WATER FOOTPRINT ASSESSMENT OF MAIZE AND ASSOCIATED BROILER PRODUCTION IN SOUTH AFRICA

By PHOKA GERALD NKHUOA

Submitted in partial fulfilment of the requirements for the degree

MASTER OF SCIENCE IN AGRICULTURAL ECONOMICS

in the

Department of Agricultural Economics
Faculty of Natural and Agricultural Sciences
University of the Free State
Bloemfontein

Supervisor: Dr Henry Jordaan
Co-Supervisor: Dr Nicolette Matthews

August 2017

DECLARATION

I, Phoka Gerald Nkhuoa, hereby declare that this dissertation, which is submitted by me for the degree Master of Science (M.Sc. Agric.) in the Department of Agricultural Economics, Faculty of Natural and Agricultural Sciences, at the University of the Free State, is my own independent work and has not been submitted by me to any other university. Furthermore, I cede the copyright of this dissertation in favour of the University of the Free State.

Phoka Gerald Nkhuoa
Bloemfontein
August 2017

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my family: my father, Mofokeng Nkhuoa, for his value for education and the principles he instilled in me – humility and education – which are key to success; and my mother, Vuyiswa Nkhuoa, for her perseverance, presence, attention, and love.

I am sincerely greatful to Drs Henry Jordaan and Nicki Matthews for their dedication in supervising me throughout this dissertation. I thank them for their patience and guidance. Their dedication during the course of the study proved to be fruitful. I will always have much respect for them both.

This study is based on a research project (k5/2397/4) that was initiated, managed, and funded by the WRC. Financial and other contributions by the WRC are gratefully acknowledged. I thank the National Research Foundation for their financial contribution towards this research. I am also grateful for the financial support from Itau Milling. The support from the staff of the Department of Agricultural Economics is greatly appreciated. I would also like to extend my gratitude to agribusinesses that were willing to provide me with production data as required.

Finally, I acknowledge God’s greatness in my life. Thank you, Father, for being faithful to me. It is through your grace that I managed to complete this dissertation. “‘As surely as I live,’ says the Lord, ‘every knee will bow before me; every tongue will acknowledge God.’” – Romans 14:11.

ABSTRACT

South Africa is a water-scarce country. Globally, the agricultural sector accounts for 75% of freshwater consumption, followed by the industrial sector with 20%, and the domestic sector with 5%. The human population is anticipated to increase by 2.3 billion people between 2009 and 2050. This will give rise to an increase in demand for food, fibre, and biofuel crops; consequently putting pressure on freshwater resources between the three economic sectors.

Despite only 1.5% of South Africa's agricultural land being under irrigation, irrigated agriculture uses about 60% of freshwater resources. The contribution of agricultural irrigation to achieve food security is seen in how it contributes to 30% of grain production. Irrigation allows farmers to harvest relatively higher yields per hectare (ha) compared to rain-fed conditions. Greater yields entail more labour requirements and thus employment opportunities. It also results in higher farm revenues.

The increase in the demand for freshwater will force economic sectors to compete for freshwater. Given the high level of water use seen in the agricultural sector as well as the dependence of the agricultural sector on freshwater, there is more potential for reducing water demand in the agricultural sector and great benefits from informing water users and policy makers of sustainable water use management in the agricultural sector. Maize is an important crop in South Africa, which is both imported and exported, with South Africa being a net exporter of maize. Furthermore, it is a major ingredient in broiler feed as it makes up more than 60% of broiler feed.

Given the pressure to use freshwater in a sustainable manner to ensure the indefinite production of irrigated crops, a water footprint assessment (WFA) may be used as a sustainability indicator to identify whether production is sustainable. A water footprint is the volume of water used to directly and indirectly produce a product or service. It comprises three components, namely the green, blue, and grey water footprints.

Internationally, a large amount of work has been published on WFAs for field crops by authors such as Aldaya and Hoekstra, (2010), Sun *et al*. (2013), Chapagain and Orr (2010), Hoekstra *et al.* (2011), and Mekonnen and Hoekstra (2010). However, very few applications have been conducted locally. These include the work of SABMiller, the World Wide Fund For Nature (WWF), Pegasys Consultants (2010), Pahlow, Snowball and

Fraser (2015), Munro *et al*. (2015), and Scheepers (2015). The volume of scientific research is therefore insufficient to effectively guide the management of local water resources.

The aim of this study was to assess the water footprint of maize and broilers as derived from irrigated maize production in the form of a case study carried out in the Bloemfontein area. This aim was attained by firstly quantifying the volumetric water footprint indicators for the production of maize and broilers as derived from maize production. Thereafter a sustainability assessment was conducted, followed by the formulation of response strategies to inform the sustainable use of freshwater.

The method of the Water Footprint Network (WFN) was identified as suitable to achieve the aim and objectives of this study. The method consists of the scope of the study, water footprint accounting, sustainability assessment, and response formulation. Maize water use data were obtained from secondary data from experiments conducted by Van Rensburg *et al*. (2012), who collected data from the Orange-Riet Irrigation Scheme. Water use data for farm-level broiler production were obtained from a broiler-producing company. Process data were obtained from a broiler-processing company, which happened to be the same firm that produces broilers on site.

At a yield level of 14.32 tonne/ha, the total maize water footprint was determined as 584.19 m^3/tonne. This comprises a green water footprint of 186.92 m^3/tonne, a blue water footprint of 275.58 m^3/tonne, and a grey water footprint of 121.69 m^3/tonne.

The total broiler water footprint was detetermined as 1 474.56 m^3/tonne of chicken meat produced. The water footprint of farm-level broiler production, excluding feed, is equivalent to 38.82 m^3/tonne, while the water footprint associated with broiler feed was 1 430.33 m^3/tonne. The slaughtering and processing of the broiler chickens used 2.70 m^3/tonne each.

The economic water productivity (EWP) was found to be higher for fresh chickens than for frozen chickens. Chicken portions had a higher associated EWP than whole chickens.

