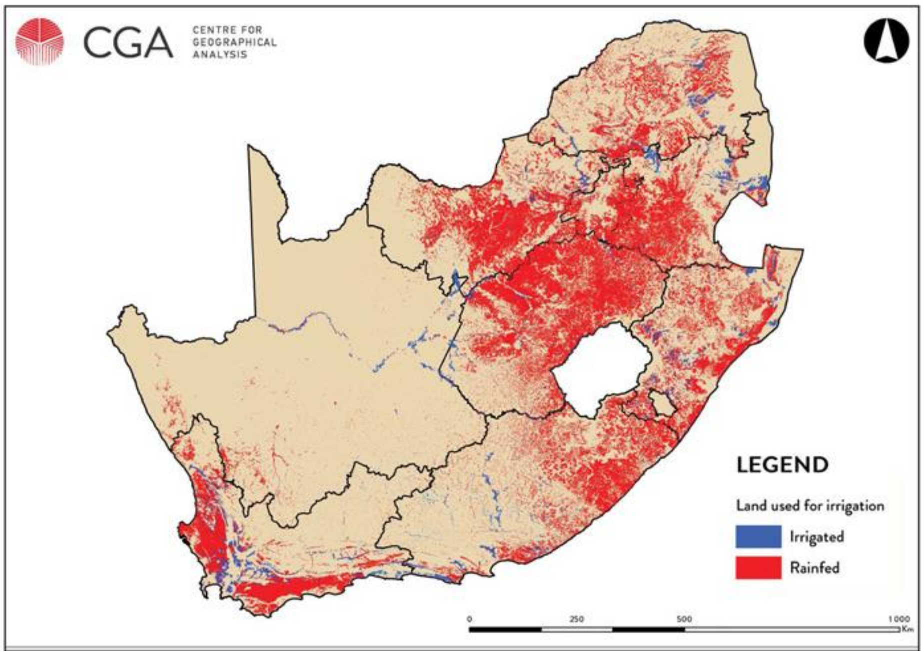


Figure 3. 1 Irrigated and rain-fed agricultural fields for 2015/2016 in South Africa Matthews, 2017).

According to the WRC report 2020 (van Heerden and van Heerden 2020), the Department of Water and Sanitation (DWS) in South Africa identified 12 irrigation schemes as either water-stressed or having issues with water allocation (Table 3.1). These schemes are located in different climatic zones. For this study, three schemes were selected, each representing a different climatic zone: Sand-Vet, Hartbeespoort, and Orange-Vaal. These three selected areas are relatively small compared to other irrigation areas in the country and have a small impact on the total water situation in South Africa, but they do play a major role in their individual provinces (Van Averbeke et al., 2011; Matthews, 2017). Moreover, these irrigation schemes represent different climatic zones, and their water allocation has not been reviewed since the initial allocations were made many years ago. They all have different cropping patterns as well as irrigation systems.

Table 3. 1 Water-stressed irrigation areas identified by the Department of Water and Sanitation (DWS) with the relevant quaternary drainage and climate classification.

Name of irrigation area	Relevant quaternary drainage regions	Climate classification
Crocodile West	A24h	Semi-arid, hot
Loskop	B32h	Semi-arid, hot
Pongola	W44d	Semi-arid, hot
Great Letaba (Tzaneen WUA)	B81d	Humid, hot
Sand-Vet*	C43b	Semi-arid cold
Great Fish River	Q30e	Semi-arid, cold
Orange-Riet	C52l	Semi-arid, cold
Hoedspruit	B71h	Semi-arid, hot
Olifantsrivier (Western Cape)	E33g	Semi-arid, hot
Hartbeespoort *	A31j	Semi-arid, hot
Boegoeberg	D72c	Arid, hot
Orange-Vaal*	D33k	Arid, hot

**Shaded rows indicate the selected irrigation schemes*

3.1.1 Sand-Vet irrigation scheme

Physical characteristics:

The Sand-Vet irrigation scheme, established in the 1960s, is located in the Free State province within the Lejweleputswa district and Matjhabeng local municipalities (Centre for Development Support, 2004). As shown in Figure 3.1, the area has a semi-arid cold climate and is supplied by two dams: Allemanskraal on the Sand River, with a capacity of 174.2 million m3, and Erfenis on the Vet River, with a capacity of 207.5 million m3 (Tlou and Joubert, 2013). A representative weather station at Sand-Vet is located at 26° 29′ 54.96′′ E and 27º 58′ 49.09′′ S. The towns of Welkom and Odendalsrus are north of the Sand River, while Theunissen is north of the Vet River (Tlou and Joubert, 2013). The Vet River flows into the Sand River about 20 km downstream of Theunissen. The bedrock in the area consists of recent gravel, Aeolian sands, concrete, alluvium, and layers from the early Precambrian (Behounek, 1980). The most significant deposits are the Vaal River gravels and the alluvial sands and silts of the Vet and Sand Rivers. Wind erosion of ancient river systems has created pans of various shapes and sizes (Behounek, 1980). The soil is generally moderate to deep with a flat to wavy relief. Four types of soils are found within the scheme, distributed as follows (Schoeman and van Deventer, 2004) and illustrated in Figure 3.3:

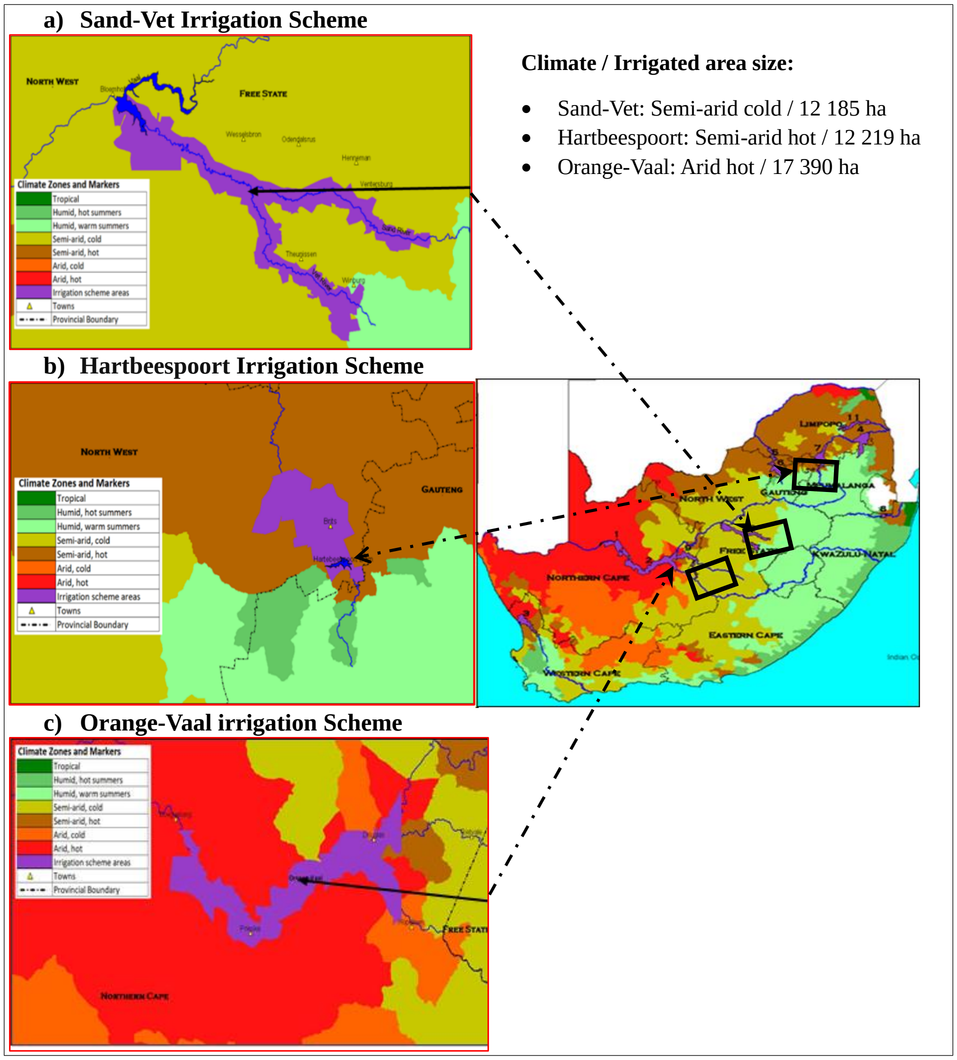


Figure 3. 2 Location of study areas and the illustration of the selected irrigation schemes: a) Sand-Vet, Hartbeespoort and Orange-Vaal schemes.

(i) *The upper catchment of the Vet River:* The average soil depth is about 1150 mm, making it difficult to determine seepages due to the likelihood of deep percolation. Downstream of the Erfenis Dam, the soil is moderate to deep and sandy. The terrain is generally flat and the soil has a lower water-holding capacity compared to other areas within the irrigation scheme.

(ii) *The middle scheme area from Sand River downstream of the confluence between the Vet River:* The average soil depth in this area is about 1150 mm. The soil is moderate to deep and clayey, with generally flat terrain. It has a good balance between water retention or the capacity to hold water (retention) and the ability to convey water (drainage).

(iii) *Outer middle scheme area:* In the lower portions of the Sand and Vet Rivers below their confluence, on the outer edges of the scheme, the average soil depth is about 853 mm. The soil is predominantly moderate to deep sandy loam on flat plains just downstream of the Erfenis and Allemanskraal Dams.

(iv) *Outer middle scheme area:* In the lower portions of the Sand and Vet Rivers below their confluence, on the outer edges of the scheme, the average soil depth is about 853 mm. The soil is predominantly moderate to deep sandy loam on flat plains just downstream of the Erfenis and Allemanskraal Dams.

Irrigated crops in the scheme

Table 3.2 shows the irrigated crops grown in the Sand-Vet irrigation scheme. The main crops are wheat, potatoes, and maize, covering 7,154 ha, 2,201 ha, and 2,201 ha respectively. Benadé et al. (2008) reported an increase in peanut and maize yields over time, while oat production decreased. There has also been a significant increase in mixed cropping, with the top three crops accounting for 77.6% of the total area (Table 3.2).

Table 3. 2 Irrigated crops in the Sand-Vet irrigation scheme (Benadé et al., 2008)

Crop Type	Total crop area (ha)	Percentage of total area (%)	Production (t ha^{-1})	
			Average farmer	Top farmer
Wheat	7 154	48.0%	5	7
Potatoes	2 201	14.8%	22	27
Maize	2 201	14.8%	8	12
Oats (grazing)	759	5.1%	3	3
Lucerne (grazing)	664	4.5%	3	3
Soya beans	551	3.7%	2	3
Cabbage	414	2.8%	25	30
Rye grass	285	1.9%	3	4
Sorghum	190	1.3%	3	4
Pumpkins	172	1.2%	25	30
Carrots	86.	0.6%	40	45
Sweet melons	86	0.6%	25	30
Watermelons	86	0.6%	25	35
Wine Grapes	34	0.2%	25	30
Tomatoes	17	0.1%	40	45
Total	**14 900**	**100%**	254	308

Figure 3. 3 Illustrations of Sand-Vet WUA – Erefenis Dam structure (top) and examples of the Vet canal system and drip irrigation for cultivation (bottom).

3.1.2 Hartbeespoort irrigation scheme

Physical characteristics:

Hartbeespoort Dam is located on the Crocodile River, on the border between Gauteng and North West provinces, with a weather station at 26° 15´ 17.28´´ E and 25º 10´ 34.68´´ S. Construction began in 1916 and, despite setbacks and political turmoil, the project was completed in April 1923. In September of that year, the road over the dam wall and through the 56.6 m tunnel was opened to traffic (North West Department of Agriculture, Conservation and Environment, 2006). This area lies in a valley to the north of the Witwatersrand Mountain range and south of the Magaliesberg mountain range. It is under Madibeng municipality in the Bojanala Platinum district (de Beer, 1975) and has a semi-arid hot climate (Figure 3.2) and illustrated in Figure 3.4.

The geology of Hartbeespoort is mostly dominated by the formations in the Pretoria Group of the Transvaal sequence, with the undifferentiated surface deposit located in areas that are low lying (North West Department of Agriculture, Conservation and Environment, 2006). Outcrops in this group noted in Hartbeespoort include Silverton, Magaliesberg, Hekpoort, Daspoort and Timeball. These are comprised largely of shales and quartzite. The quartzite ridges give rise to the Magaliesberg and Witwaterberg, which are the dominant landforms in Hartbeespoort and they are harder than shales which are easily eroded (Gouws, 2012). Silverton and Timeball Shales form the valleys in between these two quartzite ridges. The geological formations of Hartbeespoort run from the northeast to the southwest. Some particular aspects of the geology characterize the topography of Hartbeespoort such as the existence of the shales in the valleys and quartzite ridges (Brink, 1979). The dominant soils in the area are arcadia and oxidic soils, which fall under the South African vertic soil group as well as Rensburg, which is classified under vertic haplaquept (Gouws, 2012).

Irrigated crops in the scheme

Typical crops grown in the area include sunflower, wheat and maize, they are considered revenue generators of the economy around the Hartbeespoort area (North West Department of Agriculture, Conservation and Environment, 2006).

Figure 3. 4 Illustrations of Hartbeespoort WUA – Dam weir and outlets (top) and the main canal and center pivot irrigation system for cultivation (bottom).

3.1.3 Orange-Vaal Irrigation Scheme

Physical characteristics:

The Orange-Vaal irrigation scheme was initiated in 1890 when funds were allocated for the construction of a weir and canal in the Douglas region of South Africa. The construction began in 1891 and was completed in 1896. The structure, which was expanded in 1937, is situated at the top of the current Bucklands Canal on the bank of the Vaal River. Initially, the canal only served a few plots in and downstream of Douglas (van Heerden et al., 2001). The Orange-Vaal WUA is located in the Northern Cape Province of South Africa, at the confluence of the Vaal and Orange Rivers. Its management area is bounded by 23°34′ and 24°10′ E, and 28°46′ and 29°13′ S. The WUA is situated about 18 km from Douglas, which is the nearest town. The area has an arid, hot climate and is much drier than the other two irrigation schemes selected for this study, as shown in Figure 3.2. The area's topography is mostly flat, with large pans and endorheic areas that do not contribute to the Orange River system (Figure 3.5). To the west and south of the Orange River, the geology is complex, with a variety of shallow, rocky soils and rich mineral deposits. Most irrigation in this area takes place on alluvial soils near rivers, with some on nearby reddish and brownish sandy soils (Report from Agricultural Research Council [ARC-ISCW], 2016). Soils with high clay content are found at lower elevations, while those with low clay content and a predominance of fine sand are found at higher elevations. These mixed soils are prone to compaction, a problem that local farmers are aware of (van Heerden et al., 2001).

Irrigated crops in the irrigation Scheme:

In 1918, wheat, cotton, and lucerne were grown in the region, with lucerne mainly used as feed for mules working as draft animals in the diamond mines. Potato production increased significantly in the late 1950s and early 1960s, and crops are grown on soils with less clay also became popular. This was due in part to a canning facility operated by Delport near Modder River from around 1960 to the early 1970s (van Heerden et al., 2001). After the first centre pivot irrigation systems were installed in 1978, maize became a much more prominent crop in the region. Wine grapes were introduced in the late 1980s, but the limited availability of irrigation water is likely to be a constraint shortly or in the near future. Vegetable farming has always been done on a small scale in the area, but production has been limited by the lack of a local market and the distance to larger markets (van Heerden et al., 2001).

Figure 3. 5 Illustrations of Orange-Vaal WUA – Dam weir and outlets (top) and the main canal and sprinkler irrigation system for cultivation (bottom).

3.2 Data collection

3.2.1 Questionnaire and Survey

Information about the management practices in each WUA was gathered using qualitative and quantitative methods, with the assistance of an independent irrigation-planning consultant, Dr. Pieter van Heerden. The CEOs of the Sand-Vet, Orange-Vaal, and Hartbeespoort WUAs were contacted by phone to ask if they were willing to participate and to schedule meetings. All of them agreed to cooperate, and the study's proposal was explained in detail during the meetings. A questionnaire (Annexure II) was emailed to each WUA's CEO, containing basic information.

The questionnaire included basic information such as the name and phone number of the WUA's CEO, the location of the nearest town and its distance and direction from the irrigation scheme, the name of the WUA and its sub-area, and the size of the irrigated area in hectares and the amount of water allocated for irrigation in cubic meters per hectare. It also asked about the irrigation system, including the types used and their relative importance, and the area covered in hectares. Information about soil types in the area, including their relative land size in hectares, was also requested. Finally, information about crops grown in the scheme, including their type, area covered in hectares, planting date, use of double cropping and other management practices such as grain cultivation, and their relationship to soil type and the irrigation system was also included.

The first meeting was held on October 6, 2018, with Mr. Nick Fourie, the CEO of the Hartbeespoort WUA. He expressed interest in participating in the questionnaire and provided information about the irrigation scheme. The nearest town is Brits, located 34 km southwest of the scheme. The scheme has a total area of 12,219 hectares and an irrigation water allocation of 6,200 cubic meters per hectare per year. Table 3.3 presents the basic information about the Hartbeespoort irrigation scheme provided by the WUA's CEO.

The second phone conversation was held on September 27, 2019, with Mr. Andries Labuscagne, the CEO of the Sand-Vet irrigation scheme. The discussion focused on developing the questionnaire for the irrigation scheme. Table 3.3 presents the basic information about the Sand-Vet irrigation scheme provided by the WUA's CEO. The nearest town is Welkom, located 30 km northeast of the scheme. The scheme has a total area of 12 185 ha and an irrigation water allocation of 7,200 cubic meters per hectare per year.

The third phone conversation was held on October 7, 2019, with Mrs. Lizelle Beukes, the CEO of the Orange-Vaal WUA. The information she provided is presented in Table 3.3. According to her, the nearest town to the scheme is Douglas, located 18 km southeast. The scheme has a crop-growing area of 17 390 ha and an irrigation water allocation of 10,000 cubic meters per hectare per year.

Table 3. 3 General Information about the Irrigation Schemes is provided by the WUA's CEOs

Information	Selected irrigation schemes		
Water Users' Association	Sand-Vet	Hartbeespoort	Orange-Vaal
Closet town	Welkom	Brits	Douglas
Distance from town (km)	30	34	40
Direction from town	NE	SW	NE
Irrigated size (ha)	11385	21345	17 390
Irrigation water allocation (m^3/ha)	7 200	6 200	10 000

Table 3. 4 Illustration of the matrix table showing the crop, soil and irrigation combinations for the irrigation scheme.

Different crop types cultivated in the scheme	**Soil type 1**				**Soil type 2**				**Total area (ha) and percentage (%)**
	Irrigation type 1	**Irrigation type 2**	**Irrigation type 3**	**Irrigation type 4**	**Irrigation type 1**	**Irrigation type 2**	**Irrigation type 3**	**Irrigation type 4**	
Crop 1	-	-	-	-	-	-	-	-	-
Crop 2	-	-	-	-	-	-	-	-	-
Crop 3	-	-	-	-	-	-	-	-	-
Crop 4	-	-	-	-	-	-	-	-	-
Crop 5	-	-	-	-		-	-	-	-
Crop 6	-	-	-	-	-	-		-	-
Crop 7	-	-	-	-		-	-	-	-
Crop 8	-	-	-	-	-	-	-	-	-
Crop 9	-	-	-	-	-	-	-	-	-
Total area cultivated	-	-	-	-	-	-	-	-	-
Total area irrigated	-	-	-	-	-	-	-	-	-

Farmers from all three irrigation schemes provided prompt and accurate information about their irrigation systems, either through the questionnaire or through satellite map interpretations provided by the WUA management. The WUAs responded quickly and provided sufficient information to estimate crop water requirements using the SAPWAT4 program. A matrix table (shown in Table 3.4) was created to organize the information collected from the WUAs, including crop, soil, and irrigation combinations.

3.2.2 Filling missing Information/data

To fill in any missing information from the WUAs, a linkage table (Table 3.5) was created to provide guidance on common crop-soil and irrigation system practices in the scheme. The potential for double cropping, planting dates, and crops grown are largely influenced by market prices, local climate, and the types of crops that are well-suited to the area. In the three irrigation schemes, information about crop combinations and planting dates provided by the WUAs was used. If this information was not available, the generally accepted double-cropping patterns shown in Table 3.6 were used.

Table 3. 5 Linkages table to use as a guide for gap filling based on common farmers' practices in the scheme.

Irrigation systems	Usually associated with
- Centre pivot	- Field crops, sugar cane, and vegetables.
- Drip	- Orchards, vineyards, sometimes vegetables.
- Micro sprinklers and micro sprayers	- Orchards and vineyards
- Moveable sprinklers	- Sugar cane, pastures, and vegetables
- Flood irrigation	- Field crops
Soil texture	Usually not associated with
- Clay soil	- Potatoes and groundnuts
- Duplex soils	- Lucerne

Table 3. 6 Crops and follow-up crop combinations commonly found from WUA.

Crop	**Planting date**	**Following crop for double cropping**
- Wheat and barley	- (mid-June to mid-July)	Short grower maize (mid-December); dry beans (mid-December to mid-January); soya beans (mid-December); sunflower (mid-December, mid-January)
- Short grower maize	- (mid-October)	Dry beans (mid-January); soya beans (mid-January); sunflower (mid-December, mid-January)
- Summer Vegetables	- (mid- October)	Winter vegetables (mid-March) (mix of vegetables usually grown during winter)

3.3 Estimating irrigation requirement

To effectively manage water in an irrigation scheme, a WUA must know the water needed and how it will be distributed over time. This includes accounting for rainwater and the amount of water that can be added through irrigation. An irrigation specialist or farmer must also be aware of the system's efficiency in terms of water usage. The SAPWAT4 program can be used to determine the irrigation and water requirements of different crops. van Heerden and Walker (2016) identified three phases in categorizing irrigation areas: individual crop water requirements, irrigated area and sub-area per crop, and the entire irrigated field. To determine the irrigation water requirements of crops, the following information is needed:

- The types of crops grown, their planting dates, and growing seasons.
- Information about alternative crops that could be grown in the same area.
- Considering the farmer's performance and management strategy, the expected yield and production level.
- Production practices include land preparation after harvest, crop rotation, chemical weed control, pest and disease management, and water availability.
- The average area covered by individual crops and the cultivated and scheduled area.
- The weather station's location and general climatic conditions such as temperature, evapotranspiration, wind, rainfall, frost, etc.
- General soil conditions including type, texture, profile depth, compaction layers, and waterlogging.
- The type of irrigation system in use, its maintenance, aims and management level, and the preferred irrigation method for farmers.

