ASSESSING THE WATER FOOTPRINTS OF SELECTED FUEL AND FIBRE CROPS IN SOUTH AFRICA

Report to the
WATER RESEARCH COMMISSION

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EXECUTIVE SUMMARY

Background and rationale

South Africa is a water-scarce country and is ranked 30th in the world in terms of water scarcity (DWA, 2013). Climate change adds another dimension of stress to the pressure on water resources (DWA, 2012) by causing more erratic precipitation patterns and increased variability in river flows and aquifer recharge (Chapagain and Tickner, 2012). Rapid population growth and increasing variability in rainfall has led to tighter water supply in many parts of South Africa where the water demand often exceeds the supply. Despite the growing interest in water footprint assessments in the context of ever-increasing water scarcity in South Africa, no research has yet been done to assess the water footprint of fuel and fibre crops in South Africa. Given the growing need for biofuel and fibre to meet the needs of a growing population within South Africa, within the context of a freshwater resource that is becoming increasingly scarce, water-related business risks faced by role-players in the respective industries are ever increasing. Businesses, globally and in South Africa, rely on good, quality data on water footprints in the regional context to ensure that freshwater is used in a sustainable manner. Such data is not currently available in South Africa. Thus, there is a major need to assess the water footprint of fuel and fibre crops within South Africa in order to understand the current status of water risk in South Africa, and to define the benchmark of the water footprint of production in South Africa to inform businesses and other role-players regarding the sustainable use of freshwater for economic activities. Moreover, while climate change is accepted as a phenomenon that will impact on the future availability of and demand for freshwater, no research has been done to assess the water footprints of products within the context of the expected future climate. Such research is necessary to inform policymakers, water managers and water users to adapt their actions in a timeous manner to ensure the future sustainability, taking into account how the scarce freshwater resource is used.

Project aims

1. *To determine the water footprint of selected fuel and fibre crops in South Africa;*
2. *To determine the economic productivity of the water footprints of the selected fuel and fibre crops;*
3. *To assess the blue water scarcity in selected study sites where fuel and fibre crops are produced in South Africa; and*
4. *To determine the water footprints of selected fuel and fibre crops in the context of projected future climate change scenarios in South Africa.*

The research was conducted as a series of case studies. The Global Water Footprint Standard (GWFS) was used in the first four case studies to calculate the water footprints of sugarcane, cotton, biodiesel produced from sunflower, and tobacco. The last case study addressed the impact of expected climate change on the water footprint of sugarcane production. The case study of sugarcane was extended to include an analysis of the impact of certain management practices on the water footprint of sugarcane. The case studies on cotton and tobacco included an analysis of the economic water productivity and the blue water scarcity in the catchment within which the specific study areas fall. The case study of the biodiesel produced from sunflower included an economic and agricultural feasibility study to understand the future prospects of producing biodiesel from sunflower.

Main findings

Case study of sugarcane production

The WF_{tot} (blue plus green water footprints) values calculated for irrigated sugarcane production (86-103 m^3/ton) were generally lower than the values reported by other researchers (86-274 m^3/ton). This is ascribed to the fact that ideal management was assumed in simulations, leading to high cane yields and low water use arising from perfect irrigation management.

The green water footprint (WF_{green}) values calculated for rainfed sugarcane production (96-130 m^3/ton) are also mostly lower than the values reported in the literature (101-264 m^3/ton). This is ascribed to the ideal crop management assumed in simulations, leading to high yields and efficient use of water, while values from the literature are based on actual yields measured in experimental and commercial situations.

WF_{tot} (86-103 m^3/ton) and blue water footprint (WF_{blue}) (17-59 m^3/ton) for irrigated sugarcane production varied markedly between the different mill supply areas, while the WF_{green} for rainfed production also varied between mill supply areas (96-130 m^3/ton). These results suggest it might not be appropriate to have single benchmarks for irrigated and rainfed sugarcane production for all of South Africa. The spatial variation in sugarcane yield (CY), crop water use (CWU) and water footprint indicators, caused mainly by variation in climatic conditions, suggest that water footprint benchmarks will have to be context specific.

Results suggest that management practices will have an impact on the water footprint of irrigated sugarcane production. Irrigation system type had a relatively large impact on water footprint (WF) indictors. Using an efficient system like subsurface drip (SSD) reduced irrigation demand

and therefore WF_{blue} and WF_{tot} for both mulch cover types and for both soil types investigated, as compared with a less-efficient system like CP. The reduction was largest (10%) for shallow soil covered with a light mulch cover.

Improving irrigation efficiency is therefore considered a feasible way of reducing the water footprint (WF) of irrigated sugarcane production significantly, while the use of thick mulch cover of crop residue will also contribute, but to a lesser extent. These interventions are likely to have bigger impacts on soils with lower water-holding capacity

Case Study of Cotton

The cotton case study was conducted at the Loskop Irrigation Scheme, one of the largest cotton-production regions in South Africa. Based on the results, it is concluded that the $WF_{blue+green}$ of irrigated cotton of early planting season in September was 1173 m^3/ton. Of the $WF_{blue+green}$, the WF_{green} of cotton was 685m^3/ton and the WF_{blue} was found to be 488 m^3/ton. For the early cotton crop planted in September, the WF_{blue} was about 40% and the WF_{green} about 60% of the $WF_{blue+green}$. During the late planting season in October, it was concluded that the $WF_{blue+green}$ of irrigated cotton was 1054 m^3/ton. The WF_{blue} was found to be 392 m^3/ton, while the WF_{green} was 662 m^3/ton. Of the $WF_{blue+green}$ of 1054 m^3/ton, 63% of the water required was contributed by rainfall. The results show that, although the biggest part of water requirement is met through effective rainfall, cotton production at the study site does require supplementary irrigation to meet the shortfall. The dependence on irrigation water implies that the cotton industry does face water-related risk. Water users have to make sure that relevant management practices are applied to help them to minimise the water footprint of the crop they produce.

The incomes generated per unit of irrigation water used in the production of early cotton at Loskop irrigation scheme were 7.23 and 8.69 ZAR/m^3 for early and later planted cotton

With regard to the blue water scarcity and the production of cotton at the study site, the results show seasonal irrigation demand patterns fortunately match seasonal irrigation water availability patterns.

Case Study of Sunflower and biodiesel

The case study of biodiesel produced from sunflower was conducted in the Free State Province of South Africa. Both irrigated (at the Oranje-Riet Irrigation Scheme) and rainfed (in the Viljoenskroon district) sunflower productions were included in the water footprint assessment. Very little sunflower is produced under irrigation because of low profitability levels. The water footprints of the sunflower-biodiesel value chain amounted to 2625 m^3/ton and 2484 m^3/ton for biodiesel produced from rainfed sunflower and irrigated sunflower, respectively. The results confirm related studies from abroad, that around 99% of the water footprint of biodiesel is attributed to the primary production of the fuel crop. As such, it is important to ensure that water is used efficiently in the production of the fuel crop when aiming to minimise the water footprint of biodiesel.

With regard to the feasibility of biodiesel production from sunflower, it was found in this study that the biodiesel market is highly dependent upon the fossil diesel market. The economic feasibility of commercial biodiesel production in South Africa was found to be dependent upon government legislation, especially considering that the break-even price of biodiesel exceeds the fossil diesel price; therefore, the market can be sustainably created when there are certain laws and regulations in place.

Case Study of tobacco production

The tobacco case study was also conducted at the Loskop Irrigation Scheme, where the WF_{green}, WF_{blue} and $WF_{green+blue}$ were calculated for irrigated tobacco production. The WF_{green} and WF_{blue} were calculated to be 913 m^3/ton and 638 m^3/ton, respectively. $WF_{green+blue}$ thus added up to 1511 m^3/ton. Effective rainfall constituted about 60% of the total volume of water that was used to produce tobacco. Thus, while rainfall does meet a large part of the volume of water that is required to produce tobacco, a significant volume of irrigation water is still required to cover the shortfall in order to meet the crop water requirement.

The blue water scarcity assessment in the Olifants River Basin showed a blue water scarcity index in excess of 100% for the months of June to November. From December to May, the index is lower than 100%, implying that there is sufficient water to meet the demands of all users. The period of sufficient supply also corresponds with the period when tobacco requires more water. As such, the production of tobacco at Loskop Irrigation scheme may be considered sustainable, from a water use perspective. The economic blue water productivity analysis also showed that about R18 of income is generated at farm level per cubic metre of water that is used for the primary production of tobacco.

Impact of climate change on the water footprint of sugarcane

The case study exploring the impact of climate change on the water footprint of sugarcane production was conducted in the irrigated and rainfed sugarcane production areas in South Africa. The green water footprint and the blue water footprint of irrigated sugarcane production were determined under baseline and future climate scenarios. Similarly, the green water footprint of rainfed sugarcane production was determined under baseline and future climate scenarios. Results were presented in cumulative probability distribution graphs to gain insight into the expected distribution of the respective water footprint indicators. It is noted that, conventionally, the idea with a water footprint assessment is to have a relatively easily understandable indicator that can be used to inform people with different backgrounds as to the impact that their consumption behaviour has on the scarce freshwater resource. The purpose of this case study, however, was not necessarily to provide such an indicator for easy interpretation. The idea was to provide insight to the scientific community and other relevant and knowledgeable role-players in the sugar industry into what can be expected to happen with the water footprint of sugarcane production under a future climate scenario.

The results show that CY is expected to increase within all of the selected mill supply areas under the future climate scenario. Yield increases range from 1 to 4% for irrigated areas and from 4 to 32% for rainfed supply areas. The increases for rainfed cane are strongly related to expected rainfall increases in those areas, as well as increased water use efficiency during periods of drought. The future climate scenario is also associated with higher CWU than the baseline. It should be noted that simulations assumed a small increase in rainfall and adequate irrigation water supply. It should also be noted that the IPCC Assessment Report that appeared after this research was conducted points to declining rainfall. Schulze and Taylor (2016) also point to declining irrigation water supply in the future.

When considering the water footprint of sugarcane under the future climate scenario, there proved to be mixed results. While WF_{green} *increased for all of the irrigated areas,* WF_{blue} *changed little. The* WF_{green} *for rainfed sugarcane production was found to decrease in all but one of the areas under consideration. The decrease in* WF_{green} *was achieved because CY increased proportionally more than what* CWU_{green} *increased.*

Based on the results it is concluded that:

There is spatial variation in the impact of climate change on the water footprint of sugarcane production. The variation relates to the variation in expected rainfall in the future climate scenario, as well as the baseline yield potential.

Effective rainfall is currently, and will remain, a major source of water for irrigated sugarcane production, as is evident from the proportional contribution of the WF_{green} *to the total WF.*

Despite the contribution of rainfall to meet the water requirements of the crops, irrigation will still remain important to make up rainfall shortfalls in most currently irrigated areas.

The relatively large WF_{blue}*, compared with the* WF_{green}*, represents a serious risk to the sugar industry in the irrigated areas.*

The spatial variation in results suggests that recommendations should be considered, and other actions taken to mitigate the potential negative impact of climate change, or to exploit opportunities created through climate change, which have to be context specific.

There is serious pressure on water users, water managers and policymakers to ensure the future sustainability of the sugar industry.

LIST OF ACRONYMS AND ABBREVIATIONS

CP	Centre pivot irrigation system
CWP	Crop water productivity
CWU	Crop Water Use
CWU_{blue}	Blue crop water use
CWU_{green}	Green crop water use
CWU_{irr}	Crop water use under irrigated condition
CWU_{rf}	Crop water use under rainfed condition
CY	Sugarcane yield
DAFF	Department of Agriculture, Forestry and Fisheries
DMC	Direct Manufacturing Costs
DRO_{irr}	Deep drainage plus surface runoff under irrigated conditions
DRO_{rf}	Deep drainage plus surface runoff under rainfed conditions
DWA	Department of Water Affairs
EFR	Environmental Flow Requirement
EI	Effective Irrigation
ER	Effective Rainfall
ET	Evapotranspiration
$ET_{eff,irr}$	Effective Evapotranspiration under irrigated condition
$ET_{eff,rf}$	Effective Evapotranspiration under rainfed condition
ET_{irr}	Evapotranspiration under irrigated condition
ET_{rf}	Evapotranspiration under rainfed condition
EWP	Economic Water Productivity
FAO	Food and Agriculture Organization
FCI	Fixed Capital Investment
GDP	Gross Domestic Product
GHGs	Greenhouse gases
GWFS	Global Water Footprint Standard
HHV	High Heating Value
I	Irrigation
IL	Irrigation Loss
IMC	Indirect Manufacturing Costs
ISO	International Standard Organization
LCA	Life Cycle Assessment

MARR	Minimum Acceptable Rate of Return
PPECB	Perishable Products Export Control Board
R	Rainfall
RL	Rain Loss
ROI	Return on Investment
SA	South Africa
SADC	Southern African Development Community
SAPWAT	South African Procedure for estimating irrigation water requirements
SASA	South African Sugar Association
SSD	Subsurface drip irrigation system
TCI	Total Capital Investment
TMC	Total Manufacturing Cost
USA	United States of America
WCI	Working Capital Investment
WF	Water Footprint
WF_{blue}	Blue water footprint
WF_{green}	Green water footprint
WF_{tot}	Blue + green water footprint
WFA	Water Footprint Assessment
WFN	Water Footprint Network
WP	Water productivity
WRC	Water Research Commission
WS	Water Scarcity
WWF-SA	World Wide Fund for Nature South Africa

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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CHAPTER 1
INTRODUCTION

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1.1 BACKGROUND AND MOTIVATION

Sharing resources equitably among a future world population of potentially nine billion people, while maintaining the planet's natural capital, will only be possible with a paradigm shift in favour of wise, informed choices about the use of land and other natural resources, at all levels, from local to global. Current choices on how to use natural resources for economic production are driven by growing demands for food, water, fibre and biofuels and are typically dominated by narrow sector-based interests. Only by taking a holistic approach can we make better trade-offs between different ways of using the natural resources that we all need for a sustainable future (Chapagain, 2015). Water is one of the most pressing and complex issues facing sustainability practitioners. As population growth, economic development and climate change intensify pressures on rivers, lakes and aquifers, many companies are becoming aware that water scarcity and pollution present strategic risks to their operations, supply chains and reputations. The pivotal role of water in economic development and in ensuring thriving ecosystem services is gaining stronger footholds in recognition. The World Economic Forum, in its 2015 survey of global business risks (WEF, 2015), concluded that water crises are likely to have the biggest impacts on economies around the world, ahead of challenges such as fiscal crises in key economies and structural unemployment.

The combination of increased water demand, pollution, poor management and climate change, together with ever-more complex and globalised supply chains, means that water-related risks arising in different parts of the planet are affecting more and more companies (Chapagain and Tickner, 2012). For many companies, these risks pose very immediate challenges. The costs of mitigation measures can be significant, in terms of financial or social capital, or both. Food, drinks and fibre manufacturers have been the first to feel the hydrological squeeze. Major institutional investors are also now asking questions about water. The CDP (formerly the Carbon Disclosure

Project) surveys companies about water-related risks in order to inform investors of the state of play. Currently, the survey is backed by 573 different investors, representing some US $60 trillion in assets. In CDP's 2013 survey, 70% of Global 500 companies reported exposure to substantive water-related risks; and 64% of them said that such risks were expected to have an impact now or in the next five years.

South Africa is a water-scarce country and is ranked 30^{th} in the world in terms of water scarcity (DWS, 2013). Climate change adds another dimension of stress to the pressure on water resources (DWA, 2012) by causing more erratic precipitation patterns and increased variability in river flows and aquifer recharge (Chapagain and Tickner, 2012). Rapid population growth and increasing variability in rainfall has led to tighter water supply in many parts of South Africa where the water demand often exceeds the supply. Irrigated agriculture in South Africa is using roughly 40% of the exploitable runoff (Backeberg and Reinders, 2009:4). Other estimates suggest that agricultural production use is as high as 60% of the available water (DWS, 2013:08). Irrigated agriculture proves to be a major user of freshwater in South Africa. With such a high proportion of the water used by the agricultural sector, there is increasing pressure on agriculture from government and others to use less water, while maintaining crop yields. Thus, irrigated agriculture may face significant water-related risks that will constrain the contribution of irrigated agriculture towards poverty alleviation in South Africa. According to DWA (2012), water requirements already exceed availability in the majority of water management areas in South Africa, despite significant transfers from other catchments. The pressure thus is mounting on the effective management of our fresh water resource. In the proposed National Water Resource Strategy 2 (NWRS 2), it is acknowledged that appropriate strategies, skills and capabilities are required to ensure the effective management of the fresh water resource (DWA, 2012). DWA (2012) further acknowledges that economic growth has to be planned in the context of sector-specific water footprints, as well as the relevant socio-economic impacts and contributions, since economic growth targets cannot be achieved at the expense of the ecological sustainability of water resources, or the obligation to meet people's basic needs.

Globally, the concept of water stewardship is receiving increased attention by businesses to describe a growing private sector engagement with water issues. Water stewardship can be defined as a progression of increased improvement of water use and a reduction in the water-related impacts of internal and value chain operations. More importantly, it is a commitment to the sustainable management of shared water resources in the public interest through collective action with other businesses, governments, NGOs and communities. It is distinct from, but builds on, water efficiency because it obliges a company to move beyond its factory fence to engage other stakeholders in the river basin or territory where its risk is located.

The concept of a water footprint is emerging as an important sustainability indicator in the agriculture and food sectors (Ridoutt *et al.*, 2010:5114). It is a relatively new concept, well situated to contribute towards the efficient use of fresh water. A water footprint represents the volume of freshwater used to produce a product. It is measured throughout the value chain of the product, from the inputs up to the point where the end product reaches the consumer (Hoekstra *et al.*, 2011:02). Hoekstra *et al.* (2011) distinguish between three different categories of water footprint: blue, green, and grey water footprints. The first is defined as the surface and groundwater that is consumed (water that has evaporated and the water that was incorporated into the product) along the value chain of a product. All the rainwater that does not become run-off, but is consumed, represents the green water footprint. The grey water footprint is defined as the volume of freshwater needed to reduce the pollutants to ambient levels. While a water footprint thus contributes a measurable representation of the volume of freshwater that is used to produce food products, its true contribution is the fact that it also considers the degree of sustainability with which the freshwater was used (Hoekstra *et al.*, 2011). Rather than focusing merely on the volume of water that was used (volumetric water footprint indicator), the volume is interpreted in the context of freshwater availability in a spatial-temporal dimension.

Since the mid-2000s, a large number of water footprint assessments have been undertaken globally, with the Water Footprint Network leading research endeavours on this topic. A number of WFAs have also been done in South Africa since the mid-2010s. The focus of those studies was mainly on beef (Maré and Jordaan, 2019); horticultural products (Van der Laan, 2017; Munro *et al.*, 2014); field and forage crops (Jordaan *et al.*, 2019); and table and wine grapes (Jarmain, 2020). Thus, there is growing interest within the South African context to contribute to the limited body of knowledge on the water footprint of agri-food production in South Africa.

Despite the growing interest, however, no research has yet been done to assess the water footprint of fuel and fibre crops in South Africa. Given the growing need for biofuel and fibre to meet the needs of a growing population within South Africa, within the context of a freshwater resource that is becoming increasingly scarce, water-related business risks faced by role-players in the respective industries are ever increasing. Internationally, the increased risk has led to the development of tools, such as the Water Risk Filter Tool of WWF, and Aqueduct of the World Resources Institute, to use to gain insight into the water risks that businesses face globally. Businesses, globally and in South Africa, rely on good, quality data on water footprints in the regional context to ensure that freshwater is used in a sustainable manner. Such data are not currently available in South Africa. Thus, there is a major need to assess the water footprint of fuel and fibre crops within South Africa in order to understand the current status of water risk in South Africa. Accordingly, it is necessary to define the benchmark of the water footprint of production in South Africa to inform businesses and other role-player regarding the sustainable use of freshwater for economic activities. Moreover, while climate change is accepted as a phenomenon that will impact on the future availability of and demand for freshwater, no research has yet been done to assess the water footprints of products within the context of the expected future climate. Such research is necessary to inform policymakers, water managers and water users to adapt their actions in a timeous manner and to also ensure the future sustainability with which the scarce freshwater resource is used.

1.2 AIMS

1. To determine the water footprint of selected fuel and fibre crops in South Africa;
2. To determine the economic productivity of the water footprints of the selected fuel and fibre crops;
3. To determine the blue water scarcity in selected study sites where fuel and fibre crops are produced; and
4. To determine the water footprints of selected fuel and fibre crops in the context of projected future climate-change scenarios in South Africa.

1.3 LAYOUT OF REPORT

The layout of the rest of the Report is as follows: Chapter 2 is a literature review where the water situation in South Africa is briefly discussed, followed by the theoretical framework, and then by related studies that were reviewed to inform this research. Chapters 3 through 7 are case studies where the water footprints of selected fuel and fibre crops were calculated, together with assessments of the economic water productivity and the level of blue water scarcity in the catchment within which the case studies fall. More specifically, Chapter 3 is concerned with a case study of sugarcane production; Chapter 4 is a case study on cotton production; Chapter 5 covers the water footprint of biodiesel produced from sunflower; Chapter 6 is a case study of tobacco production; and Chapter 7 is a case study exploring the impact of expected climate change on the water footprint of irrigated and rainfed sugarcane production. This report is then concluded in Chapter 8, where conclusions are drawn and recommendations made, based on the results of the research reported in the earlier chapters.

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CHAPTER 2
LITERATURE REVIEW

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2.1 INTRODUCTION

The aim of Chapter 2 is to provide discussion of the relevant literature that was reviewed to inform this research. Chapter 2 starts with a brief report of the water situation in South Africa in order to provide context and explain the importance of this research. Thereafter, a discussion follows on the theoretical framework, where the theory of water footprint assessment and the different methods of water footprint assessment are addressed. Some related studies are also briefly discussed. After the discussion of the related studies, the focus of attention shifts to sustainability assessment, where the focus is placed on blue water scarcity in the catchments within which the case studies are located. The chapter then is concluded with a discussion of the economic valuation of the water footprint, and the conclusions that were drawn from the reviewed literature that is reported in Chapter 2.

2.2 WATER SITUATION IN SOUTH AFRICA

Water covers 75% of the earth's surface of which 97.5% is salt-water, with only 2.5% available as freshwater. Furthermore, water is a life-sustaining element that cannot be substituted; it is a globally crucial and invaluable resource that is necessary for all spheres of humanity and its civilisations (Chye *et al*., 2018; Jewitt and Kunz, 2011; Koehler, 2008). Although this element is critical to all living organisms, innumerable factors involving overdevelopment, pollution, and climate change threaten the sustainability of freshwater. Industrialisation has increased a growing global demand for water use, which harms the available freshwater resources (Donnenfeld *et al*., 2018). Wallace (2000) and Gerbens-Leenes *et al*. (2009a) argued that humanity will at some point struggle to attain the amount of freshwater required to satisfy their needs; therefore, it is important to implement proper and efficient ways to use water resources, worldwide.

South Africa is a water-scarce country, receiving an average rainfall of about 490 mm, which is below the global average rainfall level of 860 mm, and it has been ranked the 30th driest country in the world (Zhang *et al*., 2019; Donnenfeld *et al*., 2018; Colvin *et al*., 2016; WWF-SA, 2016; Haw and Hughes, 2007). The South African economy is developing and this is increasing the demand for water use (Colvin and Muruven, 2017). There is a reciprocal relationship between economic development and water demand, which necessitates a reliable, sufficient, and safe water supply to support this economic development, although this will also require the adequate security of water resources (Orr *et al*., 2009). Secured water resources depend on sustainable supplies from the available sources, but water sources in South Africa have recently been threatened by uncertainty in water supply because of low rainfall and the resulting drought conditions (Zhang *et al*., 2019; Wolski, 2018; Sparks *et al*., 2014). The drought has highlighted the existence of vulnerabilities in the South African water system and the need for a properly framed structure to overcome the challenge of ensuring water security for the country (Donnenfeld *et al*., 2018). Water is considered to be the most significant resource within the agricultural sector because it drives the sustainable development of the sector (Zwane, 2019; Chartzoulakis and Bertaki, 2015).

In South Africa, the agricultural sector consumes approximately 60% of the exploitable runoff (Donnenfeld *et al*., 2018; Wallace, 2000). This bulk use of freshwater within this sector exposes an inefficient utilisation of available water and an undesirable value-adding relationship, since the agricultural sector contributes about 2% to the GDP of this country (Zwane, 2019; Van Heerden *et al*., 2008; Nieuwoudt *et al*., 2004). It has been projected that the demand for freshwater within the agricultural, industrial and municipal sectors in South Africa will increase in the upcoming years (Archer *et al*., 2019). This growing demand is driven by the combined influence of growth in the population, urbanisation, the manufacturing sectors, income levels, the expansion of irrigation, energy demands, and the exploration of activities, such as biofuel production (Archer *et al*., 2019). The large national consumption of water by the agricultural sector is aligned with the global trend (see Figure 2.1 below).

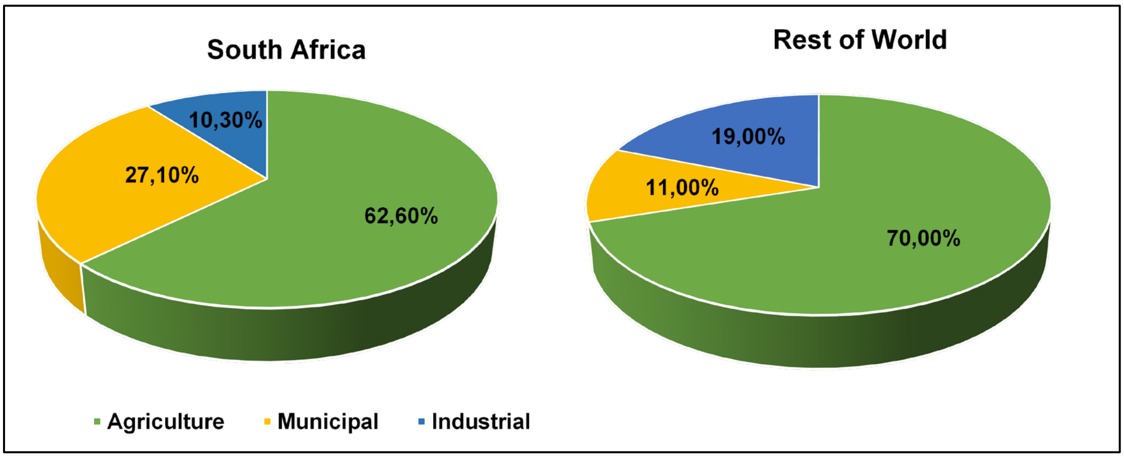

Figure 2.1: Comparison of water consumption in South Africa with the global consumption within the main water-consuming sectors
Source: adapted from Donnenfeld *et al.* (2018)

At a global scale, the industrial and municipal sectors consume the second and third largest volumes of water, respectively, behind the agricultural sector. However, in South Africa, the opposite is the case, where the municipal sector is the second-largest consumer of water resources, while the industrial sector is the third-largest consumer. Although there are limited amounts of freshwater resources in South Africa, the national average water consumption is above the global average, at about 235 litres per capita per day, compared with a global average of 175 litres per capita per day (Donnenfeld *et al*., 2018). It is important to monitor, restore, maintain, and manage water resources to secure and sustain the available water supplies (Harrison *et al*., 2016).

South Africa has been highly water-stressed recently because of drought conditions in most of its provinces (Zhang *et al*., 2019). Water usage restrictions in terms of daily quotas have been put in place to limit overuse. The extraction and use of freshwater are currently obtained at higher costs, mostly for human consumption and agricultural activities. The extensive use of water calls for the use of proper techniques that would enable increased productivity within the existing water use activities, while ensuring that adequate water supplies are available to be used for other economic significant activities (Sershen *et al*., 2016; Siebrits *et al*., 2014).

2.3 THEORETICAL FRAMEWORK

The concept of the Water Footprint was first introduced by Hoekstra (2003). A water footprint measures the direct and indirect freshwater used by consumers or producers (Hoekstra *et al*., 2011). The water footprint is a geographically and temporally explicit indicator, displaying not only the volumes of water use and pollution, but also their locations. Hoekstra *et al.* (2011) emphasised that the water footprint can be regarded as a comprehensive indicator of freshwater use and should be used along with the traditional and restricted measures of water withdrawal. Ultimately, the aim of the water footprint is to investigate the sustainability of freshwater use. This is achieved by comparing the water footprint with the freshwater availability (Hoekstra and Mekonnen, 2011; Hoekstra *et al*., 2012).

A number of methods are available to calculate the water footprint. These include the consumptive water use based volumetric water footprint method referred to as the Global Water Footprint Standard (GWFS) (Hoekstra *et al*., 2011), the stress weighted water Life Cycle Assessment (LCA) suggested by Pfister *et al*. (2009) and the hydrological water balance method loosely based on the methods developed by Hoekstra *et al*. (2011).

2.3.1 The Water Footprint according to the Global Water Footprint Standard

2.3.1.1 Conceptualising the Global Water Footprint Standard

As noted above, the concept of a Water Footprint was first introduced by Hoekstra (2003). A water footprint measures the direct and indirect freshwater used by consumers or producers, by comparing yield and the water usage. A water footprint comprises three types of water components/indicators, that is, the blue, green and grey water footprint indicators (Hoekstra *et al*., 2011). The water footprint is a geographically and temporally explicit indicator, displaying not only volumes of water use and pollution but also their locations. Characteristically, the vital intention of the water footprint assessment is to determine the sustainability of water resources by making the comparisons among water footprints and freshwater availability (Hoekstra and Mekonnen, 2011:2012). The following section focuses on explaining the concept of a water footprint and the different concepts and types of water footprints.

The consumptive water use volumetric water footprint is based on the green, blue, and grey water footprint components (Hoekstra *et al.*, 2011). Figure 2.2 below illustrates the components of the water footprint indicator according to GWFS.

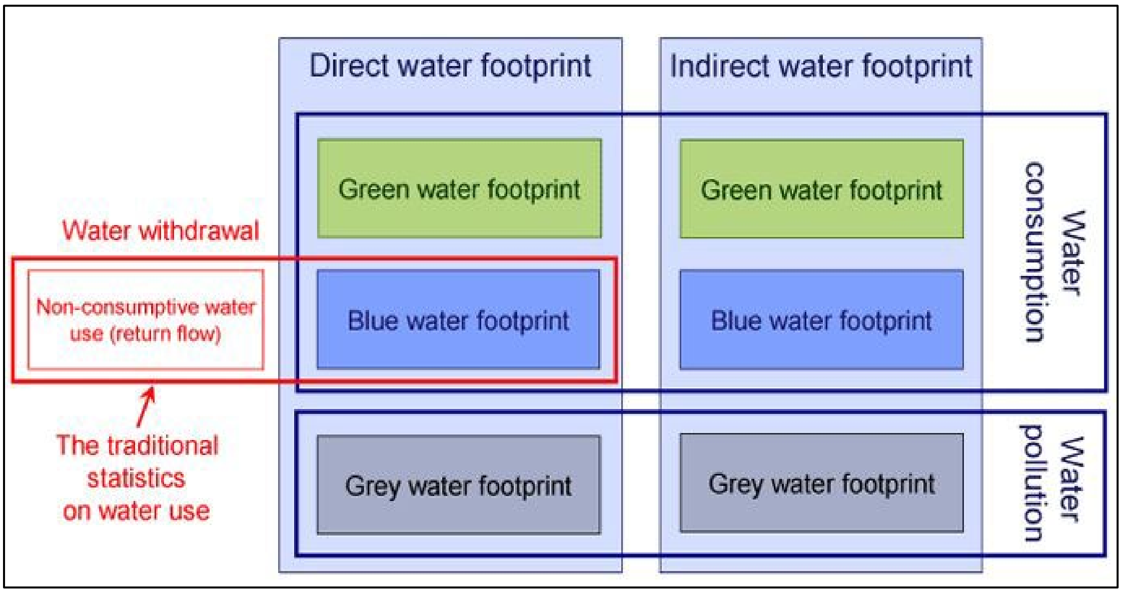

Figure 2.2: A schematic illustration of the components of a water footprint indicator
Source: adapted from (Hoekstra *et al*., 2011)

The schematic illustration of the components of a water footprint indicator shows: surface and groundwater (Blue); rainfall that does not become runoff; and the degradation of the water quality. Direct and indirect water footprint usage is included, whereby blue, green, and grey water categories are shown. The direct water footprint refers to the freshwater consumed during the production of goods and services, and the indirect water footprint refers to freshwater consumed while customers are using the product after production. Water withdrawal is part of the water footprint, as indicated in Figure 2.2.

- **Blue water footprint**

The blue water footprint is an indicator of the consumptive use water, in other words, fresh surface or groundwater. The term 'consumptive water use' covers the following four cases:

- Water evaporates;
- Water is incorporated into the product;
- Water does not return to the same catchment area, for example, it is returned to another catchment area or the sea; and
- Water does not return in the same period, for example, it is withdrawn in a water-scarce period and returned in a wet period.

Consumptive water use does not mean that the water disappears because water will remain within the cycle and always return somewhere. Water is a renewable resource, but that does not mean that its availability is unlimited. Given a certain period, the amount of water that recharges groundwater reserves and that flow through a river is always limited to a certain amount.

- **Green Water Footprint**

The green water footprint is regarded as the rainfall water on the land that does not run off but is stored in the soil and consumed by the crop. However, that does not necessarily mean that the crop has utilised all the green water. Only the rainwater utilised during production is referred to as green water. The water that has evaporated during the period where production was not taking place is not regarded as green water. The use of green water can be estimated through using empirical formulas and crop models that are used to estimate evapotranspiration. Climate, crop characteristics, and soil provide useful data for consideration when estimating the green water used by the crop.

- **Grey water footprint**

The grey water footprint refers to the volume of freshwater used to reduce the pollutants to the acceptable level. This water component indicates the severity of environmental damage caused by pollution. Moreover, it also provides a metric to use to calculate the amount of water that should actually be used to reduce pollution to an acceptable level (Hoekstra *et al*., 2011).

- **Total water footprint**

The total water footprint is calculated by adding the blue water footprint, the green water footprint and the grey water footprint components. Hoekstra *et al*. (2011) define different types of water footprints that may be used to assess the impact of human behaviour on sustainable water use. These comprise the water footprints of a consumer (or a group of consumers); of a geographically delineated area; of a business; of a product; and of the nation where consumption occurs.

2.3.1.2 Different types of Water Footprint according to the Global Water Footprint Standard

Hoekstra *et al*. (2011) defined different types of water footprints, depending on the scope and purpose of the water footprint assessment. These types comprise i) the water footprint of a consumer or a group of consumers; ii) the water footprint of a geographically delineated area; iii) the water footprint of a business; iv) the water footprint of a product; iv) and the water footprint of a nation.

- **A consumer or group of consumers**

The water footprint of a consumer or group of consumers is well defined as the total volume of freshwater consumed and polluted during the production of goods and services used by the consumer. The water footprint of a group of consumers is equal to the sum of the water footprints of individual consumers. Both freshwater consumed and the amount of water polluted during production is considered. The water footprint of a consumer is calculated by adding the direct water footprint of the individual and his/her indirect water footprint.

- **A geographically delineated area**

The water footprint within a geographic area is defined as the total freshwater consumption and pollution experienced within the boundaries of the area. The area can be a catchment area, a river basin, a province, state or nation, or any other hydrological or administrative spatial unit. The water footprint for a spatial unit is expressed as the volume of water per unit of time. Alternatively, it can also be expressed in terms of water volume per monetary unit, where one takes the water footprint per unit of time and divides it by the income in the area. Calculating the water footprint for a geographically delineated area is usually part of a larger assessment of the sustainability of the water resources in the target area.

- **A business**

The water footprint of a business is defined as the total volume of freshwater that is used directly or indirectly to run and support the business. It consists of two main components, being the operational and supply chain water footprints. The operational (or direct) water footprint of a business is the volume of freshwater consumed or polluted due to the business' own operations. The supply chain (or indirect) water footprint of a business is the volume of freshwater consumed or polluted to produce all the goods and services that form the inputs of production of the business. A business water footprint aims to assess the impact of a specific business on water resources. Often, the water footprint of a business is largely imported from elsewhere in the form of water-intensive inputs produced in another catchment. The Water Footprint (WF) of a business is the sum of the WFs of the final products produced by the business, which include the operational WF of the business as well as its supply-chain WF.

- **A product**

The water footprint of a product is defined as the total volume of freshwater that is used directly or indirectly to produce the product. It is estimated by considering water consumption and pollution in all steps of the production chain. The accounting procedure is similar for all sorts of products, be they products derived from the agricultural, industrial or service sectors. The water footprint of a product breaks down into green, blue and grey water components. It is a multidimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution, with all the components of a total water footprint specified geographically and temporally. The WF of a product is the sum of the WFs of the process steps taken to produce the product.

There are two approaches that can be used to estimate the water footprint of a product. The chain-summation approach, which can only be used where the production system produces one output product. The stepwise accumulative approach, which accounts for production processes that have more than one input and several outputs.

- **National water footprint**

A national water footprint comprises an internal component (the WF within the national territory for making products that are consumed within the country) and an external component (the WF in other countries utilised for making products imported by and consumed within the country being considered). The external WF of national consumption is made possible by importing water-intensive commodities. This trade indicates the existence of 'virtual water flows' between exporting and importing countries (Hoekstra, 2003). Finally, the total WF within a certain area (e.g. a municipality, province or state, or a hydrological unit like a catchment area) is the sum of the WFs of all processes taking place within the area. The sustainability of water use can be evaluated by comparing the WF within an area to the maximum sustainable WF in that area (Hoekstra, 2014).

2.3.2 Life Cycle Assessment

The Life Cycle Assessment (LCA) is a methodological framework that assesses and estimates the environmental impacts of products. An LCA includes investigating the impacts of depriving human users and ecosystems of water resources, as well as the potential impacts from the discharged pollutants affecting water, through different impact pathways (Canals *et al*., 2009). ISO 14046 (2014) defines LCA as a tool used to assess the potential environmental impact caused as a result of products and services production. The environmental impacts of products and services can be regarded as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, noise, and others.

For an LCA to be complete, several stages must be included in the process of evaluation, namely setting the goal and scope of the assessment; the water footprint inventory analysis; the water footprint impact assessment; and lastly, the interpretation of the results. All these stages have a direct application to product, development, strategic planning, public policy making and marketing (Boulay *et al*., 2013).

The purpose of LCA studies is to estimate the different sorts of potential environmental impacts attributable to the life cycle of a product, from the 'cradle to the grave' (Hellweg and Milà ì Canals, 2014). According to Pfister *et al*. (2009), the LCA approach accounts for all consumptive water use, comprising all freshwater withdrawals that are merged into the products, including those transmitted to different watersheds and the water loss attributed to evaporation. The study further revealed that measuring virtual water is a vital way by which to determine the consumptive water use in a production process.

Virtual water refers to the volume of water required to produce a good or service, considering all inputs throughout the supply chain of production (Hoekstra and Chapagain, 2007). Quantities of water used in LCA are often reported according to the water source and type of water used, which should clearly be included during the Life Cycle Inventory (LCI) phase (Pfister *et al*., 2009). However, according to the LCA method proposed by Pfister *et al*. (2009), only the blue virtual water footprint is considered because of the notion that green water does not contribute to environmental flows until it becomes blue water.

The LCA method makes use of the virtual water database developed by Chapagain and Hoekstra (2004) to arrive at the volume of water used to produce the relevant products. Once this is done, the Water Stress Index (WSI) is determined. The LCA does provide for water quality impacts, but this is not done with the grey water method as prescribed by Hoekstra *et al*. (2011). Ridoutt and Pfister (2010) explain that in the LCA context, it is more appropriate to include water quality impacts under other impact categories, such as freshwater toxicity or eutrophication, or to apply complex fate and effect models.

Ridoutt and Pfister (2010) argued that WFA, according to the LCA, does not account for green water use directly because the use of this water is directly related to the occupation of land, and it is accounted for somewhere in the complete LCA. An LCA addresses the different types of environmental impacts such as energy consumption and water pollution. These methods have not addressed water requirements to produce a product or a service in the life cycle of a product, but have rather looked at the impact on water resources (Hastings and Pegram, 2012). Hoekstra *et al*. (2011) criticised the LCA because it excludes the analysis of the grey water component. However, according to Ridoutt and Pfister (2010), LCA considers the water quality impacts. Ridoutt and Pfister (2010) recommended that it is more precise to indicate water quality impacts under other impact groups, such as freshwater toxicity or eutrophication, in the LCA. According to Pfister *et al*. (2009) and Bayart (2010), the LCA has its own inadequacies. Nonetheless, it promises to provide a bridge to potential users of intermediate indicators for the protection of human health, the biotic environment and other resources.

2.3.3 Hydrological Water Balance Method

The hydrological water balance method takes into consideration blue, green and grey water. The method recognises the explanation of blue, green, and grey water as defined by Hoekstra *et al*. (2011). According to Deurer *et al*. (2011), wider factor components of water balance, such as inflows, outflows and changes in water storage that are used to calculate water footprint, are considered by the hydrological water balance method. Conflicting with the consumptive water-based volumetric method, the hydrological water balance method allows both negative and positive water footprints. A negative water footprint indicates that the recharge of the blue water resources exceeds total volume abstracted. A positive water footprint indicates that the sum of blue water abstractions is higher than the total recharge through precipitation and return flows. Hence, the distinctiveness of the hydrological water balance method depends on its ability to include a negative water footprint when accounting for ground water.

2.3.4 ISO 14046

ISO 14046 aims to identify potential environmental impacts that are associated with water use (ISO/TC207, 2014). According to ISO 14046, the term "water footprint" can only be used when a comprehensive impact assessment is also undertaken. It is important to note that ISO 14046:2014 does not recommend a particular methodology for conducting a water footprint assessment. It serves as a guide as to what should be considered in the calculation of a complete water footprint assessment.

ISO 14046 defines a water footprint as the quantification of the potential environmental impacts related to water and is based on the LCA approach to environmental impact. A water footprint assessment conducted according to this international standard must be compliant with ISO 14044:2006 and should therefore include the four phases of a LCA. Although both the LCA and WFN approaches can be used to evaluate the water footprints of products in South Africa, the guidelines of the ISO 14046 must also be kept in mind in the reporting of the water footprint indicators of South Africa.

2.3.5 Discussion of Different Approaches

According to the above discussion of different methods of WFA, the methods differ on how the WF is calculated. The discussion gives the confirmation that the Global Water Footprint Standards account for blue, green, grey water, whereas the Life Cycle Assessment accounts for the blue water footprint. On the other hand, the LCA concentrates on the assessment of the potential environmental impacts of the product, although the broader issue of sustainable, resourceful and justifiable allocation of limited freshwater resources from the catchment to global level remains out of its scope (Hoekstra, 2016). The LCA has, however, been criticised for neglecting green water footprints.

Hoekstra (2016) concluded that WFN and LCA are equally worthwhile for being conducted, as they fulfil different purposes, and that it would be valuable to incorporate the two assessments of fresh water scarcity. The LCA accounts for resource depletion categories, and assumes the limited accessibility of freshwater, globally, for productive use. Hence, it is of paramount importance to measure (volumetric) WFs of the products, and to measure the relative claims of different products regarding the scarcity of freshwater. With the hydrological water balance method, the blue, green, and grey water footprints are determined annually on a local scale, and the calculation system differs from that of the Global Water Footprint Standards (GWFS). The GWFS approach is often used as a freshwater sustainability indicator, and it further formulates the strategic response to reduce the water used to produce a product.

In conclusion, the Global Water Footprint Standard proposed by Hoekstra *et al*. (2011) proves to be the suitable method to use for this study, as it accommodates the aims and objectives of the study. The GWFS will therefore be adopted for the purposes of this study.

Next follows a discussion of relevant research exploring the water footprint of fuel and fibre crops.

2.4 RELATED RESEARCH ASSESSING THE WATER FOOTPRINT OF FUEL AND FIBRE CROPS

The discussion of the related research starts with research exploring the water footprint of sugarcane production, followed by research exploring the water footprint of sunflower and biodiesel produced from sunflower.

2.4.1 Research Exploring the Water Footprint of Sugarcane Production

This section focuses on exploring the case studies on the water footprint of sugarcane. Among the studies investigated in this study are: Mekonnen and Hoekstra (2010), who applied a water footprint assessment framework according to the guidelines of WFN by Hoekstra *et al*. (2009); Gerbens-Leenes and Hoekstra (2009), who estimated the WF_{green}, WF_{blue} and WF_{grey} of sweeteners and bio-ethanol produced from sugarcane for the main producing countries; Kongboon and Sampattagul (2012), who assessed the water footprints of sugarcane and cassava in Northern Thailand; and Scarpare *et al.* (2016), who quantified the water footprints of sugarcane in Brazil.