Maize and broiler production were found to be sustainable from December to May. It is recommended that maize production in the Orange-Riet Irrigation Scheme should commence from December rather than October. Irrigation should be postponed to the later hours of the day. Optimum in-row spacing should be implemented to provide sufficient covering of the ground surface to avoid evaporation losses from the soil.

TABLE OF CONTENTS

DECLARATION i
ACKNOWLEDGEMENTS ii
ABSTRACT iii
LIST OF FIGURES ix
LIST OF TABLES x
LIST OF ABBREVIATIONS xii

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND 1
  1.1.1 PRODUCTION AND CONSUMPTION OF MAIZE IN SOUTH AFRICA 3
  1.1.2 THE IMPORTANCE OF THE MAIZE INDUSTRY TO THE SOUTH AFRICAN ECONOMY 6
    1.1.2.1 Animal feed industry 7
  1.1.3 DISCUSSION 8
1.2 PROBLEM STATEMENT 9
1.3 THE AIM OF THE STUDY 10
1.4 THE OBJECTIVES OF THE STUDY 10

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION 11
2.2 THE MAIZE INDUSTRY IN SOUTH AFRICA 11
2.3 WATER FOOTPRINT CONCEPT 12
  2.3.1 CALCULATION OF A PRODUCT WATER FOOTPRINT 13
    2.3.1.1 Chain summation approach 13
    2.3.2.2 The stepwise accumulative approach 14
2.4 VARIOUS WAYS OF QUANTIFYING WATER USE FOR WATER FOOTPRINT ASSESSMENTS 17

2.4.1 CONSUMPTIVE WATER-USE BASED VOLUMETRIC WATER FOOTPRINT APPROACH 18
2.4.1.1 Blue water footprint 19
2.4.1.2 Green water footprint 20
2.4.1.3 Grey water footprint 21
2.4.1.4 Total water footprint 24
2.4.2 STRESS-WEIGHTED WATER LIFE CYCLE ASSESSMENT APPROACH 24
2.4.2.1 Life cycle assessment approach proposed by Mila i Canals et al. (2008) 25
2.4.2.2 The Pfister, Koehler and Hellweg (2009) approach 26
2.4.3 HYDROLOGICAL WATER BALANCE METHOD 27
2.4.4 RELATED RESEARCH ON WATER FOOTPRINT ASSESSMENTS IN THE GRAIN AND BROILER INDUSTRY 27
2.4.5 DISCUSSION 35
2.5 ECONOMIC VALUE OF WATER IN SOUTH AFRICA'S AGRICULTURAL SECTOR 40
2.5.1 THE IMPORTANCE OF WATER IN SUPPORTING INCOME AND CREATING JOBS . 40
2.5.1.1 Contribution of economic sectors to gross domestic product per unit of water 40
2.5.1.2 Contribution of economic sectors to job creation 40
2.5.1.3 Contribution of irrigation to agricultural production 41
2.5.1.4 Food production versus water scarcity as a driver for productivity... 41
2.5.1.5 Water productivity 41
2.5.1.6 Water productivity in irrigated agriculture 42
2.5.1.7 Economic water productivity of crop production 42
2.5.1.8 Green versus blue water productivity 43
2.5.2 DISCUSSION ON THE ECONOMIC VALUE OF WATER IN THE AGRICULTURAL SECTOR 43
2.6 CONCLUSIONS FROM THE LITERATURE AND THE IMPLICATIONS FOR THIS RESEARCH 44

CHAPTER 3: METHODS AND DATA

3.1 INTRODUCTION 47
3.2 METHOD 47
3.2.1 STAGE 1: FORMULATING GOALS AND SCOPE 47
3.2.1.1 Goals of a water footprint assessment 47

3.2.2 STAGE 2: WATER FOOTPRINT ACCOUNTING 48
3.2.2.1 Water footprint of growing a crop 50
3.2.2.2 Water footprint of a product..... 52
3.2.2.3 Animal product water footprint 52
3.2.2.4 Total water footprint 54
3.2.3 STAGE 3: WATER FOOTPRINT SUSTAINABILITY ASSESSMENT 54
3.2.3.1 Sustainability of the water footprint of a product, process, and river basin 54
3.2.3.2 Environmental sustainability criteria for identifying environmental hotspots 55
3.3 DATA 58
3.3.1 WATER USE DATA ON MAIZE PRODUCTION 58
3.3.1.1 Location and layout of the Orange-Riet Irrigation Scheme 58
3.3.1.2 Location and layout of measuring points 60
3.3.1.3 Climate 61
3.3.1.4 Water quality 61
3.3.1.5 Data acquisition 66
3.3.1.6 Location and description of measuring points or18 and or20 67
3.3.2 LOCATION AND DESCRIPTION OF MEASURING POINTS OR4 AND OR5 69
3.3.3 WATER USED TO PRODUCE CHICKEN MEAT 71
3.3.3.1 Farm-level water use for broiler production 71
3.3.3.2 Processor level water use for broiler chickens 74
3.3.4 ORANGE RIVER BASIN SUSTAINABILITY ASSESSMENT 74
3.3.5 ECONOMIC WATER PRODUCTIVITY 75

CHAPTER 4: RESULTS

4.1 INTRODUCTION 76
4.2 THE WATER FOOTPRINT OF MAIZE PRODUCTION 76
4.2.1 THE WATER FOOTPRINT OF MAIZE PRODUCTION AT MEASURING POINTS OR18 AND OR20 76
4.2.1.1 Blue and green water footprint 77
4.2.1.2 Grey water footprint 78
4.2.1.3 Discussion 79
4.2.2 THE WATER FOOTPRINT OF MAIZE PRODUCTION AT MEASURING POINTS OR4 AND OR5 79
4.2.2.1 Blue and green water footprints 80

4.2.2.2 Grey water footprint 81
4.2.2.3 Discussion 82
4.2.3 THE TOTAL WATER FOOTPRINT OF MAIZE PRODUCTION 82
4.3 THE WATER FOOTPRINT OF BROILER PRODUCTION 83
4.3.1 BLUE WATER FOOTPRINT OF BROILER PRODUCTION 83
4.4 ECONOMIC WATER PRODUCTIVITY 85
4.5 SUSTAINABILITY ASSESSMENT 86