3.3.1 Evapotranspiration and crop coefficient factor

The FAO Penman-Monteith equation for calculating the daily reference evapotranspiration (ET_o) is based on the specific assumption about crop height, the surface resistance, and the albedo within the area where the automatic weather station is situated (Allen et al., 1998). By using a reference crop ET, it is possible therefore to estimate in a physically realistic way the interaction between soil-plant systems and the atmosphere. In this study, the calculation of the ET_o was done through the climate data by the use of the FAO Penman-Monteith method Allen et al. (1998).

$$ETo = \frac{0.408\Delta(Rn-G)+\gamma(900/(T+273))u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \quad (3.1)$$

Where ET_o is the reference evapotranspiration (mm d^{-1}), Rn the net irradiance (MJ m^{-2} d^{-1}), G the soil heat flux density (MJ m^{-2} d^{-1}), T the mean daily air temperature (°C), u_2 the mean daily wind speed at 2 m height (m s^{-1}), e_s the saturation water vapour pressure (kPa), e_a the actual water vapour pressure (kPa), Δ the slope of the saturation water vapour pressure versus temperature relationship (kPa °C^{-1}), and the psychrometric constant ($\gamma \approx 66$ kPa °C^{-1}) (Allen *et al.* 1998). Thus, for the SAPWAT4, the ET_o values were determined using data from a nearby weather station. The crop evapotranspiration (ET_c) was then estimated by multiplying the ET_o values with the crop coefficient, as described by Allen et al. in 1998.

$$ET_c = ET_o x K_c \quad (3.2)$$

where ET_c, is measured in mm and the K_c is unit less crop coefficient value representing the ratio between ET_c and ET_o, as shown in equation 3.2. This ratio reflects the properties of plants in determining evapotranspiration. Based on this estimation monthly ET_c was obtained for different crops grown on those three selected irrigation schemes. Furthermore, K_c values can be subdivided into soil evaporation coefficient (K_e) and basal crop coefficient (K_{cb}) from the crop cover. As described in Smith (1992).

$$ET_c = ET_o(K_C + K_e)\text{; where, } K_c = (K_e + K_{cb}) \quad (3.3)$$

In the SAPWAT4 model, the K_{cb} value is derived from a table that lists typical growing period lengths and K_{cb} values for various crops. The K_e value, on the other hand, is determined using weather data, when the crop is under stress, as described in Allen et al. (1998):

$$ET_c = K_s x K_C x ET_o \quad (3.4)$$

Where K_s is a dimensionless transpiration reduction factor dependent on available soil and a range between 0 and 1.

3.3.2 Estimating Effective Rainfall (ERF)

Effective rainfall is calculated using the United States Department of Agriculture’s Soil Conservation Service (USDA-SCS) method, as Jensen et al. (1990) described in the SAPWAT4 model. This method, developed by the United States Department of Agriculture’s Soil Conservation Service, is also the default method for calculating effective rainfall in the SAPWAT4 model. The development of this method was based on water balance calculations using data from 22 weather stations over a period offor 50 years. In the context of the SAPWAT4 program, the monthly maximum evapotranspiration is limited to 75 mm, which is used in the calculation of effective rainfall as follows:

$$EffRF_m = ET_c(-0.001\frac{(Rain_m)^2}{ET_c} + 0.025\frac{(Rain_m)^2}{ET_c} + 0.0016 \text{ x } (Rain_m) + 0.6\frac{(Rain_m)^2}{ET_c} \quad (3.5)$$

where $EffRF_m$ represents the monthly effective rainfall, measured in mm/month, which is less than or equal to the actual monthly rainfall. ET_c is the monthly crop evapotranspiration, also measured in mm/month, with a maximum value of 75 mm. $Rain_m$ is the actual total monthly rainfall, measured in mm/month.

3.3.3 Soil water balance

The basis for calculating the crop irrigation requirements is the standard soil water balance equation described by Bennie et al. (1998):

$$\Delta SW = I + (P - R_o) - E_s - T + CR - DP \mp SF \tag{3.6}$$

The change in soil water (ΔSW) can also be expressed in terms of irrigation requirements (IRR_{req}):

$$IRR_{req} = ET_c - R_o + DP \mp \Delta SW \tag{3.7}$$

where ΔSW represents the change in soil water content, measured in mm. P and I stand for precipitation and irrigation, respectively. The losses are represented by DP, Ro, Es, and T, which stand for deep percolation (inflow from the water table), runoff, soil evaporation, and transpiration or water uptake by plants, respectively. SF and CR represent subsurface flow and capillary rise. Therefore, the SAPWAT model uses Equation 3.7 to calculate irrigation requirements in the following manner:

i) The basic irrigation requirements are calculated by determining the ET_c, from which the effective rainfall is then subtracted. Runoff and deep percolation are accounted for by selecting the appropriate levels of efficiency, as chosen by the user. During this process, changes in soil water content are not considered.
ii) Effective rainfall can also be excluded from this calculation.
iii) The SAPWAT management module, which allows for the comparison of different irrigation strategies, includes changes in soil water content in its calculations.

3.3.4 Irrigation management approaches

In this study, four scenarios were applied when using the SAPWAT4 program for the study areas. These scenarios are described below:

Scenario 1: Conventional, effective irrigation (CON)- This approach is based on extracting 70% of readily available soil water and replacing it with a design depth of irrigation system, such as 25 mm for centre pivot systems at their slowest cycle speed. In most soils, this results in not filling does not fill the profile to field capacity, leaving space in the soil profile for rainwater storage.

Scenario 2: Conservation soil preparation (CONS)- This functionality is built into SAPWAT4 version 3 (not yet ready for distribution) and applies to field crops with larger-sized seeds such as maize, beans, sunflower, wheat, barley, etc. Research papers suggest that between 35% and 50% stubble cover can be achieved through conservation soil preparation approaches and planting in the previous crop's stubble (van Heerden et al., 2008). This practice reduces water loss through soil surface evaporation when crop cover is less than the total. SAPWAT4 estimates that when applying this approach, a reduction of at least one irrigation cycle during the young stage of the crop can be expected when canopy cover is low. Anecdotal evidence from farmers who apply this approach confirms the SAPWAT4 estimates (van Heerden et al., 2008).

Scenario 3: Application of slight water-stress (STRESS)- This approach is similar to scenario 1, except that soil water extraction is extended to 100% of readily available soil water, placing the approach crops under a low level of water stress. This would reduce yield in more sensitive crops, especially during the non-rainy season.

In addition to the three primary irrigation strategies scenario, farmers may also employ alternative irrigation methods. These estimates would then be compared with the requirements of the three primary strategies to evaluate their effectiveness and efficiency.

The following approach was used to ascertain the benefits of adaptation scenarios compared to the conventional approach. Relative change values, expressed in percentiles, were utilized to measure the differences in irrigation water requirements.

- Relative change (%) for conservation adaptation scenario:

$$CONS(\%) = \frac{CON-CONS}{CON} X100 \quad (3.8)$$

- Relative change (%) for slight-water stress adaptation scenario:

$$STRESS(\%) = \frac{CON-STRESS}{CON} X100 \quad (3.9)$$

where CONS(%) and STRESS(%) represent the relative changes in percentile for conservation and slight-water stress adaptation scenarios, respectively and CON represents the conventional approach practiced by the WUA.

The JMP Pro 14 statistical software for Windows was used for all analyses (SAS Institute, Inc., North Carolina, USA, 2010). Data were analysed taking into account the various management scenarios of the effective rainfall, irrigation water requirement and total irrigation. Means were compared using least significant difference (LSD) test. Significance levels of $P \leq 0.05$ and $P \leq 0.001$ were used based on the variability associated with the type of estimations of irrigation water requirement.

3.3.5 Set-up of SAPWAT4 Program

The main program starts with the area setup, as shown in Figure 3.5a. In this section, the user can assign a new task name, which will be the name of the irrigation scheme (e.g., Sand-Vet, Hartbeespoort, or Orange-Vaal irrigation scheme). The user can also add WUA-sub and WMA information, depending on the information provided by the irrigation scheme. Additionally, the user can edit or add more details about the irrigation scheme by clicking the "Edit/Detail" button. In the "Farm/Quaternary Drainage Region; Weather Station" section (Figure 3.6a), the user can enter information about the irrigation scheme, such as the quaternary drainage region and the cultivated area, which is the total area cultivated and planted in the drainage region. Other required information includes the irrigated area, which is the same as the cultivated area (Figure 3.6b), as well as scheduled irrigation, irrigation quota, canal flow, and the number of farmers. The quaternary drainage region information is entered according to the information provided by the irrigation scheme CEO or the WUA.

In the "Field; System; Soil" section shown in Figure 3.6c, the user can enter information about the field (e.g., size), the irrigation system, and the type of soil (e.g., loam) based on data obtained from a survey. When selecting the soil or irrigation system, the data contained in the lookup tables will be displayed, making it easier for the user to enter information. If measured data about a specific field is not available, default values are used. When calculating the soil available water, SAPWAT4 uses the minimum soil depth and plant root development. The field section is then automatically renamed according to the combination of the irrigation system and soil (e.g., centre pivot on loam).

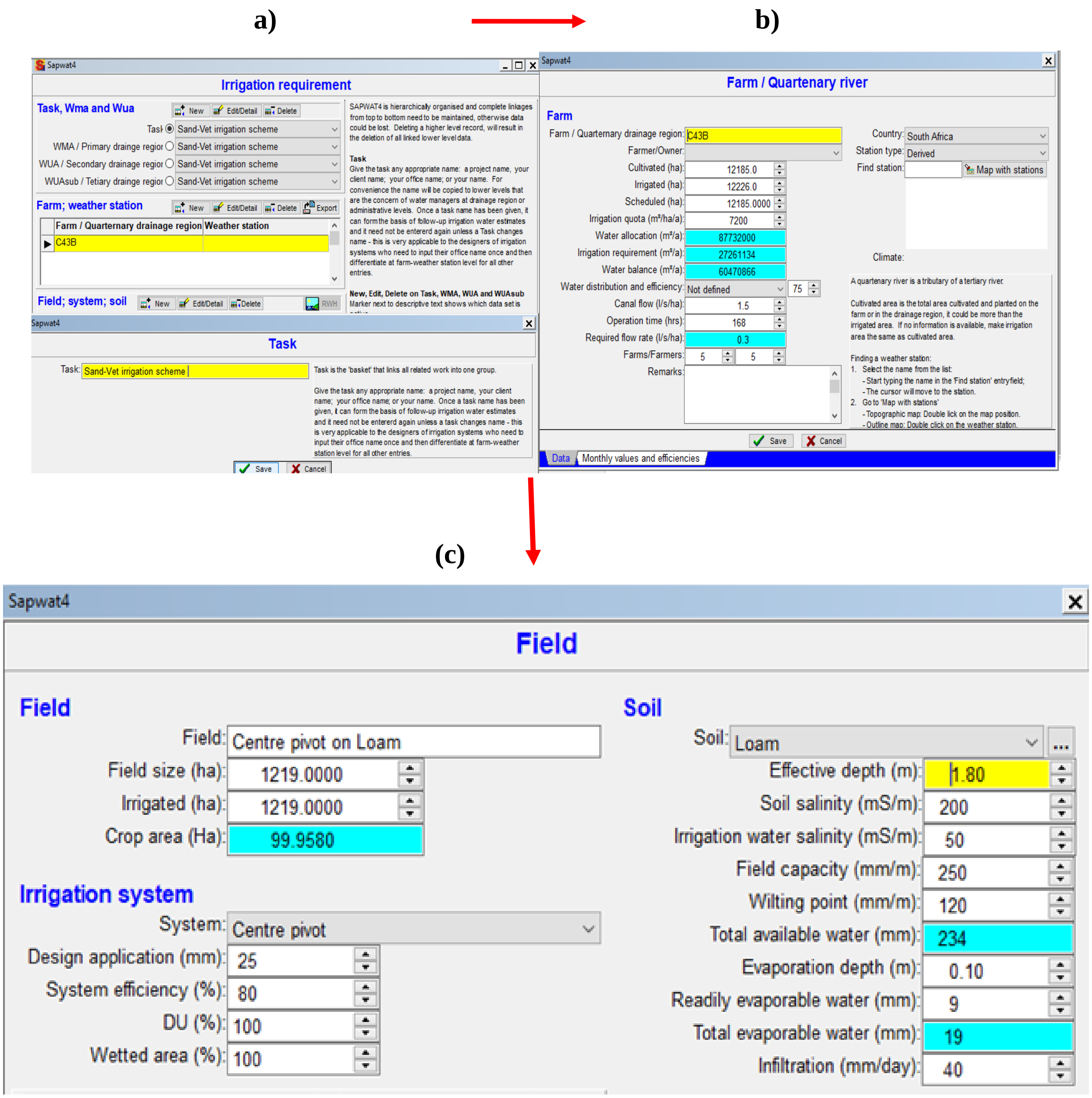
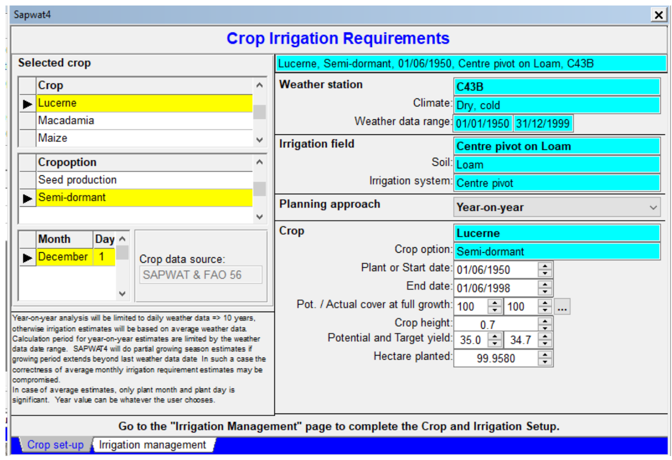


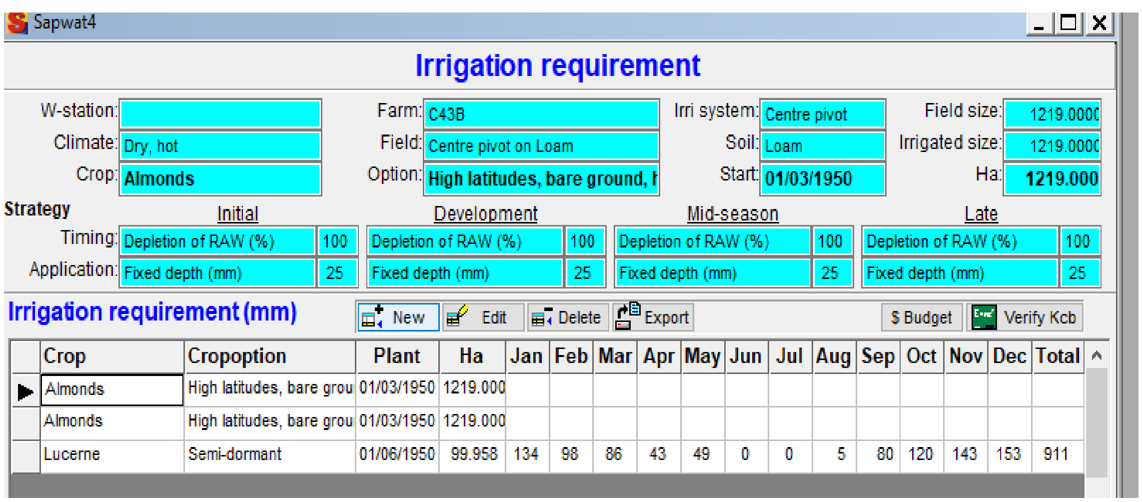
Figure 3. 6 Illustration of SAPWAT program: a) area set up b) Farm quaternary and Field set up.

The user then can navigate to the "Crop Setup and Irrigation Requirement" tab, as shown in Figure 3.6a. In this section, the user can estimate the irrigation requirements. When the user clicks on the "New" function in Figure 3.6a, Figure 3.7b will appear. The user can then select the type of crop and crop option from the database. The planting date's month and day can be selected and adjusted on the right side of the screen. If the target yield entered is lower than the potential yield, a water stress situation will be simulated, reducing the irrigation requirements so that the yield reduction approximates the target yield. The hectares planted and crop height are entered according to information collected from the CEO of the WUA.

a)



b)



c)

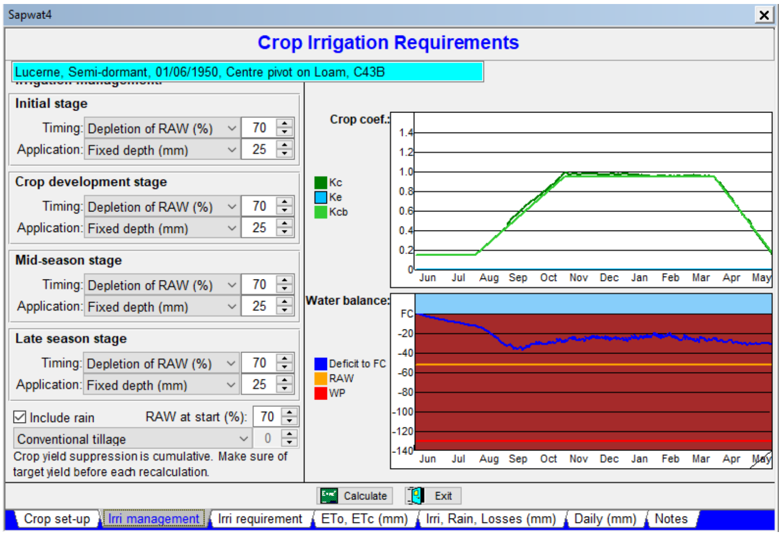


Figure 3. 7 Illustration of SAPWAT program: a) selection of crops and cropping patterns, b) crop irrigation requirement and c) outputs of estimated crop water requirement.

To complete the crop irrigation setup screen, the user must navigate to the “Irrigation Management” tab in Figure 3.6b. In this section, the initial stage, crop development stage, mid-season stage, and late-season stage can be adjusted. The timing, which is the depletion of readily available water percentage, and the fixed depth in millimetres (mm) can be adjusted according to the irrigation approaches described in section 3.7b. The user must always include rain and use a default value for RAW. The irrigation management scenarios applied in the model are shown in Figure 3.7c. Hence, to simulate the amount of irrigation requirement for different scenarios, for instance, for scenarios 1, 2, and 3 the following are applied:

- **For Scenario 1:** the timing for all the stages is adjusted to 70% and the fixed depth is set to 25 mm;
- **For scenario 2:** the timing for all the stages is still kept at 70% and the fixed depth is still set to 25 mm, but the conventional tillage is selected to be (>30% residue) from the drop-down arrow. This automatically brings in 50% of the previously planted crop as stubble cover to retain moisture in the soil; and
- **For scenario 3:** the timing for all the stages is adjusted to 100% and the fixed depth is set to 25 mm.

Crop yield suppression is cumulative, so the user must ensure that the target yield is accurate before each recalculation. When the “Calculate” button is clicked, the irrigation scheduling approach, soil water balances, and crop coefficient values are displayed graphically. This generates additional tabs for the reference evapotranspiration results (ET_o) and crop evapotranspiration (ET_c), as shown in Figure 3.7c.

3.3.6 Visitation of the irrigation scheme

After completing the irrigation water estimates and running the model, the results were sent to the CEOs of the relevant WUAs. They were then asked to arrange a meeting with the project team, WUA management members, local irrigation specialists, and farmers to discuss the results of the irrigation water estimates. Further visits to the irrigation schemes were conducted, and discussions with WUA management, farmers, and crop specialists took place. These discussions primarily focused on the following topics at a later stage:

- Comparing the crop water requirements estimated by the SAPWAT4 model with their experience.
- Demonstrating how the SAPWAT4 model can be used efficiently by knowing the correct allocation of irrigation water for maize and other crops, and how it can be used for irrigation scheduling.
- Learning about the different scheduling services available in the area and why they are used.
- Understanding the reasons why farmers do or do not apply conservation tillage.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Overview of climatic conditions

The average monthly reference evapotranspiration (ET_o) at the Sand-Vet irrigation scheme varies from 5.9 mm d^{-1} in mid-summer (December) to 2.2 mm d^{-1} in mid-winter (June), with a monthly mean ET_o of 4.1 mm d^{-1} (Figure 4.1a). Most rain occurred during summer and less in winter out of the total average of 54 rain events (Appendix Ia). The average annual precipitation was 518 mm, with the rainy season covering October to April. High relative humidity was combined with high temperatures and therefore higher ETo values during this wet period. In winter frost is most likely to occur and, the low relative humidity is combined with low temperatures and therefore there are possibilities of lower ET_o

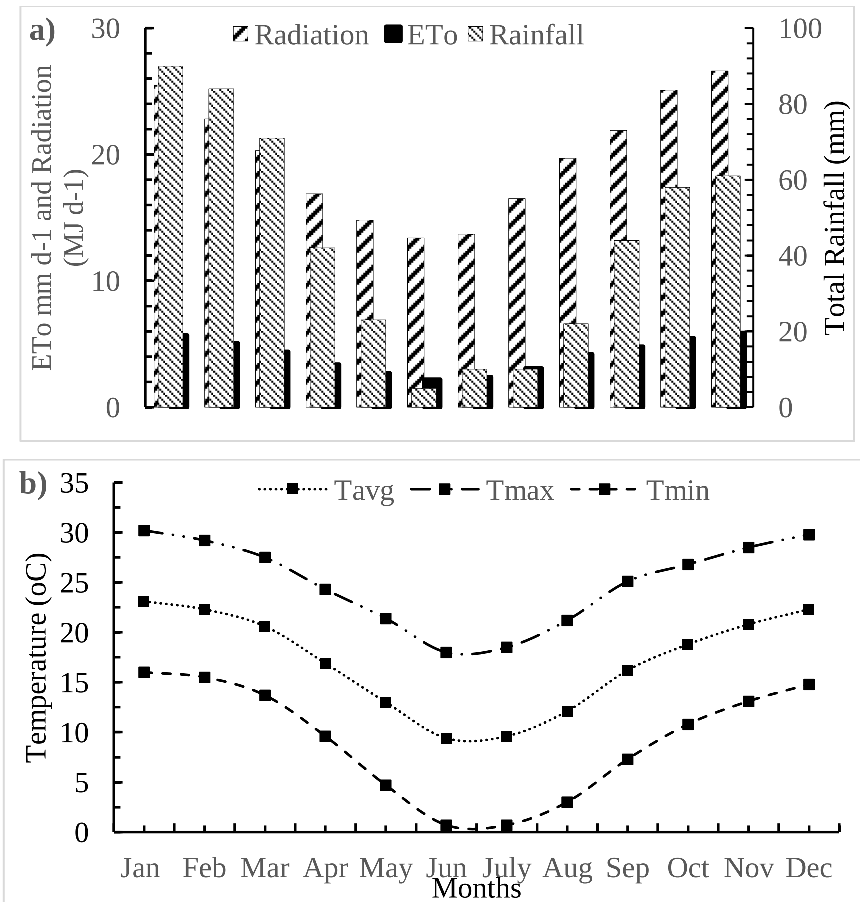


Figure 4.1 Long-term (1950-1999) average a) radiation, rainfall, and reference evapotranspiration (ET_o) and b) maximum and minimum temperature for the Sand-Vet irrigation scheme.