Mekonnen and Hoekstra (2010) estimated the national averages of the water footprints of several crops and crop products for different countries. Among the products investigated were sugarcane, raw sugar, refined sugar, and cane molasses. For South Africa, they estimated that averages of 119 m^3 of green water, 28 m^3 of blue water and 13 m^3 of grey water are required to produce one ton of sugarcane.

In a subsequent study, Mekonnen and Hoekstra (2011) estimated the global average water footprints of sugarcane at 139 m^3 of green water, 57 m^3 of blue water and 13 m^3 of grey water, required to produce one ton of sugarcane. This is significantly lower than the water footprint of raw sugar production, where the global averages come to 1107 m^3 green water, 455 m^3 of blue water and 104 m^3 of grey water, per ton of product. Their findings imply that the water footprint of the milling processes is greater than that of the sugarcane production process.

Mekonnen and Hoekstra (2011) also noted that the global average water footprint could appear larger for one product than the global average water footprint for another product. The difference could be attributable to variations in terms of rainfall, soil type, temperature and precipitation, among and across specific regions. In regions with arid and semi-arid conditions (such as South Africa), the share of WF_{blue} appeared largest, when compared with regions with abundance of rainfall, such as Northern and Western Europe. The study also highlighted the point that the average crop water requirement in Europe is around 11% lower than that in Africa. The result show that sugarcane cultivated under irrigation contained about 104 m^3/t between the 1996 and 2005 production seasons. Also found in their results is an estimated WF_{tot}, which comprises rainfed sugarcane and irrigated sugarcane, globally, as 176 m^3 and 238 m^3 per ton, respectively. They concluded that sugarcane produced under irrigation showed higher yields compared with that under rainfed production, and thus avail more water to meet crop water requirements.

Kongboon and Sampattagul (2012) analysed the water footprints (blue and green) of sugarcane production in a dry-land scenario in Thailand. They applied the water footprint concept of Hoekstra (2011) and generated the required data using the CROPWAT 8.0 model (FAO, 2009). The found that sugarcane in their study region required an average water footprint of about 202 m^3/t, which was lower than the global average estimates and this was attributable to differences in region, crop, agricultural production system and yield.

Tiewtoy *et al.* (2013) estimated the water footprints of energy crops of seasonal sugarcane, produced under rainfed and irrigated cultivation over a 30-year (1981-2010) period in Eastern Thailand. The CWU_{green} and CWU_{blue} components were calculated by accumulating the daily evapotranspiration figures over the complete growing period. The total green evapotranspiration and blue evapotranspiration figures (measured in mm) were converted to CWU in m^3/ha by multiplying by a factor 10. Their results show that the average water footprints of sugarcane production under the rainfed and irrigated cultivation systems were, respectively, 171 m^3/t (89% green and 11% grey) and 162 m^3/t (83% green, 7% blue and 10% grey). This indicates the importance of rainfall in the cultivation of sugarcane, considering the proportion of water use. The yields recorded in the study were higher under irrigated sugarcane production, as compared with those under rainfed production. This showed an influence on the water footprints, as low sugarcane yields under rainfed sugarcane production resulted in higher water footprints, while high yields under irrigated sugarcane production led to about 5% lower water footprints, compared with those under rainfed production. They concluded that water footprints can be reduced through obtaining an increase in yield, improved agricultural practices, improved irrigation schedules (by optimising timing and volumes of application) and, lastly, increases in investments in irrigation systems and techniques.

2.4.2 Research Exploring the Water Footprint of Cotton Production

Authors have conducted studies of WFA on different types of products. This section will, however, only focus on studies related to the water footprint assessment of cotton. Studies exploring the water footprints of cotton include those of Chapagain *et al*. (2006); Aldaya *et al*. (2010); Zeng *et al*. (2012); Ercin *et al*. (2013); Rudenko *et al*. (2013); and Wei *et al*. (2016).

Chapagain *et al*. (2006) assessed the impact of global consumption of cotton products on water resources in cotton-producing countries. A distinction between the three components (green, blue and grey water footprints) of the water footprint and the impact on the total water footprint was made. The CROPWAT model was used to estimate the effective rainfall and irrigation requirements of different countries. The study indicates that the global consumption of cotton products requires 256 Gm^3 of water per year. This proves that cotton requires a larger proportion of water, with 42% of the water being blue water, which entails that the global consumption of cotton products requires an abundance of irrigation water. Within the South African context, the consumption of cotton products required about 80 Mm^3 per year of blue water and 80 Mm^3 per year of green water, with 47 Mm^3 per year being associated with grey water.

Aldaya *et al*. (2010) explored the water footprint of cotton and other crops produced in Central Asia by using the Hoekstra *et al*. (2009) approach. Cotton was found to be one of the main crops produced in the southern region of the Aral Sea Basin. The results showed that an average of $6875\ \mathrm{m}^3$/ton for the blue water footprint was used to produce cotton, which is a large proportion for one crop. Their conclusion was that cotton production in the Aral Sea Basin countries contributes to the scarcity of water in Aral Sea, which results from the significant volumes of water and fertiliser being used during production. The authors recommended that reduced or improved supervision of water as a resource might possibly be attained through the importation of agricultural products from regions abundant in green water.

Zeng *et al*. (2012) assessed water footprints at a river basin level. The Heihe River basin in Northwest China was used as a case study, and cotton was one of the products that were irrigated using the water from this basin. The aim of their study was to quantify the water footprint within that basin. The water footprint assessment was based on the Global Water Footprint Standards proposed by Hoekstra *et al*. (2011). The research results recorded a large water footprint of about 1768 million m^3/year in the Heihe River basin. The virtual water content of cotton was reported as 3384 m^3/ton, and cotton was found to be the largest consumer of water, when compared with other crops. The virtual water content of cotton was exceptional, as the value estimated was double the national average value. Such results also give an indication that cotton uses a large volume of water.

Ercin *et al*. (2013) analysed the allocation of freshwater resources to quantify the water footprints of selected agricultural products. Data used for the study were obtained from Mekonnen and Hoekstra (2010; 2011) and the monthly blue water scarcity study from Hoekstra and Mekonnen (2011) and Hoekstra *et al*. (2012). Of the crops planted in those regions, eight crops were identified to be of concern. Among those, three major crops were assessed, namely cotton, sugarcane and rice. Approximately 47% of the water footprint was associated with those crops. The research results highlighted the fact that the largest share of approximately 22% of total virtual water imports relates to the import of cotton and its resulting products. The results also showed a 52.7 Gm^3/year green water footprint of imported products, with cotton products having the largest green water footprint. The blue water footprint of the imported products was 10.5 Gm^3/year. Of the 10.5 Gm^3/year of blue water, 56% was attributable to cotton products. Of the water used to assimilate pollution in the industry, cotton was the second-largest consumer of water. The researchers concluded that cotton and its derived products are leading factors contributing to the blue water scarcity.

Rudenko *et al*. (2013) explored a macroeconomic analysis of cotton production, processing and export in water bound Uzbekistan. Cotton production in this area consumes around 41% of all irrigation water. Cotton in Uzbekistan consumes about 6000 to 8000 m^3/hectare. About 6819 m^3 was needed to produce a ton of cotton. This gives the evidence that cotton uses a large proportion of water.

Lastly, Wei *et al.* (2016) incorporated water consumption into a crop water footprint. Among the crops produced in the China South-North water diversion project, cotton displayed a high blue water footprint attributable to high irrigation water dependency. Following the studies conducted by Hoekstra and Chapagain (2008), cotton was found to be one of the primary crops that use much water. The results show that cotton uses high volumes of irrigated water; thus, it is important to know the volume of water used by the crop grown in any country.

2.4.3 Research Exploring the Water Footprint of Sunflower and Biodiesel Production

Various studies have been conducted that assessed the water footprints of biofuels and the economic viability of producing biodiesel, including those by Bastianoni *et al*. (2008), Gerbens-Leenes *et al*. (2009a), Felix *et al*. (2010), Hastings and Pegram (2012), Pahlow *et al*. (2015), Chye *et al*. (2018), and Kunz *et al*. (2015).

Gerbens-Leenes *et al*. (2009a) provided an overview of the water footprints of bioenergy, which was produced from 12 crops that contributed most towards agricultural production, worldwide. To cater for regional variations in climate and production circumstances, calculations in their study were performed according to country of production. It was deduced from the study that it is more efficient to use the total biomass for biofuel production, rather than a portion of a crop. Thus, bioelectricity was found to have a lower water footprint than bioethanol and biodiesel did. Shifting towards biofuels was detected to require extensive knowledge and understanding; therefore, it is necessary to conduct studies on the appropriate feedstock and its water use within a region. The findings from such studies could be utilised to select the appropriate crop feedstock, which can use water efficiently. Moreover, regional variations require that local assessments should be made.

When first- and second-generation biofuels were assessed and compared with algae as a third-generation biodiesel feedstock, first-generation biofuels, such as biodiesel produced from sunflower, were found to be more advantageous for their significant low conversion characteristics. Using food-based crops as biofuel feedstock has significant impacts on the increase of food prices, and the production of first-generation biofuels could lead to a depletion of water resources (Chye *et al*., 2018). The use of sunflower as a biodiesel feedstock is more feasible when compared with algae, although regional conditions could affect the yields, and therefore it is important to understand the diversification of different types and sources of biofuels (Bastianoni *et al*., 2008).

The WFA is a viable method to use to inform decisions concerning sustainable, efficient, effective, and equitable water allocation and use. In South Africa, the efficient allocation and use of water were recommended when the WFA was utilised as a tool for research by Pahlow *et al*. (2015). It was found in their study that crops contributed approximately 75% of the total water footprint of national production, of which 85% was mainly contributed by fodder crops, such as sunflower, maize, sugarcane, and wheat. On the other hand, the average water footprint of a South African consumer was found to be lower than the global world average (Pahlow *et al*., 2015). Sugarcane and sweet sorghum were found to potentially use more water, while sunflower, sugar beet, canola, and soya beans did not. A more detailed mapping approach is required to properly identify feedstock cultivation areas and to better understand the use of water and respective biofuels feedstock yields (Kunz *et al*., 2015).

South Africa, as a water-scarce country, requires tools that can inform efficiency, raise awareness, and create dialogues with various stakeholders (such as policymakers) for the sustainable use of water by various sectors. The water footprint concept has the potential to be useful through its potential contribution in bringing about new and important decision techniques that cut across various sectors. Additionally, the use of water footprints is indicated as being a plausible aider and guider for decisions on water use. Understanding water footprints, in a national context, is depicted as a complex task that might require consideration of other important factors, such the costs and benefits, especially for economic sectors (such as in the production of biodiesel) (Hastings and Pegram, 2012).

The development of biofuels is highly dependent upon how far the existing agricultural industry can transform biomass into biofuels, and the roles that public and private investments might have in the development of the biofuels sector. These factors are indicated as being key determinants in the economics of the biofuel industry and are significant for determining the potential for commercialising the industry in developing countries (Felix *et al*., 2010). Venturing into the production of biofuels, in general, requires extensive knowledge and understanding of the industry at a large scale. The choice of the type of biofuel to be produced should be carefully assessed with regard to the available feedstock, the impact on water resources, and ultimately, the economic viability thereof. As for biodiesel production in South Africa, sunflower has already been stipulated as a viable feedstock, although there is still a need to delve into the use of water through the entire value chain and assess the economic viability of sunflower for this purpose.

2.4.4 Research Exploring the Impact of Climate Change on the Availability of Fresh Water

Freshwater is considered to be a scarce resource that is vital for the environmental, social and economic development of South Africa, and further changes in water supply could have major implications for most sectors, especially the agricultural sector. Water is reported to be highly vulnerable to projected climate change, within both global and national contexts. Factors that contribute to the vulnerability of the freshwater system in South Africa include seasonal and inter-annual variations in temperature and rainfall, which determine runoff and evaporation rates. The impact of climate change is expected to change precipitation and temperature patterns, which would influence runoff and hence freshwater availability in the future (Ogundeji, 2013). Thus, it is important to review the potential impacts of climate change on freshwater demand and supply, together with the projections of the future climate from the global and national perspectives.

Several studies have focused on predicting the impacts of climatic change on water resources, from global and South African perspectives. Such studies include Yang *et al.* (2010), IPCC (2007), Falloon and Betts (2010), Alcamo *et al.,* (2003), Ogundeji (2013), Nicol and Kaur (2009), Mukheibir (2008), Cavé *et al.* (2003), Hewitson *et al*. (2005), Schulze (2000), Turpie *et al.* (2002), and Arnell (1999). Their predictions range from a change in temperature to change in precipitation, which would have significant impacts on water availability and would affect crop water requirements and overall yield. A general warming across the country of higher average temperatures in sub-humid areas was predicted.

Yang *et al.* (2010) assessed the freshwater availability in Africa under the current and future climate scenarios (between 2020 and 2040), with a focus on drought and water scarcity. The study adopted a semi-distributed hydrological model to estimate the green and blue water availability for the whole of the African continent at the sub-basin level. The study revealed that the current climate still maintains sufficient water resources on a continental and annual basis, except for the large spatial and temporal variability within Africa countries and river basins. On the other hand, the simulation of the future climate impact on water resources revealed that Africa, as a whole, is expected to experience an increase in total average quantity of water resources. Their results show that dry spell and drought events are expected to increase, which will pose a threat to agricultural production; therefore, demand for irrigation water is expected to increase so as to stabilise and increase food production.

Similar to Yang *et al*. (2010), Falloon and Betts (2010) evaluated the impacts of climate change on European agriculture and water management that focused on adaptation and mitigation. In line with IPCC (2007) projections, Europe would experience greater warming during winter in the North and in summer in the South and Central regions. In addition, the average annual precipitation is expected to increase in the Northern region of Europe, while the Southern part would experience a decrease in precipitation as a result of climate change. If the magnitude and frequency of high precipitation increases for Northern, Central and Southern Europe, as projected by IPCC (2007), this would have a significant impact on both the agricultural and water sectors over the next few decades. Due to the projected increase in precipitation, Northern Europe could experience the largest increases in water supply, while the Central and Eastern regions could experience the largest decrease in water supply. Decreases in water supply in the Central and Eastern regions would result in a significant increase in irrigation water demands. Not only would irrigation water demand increase, but an extreme competition for water resources would also result, thereby increasing water stress (Alcamo *et al.,* 2003; Bogataj and Susnik, 2007; Falloon and Betts*,* 2010). Moreover, the study emphasised the possible changes in the future hydrological cycle, and that climate change adaptation in the water sector could have a significant impact on adaptation and mitigation strategies in agriculture. The primary consequences that could evolve were highlighted as causing changes in rainfall, soil moisture, evaporation, and freshwater quality and supply, which would then impact on the variability of future agriculture practices. In addition, secondary impacts could include changes in consumption patterns and competition for water between agricultural sectors and other water users, which could diminish the availability of freshwater for irrigation and other agricultural uses.

Ogundeji (2013) analysed the economics of climate change adaptation strategies in the Ceres region, South Africa. The study applied SAPWAT to estimate the crop water requirements for the base climate (1971-1990) and the possible future climate (2046-2065). He emphasised that the impact of climate change could result in changes in area of land used for production, water use and the welfare of the farmers under the future climate scenario. Three adaptation strategies were mentioned for combatting the threat of climate change to water resources, being the construction of farm dams and improving water rights, the improvement of water efficiency, and the increasing of water tariffs. The adoption of these strategies could result in increased capacities for coping with the projected future climate change effects on water resources. Furthermore, the study highlighted the point that the projected increase in temperature and decrease in rainfall would have devastating effects on water demand and supply in South Africa, thereby increasing competition for irrigation water. This is consistent with Nicol and Kaur (2009), who categorised the impacts of climate change into known and unknowns. The known impacts were referred to as factors that are plainly identifiable, such as changes in precipitation, changes in snow and ice-melt, changes in evapotranspiration and soil moisture, and changes in flooding and drought patterns. However, the unknown impacts include population growth, change in land use, change in economic growth, and technological change. All these unknown drivers could have significant impacts on changes caused in runoff and river flows. It is projected that a rise in sea level and resources scarcity would have a significant role to play in rural-urban migration, therefore placing water resources under further pressure.

According to FAO (2011), the projected rising temperatures over the ensuing 30 years would have a significant impact on crop production in terms of decreases in yields, attributable to the negative effects on the optimal temperatures required during pollination stages in crops. Thus, the increases in temperatures are expected to cause drastic reductions in yields, which could become worse as a result of shortages of the water needed for optimal plant growth. Crops such as fibre, forage, fruit and grain are expected to be specifically affected by the projected changes in climate.

In a South African context, Hewitson *et al*. (2005) applied empirical and regional downscaling tools to assess the impacts of climate change on precipitation in South Africa. They indicated that a wetter escarpment in the east, a shorter winter season in the south-west, a slighter increase in intensity of precipitation, and drying in the far west are to be expected.

Mukheibir (2008) developed a framework for strategy consideration regarding water resource management in South Africa. He suggested that temperatures are expected to increase by approximately 1.5°C along the coast, and 2°C to 3°C inland of the coastal mountains, by 2050. Aside from increases in temperature, climate change impact is expected to cause changes to evaporation and relative and specific humidity, as well as to soil moisture, which would have a significant impact on crop water requirements (Midgley *et al.,* 2005). Alongside the projected changes in temperature, a change in precipitation patterns would also have a significant effect on freshwater availability through a direct influence on runoff. Schulze (2000) has demonstrated clear runoff reductions in the already dry western part of Southern Africa. Similar to the suggestions by Turpie *et al.* (2002) that the country's main rivers are likely to have reduced runoff or become less predictable, Arnell (1999) has also predicted a substantial reduction in runoff in the Limpopo and Orange catchments, as well as decreases in the volumes of low flows in these two rivers. An increase in the occurrence of extreme events (floods and droughts), depending on the region and the time of year, may occur owing to the projected increases in rainfall and rainfall intensity that cause flooding. According to predictions, rises in sea levels in coastal zones, as well as seasonal changes, are expected to cause shifts in the annual timing of rainfall and temperature patterns. In addition to previous predictions, Van Dyk *et al.* (2005) predicted that groundwater is likely to be most severely affected, with the groundwater table dropping because of reduced recharge, particularly in the western parts of the country, and they suggested the implementation of strict groundwater management systems, with early warning mechanisms to report depleted groundwater reserves. To cap it all, Cavé *et al*. (2003) stated that the Western Cape is likely to experience extended summers. Decreases in rainfall for the Western and Northern Cape Provinces and disrupted rainfall patterns for other areas can be expected. Eastern and Southern Africa, on the other hand, can expect to have higher average annual rainfall patterns. Specifically, in drier areas where the annual rainfall is less than 500 mm, a 10% decrease in rainfall could translate into as much as a 40% decline in recharge.

2.5 ENVIRONMENTAL SUSTAINABILITY ASSESSMENT OF THE WATER FOOTPRINT

A sustainability assessment is about assessing the relationship between the availability of water and the human water footprint (Hoekstra *et al*., 2011). There are three pillars under the umbrella of wise freshwater allocation, namely environmental, social and economic water use (Hoekstra, 2015). These three pillars ensure the sustainability of freshwater use and the benefits of freshwater use to all users.

Evaluating the sustainability of the water footprint in a geographic area can be best executed at the level of a catchment area or river basin (Guo *et al.*, 2017; Awatif and Shaker, 2014; Jewitt and Kunz, 2011). The total water footprint is compared with the water availability in the particular catchment area. Water availability, in this regard, refers to the water that is available after the environmental flow requirements have been met. Production in a catchment area or river basin can be regarded as sustainable when it does not compromise the environment by also using water that is physically needed to maintain the eco-system in the river. On the other hand, when there is a compromise in the sense that the environmental flow requirement (EFR) was not met, the water footprint is considered unsustainable. This scenario is also referred to as representing an ‘environmental hotspot’ (Hoekstra *et al.*, 2012; Jewitt and Kunz, 2011).

The environmental sustainability of a water footprint is often assessed through the calculation of a blue water scarcity index for a particular catchment. The blue water scarcity index (WS_{blue}) is the ratio of the total blue water footprint ($\sum WF_{blue}$) in the river basin to the available blue water, and it can be calculated as follows:

$$WS_{blue}[x,t] = \frac{WF_{blue}\,[x,t]}{WA_{blue}\,[x,t]} \qquad \text{Equation 2.1}$$

where:

$WF_{blue}\,[x,t]$ is the total volume of blue water (in Mm^3/y) that was consumed in catchment *x* in period *t*;

$WA_{blue}\,[x,t]$ is the volume of blue water (in Mm^3/y) that was available in catchment *x* in period *t*.

The blue water availability is the difference between the natural runoff and the environmental flow requirement (EFR). As such, the blue water availability is the volume of blue water that is available after the environmental needs have been met (Hoekstra *et al*., 2011). Blue water availability (WA_{blue} in Mm^3/y) is calculated as follows:

$$WA_{blue}\,[x,t] = R_{nat}\,[x,t] - EFR\,[x,t] \qquad \text{Equation 2.2}$$

wherein:

R_{nat} is the natural run-off (in Mm^3/y) in the river basin

EFR is the environmental flow requirement (in Mm^3/y)

x is the river basin

t is the specific period.

According to Hoekstra *et al*. (2011), the blue water scarcity index in a catchment is interpreted at four levels of blue water scarcity (Table 2.1 below). If the water scarcity index is less than 100%, the water footprint is smaller than water availability in the catchment, and environmental flow requirements is not violated. Blue water scarcity then is considered to be low. A blue water scarcity index in excess of 100%, however, implies that water consumption in the particular catchment was such that EFR was not met, and the water use is considered unsustainable. Hoekstra *et al*. (2011) refer to a water scarcity index of between 100% and 150% as low water scarcity; a water scarcity index of between 150% and 200% as moderate scarcity; and a water scarcity index larger than 200% as severe water scarcity.

Table 2.1: Blue water scarcity (WS) levels

	WS < 100% (Low)
	100% < WS <150% (Moderate)
	150% < WS <200% (Significant)
	WS > 200% (Severe)

Researchers who assess the sustainability of a water footprint often use the data reported by Hoekstra *et al*. (2012) in their report on global monthly blue water scarcity.

Next, the focus of attention shifts to the economic valuation of a water footprint.

2.6 ECONOMIC VALUATION OF WATER FOOTPRINTS

The economic valuation of a water footprint is done by calculating the economic water productivity (EWP). EWP refers to the ratio of the net benefits derived from crop, forestry, fishery, livestock or mixed agriculture systems to the amount of water used to produce those benefits (Rodrigues and Pereira, 2009). The FAO (2010) also defines EWP as the ratio of product output (goods and services) to water input. The output might be products such as crops (grain, fodder) or livestock (meat, egg, fish), and can be expressed in terms of economic return. The scale used for analysing the EWP differs, based on various levels, such as plant level, field level, farm level and basin level, and the economic value changes with respect to the level being considered (Molden *et al.,* 2003).

It is important that water resources be allocated in a way that improves EWP (which shows the water use efficiency) and sustainability. The sustainability of water use involves more than the productive use of water, and also includes social, economic and environmental factors that objectively seek the best way to achieve an equitable, efficient and sustainable water use (Nieuwoudt *et al.*, 2004). In order to address the sustainable and efficient use of South Africa's scarce water resources, the water management policy emphasised the importance of attending to the imbalance in water allocation and accessibility. This is consistent with the National Water Act (No 36 of 1998), which aims to provide sufficient water to maintain economic growth and sustain the environment. This Act aims to improve water management in terms of enabling water users to attain an efficient level, as well as maximising the contributions of large-scale water users to the economic growth of South Africa.

From a water footprint perspective, Chouchane *et al*. (2015) defined EWP as the value of the marginal product of agri-food products with respect to water. The EWP of a product is calculated by multiplying the physical water productivity of the product by the price of the product (Chouchane *et al*., 2015). Essentially, the EWP is the income that is earned per cubic metre of water that was consumed in the production of the underlying product. Researchers who have followed Chouchane *et al*. (2015) to assess EWP include Jordaan *et al*. (2019); Munro *et al*. (2014); Zarate *et al*. (2014); Dumont *et al.* (2013); and Aldaya *et al*. (2010).

Other approaches to economically value the water footprint is to calculate the value added per cubic metre of water (Jordaan *et al*., 2019) and the economic water consumption (EWC) (Maré and Jordaan, 2019). In both the value added per cubic metre and the EWC approaches, the direct allocatable costs are deducted from the gross production value as a means to allow for a fairer comparison to be made of the value that was generated per cubic metre of water used in production.

2.7 CONCLUSIONS FROM THE LITERATURE

Based on the literature on the water situation in South Africa, it is evident that the national water resource is scarce and under increased pressure from different types of users. The severe droughts in the past few years have further increased the pressure on the water supply in South Africa. Given that the agricultural sector is a major user of the freshwater resource, it is crucially important that water is used efficiently in the agricultural sector.

While ample research has been done on water use efficiency over the years, a relatively new concept that has been introduced to report the volume of water used to produce a product is the water footprint. The theory of water footprint assessment (WFA) is now well developed. There are mainly two approaches that are followed for WFA: the GWFS and the LCA approaches. While there is conflict between the two schools of thought, it is evident that both approaches are useful for different scopes of analyses. The GWFS is useful when the researcher is interested in both blue and green water as sources of water in the production of the product, and where the researcher is interested in the total volume of water that was consumed to produce a particular product. Ultimately, the aim when applying the GWFS in a WFA is to assess the environmental sustainability of using the water to produce the product under consideration.

The LCA approach is useful when the researcher is interested in the impact of changed land use behaviour on the environment, including the water resource. The LCA approach does not include the green water in its assessment, and it also does not adopt the concept of a grey water footprint, as the GWFS does. It is argued that there are different tools available in LCA to assess the impact of agricultural production in term of pollution of the freshwater resource.

For the purpose of this study, we are interested in the volume of water that is used to produce the different fuel and fibre crops, as well as the contribution of both the green and blue water sources to satisfy crop water requirements. We are also interested in the blue water scarcity situation in the catchments within which the case studies fall. Thus, it is concluded that the GWFS is appropriate for the purpose of this research.

From the review of the different types of water footprint included in the GWFS, the product water footprint proves to be the appropriate type to examine to allow us to meet the aims of this research.

From the review of the related studies where the water footprints of fuel and fibre crops were analysed, it is clear that the topic has received a considerable amount of attention from researchers, globally. Except for the case of tobacco production, all of the other crops have been well researched in terms of the product water footprint of the different crops. Moreover, the GWFS has been applied in the WFA of all of the crops included in this research. It is noted, however, that the water footprints of the selected crops have not been assessed before in South Africa. All of the crops have been documented in the global studies to use large volumes of water. It is reasonable to assume that these crops will also use large volumes of water in South Africa. Given the scarcity of water in South Africa, and the importance of fuel and fibre crops to the South African economy, it is concluded that WFAs of fuel and fibre crops are needed to gain an understanding how much water is used to produce the respective crops in order to inform water users regarding the sustainable use of freshwater in the production of these crops.

Based on the literature on the sustainability assessments in the context of WFA, the sustainability is assessed by means of a water scarcity index. The water scarcity index is the ratio of the blue water footprint in the catchment to the water availability in the catchment at the particular period. The blue water footprint, in this context, is the total volume of blue water that is consumed by all water users in the catchment. Blue water availability is that part of natural runoff that is available for use, after environmental flow requirements were met. Blue water scarcity is considered low if the blue water scarcity index is less than 100%. A blue water scarcity index in excess of 100% implies that EFR is not met completely, suggesting that the water footprint is unsustainable. It is noted that, although the literature refers to this assessment as a sustainability assessment, the scope of analysis is mainly focused on the blue water scarcity, rather than on an in-depth sustainability assessment. It is, however, still considered a useful analysis for interpreting water use in a particular catchment in the context of the blue water scarcity situation in that particular catchment.

The literature on the economic valuation of the water footprint suggests that this aspect of WFA may still need some refining. Since different analyses are performed when assessing the economic value of the water that was used, it is not possible to accurately compare the values that have been reported in the literature by different studies. It is concluded that the decision regarding which of the approaches to follow is informed by the purpose of the analysis. In this research, the aim is to calculate the income that is earned from using water for the production of selected fuel and fibre crops, and not to compare the economic returns from different water uses. Thus, the EWP, as reported by Chouchane *et al*. (2012), is considered appropriate for this research.

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CHAPTER 3
CASE STUDY OF SUGARCANE PRODUCTION

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3.1 INTRODUCTION

The aim of Chapter 3 is to report the water footprints that were calculated for sugarcane produced under irrigated conditions and under rainfed conditions. Green and blue water footprints were calculated for selected mill supply areas that practise irrigated production only, for areas with irrigation and rainfed production, and for areas that practise mostly rainfed production. The impacts of selected management practices on the water footprints of irrigated sugarcane production were also explored. The results, aimed at informing cane growers on how to decrease the water footprint through the application of certain management practices, are also reported in this deliverable. The chapter is structured as follows: Section 3.2 deals with the data and methods for calculating water footprints, Section 3.3 reports results, and Section 3.4 draws conclusions.

3.2 DATA AND METHODS

This section starts with an overview of the study area, followed by the data generation process through which crop yields and water balance were modelled. The section is then concluded with a discussion of the methodology used.

3.2.1 Study Area

Three different types of sugarcane production scenarios were considered, namely areas practising irrigated production only, areas with mixed irrigation and rainfed production, and areas practising mostly only rainfed production. For the fully irrigated production, the Malelane, Pongola and Komati mill supply areas were selected; and the Amatikulu, Felixton and Umfolozi mill supply areas were selected where some irrigated and some rain-fed production take place; while the Noodsberg, Maidstone and Sezela mill supply areas represent rain-fed production. A map showing the location of the selected areas is presented in Figure 3.1 below.

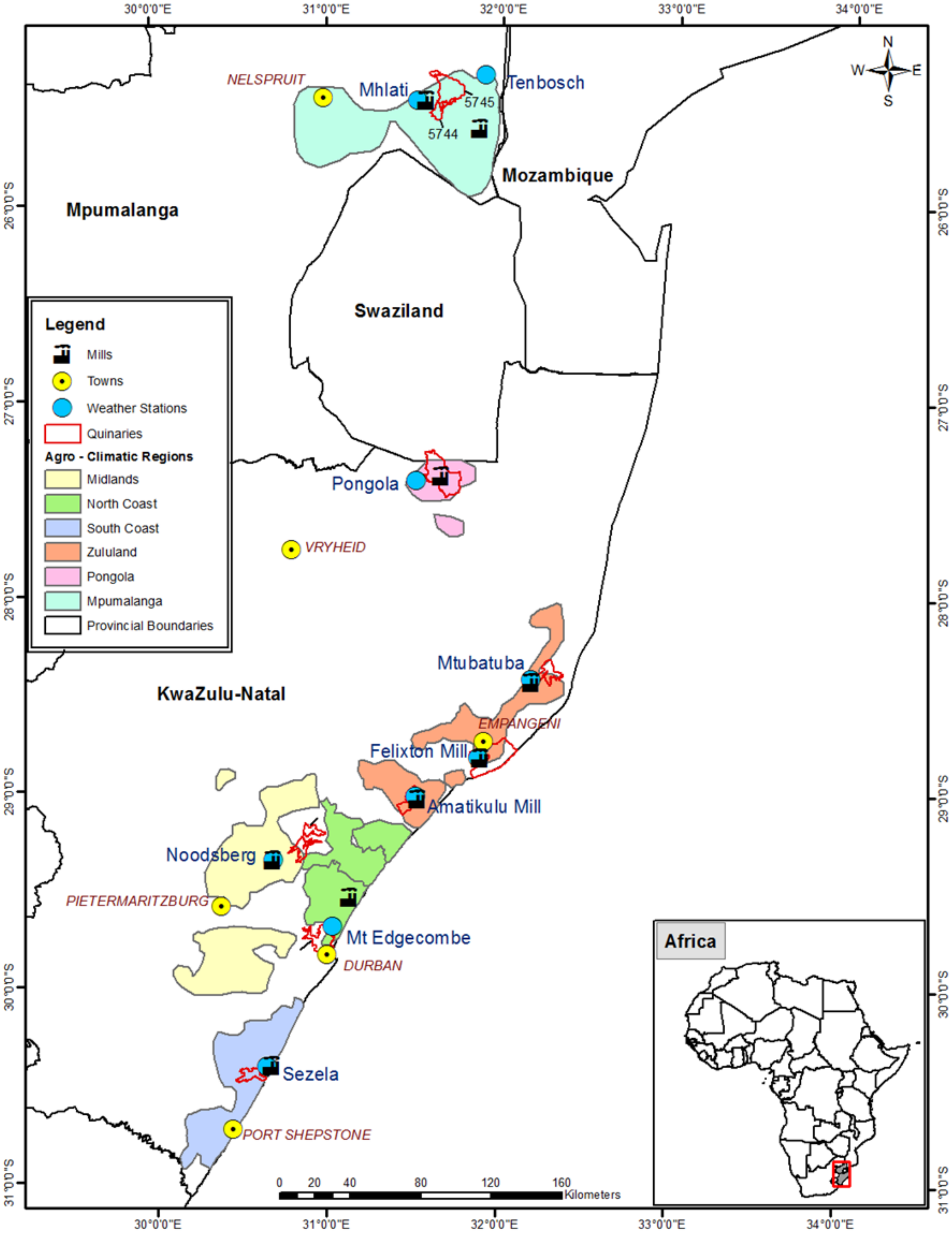

Figure 3.1: Map showing the agro-climatic region in the South African sugarcane belt

Notes: The map shows the locations of selected sugar mills, and the quinary sub-catchments selected to represent the different mill supply areas.

Source: SASRI GIS office

3.2.2 Crop Yield and Water Balance Modelling

Two methodologies were used for calculating the water footprints from simulated crop yields and crop water use, involving different crop models and different weather data sets.

Firstly, the Canegro model (Jones and Singels, 2018) and the weather and soil data for a representative catchment were used to calculate yields and water balance components for a standard (typical) management scenario for a single, typical soil type for each of the different mill supply areas. These results were obtained from a study previously conducted by Singels *et al*. (2017). The Canegro model was used because it is considered the most sophisticated sugarcane crop model available, and because it can be set up to execute large numbers of runs in batches, as required in this study.

Secondly, the MyCanesim® model (Singels and Paraskevopoulos, 2017) and weather data from a representative weather station were used to calculate yield and water balance components for different management scenarios for irrigated cane production in Malelane, for two soil types. The MyCanesim® model has better capabilities for simulating irrigation system impacts on the crop water use and crop yield, than the Canegro model has.

3.2.2.1 Modelling for standard management and soil for different areas

The primary crop and water balance data for this study were obtained from Singels *et al*. (2017). The methodology used for weather data generation, the configuration of the crop model, and the model output data processing are fully described by Lumsden (2016) and Singels *et al*. (2017), and are also summarised by Singels *et al.* (2018, 2019). Singels *et al*. (2017) used the DSSAT-Canegro model to simulate 18 ratoon crops of a high-sucrose cultivar, harvested in April and October of each year, for each of the selected sub-catchments (see Table 3.1 below). Harvest ages varied between 12 to 23 months, depending on the present thermal climate of each area. For irrigated scenarios, crop cycle length was set at 12 months. Irrigation of 20 mm was simulated whenever the profile soil water deficit exceeded 20 mm or when the profile plant available soil water dropped below 50%. A row spacing of 1.2 m was assumed for all the runs. The initial soil water content at the start of the simulations was set to 100% of the available capacity for irrigated cane, and to 50% for dryland cane.

Rainfed (rf) and irrigated (irr) simulations were conducted for irrigated scenarios to enable the calculation of the blue and green components of the water footprint.

Table 3.1: Details of the production type, harvest age and the mean annual precipitation

Quinary catchment	Sugarcane producing area (mill supply area)	Agro-climatic region	Production type	Crop harvest age (months)	Mean annual precipitation (mm)
5745	Komati	Mpumalanga	Irrigated	12	719
5744	Malelane	Mpumalanga	Irrigated	12	841
5337	Pongola	Pongola	Irrigated	12	720
5198	Umfolozi	Zululand	Irrigated, Rainfed	12	1009
5112	Felixton	Zululand	Irrigated, Rainfed	12	1316
5085	Amatikulu	Zululand	Irrigated, Rainfed	12	1166
4736	Noodsberg	Midlands	Rainfed	23	907
4707	Maidstone	North Coast	Rainfed	14	1036
4806	Sezela	South Coast	Rainfed	14	1057

Notes: These details are assumed for the simulations for the different quinary sub-catchments situated in the different mill supply areas and the agroclimatic regions.

3.2.2.2 Modelling for management and soil impacts for irrigated production

In order to assess the impacts of different management practices on the water footprint of irrigated sugarcane production, the MyCanesim model (Singels and Paraskevopoulos, 2017) was used to simulate irrigation, drainage and run-off, and cane yield. The sugarcane cultivar considered in the study was NCo376, with a row spacing of 1.4 m. Deep and shallow soils with water-holding capacities of 100 mm and 50 mm of plant available water, respectively, were considered in the model setup. Daily weather data from the Mhlati station (25°28'0"S, 31°31'0"E) were used as input. Two irrigation systems were considered, namely overhead irrigation with a centre pivot (CP), and sub-surface drip irrigation (SSD). Two soil mulch covers, namely a light cover obtained from the scattered cane tops (LIGHT, 5 ton/ha) and a thick cover obtained from the dead crop residue (THICK, 10 ton/ha), were used. Data on the irrigation systems, net (excluding conveyance and wind drift losses, but including canopy and mulch layer interception losses) irrigation amount and minimum irrigation cycles, the available water capacity of the soil, and the available soil water content threshold for irrigation are presented in Table 3.2 below. Irrigation applications were automatically scheduled when the simulated soil water content reached the chosen threshold. For data used to calculate the economic blue water productivity, relevant data on cane prices and the cost of production were obtained from the South African Sugar Association (SASA, 2016).

Table 3.2: Irrigation system properties and soil water content threshold triggers

Irrigation System	Net irrigation amount (mm)	Minimum irrigation Cycle (days)	Available water capacity of the soil (mm)	Available soil water content threshold for irrigation (mm)
Centre Pivot	14	2	100	75
Centre Pivot	14	2	50	30
Sub-surface drip	7	1	100	80
Sub-surface drip	7	1	50	35

Notes: These details are for triggering irrigations for the two soil types with different water holding capacities, used as input for Canesim simulations.

3.2.3 Water Footprint Calculation

3.2.3.1 Irrigated and Rainfed sugarcane production

The green and blue water footprints (WF_{green} and WF_{blue}, *in* m^3/ton) for each of the 18 crop seasons were calculated by using Equations 3.1 and 3.2, respectively:

$$WF_{blue} = \frac{CWU_{blue}}{CY} \quad \text{Equation 3.1}$$

$$WF_{green} = \frac{CWU_{green}}{CY} \quad \text{Equation 3.2}$$

where CY is the simulated annualised sugarcane yield (t/ha/annum) and CWU_{blue} and CWU_{green} are the simulated annualised blue crop water use and green crop water use (m^3/ha/annum), respectively.

The total water footprint (WF_{tot}) was taken as being the sum of WF_{blue} and WF_{green}.

$$WF_{tot} WF_{blue} + WF_{green} \quad \text{Equation 3.3}$$

For blue water use, the crop water use attributable to irrigation was calculated as the difference in evapotranspiration for irrigated and rainfed crops.

$$CWU_{blue} = [ET_{irr} - ET_{,rf}] \times 10 \quad \text{Equation 3.4}$$

where ET_{irr} and ET_{rf} is annualised evapotranspiration (mm/annum) simulated for irrigated and rainfed conditions, respectively.

The green water use was simply taken as the annualised evapotranspiration (mm/annum) simulated for rainfed crops:

$$CWU_{green} = ET_{rf} \times 10 \quad \text{Equation 3.5}$$

It is important to note that all key deductions in terms of drainage of water out of the root zone and surface runoff were taken into account in the model during simulations.

3.2.3.2 Impact of management practices on irrigated sugarcane production

The green and blue water footprints (*WF_{green} and WF_{blue}, in m^3/ton*) for this analysis were also calculated using Equations 3.1 and 3.2 respectively.

However, the crop water use here was calculated slightly differently to that described in Section 3.2.3.1. Here, CWU was estimated by using a shortened water balance approach that assumed no change in root zone soil water content at the start and at the end of the growing season. This was considered a reasonable assumption, as the soil water content at the start of each season was set to 50% of available capacity, limiting the maximum possible contribution of extracted soil water to seasonal CWU to +/-50 and +-25 mm for the different soil types, respectively. This method accounts for irrigation losses through interception by the crop canopy and soil mulch cover, which was important for the meaningful evaluation of irrigation systems and mulch cover effects on the water footprint.

CWU_{blue} (in m^3/ha) was calculated by deducting the difference between drainage plus runoff for an irrigated and rainfed scenario (DRO_{ir} and DRO_{rf} in mm) from the simulated seasonal total irrigation (I in mm), as shown in Equation 3.6, following the approach used by Deurer *et al*. (2011).

$$CWU_{blue} = (I - [DRO_{ir} - DRO_{rf}]) \times 10 \quad \text{Equation 3.6}$$

Seasonal CWU_{green} (in m^3/ha) was calculated by deducting the sum of drainage plus runoff (DRO_{rf} in mm) for a rainfed scenario deducted from the simulated seasonal total rainfall (R in mm), as shown in Equation 3.7:

$$CWU_{green} = (R - [DRO_{rf}]) \text{ X } 10 \quad \text{Equation 3.7}$$

3.3 RESULTS

The results of the water footprint accounting are presented and discussed in this section. The blue and green water footprints, which were calculated for typical irrigated and rainfed sugarcane production in selected mill supply areas, are discussed first. Thereafter follow the results of the analysis of the impacts of different management strategies on the water footprint of irrigated sugarcane production.

3.3.1 Water Footprint of Irrigated and Rainfed Sugarcane Production

3.3.1.1 Irrigated sugarcane production

The results for irrigated sugarcane production are presented in Table 3.3 below. The median CY ranged from 113 t/ha for Amatikulu to 130 t/ha for Umfolozi. The median CWU_{tot} ranged from 10 545 m^3/ha for Felixton to 12 705 m^3/ha for Komati. About 80% of the 10 545 m^3/ha CWU_{tot} for Felixton is attributed to CWU_{green}, while CWU_{green} only contributed about 41% to CWU_{tot} at Komati. The larger contribution of CWU_{green} at Felixton relates to the substantially larger mean annual precipitation (1 316 mm), compared with Komati (719 mm).

The median WF_{tot} ranged from 86 m^3/t at Felixton to 103 m^3/t at Pongola. Of the WF_{tot} of 86 m^3/t at Felixton, only 20% is attributed to WF_{blue}, while WF_{blue} contributes about 54% of the WF_{tot} at Pongola. The median WF_{blue}, at the irrigated production sites ranged between 17 m^3/t and 59 m^3/t, while WF_{green} ranged between 41 m^3/t and 70 m^3/t.

Table 3.3: Statistics of the cane yields of irrigated sugarcane production in different mill supply areas

		Komati	Malelane	Pongola	Umfolozi	Felixton	Amatikulu
CY	Min	124	122	117	125	120	106
	Max	132	133	125	139	127	123
	Med	127	127	121	130	123	113
CWU_{green}	Min	2980	3395	4250	5970	7155	5725
	Max	6675	7025	7355	9765	9495	8760
	Med	5228	5633	5790	7498	8445	7465
CWU_{blue}	Min	6085	5255	4985	2055	780	2135
	Max	9870	9250	8330	6580	3835	5275
	Med	7440	6635	6770	4820	2088	3560
CWU_{tot}	Min	11985	11510	11920	11720	9840	10320
	Max	13385	13115	13110	13460	11125	12130
	Med	12705	12413	12515	12165	10545	11075
WF_{green}	Min	24	27	36	44	57	51
	Max	53	57	62	77	77	76
	Med	41	45	48	58	70	68
WF_{blue}	Min	48	42	42	16	6	19
	Max	79	73	70	49	30	47
	Med	59	53	56	36	17	32
WF_{tot}	Min	95	94	92	91	82	96
	Max	104	101	119	97	88	101
	Med	100	98	103	93	86	98

Notes: The above figures show cane yields (CY in t/ha), green and blue crop water use (CWU_{green} and CWU_{blue}, in m^3/ha), and the green, blue and total water footprints (WF_{green}, WF_{blue} and WF_{tot} in m^3/t).