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS 88
5.1.1 SUSTAINABILITY ASSESSMENT 91
5.2 RECOMMENDATIONS 91
5.2.1 RECOMMENDATIONS FOR WATER USERS 91
5.2.2 RECOMMENDATIONS FOR POLICY MAKERS 92
5.2.3 RECOMMENDATIONS FOR FURTHER RESEARCH 92
5.3 LIMITATIONS OF THE STUDY 93

REFERENCES 94

LIST OF FIGURES

Figure 1.1: Graphic illustration of the production and consumption of maize in South Africa 5

Figure 1.2: Maize market value chain 6

Figure 2.1: Schematic representation of the water footprint of one output product *p* . 14

Figure 2.2: Schematic representation of the water footprint of various output products derived from several input products. 15

Figure 2.3: Schematic representation of the various components of a water footprint19

Figure 3.1: Example of annual blue water footprint versus blue water availability 57

Figure 3.2: Geographic position of the Orange-Riet Irrigation Scheme in South Africa 59

Figure 3.3: Graphical description of the Orange-Riet Irrigation Scheme.................... 60

Figure 3.4: Geographic position of measuring points or18 and or20 within the Lower Riet section of the Orange-Riet Irrigation Scheme 68

Figure 3.5: Position of measuring points or18 and or20 on the irrigated fields of the Valsrivier Aliwal soil form in the Lower Riet section of the Orange-Riet Irrigation Scheme... 68

Figure 3.6: Geographical position of measuring points or4 and or5 at the Riet River settlement section of the Orange-Riet Irrigation Scheme 69

Figure 3.7: Location of measuring points or4 and or5 on the irrigated fields at the Riet River settlement section of the Orange-Riet Irrigation Scheme 70

Figure 3.8: Factors influencing the water footprint of chicken meat........................... 71

Figure 4.1: Monthly blue water scarcity of the Orange River basin............................ 87

LIST OF TABLES

Table 1.1: National feed sales (tonne) for the period 2005 to 2013 7

Table 1.2: AFMA feed as a percentage of national feed production for the period 2005 to 2013 8

Table 1.3: Total maize fraction (tonne) incorporated into animal feed by AFMA members (1 April to 31 March) 8

Table 3.1: Minimum and maximum leaching-runoff fractions for nitrogen................. 63

Table 3.2: The score of each factor and the associated weight for the case of nitrogen at measuring points or18, or20, or4 and or5... 63

Table 3.3: Nitrogen and phosphorous removal by maize per one tonne of marketable product.. 70

Table 3.4: Water footprint of soya and sunflower oilcake 72

Table 4.1: Biophysical data of measuring points or18 and or20 77

Table 4.2: Summary of water use data at the measuring points or18 and or20 at Orange-Riet Irrigation Scheme.. 77

Table 4.3: Summary of the green and blue water footprints of producing maize in the Orange-Riet Irrigation Scheme at measuring points or18 and or20......... 78

Table 4.4: Variables necessary for estimating the pollutant load for nitrogen at measuring points or18 and or20.. 78

Table 4.5: Summary of the grey water footprint at or18 and or20............................ 79

Table 4.6: Biophysical data of measuring points or4 and or5 at Orange-Riet Irrigation Scheme.. 79

Table 4.7: Summary of water use data at the measuring points or4 and or5 at the Orange-Riet Irrigation Scheme in season 1.. 80

Table 4.8: Summary of the green and blue water footprints of producing maize in the Orange-Riet Irrigation Scheme at measuring points or4 and or5 in season 1 81

Table 4.9: Variables necessary for estimating the pollutant load for nitrogen and phosphorous at measuring points or4 and or5 81

Table 4.10: Summary of the grey water footprint at or4 and or5……………………….82

Table 4.11: The total water footprint at Orange-Riet Irrigation Scheme 83

Table 4.12: Total water footprint per tonne of broilers produced, slaughtered, and processed 85

Table 4.13: Average chicken retail prices 86

LIST OF ABBREVIATIONS

AFMA	Animal Feed Manufacturers Association
APCR	Agro-pastoral system using cereal crop residues
APB	Agro-pastoral system using barley
PB	Pastoral system using barley
CEC	Crop Estimates Committee
DoA	Department of Agriculture
DAFF	Department of Agriculture, Forestry and Fisheries
DWA	Department of Water Affairs
ELP	Economic land productivity
EWP	Economic water productivity
FAO	Food and Agriculture Organization
FCE	Feed conversion efficiency
FD	Freshwater depletion
FEI	Freshwater ecosystem impact
FSSA	Fertilizer Society of South Africa
GDP	Gross domestic product
ha	Hectare
HFMS	High Fructose Maize Syrups
JSE	Johannesburg Stock Exchange
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Analysis
SADC	Southern African Development Community
SAFEX	South African Futures Exchange
Stats SA	Statistics South Africa
UN	United Nations
UNEP	United Nations Environment Programme
USA	United States of America
USDA	United States Department of Agriculture
WFA	Water footprint assessment
WFN	Water Footprint Network

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Water is a scarce resource globally and thus the sustainable use of water is important to ensure that water demand in the agricultural, industrial, and domestic sectors is met. Globally, the agricultural sector consumes about 75% of fresh water resources, the industrial sector accounts for about 20%, and the domestic sector uses about 5% of global freshwater resources (United Nations Environment Programme (UNEP), 2008). According to Mekonnen and Hoekstra (2014), the demand for freshwater resources will increase in the next couple of years in response to the rising demand for food, fibre, and biofuel crops. This increase in the demand for freshwater resources may be attributed to the rise in the global population, which is expected to increase by 2.3 billion people between 2009 and 2050 (Food and Agriculture Organization (FAO), 2009). This will not only place pressure on the agricultural sector to increase output, which will be accompanied by an increase in water use in the sector, but it will also increase the demand for freshwater resources in the industrial and domestic sectors.