Hartbeespoort irrigation scheme is located in a semi-arid, hot climate zone of the North West province. Figure 4.2a and Appendix Ib give a summary of the climate and the reference evapotranspiration which is used for estimating irrigation requirements. The lowest average monthly temperature during winter is 12.7°C, while the highest average monthly temperature for summer is 25.0°C in January, with an average temperature of 19.8°C and the area is prone to light frost in winter (Figure 4.2b). The average monthly evapotranspiration regression (ET_o) expected at the scheme varies from a maximum of 6.0 mm d^{-1} in summer and a minimum of 2.7 mm d^{-1} during winter, with an average daily ET_o of 4.5 mm d^{-1}.

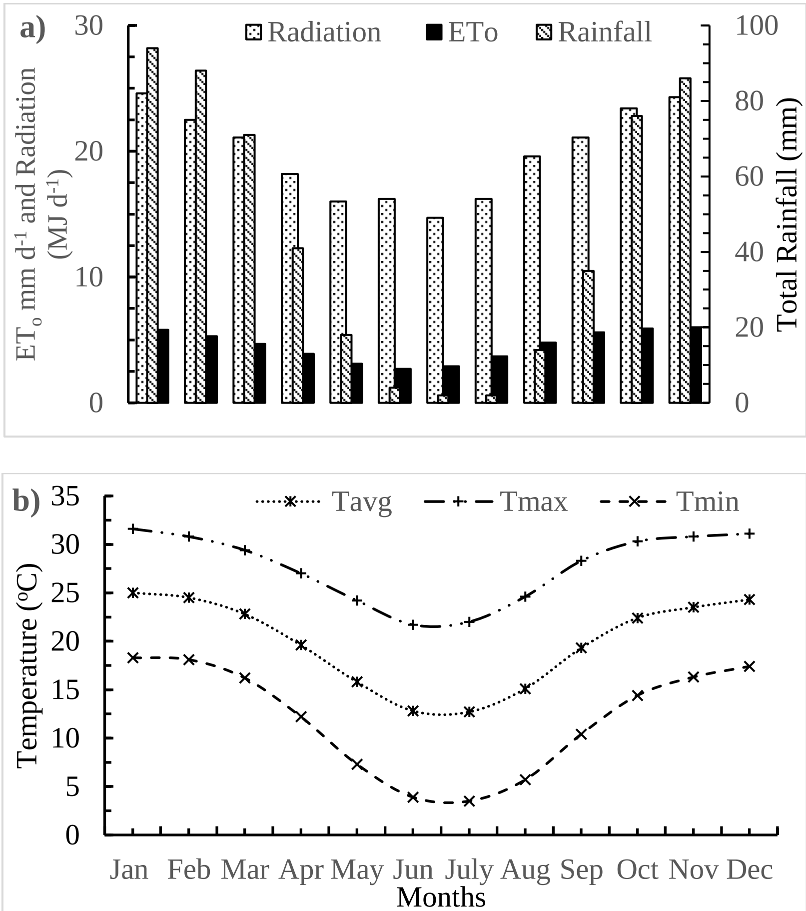


Figure 4.2 Long-term (1950-1999) average a) radiation, rainfall, and evapotranspiration regression (ET_o) and b) maximum and minimum temperature for the Hartbeespoort irrigation scheme.

There are 48 average annual rainfall events, and the rainfall season stretches from November to March. The average annual precipitation is 530 mm with the highest average monthly rainfall occurring in January (94 mm) and the lowest in July and August (2 mm). The high relative humidity occurring during summer coincides with high temperatures and high ET_o values. There is a drop in relative humidity when temperatures are low and when there is less rainfall.

As identified by the DWS, the climate of the Orange-Vaal irrigation scheme is classified as arid-hot. As per Figure 4.3b and Appendix Ic, the average monthly temperature ranges from a low of 10.7℃ in July to a high of 25.9℃ in January, with an overall average temperature of 18.7℃. The area is also susceptible to frost, which typically occurs from mid-May to the end of August. According to Figure 4.3a and Appendix Ic, the expected average monthly reference evapotranspiration (ET_o) at the scheme varies, with a maximum of 6.8 mm d^{-1} in summer and a minimum of 2.4 mm d^{-1} in winter. The average ET_o is 4.6 mm d^{-1}. Rainfall occurs from January to May and then again from October to December, resulting in 28 annual rain events. The average annual precipitation is 288 mm. The highest average monthly rainfall occurs in March (63 mm), while the lowest is in July (< 5 mm).

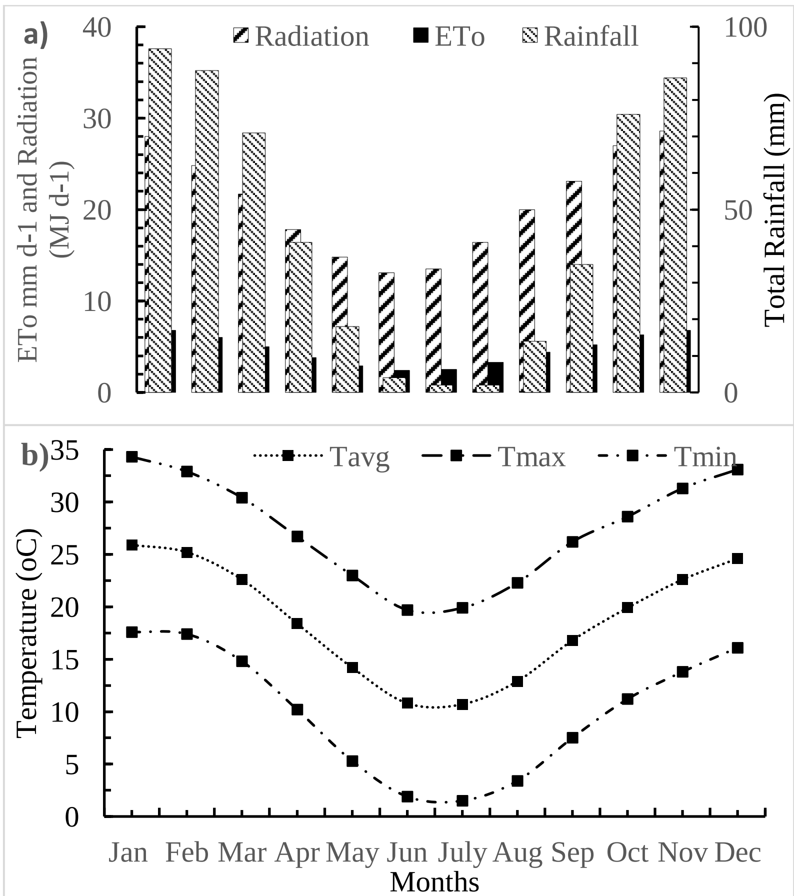


Figure 4.3 Long-term (1950-1999) average a) radiation, rainfall, and reference evapotranspiration (ET_o) and b) maximum and minimum temperature for the Orange-Vaal irrigation scheme.

4.2 Matrix of crop-soil-irrigation interactions

4.2.1 Sand-Vet irrigation scheme

As indicated in Table 4.1 the Sand-Vet irrigation scheme has a planted area of 11 835 ha without an inclusion of fallow land while the scheduled area is 12 184 ha. Double cropping is common in most irrigation areas where water availability, climate and crop choice allow for it. According to the information provided by the questionnaire (Appendix II), double cropping is practiced for all crops listed in Table 4.1, apart from pecan nuts as this is a perennial crop. The scheme's most common crop grown under irrigation is wheat, accounting for 41% of the total cropped area and is planted during the winter season. This is followed by maize, which accounts for 37% of the total cropped area and is planted at the spring season's end. Pecan nuts, which are planted towards the end of the winter season, account for 5% of the total crop area. The least dominant crops are soybeans and groundnuts, together accounting for 4% of the total crop area and planted during the spring season, followed by potatoes (2%) and white beans (2%), and planted during the summer season, and lucerne (2%), planted during the winter season.

The most dominant soil type in the scheme is sandy loam, covering 8 267 ha (70% of the total area), followed by sand, covering 2 395 ha (20% of the total area) (Table 4.2). Loam soil is the least dominant, covering only 1 173 ha. In terms of irrigation systems, centre pivot irrigation is the most dominant, covering 10 976 ha (93% of the area being irrigated). Drip irrigation covers only 730 ha (6% of the area), while linear and sprinkler dragline systems are the least dominant, covering only 40 and 89 ha (0.3% and 0.8% of the area), this gives a total irrigated area of 11 835 ha.

Table 4. 1 Soil types and irrigation systems found at Sand-Vet irrigation scheme.

Description	Area covered (ha)	Percentage (%)
Soil type/texture		
- Sand	2395	20
- Sandy Loam	8267	70
- Loam	1173	10
Irrigation system		
- Drip	730	6
- Centre pivot	10976	93
- Linear	40	0.3
- Sprinkler dragline	89	0.7

Table 4. 2 Crop, soil and irrigation system combination for the Sand-Vet irrigation scheme.

Different crop types cultivated in the scheme	Sand (2395 ha)				Sandy loam (8267 ha)				Loam (1173 ha)				Total area (ha) and percentage (%)
	Drip	**Centre pivot**	**Linear**	**Sprinkler dragline**	**Drip**	**Centre pivot**	**Linear**	**Sprinkler dragline**	**Drip**	**Centre pivot**	**Linear**	**Sprinkler dragline**	
Lucerne	-	-	-	-	-	200	-	-	-	100	-	-	300 (2%)
Maize	-	1000	-	-	-	2500	-	-	-	1000	-	-	4500 (37%)
Wheat	-	1000	-	-	-	4000	-	-	-	-	-	-	5000 (41%)
Soybeans	-	200	-	-	-	250	-	-	-	-	-	-	450 (4%)
Groundnuts	-	-	49	-	-	451	-	-	-	-	-	-	500 (4%)
Pecan nuts	146	-	-	-	421	-	-	-	73	-	-	-	640 (5%)
Potatoes	-	-	-	-		170	40	40		-	-	-	250 (2%)
White beans	-	-	-	-	90	105	-	-	-	-	-	-	195 (2%)
Fallow	-	-	-	49	-	-	131	131	-	-	24	24	359
Total planted area	**146**	**2200**	**49**	**49**	**511**	**7676**	**171**	**171**	**73**	**1100**	**24**	**24**	**11835**
Total scheduled area	**146**	**2193**	**49**	**49**	**511**	**7676**	**171**	**171**	**73**	**1097**	**24**	**24**	**12184**

4.2.2 Hartbeespoort irrigation scheme

The total planted area at Hartbeespoort is 21 345 ha and has a scheduled area of 12 239 ha, (Tables 4.3 and 4.4). Double cropping as is practiced for most crops except for citrus, tobacco, and grapes . The most cultivated crops in the scheme area are summer vegetables (5 760 ha), winter vegetables (4 588 ha), wheat (4 240 ha) and soybeans (3 975 ha). The winter and summer vegetables under sprinkler movable irrigation planted on clay soil, have the highest area at Hartbeespoort irrigation scheme. The least cultivated crops in the scheme are citrus, grapes, maize, sugar beans, oats, tobacco, barley and lucerne.

Table 4. 3 Soil and irrigation information found at Hartbeespoort irrigation scheme.

Description	Area covered (ha)	Percentage (%)
Soil type/texture		
- Sandy loam	2223	10
- Loam	1577	7.4
- Silt loam	933	4.4
- Clay	16612	78
Irrigation system		
- Drip	1260	6
- Centre pivot	7918	37
- Sprinkler fixed	955	5
- Sprinkler movable	10725	50
- Flood basin	35	0.1
- Micro sprinkler	5	0.0
- Micro spray	155	0.6
- Flood furrow	65	0.3
- Flood boarder	227	1

In this area, four soil types are identified, as shown in Table 4.3. The least dominant types of soil are sandy loam, loam and silt loam, these soils cover 2 223 ha (10%), 1 577 ha (7.4%) and 933 ha (4.4%) of the area respectively. The most dominant type of soil is clay which cover 16 612 ha (78%) of the area. A movable sprinkler irrigation system is the most dominant irrigation system covering 10 725 ha (50%) of the planted area in the irrigation scheme, followed by centre pivot irrigation system with 7 918 ha (37%). The least dominant irrigation systems are drip, fixed sprinkler, flood basin, micro sprinkler, micro spray, flood furrow, and flood border irrigation systems.

Table 4. 4 Crop, soil and irrigation combination for the Hartbeespoort.

Different crop types cultivated in the scheme	Sandy loam (2223 ha)			Loam (1577 ha)				Silt loam (933 ha)					Clay (16612 ha)									Total area (ha) and percentage (%)
	Drip	**Centre pivot**	**Sprinkler fixed**	**Sprikler movable**	**Drip**	**Centre pivot**	**Sprinkler movable**	**Drip**	**Centre pivot**	**Sprinkler fixed**	**Sprinkler movable**	**Flood basin**	**Drip**	**Micro sprinkler**	**Micro spray**	**Centre pivot**	**Sprinkler fixed**	**Sprinkler movable**	**Flood basin**	**Flood furrow**	**Flood border**	
Lucerne	-	35	-	-	-	-	-	-	-	-	47	-	-	-	-	65	-	861	-	-	222	1230 (6%)
Wheat	-	630	-	445	-	225	-	-	150	-	-	-	-	-	-	2070	-	720	-	-	-	4240 (20%)
Veg winter	70	165	135	195	12	10	20	35	20	30	193	-	370	-	20	495	305	2513	-	-	-	4588 (21%)
Veg summer	70	195	135	215	12	55	25	35	35	30	185	-	365	-	20	535	320	3463	-	65	-	5760 (27%)
Citrus	70	-	-	-	-	-	-	-	-	-	-	15	143	5	35	-	-	20	20	-	-	308 (1%)
Grapes	60	-	-	-	3	-	-	-	-	-	-	-	15	-	80	-	-	-	-	-	-	158 (1%)
Soya beans	-	575	-	50	-	210	-	-	135	-	-	-	-	-	-	2155	-	850	-	-	-	3975 (19%)
Maize CHU	-	15	-	15	-	25	-	-	-	-	-	-	-	-	-	10	-	245	-	-	-	310 (1%)
Sugar beans	-	-	-	-	-	-	-	-	-	-	-	-	-	-		7	-	37	-	-	-	44 (0.2%)
Sugar beans	-	8	-	-	-	-	-	-	-	-	-	-	-	-	-	8	-	38	-	-	-	54 (0.3%)
Oats	-	15	-	10	-	-	25	--	-	-	23	-	-	-	-	25	-	245	-	-	5	348 (2 %)
Tobacco	-	45	-	25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	70 (0.3%)
Barley	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	260	-	-	-	260 (1%)
Total area planted	**270**	**1683**	**270**	**955**	**27**	**525**	**70**	**70**	**340**	**60**	**448**	**15**	**893**	**5**	**155**	**5370**	**625**	**9252**	**20**	**65**	**227**	**21345**
Total area scheduled	**225**	**820**	**135**	**995**		**295**	**70**	**35**	**170**	**30**	**203**	**15**	**655**	**5**	**135**	**2880**	**320**	**4783**	**20**	**65**	**383**	**12239**

4.2.3 Orange-Vaal irrigation scheme

Tables 4.5 and 4.6 show that there is only sandy loam soil in this irrigation scheme, and it covers 100% of the area There are only two types of irrigation systems, centre pivot (96% of the area), and the drip irrigation (4%). According to Table 4.6, the total irrigation area at Orange-Vaal is 17 390 ha. Double cropping is practiced for most crops except for cotton, pecan nuts, and groundnuts (Appendix II). In Table 4.6, the most common irrigated crops in the scheme area are lucerne (5346 ha), wheat (4911 ha), maize (3761 ha), and cotton (1188 ha), while the least irrigated crops are onions (123 ha), groundnuts (423 ha), sunflower (495 ha) and potatoes (528 ha).

Table 4. 5 Soil and irrigation type information found at Orange-Vaal irrigation scheme.

Description	Area covered (ha)	Percentage (%)
Soil type/texture		
- Sandy loam	17390	100
Irrigation system		
- Drip	615	4
- Centre pivot	16775	96

Table 4. 6 Crop soil and irrigation system combination for Orange-Vaal irrigation scheme.

Crop	Sandy loam soil		Total (ha)
	Centre pivot (ha)	Drip (ha)	
Cotton	1188	-	1 188
Groundnuts	423	-	423
Lucerne	5346	-	5 346
Maize	3761	-	3 761
Onions	123	-	123
Pecan nuts	-	615	615
Potatoes	528	-	528
Sunflower	495	-	495
Wheat	4911	-	4 911
Total area (ha)	**16775**	**615**	**17390**
Total scheduled area	**16805**	**616**	**17421**

4.3 Irrigation water requirement: *Sand-Vet irrigation scheme*

4.3.1 Centre Pivot irrigation system

In a conventional farming approach under a centre pivot irrigation system, different crops require different different water amounts, including irrigation and effective rainfall (Table 4.7a). For instance, maize grown on sandy soil over an area of 1000 ha requires 755 mm of water, which is more than the water required for the same crop grown on loam (739 mm) and sandy loam (731 mm) soils. Lucerne, on the other hand, has the highest water requirement among the crops mentioned. It needs 1 695 mm of water for sandy loam soil (over 200 ha) and 1 692 mm for loam soil (over 100 ha). When it comes to wheat grown under the centre pivot system on sandy loam soil, it has the largest cropping area of 4000 ha and requires 471 mm of irrigation water. This is less by 22 mm compared to wheat grown on sandy soil. In the centre pivot irrigation system, potatoes and soybeans planted in sandy loam require 412 mm and 516 mm of irrigation, respectively. Overall, in a total area of 10 976 ha planted using the conventional approach, the irrigation required is 7 671 mm. Of this total irrigation amount, lucerne planted in loam and sandy loam soils consumes the most water at 2 609 mm (34%), followed by maize, which requires 1 553 mm (20%).

In the conservation scenario, different crops require varying amounts of water with less amount compared to a conventional approach except for lucerne. For instance, maize grown on sandy soil over an area of 1 000 ha requires 707 mm of irrigated water which is 6% less than the conventional approach. This is more than the water required for the same crop grown on soils of loam (484 mm over 1 000 ha) and sandy loam (478 mm over 2 500 ha). However, lucerne, under the centre pivot irrigation system, has the same irrigation water requirements as the conventional approach for loam and sandy loam soils (Table 4.7a). Wheat grown on sand and sandy loam soil has the largest cropping pattern of 1000 ha and 4000 ha respectively under the centre pivot system and requires 426 and 410 mm of irrigated water. The total crop water requirement for wheat is dominated by irrigation with rainfall contributing only 15-17%, meaning that a significant amount of the crop’s water is received through irrigation.

Similarly, a higher percentage of rainfall contribution is needed for maize, but irrigation still plays a significant role, contributing to 70% of the crop’s growth. Among all crops, lucerne requires the most irrigation at 2 609 mm, followed by maize and soybean at 1 471 mm and 971 mm respectively. As shown in Table 4.7a for the conservation scenario other crops in the scheme require a range of irrigation water from 478 mm to 298 mm, with beans needing the least amount. Despite this, the total crop water requirement for sandy soil remains higher than that for loam soil in a conservation approach.

In the slight water-stress scenario, all crops' total irrigation water requirement is estimated to be 6 879 mm. This irrigation water requirement is distributed among different crops: lucerne requires 36%, maize requires 20%, and soybean requires 14%. However, the contribution of effective rainfall is higher in this scenario compared to both conventional and conservation approaches (Table 4.7a). When considering specific crops and soil types, maize planted in loam soil and soybean and potatoes planted in sandy loam soil require less irrigation water compared to the conservation scenario (Table 4.7a). In general, under a pivot irrigation system, the water-stress scenario requires less irrigation water and makes greater use of effective rainfall than the conservation scenario. This implies that the water-stress scenario is more efficient in terms of water usage. The variations of effective rainfall values for both scenarios are due to the differences in the reduction evapotranspiration of the management practices.

Table 4. 7 Crops cultivated in Sand-Vet WUA: area planted, cultivar option, start planting date, and irrigation requirements under a) Centre Pivot b) Drip, and c) Linear/Sprinkler irrigations for conventional approach and conservation/water-stress scenarios.