3.3.1.2 Rainfed sugarcane production

The results for rainfed sugarcane production are shown in Table 3.4 below. For rainfed production, the median CY ranged between 54 t/ha at Noodsberg and 89 t/ha at Felixton. The median CWU_{green} was also the lowest at Noodsberg (5 932 m^3/ha), with the highest at Felixton (8 445 m^3/ha). The median WF_{green} ranged from 96 m^3/t at Felixton to 130 m^3/t at Amatikulu.

Table 3.4: Statistics of the cane yields of rainfed sugarcane production in different mill supply areas

		Umfolozi	Felixton	Amatikulu	Noodsberg	Maidstone	Sezela
CY	Min	36	64	21	23	35	37
	Max	102	112	87	67	80	76
	Med	67	89	59	54	59	61
CWU_{green}	Min	5970	7155	5725	4179	5366	5520
	Max	9765	9495	8760	6921	7427	7753
	Med	7498	8445	7465	5932	6508	6741
WF_{green}	Min	92	85	101	96	92	96
	Max	175	112	269	181	159	151
	Med	115	96	130	113	110	108

Notes: The above figures show cane yields (CY in t/ha), green crop water use (CWU_{green} in m^3/ha) and the green water footprint (WF_{green} in m^3/t).

3.3.1.3 Discussion

When focusing on irrigated sugarcane production, the median WF_{tot} was marginally higher in the fully irrigated regions (Komati, Malelane and Pongola), ranging from 98 m^3/t at Malelane to 103 m^3/t at Pongola, as compared with the combination of irrigated and rainfed regions (Umfolozi, Felixton and Amatikulu), where it ranged from 86 m^3/t to 98 m^3/t. The higher WF_{tot} in the fully irrigated region relates to the higher CWU_{tot} in those regions, compared with the regions where a combination of irrigated and rainfed production occurs.

The median WF_{blue} in the fully irrigated regions ranged from 53 m^3/t to 59 m^3/t, representing more than 50% of WF_{tot} in those regions. On the other hand, WF_{blue} contributes between 20% and 39% to WF_{tot} in the regions where a combination of irrigated and rainfed production takes place.

The median WF_{tot} values calculated for irrigated sugarcane production in this study relate well to those reported by Scarpare *et al*. (2016) for irrigated sugarcane that received 150 kg/ha nitrogen in a trial in Brazil (86-111 m^3/t); and by Haro *et al*. (2013) in Mexico (104.9 m^3/t). However, the median WF_{tot} values in this study are much lower than the global average reported by Mekonnen and Hoekstra (2011) (209 m^3/t), and those reported by Gheewala *et al*. (2014) (150-174 m^3/t); by Kongboon and Sampattagul (2012) in Thailand (177 m^3/t); by Su *et al*. (2015) in Taiwan (180-234 m^3/t); by Zemba and Obi (2018) in Nigeria (274 m^3/t); and by Jahani *et al*. (2017) in Iran (182-210 m^3/t). The relatively smaller WF_{tot} found in this study was probably caused by relatively high yields and the efficient use of water arising from the assumption of ideal crop and irrigation management for simulations.

When considering rainfed sugarcane production, the median WF_{green} values calculated in this study are also mostly lower than the WF_{green} reported by Scarpare *et al.* (2016) in their trial that analysed the impact of nitrogen application on sugarcane production in Brazil. The WF_{green} reported by Scarpare *et al.* (2016) ranged from 101 m^3/t (plant cane with 150 kg/ha nitrogen applied) to 264 m^3/t (fourth ratoon with zero nitrogen applied). It is only the WF_{green} of plant cane and the first ratoon (127 m^3/t), when applying 150 kg/ha nitrogen, that have WF_{green} smaller than the largest WF_{green} found in this study (130 m^3/t at Amatikulu). Again, the WF_{green} found in this study, which is relatively smaller than that reported in other studies, may be attributable to the relatively higher yields and the more efficient use of irrigation water simulated in this study, when compared with the study by Scarpare *et al.* (2016).

There is much more variation in the median CY under rainfed conditions, as compared with irrigated production. The variation in CY under rainfed conditions may be attributed to variation in rainfall, which is the sole source of water in rainfed production. The WF_{green} of rainfed cane production (by implication also the WF_{tot}) proved to be larger than the WF_{tot} achieved under irrigated conditions because the rainfed yield differences between irrigated and rainfed production were proportionally larger than the CWU differences were. The rainfed crops were therefore not able to use water as effectively as the irrigated crops did, due to the variable nature of the rainfall.

3.3.2 Impact of Management Practices on the Water Footprint of Irrigated Sugarcane Production

3.3.2.1 Simulated water balance and yields for irrigated sugarcane

Table 3.5 below presents the mean simulated cane yields and water balances for different irrigation systems and mulch covers on two soil types. The results show that the cane yields were similar for the two mulch covers for a given soil type. However, the thick mulch cover reduced evapotranspiration (ET) by 40 mm and irrigation applied by 32 mm, as compared with the light mulch cover. This could be ascribed to a reduction in evaporation from the soil occurring during the period of partial canopy cover. The thick mulch cover also resulted in higher drainage and runoff than the light mulch cover for both soil types. This is because the soil water content under the thick mulch cover is mostly higher than under a light mulch cover, with lower evaporation leading to higher drainage and less runoff when rainfall occurs. The decrease in ET and irrigation attributable to the application of a thick mulch cover is in line with the findings of Mao *et al*. (2012), Ogban *et al*. (2008), Zhao *et al*. (2003), and Zhou *et al*. (2011).

Table 3.5: Long-term mean simulated cane yield and seasonal water balance components

Soil type	Mulch Cover	Cane Yield (ton/ha)	ET (mm)	Irrigation (mm)	Rain (mm)	Drainage plus runoff (mm)
Centre Pivot system						
Deep	Light	148 (8)	1225 (128)	917 (203)	581 (204)	115 (188)
Deep	Thick	146 (8)	1185 (123)	884 (201)	581 (204)	125 (125)
Shallow	Light	132 (7)	1087 (108)	826 (162)	581 (204)	155 (132)
Shallow	Thick	130 (6)	1047 (100)	796 (160)	581 (204)	167 (134)
Sub Surface Drip system						
Deep	Light	149 (8)	1211 (137)	808 (183)	581 (204)	118 (121)
Deep	Thick	147 (8)	1182 (128)	788 (178)	581 (204)	128 (125)
Shallow	Light	133 (7)	1071 (110)	722 (140)	581 (204)	157 (132)
Shallow	Thick	131 (7)	1044 (101)	705 (137)	581 (204)	168 (135)

Notes: the above shows seasonal water balance components for different irrigation systems, and mulch covers on two soil types. Values in brackets are standard deviations.

In terms of irrigation systems, the results indicated that the mean simulated cane yield and ET was similar for both irrigation systems, whereas irrigation by SSD was substantially lower, by about 100 mm, when compared with CP. The lower amount of irrigation water use under SSD is attributable to its higher application efficiency. With CP, some of the water applied is intercepted by the crop canopy cover and mulch cover, and as such, it becomes unavailable to the crop (Singels and Paraskevopoulos, 2017).

Interestingly, the shallow soil had a lower cane yield of about 16 ton/ha, a lower ET of about 40 mm, and lower irrigation of about 85 mm, than the deep soil, regardless of the type of irrigation system used. The crops growing in the shallow soil experienced more water stress because of the irrigation settings. They also required less water to fill the soil profile at the start of the crop (initial water content assumed as 50% capacity). This finding corresponded well with that of

Raes *et al*. (2013), who found that the irrigation system influences the way in which irrigation water is applied, which in turn influences the percentage of soil wetting and plant water uptake, the determinates of ET. In summary, the results reported in Table 3.3 show that the highest management impact on water use was caused by the type of irrigation system used, followed by the type of mulch cover.

3.3.2.2 Water Footprint

The results of the estimation of the crop water-use components and the water footprint indicators are shown in Table 3.6 below. The thick mulch cover resulted in a slightly lower CWU_{green} than the light mulch cover (86 and 126 m^3/ha for the deep and shallow soils, respectively), irrespective of the irrigation system used. However, the CWU_{blue} for sugarcane grown with a thick mulch cover was substantially lower than that grown with a light mulch cover, under both irrigation systems. The difference was larger for CP-irrigated sugarcane (457 and 404 m^3/ha for the deep and shallow soils, respectively) than for SSD-irrigated sugarcane (274 and 221 m^3/ha for the deep and shallow soils, respectively). The lower CWU_{blue} of crops grown with the thick mulch cover can be ascribed to their lower irrigation demand, as demonstrated in Table 3.6. The blue and total water footprints of sugarcane grown with a thick mulch cover were only slightly lower, at about 2 and 1 m^3/ton for the deep and shallow soils, respectively, than that grown with the light mulch cover.

Comparing the irrigation systems, the CWU_{blue} of SSD-irrigated sugarcane was between 994 and 1 260 m^3/ha lower than for the CP-irrigated sugarcane. The lower CWU for the SSD system can be ascribed to its higher application efficiency when compared with that of the CP system. The WF_{green} for the two irrigation systems did not differ much, while the WF_{blue} for the SSD-irrigated sugarcane was between 8 and 10 m^3/ha lower than for the CP-irrigated sugarcane.

The water footprint values for crops grown in the shallow soil were marginally higher than those grown in the deep soil, regardless of irrigation system type or soil mulch cover.

Table 3.6: Long-term mean simulated green and blue crop water use and the green, blue and total water footprints

Soil types	Mulch Cover	CWU_{green} (m^3/ha)	CWU_{blue} (m^3/ha)	WF_{green} (m^3/ton)	WF_{blue} (m^3/ton)	WF_{tot} (m^3/ton)
Centre pivot system						
Deep	Light	5321	8916	36	60	96
		(1466)	(2371)	(11)	(15)	(8)
Deep	Thick	5236	8459	36	58	94
		(1436)	(2361)	(11)	(15)	(8)
Shallow	Light	4897	8006	37	61	98
		(1225)	(1853)	(10)	(13)	(7)
Shallow	Thick	4772	7601	37	58	95
		(1206)	(1883)	(10)	(13)	(7)
Subsurface drip system						
Deep	Light	5321	7653	36	51	87
		(1466)	(2194)	(11)	(13)	(7)
Deep	Thick	5236	7378	36	50	86
		(1436)	(2149)	(11)	(13)	(6)
Shallow	Light	4897	6829	37	51	88
		(1225)	(1644)	(10)	(12)	(7)
Shallow	Thick	4772	6607	37	50	87
		(1206)	(1619)	(10)	(12)	(6)

Notes: The above figures show the mean simulated green and blue crop water use (CWU_{green} *and* CWU_{blue}), and the green, blue and total water footprints (WF_{green}, WF_{blue} *and* WF_{tot}) for different mulch covers, soil types and irrigation systems.
Values in brackets are standard deviations.

As mentioned in Section 3.3.1.3, the WF_{tot} values calculated in this study are mostly lower than the values reported in the literature are. This can be attributed to the high yields and efficient use of irrigation water simulated for the ideal management of the crop and water.

The results show that there is scope to improve water-use efficiencies, and reduce water footprints by using efficient irrigation systems, limiting wasteful evaporation through the use of mulch covers, and scheduling irrigations accurately.

3.4 CONCLUSIONS AND RECOMMENDATIONS

3.4.1 Conclusions

The aim of this case study was to report the water footprints of irrigated and rainfed sugarcane production in South Africa. WF_{green}, WF_{blue} and WF_{tot} were calculated for selected mill supply areas. Three mill supply areas were selected to represent each of fully irrigated, combined irrigated and rainfed, and fully rainfed production regions in South Africa.

In addition to the calculation of the different WF indicators for standard management and soil for different areas, this report also reported the findings derived from an analysis of the impacts of certain management practices on the WF indicators of irrigated sugarcane production. WF_{green}, WF_{blue} and WF_{tot} were calculated for two different soil types, two mulching strategies, and two irrigation systems.

Based on the results of the water footprints of typically managed irrigated and rainfed production, the following conclusions were drawn:

- The WF_{tot} values calculated for irrigated sugarcane production (86-103 m^3/ton) were generally lower than the values reported by other researchers (86-274 m^3/ton). This is ascribed to the fact that ideal management was assumed in simulations, leading to high cane yields and low water use arising from perfect irrigation management. The WFgreen values calculated for rainfed sugarcane production (96-130 m^3/ton) are also mostly lower than the values reported in the literature (101-264 m^3/ton). This is ascribed to the ideal crop management assumed in simulations, leading to high yields and efficient use of water, while the values in the literature are based on actual yields, measured in experimental and commercial situations.
- The variation in WF_{tot} (86-103 m^3/ton), WF_{green} and WFb_{lue} (17-59 m^3/ton) for irrigated sugarcane production varied markedly between the different mill supply areas, while the WF_{green} for rainfed production also varied between mill supply areas (96-130 m^3/ton). These results suggest that it may not be appropriate to have single benchmarks for irrigated and rainfed sugarcane production for all of South Africa. The spatial variations in CY, CWU and WF-indicators, caused mainly by variations in climatic conditions, suggest that WF benchmarks will have to be very much context specific.
- The dependence on blue water resources, as shown by the proportional contribution of the WF_{blue} to the WF_{tot} for irrigated production, implies a water-related business risk faced by the sugar industry.

Based on the results of the water footprint for irrigated production, calculated for different management practices and soils, the following conclusions were drawn:

- While the impact of soil depth and mulch cover was relatively small, the impact of using SSD, as compared with CP, was much larger. Using an SSD irrigation system is the best option to take in order to minimise WF_{tot}.
- The best combination of management practices, based on the WF_{tot}, is to use SSD irrigation systems in deep soil, with thick mulch cover (85.9 m^3/t). This combination resulted in a WF_{tot} of more than 10 m^3/t lower than the worst-performing combination, where a CP irrigation system is used on shallow soil with light mulch cover (97.7 m^3/t).
- The combination of using an SSD irrigation system in deep soil with thick mulch cover also resulted in the smallest WF_{blue} (49.9 m^3/t). In a scenario where blue water resources become increasingly scarce, it is important to apply management practices that would result in minimising the WF_{blue}.
- While the impacts of soil depth and mulch cover on WF_{tot} and WF_{blue} may seem marginal, the impacts thereof on CWU_{blue} prove to be much larger. Regardless of the irrigation system that is used, both thick mulch cover and shallow soil contributed to lower CWU_{blue}. A decrease in CWU_{blue} also means a decrease in the pressure on the blue water resource.
- While it may be argued that converting from overhead to drip irrigation systems may be costly, producers would already decrease WF and CWU by implementing the less costly alternatives.

3.4.2 Recommendations

Recommendations are formulated for sugar industry role-players (sugarcane producers and other role-players), policymakers, and researchers.

3.4.2.1 Sugar Industry

Although the WF values calculated in this study are theoretically ideal (low) values, these can still be used by sugarcane producers as benchmarks to strive for. Producers therefore need to be made aware of the results derived from this study.

- Sugarcane producers should implement management practices that would contribute towards decreasing the water footprint of the sugarcane that they produce. The largest return would be achieved from using efficient irrigation systems like drip systems, rather than less-efficient overhead irrigation systems.

3.4.2.2 Policymakers

Policymakers should incentivise sugarcane growers to apply management practices that will result in smaller water footprints and reduced crop water use.

3.4.2.3 Researchers

- Research is needed to derive WF determinations from actual yield and irrigation water use data. This will require the implementation of detailed and accurate monitoring of water use and yields, using ground and remote sensing technologies.

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CHAPTER 4
CASE STUDY OF COTTON

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4.1 INTRODUCTION

4.1.1 Background and Motivation

Globally, cotton is considered to be an important crop. Cotton provides a raw material for use in clothing, textiles, footwear, and the leather industry. It plays a significant role in the economy and social development of developing and lately industrialised countries (Fairtrade Foundation, 2015). Cotton has been classified as the most important natural fibre, contributing about 40% to the global textile industry (Chapagain *et al*., 2006). Cotton accounts for 74% of fibre and 42% of all processed fibre in South Africa; therefore, it is an important source of fibre. Moreover, cotton production in South Africa is regarded as a source of employment in the agricultural sector (Fairtrade Foundation, 2015). About 60 000 to 80 000 jobs are created in the textile and clothing industry. When considering the contribution of cotton production towards GDP in South Africa, it was found that it contributes about 8% of the agricultural sector's contribution towards GDP (Business Partners, 2014).

Furthermore, water is an important input during cotton production. Given that South Africa has a water-scarce economy, it is vital to assess the amount of water used during cotton production. Cotton production has been found to consume large volumes of water (Aldaya *et al*., 2010). Of the total (blue and green) water consumed by agriculture in central Asia, 33% is used by cotton. The amount of fresh water consumed by cotton during production and its economic contribution to the South African economy stresses the importance of knowing the volume of fresh water used, the degree of sustainability in the area where cotton is produced, and the economic value of the water used during cotton production.

According to Hoekstra *et al*. (2011), it is important to evaluate the environmental sustainability of the water that is used along the chain of production of cotton. The water sustainability of a basin or catchment depends on the balance between the needs of that specific environment and the scarce water availability. The Olifants River basin has severe blue water scarcity during the times that cotton growers begin to plant their crops. Therefore, it is important that the cotton growers be aware of the water demands needed by the crop and how the water can be used sustainably, while taking the environmental implications into consideration.

The water footprint concept is developing as a vital sustainability indicator to use in the agriculture and food sectors (Ridoutt *et al*., 2011). A water footprint represents the volume of freshwater used to produce a product and is measured along the value chain of the product, from the inputs up to the last stage, where the product reaches the consumers (Hoekstra *et al*., 2011). A water footprint analysis can be a useful tool to address the use of water during cotton production. Van der Laan *et al*. (2013) concluded that a water footprint may be used in agricultural production, as it has the capability to monitor water use and provide notifications for policymakers as to how to manage water. In addition, it can also lead to an improved understanding of the risks related to water shortages, which might prompt recommendations for aiding water management. Moreover, the water use information derived could help to identify changes required to moderate water usage at a farm level.

It is also important to consider the economic productivity that can be identified through the use of water footprint analysis. Economic productivity is the measure of the value of output in relation to the input used to produce a unit of output (Pfister *et al*., 2012). Hoekstra (2015) emphasised the point that there are three pillars that determine wise freshwater allocation. These are sustainable (environmental), efficient (economical), and equitable (social) water uses. Previously, the emphasis of water footprint research was placed mainly on the environmental impacts of water (Chapagain *et al*., 2006). However, it is vital that the economic water productivity is taken into account during water footprint assessment (WFA). The water users must understand the economic contribution derived from using the scarce resource. As a result, water users are able to determine whether the current allocation is efficient or not.

4.1.2 Problem Statement

There is limited scientific information available to guide South Africans on how much fresh water is used and needed during cotton production. As a result, water users may use water inefficiently and ineffectively in the production of cotton (Eslamian and Eslamian, 2017).

Internationally, cotton is regarded as one of the crops that use abundant amounts of fresh water. Chapagain *et al*. (2006) assessed the water footprint of cotton consumption by analysing the impacts of the worldwide consumption of cotton products on water resources in cotton-producing countries. Aldaya *et al*. (2010) examined the water footprint of cotton and other crops produced in Central Asia. Hoekstra and Mekonnen (2012) assessed the water footprint of humanity in general. The above authors identify the components of a water footprint, namely green water (consumption of effective rainfall), blue water (consumption of ground or surface water for irrigation), and grey water (indicators representing water pollution arising during the growth or processing stages). From the assessments conducted, the blue water footprint was found to represent the highest volume of freshwater used. The large volume of blue water suggests increased pressure on the scarce freshwater resource. The results further indicated that cotton production requires a vast amount of fresh water.

Given the consideration that cotton production is significant to the South African economy and the above-mentioned research confirming that cotton production requires large amounts of water, it is imperative to comprehend the economic water productivity of the fresh water used during cotton production, as part of assessing the sustainability of scarce freshwater resources. The economic value of freshwater used during cotton production, however, is currently unknown in South Africa. Internationally, Chouchane *et al*. (2015) assessed the water footprint of Tunisia from an economic perspective. Schyns and Hoekstra (2014) evaluated the added value of a water footprint assessment for national water policy, using Morocco as a case study. Rudenko *et al*. (2013) also researched the added value of a water footprint though a micro- and macro-economic analysis of cotton production, processing and export in water bound Uzbekistan. The results showed that economic water efficiency is vital to ecological environment policies. To the author's knowledge, such a study has not been undertaken in South Africa for cotton production.

While water footprint assessments have been applied widely internationally, in South Africa, the use of this assessment is limited, especially for cotton. Thus, no scientific information on a water footprint for cotton is available to inform the sustainable use of water in cotton production. Considering the contribution of the cotton industry towards the South African economy, the assessment of a cotton water footprint cannot be ignored, as it is vital for sustainable water use by the cotton sector.

4.1.3 Aim and Objectives

The aim of the study is to assess the water footprint and economic water productivity of cotton produced under irrigation in South Africa.

Two sub-objectives have been formulated to achieve the aim of the study:

- Sub-Objective 1: Calculating the water footprint of cotton produced under irrigation.
- Sub-Objective 2: Evaluating the economic productivity of the water footprint of cotton.

4.2 METHODS AND DATA

This section is concerned with the methods and the data that were used to meet the objectives of this study. The discussion begins with the methods, where the specific method that was used to calculate the water footprint of cotton is presented, followed by the methods used to assess the blue water scarcity and the economic blue water productivity in the selected study area. Thereafter follows a discussion of the data that were used.

4.2.1 Methods

4.2.1.1 Water Footprint Accounting

The Global Water Footprint Standard method (Hoekstra *et al*., 2011) best suits the goal and scope of this study. The methodology discussed in this chapter is rooted in the guidelines discussed by Hoekstra *et al*. (2011) in the Water Footprint Assessment Manual.

The first objective of the study is to calculate the water footprint of cotton production at the farm level. The water footprint of a product denotes the level of stress that the product places on freshwater, which is a scarce resource in South Africa. The water footprint of growing cotton is calculated by summing the blue and green water components.

$$\mathrm{WF_{blue+green}} = \mathrm{WF_{blue}} + \mathrm{WF_{green}}$$ Equation 4.1

where:

$\mathrm{WF_{blue+green}}$ = Blue and Green water footprints

$\mathrm{WF_{blue}}$ = Blue water footprint of cotton production

$\mathrm{WF_{green}}$ = Green water footprint of cotton production

The blue water footprint ($\mathrm{WF_{blue}}$) (in $\mathrm{m^3/ton}$) is the irrigation water that evapotranspired over the cotton production period and is calculated by dividing the blue component in cotton water use ($\mathrm{CWU_{blue}}$ in $\mathrm{m^3/ha}$) by the cotton yield (Y) (in ton/ha). The green water footprint ($\mathrm{WF_{green}}$) (in $\mathrm{m^3/ton}$) used to produce cotton is the volume of rain water that evapotranspired over the cotton production period and is calculated by dividing the green component in cotton water use ($\mathrm{CWU_{green}}$ in $\mathrm{m^3/ha}$) by the cotton yield (Y) (in ton/ha). The $\mathrm{WF_{blue}}$ and $\mathrm{WF_{green}}$ were determined by Equations 4.2 and 4.3, respectively.

$$\mathrm{WF_{\,blue}} = \frac{\mathrm{CWU_{blue}}}{\mathrm{Y}}$$ Equation 4.2

$$\mathrm{WF_{green}} = \frac{\mathrm{CWU_{green}}}{\mathrm{Y}}$$ Equation 4.3

where:

$\mathrm{CWU_{green}}$ is the blue water used to produce cotton

$\mathrm{CWU_{blue}}$ is the green water used to produce cotton

Y is the cotton yield.

It is important to consider only the waste flow to freshwater by using the equations above. The blue and green crop water use ($\mathrm{CWUm^3/ha}$) can be determined by following the equations below:

$$\mathrm{CWU_{blue}} = 10 \times \sum_{d=1}^{lgp} \mathrm{ET_{blue}}$$ Equation 4.4

$$\mathrm{CWU_{green}} = 10 \times \sum_{d=1}^{lgp} \mathrm{ET_{green}}$$ Equation 4.5

where:

$\mathrm{ET_{blue}}$ is the blue water evapotranspiration.

$\mathrm{ET_{green}}$ is the green water evapotranspiration.

lgp is the length of the growing period in days.

The number 10, as indicated in Equations 4.4 and 4.5, is the factor used to convert water depths in millimetres into water volume per land surface in $\mathrm{m^3/ha}$.

4.2.1.2 Economic blue water productivity in cotton production

Following Mekonnen and Hoekstra (2010), the economic blue water productivity (EWP_{blue}) represents the income that is earned per cubic metre of blue water that was used to produce cotton. The EWP_{blue} of the crop is determined by multiplying the water productivity by the producer price:

$$\mathrm{EWP_{blue}} = \mathrm{WP_{blue}} * \mathrm{PP}$$ Equation 4.6

where:

$\mathrm{EWP_{blue}}$ is the economic water productivity

$\mathrm{WP_{blue}}$ is the physical blue water productivity

PP is the price of the cotton

The blue water productivity will be calculated as follows (Hoekstra, 2015):

$$\mathrm{WP_{blue}} = Y/\mathrm{ET_{blue}}$$ Equation 4.7

where:

Y is the cotton crop yield

4.2.1.3 Blue water scarcity analysis

The blue water scarcity was assessed to gain insight into the water availability situation in the selected cotton production areas in order to determine whether water use in the specific area is such that environmental flow requirements (EFR) are still being met. Water availability, in this regard, refers to the difference between the natural runoff (R_{nat}) and EFR (Hoekstra *et al*., 2011).

The blue water availability in the Olifants River basin ($WA_{blue,LP}$) was determined. The calculation was done by subtracting the EFR of the catchments from the natural runoff (R_{nat}) in the catchment occurring during that time in the catchment, as suggested by Hoekstra *et al*. (2011), by using Equation 4.8.

$$WA_{blue.LP} = R_{nat,LP,t} - EFR_{LP,t}$$ Equation 4.8

where $R_{nat,LP,t}$ is the natural runoff in Olifants River Basin in time *t*, and $EFR_{LP,t}$ is the EFR in Olifants River Basin in time *t*.

The blue water scarcity index was then calculated for Olifants River basin ($WS_{blue,LP}$) by dividing the total blue water footprint in the particular basin by the water availability in that particular basin (Hoekstra *et al*., 2011):

$$WS_{blue,LP} = \frac{\sum WF_{blue,LP}}{WA_{blue,LP}} \qquad \text{Equation 4.9}$$

A water scarcity index in excess of 100% implies that the water use in the particular basin is such that the EFR is not being met. According to Hoekstra *et al*. (2011), a situation where EFR is not met may be considered as constituting unsustainable water use. It is noted that the data that were used in this analysis do not consider the presence of dams in the basin. The presence of dams influences water availability, and thus may have an impact on the water scarcity index. Because of a lack of data, however, the influence of dams in the basin was not considered in this analysis.

4.2.2 Data

The discussion of the data includes a brief description of the study area, followed by the data that were used to calculate the water footprint of cotton, and the data needed to analyse the blue water scarcity in the basin within which the study area is located.

4.2.2.1 Study area

The research was conducted in Mable Hall, a town situated close to the convergence of the Mpumalanga and Limpopo Provinces. Farmers in Marble Hall fall under the Loskop Irrigation Scheme, which sources water from the Olifants River. The Olifants River flows in an eastern direction, from South Africa into Mozambique, as illustrated in Figure 4.1 below. Marble Hall receives an average rainfall of approximately 496%mm per annum, with the most rainfall occurring mainly during summer.

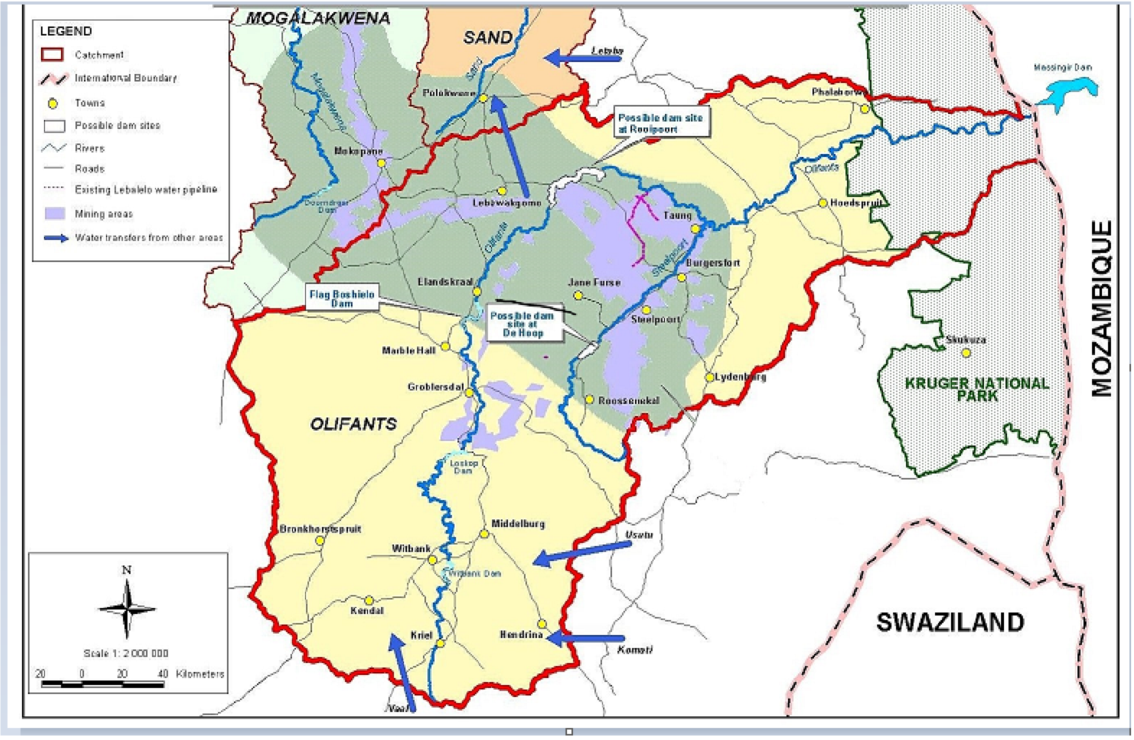

Figure 4.1: Layout of the water flow from the Olifants River basin in Limpopo and Mpumalanga
Source: Department of Water and Sanitation (2018)

The Loskop Dam serves as a source of water to the Loskop Irrigation Scheme, with the water flowing through canals. The irrigation scheme is made up of 624 farms (International Water Management Institute, 2000). The water supplied to farmers is measured at various sluice gates along the canals. Through a sluice gate, water can be delivered at 17 m^3/hour to 200 m^3/hour, depending on the size of the gate (International Water Management Institute, 2000).

4.2.2.2 Data for water footprint accounting

The scope of this study covers a case study of the water footprint of cotton in South Africa. The study made use of primary data received from a farmer located near the Loskop Dam, Marble Hall, in Limpopo. SAPWAT 4 (Van Heerden and Walker, 2016) was used to confirm the data supplied by the farmer.

The South African Procedure for Estimating Irrigation Water Requirements (SAPWAT) (Van Heerden and Walker, 2016) is a program that is used to make assumptions of the irrigation water requirements of crops, and it is based on the CROPWAT model (Allen *et al*., 1998). SAPWAT uses the CROPWAT core procedures, which contain the international guidelines that are accepted for estimating irrigation requirements. The program uses the climate data received from the closest weather station to locate where the crop is produced, and, as the program is linked with weather stations, the program receives updates as new weathers are setup (Van Heerden *et al*., 2008). Other information that needs to be input into the SAPWAT includes rainfall, type of crop planted, solar radiation, air temperature, humidity, and planting time (Allen *et al*., 1998). In this case, weather data details downloaded from the Pietersburg weather station were used.

The model employs a reference grass evapotranspiration, and the particular crop requirement is calculated based on any stage in the growth cycle of a crop (Allen *et al*., 1998). The model gives default values for all crops produced under irrigation in South Africa, and cotton is one of the crops. The monthly crop requirement is obtained by multiplying monthly grass evapotranspiration by the monthly average crop factor. After running the model, it will give the following results: crop evapotranspiration (CR (ET)), rainfall (R), rain loss (RL), Effective rainfall (ER), Irrigation water (I), irrigation loss (IL), Effective irrigation (EI), and others. The results are then used to calculate the water footprint of cotton.

4.2.2.3 Data for the blue water scarcity assessment

The monthly blue water scarcity of both the Olifants River Basin was calculated. The data needed to determine the WS_{blue} are the available monthly blue water (WA_{blue}) and the total monthly blue water footprint (WF_{blue}) within the basin. The WA_{blue} and WF_{blue} of the Olifants River Basin were obtained from the data reported by Hoekstra and Mekonnen (2011).

4.3 RESULTS AND DISCUSSION

The results are presented and discussed in this section. The discussion is started with the water footprint of cotton production, followed by the water scarcity situation and the impact thereof on cotton production. Thereafter follows the results of the analysis of the economic blue water productivity of cotton production. The section is then concluded with conclusions and recommendations, based on the results that were obtained.

4.3.1 Water Footprint of Cotton Production

The WF was calculated for two different planting dates. The early and the late cotton crops are planted in September and October, respectively. Table 4.1 below summarises the water balance data modelled with SAPWAT4 (Van Heerden *et al*., 2008) for the Loskop Irrigation Scheme. The planting season for this cotton starts in September, for the early crop. The cotton yield per hectare was 4.8 ton/ha, a typical yield at Marble Hall, with a crop evapotranspiration (ET) of 563 mm. Effective rainfall (ER) was 329 mm and Effective irrigation (EI) was 234 mm.

Table 4.1: Summary of water use data at Loskop Irrigation Scheme for a planting date in September

	YIELD	ET	ER	EI
	ton/ha	mm		
Medium Grower	4.8	563	329	234

Table 4.2 below indicates the total evapotranspiration of cotton in Loskop at 566 mm. The ET was converted from mm to m^3 indicated by $\mathrm{CWU_{green}}$ and $\mathrm{CWU_{blue}}$.

Table 4.2: Cotton water use in Loskop irrigation scheme planting as of September

CROP	ET	ET_{blue}	ET_{green}	CWU_{blue}	CWU_{green}
	mm			m^3/ha	
Cotton	566	234	329	2340	3290

Source: Own Calculation (2018)

Table 4.3 below shows the calculation of $\mathrm{WF_{blue}}(\mathrm{m}^3$/ton) and $\mathrm{WF_{green}}(\mathrm{m}^3$/ton). The $\mathrm{CWU_{blue}}(\mathrm{m}^3$/ha) in Table 4.2 was divided by the yield to obtain the $\mathrm{WF_{blue}}(\mathrm{m}^3$/ton), and the $\mathrm{WF_{blue}}$ was found to be 488 m^3. Similar to $\mathrm{WF_{blue}}$, $\mathrm{WF_{green}}$ was obtained by dividing $\mathrm{CWU_{green}}$ by yield. The $\mathrm{WF_{green}}$ of cotton was 685 m^3/ton. The $\mathrm{WF_{blue+green}}$ was then calculated by adding $\mathrm{WF_{blue}}$ and $\mathrm{WF_{green}}$, therefore, $\mathrm{WF_{b+g}}$ was 1172.92 m^3/ton.

Table 4.3: Blue and green water footprint of cotton planting, as of September

CROP	Yield	WF_{blue}	WF_{green}	$WF_{blue+green}$
	(ton/ha)	m^3/ton		
Cotton	4.8	488	685	1173
Percentage (%)		40%	60%	100%

Source: Own calculation (2018)

For the early cotton crop planted in September, the $\mathrm{WF_{blue}}$ was about 40% and $\mathrm{WF_{green}}$ was about 60% of the $\mathrm{WF_{blue+green}}$. The results show that the high water volume that cotton requires during production is met through rainfall.

Table 4.4 below depicts the summary of water use data obtained during the middle planting season, which happens in October. The yield of the middle planting season was assumed to be the same as the early cotton crop. The ET was 506 mm, with ER of 318 mm, and the EI was 188 mm.

Table 4.4: Summary of water use data at the measuring points in Loskop Irrigation Scheme, planting time in October

	YIELD	ET	ER	EI
	(ton/ha)	(mm)		
Medium grower	4.8	506	318	188

Table 4.5 below depicts how the CWU_{blue} (in m^3/ha) and the CWU_{green} (in m^3/ha) were calculated. The formula used to calculate the CWU_{blue} (in m^3/ha) and the CWU_{green} (in m^3/ha) for cotton planted in October is similar to the one that was used for cotton planted in September, the results of which are shown in Table 4.2 above. The CWU_{blue} for the season was 1880 m^3/ha and the CWU_{green} was 3180 m^3/ha. Table 4.5 below further shows the ET_{crop} of 506 mm, ET_{blue} of 188 mm, and ET_{green} of 318 mm.

Table 4.5: Cotton water use in Loskop Irrigation Scheme, planting time as of October

	ET	ET_{blue}	ET_{green}	CWU_{blue}	CWU_{green}
	mm			m^3/ton	
Cotton	506	188	318	1880	3180

Source: Own calculation (2018)

Comparing the ET_{cotton} for the planting season of September in Table 4.2 above and that for October in Table 4.5 above, it can be seen that the planting season in October does not require much irrigation water, compared with September, because cotton planted in October uses more rainfall water, as probabilities of above-normal rainfall are normally expected during that time (Viljoen, 2012). This means that cotton planted in October can produce the same yield as cotton planted in September does, while using less irrigation water. Therefore, cotton growers are advised to consider the late planting season in October to save water. Table 4.6 below illustrates the blue and green water footprints of cotton planted in October.

Table 4.6: Blue and green water footprints of cotton, planting time in October

	Yield	WF_{blue}	WF_{green}	$WF_{blue+green}$
	(ton/ha)	m³/ton		
	4.8	392	663	1055
Percentage (%)		37%	63%	100%

Source: Own calculation

Table 4.6 above shows the calculation of the blue WF and the green WF of cotton during the October planting season. The WF_{blue} of 392 m^3/ton was calculated by dividing CWU_{blue} of 1880 m^3/ton, shown in Table 4.5, by the yield of 4.8 ton/ha. Similarly, the WF_{green} of 663 m^3/ton was obtained by dividing the CWU_{green} of 3180m^3/ton by a yield of 4.8 ton/ha. Of the $WF_{blue+green}$ of 1055 m^3/ton, 63% of the water required was contributed by rainfall, which shows that, even in late planting time, the water that cotton requires is mostly met by water from rainfall. Considering the water scarcity and future climate change issues, cotton in this area might need more irrigation water in the future, although rainfall currently contributes the most to the cotton's water requirement.

The results of this study show that different planting times can have effects on the cotton water requirement, and on the water footprint as a whole. The results of this study show that cotton planted at the Loskop Irrigation Scheme, on average, uses less water than that reported in the findings of Aldaya *et al.* (2010), who examined the water footprints of cotton and other crops produced in Central Asia. Aldaya *et al*. (2010) showed that an average of 6875 m^3/ton of the blue water footprint was used to produce cotton in their study area, which is a large proportion for one crop. The yield of cotton produced in the Loskop Irrigation Scheme area was 4.8 ton/ha, compared with the yield of cotton produced in Central Asia of 2.26 ton/ha. Cotton yield seems to have a major impact on the WF of cotton, and this could be one of the reasons why the cotton WF in Central Asia is relatively high, when compared with that produced in the Loskop Irrigation Scheme area. In this vein, the study by Zeng *et al.* (2012), reported cotton to be one of the crops that use a significant amount of irrigation water, which was reported to be 3384 m^3/ton in their study.

According to Rudenko *et al*. (2013), cotton used about 6000 to 8000 m^3/ton of water in their study area, which included leaching and conveyance losses, giving an average yield of 2.6 ton in their study area. According to Zeng *et al*. (2012), a grey water footprint was not included in their study due to the lack of comprehensive data on pollutant discharges. Other authors have reported similar situations, recording that they did not include a grey water footprint of cotton from the farm level, as they could not find relevant data. For the purpose of this study, a grey water footprint was not calculated due to the lack of comprehensive data. Therefore, cotton growers are advised to record and keep data that could enable future scholars and researchers to calculate a grey water footprint and share the results with the cotton growers.

4.3.2 Blue Water Scarcity and Cotton Production

Figure 4.2 below depicts the water scarcity situation in the Olifants River catchment. The blue water scarcity index exceeds 100% during the months June through November, which implies that more water is used than what is actually available for use during those months. As such, the water users in the Olifants Catchment are tapping into the environmental flow requirement from June to November in order to meet demands. From October, there is an increase in runoff because of the start of the rainy season, which, in turn, increases the water that is available for use, and hence decreases the water scarcity index.

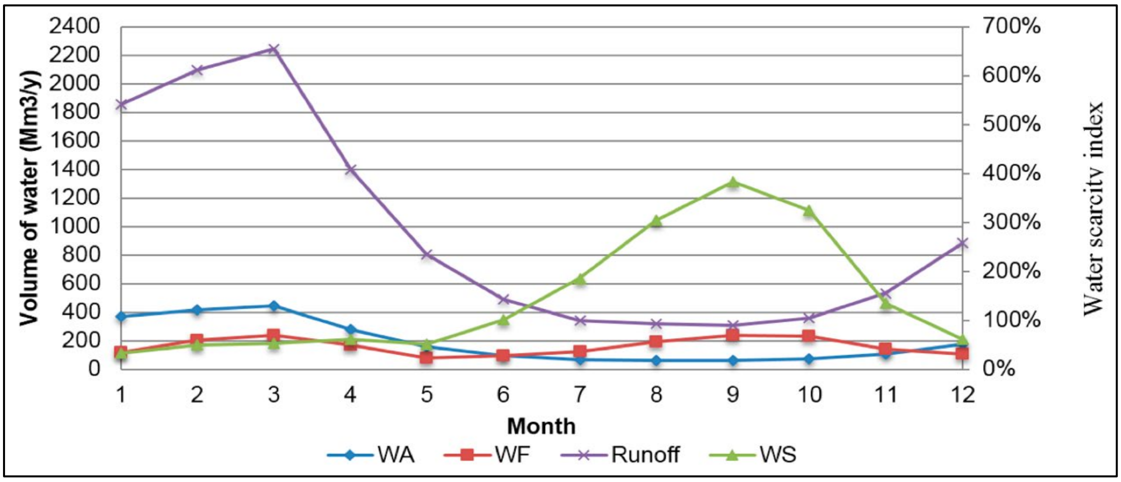

Figure 4.2: Water availability, water footprint, runoff and water scarcity, Olifants River Basin, 1996-2005

Notes: The above depicts the Water Availability (WA), Water Footprint (WF), Runoff and Water Scarcity (WS) for the Olifants River Basin in South Africa, using data for the period 1996-2005

When considering cotton production at the Loskop Irrigation Scheme, the planting periods (September and October) correspond with the period when the blue water scarcity is high. The initial period, however, is a period when cotton does not require that much water. It is only in the later growth stages that the crop water requirement for cotton increases. Those growth stages correspond with the periods when the water scarcity index is less than 100%. Thus, the main growing period of cotton at Loskop Irrigation Scheme corresponds with the period when water scarcity is not a problem.

4.3.3 Economic Blue Water Productivity of Cotton Production

Economic blue water productivity (EWP_{blue}) is the economic value obtained per unit of water utilised for the production of a product (Chouchane *et al.*, 2015). Table 4.7 below reflects the physical water productivity and economic water productivity of cotton experienced during cotton production. Physical water productivity (PWP) is usually expressed in m^3/kg. Table 4.7 below shows that cotton planted in September has a water productivity of 0.85 m^3/kg, and that cotton planted in October has a water productivity of 0.95m^3/kg. Therefore, it takes 0.85 m^3 of water to produce 1 kg of cotton planted in September, and it takes 0.95 m^3 of water to produce 1 kg of cotton planted in October. The early harvesters of cotton were receiving ZAR 8500/ton, with late harvesters receiving ZAR 9150/ton at the farm gate during the harvesting period commencing in May and running until the end of July. The cotton grower in the Loskop Irrigation Scheme provided the aforementioned information. To calculate the prices of cotton per kilogram, ZAR 8500/ton was divided by 1000 to get ZAR 8.5/kg (0.65 USD/kg) and ZAR 9.15/kg (0.69 USD/kg). The economic water productivity was calculated by multiplying the PWP by the price of cotton. The EWP of cotton in Loskop in September was 7.23 ZAR/m^3(0.55 USD/m^3), which means that the value added to cotton production is 7.23 ZAR/m^3(0.55USD/m^3). The EWP of cotton in Loskop in October was 8.69 ZAR/m^3(0.66USD/m^3). This means that the value added to cotton production is 8.69 ZAR/m^3(0.66 USD/m^3).