South Africa is a water-scarce country, with a total surface area of about 1.2 million km^2 of land, of which 12% is suitable for the purposes of crop production. Water availability is a major limiting factor for crop production (Baloyi *et al.*, 2012; World Water Council, 2004), despite the allocation of 60% of South Africa's water resources to agricultural irrigation (Department of Water Affairs (DWA), 2013). In South Africa, about 1.3 million ha (ha) of land is under irrigation (Bezuidenhout, 2013). Irrigated agriculture accounts for 30% of South Africa's crop production. With only 1.5% of land under irrigation, agricultural irrigation is not only a large consumer of freshwater but also a method of achieving food security (DWA, 2013). Irrigated agriculture contributes to the growth of the agricultural sector and thus to economic growth. It contributes to poverty reduction in various ways, such as by increasing the productivity, employment, and incomes of farms operating under irrigation (Hasnip, Vincent and Hussein, 1999). Of the irrigated crops in South Africa, maize is the most important crop. Broiler consumption accounts for 60% of total meat consumption in South Africa (United States Department of Agriculture (USDA), 2015). The increasing demand for water from the agricultural, industrial, and domestic sectors will give rise to competition for water resources among the three sectors of the economy. It is thus necessary to inform water users and policy makers on sustainable water use management in South Africa to ensure efficient and sustainable use of freshwater resources in the largest water-consuming sector, the agricultural sector, as a means to minimise the implications that will be incurred in response to inadequate freshwater supplies.

Given that maize is an important crop and broiler consumption is relatively high in South Africa, attention should be given to the water used for maize and broiler production. One method that can be used to ensure efficient and sustainable use of freshwater within the agricultural sector is a water footprint assessment (WFA). The WFA can contribute to ensuring that the objective of the National Water Act of 1998 (No. 36 of 1998) "to ensure that South Africa's water resources are protected, used, developed, conserved, managed, and controlled in a sustainable and equitable manner, for the benefit of all persons" is met. A water footprint is the volume of freshwater used (directly and indirectly) to produce a product or service. If lowered whilst yields per ha are maintained or increased, it can ensure the sustainable use of freshwater and thus increase the productivity of freshwater within the agricultural sector (Mekonnen and Hoekstra 2014).

One can distinguish between three different types of water footprints, namely blue, green, and grey water footprints. Collectively they represent the total water footprint. The blue water footprint is an indicator of the total volume of surface water (i.e. rivers, aquifers, dams, and harvested rainwater) and groundwater (i.e. renewable groundwater and fossil groundwater) consumed in the production of a commodity, product, or service. In the case of crops, water consumption refers to the blue water that is evaporated, incorporated into the crop, lost to another catchment area, or returned to the same catchment area in a different period. Thus the blue water footprint is a measure of how much of the available surface water and groundwater is consumed during production (Hoekstra *et al*., 2011). The green water footprint is an indicator of the total volume of rainfall that does not form part of runoff or groundwater but is stored in the soil, or remains temporarily on top of the soil or vegetation. This water is then evapotranspired by plants. The part of the green water that remains above the soil or vegetation may be evaporated and lost to a different catchment area or may return to the same catchment area in a different period (Hoekstra *et al*., 2011). The grey water footprint is the total volume of freshwater needed to dilute the substances that pollute water and return the water to ambient water quality standards (Hoekstra *et al*., 2011). These three types of water footprints are the backbone of a WFA.

A WFA is a science-based method to explore sustainable water use. It has been applied widely to assess the water footprint of nations, consumers, producers, regions, and so on. Although the fundamental goal of a WFA is to ensure the sustainable use of freshwater and avoid water losses where necessary, there are limited, if any, alternative uses for green water other than being consumed by natural vegetation or cultivated crops. However, blue water that is conserved may be redistributed among the agricultural, industrial, and domestic sectors. It may also be reserved to meet environmental flow requirements (EFRs). Hence alternative uses exist for conserved blue water (World Water Council, 2004).

1.1.1 PRODUCTION AND CONSUMPTION OF MAIZE IN SOUTH AFRICA

South Africa is a major maize producer in the Southern African Development Community (SADC) (DAFF, 2013a). The majority of maize production in South Africa occurs in the Free State, North West, and Mpumalanga provinces. The DAFF (2016) reported that the three provinces contributed 40%, 22%, and 20% respectively to the total commercial production of maize in South Africa for the period 2008 to 2015. In 2016 the Free State, North West and Mpumalanga provinces produced 28%, 15% and 30% of the total commercial production of maize in South Africa (Crop Estimates Committee (CEC), 2017). The general decrease in yields was attributed the drought conditions experienced in South Africa in 2016. An average of 11.3 million tonnes of maize was produced each year in South Africa from 2001 to 2014. More than 65% of South Africa experiences insufficient rainfall to support rain-fed agriculture (Food and Agricultural Organization's Statistical Database (FAOSTAT), 2014). Rainfall is therefore a limiting factor for rain-fed maize production in many areas of the country (FAOSTAT, 2014). As a means to ensure adequate water supply, a large area of maize production is under irrigation (FAOSTAT, 2014). According to the DAFF (2012), irrigated maize production makes up about 10% of total maize production at most, whilst the remainder is rain-fed (DAFF, 2012). Despite the relatively smaller contribution from irrigated maize production to the total production of maize in the country, maize production under irrigation realises considerably higher yields per ha than under dryland conditions. The average yield for white maize production under irrigation conditions is 8.65 t/ha but under dryland conditions it is 3.37 t/ha (DAFF, 2012). In contrast, the production of yellow maize under irrigation conditions is 10.05 t/ha, whereas under rain-fed conditions it is 3.86 t/ha (DAFF, 2012). These increases in yields per ha are important in order to meet the growing demand for white maize intended for human consumption and yellow maize for animal consumption.