Crop type	Cultivar option	Soil type	Planting date Day/month	Cultivate area (ha)	**Conventional Approach**			**Conservation Scenario**			**Water Stress Scenario**		
					Eff RF (mm)	IRR (mm)	Total (mm)	Eff RF (mm)	IRR (mm)	Total (mm)	Eff RF (mm)	IRR (mm)	Total (mm)
a) Pivot Centre Irrigation System													
Lucerne	Semi-dormant	Loam	01/06	100	394	1298	1692	394	1298	1692	431	1235	1666
Maize	Medium growers	Loam	15/10	1000	231	508	739	218	484	702	247	400	647
Maize	Medium growers	Sand	15/10	1000	207	548	755	198	509	707	226	497	723
Soybeans	Medium growers	Sand	15/10	200	177	596	773	167	510	677	203	497	700
Wheat	Spring types	Sand	15/06	1000	77	493	570	75	426	501	86	423	509
Beans dry	Medium growers	Sandy loam	01/01	105	187	345	532	164	298	462	201	297	498
Groundnut	Standard	Sandy loam	15/10	451	255	676	931	235	574	809	286	566	852
Lucerne	Semi-dormant	Sandy loam	01/06	200	384	1311	1695	384	1311	1695	423	1262	1685
Maize	Medium growers	Sandy loam	15/10	2500	234	497	731	224	478	702	247	478	725
Potatoes	Medium variety	Sandy loam	01/11	170	154	412	566	154	412	566	173	350	523
Soybeans	Medium growers	Sandy loam	15/10	250	220	516	736	203	461	664	236	460	696
Wheat	Spring types	Sandy loam	15/06	4000	85	471	556	88	410	498	97	414	511
Total				**10976**	**2605**	**7671**	**10276**	**2504**	**7171**	**9675**	**2856**	**6879**	**9735**
b) Drip Irrigation System													
Pecan	WRC Cullinan	Loam	01/08	73	417	774	1191	417	774	1191	446	728	1174
Pecan	WRC Cullinan	Sand	01/08	146	374	849	1223	342	864	1206	388	799	1187
Beans dry	Medium growers	Sandy loam	01/01	90	177	280	457	160	252	412	195	247	442
Pecan	WRC Cullinan	Sandy loam	01/08	421	424	801	1225	412	780	1192	442	748	1190
Total				**730**	**1392**	**2704**	**4096**	**1331**	**2670**	**4001**	**1471**	**2522**	**3993**
c) Linear Irrigation System													
Groundnut	Standard	Sand	15/10	49	197	833	1030	184	692	876	184	692	876
Potatoes	Medium variety	Sandy loam	01/11	80	313	822	1135	311	821	1132	345	703	1048
Total				**129**	**510**	**1655**	**2165**	**495**	**1513**	**2008**	**529**	**1395**	**1924**

NB: Eff RF, Irr and Total represent the effective rainfall, Irrigation water requirement and Total water irrigation requirement, respectively.

4.3.2 Drip irrigation system

Under the conventional farming method, pecan nuts grown on sandy loam soil are the primary crop when using drip irrigation (Table 4.7b). This crop covers an area of 421 hectares and requires a total of 1 225 mm of water. This water requirement is higher than that of pecan nuts grown on sand (146 ha) and loam soil (73 ha), which require 1 223 mm and 1 191 mm of irrigation water, respectively. On the other hand, beans, which have the smallest cultivation area of 90 ha, require a total of 457 mm of water. Interestingly, 39% of this water requirement is met by rainfall. This highlights the significant role that natural precipitation plays in supporting crop growth, even under conventional farming practices.

In the conservation scenario (refer to Table 4.7b), pecan nuts emerge as the most prevalent crop, with a cultivation area of 640 ha across all soil types in the scheme under the drip irrigation system. The total water requirement for pecan nuts is 3 589 mm, while beans require 412 mm. interestingly, these figures are slightly lower than those observed under conventional farming practices. However, it is important to note that these crops heavily depend on irrigation. Out of the total water requirement, only in total 1 171 mm for pecan nuts and 160 mm for beans are supplied by effective rainfall. This underscores the critical role of irrigation in supporting crop growth in the conservation scenario.

In the slight water-stress scenario at Sand-Vet, two crops, pecan nuts and beans, are grown under drip irrigation. Pecan nuts are the dominant crop, with a cultivation area of 640 hectares and an irrigation water requirement of 2 275 mm. On the other hand, beans are the least dominant crop, with a cultivation area of 90 ha and an irrigation water requirement of 247 mm. In this scenario, effective rainfall contributes (37%) a significant amount and is higher than the conservation scenario. However, as planted during the dry season of the year, irrigation plays a significant role in this scenario, contributing an estimated 63% of the total water requirement of 3 993 mm for these crops (Table 4.7b).

4.3.3 Linear irrigation system

Groundnuts and potatoes are the only crops cultivated under linear and sprinkler irrigation systems in the scheme, with cultivation areas of 49 hectares and 80 hectares, respectively, as shown in

(Table 4.7c). Under conventional farming practices, groundnut production requires a total of 1 030 mm of water, while potato cultivation requires 1 135 mm. For a cultivation area of 49 hectares, groundnuts require 876 mm of water, with effective rainfall contributing to 21% of this amount for both conservation and slight water stress approaches. In the conservation approach, all crops under both irrigation systems rely primarily on irrigated water. Only 25% of the total water requirement of 2 008 mm is met by effective rainfall.

As indicated in Table 4.7c, for a cultivation area of 80 ha, potatoes grown under linear or sprinkler irrigation systems require 1 048 mm of water, with effective rainfall contributing to 33% of this amount. In contrast, the water requirement for groundnuts grown over an area of 49 hectares is slightly higher than that of potatoes when using the same irrigation systems. In the water-stress scenario, both crops under both irrigation systems predominantly rely on irrigated water. Only 31% of the total water requirement of 495 mm is met by effective rainfall. However, both scenarios show similar effective rainfall and irrigation amount requirements. This highlights the critical role of irrigation in supporting crop growth under both conditions.

Figure 4.4 presents the relative value in irrigation requirements for the conservation (CONS) and slight water-stress (STRESS) scenarios compared to the conventional approach, under three different irrigation systems: centre pivot, drip, and linear. For the conservation approach, CONS, the linear and centre pivot irrigation systems show similar results, while the drip system requires almost half the relative change for irrigation. However, when considering effective rainfall, the drip system shows higher values compared to the other two systems. In the water-stress scenario, STRESS, the linear system requires about 15% for irrigation requirements and 11% for the total, which is significantly higher than the less than 11% and 6% required by the drip and centre pivot systems for both irrigation and total amount. However, all systems show a decrease in percentage for the stress approach, with the centre pivot system showing the largest drop of about 11%, while the drip and linear systems show decreases of about 6% and 1% respectively.

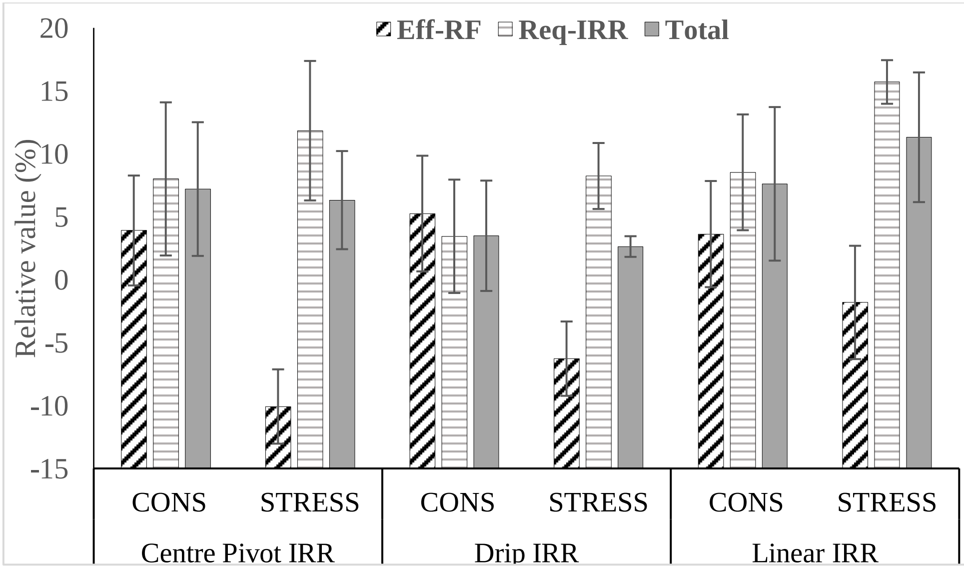


Figure 4.4 Relative values (in %) of irrigation requirement for conservation (CONS) and water-stress (STRESS) scenarios to conventional approach under centre pivot, drip and linear irrigation systems.

The statistical analysis of different irrigation types (centre pivot, drip, and linear), as presented in Appendix III, reveals that there is no significant difference between the irrigation types in terms of the estimated effective rainfall. A highly significant difference ($P < 0.0001$) of relative values is observed between the two management practices, CONS) and slight water stress (STRESS). The improved management practices also show a significant difference in irrigation water requirements, with the highest relative value of 11.31% observed for water-stress management (STRESS). The interaction for both irrigation requirements and the total irrigation amount also reveals a significant difference between the treatments, with the highest relative values of 15.7% for the conservation approach (CONS). The lowest relative values of 2.71% and 3.48% were observed for the conservation approach under drip irrigation, for irrigation water requirement and the total amount of irrigation respectively at a p-value of < 0.05. These findings highlight the impact of different irrigation types and water management practices on effective rainfall and irrigation requirements.

4.4 Irrigation water requirement: *Hartbeespoort irrigation scheme*

4.4.1 Centre Pivot irrigation system - Clay/loam soils

The SAPWAT4 estimates for the conventional irrigation method using a centre pivot irrigation system are presented in Table 4.8a for both clay and loam soils. For clay soil, the cropping pattern spans 5 370 ha, with soybeans having the largest share. The total water requirement for these crops is 6 728 mm out of a total of 9 674 mm. However, only 32% of this water comes from effective rainfall, indicating that irrigation is the primary source of water for these crops. On the other hand, loam soil covers a smaller area of 525 hectares and requires a total of 2 946 mm of water. Out of this, only 976 mm is estimated to come from effective rainfall, with the remainder being supplied through irrigation. However, by using the conservation approach (Table 4.8a), there is a significant change in the total water requirement for crop growth and development. For clay soil, the crops require 6 371 mm of water out of a total of 9184 mm. Only 31% of this water is estimated to come from effective rainfall, indicating that irrigation remains the primary source of water for these crops. For loam soil, the total water requirement is 2 813 mm. From this total, it is estimated that only 913 mm is derived from effective rainfall, with irrigation providing the remaining balance. As soybeans have the largest share of 2 365 ha and beans have the smallest share of 15 ha, under the water-stress scenario, the total water requirement for crop growth and development under clay soil is less than that of the conservation and conventional approaches. The crops under clay require 6 040 mm of water out of a total of 8 740 mm. interestingly, 38% of this water is estimated to come from effective rainfall, which is a higher percentage compared to the other approaches. For loam soil, the total water requirement is 2 698 mm. Out of this, only 1 061 mm is estimated to come from effective rainfall, which is slightly higher than the estimates for the conservation approach.

4.4.2 Centre Pivot Irrigation System - Sandy loam/Silt loam soils

Table 4.8b provides the SAPWAT4 estimates for the conventional irrigation method using a centre pivot irrigation system for sandy loam and silt loam soils. For sandy loam soil, the cropping pattern spans 1 683 ha, with wheat having the largest share. The total water requirement for these crops is 6 404 mm out of a total of 9 001 mm. However, only 31% of this water comes from effective rainfall, indicating that irrigation is the source of water for these crops. Besides, silt loam soil covers a smaller area of 340 ha and requires a total of 2 597 mm of water. Out of this, only 1 805 mm is estimated to come from irrigation, with the remainder being supplied through effective rainfall. For the conservation approach (Table 4.8b), in sandy loam soil, the crops require 6 098 mm of water out of a total of 8 535 mm. However, only 31% of this water is estimated to come from effective rainfall, indicating that irrigation is the primary source of water for these crops.

Crops grown on silt loam soil require a total of 2 437 mm of water. Out of this, only 752 mm is estimated to come from effective rainfall. It is worth noting that these total amounts of crop water for both sandy loam and silt loam are slightly less compared to the conventional farming approach. Under the water-stress scenario for sandy loam soil (Table 4.8b), the crops require 5 850 mm of water out of a total of 8 174 mm. interestingly, 37% of this water is estimated to come from effective rainfall, indicating a higher contribution from rainfall compared to the other approaches. While crops grown on silt loam soil require a total of 2 324 mm of water and only 597 mm is estimated to come from effective rainfall. It’s worth noting that these total amounts of crop water for both sandy loam and silt loam are slightly less compared to the conventional and conservation farming approaches, suggesting that water stress conditions may lead to more efficient use of rainfall

Table 4. 8 Crops cultivated in Hartbeespoort WUA: area planted, cultivar option, start planting date, and irrigation requirements under a centre pivot irrigation system a) Clay and Loam soils, and b) Sandy loam Silt loam for conventional approach and conservation/water-stress scenarios.

Crop type	Cultivar option	Soil type	Planting date Day/mon	Cultivate area (ha)	Conventional Approach			Conservation Scenario			Water Stress Scenario		
					Eff RF (mm)	IRR (mm)	Total (mm)	Eff RF (mm)	IRR (mm)	Total (mm)	Eff RF (mm)	IRR (mm)	Total (mm)
a) Centre Pivot Irrigation System (Clay and Loam soils)													
Beans	Medium growers	Clay	15/01	7	261	399	560	161	303	464	223	291	514
Beans	Medium growers	Clay	15/10	8	260	374	634	260	374	634	285	285	570
Lucerne	Semi-dormant	Clay	01/06	65	473	1314	1787	473	1314	1787	531	1196	1727
Maize	Shorter growers	Clay	15/12	10	212	220	432	186	194	380	219	162	381
Oats	Spring types	Clay	15/06	25	100	508	608	100	508	608	104	392	496
Soybeans	Medium growers	Clay	15/12	2155	266	395	661	222	317	539	292	295	587
Vegetables	Winter mix	Clay	15/03	495	76	509	585	76	509	585	82	443	525
Vegetables	Summer mix	Clay	15/10	535	377	473	850	377	473	850	415	336	751
Wheat	Spring types	Clay	15/06	2070	76	535	611	77	447	524	83	406	489
Maize	Shorter grower	Loam	15/12	25	207	213	420	183	197	380	214	162	376
Soybeans	Medium	Loam	15/12	210	257	375	632	218	321	539	282	298	580
Vegetables	Summer mix	Loam	15/10	55	364	449	813	364	449	813	405	338	743
Vegetables	Winter mix	Loam	15/03	10	73	484	557	73	484	557	78	439	517
Wheat	Spring	Loam	15/06	225	75	449	524	75	449	524	82	402	484
Total	**-**	**-**	**-**	**5895**	**3077**	**6697**	**9674**	**2845**	**6339**	**9184**	**3295**	**5445**	**8740**
b) Centre Pivot Irrigation System (Sandy loam and Silt loam)													
Beans	medium growers	Sandy loam	15/01	8	191	348	539	154	304	458	209	294	503
Lucerne	Semi-dormant	Sandy loam	01/06	35	447	1348	1795	447	1348	1795	512	1220	1732
Maize	Shorter growers	Sandy loam	15/12	15	203	214	417	181	200	381	211	160	371
Oats	Springs types	Sandy loam	15/06	15	94	471	565	94	435	529	103	391	494
Soybeans	Medium	Sandy loam	15/12	575	249	384	633	212	329	541	275	300	575
Tobacco	Standard	Sandy loam	15/11	45	276	224	500	276	224	500	302	135	437
Vegetables	Summer mix	Sandy loam	15/10	195	350	463	813	350	463	813	398	342	740
Vegetables	Winter mix	Sandy loam	15/03	165	71	485	556	71	485	556	76	439	515
Wheat	Spring types	Sandy loam	15/06	630	73	513	586	74	451	525	81	402	483
Soybeans	Medium	Silt loam	15/12	135	263	370	633	222	317	539	288	292	580
Vegetables	Winter mix	Silt loam	15/03	20	77	483	560	77	483	814	146	331	744
Vegetables	Summer mix	Silt loam	15/10	35	376	438	814	376	438	560	80	439	519
Wheat	Spring types	Silt loam	15/06	150	76	514	590	77	447	524	83	398	481
Total	**-**	**-**	**-**	**2023**	**2746**	**6255**	**9001**	**2611**	**5924**	**8535**	**3031**	**5143**	**8174**

Figure 4.5 presents the relative value in irrigation requirements for CONS and STRESS scenarios compared to the conventional approach. This comparison is made under two soil types: clay & loam and sandy loam & silt loam, for the centre pivot irrigation system. There is a similar trend in relative change across all four soil types. For the conservation approach, there is no significant differences between clay & loam and sandy loam & silt loam. This slight difference is also observed in the STRESS approach across all soil types. However, when considering the relative change in effective rainfall, sandy loam & silt loam shows a decrease that is almost 3% more than clay & loam. These observations highlight the subtle differences in irrigation requirements across different soil types under various water management scenarios.

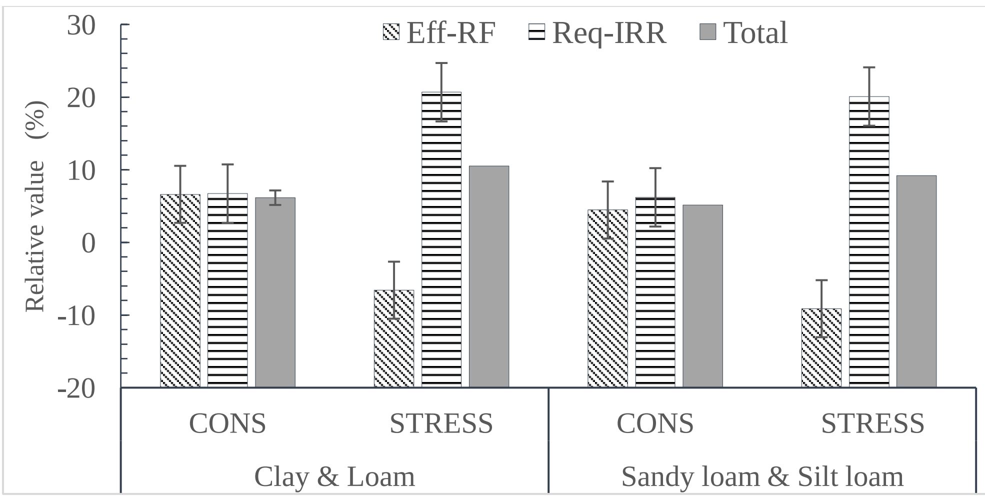


Figure 4.5 Relative changes (in %) of irrigation requirements for conservation (CONS) and water-stress (STRESS) scenarios to conventional approach under clay and loam and sandy loam and silt loam for centre pivot irrigation system.

The statistical analysis for the effective Rainfall, shows no significant difference among the two sets of four different soils represented in the Hartbeespoort irrigation scheme (as presented Appendix-IV). There is also no significant difference observed in the interaction between the soils and the management. The improved management alone shows a significant difference at p-value <0.05. In terms of Irrigation Requirements there is no significant difference among the soils. However, there is a highly significant value ($p < 0.0001$) under the management and the interaction between the soil type and the management. The highest relative value is observed for STRESS irrigation water requirements with values of 20.39%. This is also the case with the interaction,

where there is a large mean difference between sandy loam/silt loam and the conservation approach (mean value of 6.18), and the sandy loam/silt loam and the stress approach (mean of 20.08%).
In terms of total irrigation, the soil type and the management are not significant however, their interaction is significant ($p < 0.05$). This is due to the high mean values seen in clay loam/loam soil interaction with stress management, which is 10.51% of the relative value compared to conventional. This mean value is almost double that of clay/loam interaction with stress management. These findings highlight the impact of different soil types and the advantages of improved management for water productivity.

4.4.3 Drip irrigation system

According to Table 4.9a for the conventional approach, winter vegetables grown on sandy loam soil with a cropping pattern of 70 ha require a significantly higher total amount of irrigation (1 129 mm) compared to those grown on clay (743 mm under 370 ha), silt loam (731 mm under 35 ha), and loam (473 mm under 12 ha). Despite having the smallest cropping pattern, grapes require a significant amount of water (2 192 mm in total). For grapes planted on clay soil with a cropping pattern of 15 ha, 867 mm of water is required. However, those with a cropping pattern of 3 ha and 60 ha require 855 and 470 mm, respectively. Citrus, despite its small cropping pattern, requires a high amount of water. For instance, citrus planted on sandy loam with a cropping pattern of 70 ha need 726 mm of water, which is less than that planted on clay soil with a cropping pattern of 143 ha (1 143 mm).

Under the conservation approach (Table 4.9a), there is a decrease in the total amount of water required for the same cropping pattern for the same crop. For example, winter vegetables show a decrease of 65 mm for sandy loam, 13mm for clay and loam, and 17mm for silt loam. This indicates that less water is required when a conservation approach is used. A more significant decrease is observed in grapes, where only 824 mm for clay, 458 mm for loam, and 821 mm for sandy loam is required. In citrus, there is a slight difference of 75 mm and 11 mm for clay and sandy loam.

Under the water-stress scenario (Table 4.9a), there is a further decrease in the total amount of water needed for crop growth and development. For example, winter vegetables require 962 mm for sandy loam, 681 mm for silt loam, 686 mm for clay, and 439 mm for loam. Grapes and citrus show a similar change, with more than 50 mm for clay and loam and 8mm for sandy loam. For citrus, 105 mm and 35mm is retained from citrus planted on clay and sandy loam compared to the conservation approach. These findings highlight the impact of different water management approaches on the irrigation requirements of various crops, grown under different soil types and cropping patterns.