Table 4.7: Physical water productivity and Economic blue water productivity of cotton production

Planting date	PWP (m^3/kg)	Price (USD/kg)	Price (R/kg)	EWPblue (USD/m^3)	EWPblue (R/m^3)
September	0.85	0.65	8.5	0.55	7.23
October	0.95	0.69	9.15	0.66	8.69

Source: Author's calculations (2018)

Cotton growers who plant in October, for the late cotton crop, generate more income per cubic metre of water used to produce their cotton, as compared with the early cotton growers planting in September.

4.3.4 Discussion

Chapagain *et al*. (2006) assessed the impacts of the worldwide consumption of cotton products on the water resources in the cotton-producing countries. It was found that certain countries were more preferred than others due to the irrigation requirements of cotton. Brazil and the United States of America were more attractive because their blue water footprints were lower than their green water footprints, which means low irrigation requirements. Similarly, their study shows that cotton production required less irrigation water than rainfall water. The grey water footprint was not accounted for due to lack of comprehensive data on pollutant discharge.

Contrary to the results of their study, Aldaya *et al*. (2010) assessed the water footprints of cotton and other crops produced in Central Asia and concluded that about $6875\ \mathrm{m}^3$/ton for the blue water footprint was used to produce cotton. Comparing the results of Aldaya *et al*. (2010) and the findings of the present study, it is noted that cotton planted within the Loskop Irrigation Scheme uses less water. Comparing the results reported by Zeng *et al*. (2012) for the Heine River Basin, it is seen that cotton produced in the Heine River Basin used more water, when compared with the findings of this study. According to the findings of Rudenko *et al*. (2013), who explored a macroeconomic analysis of cotton production, processing and exports in water bound Uzbekistan, cotton used about 6818m^3 in their study area, which is substantially more than the findings made for the study area of this study. However, this study was only limited to a farm-level analysis, whereas Rudenko *et al*. (2013) extended their study to cotton processing and exports. Nonetheless, the findings reported by Ercin *et al*. (2013) are in alignment with the findings of this study. Ercin *et al*. (2013) reported that about 1706 m^3 of water was used to produce one hectare of cotton in their study area, and the results of this study show the total water footprint for the early planting season in September to be 1054.17 m^3 per ton, while that for the late planting season in October was 1172.9 m^3/ton.

The findings of this study show that for the September planting, about R7.23 was obtained per cubic metre of the water used for cotton production, and for the October planting, about R8.69 was obtained per cubic metre of the water used for cotton production. Cotton growers who plant in October, for the late cotton crop, acquire more value in their cotton, when compared with the early cotton crop growers in September. Hence, it is important that cotton growers should consider planting their cotton in October, as it has more value than that planted in September.

Cotton growers should consider planting the late crop in October, as it yields the same as the early crop does, but uses less water than the early cotton crop does. The yield of production also affects the water footprint print results. The plant breeders should consider breeding higher-yielding and more drought-resistant varieties of cotton, which the cotton growers could adapt for efficient production. Moreover, if the farmers could use more cost-effective irrigation methods, it would help to reduce the usage of blue water.

4.4 CONCLUSIONS AND RECOMMENDATIONS

4.4.1 Conclusions

Based on the results, it is concluded that the $\mathrm{WF_{blue+green}}$ of irrigated cotton of the early planting season in September was 1173 $\mathrm{m^3}$/ton. Of the $\mathrm{WF_{blue+green}}$, the $\mathrm{WF_{green}}$ of the cotton was 685$\mathrm{m^3}$/ton and $\mathrm{WF_{blue}}$ was found to be 488 $\mathrm{m^3/ton}$. For the early cotton crop planted in September, the $\mathrm{WF_{blue}}$ was about 40% and $\mathrm{WF_{green}}$ about 60% of the $\mathrm{WF_{blue+green}}$. The results show that the high water volume that cotton requires during production is met through rainfall. It is important that the farmer should try to use less of irrigation, as the country is experiencing water challenges. If the production of cotton is able to depend more on rainfall and still achieve the same yield as when under irrigation, then the water units could be allocated for other uses.

For the late planting season in October, it was concluded that the $\mathrm{WF_{blue+green}}$ of the irrigated cotton was 1054 $\mathrm{m^3}$/ton. The $\mathrm{WF_{blue}}$ was found to be 392 $\mathrm{m^3}$/ton while the $\mathrm{WF_{green}}$ was 662 $\mathrm{m^3}$/ton. Of the $\mathrm{WF_{blue+green}}$ of 1054 $\mathrm{m^3}$/ton, 63% of the water required was contributed by rainfall.

The economic value obtained per unit of water utilised during early cotton production in September in the Loskop Irrigation Scheme was 7.23 ZAR/$\mathrm{m^3}$(0.55USD/$\mathrm{m^3}$), while the income earned per cubic metre of water used for cotton production planted late in October was 8.69 ZAR/$\mathrm{m^3}$(0.66USD/$\mathrm{m^3}$). Cotton planted in September had a water productivity of 0.85 $\mathrm{m^3}$/kg, while that planted in October had a water productivity of 0.95 $\mathrm{m^3/kg}$. Therefore, it takes 0.85 $\mathrm{m^3}$ of water to produce 1 kg of cotton planted in September, and it takes 0.95 $\mathrm{m^3}$ of water to produce 1 kg of cotton planted in October. The early harvesters of cotton were receiving ZAR 8500/ton while the late harvesters received ZAR 9150/ton, at the farm gate during the harvesting period, commencing in May and running until the end of July. Cotton growers who plant in October, for the late cotton crop, earn more income on their cotton than the early cotton crop growers in September do. Therefore, it is important that cotton growers should consider planting their cotton in October, as it has more value than the cotton grown in September has.

Cotton growers should consider planting the late crop in October, as it yields the same as the early crop does, but uses less water than the early cotton crop does. The late cotton crop, planted in October, has more value than the early crop has. The yield of production also affects the water footprint results. The plant breeders should consider breeding higher-yielding and more drought-resistant varieties of cotton, which the cotton growers could adapt for efficient production.

Moreover, if the farmers could use more cost-effective irrigation methods, it would help to reduce the usage of blue water.

4.4.2 Recommendations

4.4.2.1 Cotton Industry

1. It is important to gain sufficient knowledge about the climate, as this is vital when considering which areas are suitable for efficient and profitable cotton production, and this would help to ensure the most advantageous growing season of cotton. Cotton growers need to be aware of the appropriate amounts of water required by their crops, and they need to know what the rainfall contributes and how much water they should use for irrigation.

2. Cotton growers should consider planting the late cotton crop in October, as it is more profitable than the early cotton crop in September is. The late cotton crop requires less water than the early crop in September does, and therefore the cotton growers should consider the late production as they would then be able reduce the volumes of water used. Cotton is a summer crop, and for optimum growth, the temperature must be above 25°C.

3. The cotton plant performs best in deep, highly fertile, sandy loam soils, with reasonably good drainage. A farmer should have knowledge on the soil type, as soil with poor drainage can cause water-logging conditions. Moreover, working soil that is too wet or too dry for cultivation can result in a breakdown of the soil structure. Therefore, it is important that farmers should use soil ridging in such situations while doing land preparation. Plant populations of approximately 70 000 plants per hectare under irrigated conditions and 30 000 plants per hectare under dryland conditions, are recommended. Fertiliser applications must, however, be complemented by good rainfall or irrigation to keep the effective soil depth in the 0.9 m zone of filed capacity. Therefore, cotton under irrigation requires about 200kg N/ha or less to achieve maximum yields.

4.4.2.2 Researchers

1. A grey water footprint should be taken into consideration when assessing the water footprint of cotton in order to better inform farmers and policymakers of the water being consumed during the production at the farm level.

2. Researchers should investigate the water footprint of cotton along the value chain of the various products produced from cotton seed, up to the point where the final product reaches the end user. This will give a good picture on where water is used the most in the process of offering the product to the end user of the final cotton product.

3. Researchers should assess where the EWP is high along the value chain of producing an end product where cotton seeds are used as the initial raw material. Researchers should conduct studies that would better explain and quantify the social sustainability of cotton production in different regions.

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CHAPTER 5
CASE STUDY OF SUNFLOWER AND BIODIESEL

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5.1 INTRODUCTION

5.1.1 Background and Motivation

Water is an invaluable resource that is required to sustain all life forms, and it is required for a civilisation to prosper (Donnenfeld *et al.*, 2018; Dominguez-Faus *et al.*, 2009). It has been projected that humanity will at some point struggle to attain adequate freshwater to sustain their needs (Gerbens-Leenes *et al.*, 2009a). Changes in the global climatic conditions are playing a significant role in reducing the availability of water resources, coupled with an increasing global demand for water in different sectors (Gerbens-Leenes, 2009). Within these different existing global sectors, agriculture consumes the majority of water resources worldwide (Gerbens-Leenes and Hoekstra, 2012).

In line with the global trend, approximately 60% of water resources in South Africa are utilised within the agricultural sector (Donnenfeld *et al.*, 2018). This country is developing and it requires reliable supplies of water resources to sustain its economic growth (Orr *et al.*, 2009). It is, however, water-scarce, as it receives rainfall that is less than the global average and it has been ranked as the 30th driest country in the world (Zhang *et al.*, 2019; Donnenfeld *et al.*, 2018; Von Bormann and Gulati, 2014; Haw and Hughes, 2007). Recently, South Africa has been struck by continuous drought conditions in some of the provinces, and the low rainfall levels have resulted in inadequate nation-wide water supplies and this has been generally unfavourable for agriculture (Zhang *et al.*, 2019).

The agricultural sector of South Africa is highly important for sustaining livelihoods. Its significance stretches from providing food security through the adequate supply of food; creating employment opportunities in various industrial links; to industrial development through increased value chain activities. The agricultural sector, however, contributes a mere 2% to the national Gross Domestic Product (GDP) and this level of contribution could indicate the sector's major use of water as being inefficient (Zwane, 2019). Maintaining the current agricultural activities and further exploring opportunities for other activities within the agricultural sector requires the important implementation of proper and efficient ways to use water resources (Gerbens-Leenes *et al.*, 2009a). There has been an increase in the global transition towards the production and use of biofuels in different forms, while in South Africa, the biofuel industry has been considered for exploration within the agricultural sector.

Biofuels are produced from biological materials called biomass, which can be in the form of energy crops, agricultural and forestry wastes, and lignocellulosic by-products (Mathimani and Pugazhendhi, 2018). There are various forms of biofuel, such as bioethanol and biodiesel, with the latter generally being produced from the esterification of first, second or third-generation feedstock, or combinations thereof. Several countries in the world are producing and using biofuels, including Brazil, the United States of America (USA), Russia, and China. South Africa is also intending to shift towards the production and utilisation of biofuels. The plan to shift towards biofuels in South Africa has been outlined in the biofuels industrial strategy. Within this strategy, the country has an initial penetration plan of using biofuels through a 2% blending with the currently utilised fossil fuels (Pradhan and Mbohwa, 2014; Minerals and Energy, 2007).

The production and use of biofuels in South Africa has the potential to offer various opportunities, such as creating jobs, reducing greenhouse gases (GHGs), increasing rural and national development, promoting the socio-economic development of small-scale farmers, and reducing dependence upon fossil fuels (Pradhan and Mbohwa, 2014). Despite the potential opportunities that could be generated from this venture, there is slow progress within the biofuel industry, and this has been indicated to stem from a lack of government incentives and the from challenges that the crops intended for use as feedstock could present for water resources (Jewitt and Kunz, 2011). Biofuels are observed to have the potential to threaten food security, globally, and this is also a crucial challenge for South Africa as a developing country. To overcome the potential food insecurity, the South African government has ruled out the use of certain crops, while other specific crops have been favoured and endorsed as acceptable and viable feedstock crops for national biofuel production. Sugar cane and sugar beet are endorsed for bioethanol, whereas sunflower, soya beans and canola are assigned for biodiesel production (Pradhan and Mbohwa, 2014; Minerals and Energy, 2007).

Sunflower is an important oil crop that is mainly cultivated to produce edible oil, worldwide. Sunflower oil is extracted from vegetable seeds and it is used for different oil-based foods, while it can also be used in the formulation of cosmetic products (Smuts and Malan, 2016). Sunflower oil cake is a by-product of sunflower oil extraction and is used as an animal feed. In South Africa, sunflower is an annual summer crop that is mainly grown in the Free State, Limpopo, Northwest, and Mpumalanga provinces. The general sunflower planting season ranges from November to January, and harvesting ranges from April to June, depending on the region and period of production. Sunflower is the primary oil crop planted in South Africa, and it constitutes approximately 70% of the total area planted with oilseeds (Mzezewa and Van Rensburg, 2019). Despite its traditional global usage as edible oil, sunflower oil has also gained intrinsic attention as a feedstock for biodiesel (Channi *et al.*, 2016).

Biodiesel is a form of biofuel and is an alternative and renewable source for diesel fuel. It is renewable, because it is derived from sustainable energy sources when compared with crude oil, which is limited and can potentially run out. Biodiesel is produced from oil that is derived from renewable oil sources, such as plant oils (e.g. sunflower oil) and animal fat (e.g. tallow) (Aníbal Sorichetti and Romano, 2012; Demirbas, 2005). It has gained attention as a strategic alternative fuel source because of the global drive to reduce the emission of GHGs and to use a cleaner and environmentally friendly fuel, as compared with fossil fuels that emit higher GHGs (Pegels, 2010).

The production of biodiesel from feedstock, such as sunflower, entails a complex process, with two direct production levels, which are sunflower (feedstock) production (farm level) and the conversion of vegetable (sunflower) oil into biodiesel (processing level). Water is required at all levels of biodiesel production, with the farming level being reported to be the main consumer of water, rather than the processing level, since the latter uses less water (Ghani *et al.*, 2019; McNabb, 2019; Fingerman *et al.*, 2010; de Fraiture *et al.*, 2008). Transitioning towards producing and using biodiesel in South Africa requires ample information, especially on its demand for water use (Haw and Hughes, 2007).

A water footprint is defined as representing the total volume of freshwater used to produce a product, measured throughout the entire supply chain (Aldaya *et al.*, 2012); (Hoekstra, 2017). It has developed as a prominent tool to use to indicate the sustainability of water use within biodiesel production, and agriculture as a whole (Pfister *et al.*, 2009). It is a measure of the volumes of water used in the production of a product, along the entire value chain. This involves assessing water volumes from the input levels and the processing levels to the point where the output/end product reaches the consumer (Aldaya *et al.*, 2012; Hoekstra *et al.*, 2009). This tool takes cognisance of the use of rainwater, surface water, and water used for pollution assimilation throughout the entire value chain (Hoekstra *et al.*, 2009). As endorsed by the Water Footprint

Network (WFN), the approach is an accepted Global Water Footprint Standard (GWFS) approach for assessing water footprints, worldwide (Aldaya *et al.*, 2012).

Water plays an important role in the growth of sunflower; hence it is important to evaluate the sustainability of producing sunflower. Environmental sustainability is one measure to determine the sustainable use of water for sunflower production, and this can be generally assessed at a river-basin level. The sustainability of water in a river basin relies upon the balance between the environmental requirements and the availability of scarce water resources (Dessu *et al.*, 2014; Zeng *et al.*, 2012). It is important for sunflower farmers to understand the balance between water scarcity and the water footprint of growing sunflower within the river basin. This will unlock the proper understanding for identifying sunflower production periods that enable and cater to meet environmental requirements.

For biodiesel to be a viable alternative over other fuels, it needs to have environmental benefits, be producible without compromising food supplies, and also be economically competitive (Brent *et al.*, 2009). Exploring the production of biodiesel at a large scale requires ample planning and investigation of its feasibility in an economic context. This involves assessing some of the main economic factors that influence the commercialisation of biodiesel. These factors include market, agricultural, and financial feasibility (Nolte, 2007).

5.1.2 Problem Statement and Objectives

For several decades, there has been a global transition towards the production and use of more sustainable, efficient, and renewable fuels (biofuels). In South Africa, the adoption of biofuels has the potential to provide a sustainable fuel supply for the country. The adoption of biofuels in this country requires ample knowledge and attention towards resource use to avoid posing socioeconomic and environmental problems, such as invasion of food security, land competition, and water use competition (Blanchard *et al.*, 2011). There is a need to also understand the required financial inputs and respective benefits to enable the proper assessment to be made of the financial viability of producing biodiesel in the country. To help remedy food security issues, non-staple food crops, such as sunflower, have been endorsed as being acceptable feedstock for biodiesel production. The competition that could arise for land was resolved by stipulating underutilised land in the former rural homelands as the targetable land for biodiesel feedstock growth. However, solutions to the negative impacts that biodiesel production could pose for water resources are not clear.

South Africa is a water-scarce country, and it has been continuously experiencing high drought conditions for some time. The majority of its water resources are used within the agricultural sector; therefore, sustaining the current agricultural conditions and exploring any further water-utilising activities requires adequate approaches to be adopted for ensuring the sustainable use of the limited water resources (Viljoen and Van der Walt, 2018). Exploring biodiesel production requires ample knowledge on the use of input resources, such as adequate, sustainable feedstock, and effective and efficient water use. The use of sunflower as a biodiesel feedstock has received ample global attention through various research studies. Some of these studies mainly focused on: i) the analysis of sunflower as a significant biodiesel feedstock, ii) computing the best conversion or processing approach for extracting biodiesel from sunflower oil, iii) the position of sunflower as a biodiesel feedstock, as compared with other feedstock, and iv) water use required for biodiesel production from sunflower, assessed using the GWFS methodology (Hogeboom and Hoekstra, 2017; Hoekstra *et al.*, 2015; Dominguez-Faus *et al.*, 2009). Most of these studies were conducted in various parts of the world, including some European Union countries, Brazil and the USA. It should be noted, however, that although there is a plethora of information available at a global scale, there still is a necessity for a relevant study to be conducted in South Africa to cater for the local climate, environmental and water aspects, as these vary worldwide (Brent, 2014).

All human activities generally involve water consumption, and biodiesel production presents a significant demand on water resources, as the production process requires water use at all levels (Pfister *et al.*, 2017; Siddiqi and Anadon, 2011; Ridoutt and Pfister, 2010). The growing demand for biofuels could generally lead to decreases in water supplies; hence, the use of water in the production of biodiesel requires attention (Von Bormann and Gulati, 2014). In South Africa, there is ample literature on water use for various agricultural activities. Most of these studies focus predominantly on the water requirements of crops, and usually concentrate on crop irrigation and the volumes of water required to optimise yield. However, such sources do not give consideration to consumptive water use throughout the crop's growth cycle, and ultimately without giving consideration to the economic aspects. However, the GWFS approach can be used with consideration of these aspects. Water footprints can also be assessed by using life cycle assessments (LCA), in which all the inputs, outputs and the potential environmental impacts throughout the entire life cycle of a product are considered (Scheepers, 2015).

Concerning the financial analysis, the economic aspects of producing biodiesel have been explored in the past. Studies of these aspects were conducted mostly in the early foundational periods of formulating a strategy for biofuel in South Africa. However, there is a need to explore and analyse the economic aspects of producing biodiesel at a different and newer economic stage in the country, because affordability is one factor that has limited the progress of biodiesel production (Brent, 2014). This exploration will provide an array of information that could aid in delving further into biodiesel production, considering the increase in fuel demand and ever-changing economic conditions.

Ultimately, a better understanding of water use can be obtained through the Water Footprint Assessment (WFA) approach, thereby formulating necessary response strategies that provide inputs for development and improvement of policies on water use for biodiesel production (Stebbins, 2009). Assessing the economic viability, on the other hand, provides an array of possibilities on how to embark upon the production of biodiesel at an economically competitive level (Von Maltitz and Stafford, 2011). The water use assessment and financial analysis, coupled together, can provide an addition to the pool of knowledge for sustainable water use for biodiesel production that is economically beneficial and justifiable in South Africa. This can also lead to a better understanding of preserving the scarce water resource, while obtaining high production yields and unlocking more potential for sustainable water use at financially beneficial levels.

Although sunflower is stipulated as a viable biodiesel feedstock in South Africa, there is a lack of information on its use of water in the production of biodiesel and on the economic feasibility of commercialising the biodiesel produced in this economic era. Therefore, this study explored the biodiesel produced from sunflower as a first-generation feedstock. The Orange River Basin was observed in this study to evaluate whether the production of sunflower was sustainable or whether it created an environmental hotspot. Furthermore, the costs and returns/benefits of biodiesel commercialisation were analysed to enable a proper economic, feasibility assessment to be made.

This study utilised the GWFS method for determining water footprints, as endorsed by the WFN, to assess the water footprints of producing biodiesel in South Africa. Although the WFA tool has received ample attention internationally, its usage in this country has received minimal attention. Regarding economic viability, the study assessed the Financial, Agricultural and Market factors of the produced biodiesel to assess the benefits derived from its production. For the economic feasibility assessment, this study adopted and modified a combination of the framework developed by Walekhwa *et al.* (2009) and the approach used by Nolte (2007). There is a limited volume of information that can aid policymakers in making effective policies for guiding the sustainable use of freshwater resources during biodiesel production and in assessing the respective financial viability. Thus, this study was intended to add more information to the pool of knowledge on the effective and efficient use of water in the production of biodiesel and the resulting economic costs and benefits.

The main aim of this study is to evaluate the water footprint of producing biodiesel, and its economic viability, through using sunflower in South Africa. The complete value chain of producing biodiesel from sunflower was assessed regarding the volumes of water allocated and utilised, throughout each process step of production, and the costs and benefits that pertain to the entire production process. Ultimately, the total water footprint and financial viability of producing biodiesel were deduced. The aim of this study was achieved through the following objectives:

- **i)** To quantify the water footprint of producing biodiesel using sunflower
- **ii)** To evaluate the blue water scarcity in relation to the production of sunflower as a fuel crop
- **iii)** To evaluate the economic feasibility of commercialising biodiesel produced using sunflower.

5.1.3 Scope of the Study

Biodiesel production, through transesterification, was selected for this case study and the water footprint methodology was applied. The sunflower was selected as the feedstock crop for this study. The sunflower was selected based on: i) its endorsement as an acceptable feedstock in South Africa, and ii) the existence of necessary knowledge on the crop to enable water use modelling to be implemented, as compared with other endorsed feedstock crops (Enwerenmadu *et al.*, 2014; Minerals and Energy, 2007; Nolte, 2007). The analysis of this study focuses on two stages of the value chain, being the farm phase (sunflower growth) and the processing phase (biodiesel conversion). The scope of this study was limited to the following:

- Evaluating the water footprint of producing biodiesel at the farm level and the processing level to attain the total water footprint. The green and blue water footprints were assessed. There is a general consideration made of the limitation of blue water and the higher opportunity costs associated with it, as compared with green water. This led to a greater level of emphasis and attention being given to the accounting of green water.

- The total water footprint of producing biodiesel was estimated. When calculating the total water footprint of biodiesel, the grey water footprint was excluded, as there was a limited data supply for incorporating this water footprint in the study.

- Considering the fluctuations in water availability and timeous variations in water demand, this study incorporates data from the 2018 period. The CROPWAT 8.0 (Allen *et al*., 1998), CLIMWAT 2.0 and SAPWAT4 (Van Heerden and Walker, 2016) applications were used to analyse the data utilised in this study.

- Following the accounting of water footprints, the results obtained were utilised to provide response strategies for adding to the pool of knowledge of biodiesel production in South Africa and the respective policies.

5.2 DATA AND METHODS

The Global Water Footprint Standard (GWFS), set out by Hoekstra *et al.* (2011), and the economic feasibility methodology used by Nolte (2007) and Walekhwa *et al.* (2009), are best suited to use to give a comprehensive assessment of the links between biodiesel production from sunflower and water resources and the relative economic feasibility, respectively. Both of these frameworks were utilised to achieve the aim and objectives of this study. The WFA framework by Hoekstra *et al.* (2011), which was used in this study, comprises four distinct phases, which are setting goals and scope, water footprint accounting, sustainability assessment, and response formulation. The economic feasibility assessment methodology, on the other hand, is comprised of agricultural, market, and financial feasibility assessment steps. These phases and steps of both methodologies were used as guiding steps to achieve the objectives of this study. The sections below outline the different methodological steps followed to achieve the aim and objectives of this study.

5.2.1 Data

The discussion of the data starts off with a description of the study area, followed by brief descriptions of the data that were used to calculate the water footprint and to conduct the economic and financial feasibility analyses of producing biodiesel from sunflower.

5.2.1.1 Study area

The Viljoenskroon region and the Orange-Riet Irrigation Scheme were identified as the areas of study for rain-fed and irrigated sunflower production, respectively. The sunflower was grown and harvested in the period from November to April. Both study areas are in the Free State province of South Africa. The Free State province is the third largest province in South Africa, and it is dominated by agricultural activities, comprising approximately 30 000 farms. It contributes significantly to the agricultural economy of the nation, mainly producing maize and sunflower, and it is the largest producer of sunflower in South Africa (SAGL, 2018). The natural vegetation of the Free State comprises grassland in the eastern parts of the province, savanna in the north-west part, and Nama-Karoo in the south-west part (Brand *et al.*, 2011). Agriculture in this province is mainly rain-fed, with less than 10% of the arable land being under irrigation (Moeletsi and Walker, 2012). The province receives an average of approximately 600 mm rainfall annually, of which 70% is received from September to April, with average temperatures ranging between 8.3°C and 22.7°C (Moeletsi *et al.*, 2011).

For rain-fed sunflower, the research was conducted at the Huntersvlei farm in Viljoenskroon, as a case study. This farm was selected because it is one of the main sunflower-producing farms in the province and has been farming for over 100 years. Furthermore, the data against which the WF assessment could be conducted, were available.

The Orange-Riet Irrigation Scheme, which sources its water from the Orange River and the Riet River, was used as the study location for irrigated sunflower. It is in a semi-arid area, mainly in the Free State, with a small portion positioned in the Northern Cape, and the area receives about 397 mm of rainfall per year. The Orange-Riet Basin receives its water from the Vanderkloof Dam, from where the water is distributed to the different users through a canal system. Approximately 17 050 ha are irrigated in the Orange-Riet canal system.

5.2.1.2 Data

- Data for the calculation of the water footprint of rainfed sunflower production

Data for the calculation of the water footprint of rainfed sunflower production were obtained from rainfed sunflower producers in the Viljoenskroon region, and by using the CROPWAT 8.0 (Allen *et al*., 1998) model. The CROPWAT 8.0 (Allen *et al.*, 1998) model makes use of the nearest and best representative weather station in the Free State, and this was obtained from CLIMWAT 2.0 (Deurer *et al.*, 2011).

- Data for the calculation of irrigated sunflower production

The data were sourced from publications about irrigated sunflower production in the Orange-Riet Irrigation Scheme, and by using SAPWAT4 (Van Heerden and Walker, 2016) to model the water balance data of irrigated sunflower production in the region.

- Data for biodiesel processing

Secondary data were used to evaluate the water footprint at the processing level. The secondary data on the use of water throughout the processing/conversion level were obtained from several authors (De Marco *et al.*, 2016; Iriarte and Villalobos, 2013; Iriarte *et al.*, 2010) who have explored the production of biodiesel from sunflower in various parts of the world.

- Data for economic feasibility analysis

Secondary data were utilised to assess the economic feasibility of producing biodiesel from sunflower in South Africa. The data were sourced from various items in available literature, based on the South African context (Esterhuizen, 2019; SAGIS, 2019; and SAGL, 2018).

5.2.2 Methods

5.2.2.1 Water footprint accounting at farm level

First, the green and blue crop evapotranspiration details were estimated, using SAPWAT4 (Van Heerden and Walker, 2016) and CROPWAT 8.0 (Allen *et al.*, 1998) for the irrigated sunflower and the rain-fed sunflower, respectively. Under CROPWAT 8.0 (Allen *et al.*, 1998), there are two different pathways to do this: using the crop water requirement option or the irrigation schedule option. In this study, the irrigation schedule option was used, using the no irrigation (rain-fed) option. The framework followed to evaluate the water footprints of sunflower is depicted in Figure 5.1 below.

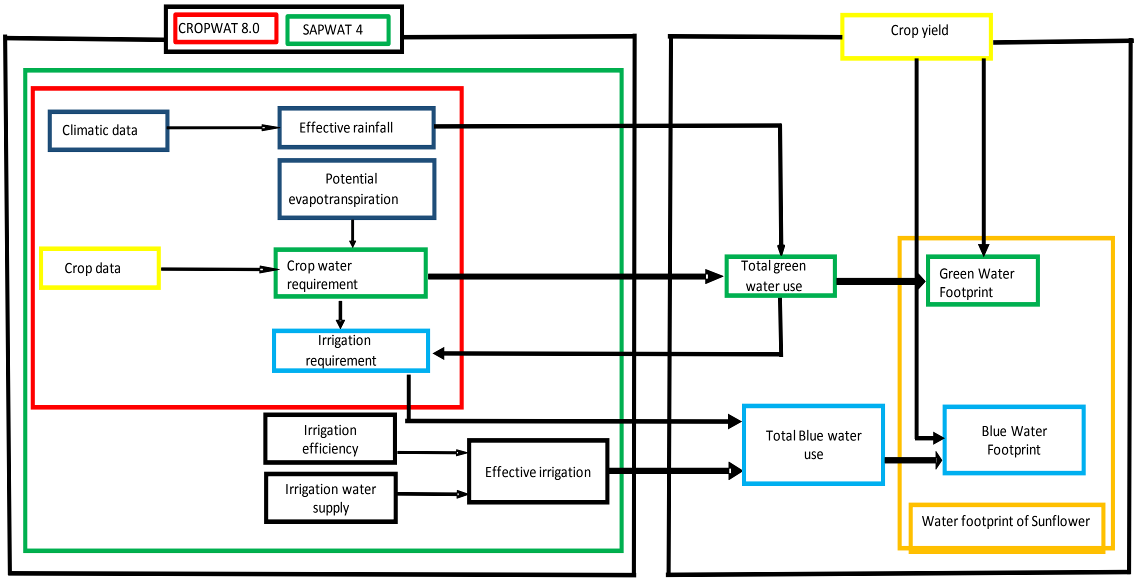

Figure 5.1: Water Footprint calculation steps at farm level
Source: adopted and modified from (Shrestha *et al*., 2013)

From the framework depicted in Figure 5.1, it will be seen that only the green water footprint was evaluated for rain-fed sunflower, as no blue water was used in production. The factors used for the evaluation of WF under rain-fed sunflower can be seen within the red block in the figure, and these were estimated using CROPWAT 8.0 (Trivedi *et al.*, 2018; Hoekstra *et al.*, 2011; CROPWAT, 2010). The factors contained within the green block in the figure were used for the evaluation of the irrigated sunflower water footprint, using SAPWAT4 (Van Heerden and Walker, 2016; Van Heerden *et al.*, 2001).

Within the irrigation schedule option, the crop evapotranspiration can be calculated over the growing season by using the daily soil balance approach. The calculated evapotranspiration is called the adjusted crop evapotranspiration and denoted as ET_a, and it can be calculated as follows:

$$ET_a = K_s \times K_c \times ET_0 \qquad \text{Equation 5.1}$$

K_s describes the effect of water stress on crop transpiration, wherein if $K_s < 1$, there is a soil water limiting condition; and $K_s = 1$ when there is no soil water stress. ET_0 = the reference evapotranspiration (mm/day) and K_c = crop coefficient.

The water footprint of growing sunflower is equivalent to the sum of the blue and green water components, which is calculated using the following equations:

$WF_{sunflower} = WF_{sunflower,\ green} + WF_{sunflower,\ blue}$ Equation 5.2

where:

$WF_{sunflower}$ = the water footprint of the sunflower crop Equation 5.3

$WF_{sunflower,\ green}$ = green water footprint Equation 5.4

$WF_{sunflower,\ blue}$ = blue water footprint Equation 5.5

The green water footprint generally constitutes the major part of the water used in this level (Mzezewa and Van Rensburg, 2019; Dalla Marta *et al.*, 2010). The green water footprint is defined as the amount of rainwater incorporated in the growth of sunflower. The blue water footprint is the volume of surface water furnished on the field through irrigation, and this usually constitutes the minor part of the water used in this level. These water footprints are calculated by following the formulae below:

$WF_{sunflower,\ green} = \frac{cwu_{green}}{y}$ Equation 5.6

$WF_{sunflower,\ blue} = \frac{cwu_{blue}}{y}$ Equation 5.7

wherein: CWU = volume of sunflower water use (m^3) and Y = yield of sunflower (t).

The estimated crop evapotranspiration is multiplied by a factor of 10 to convert it from mm to $m^3/_{ha}$ from which CWU is derived. This derivation generally follows the formula:

$CWU_{green} = 10X\sum_{d=1}^{lgp} ETgreen$ Equation 5.8

$CWU_{blue} = 10X\sum_{d=1}^{lgp} ETblue$ Equation 5.9

where:

ET_{green} = Green water evapotranspiration Equation 5.10

ET_{blue} = Blue water evapotranspiration Equation 5.11

For rain-fed sunflower, the ET_{blue} = 0, as no blue water is used for sunflower growth. The calculations were conducted, based on climatic data retrieved from the nearest and most representative meteorological station in the sunflower production regions of the Free State province.

5.2.2.2 Water footprint accounting at processing stage

This phase entails the conversion of the sunflower input from the farm phase into biodiesel. No green water is used in the processing of biodiesel; therefore, the farm phase is the only green water user in the entire value chain. Blue water is used in the processing level of this value chain, thus the blue water footprint of the processing phase was calculated following the formula below:

$WF_{conversion} = wwu_{blue}$ Equation 5.12

where:

wwu_{blue} is the volume of blue water used for conversion (m^3) and calculated using the equation:

$wwu_{blue} = wwu_{blue1} + wwu_{blue2} + wwu_{blue3}$ Equation 5.13

wwu is the amount of blue water used in the washing step process, per step in the conversion process.

The water footprint of biodiesel is therefore calculated as:

$WF_{biodiesel} = {wwu_{blue}}/{E_{biodiesel}}$ Equation 5.14

$E_{biodiesel}$ = the amount of energy (in the form of biodiesel), obtained from sunflower.

The amount of energy obtained is calculated based on Gerbens-Leenes *et al.* (2009a)'s formulae:

$E_{biodiesel}$ (sunflower) = DMF_y(sunflower) X f_{Fat}(sunflower) X $f_{biodiesel}$ X $HHV_{biodiesel}$ Equation 5.15

wherein:

DMFy (sunflower) = dry mass fraction in sunflower yield Equation 5.16

Fat (sunflower) = fraction of fats in the dry mass of sunflower yield Equation 5.17

$F_{biodiesel}$ = amount of biodiesel obtained per unit of fat Equation 5.18

$HHV_{biodiesel}$ = higher heating value of biodiesel Equation 5.19

5.2.2.3 Blue water scarcity and the production of sunflower for biodiesel

The blue water scarcity was assessed by calculating a blue water scarcity index, following Hoekstra *et al.* (2012). The blue water scarcity index is the ratio between the blue water footprint in the catchment under consideration and the water that is available for use, after meeting the environmental flow requirement. Blue water availability (WA_{blue}) is calculated as:

$$WA_{blue}[x, t] = R_{nat}[x, t] - EFR[x, t] \qquad \text{Equation 5.20}$$

wherein:

R_{nat} is the natural run-off in the river basin
EFR is the environmental flow requirement
x is the river basin
t is the specific period

The blue water footprint in a river basin not only affects the run-off flow, but also the availability of blue water within the river basin. Blue water scarcity (WS_{blue}) is the ratio of the total blue water footprint ($\sum WF_{blue}$) in the river basin to the available blue water, and it can be calculated as follows:

$$WS_{blue}[x,t] = \frac{WF_{blue}[x,t]}{WA_{blue}[x,t]} \qquad \text{Equation 5.21}$$

It is important to ascertain whether sunflower production is sustainable or not within a river basin. This can aid in developing appropriate sunflower production strategies to assist within periods that retain and maintain the environmental sustainability in a river basin.

5.2.2.4 Economic feasibility of biodiesel commercialisation

The technical evaluation of producing biodiesel is not the only factor to consider when evaluating the viability of the project process; there are other factors to take into account, such as the relevant economic, environmental, and social factors. The environmental factors of this study process were examined through the WFA, the social aspect was lightly examined in the literature, and the economic factor is assessed in this section. The economic factor is an important performance factor that investigates the viability of the process. To achieve this, the investigation looks at the profitability of the project; whether it will lose or earn money. Factors, such as the plant capacity, process technology, raw material and chemical costs, are identified in order to lay out the economic aspects of a biodiesel plant. Financial factors, such as fixed capital costs, total manufacturing costs, and the break-even price of biodiesel, are then used to determine the economic performance of the plant. To assess the economic feasibility of commercialising biodiesel, produced from sunflower, this study followed the approaches applied by El-Galad *et al.* (2015); Swart (2012); Nolte (2007) and Walekhwa *et al.* (2009).

To achieve this objective, this assessment was performed in three partitions, comprising the agricultural, financial and market feasibilities that could enable commercialisation. The economic feasibility assessment was based on the general assumption that sunflower farmers sell their sunflower seed to the biodiesel producer at market price, and the biodiesel product is sold to the distributor who blends it to the acceptable (2%) initial penetration level, and further assumptions for each partition are portrayed per partition (Minerals and Energy, 2007).

- Financial feasibility of producing biodiesel

Achieving profit at a national level when starting a biodiesel industry would depend on the regulating government legislation; but, as the industry progresses, it needs to be able to self-sustain through the maintenance of profits (Nolte, 2007).

The financial feasibility assessment was calculated, based upon the assumption that the plant produces 2500 kg/hr of biodiesel, and this was chosen because it is a median, ideal, optimum biodiesel production by a typical plant in South Africa (López-Urrea *et al.*, 2014; Nolte, 2007). To enable proper calculations to be made, certain assumptions were made, as follows:

- The biodiesel producer purchases sunflower oilseeds from the sunflower farmer at market price. The biodiesel producer is responsible for extracting the sunflower vegetable oil and processing it into biodiesel. The resulting oil cake is then sold to livestock farmers and the biodiesel to retailers for sale the end-users.
- The market prices used are those applicable at January 2018.
- The biodiesel plant operates for 330 days per annum.
- There is no market for the glycerol by-product, and therefore it is not sold.
- Depreciation of 10% applies on all fixed capital per annum, using the straight-line method.

The following calculations were conducted:

a. Total capital investment (TCI)

TCI is divided into fixed and working capital investments. Fixed capital investment (FCI) is the amount of investment needed to get the plant ready for start-up and it includes the costs of equipment, installation, building contractor's fee, and contingencies. Working capital investment (WCI) is defined as the investment required to run the plant. FCI, WCI and TCI were calculated by using Equations 5.22, 5.23, and 5.24, respectively.

$FCI = X_1 + X_2 + X_3 + \ldots\ldots + X_n$ Equation 5.22

$WCI = Y_1 + Y_2 + Y_3 + \ldots\ldots + Y_n$ Equation 5.23

$TCI = FCI + WCI$ Equation 5.24

wherein X and Y are all the respective variables of each form of capital investment.

b. Total manufacturing cost (TMC)

The manufacturing costs must be identified to make a profit, and this also assists in determining the product's selling price, which makes selling it secured. Manufacturing costs are divided into direct manufacturing costs (DMC) and indirect manufacturing costs (IMC). DMC include costs of raw materials, utilities, shipping and packaging, labour, depreciation, miscellaneous, supervision, plant overhead, interest, insurance, rent, and maintenance. IMC include sales, distribution, general overheads, and research and development, and it is assumed to be equivalent to 25% of DMC (El-Galad *et al.*, 2015).

The manufacturing costs were calculated through using the following equations:

$DMC = U_1 + U_2 + U_3 + \ldots\ldots + U_n$ Equation 5.25

$IMC = 25\%DMC$ Equation 5.26

$TMC = DMC + IMC$ Equation 5.27

where U comprises all the variables of the direct manufacturing costs.

c. Return on investment (ROI) and break-even point

All the associated costs must be subtracted to obtain the revenues from which the net profit, or loss, results. This net profit is, in turn, used to determine ROI, which is derived from the equation below:

ROI = Sales – TMC Equation 5.28

Sales are the proceeds that are generated from selling biodiesel.

ROI is used to assess the feasibility of the project by comparing it with the minimum acceptable rate of return (MARR, it is assumed that MARR = 25%), therefore if:

ROI > MARR – project is economically feasible, and

ROI < MARR – Project is not economically feasible.

The break-even point is the point at which the product stops costing money to produce and sell; and the costs and sales income are equivalent at this point.

- Agricultural feasibility

This considers the current agricultural situation concerning the capacity of producing sunflower, the market prices, the sunflower oil demand, and the capability of the agricultural industry to support commercialisation of the biodiesel. The volumes of sunflower seeds required to produce biodiesel in the optimum biodiesel plant of this study were assessed, and the potential benefits that could be derived from farming for biodiesel production were identified.

- Market feasibility

The availability of potential markets for biodiesel was examined. The potential biodiesel market is defined by the size of the existing fossil diesel market. However, this was based on the principal blending of 2% of the produced biodiesel into the fossil diesel. The potential level of feedstock required to fully penetrate the fossil diesel, at 2%, was estimated. Certain factors, including the willingness of consumers to accept biodiesel being blended in fossil diesel, are not considered as factors in this study, and the biodiesel produced is assumed to be compatible for use in various diesel-utilising machines, such as vehicles and electricity generators. Although there is potential for a biodiesel market in South Africa, the policies governing the production of biodiesel have a significant role to play in stimulating the growth and the sustainability of the market.

5.3 RESULTS AND DISCUSSION

This section presents the results that were obtained from analysing the water footprint of sunflower production at farm level, followed by the water footprint of biodiesel produced from sunflower. Thereafter follows a discussion of the water scarcity situation in the selected production regions. The section is concluded with the results from the economic and financial feasibility analysis of producing biodiesel from sunflower.

5.3.1 Water Footprint of Sunflower at Farm Level

The sunflower water footprint calculations in this study were based on two different production systems for sunflower growth, i.e. irrigation and rainfed. November and December planting dates were considered for irrigated and rain-fed sunflower, respectively. The irrigated sunflower growth stage was about 144 days long, and the rain-fed sunflower was approximately 130 days long. In each sunflower growth stage, the sunflower water use was found to have varied distinctively across all stages.

At the initial growth stage, the sunflower plants were small, and their water use level was relatively low. As the sunflowers grew during the development stage, the water use levels gradually increased. At the middle stage period, the sunflowers developed an increased leaf area, which led to increased transpiration levels. At this stage, water use increased rapidly, and peak levels were reached during this period. At the end stage, water levels decreased as the sunflowers were fully matured and reached harvest time. Figure 5.2 below sets out a summary of the water used through the different growth stages for both irrigated and rain-fed sunflower.