South Africa has exhibited an increasing trend in its population growth rate since 2002 (Statistics South Africa (Stats SA), 2014). The annual population growth rate in South Africa increased from 1.27% in 2002 to 1.58% in 2014 (Stats SA, 2014). This is a 0.31% increase in the population growth rate of the country in 12 years (Stats SA, 2014). An increase in population growth will not only be accompanied by an increase in the demand for maize but also in the demand for land and water. This further confirms the importance of irrigated maize production in increasing maize yields per ha. It is also important in assessing the economic viability and sustainability of irrigated versus dryland maize production.

Figure 1.1 depicts how the production and consumption of maize have changed over time. The total production of maize has decreased from 11.450 million tonnes in 2004/2005 to 9.942 million tonnes in 2014/2015 due to the steady decline in land allocated to maize production as well as unfavourable weather conditions. Nevertheless, the drop in yields has been limited by higher yields per ha which has in part been promoted by the production of genetically modified crops. However, during 2005/2006 and 2006/2007, the total domestic maize production was below the total consumption of maize. According to the Department of Agriculture (DoA, 2006), the low maize production during this period was due to the decline in areas planted with maize and the late start of the season. Nevertheless, the industry managed to realise drastic increases in yields in 2007/2008. These high yields were maintained right through 2009/2010, with slight decreases in 2008/2009. In 2010/2011, there was a moderate drop in yield, which reached a low of 10.360 million tonnes. This was followed by an increase of 3.947 million tonnes that allowed the country to reach a total production of 14.307 million tonnes in 2013/2014. The 2014/2015 seasons production was estimated at 9.942 million tonnes, slightly below the consumption levels seen at 10.165 million tonnes.

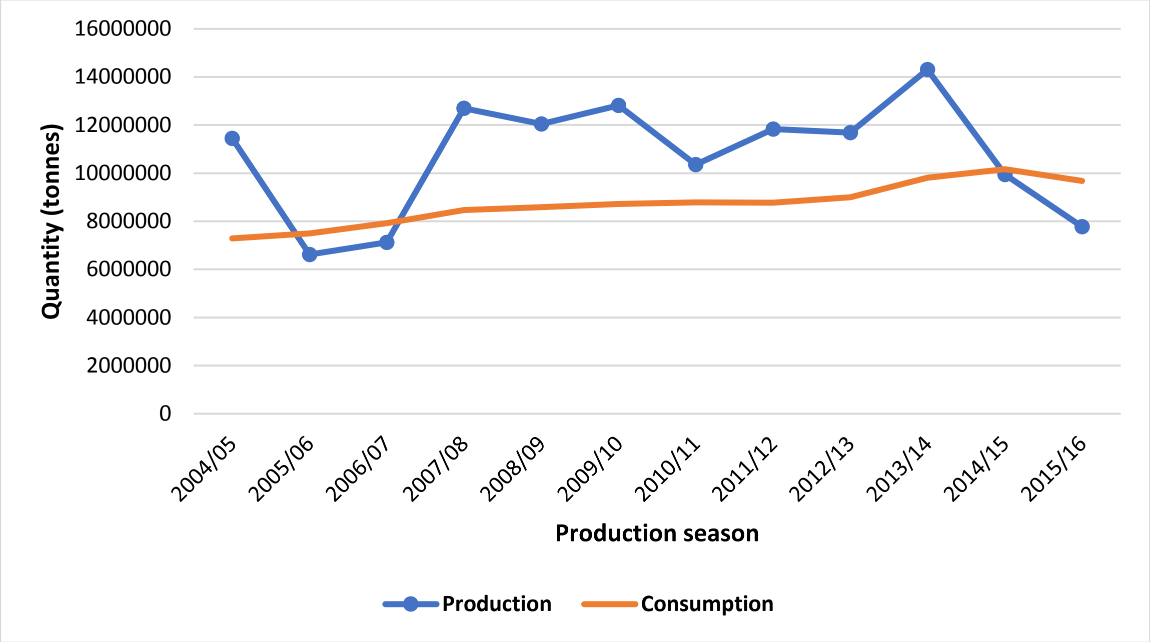

Figure 1.1: Graphic illustration of the production and consumption of maize in South Africa

Source: CEC (2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017)

The consumption of maize has exhibited a gradual increase from 7.288 million tonnes in 2004/2005 to 9.942 million tonnes in 2014/2015. Showing no signs of declining, the consumption of maize is slowly narrowing the gap between total production and consumption. Maize production in the 2015/2016 season dropped to 7.779 million tonnes while consumption dropped slightly to 9,.681 million tonnes. The decrease in maize production was mainly attributed to the drought conditions at the time and was accompanied by high maize prices. The maize deficit left many South Africans concerned about being forced to eat yellow maize. Nevertheless, rainfall relief was seen in the 2016/2017 production season. As a result, South Africa's CEC (2017) has pegged South Africa's 2016/2017 season maize yield at 15.631 million tonnes in it's fourth production forecast released on 26 of May 2017.

The low maize yields of 2005/2006 were attributed to the decrease in the areas planted with maize, amongst others (DoA, 2006). Irrigated agriculture has an important role to play in such an instance, given that it can increase yields per ha, as described by the DAFF (2012).

1.1.2 THE IMPORTANCE OF THE MAIZE INDUSTRY TO THE SOUTH AFRICAN ECONOMY

Maize production for the period 2004/05 to 2014/15 seasons has occurred on an average of 2.557 million ha with an 11-year average yield of 10.990 million tonnes (CEC). In 2011, maize was produced on 2.86 million ha of agricultural land. Wheat accounted for 605 000 ha, while sorghum and barley accounted for 69 000 and 80 000 ha respectively. Field crops contributed 27.5% to the total gross value of agricultural production. Maize contributed 13.2% to the gross value of agricultural production (DAFF, 2013b).

Figure 1.2 is a graphic illustration of the value chain of maize. It describes each component of the value chain, from research and biotechnology to the end-consumer.