4.4.4 Flood irrigation system

In the conventional approach of the flood irrigation system, four types of crops are cultivated: citrus, lucerne, oats, and summer vegetables (Table 4.9b). Lucerne is the most prevalent crop in the scheme, spanning an area of 222 hectares. It also has the highest water requirement, with 82% sourced from irrigation and the rest from effective rainfall. Despite having a smaller cropping pattern of 35 ha, citrus requires a substantial amount of water, totalling 2 679 mm. This water is equally contributed by effective rainfall and irrigation, both of which are vital for the crop's growth and development. Citrus and lucerne are the crops that consume the most water. As per Table 4.9b, under a conventional approach, citrus, grown over an area of 20 hectares on clay soil, requires a total crop water of 1 346 mm. This is 13 mm more than that planted on silt loam soil. Under the conservation approach, 1 221 mm is needed, and under the stress approach, 1061 mm is required for citrus planted on clay soil. Comparing these results to silt loam, there is a very small difference. The results clearly show a difference of 620 mm in irrigation water and 183 mm in effective rainfall when conservation scenario is used. When the water-stress approaches are applied to all crops a further decrease of 362 and 1 493 mm for effective rainfall and irrigation is observed when compared to a conventional approach.

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Table 4. 9 Crops cultivated in Hartbeespoort WUA: area planted, cultivar option, start planting date, and irrigation requirements under a Centre pivot irrigation system a) Drip Irrigation System b) Flood Irrigation System for conventional approach and conservation/water-stress scenarios.

Crop type	Cultivar option	Soil type	Planting date Day/mon	Cultivate area (ha)	**Conventional Approach**			**Conservation Scenario**			**Water Stress Scenario**		
					Eff RF (mm)	IRR (mm)	Total (mm)	Eff RF (mm)	IRR (mm)	Total (mm)	Eff RF (mm)	IRR (mm)	Total (mm)
a) Drip Irrigation System													
Citrus	FAO 66 data	Clay	01/06	143	427	716	1143	479	589	1068	525	438	963
Grapes	Based on FAO 66	Clay	01/09	15	385	482	867	429	395	824	475	290	765
Vegetables	Winter mix	Clay	15/03	370	324	419	743	360	370	730	407	279	686
Vegetables	Summer mix	Clay	15/10	365	63	421	484	70	401	471	76	368	444
Grapes	Based on FAO 66	Loam	01/09	3	378	477	855	420	401	821	466	298	764
Vegetables	Summer mix	Loam	15/10	12	319	409	728	349	364	713	396	282	678
Vegetables	Winter mix	Loam	15/03	12	59	414	473	67	393	460	73	366	439
Vegetables	Winter mix	Sandy loam	15/03	70	408	721	1129	457	607	1064	510	452	962
Vegetables	Summer mix	Sandy loam	15/10	70	370	483	853	411	409	820	459	305	764
Citrus	FAO 66 data	Sandy loam	01/06	70	307	419	726	336	375	711	386	290	676
Grapes	Based on FAO 66	Sandy loam	01/09	60	58	412	470	65	393	458	72	378	450
Vegetables	Winter mix	Silt loam	15/03	35	324	407	731	362	352	714	405	276	681
Vegetables	Summer mix	Silt loam	15/10	35	62	414	476	70	390	460	75	364	439
Total	**-**	**-**	**-**	**1260**	**3484**	**6194**	**9678**	**3875**	**5439**	**9314**	**4325**	**4386**	**8711**
b) Flood Irrigation System													
Citrus	FAO 66 data	Clay	01/06	20	431	915	1346	485	736	1221	527	534	1061
Citrus	FAO 66 data	Silt loam	01/06	15	428	905	1333	485	733	1218	526	534	1060
Lucerne	Semi-dormant	Clay	01/06	222	408	1867	2275	484	1734	2218	538	1567	2105
Oats	Springs types	Clay	15/06	5	84	781	865	100	661	761	105	510	615
Vegetables	Summer mix	Clay	15/10	65	401	584	985	381	568	949	418	414	832
Total	**-**	**-**	**-**	**327**	**1752**	**5052**	**6367**	**1935**	**4432**	**6367**	**2114**	**3559**	**5673**

NB: Eff RF, Irr and Total represent the effective rainfall, Irrigation water requirement and Total water irrigation requirement, respectively.

Figure 4.6 illustrates the relative changes (in %) of irrigation requirements for the CONS and STRESS scenarios compared to the conventional approach, under two irrigation systems (drip and flood) . From the results, it is evident that there is a minimal difference between the drip and flood irrigation systems relative change for both the CONS and STRESS approaches. For the CONS approach, the flood irrigation system requires almost double the total amount compared to the drip irrigation system, this is also observed in the STRESS approach. However, when considering effective rainfall, there is less than 1% and 3% difference in both irrigation systems for the STRESS and CONS approaches, respectively. About 5% more is required for the drip irrigation system to match the level of the flood irrigation system for the STRESS approach. This is also the case with the CONS approach, but only 2% more is required. These observations highlight the subtle differences in irrigation requirements between the drip and flood irrigation systems under various water management scenarios.

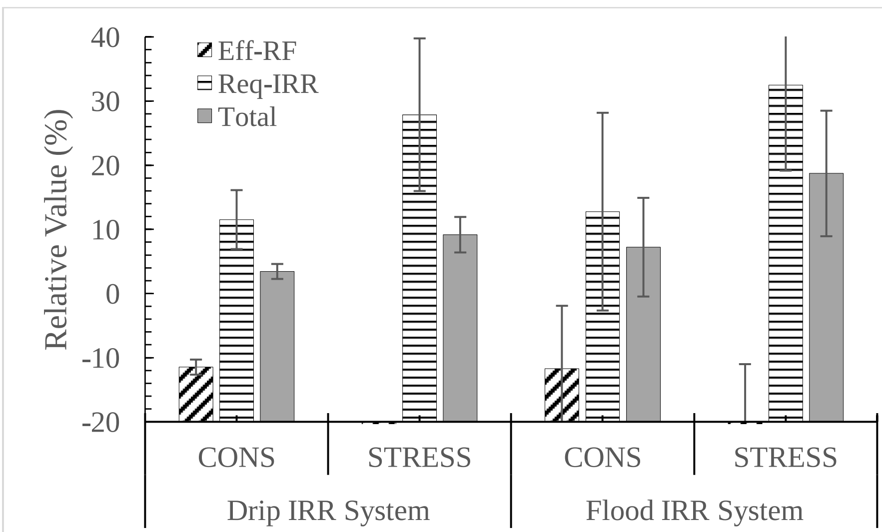


Figure 4.6 Relative changes (in %) of irrigation requirements for conservation (CONS) and water-stress (STRESS) scenarios to conventional approach under drip and flood irrigation system.

The table presents a statistical analysis (Appendix-V) of two irrigation types (drip and flood), management practices, and their interactions under effective rainfall, irrigation requirement, and total irrigation water. The effective rainfall shows no significant difference between the drip and flood irrigation types ($p>0.05$). However, there is a highly significant difference in the management practices and the interaction between the irrigation type and the management at p-value < 0.0001. Under management, there is a large variation between the relative values of conservation (11.08%) and Stress (22.21%). Similar to effective rainfall, irrigation requirements, and total irrigation amount, highly significant ($p < 0.0001$) differences in relative values are observed under management and interaction. Very high relative values are observed for STRESS management for the drip and flood irrigation with values of 29.67% and 28.74%, respectively. A large difference is also observed in the relative value of flood and stress interaction (19.26%) and the small relative value of drip and CONS interaction (4.19%). These results underscore the influence of drip irrigation methods over inefficient flood irrigation methods with improved management practices.

4.4.5 Micro-spray and Sprinkler permanent

Under the conventional approach in this field, most crops receive summer rainfall, except for summer vegetables that require less effective rainfall (74 mm). There is a small difference between the effective rainfall and the amount of irrigation, particularly for grapes, as shown in Table 4.10a. However, summer vegetables stand out as they require 86% of their water needs to be met through irrigation. The citrus crop has a total water requirement of 2 291 mm, which accounts for 51% of the total water supplied to crops in this area. For all these crops, 4 232 mm of water is needed for a conservation approach and 4 013 mm is needed for a slight stress approach, a difference of about 200 mm. In a stress scenario, effective rainfall contributes a bit more, but this is not the case with conventional and conservation approaches where irrigation has the greatest contribution.

In Table 4.10b, this 955 ha field requires a total irrigation amount of 2 662 mm for the conventional approach. Additionally, an effective rainfall contribution of 2 248 mm is necessary for the crops to thrive and mature. From Table 4.10b, in all the winter vegetables about 55% of crop water needs to be supplied by irrigation. This is also similar to summer vegetables where the majority of the water supply comes from irrigation, but effective rainfall also contributes large portions. The total water requirement for crops under the conservation approach is 4 820 mm with irrigation contributing 54%, making it the primary source of water for these crops' growth and development. The winter vegetables planted on clay soil with a cropping pattern of 30 ha needs 864 ha for a conventional approach, which is slightly more than those planted on sandy loam (305 ha) and silt loam (135 ha) with water requirement of 835 and 838 mm. These amounts are the same when it comes to the conservation approach but are lower when it comes to stress with a difference of 160 mm for clay, 41 mm for sandy loam, and silt loam.

Table 4. 10 Crops cultivated in Hartbeespoort WUA: area planted, cultivar option, start planting date, and irrigation requirements under a centre pivot irrigation system a) Micro spray b) Sprinkler Permanent for conventional approach and conservation/water-stress scenarios.

Crop type	Cultivar option	Soil type	Planting date Day/mon	Cultivate area (ha)	Conventional Approach			Conservation Scenario			Water Stress Scenario		
					Eff RF (mm)	IRR (mm)	Total (mm)	Eff RF (mm)	IRR (mm)	Total (mm)	Eff RF (mm)	IRR (mm)	Total (mm)
a) Micro-spray Irrigation System													
Citrus	FAO 66 data	Clay	01/06	35	483	641	1124	525	489	1014	525	472	997
Grapes	Based on 66	Clay	01/09	80	433	428	861	433	428	861	476	314	790
Vegetables	Winter mix	Clay	15/03	20	369	438	807	369	438	807	414	306	720
Vegetables	Summer mix	Clay	15/10	20	74	464	538	74	464	538	81	402	483
Citrus	FAO 66 data	Clay	01/06	5	482	685	1167	482	530	1012	525	498	1023
Total	-	-	-	**160**	**1841**	**2656**	**4497**	**1883**	**2349**	**4232**	**2021**	**1992**	**4013**
b) Sprinkler Permanent Irrigation System													
Vegetables	Summer mix	Clay	15/10	30	392	391	783	374	359	733	320	315	635
Vegetables	Winter mix	Clay	15/03	30	376	488	864	376	488	864	322	382	704
Vegetables	Summer mix	Sandy loam	15/10	320	360	433	793	351	402	753	328	396	724
Vegetables	Winter mix	Sandy loam	15/03	305	371	464	835	371	464	835	418	376	794
Vegetables	Summer mix	Silt loam	15/10	135	373	424	797	373	424	797	317	411	728
Vegetables	Winter mix	Silt loam	15/03	135	376	462	838	376	462	838	417	380	797
Total	**-**	**-**	**-**	**955**	**2248**	**2662**	**4910**	**2221**	**2599**	**4820**	**2122**	**2260**	**4382**

NB: Eff RF, Irr and Total represent the effective rainfall, Irrigation water requirement and Total water irrigation requirement, respectively.

Figure 4.7 illustrates the relative changes in irrigation requirements for the CONS and STRESS scenarios compared to the Conventional approach, under two irrigation systems: Micro-spray and sprinkler permanent. The observations from the figure indicate that the micro-spray system shows higher relative percentages for the total amount of water required and the irrigation amounts for both the CONS and STRESS approaches. For the conservation approach, the relative value of the micro-spray system is almost twice that of the sprinkler permanent system for the total amount, irrigation requirements, and effective rainfall. This trend is also observed in the water stress approach for the irrigation requirements. However, for effective rainfall, the micro-spray system shows about a 5% greater decrease than the sprinkler permanent system. For the total amount of water needed, the relative change is almost similar for both irrigation systems under the water-stress approach. These findings highlight the differences in irrigation requirements between the Micro-spray and Sprinkler Permanent systems under various water management scenarios.

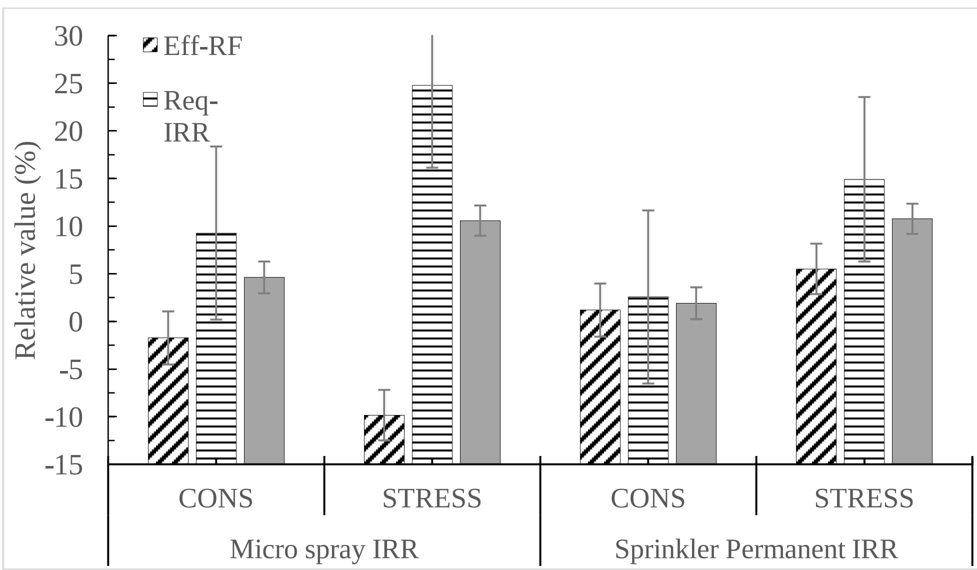


Figure 4.7 Relative changes (in %) of irrigation requirements for conservation (CONS) and water-stress (STRESS) scenarios to conventional approach under micro-spray and sprinkler permanent irrigation system.

The statistical analysis of two irrigation types, micro spray and micro sprinkler permanent, along with the management treatments and their interactions, reveals interesting findings with no significant difference in water irrigation requirements between the two irrigation types Appendix-VI). However, the effective rainfall shows a significant difference between the two irrigation systems (p-value < 0.05). The management treatments exhibit highly significant differences for both estimations of irrigation requirements and the total amount of irrigation (p-values < 0.001 and 0.005, respectively). The highest relative value is observed in the water stress (STRESS) treatment (20.04%), which is almost double the relative value of the total irrigation amount required. Significant differences are also found between the interaction of the irrigation types and the improved management practices in terms of irrigation requirements and total irrigation amount estimations. These findings underscore the benefits of improved management practices over conventional ones in this irrigation scheme.

4.4.6 Quick coupling Irrigation system

4.4.6.1 Clay soils

Table 4.11a presents the crops grown under a sprinkler quick coupling irrigation system on clay soil under a conventional, conservation and water stress scenarios. Winter and summer vegetables have the highest cropping pattern compared to other crops, while citrus and beans have the least. Despite the dominance of vegetable crops, they consume less water than lucerne and citrus, which require 1 857 mm and 1 221 mm of water respectively on a single planting date under conventional approach. Most of the water consumed by these crops is from irrigation, and for other crops in the scheme, about 8 802 mm of crop water is needed for growth and development. There is a decrease of 630 mm in the total amount of water needed by the crops for the conservation approach compared to the conventional approach. The water requirement for most crops decreased, except for lucerne, citrus, and vegetables, which remained the same. According to Table 4.11a under conservation scenario, these crops also utilize the majority of irrigated and effective rainfall water, while for other crops, an average crop water of about 516 mm is needed. Irrigation plays a crucial role for all the crops, contributing 70% of the total 8 172 mm required for the development and growth of all the crops in the scheme. Under the water stress scenario, even though the vegetable crops are dominant, they use less water than lucerne and citrus, which require 1 790 mm and 1 061 mm of water respectively on a single planting date. Most of the crop water needed by these crops at the scheme is irrigated, except for summer vegetables, which get 54% of their crop water supply from effective rainfall.

4.4.6.2 Loam and silt loam

Table 4.11b presents the crops grown on loam and silt loam soil under three different approaches (conventional, conservation, slight stress). Crops under loam soil (Oats, winter and summer vegetables) have a small cropping pattern 70 ha combined and require up to 2 011 mm of crop water out of a total of 5 897 mm for conventional approach. Only 27% of this amount is effective rainfall, making irrigation the primary source of crop water. The silt loam soil covers 448 ha and needs 3 886 mm of total crop water, of which only 1 041 mm is estimated to be effective rainfall, with the rest being irrigated. For a conservation approach, crops grown on loam and silt loam soil, as presented in Table 4.11b, maintain the same cropping pattern, irrigated water, and effective rainfall as compared to conventional farming. All the crops in this field require a total of 5 876 mm of crop water, with only 26% of this amount being effective rainfall, again making irrigation the highest contributor to crop water requirement. In Table 4.11b, crops grown on loam soil require up to 1 962 mm of water, with only 32% of this amount being effective rainfall, reinforcing irrigation as the primary source of crop water. Crops grown on silt loam soil need 3 886 mm of total crop water, with lucerne being the highest contributor. Only 1 024 mm of this amount is estimated to be effective rainfall, with the rest being irrigated. Oats is one crop that is planted on different soils, the one planted on loam with a cropping pattern of 25 ha needs 597 mm of water and the one planted on silt loam needs 594 mm, these amounts remain the same for the conservation approach but show a difference of more than 80 mm for a stress approach. Interestingly, a much higher contribution is made by effective rainfall in stress approach only for summer vegetables compared to the conventional and conservation approach.

Table 4. 11 Crops cultivated in Hartbeespoort WUA: area planted, cultivar option, start planting date, and irrigation requirements under sprinkler quick-coupling irrigation system a) Clay soil b) Loam and Silt loam and c) Sandy loam for conventional approach and conservation/water-stress scenarios.

Crop type	Cultivar option	Soil type	Planting date Day/mon	Cultivate area (ha)	Conventional Approach			Conservation Scenario			Water Stress Scenario		
					Eff RF (mm)	IRR (mm)	Total (mm)	Eff RF (mm)	IRR (mm)	Total (mm)	Eff RF (mm)	IRR (mm)	Total (mm)
a) Clay soil													
Barley	Spring type	Clay	15/06	260	99	532	631	98	453	551	105	411	516
Beans	Medium growers	Clay	15/01	37	206	368	574	163	309	472	223	307	530
Beans	Medium growers	Clay	15/10	38	260	390	650	233	314	547	285	300	585
Citrus	FAO 66 data	Clay	01/06	20	485	736	1221	485	736	1221	527	534	1061
Lucerne	Semi-dormant	Clay	01/06	861	475	1382	1857	475	1382	1857	532	1258	1790
Maize	Short growers	Clay	15/12	245	212	232	444	186	205	391	219	172	391
Oats	Spring type	Clay	15/06	245	99	532	631	98	453	551	105	411	516
Soybeans	Medium growers	Clay	15/12	850	267	412	679	223	332	555	291	313	604
Vegetables	Summer mix	Clay	15/10	3463	375	496	871	375	496	871	417	352	769
Vegetables	Winter mix	Clay	15/03	2513	76	533	609	76	533	609	82	467	549
Wheat	Spring type	Clay	15/06	720	76	559	635	76	471	547	83	427	510
Total	**-**	**-**	**-**	**9252**	**2630**	**6172**	**8802**	**2488**	**5684**	**8172**	**2869**	**4952**	**7821**
b) Loam and Silt loam soil													
Oats	Spring types	Loam	15/06	25	101	496	597	97	451	548	104	409	513
Vegetables	Winter mix	Loam	15/03	20	73	507	580	73	507	580	78	463	541
Vegetables	Summer mix	Loam	15/10	25	363	471	834	363	471	834	406	355	761
Lucerne	Semi-dormant	Silt loam	01/06	47	492	1382	1874	475	1351	1826	532	1258	1790
Oats	Spring types	Silt loam	15/06	23	99	495	594	99	495	594	105	408	513
Vegetables	Winter mix	Silt loam	15/03	193	76	507	583	76	507	583	80	463	543
Vegetables	Summer mix	Silt loam	15/10	185	374	461	835	374	461	835	413	348	761
Total	**-**	**-**	**-**	**518**	**1578**	**4319**	**5897**	**1557**	**4319**	**5876**	**1718**	**3704**	**5422**
c) Sandy loam													
Maize	Short growers	Sandy loam	15/12	15	208	201	409	182	201	383	211	169	380
Oats	Spring types	Sandy loam	15/06	10	96	491	587	94	458	552	103	412	515
Soybeans	Medium growers	Sandy loam	15/12	50	250	401	651	212	348	560	264	348	612
Tobacco	Standard	Sandy loam	15/11	25	277	231	508	277	231	508	302	142	444
Vegetables	Summer mix	Sandy loam	15/10	195	351	483	834	351	483	834	397	362	759
Vegetables	Winter mix	Sandy loam	15/03	215	71	508	579	71	508	579	76	462	538
Wheat	Spring types	Sandy loam	15/06	445	75	535	610	74	474	548	81	421	502
Total	**-**	**-**	**-**	**955**	**1328**	**2850**	**4178**	**1261**	**2703**	**3964**	**1434**	**2316**	**3750**

4.4.6.3 Sandy loam

Table 4.11c shows that for a conservation approach, crops grown on sandy loam soil show a decrease in total effective rainfall and the irrigated amount. Crops that show a decrease in the total amount of water are soybean, wheat, maize, and oats, but for other crops, the total amount of water remains constant. Maize utilizes the least water, with 383 mm for the conservation approach, 48% of which is from effective rainfall while summer vegetables utilize the most water, with 834 mm. Irrigation plays a significant role, contributing 68% of the total 3964 mm of water required for all the crops at the scheme.

As seen in Table 4.11c, the crop with the highest cropping pattern is wheat (445 ha), while oats, maize, and tobacco have the least cropping pattern. Summer vegetables require 759 mm of water for the slight stress, 52% of which is irrigated. This is followed by soybean with 612 mm and wheat with 502 mm. Most of these crops, especially wheat, oats, and winter vegetables, rely heavily on irrigation, which provides approximately 83% of their crop water. Other crops such as tobacco and maize rely mostly on rainfall since they are summer crops, with about 68% of the crop water for tobacco and 52% for maize coming from effective rainfall.