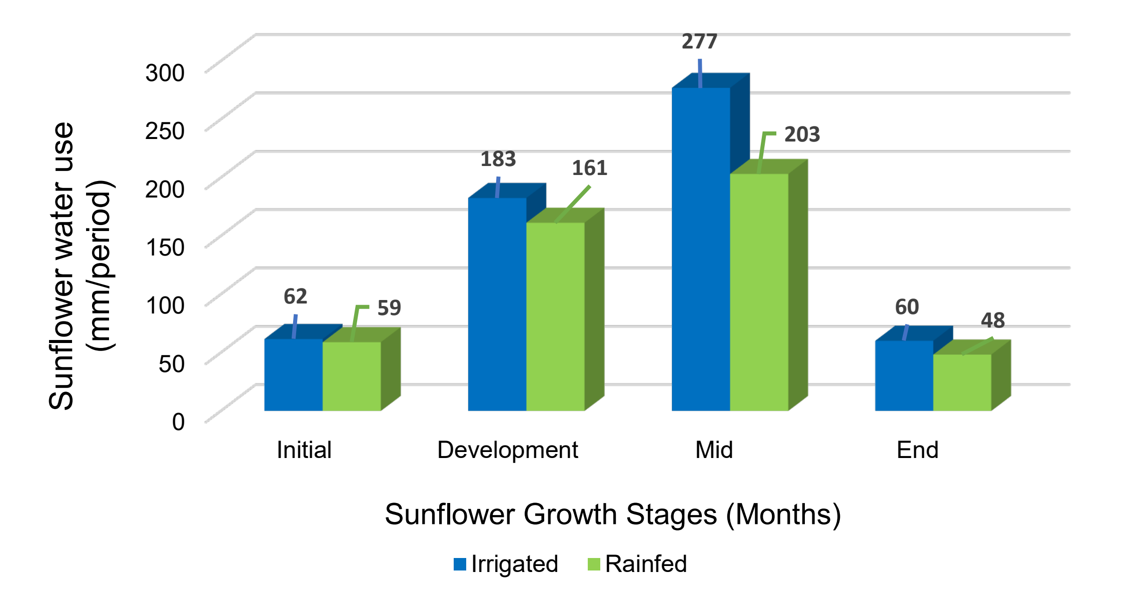

Figure 5.2: Sunflower water use (mm/stage) at various sunflower growth stages (Monthly periods)

The initial growth stages for irrigated and rain-fed sunflower lasted about 27 days and 25 days, respectively, consuming about 62 mm and 59 mm of water, respectively. Most of the water used in this stage was required to retain soil moisture to enable proper seed germination, and the low levels of water used are attributed to the small size of the sunflower crop at this stage. As the sunflowers developed, their water use increased accordingly, and it was found that irrigated sunflower used about 183 mm, while the rain-fed sunflower utilised about 161 mm of water, throughout, for 39 days and 35 days respectively. A maximum level of water use was observed for both irrigated and rain-fed sunflower at the mid-stage, with optimal consumptions of 277 mm and 203 mm, respectively. This stage lasted about 50 days for irrigated sunflower and 45 days for rain-fed sunflower. At the end stage, the least amounts of water were consumed, at 60 mm and 48 mm for irrigated and rain-fed sunflower, respectively. At this stage, the sunflowers matured fully and harvesting took place, with this stage lasting about 28 and 25 days. Most of the water used in this stage was required to retain soil moisture to support a good harvest, as indicated by de Fraiture and Berndes (2009) and de Fraiture *et al.* (2008)

Matev *et al.* (2012) analysed the influence of irrigation on the evapotranspiration of sunflower in Bulgaria. Their study observed sunflower growth without irrigation and with irrigation at 50% and 150% irrigation rates. It was found that the ET increased relative to the irrigation level, such that the daily ET_c of rain-fed sunflower varied between 3.3 and 5.6 mm, while at a 50% irrigation rate, the ET_c was found to be between 5.2 and 6.1 mm, and an ET_c of between 6 and 7 mm was observed at a 150% irrigation rate. Contrary to Matev *et al.* (2012)'s findings, the ET_c of rain-fed sunflower in this current study varied from 1.1 to 6.6 mm, while the irrigated sunflower had an ET_c

that varied between 0.4 and 7.3 mm. However, the findings of both this study and that of Matev *et al.* (2012) concur with the findings of López-Urrea *et al.* (2014)'s study. López-Urrea *et al.* (2014) quantified the consumptive water use and crop coefficients of irrigated sunflower during two growing seasons. It was observed that irrigated sunflower with longer growing seasons resulted in a higher ET_c value. Similar results were observed in this current study, with the irrigated sunflower having a longer growing season, by 14 days, as compared with the 130 days for rain-fed sunflower. Furthermore, the resulting ET_c for irrigated sunflower was found to be 582 mm, which is 111 mm higher than the corresponding rain-fed sunflower ET_c of 471 mm. The resulting ET_c was used in this current study to assess the water footprint of producing sunflower, and this is further detailed below.

The irrigated sunflower yield per hectare was 2.22 ton/ha, with a crop evapotranspiration of (ET) of 581 mm, rainfall (R) of 354 mm, and rain loss (RL) of 29 mm. It was ascertained that there was effective rainfall (ER) of 325 mm, irrigation water (I) of 275 mm, irrigation loss (IL) of 55 mm, and effective irrigation (EI) of 220 mm (see Table 5.1 below).

Table 5.1: Summary of water use data for sunflower at Orange-Riet irrigation Scheme

CROP	Yield	ET	R	RL	ER	I	IL	EI	EI + ER
	ton/ha	mm							
Sunflower	2.22	581	354	29	325	275	55	220	545

Table 5.2 below indicates the total evapotranspiration of sunflower in Orange-Riet, which was found to be 581 mm, of which the green evapotranspiration accounted for about 56% of this total evapotranspiration.

Table 5.2: Irrigated Sunflower water use in Orange-Riet Irrigation Scheme

CROP	ET_{crop}	ET_{blue}	ET_{green}
	mm		
Sunflower	581	220	325

To enable for the conversion of the ET in mm to m^3, the ETs were multiplied with a factor of 10 to obtain the green and blue CWU, and these were used to evaluate the blue and green WFs of sunflower. Table 5.3 below shows the calculation of WF_{blue} and WF_{green}. The CWU_{blue} and CWU_{green} in Table 5.3 were divided by the sunflower yield to obtain the green and blue WFs. The WF_{blue} was found to be 1 000 m^3/ton. The WF_{green} of irrigated sunflower was 1 477 m^3/ton. The green and blue WFs were added together to obtain the $WF_{blue+green}$, which was 2 477 m^3/ton.

Table 5.3: Blue and Green water footprints of irrigated sunflower at Oranje-Riet Irrigation Scheme

CROP	Yield	CWU_{blue}	CWU_{green}	WF_{blue}	WF_{green}	$WF_{blue+green}$
	ton/ha	m^3/ha		m^3/ton		
Sunflower	2.22	2200	3250	1000	1477	2477

Source: Own calculations

From Table 5.3, the difference among the water footprints can be seen, with the WF_{blue} accounting for about 40%, and the WF_{green} contributing approximately 60%, of the $WF_{blue+green}$. The results indicate that a large volume of water required for sunflower production is supplied through rainfall. Sunflower is generally characterised by drought tolerance and this was observed in this study. The results indicated that a large volume of water required for sunflower growth was supplied through rainfall, and this is in line with the findings of Agele (2003). Therefore, it is important for sunflower farmers to limit irrigation, more significantly if the optimum yield can be obtained at minimal irrigation levels, and especially in periods with high levels of rainfall.

Table 5.4 below summarises the water use data for rain-fed sunflower in Viljoenskroon. The yield of rain-fed sunflower was lower than the irrigated sunflower at 1.8 ton/ha. The crop evapotranspiration (ET) of 471 mm, rainfall (R) of 339 mm, rain loss (RL) of about 3 mm, and effective rainfall (ER) of 336 mm, were found in Viljoenskroon.

Table 5.4: Rain-fed sunflower water use in Viljoenskroon

CROP	Yield	ET	R	RL	ER
	ton/ha	mm			
Sunflower	1.8	471	339	3	336

Source: CROPWAT

No blue water was used to grow sunflower in Viljoenskroon, as all water used was derived from green water, hence the WF_{blue} is zero. The estimated total water footprint was found to be about 2617 m^3/ton for growing sunflower without irrigation, and this was fully attributed to the green water footprint. The results are summarised in Table 5.5 below.

Table 5.5: Water footprint of rain-fed sunflower production at Viljoenskroon

CROP	yield	CWU_{green}	CWU_{blue}	WF_{green}	WF_{blue}	$WF_{blue+green}$
	ton/ha	m^3/ha		m^3/ton		
Sunflower	1.8	4710	0	2617	0	2617

Source: Own calculations

Mekonnen and Hoekstra (2011) have assessed the water footprints of sunflower and derived sunflower products. It was found in their study that the water footprint of sunflower was largely constituted by the green water footprint, which accounted for approximately 90% of the total water footprint. It was also found that the consumptive water footprint of sunflower (per ton) was lower for irrigated sunflower than for rain-fed sunflower, and this was because irrigated sunflower yields are generally larger than rain-fed sunflower yields. Qin *et al.* (2016) also assessed the water footprint of sunflower growth in China, intending to explore the variations in the water footprints of growing sunflowers. It was found in their study that the green, blue and grey water footprints accounted for about 93.7-94.7%, 0.4-0.5%, and 4.9-5.8%, respectively. Figueiredo *et al.* (2017) assessed the environmental life cycle of cultivated sunflower under irrigation and rain-fed systems in Portugal. It was found in their study that the average productivity of irrigated sunflower was 3.5 times higher than that of rain-fed sunflower.

The findings of this current study concur with the findings of Mekonnen and Hoekstra (2011)'s study, in that the consumptive water footprint of irrigated sunflower was found to be lower when compared with that of rain-fed sunflower, and this was attributable to the higher sunflower yield obtained under irrigation. Furthermore, in alignment with the other findings by Qin *et al.* (2016) and Mekonnen and Hoekstra (2011) with regard to the green WF being the main constituent of sunflower growth, the green WF of irrigated sunflower in this current study was found to be relatively higher than its blue WF, and for rain-fed sunflower, this is true as no blue water is used. In addition, the sunflower yield obtained under irrigation was higher than that found under rain-fed conditions. However, contrary to Figueiredo *et al.* (2017)'s findings of a 3.5 times higher variation in yield, the sunflower yield under irrigation in this current study was found to be 0.4 times higher than the rain-fed sunflower yield, increasing the yield by about 10% per ha.

5.3.2 Water Footprint of Biodiesel Produced from Sunflower

The determined biodiesel yield was 213 L/ton. This biodiesel yield was evaluated by using the sunflower dry mass fraction of 85%, a fat fraction of 2 g / g of sunflower dry mass, obtainable biodiesel of 1 g / g of fat, a high heating value (HHV) of 37.7 kJ/g, an energy yield of 7.05 GJ/ton and a density of 0.88 kg/J. Table 5.6 below outlines these energy properties.

Table 5.6: Characteristics of sunflower providing biodiesel

Oil crop	Dry mass Fraction (%)	Fraction of fat in dry mass (g/g)	Biodiesel per unit of fat (g/g)	HHV (KJ/gram)	Energy yield (GJ/ton)	Density (Kg/L)	Biodiesel yield (L/ton)
Sunflower	85	0.22	1	37.7	7.05	0.88	213

Source: (Gerbens-Leenes *et al*., 2008, Mekonnen and Hoekstra, 2011a)

An area of cultivated land measuring 200 ha was used as a model for this study. From this model farm size, it was estimated that about 76 680 litres and 93 720 litres of biodiesel could be produced from rain-fed and irrigated sunflower, respectively. The biodiesel density of 0.88 kg/L was used to convert the evaluated biodiesel output into tons. The resulting biodiesel outputs were found to be approximately 67 tons and 82 tons for rain-fed and irrigated sunflower, respectively. This biodiesel was used to evaluate the resulting water footprint of producing biodiesel in the processing level.

Table 5.7: Amount of biodiesel output

Biodiesel feedstock	Yield	Farm size	Density	Biodiesel output	
	t/ha	Ha	Kg/L	Litres	tons
Rain-fed sunflower	1.8	200	0.88	76 680	67
Irrigated sunflower	2.2	200	0.88	93 720	82

Source: Own calculations

Table 5.8 below shows the water footprint of biodiesel at the processing level. Regardless of the water source used at the farm level to produce the sunflower feedstock, about 0.00712 m^3 (7.12 litre) of water is used to produce 1 litre of biodiesel. No green water is used to process sunflower into biodiesel, and only blue water is used. Thus, there are no green water footprints at the processing level. Large total amounts of water were used to produce biodiesel from irrigated sunflower, at about 667 m^3, as compared with about 546 m^3 of water used to produce the same amount of biodiesel from rain-fed sunflower. However, the resulting water footprint per unit of biodiesel produced is lower for biodiesel produced from the irrigated sunflower. This can be observed in Table 5.8 below, where the water footprint of biodiesel produced from irrigated sunflower is shown to be approximately 8.09 m^3/ton, translating to about 1.15 m^3/GJ of biodiesel energy. The resulting WF of biodiesel produced from irrigated sunflower was found to be about 7.1 m^3/ton and about 1.01 m^3/GJ.

Table 5.8: Amount of water used to process sunflower to biodiesel and the respective WF

Product	Amount of water		WF_{green}	WF_{blue}	Total WF	WF_{green}	WF_{blue}	Total WF
Biodiesel	**m³/litre**	**m³**	**m³ water/ton biodiesel**			**m³ water/GJ biodiesel**		
Rain-fed sunflower	0.00712	546	0	8.09	8.09	0	1.15	1.15
Irrigated sunflower	0.00712	667	0	7.1	7.1	0	1.01	1.01

The observed water footprint of biodiesel in this current study was found to be between approximately 1 and 1.2 m^3/GJ. These findings are relatively in line with the results obtained in the study Berger *et al.* (2015), where they assessed the water footprints of biofuels produced from various feedstock crops, including sunflower, in Europe. The water footprint of biodiesel in that study was found to be about 1.9 m^3/GJ. Ultimately, Gerbens-Leenes *et al.* (2009a), while studying the water footprint of bioenergy in various countries in the world, found that there is a wide variation in the water footprints of biofuels, worldwide. It was found that this variation in the WFs was dependent upon 1) the feedstock crop used, 2) the climate of the production region, and 3) the agricultural practise being used. The findings of this current study concur with those of Gerbens-Leenes *et al.* (2009a) and Gerbens-Leenes (2018) in that the water footprint of biodiesel (m^3/GJ), as found in this current study, indeed showed a variation among the biodiesel fuels produced from the different production systems, and also varied from the WFs found by Gerbens-Leenes (2018) and Berger *et al.* (2015).

The evaluated water footprints at the farm level and the processing level were added together to obtain the total water footprint of the complete sunflower-to-biodiesel value chain. The total water footprint of producing biodiesel, using rain-fed sunflower, was found to be about 2625 m^3/ton, and this was mainly comprised of the green water footprint. Biodiesel produced from irrigated sunflower was found to have a total water footprint of approximately 2484 m^3/ton, of which the green water footprint accounted for about 60% (see Table 5.9 below). Furthermore, the total water footprint of biodiesel produced from both irrigated and rain-fed sunflower was largely comprised of the water footprint of growing the sunflower feedstock. The water footprint at the farm level was the largest contributor to the total water footprint of biodiesel, from both irrigated and rain-fed sunflower feedstock.

Table 5.9: Water footprint of sunflower-biodiesel value chain

Product	Farm level		Processing level	Sunflower-Biodiesel value chain
Biodiesel	WF_{green}	WF_{blue}	WF_{blue}	WF_{total}
Feedstock	m^3/ton			
Rain-fed sunflower	2617	0	8.09	2625
Irrigated sunflower	1477	1000	7.1	2484

Gerbens-Leenes *et al.* (2009b) conducted a study to assess the water footprints of producing biodiesel from various types of feedstock in different locations. It was found that the water footprint of producing feedstock was larger than that of the processing level. The same results were observed in this current study, with approximately 99% of the total water footprint being accounted for by the water footprint of growing sunflower, for both rain-fed and irrigated sunflower. In addition, the volumetric water footprint results in this current study also concur with the findings of Gerbens-Leenes *et al.* (2009a)'s study. In their study, Gerbens-Leenes *et al.* (2009a) assessed the water footprints of bioenergy derived from 12 crops, and it was found that there was a large variation in water footprints of similar crops, and it was indicated that this is dependent upon the agricultural system being used and the climatic conditions. They further found that, when the feedstock yields are relatively low, the water footprint of biodiesel will be higher. Similar results were observed in this current study, in that the water footprint of rain-fed sunflower was larger than the water footprint of irrigated sunflower was. The variation in this water footprint can be mainly attributed to the difference in the agricultural system being followed, in this case being the irrigation and rain-fed systems, with the climate having not much impact, as the sunflower feedstock was grown in the same region, with little climatic variation. Furthermore, in line with Gerbens-Leenes *et al.* (2009b)'s findings, it was observed in this study that the water footprint of biodiesel produced from rain-fed sunflower was relatively higher than that of biodiesel from irrigated sunflower was, and this can be mainly attributed to the lower yields of the rain-fed sunflower.

5.3.3 Environmental Sustainability of Producing Sunflower in the Orange River Basin

The irrigated sunflower in this study was produced in the Orange-Riet Irrigation Scheme, which lies in the Orange River Basin, and it was produced within the December to April/May period. (Pahlow *et al.*, 2015) assessed the water footprint sustainability of sunflower, among other crops, in different river basins in South Africa. It was found that the Orange River Basin experiences severe blue water scarcity for about 3 months in a year. Several crops, such as fodder crops, wheat, maize, sugarcane, potatoes and grapes, were found to play a significant role in taking the Orange River Basin into severe blue WS, which causes environmental hotspots, although sunflower was found to not form part of these crops. In addition, Scheepers and Jordaan (2016) assessed the blue and green water footprints of lucerne used in milk production in South Africa. In their study, they found that the Orange River Basin experiences low blue WS during the January, February, March, April, May and December periods. Furthermore, Novoa *et al*. (2019), in their study assessing the water footprint sustainability of agricultural practices in Chile, found that there are critical times during which crop production uses water intensively. It was thus recommended in that study to revise planting periods for the crops that are intensive water users and to grow them in river basins with greater water supplies to cater for periods with high levels of unsustainability. Following the findings of the studies by Pahlow *et al.* (2015) and Scheepers and Jordaan (2016), the results of this current study are indicative that the sunflower growth in the Orange River Basin is environmentally sustainable, as it is grown within the December to April/May period, in which there is low blue water scarcity and the environmental flow requirements are adequately met. Therefore, it is not necessary to consider growing the sunflower in another river basin, as it does not compromise the environmental sustainability of the Orange River Basin during this period.

5.3.4 Economic Feasibility Assessment

5.3.4.1 Plant size

The analysis in this study considered a generic form of a biodiesel production plant, with a scenario production capacity of approximately 2500 kg/hr, and it does not reflect any specific technology provider's designs. To meet this supply capacity, a certain amount of sunflower seed oil is required, and the possible required estimates are summarised in Table 5.10 below.

Table 5.10: Amount of sunflower oil seed required for 2500 Kg/h biodiesel production

		L/hr	Kg/hr	t/a	L/a
Input	Sunflower seed	-	7216	57149	-
	Crude sunflower oil	2991	2742	21725	23 688 720
Output	Sunflower oil cake	-	4113	32575	-
	Biodiesel	2841	2500	19800	22 500 000
	Glycerine	345	-	2732	-

Source: Own calculations

From Table 5.10, it can be seen that the 2500 kg/hr plant was found to be capable of producing about 22.5 million litres of biodiesel per year. This production capacity was based upon a 330-day working period. To meet the scenario capacity, it was found that approximately 57 thousand tons of sunflower seeds are required per year, and that this number of seeds produces approximately 23 689 thousand litres of crude vegetable oil, about 2700 tons of glycerine, and approximately 32 thousand tons of oil cake per year. The resulting crude vegetable oil is used to produce about 22.5 million litres of biodiesel per year, while the oil cake would be sold for animal feed. The glycerine by-product in this study was not considered for further use or sale.

Necessary conversions were performed to calculate the production capacity in litres, based on the biodiesel density of 0.88 kg/L depicted in Table 5.10 (above). The results indicate that supplying a 2% biodiesel blend would require about 11 biodiesel production plants, each with a 2500 kg/hr production capacity, based on the 2018 figures used in this study. It should also be noted that the crude sunflower oil input supply should be readily available for the scenario to be achieved, and this indicates that the biodiesel producers should have adequate sunflower seed feedstock available to meet the annual production of biodiesel, as sunflowers are seasonal crops.

5.3.4.2 Market feasibility

The biodiesel market in South Africa is reliant upon the current fossil diesel market, as the penetration plan is to be achieved through blending ratios. It was found that the total diesel consumption for the year 2018 was about 12 538 744 326 L, and this was then estimated to increase by approximately 3% annually. The possible biodiesel requirements are depicted in Table 5.11 below, at 2% and 5% blending ratios.

Table 5.11: Biodiesel blending estimates (2018-2030)

Period (years)	**Biodiesel blending requirement (L/a)**			
	2018	**2022**	**2026**	**2030**
Diesel demand	12 538 744 326	14 112 467 205	14 535 841 221	14 971 916 458
Blending ratio				
2%	250 774 887	282 249 344	290 716 824	299 438 329
5%	626 937 216	705 623 360	726 792 061	748 595 823

Source: Own calculations based on (Energy, 2019)

There is a reciprocal relationship between the biodiesel demand and biodiesel blending amounts, and this can be seen in Table 5.11 above. It was found that, for the 2018 period, approximately 250 million litres and about 626 million litres of biodiesel per annum would be required for the 2% and 5% blending ratios, respectively. The projected 3% annual increase in diesel demand creates an opportune avenue for exploring biodiesel. Thus, from the results attained, there seems to be a viable market for the supply of biodiesel in South Africa, based upon the national penetration plan. Nonetheless, to enable the production of adequate biodiesel supplies, meeting the blending requirements would require enough production of the feedstock crop. The results of the feedstock volumes required are set out in the agricultural feasibility section.

5.3.4.3 Agricultural feasibility

Biodiesel feedstock is the most important input in the production of biodiesel. The availability of adequate amounts of feedstock for biodiesel production could be a limiting factor in South Africa to fully replacing the use of fossil diesel, and this has also been observed by Stafford *et al.* (2019) and Mac Dowell *et al.* (2017). The amounts of sunflower seeds required to meet the needs of a 2500 kg/hr biodiesel production plant and the amount of sunflower seeds required to meet the level of biodiesel demand, were evaluated.

To achieve an adequate biodiesel output yield of biodiesel, the 2500 kg/hr production plant was estimated to require about 7216 kg/hr of sunflower seeds, which equates to about 19 800 tons/a of biodiesel produced by the plant. Further estimates were done to evaluate the amounts of sunflower seeds that would be required to meet the recommended 2% blend into the fossil diesel supply, and these are portrayed in Table 5.12 below.

Table 5.12: Amount of sunflower seeds required for a 2500 Kg/h biodiesel production plant

Blending ratio (%)	Sunflower seed yield (ton) for a selected period (years)			
	2018	2022	2026	2030
2%	1177347	1325114	1364868	1405814
5%	2943367	3312786	3412170	3514534

Source: Own calculations based on (Gerbens-Leenes *et al*., 2008, Energy, 2019)

It was found that for the 2018 period, about 1.1 million tons/a and 2.9 million tons/a would be required for the 2% and 5% blending ratios, respectively. The depicted values are based upon a 213 L/ton yield of biodiesel and the required supply for adequate blending. Considering the amount of input seeds required for a 2500 kg/hr biodiesel plant and the amount of seeds required to meet the blending percentages, it was estimated that, to meet the 2% blending estimates, would require about 11 biodiesel production plants, and 28 plants for a 5% blend, based on the 2018 figures.

This reflects a need to expand production, should a higher percentage blending requirement be made, and the same would apply to enable the production of an adequate supply of biodiesel to meet the growing demand over the years. However, erecting additional production plants might not necessarily be ideal, as this would require more land for plant erection, with high capital costs. Nevertheless, the expansion of existing plants could be deemed viable, as this could be achieved at lower costs and could also provide adequate time for implementing sustainable production and appropriate operational practices in the already existing plants.

5.3.4.4 Financial feasibility

- **Total capital investment**

The capital investment required for establishing a biodiesel production plant includes the civil engineering construction of the plant and the installation costs. The capital investment analysis in this study was classified as a study estimate, and it can be expected to have a limited degree of accuracy. Nonetheless, this evaluation was conducted, based on the biodiesel studies conducted by Minerals and Energy (2007), Nolte (2007), and Jacobs (2016). The results for the evaluation of the required capital investment for a 2500 kg/hr biodiesel plant are depicted in Table 5.13 below.

Table 5.13: Capital costs of producing biodiesel using sunflower

2500 Kg/hr sunflower seed plant	Fixed Costs (R)	Variable Costs (R)	Capital Costs (R)
	Thousand Rand		
	117 536	58 406	175 942

Source: Own calculations

To cater for the current economic position in South Africa, inflation was used, relative to the findings from the reference studies of this analysis. The fixed costs associated with the construction and initial operation of the scenario plant were found to be about R118 million. The variable costs required to start up and operate the plant, until income is earned, were found to be approximately R58 million. Ultimately, the sum of the fixed cost and variable cost, results in capital investment. Therefore, the total capital investment required for a 22.5 million L/a biodiesel plant was found to be about R176 million, as seen in Table 5.13 above.

Table 5.14 below depicts the average inflation rate from 2011 to 2018. The results show a fluctuation in the inflation rate over the years, with no specific fluctuation pattern. This fluctuation plays a pivotal role in the operation of the plant, and not just the start up, as it has a direct influence on the operational costs of the plant.

Table 5.14: Average inflation rate 2011-2018

Year	2011	2012	2013	2014	2015	2016	2017	2018
Inflation rate	**Percentage (%)**							
	4.99	5.62	5.76	6.09	4.58	6.34	5.27	4.62

Source: (FocusEconomics, 2020; StatsSA, 2020)

It should be noted that there is a direct relationship between inflation and the costs associated with the plant, and more significantly with the operating costs. As the inflation rate increases, the operational costs are most likely to increase at a reciprocal rate, or more, and this has a direct effect on the attainable returns. This effect plays a significant role in the sustainability of the plant and the selling prices of the final biodiesel product.

- **Manufacturing costs**

These pertain to the costs related to the day-to-day operation of the plant. These generally consist of raw material costs, labour costs, maintenance expenses, administrative costs, overheads, and research and development, amongst others. The biodiesel production plant scenario in this study made use of sunflower seed oil, and the scenario entailed acquiring a supply of sunflower seeds from a local farm at market price, extracting the oil from the seeds, and processing it into biodiesel. The resulting oil cake is sold for livestock feed at market price for additional income. In January 2018, sunflower seeds were sold at a spot price of R4 659/ton (SAGIS, 2019) and this price was utilised to derive the manufacturing costs of the plant.

The availability of sunflower seeds plays a pivotal role in the financial success of the plant, as they are the main input. It should thus be noted that the prices of the seeds vary significantly, and this can have an impact on the actual production costs. A 2500 kg/hr plant has an annual manufacturing cost of approximately R343 million, and this indicates a unit cost of about R15.24/L of biodiesel produced. The associated manufacturing costs are summarised in Table 5.15 below.

Table 5.15: Manufacturing costs of a 2 500 Kg/hr biodiesel plant

Manufacturing Costs	Annual	Cost/litre
	Thousand Rand	R/litre
Oilseeds + Extraction cost	266 244	11.83
Alcohol and catalyst	20 816	0.92
Transport	24 018	1.07
Other variable manufacturing costs	11 347	0.50
Indirect manufacturing & general expenses	21 427	0.95
Total	342 853	15.24

Source: Own calculations

From the results summarised in Table 5.15 above, it can be seen that the seed and the oil extraction costs contribute the largest portion of the total manufacturing costs, with the cost of sunflower oilseeds having the largest contribution. The individual cost contributions towards the total manufacturing costs are depicted in the Figure 5.3 below.

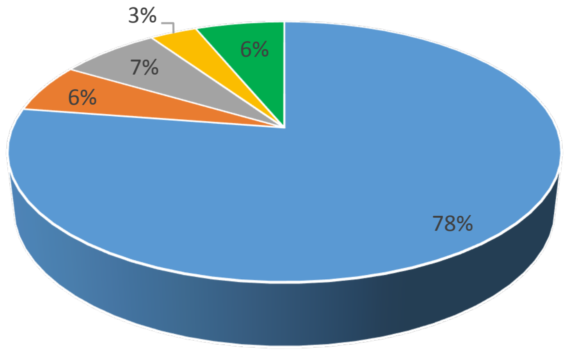

Figure 5.3: Summary of the individual cost contributions towards the total manufacturing costs

- **Financial benefits**

For biodiesel production to be economically beneficial, the biodiesel should be produced if a profit can be generated from its sales. One of the key determinants of whether biodiesel will be profitable is its selling price. Therefore, for this study, the fossil diesel cost was used as a baseline against which the cost of biodiesel was to be compared. Thus, world crude oil prices have a direct influence on the financial feasibility of biodiesel production. According to Energy (2019), the average basic price of 0.005% sulphur diesel was R7.38/L between January and December 2018, and this cost represents the realistic costs of importing oil into South Africa. The potential revenue that could be generated from a 2 500 kg/hr plant, at a baseline price, is shown in Table 5.16 below.

Table 5.16: Projected annual revenue of a 2 500 Kg/hr sunflower plant

	22 .5 million l/a sunflower plant
Revenue	Million Rand
Biodiesel	166.05
Sunflower oil cake	98.83
Total revenue	264.88

Source: Own calculations

The potential revenue was estimated to be approximately R264 879 618 for the 2 500 kg/hr biodiesel plant. This estimated revenue was inclusive of the potential additional revenue that could be potentially obtained from the sale of the sunflower oil cake by-product. The average sunflower oil cake price of R3 033 was used for the sunflower oil cake revenue estimate, which was the average price for the 2018 year (SAGIS, 2019).

The revenue obtained does not necessarily indicate the profitability of the production plant. The break-even price of the biodiesel was determined, taking into account the addition of a biodiesel fuel tax of R1.01/L to the total manufacturing costs of the plant. This tax was added according to the SARS regulation for biodiesel production of more than 300 000 litres per year (Nolte, 2007). This section further evaluates the profitability of the biodiesel plant at different selling prices. The profitability assessment in this study assumed that 100% of the biodiesel produced is sold and that none is utilised for free in the plant. Therefore, the figure of 22.5 million litres was used to calculate the potential net profit or loss of the plant at various selling prices. Initially, the profit per litre of biodiesel produced was estimated, and then the 29% company tax rate was deducted to obtain the net profit/loss. Ultimately, the rate of return on investment was deduced. It should be noted that all other variables were held constant, and only the price was changed. Table 18 below summarises the various profitability estimates.

Table 5.17: Profitability estimates at various price levels

Biodiesel selling price	Total biodiesel sale income	Total sales (biodiesel & Oilcake)	Profit per litre before tax	Net Profit after 29% income tax
R/litre	Thousand Rand		R/litre	Thousand Rand
7.00	157	256	-3.89	182
8.00	180	279	-2.89	198
9.00	202	301	-1.89	214
10.00	225	324	-0.89	230
11.00	247	346	0.11	246
12.00	270	369	1.11	262

Source: own calculations

The biodiesel break-even price was found to be about R10.90/L, and the plant was estimated to be profitable at prices above the break-even price. The profitable selling price found of about R11.00 was largely influenced by the revenue generated from the oil cake by-product. Without considering the oil cake sales, the plant was breaking even at a price of R15.28/L. Furthermore, the total manufacturing costs are largely influenced by the sunflower feedstock cost, which is highly influenced by the market trends. It is therefore advisable to consider the income that could be potentially generated from all possible by-products of the production process, as this has a positive influence on the ultimate profitable price.

5.4 CONCLUSIONS AND RECOMMENDATIONS

5.4.1 Conclusions

5.4.1.1 Water footprint of biodiesel produced from sunflower

The WFA concept has received global attention, more significantly in the agricultural sector and the biofuels industry, worldwide. Sunflower feedstock, produced under rain-fed and under irrigation systems, was selected as a crop of interest in this study, based on the availability of data to conduct the study, its endorsement as an acceptable biodiesel feedstock by the biofuels industry strategy in South Africa, and its prominent growth as a biodiesel feedstock, globally.

It was found in this study that sunflower grown under irrigation achieved 10% more in yield than rain-fed sunflower achieved. Furthermore, sunflower was found to reach its peak water use in the mid-stage, where the irrigated sunflower had adequate soil water balance with a Ks that was equivalent or greater than 1. However, the opposite was the case for rain-fed sunflower. The WFA results indicated that the rain-fed sunflower had the largest water footprint of the two. Furthermore, the water footprints at the farm level were dominated by the green water footprint.

At the processing level, no green water was used, and the water footprint of biodiesel produced from rain-fed sunflower had a higher water footprint than that produced from irrigated sunflower. This variation in the water footprint can be attributed to the larger yield obtained from irrigated sunflower, which enabled less water to be used per GJ of biodiesel produced. Ultimately, the overall water footprint of biodiesel production was found to be relatively low for biodiesel produced from irrigated sunflower. The water footprint of the entire sunflower-to-biodiesel production process was found to be dominated by the water footprint of sunflower production, and this accounted for about 99% of the total water footprint.

The period in which the sunflower was grown and harvested in this study falls within the periods in which there is adequate water supply in the Orange River Basin, and thus the sunflower production was found to be environmentally sustainable.

The findings of the WFA in this current study were found to correlate with findings of other relevant studies in literature, in that:

i) The farm level production consumes the largest volume of water, while the conversion level uses the least amounts of water in the entire sunflower-biodiesel value chain.

ii) The mid-stage of sunflower growth requires the largest amount of water in the entire sunflower growth period, due to an increased leaf area.

iii) Sunflower is a drought-tolerant crop because, even in times of dire water needs and deficit soil moisture, the crop grows well and the available rainwater supply is highly efficient for the sunflower crop growth.

iv) Water footprints vary by region, regardless of the similarity in the type of biofuel produced and its feedstock. It was necessary to conduct this WFA to gain a better understanding of the water use of producing biodiesel, using sunflower in South Africa.

The transition towards the production and use of biofuels in South Africa requires an adequate understanding of water use. This study quantified the water footprint of sunflower as a biodiesel feedstock, by analysing and tabulating the extent to which sunflower consumes water, together with the amounts of water that would be required to process sunflower into biodiesel. Furthermore, it was demonstrated that growing sunflower in the Orange River Basin could be feasible when produced during the December to May period, as there is adequate water available and thus no hotspots are created, therefore making sunflower environmentally sustainable.

5.4.1.2 Feasibility of biodiesel produced from sunflower

Venturing into any activity requires an understanding of the monetary requirements and returns associated with the activity. In this study, the economic feasibility of establishing a commercial biodiesel production plant of 2500 kg/hr was evaluated. This assessment was threefold, in which the market, agricultural, and financial feasibilities were assessed.

Aligned with the national penetration plan, it was found in this study that the biodiesel market is highly dependent upon the fossil diesel market. It was recognised that a reciprocal relationship exists between the biodiesel market and the fossil diesel market. Furthermore, the results obtained indicated that a biodiesel market is available in South Africa. Nonetheless, the existence of the market does not necessarily create the viability of commercial production, because there is also a need to understand the agricultural capability to supply the required biodiesel feedstock.

The selected feedstock is a highly significant input for the biodiesel production process. It was therefore estimated in this study that a 2500 kg/hr production plant requires approximately 57 149 tons of sunflower seeds per year, resulting in the production of about 19 800 tons of biodiesel per annum. However, meeting a 2% blend for the nominal 2018 fossil diesel demand required about 1.1 million tons of sunflower seeds. It was also observed that there is adequate and underutilised land in South Africa that could be used for the production of sunflower feedstock to meet the biodiesel blending requirements, and this would limit land competition issues.

In addition, the production costs of a biodiesel production plant were found to be highly dependent upon the price of the feedstock. Therefore, the fluctuating nature of the prices of sunflower seeds was observed to potentially create a great variation in the production costs. The 2018 January sunflower seed price of about R6 569 was utilised to determine the costs associated with the production plant. It was then found that the manufacturing costs of a sunflower biodiesel plant of 2500 kg/hr were approximately R342 million, equating to a cost price of about R15.24 per litre of biodiesel. Furthermore, the capital investment costs were found to be R175 million, and this was largely constituted by the total fixed costs. For the financial returns associated with the plant, the break-even price of the plant was found to be about R10.80/L, which takes into consideration the sales of the sunflower oil cake. This implies that the by-products could be economically significant for the profitability of biodiesel production.

It is therefore concluded in this study that:

i) There is a potential market for biodiesel production and utilisation in South Africa.

ii) Sunflower feedstock costs are significantly linked to its adequate supply for biodiesel production, and water was found to have a significant role in the amount that could be produced and supplied.

iii) The agricultural sector has the potential to produce adequate sunflower feedstock for a 2500 kg/hr production plant.

iv) The sale of the by-products of biodiesel production could be significant in making biodiesel production profitable.

v) Biodiesel production from sunflower is sustainable in terms of both monetary and water resources, as it uses water sustainably while bringing about economic returns.

The economic feasibility of commercial biodiesel production in South Africa was found to be dependent upon the applicable government legislation, especially considering that the break-even price of biodiesel exceeds the fossil diesel price. Therefore, the market can be sustainably created when appropriate laws and regulations are put in place.

5.4.2 Recommendations

5.4.2.1 Sunflower industry and policymakers

From the findings of this study, several implications were drawn for the biofuels industry's role-players and stakeholders, as water users and investors, and more significantly for biodiesel production:

i) Biofuels pose sustainability risks, more significantly concerning land and water resources. It is therefore important to align biofuels policies with the agricultural sector to minimise such risks. Decisions made today should not be overly influenced only by short-term economic gains. Moreover, the production of biofuels, such as biodiesel, should take into account optimising land use and optimising water use with minimal impacts, while being environmentally and economically advantageous. Therefore, it is necessary to adopt agricultural practices that could enhance the sustainability of the entire biodiesel production system. It was found in this study that the reliance upon green water could potentially limit the impacts on blue water use. However, this also could limit the soil water balance over time, and it is therefore recommended to focus on suitable agricultural practices, such as crop rotation, as this could enhance agricultural productivity and sustain biofuel production.

ii) There is a dearth of quality data on water use for various processes in South Africa, and this plays a significant role as a hindering factor in assessing impacts of water use. More significantly, actual water use data are scarce for most agricultural and industrial activities. This is because only a few farmers collect and report their water usage details. Furthermore, the data that do exist and are readily available are not necessarily reported consistently. Therefore, following the findings of this study, it is recommended that a consistent and uniform format should be developed in which to collect, record, and make data available, as this would be significant for improved assessments of water use and the respective impacts.

iii) South Africa's current water landscape is moving towards a state of crisis, and this necessitates the formation of a well-equipped task force that can deal with assessing the use of water resources and the related impacts. The systematic evaluation of the water footprints of various activities has received global attention, and this has enabled a better understanding of water use to be gained, worldwide. However, there is still limited attention being given to the assessments of water footprints, more significantly for biodiesel production. Thus, there is a need to emphasise the involvement of the available national water experts to share their knowledge, skills, and experience on sustainable approaches that could be taken towards achieving sustainable water use. It is also important to nurture individuals with the capacity to adapt to future water uncertainties, to limit the effects faced when there are further drought years, and to improve intellectual capacity required to help to avert facing an actual "day zero" for water.

iv) There is a need for focused attention to be given in the following areas:

- First-generation biodiesel producers should be encouraged to seek increased water-efficient approaches, including better use and limited irrigation of biodiesel feedstock that could still enable profitability, as well as smarter techniques that could enable sustainable expansion, rather than using more amounts of scarce water resources.
- For the success of the biofuel industry at large in South Africa, it is vital to address any outstanding issues, conflicts, and misunderstandings that may exist between the key role-players and stakeholders, before the rollout of biodiesel production at a national, commercial scale.
- The implications of voluntary blending against mandatory blending should be intensely assessed, more significantly concerning issues of quality control and potential market creation for biodiesel.
- Resources should be committed towards implementing research and development, capacity building, and technical support for the sustainable development and operation of the biofuels industry in South Africa.

5.4.2.2 Researchers

The following limitations were identified in this study:

i) There is limited primary data available for the processing level of biodiesel production in South Africa.

ii) At the time of the study, there was no actual or prototype production plant available from which to collect primary data to help reinforce the analysis conducted in this study.

iii) The economic feasibility assessment did not take into consideration the potential governmental incentives for producing biodiesel, such as levies, due to the limited nature of the existing policies and guidelines for biodiesel production.

The following recommendations arise from this study for further research:

i) The research could be extended to include the grey water footprint.

ii) Investigate whether the underutilised land endorsed in the former homelands is suitable for sunflower production, or has greater potential for maize production. To identify whether it might be necessary (or more ideal) to use this identified land for maize production, while using other arable land for sunflower production.

iii) Explore the value added to water along the value chain for the by-products of the sunflower-biodiesel value chain.

iv) Ideally, all information about determining the amounts of water consumed at the processing level should be obtained from actual measurements at a South African scale. This will eliminate the reliance upon literature and could ultimately provide more accurate water use results. Furthermore, this data could enable the proper comparison of the water footprints and potentially add to the sustainability of water use in the biofuel industry at large.

v) An actual, revised economic feasibility study that considers the current economic situation of South Africa, more significantly by the biofuels industry. This would enable the formulation of proper revised policies and new views that concern the viability of the industry, as well as a review to confirm the existence of the initial benefits that the industry was envisioned to potentially bring for the economy.

vi) Investigate and propose further policies and guidelines for the production of biofuels, including the potential incentives of producing biodiesel. Examine the effects of these policies on the overall sustainability of biofuel production, more specifically in line with the challenges of food security.

vii) Evaluate ways in which to ensure the adequate supply of sunflower to be used as feedstock, as well as the influence of variation in rainfall on sunflower supply in various years.

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CHAPTER 6
CASE STUDY OF TOBACCO PRODUCTION

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6.1 INTRODUCTION

6.1.1 Background and Motivation

The agriculture sector in South Africa contributes to economic growth, food security and environmental sustainability, while adding value to raw materials (DAFF, 2010; DWA, 2013). The Central Intelligence Agency (CIA) (2016) has reported that, in South Africa, approximately 80% of the total available land surface is useful for agricultural production. However, of the total agricultural land surface, only 12.5% is fertile and 0.4% is planted with permanent crops (DRDLR, 2017). Crop production accounts for 13% of South Africa's surface area, of which 1.3 million hectares are under irrigation (DAFF, 2016).

The tobacco industry has been under pressure over the past decades in South Africa. Along with the decline in the area cultivated with tobacco, the numbers of primary producers and tobacco processors have decreased (DAFF, 2016). Notwithstanding this, the tobacco market contributed approximately R22.4 billion in excise duty and VAT to the government, and R23 billion to the country's GDP, in 2017 (TISA, 2017). The DAFF (2016) has reported the industry as having a market value of R28.8 billion per annum, and as providing 8 000 to 10 000 job opportunities in the agricultural sector, and more than 179 000 among wholesalers and retailers. Tobacco is one of the agricultural commodities that can be considered as an important cash crop in terms of an economic perspective.

The tobacco value chain consists of various stages, from farm requisites suppliers to the end-users of processed tobacco products, such as cigarettes, snuff and pipe tobacco (DAFF, 2016). Water is used throughout the value chain, with the primary tobacco production stage being the largest user of water (FAO, 2017). The fact that the tobacco industry is exploiting vast volumes of water to produce tobacco products should be used to focus an emphasis on the use of freshwater, from the environmental and economic points of view.

According to the Water Footprint Network (WFN), a water footprint is a useful indicator of freshwater use that takes into account both direct and indirect water uses (Chapagain and Hoekstra, 2008; Hoekstra *et al*., 2011). It can be estimated for a product, a process step, a business, a country or in an international context, and considers three types of water – blue, green and grey water (Chapagain and Hoekstra, 2008; Hoekstra *et al*., 2011).

Agricultural irrigation merits serious consideration with regard to improving existing water uses to ensure that water is available for future use (DAFF, 2011). Water resources should be allocated in a sustainable manner that ensures efficiency in the use of water (Hoekstra *et al*., 2017). This not only involves merely the productive use of water, but also includes social, economic and environmental determinants that objectively aim at obtaining the equitable, efficient and sustainable use of water (Hoekstra *et al*., 2012). In order to address the sustainable and efficient use of South Africa's scarce water resources, the government's water management policy emphasises the concern to redress the imbalances in water allocation and accessibility (DWA, 2013). This study is formed with the aim to promote a management approach that would enable water users to attain an efficient level of water use, as well as increasing the contributions of large water users to the economic growth of South Africa (Hoekstra *et al*., 2017).

Conventionally, the main focus is typically placed on reducing the effects of agriculture on freshwater through improving the technical aspects of irrigation and drainage (Deurer *et al*., 2011). However, the use of water footprints will provide information that could be used to address water situations through regional trade policies and to better inform end-user attitudes. Moreover, Mekonnen and Hoekstra (2014) have highlighted the point that a water footprint can be a useful instrument for benchmarking actual WFs in certain regions, or even at a field level, to certain reference levels, and can provide a basis for formulating WF reduction targets, aimed at reducing water consumption and pollution per unit of crop.

6.1.2 Problem Statement and Objectives

In South Africa, there is radical need to properly inform sustainable and efficient freshwater management policies because freshwater in the country is becoming scarce. There is insufficient scientific knowledge currently available to effectively inform water users, managers and policymakers regarding the sustainable use of freshwater for tobacco production. Moreover, the economic productivity of the water footprint of tobacco is neglected.