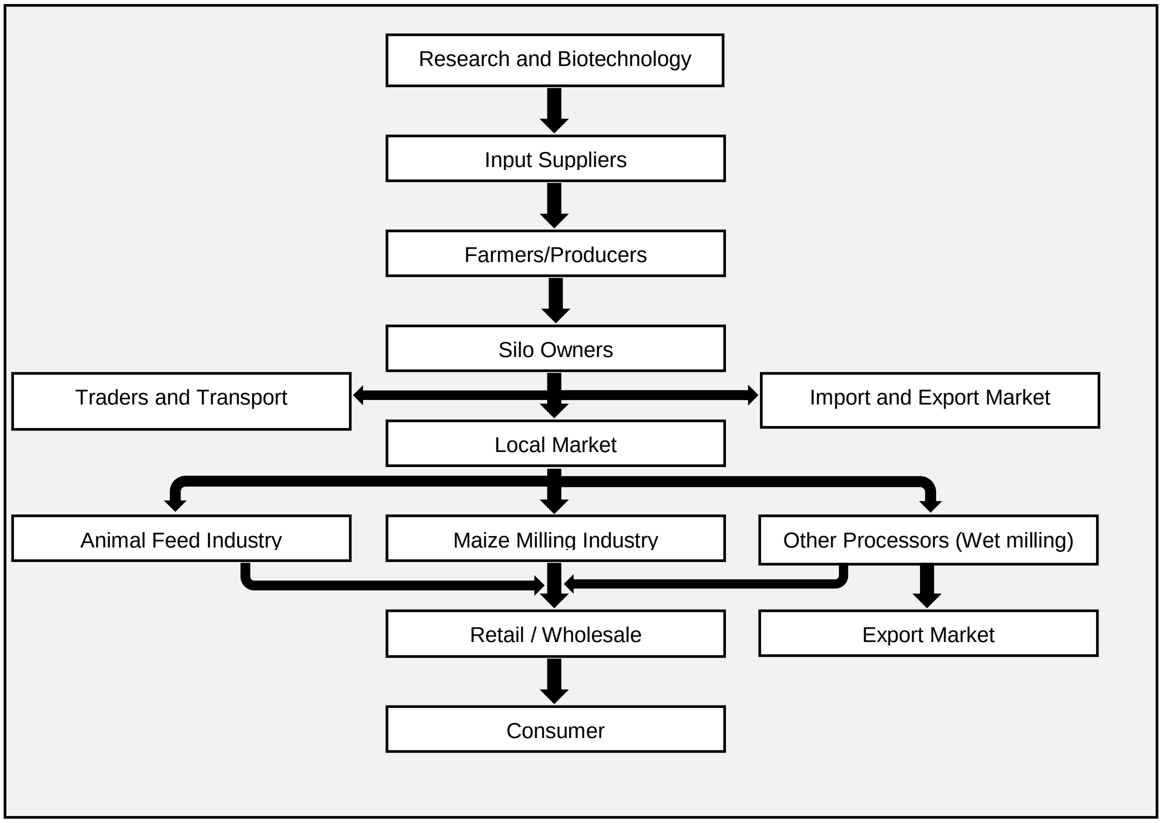

Figure 1.2: Maize market value chain

Source: (DAFF, 2012)

Research and development are responsible for innovation within the maize sector. Input suppliers are firms that provide farmers or producers with production inputs such as fertiliser, fuel, seed, mechanisation, pesticides, herbicides, financing, etc. Farmers or producers use these inputs to produce maize. After the maize has been harvested, it is transported from farmers or producers to silos. In some instances, silos are located on the farm. At the silo, the maize is graded and stored, and a certain quantity of the maize is traded in the local market whilst the remainder is exported to international markets. In the local market, one can distinguish between various alternatives of adding value to maize. These include the animal feed industry, the milling industry, and the processing of maize by processors who use it for the purpose of wet milling or brewing. From the various value-adding processors, the maize is transported to retailers and wholesalers, who make it available for the final consumer to purchase. Of the various value-adding processors, the animal feed industry is of importance for the purposes of this study.

1.1.2.1 ANIMAL FEED INDUSTRY

The animal feed industry is made up of a formal and an informal sector. The Animal Feed Manufacturers Association (AFMA) represents a large share of the roleplayers in the formal sector, and contributes about 60% to the total production of animal feed in South Africa (DAFF, 2012). The informal feed industry comprises small feedlots, smaller feed mills, and home mixers (DAFF, 2012). Broiler feed is amongst the highest consumed animal feed in South Africa, with maize being a major ingredient in broiler feed. Table 1.1 provides a record of broiler national feed sales for the period 2005 to 2013 by AFMA.

Table 1.1: National feed sales (tonne) for the period 2005 to 2013

	Tonne/year						
Year	**2005**	**2007**	**2009**	**2010**	**2011**	**2012**	**2013**
Broilers	2439567	2769522	3088618	3176991	3292364	3217707	3280052

Source: AFMA (2007, 2008, 2010, 2011, 2012, 2013, 2014)

Broiler production by far accounts for the largest share of feed sales in South Africa. Table 1.1 shows that broiler feed production increased from 2005 to 2013. Feed sales associated with broiler production increased by 34.45% for the period 2005 to 2013. In order to meet the increased demand for broiler feed, there is also increased demand for freshwater to grow the crops that are used to produce broiler feed.

Table 1.2 highlights feed sales in the form of percentages. It emphasises that broiler production accounts for the largest share of feed sales in South Africa. For the period 2005 to 2013, AFMA broiler feed accounted for 95% to 100% of national broiler feed production. The total AFMA feed production ranged from 53.89% to 60.01% for the period 2005 to 2013. It therefore contributes significantly to feed production.

Table 1.2: AFMA feed as a percentage of national feed production for the period 2005 to 2013

	%/year						
Year	2005	2007	2009	2010	2011	2012	2013
Broilers	95.49	98.08	96.80	99.46	99.92	96.97	97.50
Total	**58.08**	**55.20**	**53.89**	**59.05**	**59.92**	**59.77**	**60.01**

Source: AFMA (2007, 2008, 2010, 2011, 2012, 2013, 2014)

According to AFMA (2010; 2014), maize is the main ingredient in animal feed. Table 1.3 shows that about 49% of total feed produced per year consists of maize.