Figure 4.8 illustrates the relative changes (in %) of irrigation requirements for the conservation (CONS) and water stress (STRESS) scenarios compared to the conventional approach, under three soil types: clay, loam & silt loam, and sandy. The findings from the figure illustrate that for the conservation approach, clay soils show a much higher relative change in effective rainfall (6%) compared to loam & silt loam and sandy soils (1% and 4% respectively). This trend is also observed in the irrigation and total water amount, where a relative change of almost 10% is needed for clay, 5% for sandy, and only 1% for loam & silt loam. Unlike the STRESS approach, there isn’t a significant discrepancy between the effective rainfall and the required irrigation amount in the conservation approach. For the stress approach, clay soils require the most irrigation (22%), followed by sandy soil (20%), and lastly loam and silt loam (16%). In terms of effective rainfall, there is a decrease of about 8% for clay soils, which is about a 1% difference when compared to the other soils that have a decrease of about 7%. These findings highlight the differences in irrigation requirements under various water management scenarios and soil types.

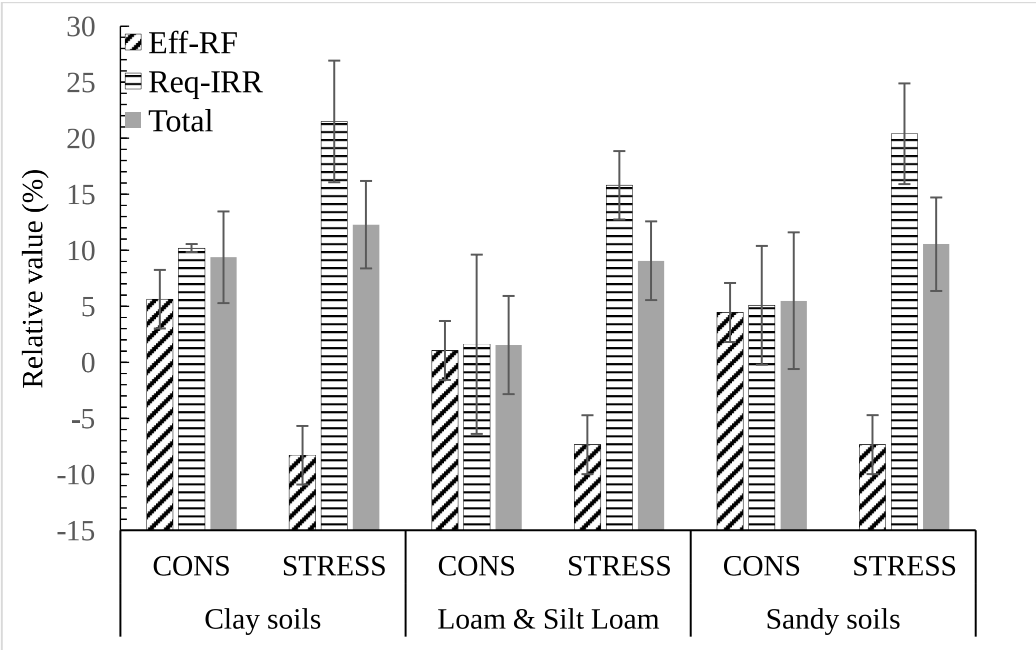


Figure 4.8 Relative values (in %) of irrigation requirements for conservation (cons) and water-stress (stress) scenarios to conventional approach under clay, loam and silt loam and sandy soils.

The table presents a statistical analysis of three soil types (clay, loam/silt, and sandy) (Appendix VII), show that the effective rainfall has no significant difference between the soil types or the interaction between the management and the soil types. However, the CONS and STRESS management practices are highly significant. In contrast, the soil types and the interactions between the soil types and management practices are significant with p-values of < 0.006 and 0.026, respectively. The high relative value of 19.59% in STRESS and the low relative value of 8.64% for CONS result in a highly significant difference (p-value < 0.0001) for the improved management for the estimation of irrigation requirement of the crops. In total irrigation water amount, The clay soil type, with a relative value of 12.21%, is significant (p-value is 0.007) compared to loam/silt loam and sandy loam soils (with mean relative values of 6.41% and 8.03% respectively. The management practices do not show any significance. Nevertheless, the interaction between the management and the soil types is significant (p-value of < 0,05).

Therefore, based on these findings from Hartbeespoort irrigation scheme estimations, it is crucial to consider the specific soil types and irrigation types for varying cropping patterns in identifying the water management strategies when planning for irrigation needs, and overall irrigation water requirements. Understanding the influence of these factors can lead to more efficient use of water resources and potentially improve crop yields. It is crucial to tailor the water management strategies to the specific soil types to maximize the effectiveness of rainfall and irrigation. This could lead to significant improvements in water conservation and agricultural productivity.

4.5 Irrigation Water Requirement: *Orange-Vaal irrigation scheme*

4.5.1 Centre pivot and drip irrigation systems

Table 4.12 reveals that the irrigation scheme exclusively uses sandy loam soil, which covers 100% of the area. There are two types of irrigation systems in use. The centre pivot system is the most dominant, covering 96% of the irrigated area, while the remaining area is covered by a drip irrigation system. The total scheduled irrigation area at Orange-Vaal for 10 different types of crops is 17,390 ha, as shown in Table 4.12. Double cropping is practiced for most crops, with the exception of cotton, pecan nuts, and groundnuts. Table 4.6 indicates that the most commonly irrigated crops in the scheme area are lucerne (5346 ha), wheat (4911 ha), maize (3761 ha), and cotton (1188 ha). The least irrigated crops are onions (123 ha), groundnuts (423 ha), sunflower (495 ha), and potatoes (528 ha). The cropping pattern remains constant across all three scenarios.

Table 4. 12 Crops cultivated in Orange-Vaal WUA: area planted, cultivar option, start planting date, and irrigation requirements under sprinkler quick coupling irrigation system for conventional approach and conservation/water-stress scenarios.

Crop type	Cultivar option	Soil type	Planting date Day/mon	Cultivate area (ha)	Conventional Approach			Conservation Scenario			Water Stress Scenario		
					Eff RF (mm)	IRR (mm)	Total (mm)	Eff RF (mm)	IRR (mm)	Total (mm)	Eff RF (mm)	IRR (mm)	Total (mm)
Sprinkler Quick Coupling Irrigation System													
Cotton	Medium growers	Sandy loam	15/10	1188	176	817	993	170	712	882	192	608	800
Groundnuts	Standard	Sandy loam	15/10	423	133	1061	1194	135	996	1131	158	859	1017
Lucerne	Semi-dormant	Sandy loam	01/06	5346	217	1816	2033	217	1816	2033	244	1719	1963
Maize	Shorter growers	Sandy loam	15/10	136	89	582	671	84	466	550	94	437	531
Maize	Shorter growers	Sandy loam	15/12	3 625	82	450	532	79	425	504	85	335	420
Onion	Short day	Sandy loam	15/05	123	28	643	671	27	504	531	34	512	546
Potatoes	Medium Variety	Sandy loam	15/01	528	99	478	577	102	428	530	122	340	462
Sunflower	Shorter growers	Sandy loam	15/12	495	77	352	429	70	329	399	80	261	341
Wheat	Spring types	Sandy loam	15/06	4 911	33	577	610	33	482	515	34	439	473
Pecan**	WRC Cullinan	Sandy loam	01/08	615	240	963	1203	240	963	1203	256	928	1184
Total	**-**	**-**	**-**	**17390**	**1174**	**7739**	**8913**	**1157**	**7121**	**8278**	**1299**	**6438**	**7737**

** *Drip Irrigation System*

NB: Eff RF, Irr and Total represent the effective rainfall, Irrigation water requirement and Total water irrigation requirement, respectively

The SAPWAT4 estimates under a conventional irrigation approach, lucerne continues to be the most dominant crop, requiring the most water (2 033 mm), while onions are the least dominant crop, requiring less water (671 mm). However, there is a slight decrease in the total amount of water required for the growth and development of crops under the conservation approach compared to the conventional approach. This is due to all crops requiring more water except for lucerne and pecan. The total water needed for crops in this approach is 8 278 mm, with 14% of this amount being effective rainfall. This scenario requires 635 mm less water compared to the conventional approach. Under a stress irrigation approach, the total water required for the growth and development of crops is less than that required under the conservation and conventional approaches. A total of 7 737 mm of crop water is needed, with 17% of this amount being effective rainfall and the remaining 83% being irrigated. A decrease in water usage is observed in all crops, saving 1 176 mm of water when using the stress irrigation approach compared to the conventional scenario, and 541 mm of water compared to the conservation scenario.

Figure 4.9 presents the relative values in irrigation requirements for the CONS) and STRESS scenarios compared to the conventional approach, under sandy loam soil. The STRESS approach requires more water compared to the CONS approach, except in the case of effective rainfall. The irrigation requirements for the STRESS approach are about 20%, which is almost double that of the CONS approach. The total irrigation for the STRESS approach is about 15%, which is almost 5% more than what is required for the CONS approach. There is a decrease in effective rainfall of about 11% for the STRESS approach, but a 3% increase is required for the CONS approach. These observations highlight the differences in irrigation requirements under various water management scenarios for sandy loam soil.

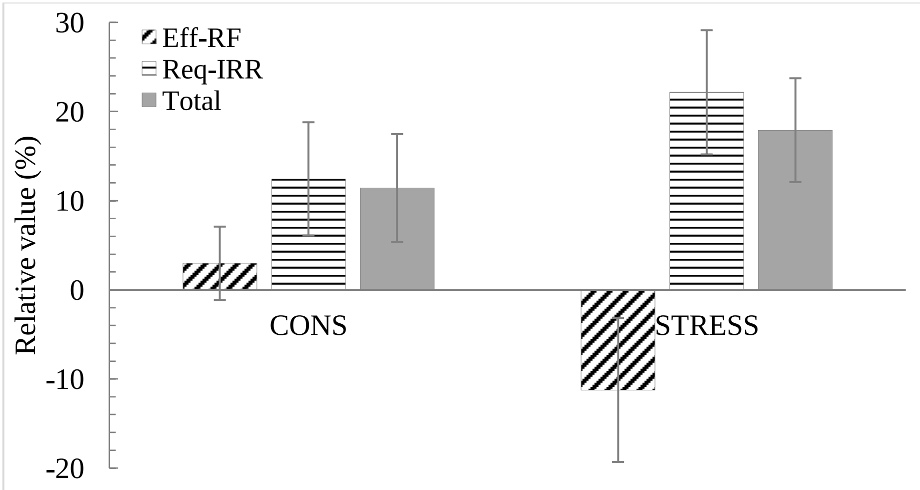


Figure 4.9 Relative changes (in %) of irrigation requirements for conservation (CONS) and water-stress (STRESS) scenarios to the conventional approach under sandy loam.

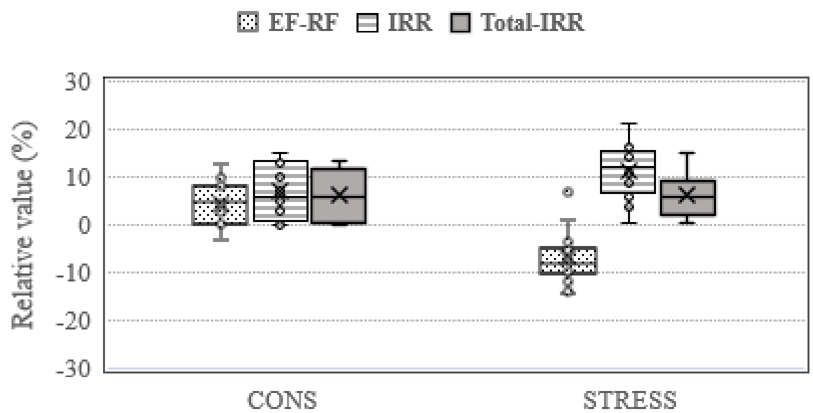
The table in Appendix-VIII indicates that both management practices, conservation and Stress, have significant difference in all estimation under effective rainfall, irrigation requirements, and total irrigation. This is evident from their p-values, which are 0.0003, 0.0093, and 0.0405 respectively. This significance is also reflected in the difference between the relative values of the two management practices. For effective rainfall, the mean relative value for conservation management is 3.46%, while for Stress management it is significantly lower at the p-value of <0.0001 compared to conventional (-11.23%). For both irrigation requirements and total irrigation, there is a substantial difference of about 10% between the mean values of the two management practices. These findings underscore the significant impact of different water management practices on various planting patterns.

4.6 Comparing relative values of improved management practices

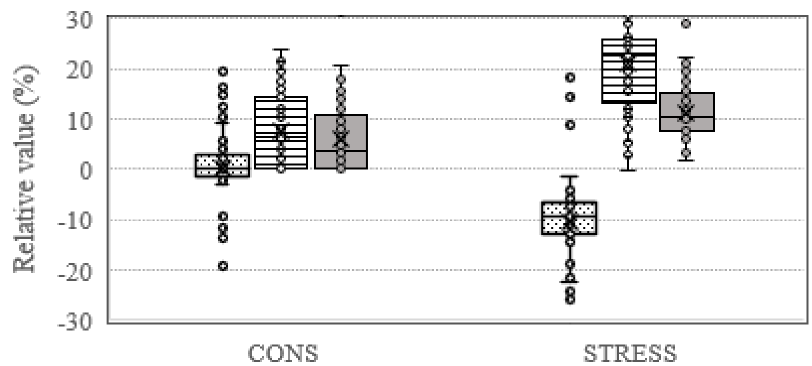
The box and whisker plots (Figure 4.10) illustrate the data variations for all climatic locations, as indicated by the mean and median values. In semi-arid cold climates (Figure 4.10a) the effective rainfall remains unchanged in the conservation (CONS) approach, while the Water-stress (STRESS) approach shows a decrease of about 10% compared to the conventional approach. The irrigation requirement for STRESS (> 10%) is double the relative value compared to CONS

(4.7%). However, in terms of total irrigation requirement, both the CONS and STRESS show similar relative values compared to the conventional approach (Figure 4.10a). In semi-arid hot climatic conditions (Figure 4.10b) the effective rainfall depicts the same trend as semi-arid cold but with high variations of relative value across all cropping patterns (Figure 4.10b). The highest relative values (21%) for irrigation requirements are under slight-water stress conditions, which is double compared to the total irrigation requirement (11%). In arid-hot climatic conditions (Figure 4.10c) the relative values of effective rainfall dropped to less than -20% with significant variations across different soils and cropping patterns under STRESS management practices, while the CONS shows no significant changes compared to the conventional approach. The total irrigation requirement remains high under STRESS treatment, while in CONS it remains about one-third (7%) of the relative value compared to the conventional approach. These findings highlight the impact of different water management approaches on irrigation requirements under various climatic conditions.

a) Semi-arid Cold Climate (Sand-Vet IRR. Scheme)



b) Semi-arid Hot Climate (Hartbeespoort IRR. Scheme)



c) Arid Hot Climate (Orange-Vaal IRR. Scheme)

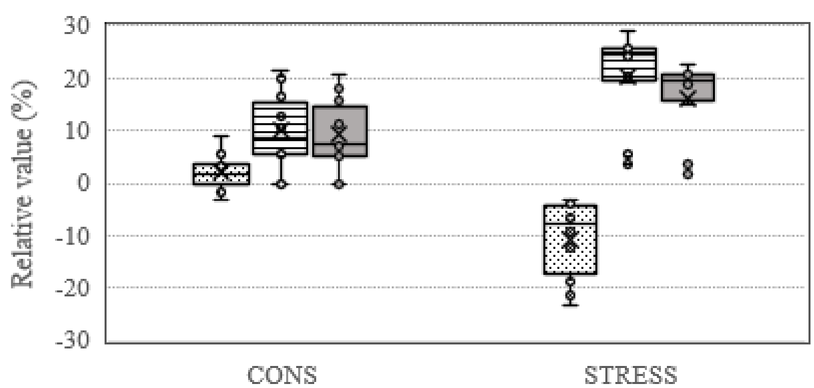


Figure 4.10 Relative values (%) for the general Irrigation requirement as estimated by SAPWAT4 model for WUAs a) Sanda-Vet, b) Hartbeespoort, and c) Orange-Vaal irrigation schemes.

Table 4.12a, b, and c present statistical analyses of relative values of effective rainfall, irrigation requirements, and total irrigation requirements respectively, across different climatic locations (Semi-arid cold, Semi-arid hot, Arid hot) and treatments CONS and STRESS scenarios. Table

4.12a indicates that there is no significant difference between the climatic locations of the schemes in terms of effective rainfall relative values at a P value of 0.0867. However, a highly significant difference is observed between the two treatments ($p<0.0001$). The interaction of the treatment and the climatic conditions does not show any significance ($p=0.8082$). In Table 4.12b the statistical analysis indicates there is a very high significance between Semi-arid cold and Semi-arid hot locations, and between Semi-arid cold and Arid hot ($p<0.0001$) in terms of irrigation requirements. However, no significant difference is observed between Semi-arid hot and Arid hot. The P-value between the two treatments is less than 0.0001, indicating a high significance. Moreover, there is no significance between the approaches and the different climate locations of the schemes ($p=0.0787$). Table 4.12c reveals that there is a highly significant difference between all the climatic zones in terms of total irrigation requirements ($p=0.0006$). There is also significance between the conservation and stress approach. However, the interaction between the climate zones and the approaches shows no significant difference. These findings highlight the impact of different climatic zones and water management approaches on irrigation requirements.

Table 4. 13 Summary of statistical analysis of the location/climate, the improved management practices (Treatments0 and their interactions.

a) Effective Rainfall (ERF)

Location/(Climate)	mean	SE	P-value	Treatment	mean	SE	P-value	Interaction	mean	SE	P-value
Semi-arid cold	-2.19a	1.52	0.0867	CONS	1.30a	1.27	0.0001**	CONS	4.84a	2.34	0.8082
				STRESS	-9.71b	1.18		STRESS	-7.12a	1.96	
Semi-arid hot	-5.83a	0.73						CONS	0.36a	1.12	
								STRESS	-10.18a	0.94	
Arid hot	-4.35a	1.96						CONS	2.08a	2.77	
								STRESS	-10.79a	2.78	

b) Irrigation water requirement (IRR)

Location/(Climate)	mean	SE	P-value	Treatment	mean	SE	P-value	Interaction	mean	SE	P-value
Semi-arid cold	9.79b	1.31	0.0001**	CONS	10.56b	1.09	<0.0001**	CONS	7.84b	2.01	0.0487
				STRESS	19.27a	1.01		STRESS	11.17b	1.68	
Semi-arid hot	16.96a	0.63						CONS	11.28b	0.96	
								STRESS	21.05a	0.81	
Arid hot	15.13a	1.68						CONS	9.95b	2.37	
								STRESS	20.31a	2.37	

c) Total Irrigation requirement (Total-IRR)

Location/(Climate)	mean	SE	P-value	Treatment	mean	SE	P-value	Interaction	mean	SE	P-value
Semi-arid cold	6.59c	0.96	0.0006**	CONS	8.24b	1.48	0.0057*	CONS	7.16c	1.48	0.0347
				STRESS	10.89a	1.24		STRESS	6.21c	1.24	
Semi-arid hot	10.10b	0.46						CONS	8.33c	0.71	
								STRESS	11.34b	0.59	
Arid hot	12.70a	1.24						CONS	9.13bc	1.76	
								STRESS	16.27a	1.77	

4.7 Comparing water quotas and irrigation requirements

The quotas, general irrigation water requirements, and the overall relative values for the three theoretical approaches used in the SAPWAT4 simulation are summarized in Table 4.11. This table presents data for three different climatic conditions: Semi-arid cold, Semi-arid hot, and Arid hot. The findings are categorized according to the different irrigation management systems practiced by the WUAs. This organization of data provides a comprehensive overview of the irrigation requirements under various conditions and management practices. According to the survey data, the Sand-Vet irrigation scheme revealed similarity for the size of the cultivated and scheduled areas, but for the other two schemes (Hartbeespoort and Orange-Vaal) the cultivated bigger by 75% and 50% respectively compared to the scheduled area. This suggests that the size of the cultivated area is flexible, adjusting according to the availability of water in the schemes and other climatic factors, particularly in light of changing climate conditions. Additionally, farmers consider various factors such as market demand, availability of inputs and supplies, mechanization, and labor availability when deciding on the size of the cultivated area.

The study found that under a centre pivot irrigation system, about 6.97% of water is retained under the conservation approach and 10.32% under the stress approach. This suggests that the WUAs should increase their water allocation by at least 5 169 696 m³ per annum for crops to thrive under the conventional approach. The drip irrigation system showed a very small relative change under conservation (1.27%), indicating that not much water is conserved when this approach is used. However, about 6.73% of water is retained under the stress approach. In the linear irrigation system, about 9% and 16% of water is retained for conservation and stress respectively. However, the quotas should be revisited as the WUAs are receiving 3 282 080 m³ per annum and 715 305 m³ per annum more irrigation water under the conventional approach.

In a semi-arid hot region, crops grown under a centre pivot irrigation system retain about 5% of water from the quota under the conservation approach, but under stress, about 18% is saved. For drip and flood irrigation systems, a similar amount is conserved for the stress approach, which is about 13%, but the conservation approach conserves about 20% for drip and 29% for flood.

Micro spray conserves more water than the sprinkler permanent irrigation system, with about 13% conserved for conservation while stress retains 25%. These amounts are 11% and 10% more compared to the relative values of the conservation and stress of the sprinkler irrigation system. On the contrary, the conventional approach quota is lower when compared to the estimation of the CONS, meaning the scheme will be running at a loss of 5%. However, 17% is conserved for crops grown under a sprinkler quick-coupling irrigation system for the stress approach. In an arid-hot climate, when crops cultivated under the conservation approach using a centre pivot irrigation system, 10% is retained and almost double is conserved when they go through the stress approach. These findings highlight the importance of understanding the specific water needs of different regions and crops for efficient water management by practicing improved interventions with the expectation of changing of the climate. From this general finding suggests potential for water conservation under different irrigation systems and approaches, with notable differences observed between the systems and climatic conditions. However, it also underscores the need for revisiting quotas to ensure adequate water allocation. The findings emphasize the importance of understanding the specific water needs of different regions and crops for efficient water management, particularly in the face of changing climate conditions. This knowledge can guide the implementation of improved interventions for sustainable and efficient water use in agriculture.