The use of a water footprint indicator for crop production enables a comparison to be made of actual the WFs in specific areas, and even at field level to a certain degree, and this could lead to the formulation of WF reduction potentials, with the purpose of reducing water consumption and pollution per unit of the crop. Numerous studies, such as those conducted by Sibert and Dőll (2010); Brauman *et al*. (2013); Ercin *et al*. (2013); and Pahlow *et al*. (2015), have revealed that the WFs of crops vary extensively within and across regions.

Measuring water availability and its vulnerability would be important in defining and implanting water management in the continuously changing environment. For example, Wan *et al*. (2017) provided a quantitative assessment of the WF components for crop production, based on data from period 1996-2005, and Hoekstra *et al.* (2011) have investigated the volumetric water indicators for South Africa's crop production. In order to address water security, freshwater resources are classified into three categories: blue, green and grey water (Ercin and Hoekstra, 2014). The blue WF calculates the volume of surface and groundwater consumed, and the green WF measures the volume of rainwater stored in the soil as soil moisture during the growing period of the crop. The grey WF calculates the volume of freshwater required to assimilate the nutrients and pesticides that leach and run off from crop fields and flow into the surface or groundwater, based on existing ambient water quality levels (Mekonnen and Hoekstra, 2011). However, no studies have yet been developed to measure a water footprint assessment of tobacco production in South Africa. There is no scientific-based evidence of the water footprint of tobacco available for informing water users and policymakers regarding the sustainable use of water for tobacco production.

The aim of this study is to assess the water footprint of irrigated tobacco production in order to gain insight into the volume of freshwater that is used to produce tobacco, and to understand the economic returns from using the scarce water resource for the production of tobacco.

The study aim will be achieved through the following sub-objectives:

Sub-objective 1: Assessing the water footprint of irrigated tobacco production to gain insight into the volumes of water and the sources of water used for tobacco production.

Sub-objective 2: Assessing the blue water scarcity levels in relation to the growing season in the selected tobacco production region.

Sub-objective 3: Calculating the economic water productivity of the tobacco production to ascertain the income that is generated per cubic metre of water used to produce tobacco.

6.2 DATA AND METHODS

This section presents the data and the methods that were used to meet the objectives of this study. The discussion starts with an overview of the study area, followed by the data that were used. The section is then concluded with a discussion of the methods that were used to calculate the water footprint and economic water productivity.

6.2.1 Data

6.2.1.1 Study area

This research was conducted in the Loskop Irrigation Scheme in the Mpumalanga province of South Africa. The Loskop Irrigation Scheme is in the Olifants River System. The Olifants River System begins just within and to east of the Gauteng province, and the main stem flows in a northerly direction. After flag Boshielo Dam, it changes direction eastwards, and after cutting through the Drakensberg Mountains, enters the Kruger National Park near Phalaborwa, and then flows further east to the Mozambican border (DAFF, 2016). Just beyond this border is the Massingir Dam in Mozambique (DAFF, 2015). Further downstream, the Olifants River joins the Limpopo River (Bjorn *et al*., 2018). Before the Olifants River reaches the Mozambican border, the Letaba River joins with it. The Olifants River Catchment covers approximately 54 570 km^2 (Bjorn *et al*., 2018).

The Olifants Water Management Area (WMA) falls within three provinces, being the Gauteng, Mpumalanga and the Limpopo provinces (Oberholster *et al*., 2017). It is divided into four sub-categories, namely the Upper Olifants, Middle Olifants, Lower Olifants and Escarpment (Oberholster *et al*., 2017).

The Middle Olifants has an area of approximately 22 500 km^2, with 114 000 hectares used for dryland agriculture and 50 000 hectares planted for irrigation agriculture. The mean rainfall for this region is estimated at 500-600 mm. There is escalating competition between water users and, in consequence, an overuse of water resources, with water requirements (395 $Mm^3.a^{-1}$) exceeding availability (310 $Mm^3.a^{-1}$). According to recent statistics, the Middle Olifants is the 3rd most water-stressed basin in South Africa. Large-scale irrigation farmers cultivate high-value crops, which have relatively high water footprints.

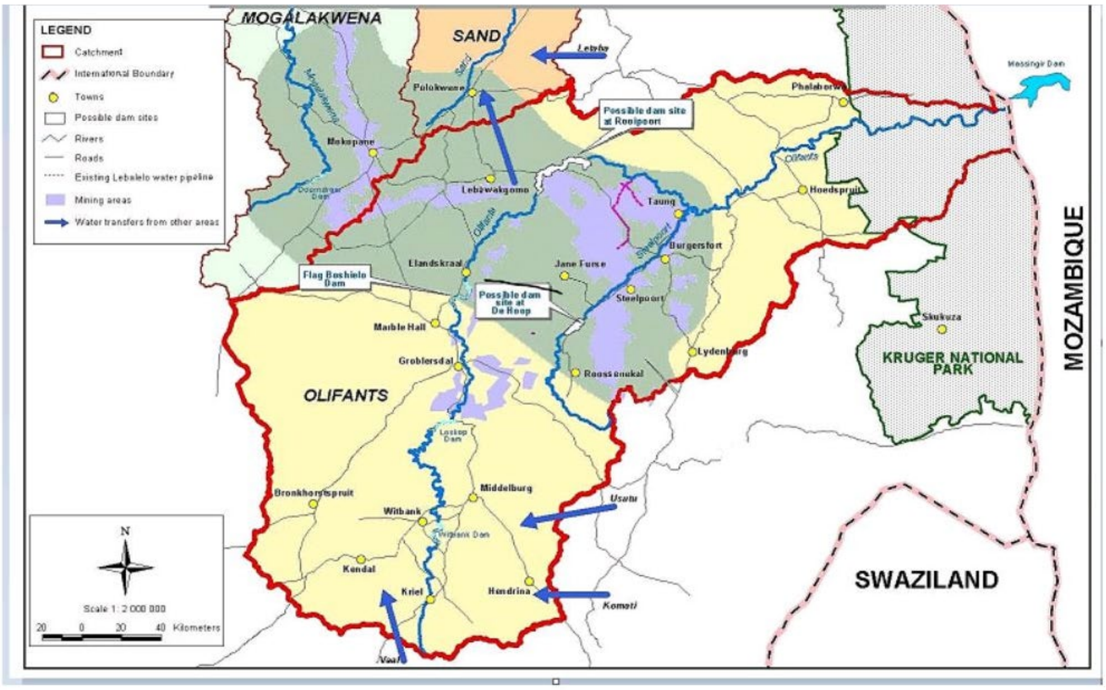

Figure 6.1: Layout of the water flow from the Olifants River Basin in the Mpumalanga province
Source: Google maps (2018)

The Olifants River is a major tributary of water to the Loskop Dam (25º 26' 57. 05" S 29º 19' 44. 36 E), situated in the Mpumalanga province of South Africa (DAFF, 2011). The Loskop Dam is the main water supplier to the Loskop Irrigation Scheme (study area). The scheme falls within the summer precipitation areas (DWA, 2015). The annual rainfall for the scheme is estimated to be more than 700 mm (DAFF, 2015). Between November and February, the long-term rainfall for the region is normally more than 40 mm per month, with a mean of 59 mm (DAFF, 2016). The long-term maximum temperature between November and February for Loskop is 31°C, while the minimum temperatures vary between 14 and 17°C (DWA, 2015). During the winter months, the maximum temperature is around 20°C, with the mean minimum temperature just above 0°C (DWA, 2015). The Loskop Irrigation Scheme is ranked as the second largest irrigation area in South Africa, made up of 25 600 ha, with a total of about 480 km of irrigation channels, as reported by the Loskop Irrigation Board in 2010 (DAFF, 2011). DWA (2009) estimated that the water supply for the irrigation scheme is withdrawn from the upper-hypolimnia of Lake Loskop, which is then conducted to crops through the use of two concrete channels. The lengths of these two channels are approximately 46 km (the short channel) and 330 km (the long channel) (DWA, 2009).

6.2.1.2 Data to calculate the water footprint of tobacco

CROPWAT 8.0 (Allen *et al*., 1998) was used to model the water balance data for the calculation of the water footprint of tobacco. It includes a simple water balance model that enables a simulation of crop water stress conditions and estimations of yield reductions, based on well-established methodologies for the determination of crop evapotranspiration (FAO, 1998), yield responses to water (FAO, 1979), and irrigation and rainfall efficiencies. In addition, the program facilitates the development of irrigation schedules for various management conditions that calculate the measures of scheme water to supply for different crop patterns (FAO, 2016). The CROPWAT 8.0 program (Allen *et al*., 1998) can also be applied to examine farmers' irrigation practices and to predict crop performance under both rainfed and irrigated agriculture (FAO, 2016).

Calculation procedure

The reference evapotranspiration (ETo) is measured by the FAO Penman-Monteith method (FAO, 1998). The input parameters for the model include monthly and ten-daily inputs for temperature (maximum and minimum), humidity, sunshine, and wind-speed. The crop water requirements (ETcrop) over the growing season are determined from ETo and estimates of crop evaporation rates, expressed as crop coefficients (Kc), based on well-established procedures, as stated in the following equation:

$$ET_{crop} = K_c \times ET_O \quad \text{Equation 6.1}$$

FAO (1998) has presented updated values for crop coefficients. Through the estimations of effective rainfall, crop irrigation requirements are calculated, assuming optimal water supply. The inputs on the cropping pattern will enable estimates to be made of scheme irrigation requirements.

The crop parameters used for the estimation of the crop evapotranspiration, water balance calculations, and yield reductions due to stress include: Kc, length of the growing season, critical depletion level p, and yield response factor ky. The program includes standard data for main crops and it is possible to adjust them to meet actual conditions (FAO, 2016).

Table 6.1: Parameters of tobacco crop production in South Africa

Growth stages (Planted 15 September)					
Crop characteristics	**Init**	**Develop**	**Mid**	**Late**	**Total**
Stages length, days	20	30	30	30	110
Depletion coefficient, p	0.4	-	0.5	0.65	-
Root Depth, m	0.25	-	-	0.8	-
Crop coefficient, kc		-	-		-
Yield Response Factor, ky	0.2	1	0.5	0.5	0.9

Source: FAO (2018)

6.2.2 Methods of Analysis

6.2.2.1 Water footprint of tobacco

The water footprint of a growing crop is comprised of the sum of the process water footprints of the different sources of water (Hoekstra *et al*., 2011). Hoekstra *et al*. (2011) demonstrated the water footprint of the process of growing a crop (WF) as:

$$WF_{green+blue} = WF_{blue} + WF_{green}$$ Equation 6.2

where WF_{blue} is the blue crop water footprint (m^3/ton) and WF_{green} is the green crop water footprint (m^3/ton).

The WF_{blue} is expressed as the blue component in crop water use (CWU_{blue}), divided by the crop yield (Y) (Equation 6.3). Similarly, the green water footprint ($WF_{,green}$) is measured as the green component in crop water use (CWU_{green}), divided by the crop yield (Y) Equation 6.4

$$\boldsymbol{WF_{blue}} = \frac{cwu_{blue}}{Y}$$ Equation 6.3

$$\boldsymbol{WF_{green}} = \frac{cwu_{green}}{Y}$$ Equation 6.4

Blue (CWU_{blue}) and green (CWU_{green}) crop water use (measured in m^3/ha) is the sum of the daily evapotranspiration of surface and ground water, and the green water resources respectively over the complete growing period of the crop:

$$\mathbf{CWU}_{\mathbf{blue}} = 10 \times \sum_{d-1}^{lg\,p} ET_{c,blue}$$ Equation 6.5

$$\mathbf{CWU}_{\mathbf{green}} = 10 \times \sum_{d-1}^{Lg\,p} ET_{c,green}$$ Equation 6.6

ET_{blue} and ET_{green} are the blue and green water evapotranspiration amounts, respectively. The water depths are converted from millimetres to volumes per area (m^3/ha) with the use of a factor of 10. The total is calculated over the complete duration of the growing period (lgp), from day one to harvest (Hoekstra *et al*., 2011).

6.2.2.2 Blue water scarcity and the production of tobacco

The Olifants River System is classified as one of the most stressed catchments in South Africa (DAFF, 2016). It has been reported that the river cannot supply sufficient water to meet the present and future demands from agriculture, residential developments, industry, mining and the environment (DWA, 2015).

The Olifants River had already showed a negative water balance in 2004 (Havenga, 2007). This means that more water is being abstracted from the river than is available, and as such, the negative water balance is estimated to amount to -242 million m^3 per annum by the year 2025 (DAFF, 2016). There are approximately 2 500 dams in the Olifants River Catchment, 90% of which have a volume of less than 20 000 m^3, while the thirty dominant dams have capacities of more than 2 000 000 m^3 (Buermann *et al*.,1995; Ashton, 2010; Thiam *et al*., 2015). According to Leonard *et al*. (2015), irrigation constitutes the largest use of groundwater in the catchment. Blue water is used extensively to irrigate the crops; therefore, the focus will be placed on the sustainability assessment on the blue water availability in the basin (Ercin and Hoekstra, 2014).

Using the methodology of Hoekstra and Mekonnen (2012), a blue water scarcity index was calculated as an indicator of the relationship between the blue water footprint and the water availability in the catchment. An index in excess of 100% implies that more water is used than what is available, meaning that the environmental flow requirement is not completely met. For the purpose of assessing the blue water scarcity, the blue WF and blue water availability were determined for the particular catchment (Mekonnen and Hoekstra, 2012). Moreover, seasonal variation in water use and run-off implies that the water footprint and water availability have to be determined for the particular catchment at specific time intervals, normally monthly. According to Hoekstra *et al*. (2011), blue water availability (WA_{blue}) in a catchment x in a certain period t is the difference between the natural run-off in the catchment (R_{nat}) and the environmental flow requirement (EFR), calculated as follows:

$$WA_{blue}\ [x,t] = R_{nat}[x,t] - ERF[x,t] \qquad \text{Equation 6.7}$$

Thus, when the WF_{blue} exceeds the blue water availability in the catchment during a certain period, the EFR is not met for that period. The EFR indicates the volume and timing of water flows required to sustain freshwater ecosystems and human livelihoods. Failing to meet the EFR implies an unsustainable water use in the catchment (Hoekstra *et al*., 2011).

Following Hoekstra *et al*. (2009) and Mekonnen *et al*. (2015), the blue water scarcity was assessed by means of a blue water scarcity index (WS_{blue}):

$$WS_{blue}[x,t] = \frac{\sum WF_{blue}[x,t]}{WA_{blue}[x,t]}$$ Equation 6.8

WS_{blue}[x,t] is the blue water scarcity index for a particular catchment during a particular period of time; $\sum WF_{blue}$[x,t] is the sum of the blue water footprints of all the blue water that was used in the catchment for a particular period of time; and WA_{blue} [x,t] is the blue water availability as defined above (Hoekstra *et al*., 2009). The blue WF is considered to be unsustainable if WS_{blue}[x, t] is greater than one in a particular catchment for a particular period of time (Mekonnen *et al*., 2015). A catchment where WS_{blue} [x, t] is greater than one at a particular period of time is regarded to be a hotspot (Mekonnen and Hoekstra, 2012; Hoekstra *et al*., 2011) and needs intervention to ensure the sustainable use of freshwater in that specific catchment.

6.2.2.3 Economic blue water productivity

The economic blue water productivity (EWP_{blue} in R/m^3) of a crop is an indication of the income that is generated per cubic metre of blue water that was used in the production process, and is calculated as:

$$EWP_{blue} = WP_{blue} \times P$$ Equation 6.9

where:

EWP_{blue} = Economic blue water productivity

WP_{blue} = Blue Water productivity (in ton/m^3)

P = Price of tobacco (in R/ton).

6.3 RESULTS AND DISCUSSION

This section presents the results that were obtained by this study. The discussion starts with the results of the water footprint of tobacco that was calculated, followed by the results of the assessment of the blue water scarcity in the study area. The blue water scarcity is an indication of whether the region may be considered a hotspot in terms of water availability; hence, it is an indication of the degree of sustainability with which water is used for, among others, tobacco production.

6.3.1 Water Footprint of Tobacco

Table 6.2 below sets out a summary of water used to produce tobacco at Loskop Irrigation Scheme. ET_{crop} (mm/growing period) refers to crop evapotranspiration and is an indication of the water requirement of the crop. Eff_{rain} (mm/growing period) represents effective rainfall, Eff_{Irr} (mm/growing period) represents effective irrigation, and IR is the irrigation requirement to supplement effective rainfall in order to meet the crop water requirement.

The blue crop water requirement (ET_{Blue}) of a growing crop is the minimum of the crop water requirement and the effective irrigation. Irrigation requirement (IR) is the difference between the crop water requirement and the effective rainfall. The IR of 191 mm is smaller than the effective irrigation (199 mm) and therefore the ET_{Blue} of producing tobacco in Loskop is 191 mm per growing period.

Table 6.2: Summary of ET, CWU, Yield and WF of tobacco production at Loskop Irrigation Scheme

ET_{crop}	ET_{green}	ET_{blue}	CWU_{green}	CWU_{blue}	Yield	WF_{green}	WF_{blue}	$WF_{green+blue}$
mm/growing period			m³/ha		ton/ha	m³/ton		
465	274	191	2740	1910	3	913	638	1551

Notes: ET is shown for crop, green and blue, CWU for green and blue, and WF for green, blue, and green+blue.

The ET_{crop}, ET_{green}, and ET_{Blue} reflected in Table 6.2 above are expressed in depth per growing period and have to be converted to volume of CWU by multiplying the ET by a factor of 10. The CWU_{Green} and the CWU_{Blue} were calculated to be 2740 m^3/ha and 1910 m^3/ha, respectively. The $CWU_{green+blue}$ thus amounts to 4650 m^3/ha. Thus, a total volume of 4650 m^3 of water is used per hectare to produce tobacco at Loskop Irrigation Scheme. Of the total volume, 2740 m^3 is met in the form of effective rainfall, while the remaining 1910 m^3 is required in the form of supplementary irrigation.

By dividing the CWU (green and blue) by the Yield, the WF_{green} and the WF_{blue} were calculated to be 913 m^3/ton and 638 m^3/ton, respectively. The $WF_{green+blue}$ thus added up to 1511 m^3/ton. Accordingly, in order to produce one ton of tobacco at Loskop Irrigation Scheme, 1511 m^3 of water is used. Effective rainfall constituted about 60% (913/1511) of the total volume of water that was used to produce tobacco. Thus, while rainfall does meet a large part of the volume of water that is required to produce tobacco, a significant volume of irrigation water is still required to cover the shortfall in order to meet the crop water requirement.

Mekonnen and Hoekstra (2010) estimated the global average water footprint of tobacco (*Nicotiana tabacum)*, and found the global average $WF_{green +blue}$ to be 2000 m^3/ton. The WF_{green} accounts for more than 70% of the global average $WF_{green+blue}$. Effective rainfall thus is an important source of water for tobacco production, globally, and so too at the Loskop Irrigation scheme. The smaller water footprint found in this study may be attributable to the relatively higher yields that were used in the calculation of the water footprint, compared with those used in the calculation by Mekonnen and Hoekstra (2010).

6.3.2 Blue Water Scarcity at Loskop Irrigation Scheme

Figure 6.2 below depicts the water scarcity situation in the Olifants Catchment in order to give insight into the water availability during the peak growing season.

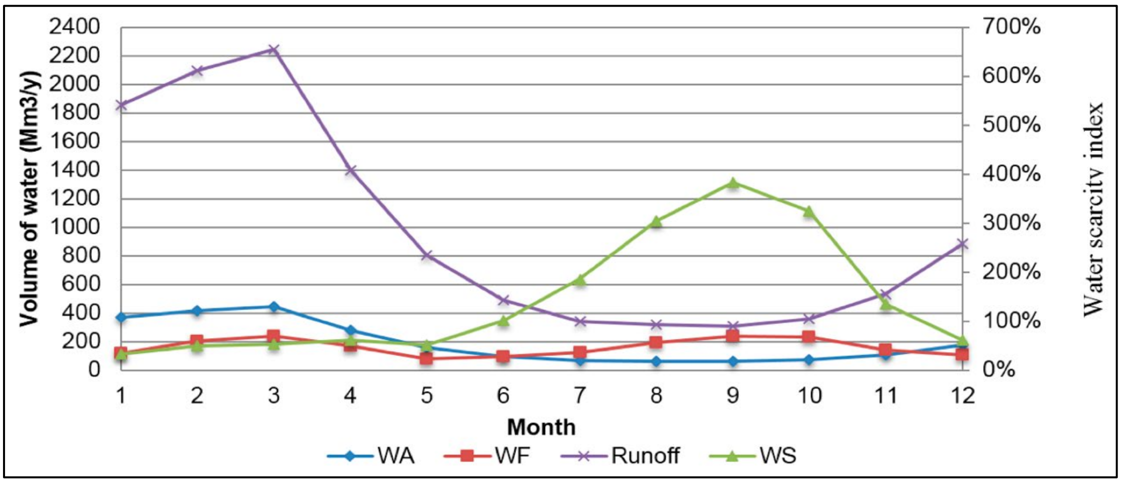

Figure 6.2: Water Availability, Water Footprint, Runoff, and Water Scarcity in the Olifants River Basin, 1996-2005

Notes: The above shows the Water Availability (WA), Water Footprint (WF), Runoff, and Water scarcity (WS) over the years for the Olifants River Basin in South Africa, using data for the period 1996-2005.

Figure 6.2 shows that the blue water scarcity index exceeds 100% during the months between June and November. A water scarcity index in excess of 100% implies that more water is used than what is actually available for use. As such, the water users in the Olifants Catchment are tapping into the environmental flow requirement during those months. From October, there is an increase in runoff because of the start of the rainy season. The increase in runoff, in turn, increases the water that is available for use, and hence decreases the water scarcity index.

When considering tobacco production at the Loskop Irrigation Scheme, the planting period (September to November) corresponds with the period when blue water scarcity is high. The growth stages (group, vigorous and mature) when the water requirement is high (Peng *et al*., 2015), however, occur during the period when the water scarcity index is less than 100%. Thus, the main growing period of tobacco at Loskop Irrigation Scheme corresponds with the period when water scarcity is not a problem.

6.3.3 Economic Blue Water Productivity of Tobacco Production

The results of the calculation of the EWP_{blue} are presented in Table 6.3 below. The PWP_{blue} was calculated to be 0.0016 m^3/ton. When multiplying the PWP_{blue} by the price of tobacco, the EWP_{blue} was calculated to be R18.03/m^3. Accordingly, an income of R18.03 was generated per cubic metre of freshwater that was used to produce tobacco at Loskop Irrigation Scheme.

Table 6.3: Economic Blue Water Productivity of tobacco production at Loskop Irrigation Scheme

	Producer price	WF_{blue}	PWP_{blue}	EWP_{blue}
	(R/ton)	(m^3/ton)	(m^3/ton)	(R/m^3)
Tobacco	11500	638	0.0016	18.03

6.4 CONCLUSIONS AND RECOMMENDATIONS

6.4.1 Conclusions

A water footprint is expressed in terms of water per unit of production. The results showed that the green water footprint of tobacco is higher than the blue water footprint of tobacco production is. Given a tobacco yield of 3 ton/ha, the WF_{green} amounted to 912 m^3/ton, and the WF_{blue} amounted to 637 m^3/ton for the production of tobacco at Loskop. Therefore, the results indicate that in order to produce one ton of tobacco at Loskop, 912 m^3 of rainfall and additional 637 m^3 irrigation is required. It is concluded that effective rainfall does contribute substantially towards meeting the water requirement of tobacco production in the Loskop Irrigation Scheme.

Tobacco production in the study area shows a lower water footprint than the global averages reported by Mekonnen and Hoekstra (2011). Mekonnen and Hoekstra (2011) reported a global average water footprint of 2 000 m^3/ton, compared with a water footprint of 1 550 m^3/ton in this study. Based on the global comparison, tobacco production in South Africa may be considered an efficient use of the limited freshwater resource. Regardless of being smaller than global averages, it is crucial to assess the water footprint indicator in the context of water availability in various production areas. Only then can strategies be formulated regarding the sustainable use of freshwater for the tobacco production in South Africa. Moreover, local, context-specific information is required to inform all the role-players involved in the production of tobacco products about the sustainable use of freshwater.

6.4.2 Recommendations

6.4.2.1 Recommendations for water users

- Farmers should utilise crop residues and mulches to decrease soil water evaporation and enhance nutrient recycling.
- Enhanced irrigation methods, such as drip and subsurface irrigation, should be used to improve water use efficiency.

6.4.2.2 Recommendations for researchers

It is of importance for future researchers to conduct a sustainability assessment with local, context-specific information in order to acquire a more accurate indication of sustainability, because the monthly blue water data provided by Hoekstra and Mekonnen (2011) did not take into account the water in dams and inter-basin water transfers.

A water footprint is composed of three components, being the blue, green and grey water footprints. The grey water footprint should be assessed in future research at the Loskop Irrigation scheme to calculate the total water footprint of tobacco production.

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CHAPTER 7
IMPACT OF CLIMATE CHANGE ON THE WATER FOOTPRINT OF SUGARCANE PRODUCTION

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7.1 INTRODUCTION

7.1.1 Background

The need for agriculture to feed the growing global population in the context of declining supplies of water for food production is a major challenge, globally (Alexandratos and Bruinsma, 2012; FAO, 2018). Sugarcane is an important industrial crop produced in tropical and subtropical regions globally, and is cultivated on about 23.8 million hectares in more than 90 countries (Mnisi and Dlamini, 2012), including South Africa. The South African sugar industry is one of the world's leading producers of high-quality sugar, producing approximately 20 million tons of sugarcane and 2.2 million tons of sugar per season (SASA, 2019). From an economic perspective, the industry contributes significantly to the national economy through its agricultural and industrial investments, foreign exchange earnings, provision of employment opportunities, and its linkages with suppliers, while providing support to other industries and customers (DAFF, 2014). Moreover, more than 2% of South Africa's population depends on the sugar industry for a living and sustainable socio-economic development, particularly in rural areas (SASA, 2019).

However, sugarcane production, globally, is a large user of freshwater, and so too in South Africa, as reported by Pahlow *et al*. (2015). The concern is that South Africa is a water-scarce country; ranked 30th in the world in terms of water scarcity (DWA, 2013). Rapid population growth and increasing variabilities in rainfall have led to tighter water supply in many parts of South Africa where the water demand often exceeds the supply. Climate change adds another dimension of stress to the pressure on water resources (DWA, 2013) by causing more erratic precipitation patterns and increased variability in river flows and aquifer recharge (Chapagain and Tickner, 2012). It is within this context that sugarcane has to be produced.

Sugarcane is one of the world's main C_4 crops, with weather and climate-related events (i.e. growth environment of atmospheric CO_2, temperature, precipitation, and other extreme weather) being the key factors affecting its production (Zhao and Li, 2015). Climate change thus is expected to have a direct impact on sugarcane production. Given the economic importance of the sugar industry to the South African economy, it is important to plan strategically to manage the water-related risk faced by sugarcane producers in an environment where climate change is expected to increase water demand and decrease the security of water availability.

The concept of a water footprint is emerging as an important sustainability indicator in the agriculture and food sectors (Ridoutt *et al*., 2010). The water footprint of a product is the volume of freshwater used to produce a particular product, measured along the complete value chain of the product (Hoekstra and Chapagain, 2008). Hoekstra *et al*. (2011) defined three components of the water footprint: the blue, green and grey water footprints. The blue water footprint is defined as the consumption of blue water resources (surface and groundwater) along the supply chain of a product. 'Consumption' refers to loss of water from the available ground-surface water body in a catchment area. The green water footprint refers to consumption of green water resources (rainwater insofar as it does not become run-off). The blue and green water footprints thus refer to the sources of water that were used in the production process. The grey water footprint is concerned with pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants, given the natural background concentrations and existing ambient water quality standards.

Water Footprint Assessment (WFA) is a fast-growing research field (Chapagain, 2017), as is evident from the exponential growth in the number of articles in this field, globally (Hoekstra *et al*., 2016). Internationally, the water footprint of sugarcane, in particular, has been assessed by, among others, Kongboon and Sampattagul (2012); Haro *et al*. (2014); Da Silva *et al*. (2015); Scarpare *et al*. (2016); Jahani *et al*. (2017); and Zemba and Obi (2018). Kongboon and Sampattagul (2012) and Haro *et al*. (2014) assessed the water footprints of sugarcane in relation to bioethanol production in Thailand and Mexico, respectively. Scarpare *et al*. (2016) and Jahani *et al*. (2017) explored the impacts of management practices on the water footprints of sugarcane in Brazil and Iran, respectively. Da Silva *et al*. (2015) explored the impacts of different measurements and modelling on the water footprint of sugarcane in Brazil. Lastly, Zemba and Obi (2018) assessed the relationship between climate variability and the water footprint of sugarcane at the Dangote Sugar Company in Nigeria. The water footprint of sugarcane has thus received ample attention from researchers, internationally.

While a number of WFAs have also been done in South Africa since the mid-2010s, the focus was mainly placed on other crops, i.e. horticultural products (Van der Laan, 2017); field and forage crops (Jordaan *et al*., 2019); and table and wine grapes (Jarmain, 2020). Only Mekonnen and Hoekstra. (2010), Pahlow *et al*. (2015) and Adetoro (2017) have addressed the water footprint of sugarcane production in South Africa, to certain extents. Mekonnen and Hoekstra. (2010) estimated the water footprint of sugarcane in South Africa as part of the estimation of the global water footprint of crop production for the period 1996-2005. A crop water-use model was used at a 5-by-5 arc minute spatial resolution for this purpose. Pahlow *et al*. (2015) used the data of, among others, Mekonnen and Hoekstra. (2010) to demonstrate how WFA can be used to inform water management and policymaking in South Africa. Pahlow *et al*. (2015) reported, among other things, that the water footprint of sugarcane was among those of the top three crops in terms of blue (second) and green (third) water use in South Africa.

Adetoro (2017) has provided the most detailed WFA on sugarcane production in South Africa, to date. He estimated the water footprint of irrigated sugarcane production at Malelane, one of the important irrigated production areas in South Africa. Adetoro (2017) also explored the impacts of certain management practices (mulching and type of irrigation system) and soil depth on the water footprint for the purpose of formulating response strategies as to how producers could decrease the water footprint.

7.1.2 Problem Statement

Despite the recognition that climate change will lead to increased demand for water within a context of lower security in the availability of water, and the growing interest in WFA to inform sustainable water use, the impact of climate change on the water footprint of sugarcane production in South Africa has not been assessed before.

Researchers have explored the impacts of climate change on sugarcane production in South Africa. Such research has explored the impact of climate change on crop yields and water use (Schulze and Kunz, 2010; Singels *et al*. 2014; Singels *et al.* 2018; Singels *et al*., 2019) and on yields, water use and irrigation demand (Jones *et al*., 2015). The knowledge generated through this research is valuable and already provides scientific guidance to inform the sugar industry on what to expect from climate change. However, some of these studies relied on older versions of crop and climate models, while none of these studies focused on the water footprint concept per se.

The distinction between the blue and green components in WFA can provide additional insight when assessing the impact of climate change on the water footprint of sugarcane. Such insights can be used to further assist the sugar industry in their strategic planning processes to manage water-related risk associated with climate change.

7.1.3 Objectives

The aim of this study was to assess the impact of climate change on the water footprint of sugarcane production in South Africa. The aim was achieved through the following sub-objectives:

Sub-objective 1: To determine the green water footprint and the blue water footprint of **irrigated** sugarcane production in selected areas under baseline and future climate scenarios.

Sub-objective 2: To determine the green water footprint of **rainfed** sugarcane production in selected rainfed areas under baseline and future climate scenarios.

7.2 DATA AND METHODS

7.2.1 Overview

This section presents the study area where the research was conducted, followed by a discussion of the data and the methods that were used to assess the impact of climate change on the blue and green water footprint of sugarcane production. The water balance and crop data used in this study were obtained from Singels *et al*. (2017) and a brief summary thereof is presented. The weather data and other model inputs used in this study are fully described by Lumsden (2016) and Singels *et al*. (2017).

7.2.2 Study Area

This research included the main sugarcane-producing areas in South Africa. For the purpose of this research, three different types of sugarcane production were considered: fully irrigated, a combination of irrigation and rainfed, and fully rainfed. For the fully irrigated production, Malelane, Pongola and Komati mill supply areas were selected; while Amatikulu, Felixton and Umfolozi mill supply areas were selected for the combination of irrigated and rain-fed production; and Noodsberg, Maidstone and Sezela mill supply areas represent the fully rain-fed production. A map showing the locations of the selected areas is presented in Figure 7.1 below.

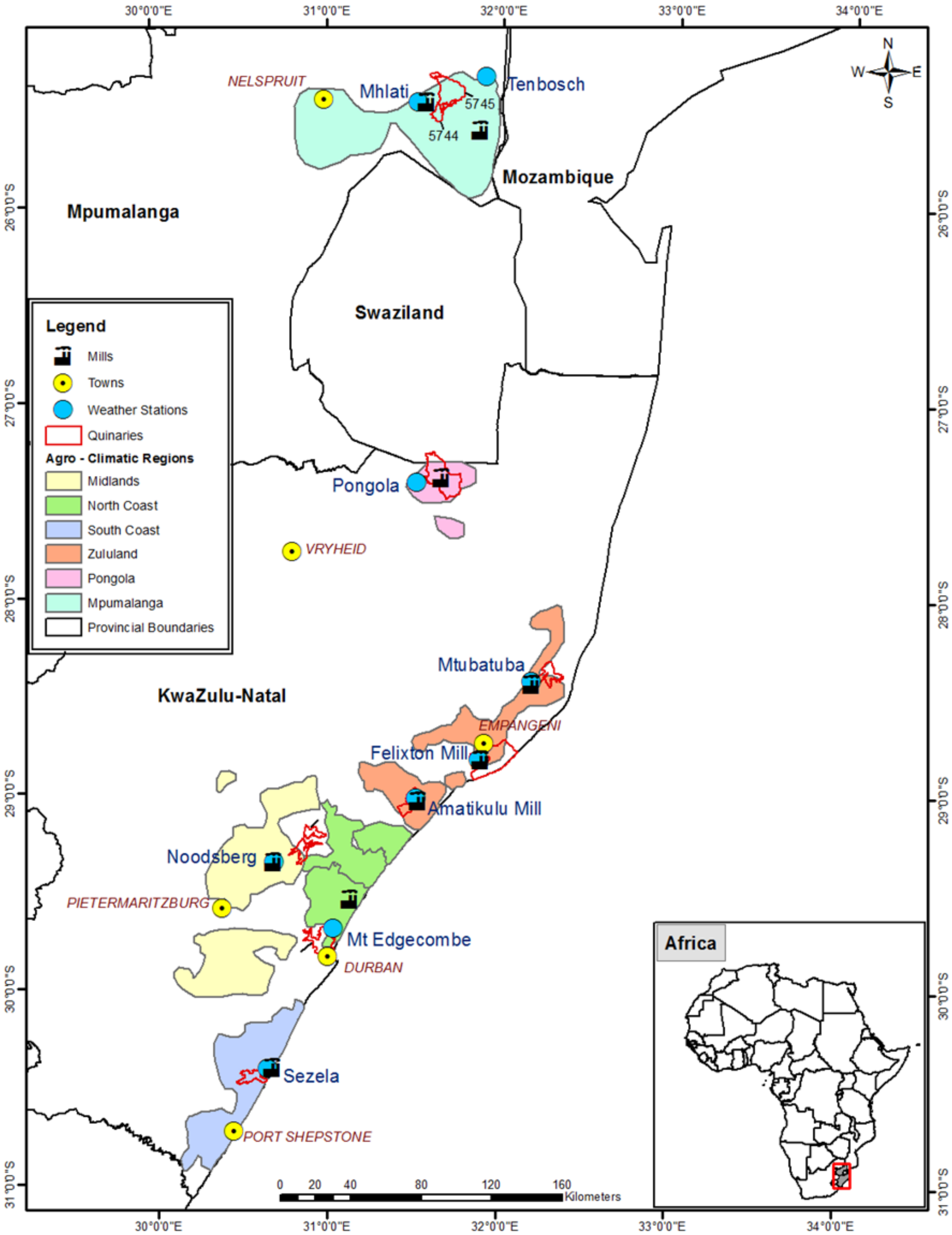

Figure 7.1: Map showing agro-climatic regions in the South African sugarcane belt, the location of selected sugar mills, and the quinary sub-catchments selected to represent the different mill supply areas
Source: SASRI GIS office

7.2.3 Crop Yield and Water Balance Modelling

The primary crop and water balance data for this study were obtained from Singels *et al*. (2017). The methodology for weather data generation, configuration of the crop model and model output data processing are fully described by Lumsden (2016) and Singels *et al*. (2017), and are also summarised by Singels *et al.* (2018, 2019). Singels *et al*. (2017) used the DSSAT-Canegro model to simulate 18 first ratoon crops of a high sucrose cultivar, harvested in April and October of each year, for each of the selected sub-catchments (see Table 7.1 below). Harvest age varied between 12 and 23 months, depending on the present thermal climate of each area. For irrigated scenarios, the crop cycle length was set at 12 months. Irrigation of 20 mm was simulated whenever the profile soil water deficit exceeded 20 mm or when the profile plant available soil water dropped below 50%. A row spacing of 1.2 m was assumed for all runs. Initial soil water content at the start of the simulations was set to 100% of available capacity for irrigated cane, and to 50% for dryland cane.

Crop simulations were performed for three sets of weather data, namely observed data for the baseline period (1971-1990, bl_{obs}), simulated data for the baseline (1971-1990), and future (2046-2065) periods (bl_{sim}, fut_{sim}) derived through statistical downscaling of the three global circulation models (GCMs) that contributed to the IPCC 4th Assessment report (IPCC, 2007), namely CSIROmk3.5, GFDLcm2.1 and MPI-ECHAM5 (Singels *et al.*, 2017). Climate projections derived from these GCMs assumed the A2 emission scenario (IPCC, 2000), with an assumed atmospheric CO_2 concentration of about 550 pm for the future period, which corresponds roughly to "Representative Concentration Pathway" 8.5 (IPCC, 2013). GCM data were downscaled empirically by using a methodology developed by the Climate Systems Analysis Group of the University of Cape Town (CSAG).

In general, the climate projections for the study area indicate that temperatures are expected to increase by about 2°C from the baseline to the future period. Projected rainfall increases varied from 6% to 15%. It should be noted that rainfall projections varied considerably between GCMs, indicating a high level of uncertainty. Solar radiation is not expected to change markedly (Singels *et al*., 2019).

Crop simulations for the baseline and future periods utilised atmospheric CO2 concentration of 340 and 550 ppm, respectively. Rainfed (rf) and irrigated (irr) simulations were conducted for irrigated scenarios to enable the calculation of the blue and green components of the water footprint.

Future seasonal evapotranspiration (*ET* in mm) and cane yield (*CY* in t/ha), for a given set of GCM derived weather data, for each of the 18 seasons, were calculated as the product of the mean ratio between values derived from simulated weather data for the future and baseline period, and the values derived from observed weather data for the baseline period. The figures for each of these 18 values were then averaged for the three weather data sets derived from the three GCMs. These calculations are summarised in Equation 7.1:

$$Xfut = 1/3\ \sum_{GCM=1}^{GCM=3}[(1/18 \sum_{CS=1}^{CS=18} Xfut_{sim})/\ (1/18 \sum_{CS=1}^{CS=18} Xbl_{sim})]Xbl_{obs} \quad \text{Equation 7.1}$$

where the number 3 refers to the number of GCM derived weather data sets, and *X* represents the value of a given variable (ET_{irr}, ET_{rf}, and *CY*) for each of the 18 crop seasons (CS), averaged for the April and October harvested crops. All values were annualised to enable meaningful comparisons to be made between areas.

Table 7.1: Details of the production type, harvest age and the baseline climate and expected future climate change assumed for the simulations for the different quinary sub-catchments situated in the different mill supply areas and agroclimatic regions

Quinary catchment	Sugarcane producing area (mill supply area)	Agro-climatic region	Production type	Crop harvest age	Baseline mean annual precipitation (mm)	Future increase in mean annual precipitation (%)	Baseline mean annual temperature (°C)	Future increase in temperature (vbvbC)	Baseline mean annual reference evaporation (mm)[1]	Future increase in reference evaporation (%)
5745	Komati	Mpumalanga	Irrigated	12	719	9.78	22.21	2.35	1607	9.88
5744	Malelane	Mpumalanga	Irrigated	12	841	9.11	22.2	2.32	1524	10.51
5337	Pongola	Pongola	Irrigated	12	720	11.11	21.14	2.16	1561	9.44
5198	Umfolozi	Zululand	Irrigated, Rainfed	12	1009	6.34	21.93	1.94	1414	9.72
5112	Felixton	Zululand	Irrigated, Rainfed	12	1316	1.73	21.82	1.92	1236	10.82
5085	Amatikulu	Zululand	Irrigated, Rainfed	12	1166	10.1	21.45	1.97	1404	10.03
4736	Noodsberg	Midlands	Rainfed	23	907	8.4	17.93	2.02	1229	10.3
4707	Maidstone	North Coast	Rainfed	14	1036	10.34	20.38	1.89	1106	10.91
4806	Sezela	South Coast	Rainfed	14	1057	12.11	19.83	1.87	1099	10.99

1. FAO56 short grass reference evaporation calculated with limited humidity data

7.2.4 Water Footprint Calculation

The green and blue water footprints (WF_{green} and WF_{blue}, *in* m^3/ton) for each of the 18 crop seasons and different climate scenarios were calculated through using Equations 7.2 and 7.3, respectively:

$$WF_{blue} = \frac{CWU_{blue}}{CY} \quad \text{Equation 7.2}$$

$$WF_{green} = \frac{CWU_{green}}{CY} \quad \text{Equation 7.3}$$

where C*Y* is the simulated annualised sugarcane yield (t/ha/annum) and CWU_{blue} and CWU_{green} are simulated annualised blue crop water use and green crop water use (m^3/ha/annum), respectively.

Blue water use, the crop water use attributable to irrigation, was calculated as the difference in evapotranspiration for irrigated and rainfed crops:

$$CWU_{blue} = \left[ET_{irr} - ET_{,rf}\right] \times 10 \quad \text{Equation 7.4}$$

where ETirr and ETrf are the annualised evapotranspiration figures (mm/annum) simulated for irrigated and rainfed conditions, respectively.

The green water use was simply taken as the annualised evapotranspiration (mm/annum) simulated for rainfed crops:

$$CWU_{green} = ET_{rf} \times 10 \quad \text{Equation 7.5}$$

It is important to note that all key deductions in terms of drainage of water out of the root zone and surface runoff were taken into account in the model during simulations.

7.3 RESULTS AND DISCUSSION

The results of the water footprint accounting are presented and discussed in this section. The blue and green water footprints were calculated for a baseline and a future climate scenario in order to gain insight into the potential impacts of climate change on the water footprint of sugarcane production in the future.

For the purpose of discussion, one irrigated and one rainfed mill supply area are presented and discussed in detail. The results for the other mill supply areas are summarised in a table, while the background charts are presented in Appendix 7.6 below.

7.3.1 Irrigated Sugarcane Production

7.3.1.1 Malelane

Figure 7.2 below shows that the baseline *CY* ranged from 122 to 133 t/ha, with a median of 127 t/ha. Under the future climate scenario, the CY ranged from 12 to 135 t/ha, with a median of 128 t/ha. The increase in median CY is 1.3%. The increase in CY yield under the future climate scenario is ascribed to a faster rate of canopy cover development due to higher temperatures, thereby enabling more radiation to be intercepted for slightly higher biomass accumulation (Singels *et al*., 2018; 2019).

The CWU_{green} ranged from 3 395 to 7 025 m^3/ha, with a median value of 5 633 m^3/ha, under the baseline condition. Under the future climate scenario, the CWU_{green} ranged from 3 727 to 7 713 m^3/ha, with a median value of 6 182 m^3/ha, being an increase of 9.8% from the baseline. This increase in CWU_{green} can be ascribed to a projected increase in future rainfall (about 7%) and evaporative demand for Malelane.

The WF_{green} for the baseline climate ranged from 27 to 57 m^3/ton, with a median value of 45 m^3/ton. The median value increased by 8.4% under the future climate scenario.