Table 1.3: Total maize fraction (tonne) incorporated into animal feed by AFMA members (1 April to 31 March)

Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Maize incorporated into feed (tonne)*	2202093	2273544	2465239	2649320	2685600	2824646	2997896	2988544	3085968
Total feed production (tonne)	4462088	4687097	5122460	5262693	5498297	5750578	6143576	6176151	6397555
Maize fraction in feed (%)	49.35	48.51	48.13	50.34	48.84	49.12	48.80	48.39	48.24

Source: AFMA (2010; 2014)

* **(including maize meal)**

1.1.3 DISCUSSION

Broiler feed sales make up the largest share of animal feed sales in South Africa as shown in Table 1.2. This means that broiler production consumes more feed than any other animal production activity. The significance of maize in broiler production is seen in its role as the main feed ingredient in broiler feed. Hence maize will be given attention as the main feed ingredient in determining a WFA of broiler production.

1.2 PROBLEM STATEMENT

Despite wide applications internationally, WFAs in South Africa have not been applied to a great extent. Only five studies have been published in South Africa on WFAs. SABMiller published the first, while Pegasys Consulting (2010) published the second. These were followed by three publications in 2015 by Pahlow, Snowball and Fraser (2015), Munro *et al*. (2015), and Scheepers (2015).

Globally, the water footprints of grain products have been quantified. The water footprint of maize production in particular has been calculated using the consumptive water-use based volumetric water footprint approach (hereafter referred to as the volumetric water footprint approach) (Mekonnen and Hoekstra, 2013; Mekonnen and Hoekstra, 2014; Schyns and Hoekstra, 2014). The water footprint of animal production, particularly that of broilers, has also been widely determined using the WFN approach (Mekonnen and Hoekstra, 2012; Gerbens-Leenes, Mekonnen and Hoekstra 2011).

Pahlow, Snowball and Fraser (2015) conducted a national WFA in South Africa, following the approach presented by Hoekstra *et al.* (2011). Their study identified crop production as a major activity in terms of water consumption, accounting for about 75% of the total water footprint of national production. Of the different crops, maize was found to be one of the major consumers of the water resource. The degree of water pollution associated with nitrogen and phosphorous fertilisation was reported as unsustainable for all South African river basins. In the context of ample international applications and limited local use, there is a lack of scientific water footprint information to effectively guide water use in South Africa’s maize and poultry industries. Considering the importance of the maize industry, seen in its role as a staple food for South Africans, a WFA of maize and broiler production is critical to ensure sustainable water use in the value chain.

To the author’s knowledge, no study has been conducted in South Africa on the water footprint of maize and derived maize products. Thus, no information is available to inform water users on the production of maize and derived maize products in South Africa.

1.3 THE AIM OF THE STUDY

The aim of this study was to assess the water footprint of maize and broilers as derived product from irrigated maize production in the form of a case study carried out in the Bloemfontein area. This was done to inform water users, water managers, and policy makers regarding the sustainable use of water for the production of irrigated maize for broiler feed, and ultimately broilers for human consumption.

1.4 THE OBJECTIVES OF THE STUDY

The aim of the study was formulated around the following objectives:

Objective 1: Quantify the volumetric water footprints associated with the production of maize and broilers as derived maize products.

Objective 2: Assess the sustainability of the green, blue, and grey water footprints of maize, as well as derived maize products in a particular catchment at a certain time from an environmental, social, and economic perspective.

Objective 3: Formulate response strategies to inform sustainable use of freshwater.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The maize industry in South Africa is one of the strongest maize industries in Southern Africa. Maize production is critical and its consumption is considerable. The maize industry makes a positive contribution to the South African economy. Maize is produced in either rain-fed or irrigated conditions (Theunissen, 2005). In some instances, both sources of freshwater are used. Freshwater is a fundamental input for maize production, therefore the availability of freshwater in South Africa is a crucial issue to investigate. Nevertheless, one should not explore water availability in isolation; one should focus on availability and use, as well as the impact(s) thereof. There are various methods available to conduct such a study, which are discussed in this chapter. This chapter also explores the link between water and the economy. The role of water in economic growth is regarded in this chapter as an indirect relationship. The value of water is measured as the economic returns obtained from the broiler product.

2.2 THE MAIZE INDUSTRY IN SOUTH AFRICA

Maize is the most widely consumed grain crop in South Africa, serving as both a feed grain and a staple food for the bulk of the South African population. White maize constitutes 48% of the total maize produced in South Africa, whereas 52% is yellow maize. Furthermore, white maize is mainly produced for human consumption and yellow maize is used as animal feed. Maize contributes 46.1% to the gross value of field crops, followed by sugar cane with 14.2% (Department of Agriculture, Forestry and Fisheries (DAFF), 2013). Whilst it is true that maize accounts for a considerable share of the revenue derived from field crops in South Africa, it is one of the major users of the scarce freshwater resource. Pahlow *et al.* (2015) reported that maize production contributes 8% to the total blue water footprint in the Orange River Basin, where most of the maize is produced in South Africa.

2.3 WATER FOOTPRINT CONCEPT

Hoekstra *et al.* (2009) defined the water footprint concept as the direct and indirect freshwater consumption by the user. Mekonnen *et al*. (2014) found that by reducing the water footprint of a product, sustainability and productivity of freshwater can be achieved within the agricultural sector. The blue, green, and grey water footprints are fundamental to a WFA.