Table 4. 14 Summary of the Quota listed and Irrigation water requirement estimations using SAPWAT4 in three irrigation schemes.

Study area	**Sand-Vet WUA**			**Hartbeespoort WUA**						**Orange-vaal**
• Climate zone	Semi-arid, cold			Semi-arid, hot						Arid, hot
• Rainfall (mm)	517			529						288
• ETo (mm d^{-1})	4.1			4.5						4.6
• Quota per listed area ($m^3\ ha^{-1}\ a^{-1}$)	7 200			6 200						10 000
• Planted area (ha)	11 835			21 345						17 390
• Scheduled size (ha)	12 184			12 219						11 617
Summary of Simulations										
Irrigation System	**Centre Pivot**	**Drip-IRR**	**Linear -IRR**	**Centre Pivot**	**Drip-IRR**	**Flood-IRR**	**Micro-spray**	**Fixed-Sprinkler**	**Moveable Sprinkler**	**Centre Pivot**
Irrigated area (ha)	10976	730	129	7918	1260	327	160	955	10725	17 390
Irrigation allocation based on quota multiplied by listed area ($m^3\ a^{-1}$)	79 027 200	5 256 000	928 800	49 091 600	7 812 000	2 027 400	992 000	5 921 000	66 495 000	173 900 000
SAPWAT4 estimated irrigation requirement ($m^3\ a^{-1}$) **conventional irrigation strategy**	84 196 8 96	1 973 920	213 495	102 553 936	7 804 440	1 652 004	424 960	2 542 210	143 178 750	113 667 400
SAPWAT4 estimated irrigation requirement ($m^3\ a^{-1}$) ***Conservation irrigation strategy***	78 708 896	1 949 100	195 177	97 098 434	6 853 140	1 449 264	375 840	2 4820 45	150 868575	103 300 450
SAPWAT4 estimated irrigation requirement ($m^3\ a^{-1}$) ***Slight Water-stress irrigation strategy***	75 503 904	1 841 060	179 955	83 835 784	5 526 360	1 163 793	318 720	2 158 300	117 674 700	9 2430 250
Relative changes to Conventional										
• Relative Changes for Conservation Strategy (%)	6.97	1.27	9.39	5.62	13.88	13.99	13.07	2.42	-5.10	10.04
• Relative Changes for Slight Water-stress Strategy (%)	10.32	6.73	15.71	18.25	20.19	29.55	25.00	15.10	17.81	18.68

4.8 Visitation and sharing findings

The results of the study were shared with each WUA in the schemes to provide a highlight estimate of the crop water requirement. The SAPWAT4 program was introduced as a tool to assist the farming community. This tool can help farmers consider the existing water quotas and distribution systems to enhance their effectiveness and efficiency. By understanding their water usage and requirements better, farmers can make more informed decisions and potentially increase their yield while conserving water. Based on the feedback from the visitation of Orange-Vaal WUA, the management of over-use of irrigation water in an area is partly handled by transferring water from adjoining areas. This is permissible if a farmer has irrigation in these areas and some of this surplus water is then moved to the area where it is needed. The CEO of the WUA maintains that they do not exceed their water quota. The water pumped into the irrigation area through the Orange-Vaal transfer scheme is measured, and they ensure not to exceed the allowed volume. They have approached the Department of Water and Sanitation (DWS) to increase their quota, given that the areas upstream and downstream of the Orange River have quotas of 11 000 $m^3\ ha^{-1}\ a^{-1}$ and 15 000 $m^3\ ha^{-1}\ a^{-1}$ respectively. However, DWS responded that they could increase their quota only at the industrial water price, making the irrigation water cost unaffordable for the irrigators.

The Hartbeespoort WUA's irrigation area uses 189% of the allocated water quota. The use of borehole water mitigates this issue, although the exact volume is unknown. It is further mitigated by buying back water allocated to the mines, which can then be used for irrigation The water quality in this irrigation scheme is poor, and the chemicals in the Hartbeespoort Dam water could negatively affect both crop yield and quality. Applying slightly stressed irrigation can lead to a yield loss of up to 8% for citrus, maize, and wheat. However, the negative impact on quality and income might be substantial, particularly for vegetables. Anecdotal evidence suggests that more farmers are using soil water measurement probes and scheduling services than what previous research indicated. During the visitation, the Sand-Vet WUA provides information, about canal water supply that could become insufficient during October to December when the wheat is in its peak water demand and the young growth of the maize needs reliable water application to prevent water stress, which could reduce yield. And the farmers demand monthly estimates of irrigation requirements according to the cropping patterns, Besides the WUA described that the canal system capacity is not sufficient to supply water to the area during the peak demand of wheat if the total area exceeds about 40% - the current planting area.

In conclusion, these visitations and the sharing of findings have provided valuable insights into the challenges and potential solutions for managing water resources in these regions. The introduction of the SAPWAT4 program as a tool to assist the farming community has been beneficial. This tool aids farmers in considering their existing water quotas and distribution systems, thereby enhancing their effectiveness and efficiency. It underscores the importance of continuous engagement with the farming community and the need for innovative tools and strategies to ensure sustainable and efficient use of water resources.

4.9 Discussion and Summary

Overview of the study

The study aimed to compare water allocation quotas with irrigation requirements as estimated by SAPWAT4, focusing on selected irrigation schemes in South Africa. The comparison revealed variations for different climatic conditions, suggesting that the current water allocation quotas may not be sufficient to meet the irrigation requirements in certain regions of South Africa (van Heerden 2015; van Heerden and van Heerden 2020). This insufficiency could potentially lead to water stress in some areas of the irrigation schemes, affecting crop yield, agricultural productivity, and water use efficiency. The SAPWAT4 tool provided valuable estimates of irrigation requirements for different cropping patterns under varying soils and irrigation systems. Compared with the actual water allocation quotas, these estimates can help identify areas where water resources are underutilized or overexploited. This information can guide farmers, Water User Associations (WUAs), extension/researchers, and policymakers in making informed decisions about water allocation, ensuring a balance between agricultural needs and water sustainability. This study sets the stage for the discussion on the importance of accurate water allocation and efficient irrigation practices in South Africa's agriculture sector.

In the study, three distinct irrigation schemes were identified, each representing different climatic conditions: semi-arid cold (San-Vet irrigation scheme), semi-arid hot (Hartbeespoort), and arid hot (Orange-Vaal irrigation scheme). These schemes were used to estimate the irrigation water requirements based on surveys and information collected from the WUAs. The SAPWAT4 tool was employed to estimate the effective rainfall (ERF) and irrigation water requirement (IRR) for different cropping patterns under various soils and irrigation systems. Initially, the crop water requirement was estimated under the conventional approach for the cropping patterns in the schemes. Furthermore, two improved management practice scenarios were compared: the conservation approach, which adds 35% stubble mulch (CONS), and the slight-water stress approach, which fills up to 100% of the soil profile (STRESS). These adaptation scenarios were compared using relative values to the conventional approach to determine the benefits of the improved practices in increasing productivity and water use efficiency. The study highlighted regional variations in both water allocation quotas and irrigation requirements as estimated by SAPWAT as shown in Table 4:11. These variations are likely due to differences in climate, soil type, and crop choices in different schemes under different irrigation systems. Understanding these variations is crucial for developing region-specific water management strategies. This clarity in the study's findings can guide future research and policymaking in the field of irrigation and water management.

Water scarcity in South Africa is a significant factor when contemplating changes to irrigation water quotas (Tlou and Joubert, 2013; Van Averbeke et al., 2011). Despite this, it should not prevent the adjustment of irrigation water quotas, particularly in instances where they have been inaccurately determined at low levels. This problem appears to be more common in arid hot and adjacent semi-arid hot climates, such as the Orange-Vaal and Hartbeespoort schemes (Woyessa et al., 2004; van Heerden and van Heerden 2020). Historically, the successive Departments of Water (DWAF, DWA, and DWS) have allocated quotas based on geographic patterns. This approach does not take into account cropping patterns and the impact of climate on the water requirements of crops. As a result, it may not accurately reflect the actual water needs of different regions, crops, and varying soil types, potentially leading to inefficiencies in water use (Van Averbeke et al., 2011; van Heerden and van Heerden 2020). Therefore, a more nuanced approach that considers these factors is crucial for efficient water management.

Semi-arid Cold climatic conditions

In semi-arid, cold climates, such as the Sand-Vet Irrigation Scheme, the irrigation water requirement for the three scenarios shows that the quota is sufficient for the current cropping pattern, as indicated in Table 4.11. Applying a slight water stress approach could reduce the amount of water required for irrigation, but the potential loss of approximately 13% for maize, according to yield loss data (not presented), makes this approach unacceptable. The conservation scenarios could be an option to reduce irrigation requirements. However, this approach has not been widely adopted by the farmers in this area, primarily due to the high costs associated with implementation adaptation. According to WUA members, one limitation is that the canal system's capacity is insufficient to supply water to the area during the peak irrigation demand of wheat. This limitation becomes apparent if the total area of wheat planted exceeds 40% of the current planting area. Despite this, the water quota for this area balances out with the irrigation requirement, indicating effective water management under the current conditions.

In semi-arid cold climates, irrigation plays a significant role, particularly in the centre pivot and linear irrigation systems. As Sneed and Evans (1996) described, these systems are energy-saving and water-efficient methods for irrigating large fields.The only time when effective rainfall contributes less is during drip irrigation under a conservation approach. However, there were no significant differences in terms of effective rainfall among these three irrigation systems.
When it comes to irrigation requirements and total irrigation, the linear irrigation system showed much higher relative values compared to the conventional approach. This was followed by the centre pivot and then the drip irrigation. These results align with a study conducted by Woyessa, et al. (2004), where the SAPWAT model was used as a planning tool for irrigation in the Sand-Vet irrigation scheme monthly. Crops grown in this region are not row crops, which explains the smaller relative values for drip irrigation compared to linear and centre pivot. A case study by Felix Reinders (2013) for the Agricultural Research Council ARC South Africa further emphasizes the importance of choosing an appropriate irrigation system for an area. He explains that drip irrigation is only suitable for row crops, and based on the results obtained, his remarks are valid.

Semi-arid Hot climatic conditions

A similar pattern was noticed in a scenario involving a semi-arid hot climate, where two groups of four different soil types were examined under a centre pivot irrigation system. Irrigation continues to be a more significant factor than effective rainfall, particularly in a STRESS scenario for both sets of soil types. The pairing of clay and loam soils results in relative values for the irrigation requirement that are nearly identical to those of sandy loam. This could be attributed to the water retention capabilities of clay and loam soils due to their small particle size (Ball, 2023), which reduces the need for irrigation. While there is no significant difference among these soil types, a high significance is observed between the management and the interaction between the soil types and the management in terms of irrigation requirements. When considering the total amount of water needed for crop growth and development, neither the soil type nor the management is significant. However, their interaction is significant (at p-value < 0.05). An increase in irrigation from CONS to STRESS can be observed in clay and loam soils. Under a conventional approach, the relative values for effective rainfall and irrigation are estimated at approximately 7.2%. Under STRESS, the effective rainfall shows a negative relative value of -6.7%), while the irrigation requirement increases to 20.7%. This is likely due to the fact that effective rainfall contributes more to cases where irrigation is scarcely utilized. These findings align with a similar pattern of results gathered by Pieter van Heerden (2001) in a study conducted in the Orange-Riet and Orange Vaal regions, where the SAPWAT tool was used to estimate the water requirements of crops.

The comparison between the use of flood and drip irrigation systems shows that the flood irrigation system requires almost double the total amount of water compared to the drip irrigation system (Figure 4.6 and Table 4.9). According to the report of the United States Geological Survey (USGS) (2016), drip irrigation is significantly more efficient than flood irrigation for irrigating fruits and vegetables. This is because water is delivered directly to the roots of the crop through plastic pipes with holes, significantly reducing evaporation and retaining up to 50% less water compared to flood irrigation (USGS, 2016). Given that this field of study primarily involves vegetables and fruits, these results are logical. Irrigation still constitutes a larger portion of the water used for crop growth and development than effective rainfall. Results show that there is a minimal difference in both irrigation systems for the STRESS and CONS approaches in terms of effective rainfall, and no significant difference between the two approaches under effective rainfall. However, there is a highly significant difference between CONS and STRESS management, and the interaction between the irrigation type and the management at a p-value < 0.0001. The highest relative values are observed for STRESS management for both the drip and flood irrigation systems in other water-scarce schemes using flood and drip irrigation systems as indicated in the report of water estimation (van Heerden and van Heerden, 2020).

On the other hand, there is a significant difference between the micro-spray and sprinkler irrigation systems in terms of their relative value under irrigation. The micro spray system is 6% more than the sprinkler system for the CONS approach and about 10% more for STRESS. This is probably due to the smaller contribution received by the micro-spray system compared to the sprinkler system. Moreover, if an equal amount of effective rainfall were utilized, then the sprinkler system would be more than the micro irrigation system. This is because the micro spray system is a type of localized, low-pressure irrigation similar to drip irrigation (Hla and Scherer, 1998). Therefore, the differences in the relative values are not surprising since the conveyance loss will be minimal, and runoff, evaporation, and deep percolation will also be significantly reduced when compared to a permanent sprinkler irrigation system (Hla and Scherer,1998). Thus, the greater portion of water still comes from irrigation, except in the case of the sprinkler irrigation system where almost equal amounts of effective rainfall and irrigation contribute towards crop growth and development.

The citrus crop, which is water-intensive and thrives better under a macro-irrigation system (Vahrmeijer and Taylor, 2008), is the most irrigated crop under a micro - spray irrigation system. This could explain the higher relative values in micro-spray irrigation compared to sprinkler systems. While there’s no significant difference in the irrigation requirements of these two systems, they do show some significance under effective rainfall conditions. In most cases, a larger portion of water comes from irrigation, except for the sprinkler irrigation system where the contribution towards crop growth and development is almost equally divided between effective rainfall and irrigation. The CONS and STRESS approaches show significant differences in both the estimations of irrigation requirements and the total amount of irrigation.

The study also compared the effective rainfall and irrigation requirements of three soil types: Clay, loam, silt loam, and sandy under a CONS approach. It was found that the relative change for clay soils was higher compared to loam & silt loam and sandy soils. This is attributed to the larger cultivated area of crops planted under clay (9 252 ha), which requires more water for irrigation. Farmers in semi-arid hot regions tend to favor clay soils due to their superior fertility and capacity to hold water and minerals (Kerr, 2012), which accounts for the extensive area under cultivation. When crops undergo a STRESS approach, the effective rainfall decreases significantly and remains almost equal for all the soils at a relative value of 7 - 8%. However, irrigation increases under stress, with relative values almost doubling in clay and changing by 10% and 13% in loam and silt loam, respectively, and 15% in sandy soils. This increase aligns with a study conducted by van Heerden and van Heerden (2020). The soil types and their interactions with management practices significantly impact irrigation requirements, but not effective rainfall. The two management practices, CONS and STRESS, show a highly significant difference (at $p\text{-value} < 0.0001$) in the estimation of irrigation requirements of the crops, with the highest relative value of 20% in STRESS and the lowest relative value of 9% for CONS.

Arid- hot climatic conditions

In an arid-hot climate, using a centre pivot irrigation system under sandy loam soil, the STRESS approach requires more water compared to the CONS approach. The relative values indicate that the water requirement for the STRESS approach is almost double that of the CONS approach. However, in the case of effective rainfall, a decrease of about 11% is needed for the STRESS approach, while only a 3% decrease is required for the CONS approach. These findings align with the results acquired by van Heerden et al. (2001). It is also noteworthy that these two management methods show significant differences in terms of effective rainfall, irrigation requirements, and total irrigation. This underscores the importance of choosing the appropriate management method based on the specific conditions of the region.

Therefore, the study reveals how irrigation systems and soil types can have a substantial impact on the irrigation needs of crops. It provides insights into the effects of the CONS and STRESS management approaches on effective rainfall and irrigation requirements, with a particular emphasis on clay soils. These findings highlight the critical role these practices play in promoting efficient water use. Interestingly, these results align with those of a study conducted by van Heerden and van Heerden (2020). This research could prove to be a valuable resource for shaping future irrigation strategies and management practices within irrigation schemes.

CHAPTER 5: OVERALL CONCLUSION AND RECOMMENDATIONS

5.1 Overall conclusion

This study emphasizes the importance of accurate water allocation and efficient irrigation practices in South Africa's selected irrigation schemes. The use of tools like SAPWAT4 can help identify areas where water resources are either underutilized or overexploited, guiding farmers, Water WUAs, extension/researchers, and policymakers in making informed decisions about water allocation. This ensures a balance between agricultural needs and water sustainability, setting the stage for future discussions on this critical issue. The findings also highlight the potential for water stress in some areas if current water allocation quotas are insufficient to meet irrigation requirements, emphasizing the need for ongoing monitoring and adjustment of these quotas.

The study provides valuable insights into the irrigation requirements of different climatic conditions in South Africa, using the SAPWAT4 tool. The tool was used to estimate the effective rainfall and irrigation water requirement for different cropping patterns under various soils and irrigation systems in three distinct irrigation schemes. The study also compared two improved management practice scenarios, revealing the benefits of these practices in increasing productivity and water use efficiency. The findings highlight the regional variations in both water allocation quotas and irrigation requirements, which are crucial for developing region-specific water management strategies. These findings can guide future research and policymaking in the field of irrigation and water management, ensuring sustainable and efficient use of water resources.

The findings reveal that in semi-arid, cold climates like the Sand-Vet Irrigation Scheme, the current water quota is sufficient for the existing cropping pattern. While applying a slight water stress approach could reduce the irrigation water requirement. The CONS scenarios could be an option to reduce irrigation requirements, but the high costs associated with implementation adaptation have limited its adoption. Despite certain limitations, the water quota for this area balances out with the irrigation requirement, indicating effective water management under the current conditions. The study also highlights the significant role of irrigation in semi-arid cold climates, particularly in the centre pivot and linear irrigation systems, which are energy-saving and water-efficient methods for irrigating large fields.

On the other hand, in semi-arid hot climates, like Hartbeespoort schemes irrigation continues to be a more significant factor than effective rainfall, particularly in a STRESS scenario for different soil types. The clay and loam soils result in relative values for the irrigation requirement that are nearly identical to those of sandy loam, likely due to the water retention capabilities of clay and loam soils. The study also shows that the flood irrigation system requires almost double the total amount of water compared to the drip irrigation system. Drip irrigation is significantly more efficient than flood irrigation for irrigating fruits and vegetables as water is delivered directly to the roots of the crop, significantly reducing evaporation.

In semi-arid hot climates, the study also shows that there is a significant difference between the micro-spray and sprinkler irrigation systems in terms of their relative value under irrigation. The micro spray system is more efficient than the sprinkler system for both the CONS and STRESS approaches. This is likely due to the localized, low-pressure nature of the micro spray system, which reduces conveyance loss, runoff, evaporation, and deep percolation compared to a permanent sprinkler irrigation system. The study also indicates that the citrus crop in semi-arid hot climatic conditions, which is water-intensive and thrives better under a macro-irrigation system, is the most irrigated crop under a micro-spray irrigation system. This could explain the higher relative values in micro-spray irrigation compared to sprinkler systems. While there's no significant difference in the irrigation requirements of these two systems, only show some significance under effective rainfall conditions.

In the study, it is also indicated that soil types and their interactions with management practices significantly impact irrigation requirements. Clay soils, favored by farmers in semi-arid hot regions due to their superior fertility and water retention capabilities, showed a higher relative change compared to loam, silt loam, and sandy soils. Under a STRESS approach, effective rainfall decreases significantly while irrigation increases, with the highest increase observed in clay soils. These findings highlight the importance of considering soil types and management practices in irrigation planning, ensuring sustainable and efficient use of water resources. Moreover, in an arid-hot climate, using a centre pivot irrigation system under sandy loam soil, the STRESS approach requires significantly more water compared to the CONS approach. These two management methods show significant differences in terms of effective rainfall, irrigation requirements, and total irrigation, highlighting the need for careful consideration in irrigation planning to ensure sustainable and efficient use of water resources.

In general, this research provides valuable insights into how irrigation systems and soil types can significantly impact the irrigation needs of crops. It highlights the effects of the CONS and STRESS management approaches on effective rainfall and irrigation requirements, These findings underscore the crucial role these practices play in promoting efficient water use.. These findings highlight the importance of choosing an appropriate irrigation system and management approach for an area, ensuring sustainable and efficient use of water resources. This can guide future research and policymaking in the field of irrigation and water management.

5.2 Recommendations for Further Research

The use of SAPWAT4 as a planning tool for irrigation water requirements can promote sustainable use of water and soil resources in irrigation. By applying the correct quantities of water, especially in soils prone to water stress problems, the economic lifespan of an irrigation area can be extended and used more efficient resources. Thus, engaging and educating farming communities on the use of tools to estimate water use such as SAPWAT4 can empower them to implement their own irrigation water requirement planning. This knowledge highlights in choosing suitable crops for their areas within the limits of allowed water authorizations, potentially enhancing the sustainability of irrigated agriculture in the area. In addition to SAPWAT4, there are other tools crop models, and frameworks that can inform water allocation policies. For instance, the OECD has developed principles on water governance and a water governance indicator framework. context.

5.3 Limitations

The methodology applied in this study where the WUAs are requested to indicate crop areas planted and management practices, is a weakness in this study, because of generalized information or unreliable data. Besides the cropping patterns are variable and largely influenced by changes in markets and farmers' choice. The determination of irrigation requirements as employed in this study should not be a long term once off exercise. It should be repeated as often as, say every ten years to keep up with changes in climate, cropping patterns and markets. Economic viability studies should be also an integral part of such studies. South Africa is a water scarce country, a fact that should be kept in mind when considering changes in irrigation water quota. However, this should not be an excuse not to adapt irrigation water quotas in cases where irrigation water quotas have erroneously been determined on too low levels. The results of this study should be discussed with policy and decision-makers in the DWS for future application.