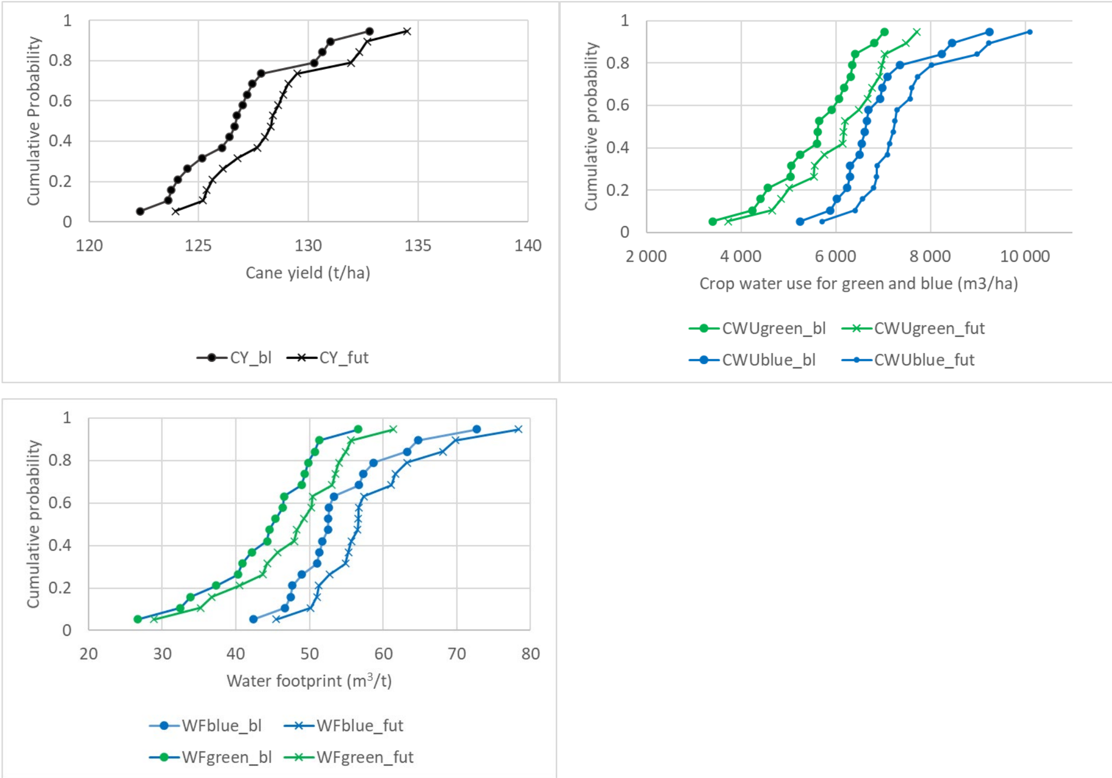

Figure 7.2: The cumulative distribution function of simulated cane yields, green crop water use, green water footprint, blue crop water use and blue water footprint of sugarcane production for Malelane under baseline and future climate scenarios

Notes: The above Figure shows the cumulative distribution function of simulated cane yields (CY), green crop water use (CWUgreen), green water footprint (WFgreen), blue crop water use (CWUblue) and blue water footprint (WFblue) of sugarcane production for Malelane under the baseline (bl) and future (fut) climate.

Under the baseline climate, the CWU_{blue} ranged from 5 255 to 9 250 m^3/ha, with a median value of 6 635 m^3/ha. The range of the CWU_{blue} under the future climate scenario was 5 717 8 to 10 099 m^3/ha, with a median value of 7 232 m^3/ha. The increase in the median values amounts to 9.0%. The increase in CWU_{blue} is ascribed to higher evaporative demand and accelerated canopy development under increased future temperatures (Singels *et al*., 2018, Singels *et al*., 2019).

The WF_{blue} for the baseline climate ranged from 42 to 73 m^3/ton, with a median value of 53 m^3/ton, compared with the range of 46 to 78 m^3/ton, with a median value of 57 m^3/ton, under the future climate scenario. The increase in the median value of the WF_{blue} under the future climate scenario amounts to 7.7%.

The results suggest that the total water footprint of sugarcane production in the Malelane area is likely to increase by about 7.9%, assuming an adequate water supply under the future climate. This is because crop water use is expected to increase by about 8.2%, while yields are expected to increase by only about 1.3%.

7.3.1.2 Other irrigated mill supply areas

The results for the other irrigated mill supply areas are summarised in Table 7.2 below, with the background charts that underlie the summary being presented in Appendix 7.6 below.

The median CY under the baseline ranged from 86 t/ha for Felixton to 103 t/ha for Pongola, generally declining from north to south as determined by radiation and temperature. Under the future climate scenario, the median CY is expected to increase by between 1 and 4%, roughly inversely proportional to the baseline yield potential.

The median crop water use under the baseline climate ranged from 10 545 for Felixton to 12 705 m^3/ha for Komati, as determined by climatic conditions. The CWU_{blue} ranged from 2 088 for Felixton to 7 440 m^3/ha for Komati, comprising 20 and 59% of total crop water, respectively. Under the future climate scenario, the CWU is expected to increase by about 8%, while the CWU_{blue} is expected to increase by between 3.8 (Pongola) and 14.9% (Felixton).

The median WF_{tot} for the baseline period ranged from 86 m^3/ton for Felixton, to 102 m^3/ton for Pongola. The variation between areas is attributable to variations in yield potential, temperature and atmospheric evaporative demand (all generally declining from north to south). The median blue WF for the baseline period ranged from 17 m^3/ton for Felixton to 59 m^3/ton for Komati, comprising 20 and 60% of the total WF, respectively. This variation is attributable to the variations in the extent to which rainfall meets crop demand for water.

The median WF_{tot} is expected to increase under a future climate by 3-7%, assuming adequate irrigation supplies. The reason is that the expected increases in yield (due to elevated temperatures and atmospheric CO2) are much smaller than the expected increases in crop water use (due to elevated temperatures). The expected changes in WF_{blue} range from nil for Pongola to 12% for Felixton, largely depending on uncertain projections of changes in rainfall (10% increase for Pongola and 1% increase for Felixton). It is noteworthy that the expected yield increases in Komati and Malelane are very small (2%), while demand for irrigation water will increase by about 8%, despite expected increases in rainfall of about 7%, resulting in an increase in the blue WF of about 7%.

Table 7.2: Statistics of the distribution of simulated annualised cane yield (*CY in t/ha*), green and blue crop water use (*CWU_{green}*, *CWU_{blue} in m^3/ha*), green, blue and total water footprint (*WF_{green}*, *WF_{blue} and WF_{tot} in m^3/t*) of irrigated sugarcane production in different mill supply areas under the baseline climate, and the expected change (Delta) in median values under the future climate

		Komati			Malelane			Pongola			Umfolozi			Felixton			Amatikulu		
		Baseline	Future	Delta	Baseline	Future	Delta	Baseline	Future	Delta	Baseline	Future	Delta	Baseline	Future	Delta	Baseline	Future	Delta
CY	Min	124	125	1.6	122	124	1.3	117	122	4.2	125	129	3.1	120	123	3.0	106	110	3.6
	Max	132	134	1.5	133	135	1.3	125	130	4.2	139	144	3.1	127	130	3.0	123	127	3.6
	Med	127	129	1.5	127	128	1.3	121	126	4.2	130	134	3.1	123	126	3.0	113	117	3.6
CWUgreen	Min	2 980	3 258	9.3	3 395	3 727	9.8	4 250	4 776	12.4	5 970	6 610	10.7	7 155	7 749	8.3	5 725	6 333	10.6
	Max	6 675	7 298	9.3	7 025	7 714	9.8	7 355	8 265	12.4	9 765	10 817	10.8	9 495	10 284	8.3	8 760	9 691	10.6
	Med	5 228	5 716	9.4	5 633	6 182	9.8	5 790	6 511	12.5	7 498	8 313	10.9	8 445	9 147	8.3	7 465	8 257	10.6
CWUblue	Min	6 085	6 530	7.3	5 255	5 717	8.8	4 985	5 033	1.0	2 055	2 020	-1.7	780	981	25.8	2 135	2 098	-1.8
	Max	9 870	10 664	8.0	9 250	10 099	9.2	8 330	8 780	5.4	6 580	7 020	6.7	3 835	4 301	12.2	5 275	5 562	5.4
	Med	7 440	8 008	7.6	6 635	7 232	9.0	6 770	7 030	3.8	4 820	5 057	4.9	2 088	2 399	14.9	3 560	3 659	2.8
CWUtot	Min	11 985	12 988	8.4	11 510	12 588	9.4	11 920	12 845	7.8	11 720	12 728	8.6	9 840	10 788	9.6	10 320	11 160	8.1
	Max	13 385	14 503	8.4	13 115	14 343	9.4	13 110	14 126	7.8	13 460	14 617	8.6	11 125	12 198	9.6	12 130	13 118	8.1
	Med	12 705	13 767	8.4	12 413	13 573	9.4	12 515	13 486	7.8	12 165	13 212	8.6	10 545	11 562	9.6	11 075	11 977	8.1
WFgreen	Min	24	26	7.7	27	29	8.4	36	38	7.8	44	48	7.4	57	59	5.2	51	54	6.8
	Max	53	57	7.7	57	61	8.4	62	67	7.9	77	83	7.4	77	81	5.2	76	82	6.8
	Med	41	45	7.7	45	49	8.4	48	52	7.9	58	63	7.5	70	73	5.2	68	72	6.8
WFblue	Min	48	51	5.7	42	46	7.4	42	41	-3.1	16	15	-4.7	6	8	22.2	19	18	-5.2
	Max	79	84	6.4	73	78	7.8	70	71	1.2	49	51	3.4	30	33	8.9	47	48	1.8
	Med	59	62	6.0	53	57	7.7	56	55	-0.4	36	37	1.7	17	19	11.8	32	31	-0.8
WFtot	Min	95	102	6.7	94	102	8.0	99	102	3.4	91	96	5.3	82	87	6.5	96	100	4.4
	Max	104	111	6.7	101	109	8.0	110	113	3.4	97	103	5.3	88	94	6.5	101	106	4.4
	Med	100	106	6.7	98	106	7.9	103	107	3.4	93	98	5.3	86	92	6.5	98	102	4.4

7.3.2 Rainfed Sugarcane Production

7.3.2.1 Sezela

The Sezela mill supply area is used to represent rainfed sugarcane production for the purpose of discussing the results. The cumulative probability distributions of *CY*, CWU_{green}, and WF_{green}, are presented in Figure 7.3 below.

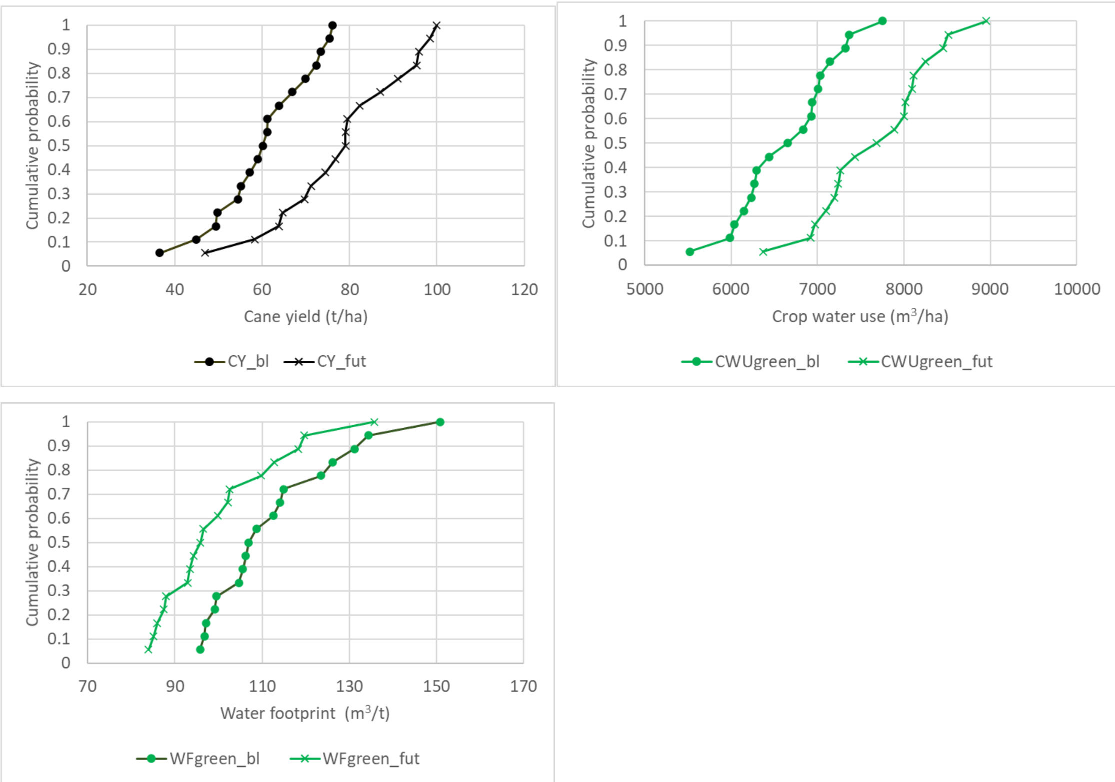

Figure 7.3: The cumulative distribution function of simulated cane yields, green crop water use and green water footprint of rainfed sugarcane production for Sezela mill supply area under baseline and future climate scenarios

Notes: The figure above shows the cumulative distribution function of simulated cane yields (CY), green crop water use (CWUgreen) and green water footprint (WFgreen) of rainfed sugarcane production for Sezela mill supply area under the baseline (bl) and future (fut) climate.

Figure 7.3 above shows that the *CY* for the baseline climate ranged from 36 to 76 t/ha, with a median value of 61 t/ha. For the future climate scenario, the *CY* ranged from 47 to 100 t/ha, with a median value of 79 t/ha, which is 32% higher than for the baseline scenario. These yield increases are ascribed to a combination of an expected increase in rainfall (about 11%, Table 7.1 above), increased radiation and water capture (through accelerated canopy development brought about by increased temperatures), and increased water use efficiency (brought about by increased atmospheric CO_2 concentration) (Singels *et al*., 2019).

Figure 7.3 further shows that, under the baseline climate scenario, the CWU_{green} ranged from 5 520 to 7 753 m^3/ha, with a median value of 6 741 m^3/ha. The range of CWU_{green} under the future climate scenario was from 6 371 to 8 955 m^3/ha, with a median value of 7 784 m^3/ha. The median CWU_{green} thus increased by 15.5%. The increase in CWU_{green} could be ascribed to increased atmospheric water demand and accelerated canopy development (Singels *et al*., 2019) due to an expected increase in temperatures, as well as the expected increase in rainfall.

The WF_{green} for the baseline climate ranged from 96 to 151 m^3/ton (median value of 108 m^3/ton), compared with 84 to 6 m^3/ton (median 96 m^3/ton) for the future climate. The results show a decrease of about 10% in the median WF_{green} from the baseline to the future climate scenario. The decrease in the projected WF_{green} could be ascribed to the proportionally larger increase in cane yield compared with the increase in CWU_{green}.

7.3.2.2 Other rainfed mill supply areas

The results for the other rainfed mill supply areas are summarised in Table 7.2. The background charts underlying the summary are presented in Appendix 7.6 below.

The median *CY* in the rainfed areas, under baseline conditions, ranged between 54 t/ha/annum for Noodsberg to 89 t/ha/annum for Felixton. Table 7.2 shows that the *CY* increased for all rainfed areas under the future climate scenario. Expected increases in the median CY under a future climate scenario ranged from 4.2% for Felixton to 30% for Sezela. The size of the increase relates to the yield level. High potential (wet and/or warm) areas like Felixton show a small increase, compared with low potential (dry and/or cool) areas like Amatikulu, Noodsberg and Sezela, because the main effect of future climate is mitigation of drought and cold effects.

The baseline median CWUgreen ranged from 5 932 m^3/ha/annum for Noodsberg to 8 445 m^3/ha/annum for Felixton. The expected future increase in median CWU_{green} ranged from 8.3% for Noodsberg to 15.5% at Sezela, strongly determined by the expected increases in rainfall. While *CY* and CWU_{green} increased for all of the areas, the median WF_{green} was found to decrease in all but one of the areas (Felixton). The decreases ranged between -4 and -10%. These decreases occur because of the proportionally larger increase in *CY* compared with the increase in CWU_{green} attributable to improved water use efficiency brought about by future elevated atmospheric CO^2 concentration At Felixton, however, the median CWU_{green} increased proportionally more than the *CY* did, causing an increase in the median WF_{green} of about 4%. Interestingly, Felixton is the area where the smallest increase in mean annual precipitation is expected under the future climate scenario (Table 7.3 below).

Table 7.3: Statistics of the distribution of simulated annualised cane yield (*CY in t/ha*), green crop water use (*CWU_{green} in m^3/ha*) and green water footprint (*WF_{green} in m^3/t*) of sugarcane production in rainfed mill supply areas under the baseline, and the expected change (*Delta in %*) in median values under the future climate

		Umfolozi			Felixton			Amatikulu			Noodsberg			Maidstone			Sezela		
		Baseline	Future	Delta	Baseline	Future	Delta	Baseline	Future	Delta	Baseline	Future	Delta	Baseline	Future	Delta	Baseline	Future	Delta
CY	Min	36	42	15.7	64	67	4.2	21	25	15.0	23	28	20.7	35	40	14.5	37	47	28.2
	Max	102	119	15.9	112	117	4.2	87	100	15.0	67	81	20.8	80	92	15.7	76	100	31.3
	Med	67	78	15.7	89	93	4.2	59	68	15.0	54	65	20.8	59	69	15.7	61	79	30.4
CWUgreen	Min	5 970	6 610	10.7	7 155	7 749	8.3	5 725	6 333	10.6	4 179	4 524	8.3	5 366	5 820	8.5	5 520	6 371	15.4
	Max	9 765	10 817	10.8	9 495	10 284	8.3	8 760	9 691	10.6	6 921	7 494	8.3	7 427	8 057	8.5	7 753	8 955	15.5
	Med	7 498	8 313	10.9	8 445	9 147	8.3	7 465	8 257	10.6	5 932	6 424	8.3	6 508	7 058	8.5	6 741	7 784	15.5
WFgreen	Min	92	88	-4.6	85	88	3.9	101	97	-3.8	96	86	-10.4	92	86	-6.3	96	84	-12.3
	Max	175	168	-4.1	112	116	3.9	269	259	-3.8	181	162	-10.3	159	150	-5.2	151	136	-10.0
	Med	115	110	-4.2	96	99	3.9	130	125	-3.8	113	102	-10.3	110	103	-6.2	108	96	-10.8

7.3.3 Discussion

The results show that *CY* is expected to increase in all of the selected mill supply areas under the future climate scenario (given the assumption of adequate water supply now and in the future). Yield increases range from 1 to 4% for irrigated areas and from 4 to 32% for rainfed supply areas. The increases for rainfed cane are strongly related to expected rainfall increases in those areas, as well as increased water use efficiency during periods of drought.

The future climate scenario is also associated with a higher *CWU* than that for the baseline. The median CWU_{green} increased by between 8 and 15%. The variation in the increase in CWU_{green} relates to the variation in the future rainfall increases that are expected for the different areas. The median CWU_{blue}, in the irrigated areas increased by between 2 and 15%. The wide range in CWU_{blue} values reflects the extent of irrigation required to make up rainfall shortfall. The differences in future increases in CWU_{blue} also reflect expected changes in rainfall.

The median values for WF_{green} are generally higher for rain-fed production than for irrigated production under the baseline climate. This is the result of a higher rainfall and lower yields in rain-fed production areas, as compared with irrigated areas. The WF_{green} is predicted to decline in the future for most rainfed areas because yields will increase more than crop water use will due to improved resource capture brought about by elevated temperatures and increased rainfall, as well as improved water use efficiency brought about by elevated atmospheric CO_2. The WF_{green} for irrigated areas is expected to increase because the yield increases are proportionally smaller than the *CWU* increases are. The latter is brought about mainly by increased evaporative demand caused by elevated temperatures.

The variations in WF_{blue}, ranging from 17 m^3/ton at Felixton to 58 m^3/ton at Komati, reflect the spatial variation in rainfall shortfall. Future changes in WF_{blue} varied from a small decrease of 1% at Amatikulu to an increase of 12% at Felixton. The increase is determined by projected changes in rainfall, and the proportion of CWU_{blue} to total *CWU*.

In general, the findings derived from this study show that the water footprint of sugarcane produced under rainfed conditions is expected to decrease for most areas, while both the WF_{green} and WF_{blue} of irrigated sugarcane are expected to increase for most areas. Increased CWU_{blue} and WF_{blue} under the future climate scenario suggest an increased demand for irrigation water in those areas in future, in spite of the assumed increase in rainfall. Singels and Jones (2018) reported that the expected reductions in irrigation water supply in the north-eastern parts of South Africa (Schulze and Taylor, 2016) pose a threat to the sustainability of irrigated sugarcane production in this area. The findings of this study strongly support the concern raised by Singels and Jones (2018).

It should be noted that these results are heavily dependent on the projected changes in future rainfall. Rainfed crop water use and yields rely on rainfall, while irrigation requirements also depend on it. It should further be noted that the projected rainfall changes are quite uncertain, as is evident in the large variations in these predictions between the different climate models used in this study (Singels *et al*., 2017).

It should be noted that the latest rainfall projections by the Intergovernmental Panel on Climate Change (IPCC, 2021) suggest a decline in annual rainfall for the study area, contradicting the projected rainfall increases used in this study. A decline in future rainfall will have a profound effect on rainfed CY and CWU_{green}, as well as on irrigated CWU_{green} and CWU_{blue}, and hence on the different WF indicators.

Another aspect to remember is that an adequate water supply was assumed for the irrigated production scenarios. Indications are that streamflow in the current irrigated sugarcane production areas could very well decline in future (Schulze and Taylor, 2016), which could reduce yields substantially (Singels and Jones, 2018). Water footprint estimates for the future climate must be considered in this context.

It should further be noted that the WF estimates for the baseline and future climates are probably optimistic (best-case), because ideal agronomic management and irrigation efficiency were assumed for the simulations. In practice, the actual WF could be much larger due to practical constraints and suboptimal crop and water management. WF estimates based on simulations should ideally be augmented by measurements of actual yields and water use.

7.4 CONCLUSIONS AND RECOMMENDATIONS

7.4.1 Conclusions

The aim of this study was to explore the potential impacts of climate change on the water footprint of sugarcane production in South Africa. The WF_{green} and WF_{blue} were estimated for irrigated sugarcane production at selected mill supply areas for a baseline (1971-1990) and a future (2046-2065) climate scenario. The WF_{green} was also estimated for rainfed sugarcane production for the two climate scenarios at selected mill supply areas.

The results showed increases in *CY* at all of the selected mill supply areas under the future climate scenario, which suggests that the sugar industry may benefit from climate change. However, the results also showed that the increase in *CY* is associated with an increase in *CWU* in all of the areas. Both CWU_{green} and CWU_{blue} increased for the irrigated areas, implying that more green water (effective rainfall), but also more blue water (surface and groundwater), will be used to sustain the increased *CY*. For the rainfed areas, the increase in CWU_{green} is caused by the expected increase in rainfall as well as improved rainfall use efficiency. The increase in *CWU*, especially CWU_{blue}, represents a serious risk for the industry.

The WF results were mixed. While WF_{green} increased for all of the irrigated areas, WF_{blue} remained unchanged for one area, and marginally decreased for another. The WF_{green} for the rainfed areas was found to decrease in all but one of the areas under consideration. The decrease in WF_{green} when CWU_{green} increased was achieved because the *CY* increased by proportionally more than the increase in the CWU_{green}.

It should be noted that the more-recent information emanating from climate change research suggests that annual rainfall in the study area may actually decline in future (IPCC, 2021) and that irrigation water availability may also decline in future (Schulze and Taylor, 2016), contradicting the assumptions made in this study. These results should therefore be treated with caution, taking into account the underlying assumptions used in the simulations.

Based on the results, it is concluded that:

- There is spatial variation in the impact of climate change on the water footprint of sugarcane production, and the variation relates largely to the variation in expected rainfall in the future climate scenario, as well as the baseline yield potential.

- The spatial variation in results suggests that recommendations and other actions to mitigate the potential negative impacts of climate change, or to exploit opportunities created through climate change, have to be context specific.

- Rainfall is currently, and will remain, a major source of water for sugarcane production, as is evident from the proportional contribution of the WF_{green} to WF_{tot}.

- Despite the contribution of rainfall to crop water use, irrigation will remain important for supplementing rainfall shortfalls in most of the currently irrigated areas.

- The relatively large WF_{blue}, compared with the WF_{green}, represents a serious risk to the sugar industry in the irrigated areas.

- There is serious pressure on water users, water managers and policymakers to ensure the future sustainability of the sugar industry.

7.4.2 Recommendations

For the purpose of discussion, the recommendations are divided into recommendations to the sugar industry (sugarcane producers and other role-players), recommendations to policymakers, and recommendations for future research.

7.4.2.1 Sugar Industry

The research reported in Chapter 3 shows that certain management practices, such as improved irrigation system efficiency and the use of soil mulching, can contribute towards decreasing the water footprint of sugarcane production. Given the expectations of the conditions that may prevail under the future climate, sugarcane growers should actively begin to implement such practices. Even costly investments, i.e. implementation of drip irrigation systems that were proven to decrease the water footprint, may seem more affordable now, given the findings of this research about the expected changes in *CY*, *CWU* and *WF*.

All of the role-players in the sugar industry have to contribute collectively towards the promotion of sustainable production practices. Other research has shown that consumers are willing to pay a premium for products that are proven to have been produced using water in a sustainable manner (Jordaan *et al*., 2019). The premium can be channelled to producers to reward them for their endeavours to use water sustainably. The sugar industry should explore the prospects of implementing such a model.

7.4.2.2 Policymakers

Government and other relevant role-players have to ensure that the water distribution infrastructure is sufficient, and sufficiently maintained and managed, to ensure a secure supply of water to sugarcane growers in the irrigated areas. The dependence of sugarcane production on increased access to blue water in the future demands infrastructure to supply the required water.

7.4.2.3 Researchers

Researchers should further explore the management practices that could contribute towards decreasing the water footprint of sugarcane. Research should be site specific in order to provide growers with reliable, context-specific recommendations.

Given the potential contribution of drip irrigation systems towards decreasing the water footprint, the financial viability of replacing existing irrigation infrastructure with the costly, but more efficient, drip irrigation system, has to be explored. Drip irrigation systems may be more suitable under the future climate scenario, where blue water availability may be lower.

The research in this study assumed that adequate water was available to cover rainfall shortfalls through irrigation in the irrigated areas. Researchers should also explore the implications of a scenario where sufficient water is not available in future and use more recent and more reliable rainfall projections for estimating WF values.

The variations in *CY*, *CWU* and *WF* over the simulated period at each of the selected areas imply that a certain level of risk is present. This is attributable to the annual variation in rainfall. Added to the risk is the annual variation in irrigation supply – historic data show that supply in the study area is often limited. An analysis of such risk will provide more insight into the risk faced by the sugar industry regarding the sustainability of sugarcane production under climate change.

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7.6 APPENDIX, CHAPTER 7

7.6.1 Amatikulu (Irrigated)

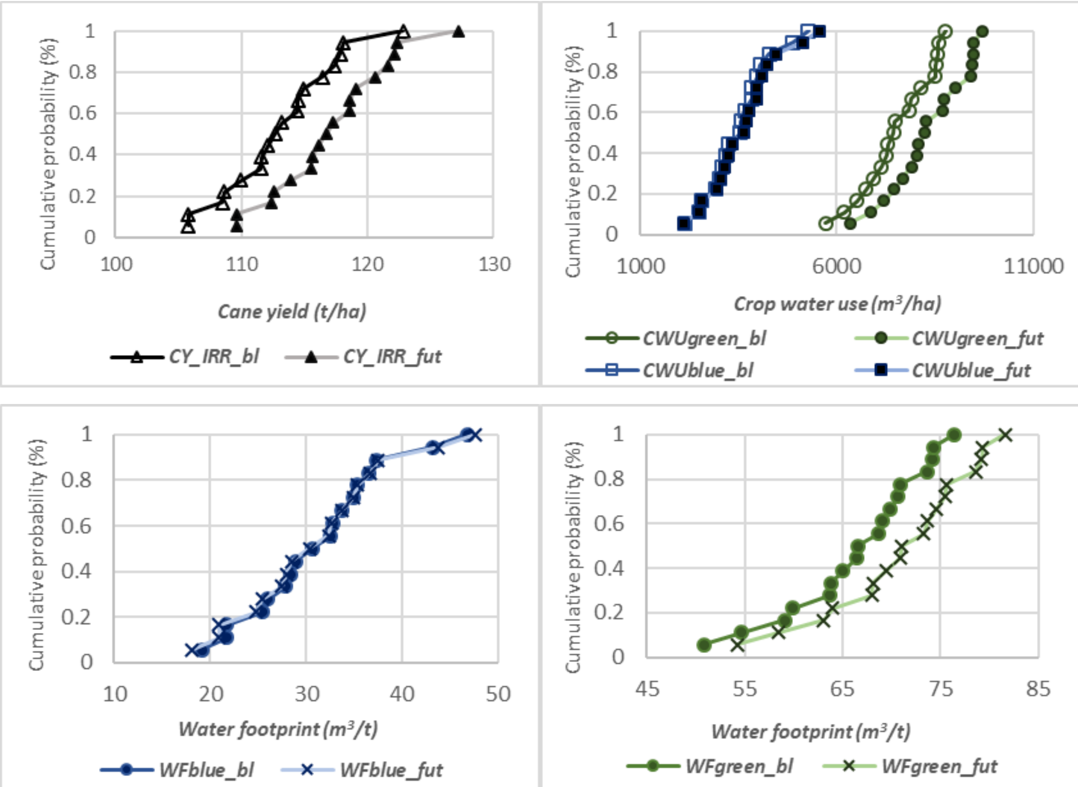

Figure 7.4: The cumulative distribution function of the cane yields (*CY*), crop water use green (CWU_{green}), green water footprint (WF_{green}), crop water use blue (CWU_{blue}) and blue water footprint (WF_{blue}) of sugarcane production for Amatikulu under the baseline (bl) and future (fut) climate

7.6.2 Felixton (Irrigated)

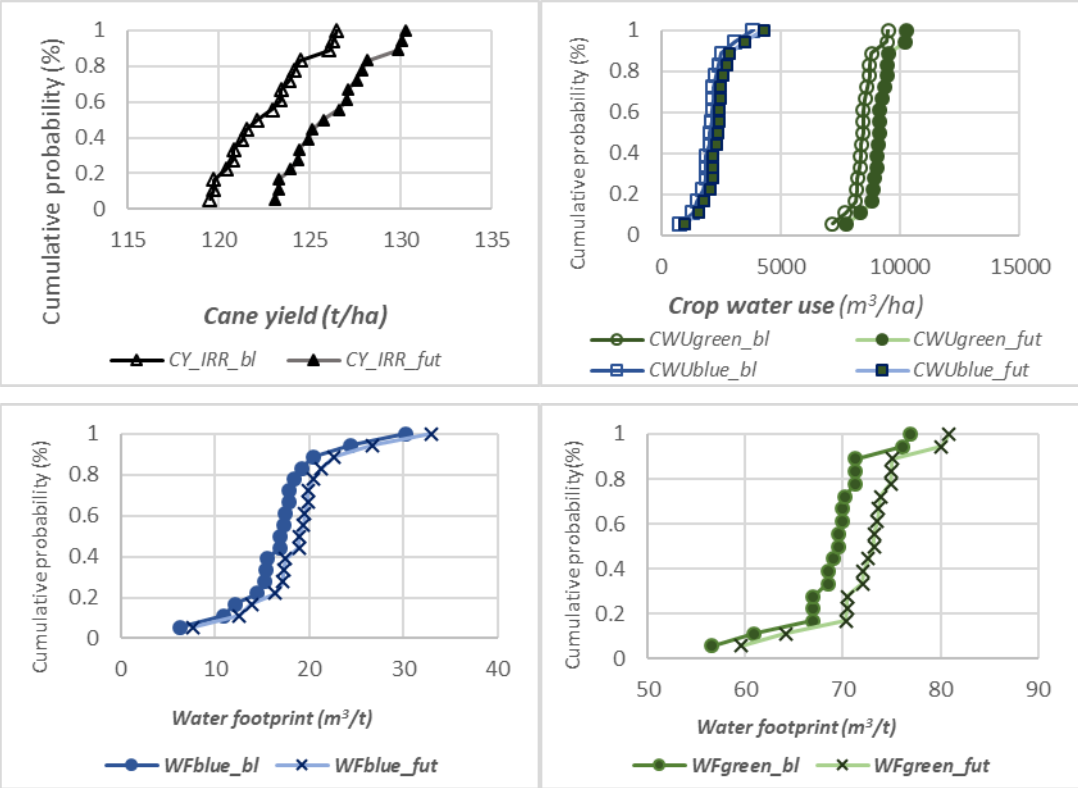

Figure 7.5: The cumulative distribution function of the cane yields (*CY*), crop water use green (CWU_{green}), green water footprint (WF_{green}), crop water use blue (CWU_{blue}) and blue water footprint (WF_{blue}) of sugarcane production for Felixton under the baseline (bl) and future (fut) climate.

7.6.3 Komati (Irrigated)

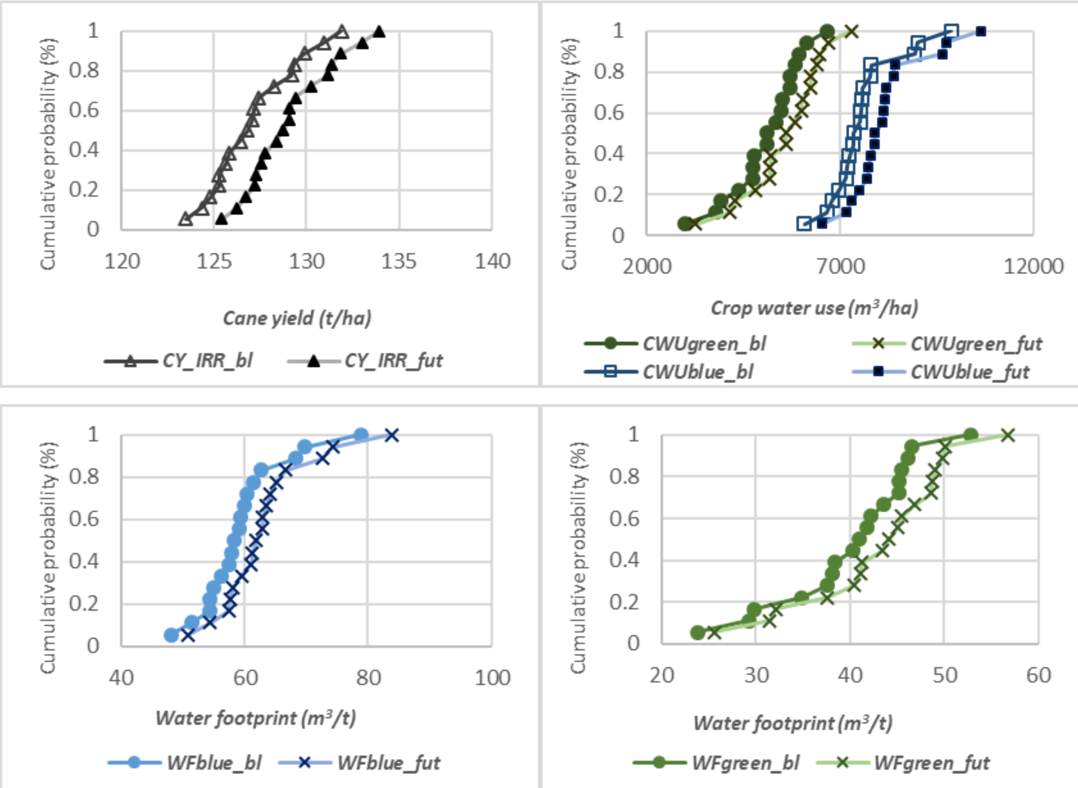

Figure 7.6: The cumulative distribution function of the cane yields (*CY*), crop water use green (*CWU_{green}*), green water footprint (*WF_{green}*), crop water use blue (*CWU_{blue}*) and blue water footprint (*WF_{blue}*) of sugarcane production for Komati under the baseline (bl) and future (fut) climate

7.6.4 Umfolozi (Irrigated)

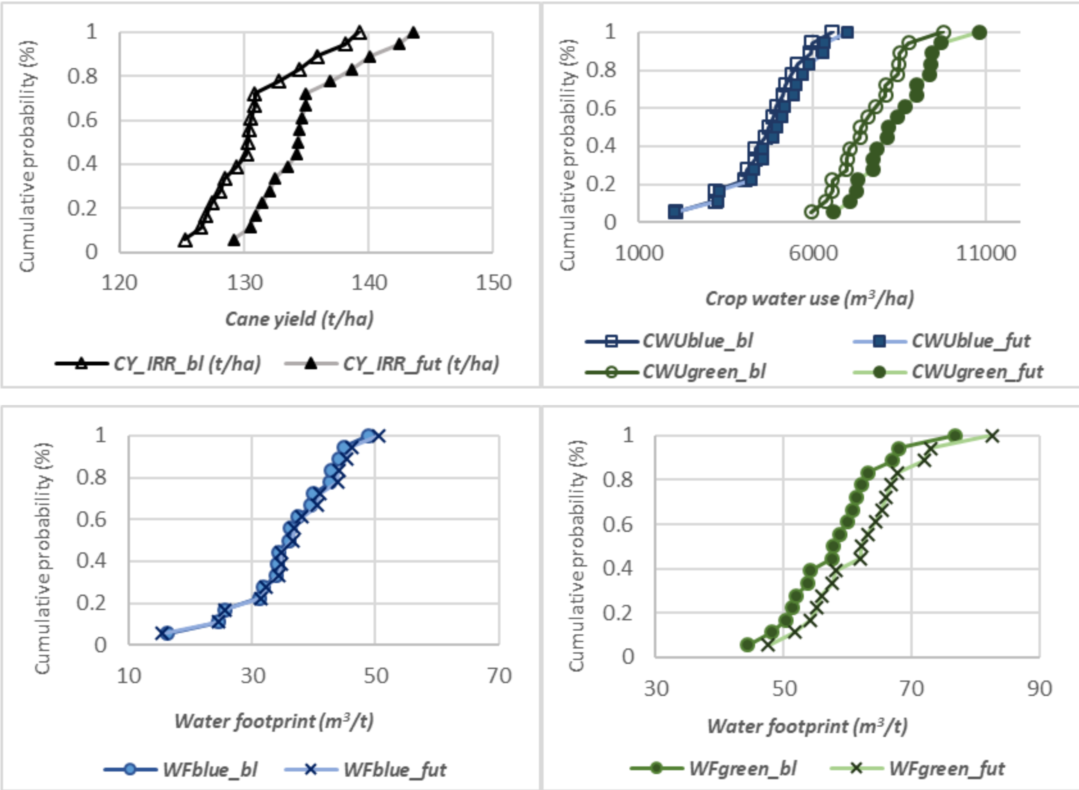

Figure 7.7: The cumulative distribution function of the cane yields (*CY*), crop water use green (*CWU_{green}*), green water footprint (*WF_{green}*), crop water use blue (*CWU_{blue}*) and blue water footprint (*WF_{blue}*) of sugarcane production for Umfolozi under the baseline (bl) and future (fut) climate

7.6.5 Pongola (Irrigated)

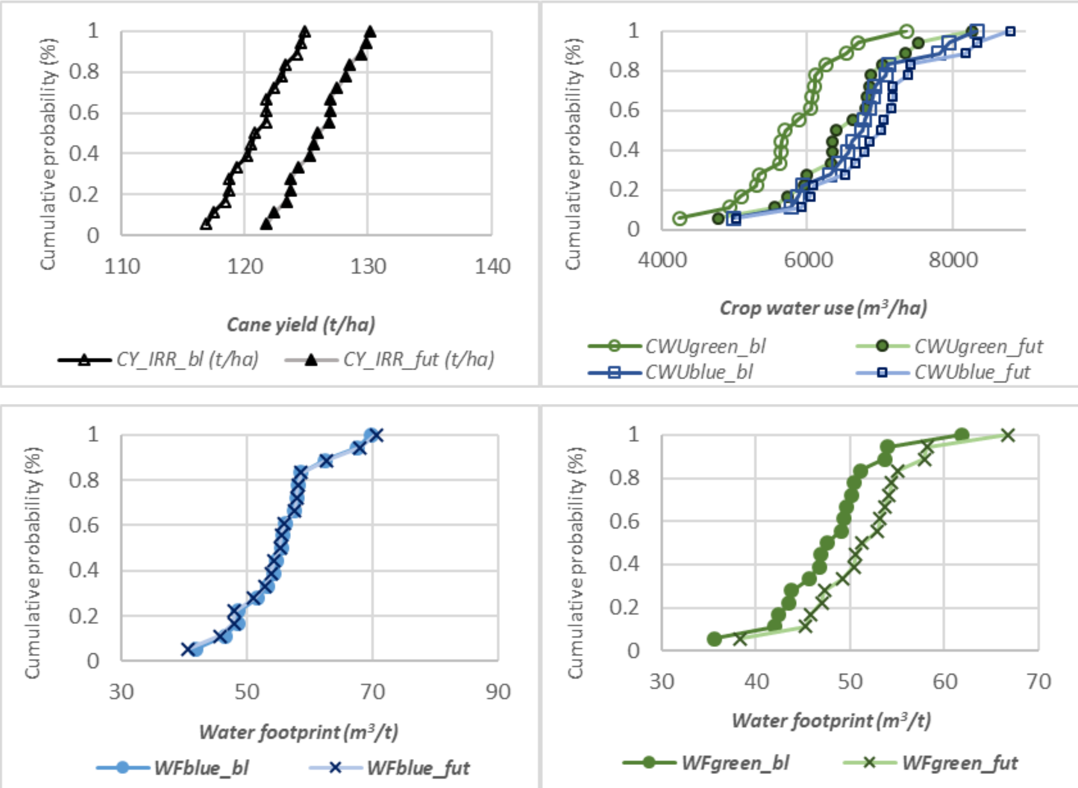

Figure 7.8: The cumulative distribution function of the cane yields (*CY*), crop water use green (*CWU*$_{green}$), green water footprint (*WF*$_{green}$), crop water use blue (*CWU*$_{blue}$) and blue water footprint (*WF*$_{blue}$) of sugarcane production for Pongola under the baseline (bl) and future (fut) climate

7.6.6 Amatikulu (Rainfed)

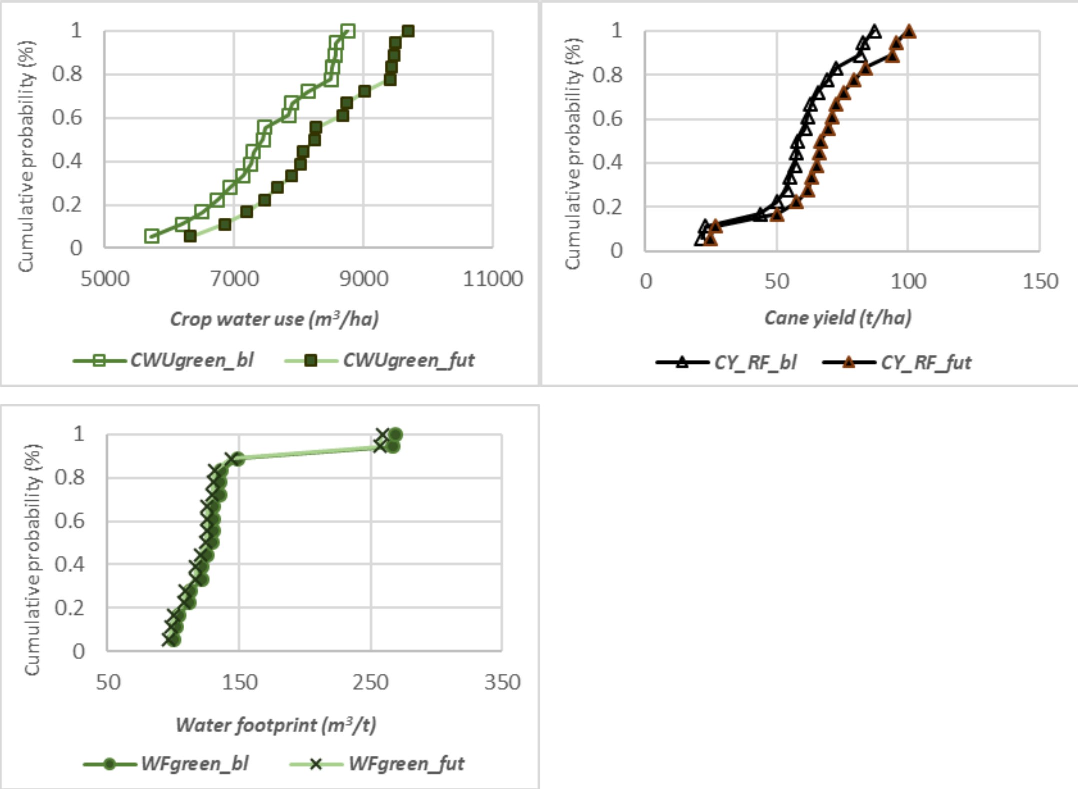

Figure 7.9: The cumulative distribution function of the cane yields (CY), green crop water use (CWU_{green}), and green water footprint (WF_{green}) of rain-fed sugarcane production for Amatikulu under the baseline (bl) and future (fut) climate

7.6.7 Felixton (Rainfed)

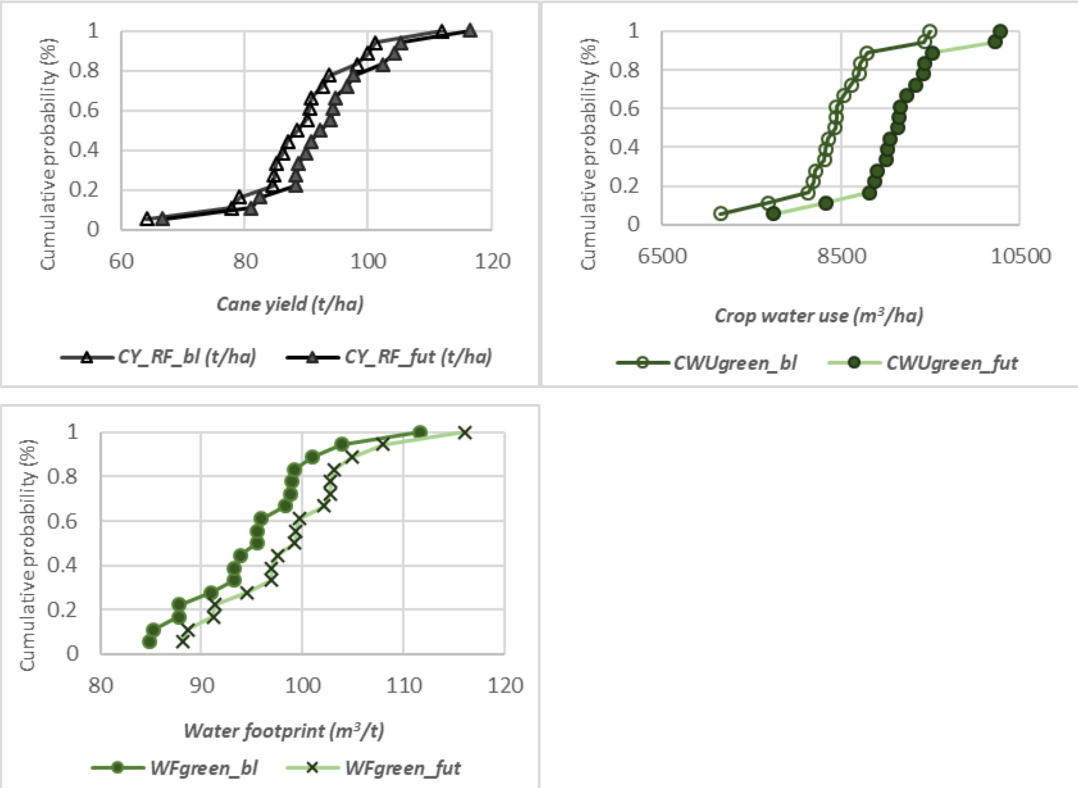

Figure 7.10: The cumulative distribution function of the cane yields (CY), green crop water use (CWU_{green}), and green water footprint (WF_{green}) of rain-fed sugarcane production for Felixton under the baseline (bl) and future (fut) climate

7.6.8 Maidstone (Rainfed)

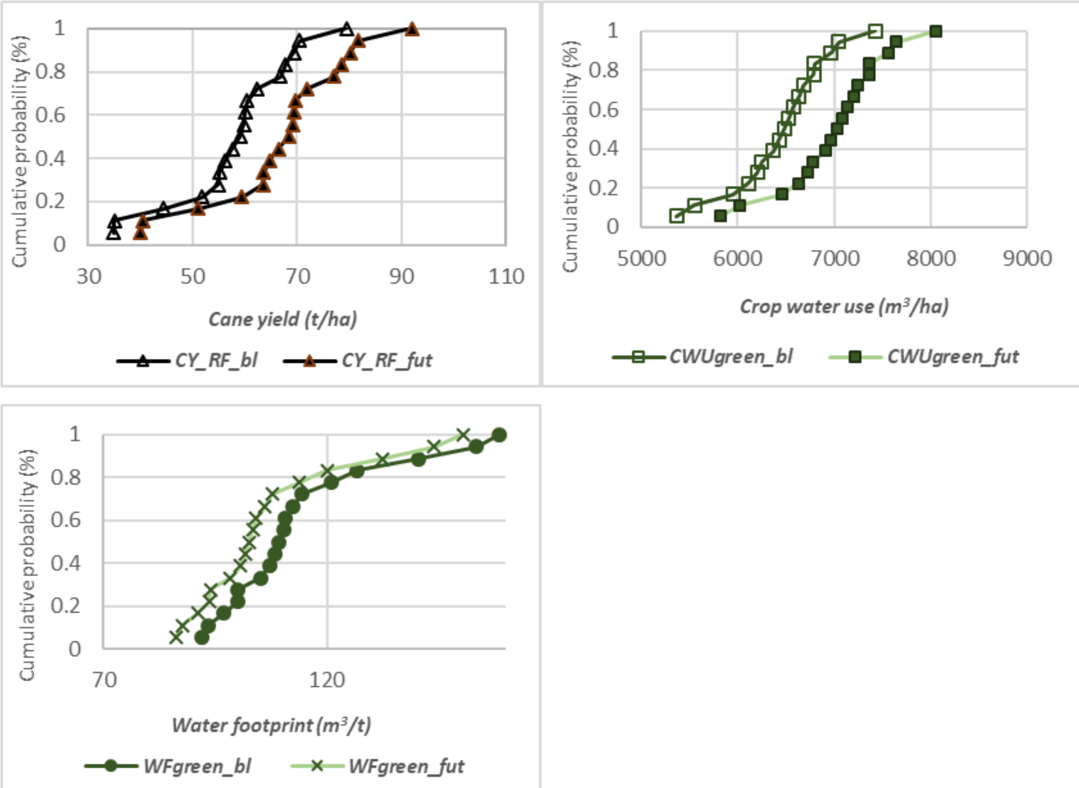

Figure 7.11: The cumulative distribution function of the cane yields (CY), green crop water use (CWU_{green}), and green water footprint (WF_{green}) of rain-fed sugarcane production for Maidstone under the baseline (bl) and future (fut) climate

7.6.9 Umfolozi (Rainfed)

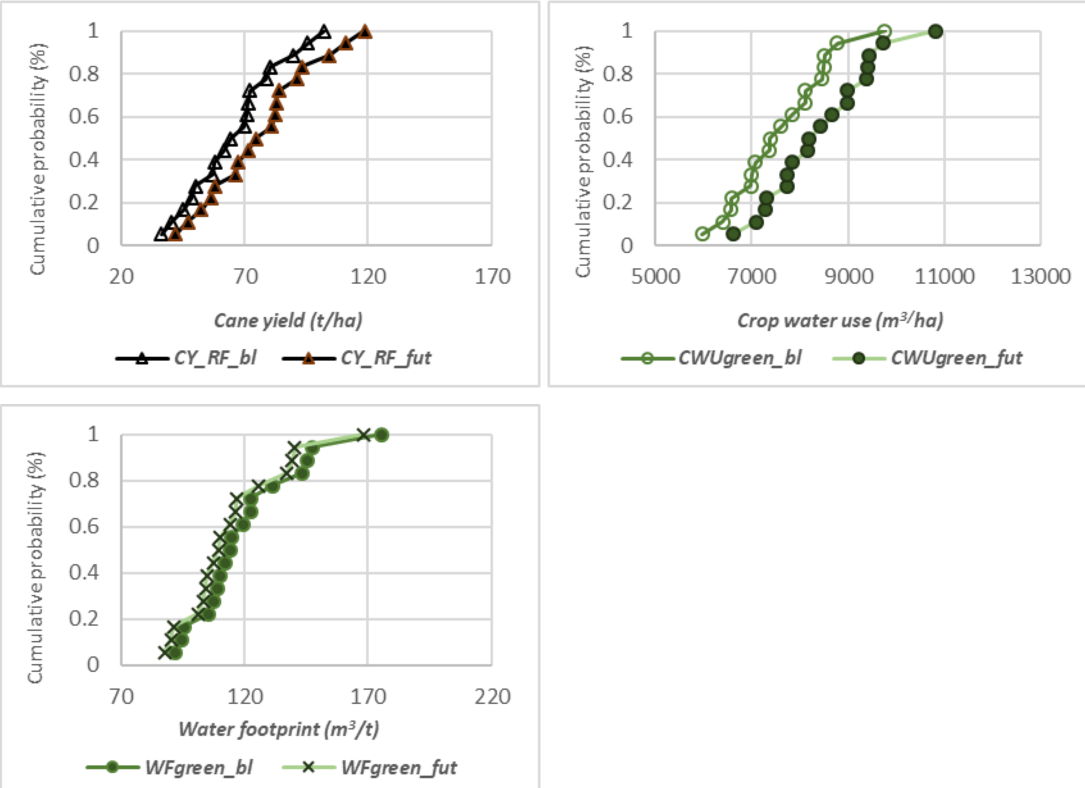

Figure 7.12: The cumulative distribution function of the cane yields (CY), green crop water use (CWU_{green}), and green water footprint (WF_{green}) of rain-fed sugarcane production for Umfolozi under the baseline (bl) and future (fut) climate

7.6.10 Noodsberg (Rainfed)

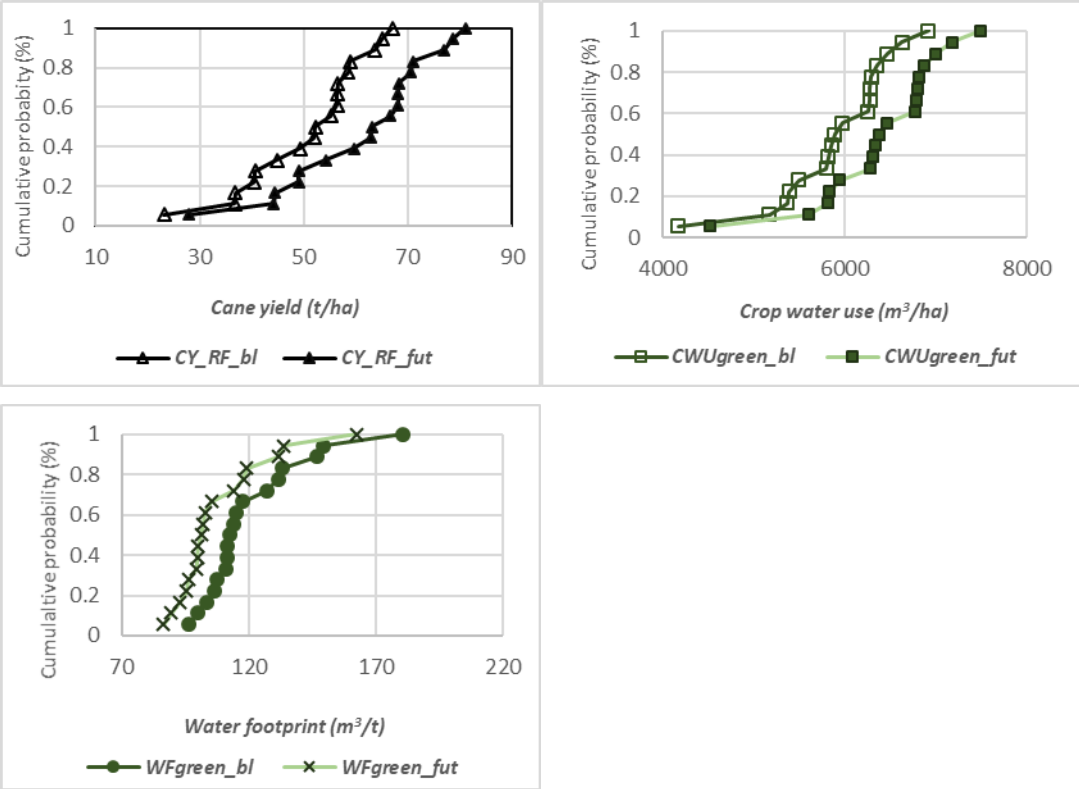

Figure 7.13: The cumulative distribution function of the cane yields (CY), green crop water use (CWU_{green}), and green water footprint (WF_{green}) of rain-fed sugarcane production for Noodsberg under the baseline (bl) and future (fut) climate

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

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8.1 CONCLUSIONS AND RECOMMENDATIONS FOR THE CASE STUDIES

8.1.1 Case Study of Sugarcane Production

The aim of this case study was to assess the water footprints of irrigated and rainfed sugarcane production in South Africa. WF_{green}, WF_{blue} and WF_{tot} were calculated for selected mill supply areas. Three regions were selected to represent fully irrigated production, combined irrigated and rainfed production, and fully rainfed production, respectively, in order to cover the main production region in South Africa.

In addition to the calculation of the different WF indicators, this report also reported the findings from an analysis of the impact of certain management practices on the water footprint of irrigated sugarcane production. WF_{green}, WF_{blue} and WF_{tot} were calculated for two different soil types, two mulching strategies, and two irrigation systems to determine the impact of the management practices on the respective WF indicators.

8.1.1.1 Conclusions

Based on the results of the water footprints of irrigated and rainfed production, the following conclusions were drawn:

- The WF_{tot} values calculated for irrigated sugarcane production (86-103 m^3/ton) were generally lower than values reported by other researchers (86-274 m^3/ton). This is ascribed to the fact that ideal management was assumed in simulations, leading to high cane yields and low water use arising from perfect irrigation management. The WFgreen values calculated for rainfed sugarcane production (96-130 m^3/ton) are also mostly lower than values reported in the literature (101-264 m^3/ton). This is ascribed to the ideal crop management assumed in simulations, leading to high yields and efficient use of water, while values from the literature are based on actual yields measured in experimental and commercial situations.

- The variations in WF_{tot} (86-103 m^3/ton), WF_{green} and WF_{blue} (17-59 m^3/ton) for irrigated sugarcane production varied markedly between the different mill supply areas, while the WF_{green} for rainfed production also varied between mill supply areas (96-130 m^3/ton). These results suggest that it may not be appropriate to have single benchmarks for irrigated and rainfed sugarcane production for all of South Africa. The spatial variation in CY, CWU and WF-indicators, caused mainly by variation in climatic conditions, suggest that WF benchmarks will have to be very much context specific.
- The dependence on blue water resources, as shown by the proportional contribution of the WF_{blue} to the WF_{tot} for irrigated production, implies a water-related business risk faced by the sugar industry.

Based on the results of the water footprint for irrigated production calculated for different management practices and soils, the following conclusions were drawn:

- Irrigation system type had a relatively large impact on WF indictors. Using an efficient system like SSD reduced irrigation demand and therefore the WF_{blue} and WF_{tot} for both mulch cover types and for both soil types, when compared with a less-efficient system like CP. The reduction was largest (10%) for the shallow soil covered with a light mulch cover.
- The WF_{blue} and WF_{tot} indicators were slightly lower (1-3%) for cane produced with thick mulch layer, compared with that grown with a light mulch cover. The difference was largest (around 3%) for CP irrigated cane grown on a shallow soil.
- The lowest WF_{tot} (50 m^3/ton) and WF_{blue} (87 m^3/ton) were achieved for cane produced under an SSD irrigation system and a thick mulch cover, regardless of soil type. These values increased to 60 and 95 m^3/ton, respectively, for cane produced under CP irrigation and a light mulch cover. Improving irrigation efficiency is therefore considered a feasible way of reducing the WF of irrigated sugarcane production significantly, while the use of thick mulch cover will also contribute, but to a lesser extent. These interventions seem to have bigger impacts on poorer soils.

8.1.1.2 Recommendations

The recommendations to the sugar industry are:

- Sugarcane producers should be aware of the WF benchmarks for their regions. While the WF indicators reported here might be lower than what could be achieved in reality, they can still can serve as benchmarks, towards which the producers should strive.

- Sugarcane producers should implement management practices that may contribute towards decreasing the water footprint of the sugarcane that they produce. The biggest return will be achieved from using efficient irrigation systems like drip systems, rather than less-efficient overhead irrigation systems.

The recommendation to policymakers is:

- Policymakers should incentivise sugarcane growers to apply management practices that will result in smaller water footprints and reduced crop water use.

The recommendation to researchers is:

- Research should be conducted to derive WF determinations from actual yield and irrigation water use data. This will require detailed and accurate monitoring to be made of water use and yield through using ground and remote sensing technologies.

8.1.2 Case Study of Cotton

The aim of this study was to assess the water footprint and economic water productivity of cotton produced under irrigation in South Africa.

Three sub-objectives were formulated to achieve the aim of the study:

- Sub-Objective 1: Calculating the water footprint of cotton produced under irrigation.
- Sub-Objective 2: Evaluating the economic productivity of the water footprint of cotton
- Sub-Objective 3: Evaluating the blue water scarcity in the Olifants River Basin.

8.1.2.1 Conclusions

Based on the results, it is concluded that the $\mathrm{WF_{blue+green}}$ of irrigated cotton produced in the early planting season in September was 1173$\mathrm{m^3}$/ton. Of the $\mathrm{WF_{blue+green}}$, the $\mathrm{WF_{green}}$ of cotton was 685$\mathrm{m^3}$/ton and the $\mathrm{WF_{blue}}$ was found to be 488$\mathrm{m^3/ton}$. For the early cotton crop planted in September, the $\mathrm{WF_{blue}}$ was about 40% and $\mathrm{WF_{green}}$ about 60% of the $\mathrm{WF_{blue+green}}$. Effective rainfall is thus an important source of water for irrigated cotton production. Supplementary irrigation, however, is still needed to cover shortfall in the rainfall. The dependence on irrigation water suggests that the cotton industry does face water-related risk.

For the late planting season in October, it was concluded that the $\mathrm{WF_{blue+green}}$ of irrigated cotton was 1054$\mathrm{m^3}$/ton. The $\mathrm{WF_{blue}}$ of the cotton was found to be 392$\mathrm{m^3}$/ton, while the $\mathrm{WF_{green}}$ was 662$\mathrm{m^3}$/ton. Of the $\mathrm{WF_{blue+green}}$ of 1054$\mathrm{m^3}$/ton, 63% of the water required was contributed by rainfall, which shows that even in late planting time, the water that cotton requires is mostly met by water from the rainfall.

The economic value obtained per unit of water utilised in the Loskop Irrigation Scheme during early cotton production in September was 7.23 ZAR/$\mathrm{m^3}$(0.55 USD/$\mathrm{m^3}$). The income earned per cubic metre of water used for cotton production in the late planting time in October was 8.69 ZAR/$\mathrm{m^3}$(0.66 USD/$\mathrm{m^3}$). Cotton planted in September had a water productivity of 0.85 $\mathrm{m^3}$/kg and that planted in October had a water productivity of 0.95 $\mathrm{m^3/kg}$. The early harvesters of cotton received ZAR 8500/ton, and late harvesters ZAR 9150/ton, at the farm gate during the harvesting period running from May to end of July.

The blue water scarcity index in the Olifants River Basin was found to be larger than 100% from June to November, implying that the EFR is not being met for that period. The period when cotton requires more water to grow (December to March), however, corresponds with the period when the water scarcity index is less than 100%. The conclusion is thus that cotton production in the Loskop Irrigation Scheme area may be regarded sustainable from a water use perspective.

8.1.2.2 Recommendations

The recommendations to the cotton industry are:

- Although the period when crop water requirement is high corresponds with the period when the blue water scarcity index is less than 100%, cotton producers still have to ensure that they do use water efficiently.

- It is important to have sufficient knowledge about the climate, as this is vital when identifying which areas may be suitable for efficient and profitable cotton production, and the appropriate knowledge will help to ensure that the most advantageous growing season of cotton is selected. Cotton growers must be aware of the amount of water required by the crop, and they need to know the rainfall contribution and how much water they have to use for irrigation.

The recommendations for researchers are:

- This research needs to be repeated in other cotton-production areas to gain insight into the water footprints of cotton production in the different regions. The context specificity of water footprints implies that the water footprints calculated in this research are not necessarily representative for all of South Africa.

- The grey water footprint must be taken into consideration when assessing the water footprint of cotton in order to better inform farmers and policymakers of the water consumed during the production at the farm level.

- The water footprint of cotton should be investigated along the entire value chain of products produced from cotton seed, up to point when the final product is obtained by the end user. This will give a good indication as to where water is used the most in the process of offering the product to the end user of the cotton final product.

8.1.3 Case Study of Sunflower and Biodiesel

The aim of the third case study was to evaluate the water footprint of producing biodiesel from sunflower in South Africa and its economic viability. The complete value chain of producing biodiesel from sunflower was assessed for the volumes of water allocated and utilised throughout each process step of production, together with the costs and benefits that pertain to the entire production process. Ultimately, the total water footprint and financial viability of producing biodiesel were deduced. The aim of this study was achieved through pursuing the following objectives:

i) To quantify the water footprint of producing biodiesel from sunflower;

ii) To evaluate the blue water scarcity in relation to the production of sunflower as a biofuel crop;

iii) To evaluate the economic feasibility of commercialising biodiesel produced from sunflower.

8.1.3.1 Conclusions

Conclusions on the water footprint of biodiesel produced from sunflower:

- It was found in this study that sunflower grown under irrigation had a 10% higher yield than that of rain-fed sunflower. The WFA results indicated that the rain-fed sunflower had the largest water footprint of the two. Furthermore, the water footprints at the farm level were dominated by the green water footprint.

- At the processing level, no green water was used, and the water footprint of biodiesel produced from rain-fed sunflower had a higher water footprint than that produced from irrigated sunflower. This variation in the water footprint can be attributed to the larger yield obtained from irrigated sunflower, which enabled less water to be used per GJ of biodiesel produced. It is noted, though, that biofuel feedstock might not always be irrigated. The water footprint of the entire sunflower-to-biodiesel production process was found to be dominated by the water footprint of sunflower production, and this accounted for about 99% of the total water footprint.

- The period in which the sunflower was grown and harvested in this study falls within the periods in which there is adequate water supply in the Orange River Basin, and thus the sunflower production was found to be environmentally sustainable.

The findings of the WFA in this current study were found to correlate with the findings of other relevant studies in literature in that:

i) Production at the farm level consumes the largest volume of water, while the conversion level uses the least amounts of water in the entire sunflower-to-biodiesel value chain.

ii) The mid-stage of sunflower growth requires the largest amounts of water in the entire sunflower growth period, due to the increased leaf area.

iii) Sunflower is a drought-tolerant crop because, even in times of dire water needs and deficit soil moisture, the crop grew well and the rainwater supply was highly efficient for the sunflower crop growth.

iv) Water footprints vary by region, regardless of the similarity in the type of biofuel produced and its feedstock. It was necessary to conduct this WFA to gain a better picture of the water use of producing biodiesel, using sunflower in South Africa.

Conclusions on the economic viability of producing biodiesel from sunflower:

- Aligned with the national penetration plan, it was found in this study that the biodiesel market is highly dependent upon the fossil diesel market. It was recognised that a reciprocal relationship exists between the biodiesel market and the fossil diesel market. Furthermore, the results obtained indicated that a biodiesel market in South Africa is available. Nevertheless, the existence of the market does not necessarily create viability for commercial production, because a need also exists to understand the agricultural capability for supplying the required biodiesel feedstock.

- The selected feedstock is a highly significant input for the biodiesel production process. It was estimated in this study that a 2 500 kg/hr production plant requires approximately 57 149 tons of sunflower seeds per year, resulting in about 19 800 tons of biodiesel per annum. However, meeting a 2% blend, based on figures for the 2018 fossil diesel demand, would require about 1.1 million ton of sunflower seeds. It was also observed that there is adequate, underutilised land available in South Africa that could be used for the production of sunflower feedstock to meet the biodiesel blending requirements, in such a way that would mitigate land competition issues.

- In addition, the production costs of a biodiesel production plant were found to be highly dependent upon the price of the feedstock. Therefore, the fluctuating nature of the prices of sunflower seeds was observed to potentially create a great variation in the production costs. The 2018 January sunflower seed price of about R6 569 was utilised to determine the costs associated with the production plant. It was then found that the manufacturing costs of a sunflower biodiesel plant producing 2500 kg/hr were approximately R342 million, equating to a cost price of about R15.24 per litre of biodiesel. Furthermore, the capital investment costs were found to be R175 million, and these were largely comprised of the total fixed costs. For the financial returns associated with the plant, the break-even price of the plant was found to be about R10.80/L of biodiesel, taking into consideration potential revenue generated from the sales of the sunflower oil cake derived during production. This indicates that the by-products could be economically significant for the profitability of biodiesel production.

It is therefore concluded in this study that:

- There is a potential market for biodiesel production and utilisation in South Africa.
- Sunflower feedstock costs are significantly linked to the adequate supply of sunflower for biodiesel production, and water was found to have a significant role in the amount that could be produced and supplied.
- The agricultural sector has a potential to produce adequate sunflower feedstock for a 2500 kg/hr biodiesel production plant
- The sale of by-products derived from biodiesel production could be significant in making biodiesel production profitable.
- Biodiesel production from sunflower is sustainable in terms of both monetary and water resources, as it uses water sustainably while bringing about economic returns.
- The economic viability of commercial biodiesel production in South Africa was found to be dependent upon government legislation, especially considering that the break-even price of biodiesel exceeds the fossil diesel price; therefore, the market could be sustainably created when appropriate facilitating laws and regulations are put in place.

8.1.3.2 Recommendations

Recommendations to the sunflower industry and policymakers:

Several implications were drawn from the findings of this study for the role-players and stakeholders in biofuels industry, as well as for water users and investors, particularly in regard to biodiesel production:

i) Biofuels have the potential to pose sustainability risks, more significantly concerning land and water resources. It is therefore important to align biofuels policies with those of the agricultural sector to minimise such risks. Decisions made today should not be only overly influenced by short-term economic gains. However, the production of biofuels, such as biodiesel, should take into account optimising land use and optimising water use with minimal impacts, while being environmentally and economically advantageous. Therefore, it is necessary to adopt agricultural practices that could enhance the sustainability of the entire biodiesel production system. It was found in this study that the reliance upon green water could potentially limit the impacts on blue water use, although it also could limit the soil water balance over time, and it is therefore recommended that focus be placed on agricultural practices, such as crop rotation, as this could enhance agricultural productivity and sustain biofuel production.

ii) There is a dearth of quality data on water use for various processes in South Africa, and this plays a significant role as a hindering factor when assessing the impacts of water use. More significantly, actual water use data are scarce for most agricultural and industrial activities. This is because only a few farmers collect and report their water usage details. Furthermore, the data that do exist and are readily available are not necessarily reported consistently. Therefore, following the findings of this study, it is recommended that a consistent and uniform format should be developed in which to collect, record, and make data available, as this would be significant for improved assessments of water use and the respective impacts.

iii) South Africa's current water landscape is moving towards a state of crisis, and this necessitates the formation of a well-equipped task force that can deal with assessing the use of water resources and the related impacts. Global attention has been given towards evaluating the water footprints of different activities, and this has enabled a better understanding of water use to be gained, worldwide. However, there is still limited attention being given to the assessments of water footprints, more significantly for biodiesel production. Thus, there is a need to emphasise the involvement of the available national water experts to share their knowledge, skills, and experience on sustainable approaches that could be taken towards achieving sustainable water use. It is also important to nurture individuals with the capacity to adapt to future water uncertainties, to limit the effects faced when there are further drought years, and to improve intellectual capacity required to help to avert facing an actual "day zero" for water.

iv) There is a need for focused attention to be given in the following areas:

- First-generation biodiesel producers should be encouraged to seek increased water-efficient approaches, including better use and limited irrigation of biodiesel feedstock that could still enable for profitability, as well as smarter techniques that could enable sustainable expansion, rather than using more amounts of scarce water resources.

- For the success of the biofuel industry at large in South Africa, it is vital to address any outstanding issues, conflicts, and misunderstandings that may exist between the key role-players and stakeholders, before the rollout of biodiesel production at a national, commercial scale.

- The implications of voluntary blending against mandatory blending should be intensely assessed, more significantly concerning issues of quality control and potential market creation for biodiesel.

- Resources should be committed towards implementing research and development, capacity building, and technical support for the sustainable development and operation of the biofuels industry in South Africa.

Recommendations to researchers:

- One of the limitations of this study was that limited primary data is available for the processing level of biodiesel production in South Africa. At the time of the study, there was no actual or prototype production plant available from which to collect primary data to help reinforce the analysis in this study.

- Furthermore, the economic feasibility assessment did not take into consideration the potential governmental incentives of producing biodiesel, such as levies, due to the limited nature of the existing policies and guidelines for biodiesel production.

- The following recommendations arise from this study for further research:

  i) The research could be extended to include the grey water footprint.

  ii) Investigate whether the underutilised land endorsed in the former homelands is suitable for sunflower production, or greater potential for maize production. To identify whether it might be necessary (or more ideal) to use this identified land for maize production, while using other arable land for sunflower production.

  iii) Explore the value added to water along the value chain for the by-products of the sunflower-biodiesel value chain.

  iv) Ideally, all information about determining the amounts of water consumed at the processing level should be obtained from actual measurements at a South African scale. This will eliminate the reliance upon literature and could ultimately provide more accurate water use results. Furthermore, this data could enable the proper comparison of the water footprints and potentially add to the sustainability of water use in the biofuel industry at large.

  v) An actual, revised economic feasibility study that considers the current economic situation of South Africa, more significantly by the biofuels industry. This would enable the formulation of proper revised policies and new views that concern the viability of the industry, as well as a review to confirm the existence of the initial benefits that the industry was envisioned to potentially bring for the economy.

vi) Investigate and propose further policies and guidelines for the production of biofuels, including the potential incentives of producing biodiesel. Examine the effects of these policies on the overall sustainability of biofuel production, more specifically in line with the challenges of food security.

vii) Evaluate ways in which to ensure the adequate supply of sunflower to be used as feedstock, as well as the influence of variation in rainfall on sunflower supply in various years.

8.1.4 Case Study of Tobacco Production

The aim of this case study was to assess the water footprint of irrigated tobacco production in order to gain insight into the volume of freshwater that is used to produce tobacco, and to understand the economic returns derived from using the scarce water resource for the production of tobacco.

The aim was achieved through pursuing the following sub-objectives:

Sub-objective 1: Assessing the water footprint of irrigated tobacco production to gain insight into the volume of water, and the sources of water, used for tobacco production.

Sub-objective 2: Assessing the blue water scarcity levels in relation to the growing season in the selected tobacco production region.

Sub-objective 3: Calculating the economic water productivity of the tobacco production to understand the income that is generated per cubic metre of water used to produce tobacco.

8.1.4.1 Conclusions

The results showed that the WF_{green} of tobacco is higher than the WF_{blue} of tobacco production. Given a tobacco yield of 3 ton/ha, the WF_{green} amounted to 912 m^3/ton, and the WF_{blue} amounted to 637 m^3/ton for the production of tobacco at Loskop. Therefore, the results show that, in order to produce one ton of tobacco at Loskop, 912 m^3 of rainfall and 637 m^3 irrigation water are required. It is concluded that the effective rainfall does contribute substantially towards meeting the water requirement of tobacco production in the Loskop Irrigation Scheme, although tobacco production does rely on the scarce fresh water resource.

Tobacco production in the study area shows a lower water footprint when compared with the global averages reported by Mekonnen and Hoekstra (2011). Mekonnen and Hoekstra (2011) reported a global average water footprint of 2 000 m^3/ton, as compared with a water footprint of 1 550 m^3/ton found in this study. Based on the global comparison, tobacco production in South Africa may be considered an efficient user of the limited freshwater resource. Regardless of this production being smaller than global averages, it is crucial to assess the water footprint indicator in the context of water availability in various production areas. Only then can strategies be formulated regarding the sustainable use of freshwater for tobacco production in South Africa. However, local, context-specific information is required to inform all role-players involved in the production of tobacco products considering the sustainable use of freshwater.

While blue water scarcity is considered to be a problem in the Olifants River Basin, the period when tobacco requires larger volumes of water corresponds with the period when sufficient water is available to meet the demands. It is thus concluded that tobacco production at Loskop Irrigation Scheme may be considered to be sustainable from a water use perspective.

8.1.4.2 Recommendations

Recommendations to the tobacco industry:

- Although the period when tobacco requires more water corresponds with the period when water scarcity is low, producers should still implement management practices, such as utilising crop residues and mulch cover to decrease soil water evaporation and enhance nutrient recycling, in order to decrease the water footprint.
- Enhanced irrigation methods, such as drip and subsurface irrigation, may also contribute to improved water use efficiency.

Recommendations for researchers:

- Researchers should conduct similar research in other areas where tobacco is produced in order to gain further insight into the water footprint of tobacco production in South Africa. Such research is necessary, since a water footprint is very much context specific; hence, the water footprint of tobacco produced at Loskop Irrigation Scheme is not representative for all of South Africa.

- In the current study, the researchers were unable to acquire water use information from tobacco-processing companies. Future research should approach processing companies again to seek the necessary data to allow for an assessment to be made of the water footprint of tobacco and derived tobacco products.
- A water footprint is composed of three components, being the blue, green and grey water footprints. The grey water footprint should also be assessed in the Loskop Irrigation Scheme in order to obtain total water footprint of tobacco production.

8.1.5 Impact of Climate Change on the Water Footprint of Sugarcane Production

The aim of this case study was to assess the impact of climate change on the water footprint of sugarcane production in South Africa. The aim was achieved through pursuing the following sub-objectives:

Sub-objective 1: To determine the green water footprint and blue water footprint of **irrigated** sugarcane production in selected areas under baseline and future climate scenarios.

Sub-objective 2: To determine the green water footprint of **rainfed** sugarcane production in selected rainfed areas under baseline and future climate scenarios.

8.1.5.1 Conclusions

The WF_{green} and WF_{blue} were estimated for irrigated sugarcane production at selected mill supply areas for a baseline (1971-1990) and future (2046-2065) climate scenario. WF_{green} was also estimated for rainfed sugarcane production for the two climate scenarios at selected mill supply areas.

The results showed increases in *CY* at all of the selected mill supply areas under the future climate scenario, which suggests that the sugar industry may benefit from climate change. However, the results also showed that the increase in *CY* is associated with an increase in *CWU* in all of the areas. Both CWU_{green} and CWU_{blue} increased for the irrigated production areas, implying that more green water (effective rainfall), but also more blue water (surface and groundwater), will be used to sustain the increased *CY*. For the rainfed production areas, the increase in CWU_{green} is caused by the expected increase in rainfall as well as improved rainfall use efficiency. The increase in *CWU*, especially CWU_{blue}, represents a serious risk for the industry.

The WF results were mixed. While WF_{green} increased for all of the irrigated areas, WF_{blue} remained unchanged for one area, and marginally decreased for another. The WF_{green} for the rainfed areas was found to decrease in all but one of the areas under consideration. The decrease in WF_{green} when CWU_{green} increased was achieved because the *CY* increased by proportionally more than by what the CWU_{green} increased.

It should be noted that more-recent information emanating from climate change research suggests that annual rainfall in the study area may actually decline in future (IPCC, 2021) and that irrigation water availability may also decline in future (Schulze and Taylor, 2016), which would contradict the assumptions made in this study. These results should therefore be treated with caution, taking into account the underlying assumptions used in the simulations.

Based on the results, it is concluded that:

- There is spatial variation in the impact of climate change on the water footprint of sugarcane production, and the variation relates largely to the variation in expected rainfall in the future climate scenario, as well as the baseline yield potential.

- The spatial variation in the results suggests that recommendations and other actions to mitigate the potential negative impacts of climate change, or to exploit opportunities created through climate change, have to be context specific.

- Rainfall is currently, and will remain, a major source of water for sugarcane production, as is evident from the proportional contribution of the WF_{green} to WF_{tot}.

- Despite the contribution of rainfall to crop water use, irrigation will remain important to make up rainfall shortfalls in most of the currently irrigated areas.

- The relatively large WF_{blue}, compared with the WF_{green}, represents a serious risk to the sugar industry in the irrigated areas.

- There is serious pressure on water users, water managers and policymakers to ensure the future sustainability of the sugar industry.

8.1.5.2 Recommendations

Recommendations to the sugar industry:

- The research reported in Chapter 3 shows that certain management practices, such as improved irrigation system efficiency and the use of soil mulching, can contribute towards decreasing the water foot print of sugarcane production. Given the expectations of the conditions that may prevail under the future climate, sugarcane growers should actively begin to implement such practices. Even costly investments, i.e. implementation of drip irrigation systems, that have been proven to decrease the water footprint, may seem more affordable now, given the findings of this research about the expected changes in *CY*, *CWU* and *WF*.

- All of the role-players in the sugar industry should contribute collectively towards the promotion of sustainable production practices. Other research has shown that consumers are willing to pay a premium for products that have been proven to have been produced through using water in a sustainable manner (Jordaan *et al*., 2019). The premium received could be channelled to producers to reward them for their endeavours to use water sustainably. The sugar industry should explore the prospects of implementing such a model.

Recommendations to policymakers:

- Government and other relevant role-players have to ensure that the water distribution infrastructure is sufficient, and sufficiently maintained and managed, to ensure the secure supply of water to sugarcane growers in the irrigated areas. The dependence of sugarcane production on increased access to blue water in the future requires the provision of appropriate infrastructure to supply the required water.

Recommendations to researchers:

- Researchers should further explore management practices that could contribute towards reducing the water footprint of sugarcane. Research should be site specific in order to provide growers with reliable, context-specific recommendations.

- Given the potential contribution of drip irrigation systems for decreasing the water footprint, the financial viability of replacing existing irrigation infrastructure with the costly, but more efficient drip irrigation system, has to be explored. Drip irrigation systems may be more suitable under the future climate scenario, where blue water availability may be lower.

- The research in this study assumed that adequate water was available to cover rainfall shortfalls through irrigation in the irrigated areas. Researchers should also explore the implications should sufficient water not be available in the future.

- This research should also be repeated through using more recent and more reliable rainfall projections.

- The variations in *CY*, *CWU* and *WF* over the simulated period at each of the selected areas imply that a certain level of risk is present. This is attributed to annual variations in rainfall. Added to the risk is the annual variation in irrigation supply – historic data show that supply in the study area is often limited. An analysis of such risk would provide further insight into the risk faced by the sugar industry regarding the sustainability of sugarcane production under conditions of climate change.

8.2 IMPACTS

This research is expected to have several impacts for the benefit of society, the economy, health and the environment.

Society: Irrigated agriculture is an important contributor to the livelihoods of a large number of people in South Africa. This research will contribute towards ensuring that recommendations for change in water use behaviour (i.e. through the implementation of policies) will be based on sound projections of the potential social consequences, and to preventing the implementation of recommendations that may be at the expense of the society under consideration.

Economy: The economic contribution of the proposed project will be in terms of the maximisation of the economic returns derived from having access to fresh water. Importantly, the economic benefit extends the financial benefit to water users from sales of irrigated products. It also includes the positive spin-offs, such as increased employment along the value chain and increased purchase power within the communities. It will inform investors of the water-related risks and help them to formulate appropriate response strategies, sustaining economic activities in the region.

Health: Since a substantial proportion of the South African population lives below the poverty line, food security is a major cause for concern. It has to be noted that food security is more than merely the physical access to food – it is also concerned with economic access to food. The economic contribution of this research will, by implication, also contribute to improving the economic access to food for members of communities all along the value chains. Thus, by contributing towards food security, this research is also expected to have significant health benefits for the people in the surrounding communities.

Environment: The proposed research project is expected to have a significant impact on the environment by contributing towards the sustainable use of our scarce fresh water resource for the production of fuel and fibre crops in South Africa. Importantly, the research extends the current situation to consider the environmental impact in the future, within the context of projected climate change scenarios.

8.3 INNOVATION

This research is innovative in a few aspects. First, this study was the first to assess the water footprints of selected fuel and fibre crops in South Africa. As such, this research is the first step towards providing scientific, evidence-based benchmarks for the water footprint of selected fuel and fibre crops in South Africa.

A second innovation of this project was to combine the assessment of the water footprint of biofuel with the assessment of the economic and financial feasibility of producing biofuel from sunflower seed in South Africa. The use of the scarce freshwater resource must be such that it is sustainable from an environmental perspective, and also from the economic and social perspectives. The combination of the water footprint assessment with the economic feasibility study in this project is an innovative approach for addressing two of the three pillars of sustainable water use.

Thirdly, extending the water footprint assessment from the current climatic context to assess the water footprint within the context of projected future climate, as caused by climate change, is also an innovation of this research project. By extending the focus to consider the future climate, knowledge and information can be generated to timeously provide policymakers, water managers and water users with science-based knowledge in order to inform water use behaviour towards securing the sustainable use of the scarce freshwater resource in future.

In addition to innovation in terms of the research that was conducted, it is noted that some innovative findings were also achieved from this research. Certain management practices were found to be associated with a lower water footprint of sugarcane production. As such, water users can decrease the water footprint of the crops they grow through the application of such management practices. The assessment of the water footprint of sugarcane in the context of a future climate showed that the impact may vary from one region to the next. Contrary to expectations, the water footprints of the crops are not expected to increase everywhere. At certain production sites, the water footprint might even decrease. This research thus shows that it will not be possible to provide a single solution to fuel and fibre crop industries regarding how to decrease the water footprint in future. The results showed that this will not be feasible even for a single industry, such as the sugar industry, given the variations in the expected impacts of climate change on the water footprint. The implementation of beneficial management practices, however, will have an important role in decreasing the water footprint under the future climate.

The results also showed how a change in the planting date of cotton could have an influence on the water footprint of the crop. In this study, cotton planted in October was found to be associated with a lower water footprint than the cotton planted in September. Again, understanding the impact of such practices on the water footprint of the crops to be produced can contribute towards decreasing the water footprint of crops in a context where water availability may come under increased pressure.

APPENDICES

APPENDIX 1: CONSOLIDATED CAPACITY BUILDING REPORT

The following capacity-building activities took place during the course of this project:

1. Presentations at international and local conferences:

   a. Jordaan, H. (2016). *Water footprint of agri-food products in South Africa*. Paper presented at the 1st conference of the Water Footprint Research Alliance, Garden Court Nelson Mandela Boulevard, Cape Town, 4-7 April 2016.

   b. Adetoro, A.A., Singels, A., Paraskevopoulos, A.L. and Jordaan, H. (2017). Management practices and the water footprint of irrigated sugarcane production in South Africa. Paper presented at the 23rd International Congress on Irrigation and Drainage, Mexico City, Mexico, 8-14 October 2017.

   c. Motaung, N.A., Owusu-Sekyere, E., Jordaan, H. Ogundeji, A.A. and Chapagain, A.K. (2018). Water Footprint of tobacco production in South Africa: Implications for water use policies at a farm level. Paper presented at the 7th South African National Commission on Irrigation and Drainage Symposium: Ingwenyama Conference and Sport Resort, White River, South Africa, 13-15 November 2018.

   d. Bahta, Y. and Jordaan, H. (2019). The economic impact of policy interventions to mitigate water use in irrigation agriculture in South Africa. Paper presented at the 57th conference of the Agricultural Economics Association of South Africa: Bloemfontein, South Africa, 8-10 October.

2. Publication of theses:

   a. Neshifhefhe, K. (2020). Water footprint and economic feasibility assessment of biodiesel produced from sunflower in South Africa. MSc Agric Thesis, Department of Agricultural Economics, University of the Free State, Bloemfontein.

   b. Tshibalo, T. (2019). *Water footprint assessment of irrigated cotton production in South Africa*. MSc Agric Thesis, Department of Agricultural Economics, University of the Free State, Bloemfontein.

   c. Adetoro, A. (2018). *Sustainability of irrigated sugarcane production*. MSc Agric Thesis, Department of Agricultural Economics, University of the Free State, Bloemfontein.

APPENDIX 2: ARCHIVING OF DATA

The data are archived by Prof Henry Jordaan at the Department of Agricultural Economics, University of the Free State. Prof Jordaan can be contacted at jordaanh@ufs.ac.za.