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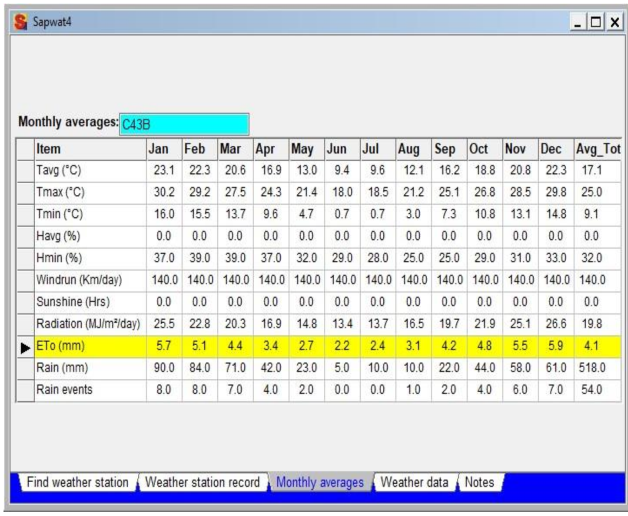
APPENDICES

Appendix- I-a: Sand-Vet – Weather Station record (C43B) analysis as per SAPWAT4

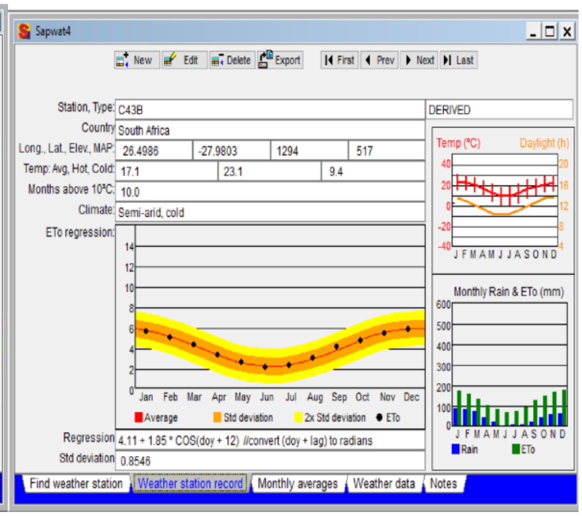


Sapwat4

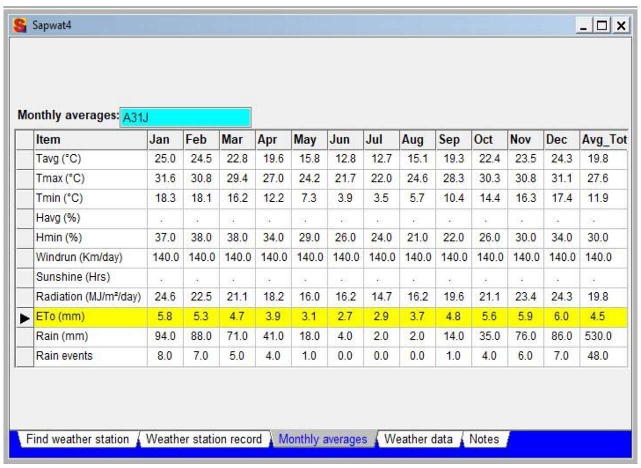
Monthly averages: C43B

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg_Tot
Tavg (°C)	23.1	22.3	20.6	16.9	13.0	9.4	9.6	12.1	16.2	18.8	20.8	22.3	17.1
Tmax (°C)	30.2	29.2	27.5	24.3	21.4	18.0	18.5	21.2	25.1	26.8	28.5	29.8	25.0
Tmin (°C)	16.0	15.5	13.7	9.6	4.7	0.7	0.7	3.0	7.3	10.8	13.1	14.8	9.1
Havg (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hmin (%)	37.0	39.0	39.0	37.0	32.0	29.0	28.0	25.0	25.0	29.0	31.0	33.0	32.0
Windrun (Km/day)	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0
Sunshine (Hrs)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Radiation (MJ/m²/day)	25.5	22.8	20.3	16.9	14.8	13.4	13.7	16.5	19.7	21.9	25.1	26.6	19.8
ETo (mm)	5.7	5.1	4.4	3.4	2.7	2.2	2.4	3.1	4.2	4.8	5.5	5.9	4.1
Rain (mm)	90.0	84.0	71.0	42.0	23.0	5.0	10.0	10.0	22.0	44.0	58.0	61.0	518.0
Rain events	8.0	8.0	7.0	4.0	2.0	0.0	0.0	1.0	2.0	4.0	6.0	7.0	54.0

Find weather station | Weather station record | Monthly averages | Weather data | Notes



Appendix- I-b: Hartbeespoort - Weather Station record (A31J) analysis as per SAPWAT4.

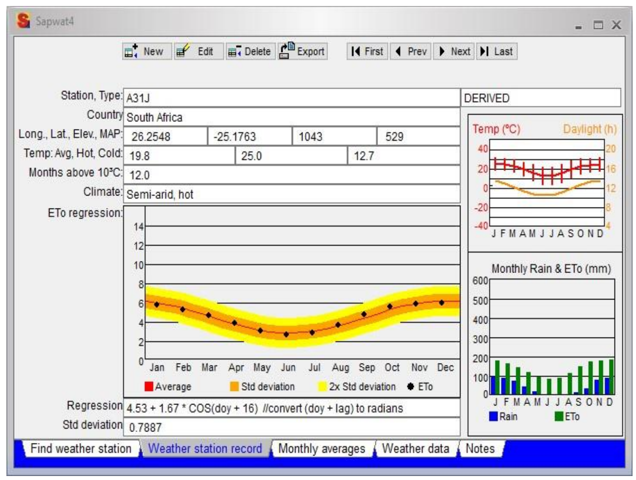


Sapwat4

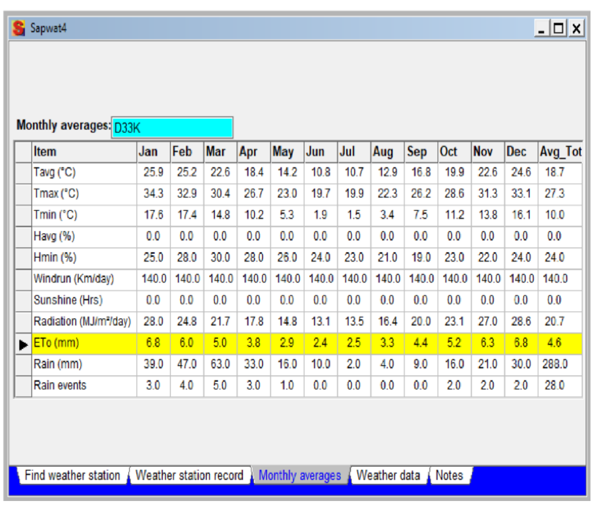
Monthly averages: A31J

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg_Tot
Tavg (°C)	25.0	24.5	22.8	19.6	15.8	12.8	12.7	15.1	19.3	22.4	23.5	24.3	19.8
Tmax (°C)	31.6	30.8	29.4	27.0	24.2	21.7	22.0	24.6	28.3	30.3	30.8	31.1	27.6
Tmin (°C)	18.3	18.1	16.2	12.2	7.3	3.9	3.5	5.7	10.4	14.4	16.3	17.4	11.9
Havg (%)	.	.	.	.	.	.	.	.	.	.	.	.	.
Hmin (%)	37.0	38.0	38.0	34.0	29.0	26.0	24.0	21.0	22.0	26.0	30.0	34.0	30.0
Windrun (Km/day)	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0
Sunshine (Hrs)	.	.	.	.	.	.	.	.	.	.	.	.	.
Radiation (MJ/m²/day)	24.6	22.5	21.1	18.2	16.0	16.2	14.7	16.2	19.6	21.1	23.4	24.3	19.8
ETo (mm)	5.8	5.3	4.7	3.9	3.1	2.7	2.9	3.7	4.8	5.6	5.9	6.0	4.5
Rain (mm)	94.0	88.0	71.0	41.0	18.0	4.0	2.0	2.0	14.0	35.0	76.0	86.0	530.0
Rain events	8.0	7.0	5.0	4.0	1.0	0.0	0.0	0.0	1.0	4.0	6.0	7.0	48.0

Find weather station | Weather station record | Monthly averages | Weather data | Notes



Appendix-I-c: Orange-Vaal Weather Station record (D33K) analysis as per SAPWAT4

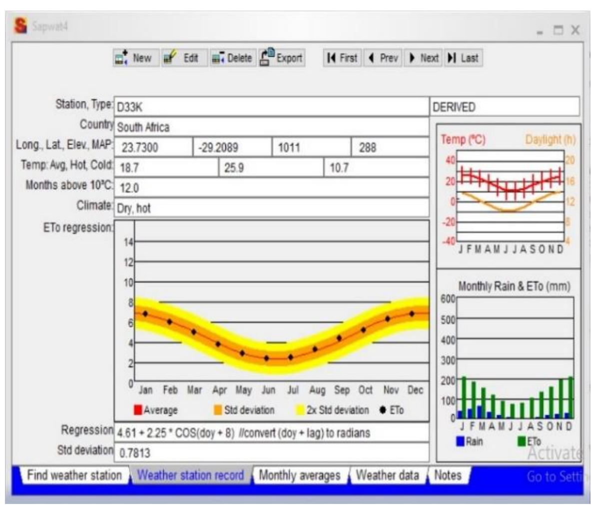


Sapwat4

Monthly averages: D33K

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg_Tot
Tavg (°C)	25.9	25.2	22.6	18.4	14.2	10.8	10.7	12.9	16.8	19.9	22.6	24.6	18.7
Tmax (°C)	34.3	32.9	30.4	26.7	23.0	19.7	19.9	22.3	26.2	28.6	31.3	33.1	27.3
Tmin (°C)	17.6	17.4	14.8	10.2	5.3	1.9	1.5	3.4	7.5	11.2	13.8	16.1	10.0
Havg (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hmin (%)	25.0	28.0	30.0	28.0	26.0	24.0	23.0	21.0	19.0	23.0	22.0	24.0	24.0
Windrun (Km/day)	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0
Sunshine (Hrs)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Radiation (MJ/m²/day)	28.0	24.8	21.7	17.8	14.8	13.1	13.5	16.4	20.0	23.1	27.0	28.6	20.7
ETo (mm)	6.8	6.0	5.0	3.8	2.9	2.4	2.5	3.3	4.4	5.2	6.3	6.8	4.6
Rain (mm)	39.0	47.0	63.0	33.0	16.0	10.0	2.0	4.0	9.0	16.0	21.0	30.0	288.0
Rain events	3.0	4.0	5.0	3.0	1.0	0.0	0.0	0.0	0.0	2.0	2.0	2.0	28.0

Find weather station | Weather station record | Monthly averages | Weather data | Notes



Appendix – II: Survey Questionnaire

Vraelys om die relevantheid van besproeiingswater-toekennings te bepaal / *Questionnaire for determining the relevance of irrigation water allocations*

Onder die vorige Waterwet (Wet 54 van 1956) was die watergebruiksreg wat aan 'n plaas toegeken was, uitgedruk as 'n aantal hektaar teen 'n water hoeveelheid per hektaar (bv. 80 ha @ 13500m^3 per ha). In hierdie vraelys word na daardie water-toekenning (13500 m^3 per ha, of wat ook al geldig vir u gebied is) gesoek. Die hektaar besproei is die werklike oppervlakte wat u besproei en nie die toegekende oppervlakte nie.

Under the previous Water Act (Act 54 of 1956) the irrigation water allocation of a farm was expressed as an area in hectares at a water allocation per hectare (e.g. 80 ha @ 13500 m^3 per ha). In this questionnaire reference to water allocation refers to that water allocation (13500 m^3 per ha, or whatever was relevant for your area). The area irrigated is the actual area irrigated and not the reference area as per water allocation.

Location and other background information

Inligting gevra / ***Information asked***	**Voorbeeld /** ***Example***	**Inligting voorsien /** ***Information given***
Naam / *Name*	Mnr John Anybody	
Telefoon / *Telephone*	0101234567	
Naaste dorp / *Closest town*	Cradock	
Afstand van naaste dorp (km) / *Distance from town (km)*	34	
Rigting van dorp (N, S, W, O) / *Direction from town (N, S, W, E)*	SW	
Water Gebruikersvereniging / *Water Users' Association (previous: Irrigation board or government scheme)*	Great Fish River WUA	
Water Gebruikersvereniging sub-area / *Water Users' Association sub-area*	Tarka Bridge	
Besproeide grootte (ha) / *Irrigated size (ha)*	1234	
Besproeiingswater-toekenning (m^3/ha) / Irrigation water allocation (m^3/ha)	13500	

Grond / Soil

Grondtekstuur / ***Soil texture***	**Effektiewe diepte (m) /** ***Effective depth (m)***	**Ha**
Sand / *Sand*		
Sanderige leem / *Sandy loam*		
Leem / *Loam*		
Slikleem / *Silty loam*		
Slikklei / *Silty clay*		
Klei / *Clay*		

Besproeiingstelsel / Irrigation system (Ha)

Irrigation system	**Ha**
Drup: bo-gronds / *Drip: above ground*	
Drup: ondergronds / *Drip: sub-surface*	
Mikro sprinkel / *Micro sprinkler*	
Mikrospuit / *Micro spray*	
Spilpunt / *Centre pivot*	
Linieêr / *Linear*	
Sprinkelaar vas / *Sprinkler fixed*	
Sprinkelaar beweegbaar / *Sprinkler movable*	
Vloed bak / *Flood basin*	
Vloed voor / *Flood furrow*	
Vloed bedding / *Flood border*	

Gewasse (voorbeeld) / ***Crops (example)***

(Dui asseblief aan gewas area per tekstuurklas en besproeiingstelsels kombinasies)Please indicate crop area per soil texture class and irrigation system combinations)

Crop	**Crop type**	**Soil**	**Irrigatin system**	**Plant or start date**	**Double crop (Yes/No)**	**Ha**
Lusern / *Lucerne*	Semi-dormant / *Semi-dormant*	Clay loam	Flood	***	No	240
Lusern / *Lucerne*	Semi-dormant / *Semi-dormant*	Loam	Pivot	***	No	280
Lusern / *Lucerne*	Semi-dormant / *Semi-dormant*	Sandy loam	Pivot	***	No	200

Mielies / *Maize*	Kort groeiers / *Short growers*	Loam	Pivot	15/12	Yes	300
Koring / *Wheat*	Intermediêre tipe / *Intermediate type*	Loam	Pivot	15/6	Yes	300
Sitrus / *Citrus*	Geen grondbedekking / *No ground cover*	Sandy loam	Micro sprinkler	***	No	75

Crops (ha) (your information)
(Dui asseblief aan gewas-area per tekstuurklas en besproeiingstelsel-kombinasies.) Please indicate crop area per soil texture class and irrigation system combinations)

Crop	Crop type	Soil	Irrigation system	Plant or start date	Double crop (Yes/No)	Ha
Lusern / *Lucerne*	Semi-dormant / *Semi-dormant*	Clay loam	Flood	***	No	240

Appendix- III: Statistical analysis of different irrigation systems for Semi-arid cold (Sand-Vet Irrigation scheme)

	Effective rainfall			Irrigation requirements			Total irrigation water		
Description/Treatment	mean	SE	P-value	mean	SE	P-value	mean	SE	P-value
Irrigation Type									
Centre Pivot IRR	-2.89a	O,86	0.157	10.16a	1.14	0.0636	6.99a	0.93	0.051
Drip IRR	-0.52a	1.50		5.14a	1.97		3.06a	1.61	
Linear IRR	0.91a	2.11		12,12a	2.79		9.56a	2.67	
Management									
CONS	4.44b	1.29	0.0001*	7.21b	1.70	0.041	6.74a	1.38	0.803
STRESS	-8.32a	1.31		11.31a	1.65		6.04a	1.27	
Interactions (Climate x Management)									
Centre Pivot x CONS	4.30a	1.22	0.147	8.49b	1.61	0.0479	7.68b	1.31	0.045
Centre Pivot x STRESS	-10.09a	1.28		11,3b	1.63		6.30b	1.25	
Drip x CONS	5.25a	2.11		2.71c	2.79		3.48c	2.27	
Drip x STRESS	-6.28a	2.05		7.56b	2.69		2.63c	2.29	
Linear x CONS	3.62a	2.99		8.53b	3.94		7.61b	3.31	
Linear x STRESS	-1.81a	2.95		15.71a	3.84		11.31a	3.30	

Appendix- IV: Statistical analysis of different soil types under centre pivot irrigation system for Semi-arid cold (Hartbeespoort Irrigation scheme)

	Effective rainfall			Irrigation requirements			Total irrigation water		
Description/Treatment	mean	SE	P-value	mean	SE	P-value	mean	SE	P-value
Soil Type									
Clay/loam	0.02a	3.51	0.645	13.69a	1.56	0.8046	8.33a	2.30	0.7299
Sandy loam/Silt loam	-2.33a	3.64		13.13a	1.61		7.17a	2.39	
Management									
CONS	5.58a	3.57	0.011*	6.46b	1.58	<0.0001	5.66a	2.35	0.2088
STRESS	-7.80b	3.61		20.39a	1.61		7.89a	2.01	
Interactions									
Clay/loam x CONS	6.61a	4.96	0.9698	6.71b	2.21	<0.0001	6.14b	3.25	<0.05
Clay/loam x STRESS	-6.57a	4.75		20.67a	2.23		10.51a	3.01	
Sandy/silt x CONS	4.46a	5.15		6.18b	2.28		5.13b	3.38	
Sandy/silt x STRESS	-7.11a	5.16		20.08a	2.26		9.22a	3.42	

Appendix- V: Statistical analysis of different irrigation systems (Drip and flood irrigation) for Semi-arid hot (Hartbeespoort Irrigation scheme)

	Effective rainfall			Irrigation requirements			Total irrigation water		
Description/Treatment	mean	SE	P-value	mean	SE	P-value	mean	SE	P-value
Irrigation Type									
Drip IRR	-17.62a	1.14	0.0936	21.11a	1.62	0.462	7.46b	0.91	0.0042
Flood IRR	-13.69a	1.98		18.70a	2.81		13.02a	1.58	
Management									
CONS	-11.08b	1.61	<0.0001	11.58b	2.29	<0.0001	4.84b	1.28	<0.0001
STRESS	-22.21a	1.60		29.44a	2.32		12.86a	1.31	
Interactions									
Drip x CONS	-11.66	1.61	<0.0001	12.55b	2.29	<0.0001	4.19b	1.28	<0.0001
Drip x STRESS	-23.59a	1.62		29.67a	2.13		10.73a	1.25	
Flood x CONS	-9.32b	2.76		8.66b	3.97		6.78b	2.23	
Flood x STRESS	-18.06a	2.59		28.74a	3.75		19.26a	2.11	

Appendix- VI: Statistical analysis of different irrigation systems for Semi-arid hot (Hartbeespoort scheme)

	Effective rainfall			Irrigation requirements			Total irrigation water		
Description/Treatment	mean	SE	P-value	mean	SE	P-value	mean	SE	P-value
Irrigation Type									
Micro-spray IRR	-5.83b	2.46	0.028	17.01a	1.52	0.127	7.59a	1.63	0.872
Sprinkler Permanent	2.23a	1.08		11.05a	0.73		7.26a	1.38	
Management									
CONS	-0.13a	2.18	0.391	7.20b	2.86	0.001	3.98b	1.52	0.005
STRESS	--2.08a	2.84		20.04a	2.42		10.81a	0.73	
Interactions									
Micro-spray x CONS	-1.74a	3.48	0.120	9.26b	1.52	0.001	4.62b	1.52	0.032
Micro-spray x STRESS	-9.84a	3.30		24.76a	0.73		10.56a	0.73	
Sprinkler Per. x CONS	-1.01a	2.94		5.42b	1.52		3.52b	1.52	
Sprinkler Per x STRESS	3.64a	2.82		16.67a	0.73		10.98a	0.73	

Appendix- VII: Statistical analysis of different soil types for Semi-arid cold (Hartbeespoort Irrigation scheme)

Description/Treatment	Effective rainfall			Irrigation requirements			Total irrigation water		
	mean	SE	P-value	mean	SE	P-value	mean	SE	P-value
Soil type									
Clay	-0.31a	0.97	0.521	17.35a	1.33	0.006	12.21a	0.93	0.007
Loam-Silt	-2.04a	1.21		10.41b	1,67		6.41b	1.16	
Sandy	-1.45a	1.96		12.74b	1.04		8.03b	1.19	
Management									
CONS	5.54b	0.93	<0.0001	8.64b	1.27	<0.0001	7.94b	0.89	0.082
STRESS	-7.77a	0.94		19.59a	1.56		10.89a	0.85	
Interactions									
Clay x CONS	7.69a	1.37	0.185	13.21b	1.88	0.026	12.14a	1.31	0.013
Clay x STRESS	8.30a	1.35		21.49a	1.95		12.27a	1.45	
Loam-Silt x CONS	3.28a	1.72		5.02c	2.36		3.75b	1.68	
Loam-Silt x STRESS	7.35a	1.65		15.08b	2.34		9.07a	1.64	
Sandy x CONS	4.44a	1.72		5.08c	2.36		5.51b	1.04	
Sandy x STRESS	7.34	1.69		20.40a	2.05		10.54a	1.78	

Appendix- VIII: Statistical analysis of different cropping patterns for Arid- hot (Orange-Vaal Irrigation scheme)

Description/Treatment	Effective rainfall			Irrigation requirements			Total irrigation water		
	mean	SE	P-value	mean	SE	P-value	mean	SE	P-value
Management									
CONS	3.463b	1.52	0.0003	12.45b	2.24	0.0093	11.425b	2.10	0.0405
STRESS	-11.233a	2.16		22.16a	2.33		17.901a	1.98	