The blue water footprint is an indicator of the total volume of surface water and groundwater consumed in the production of a commodity, product, or service (Hoekstra *et al.*, 2011). Surface water refers to water that exists on the surface of the earth. It comprises streams, rivers, lakes, dams, oceans, seas, aquifers, and wetlands. Surface freshwater supplies are sustained by both precipitation and groundwater. In contrast, groundwater is the water available below the surface of the earth in soil pores and in the cracks of rock structures (Harter, 2001). One may distinguish between renewable groundwater and fossil groundwater. According to Margat, Foster and Droubi (2006), non-renewable groundwater is "groundwater resource available for extraction, of necessity over a finite period, from the reserves of an aquifer which has a very low current rate of average annual renewal but a large storage capacity". In the case of a crop, water consumption refers to the blue water that is evaporated, incorporated into the crop, lost to another catchment area, or returned to the same catchment area in a different period. Thus the blue water footprint is a measure of how much of the available surface water and groundwater is consumed during production (Hoekstra *et al*., 2011). The green water footprint is an indicator of the total volume of rainfall that does not form part of runoff or groundwater but is rather stored in the soil or remains temporarily on top of the soil or vegetation. This water is then evapotranspirated by plants. The part of the green water that remains above the soil or vegetation may be evaporated and lost to a different catchment area or may return to the same catchment area in a different period (Hoekstra *et al*., 2011). The grey water footprint is the total volume of freshwater needed to dilute the substances that pollute water and return the water to ambient water quality standards (Hoekstra *et al*., 2011). These three types of water footprints are the backbone of a WFA. Water footprint assessment studies have been conducted for a variety of applications, ranging from a process step, product, consumer, group of consumers, consumers in a nation, consumers in an administrative unit such as a municipality, catchment area or river basin, business, business sector, or humanity as a whole (Hoekstra *et al*., 2011). This study focuses on the water footprint of maize and broiler as derived product.

2.3.1 CALCULATION OF A PRODUCT WATER FOOTPRINT

The discussion of the calculation of the water footprint of a product is based on the Global Water Footprint Standard reported by Hoekstra *et al.* (2011). Hoestra *et al*. (2011) described two approaches of calculating the water footprint of a product: the chain summation approach and the stepwise accumulative approach

2.3.1.1 CHAIN SUMMATION APPROACH

There are value chains from which only one output product may be derived. Output products that belong to such value chains follow the chain summation approach. In this approach, the water footprint of the output product reflects the total water consumption of all the process steps that make up the value chain of that particular product. In other words, the sum of all the water footprints associated with each process step divided by the number of output products p produced is the total water footprint of each unit of output product p produced. This may be presented mathematically as follows:

$$WF_{prod}[p] = \frac{\sum_{s=1}^{k} WF_{proc}[s]}{P[p]} \quad [volume/time] \qquad [1]$$

In the above equation, the process water footprint of process step s (volume/time) is represented by $WF_{proc}[s]$, whereas $P[p]$ is the amount of product p (mass/time) that is produced. In instances where more than one output product is realised from a value chain, the chain summation approach becomes irrelevant and the stepwise accumulative approach may be used.

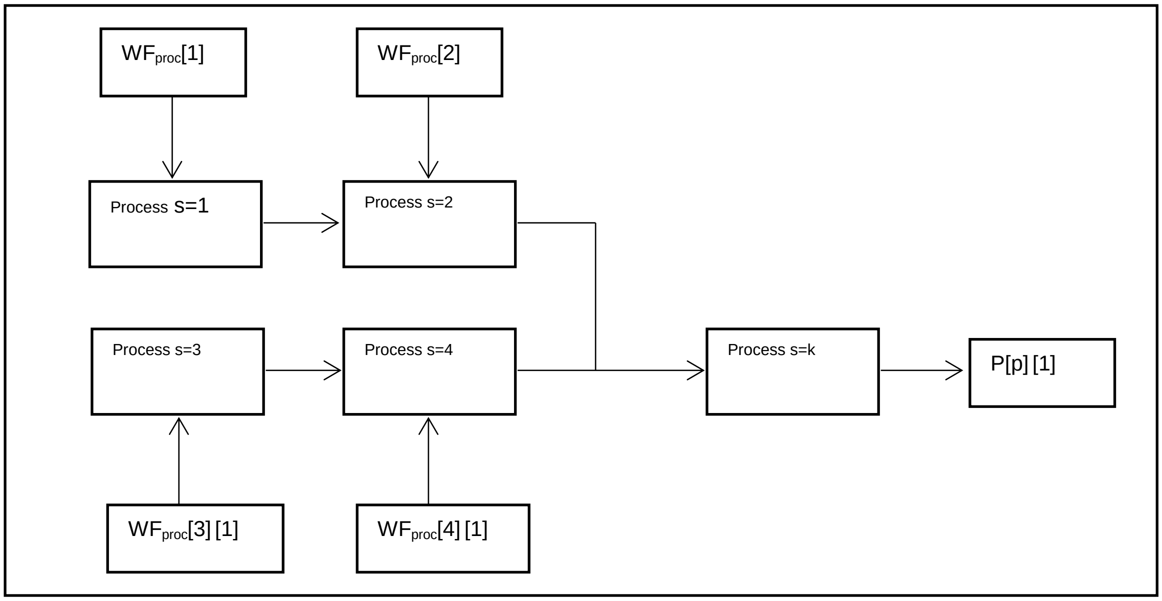

Figure 2.1: Schematic representation of the water footprint of one output product *p*
Source: Hoekstra *et al*. (2011)

Figure 2.1 is a schematic representation of the water footprint of one output product *p*. It comprises four process steps (s1 to s4). Each process step is associated with its own water footprint. The sum of these process steps forms the total process water footprint of producing output product *p*. The total process water footprint is represented here as *k*. It is then incorporated or embedded within output product *p* (Hoekstra *et al.*, 2011).

2.3.2.2 THE STEPWISE ACCUMULATIVE APPROACH

In contrast to the chain summation approach, the stepwise accumulative approach is an all-encompassing approach. It may be used to calculate the water footprint of a product that is produced from several input products or a product that is produced with various other output products from a single input product. It may also be used to determine the water footprint of a product that is produced with a number of other products from different input products. This approach clearly accounts for a wide range of value chains.

Figure 2.2 is a schematic representation of the water footprint of various output products derived from several input products. Each input product has a process water footprint that is embedded in it. The input products are then processed collectively to produce the output products. Thus the water footprint of each output product is the sum of the process water footprint of each input product, as well as the process water footprint of the process step that was used to convert the input products into the output products. This water footprint is then distributed accordingly to each output product based on the product fraction and value fraction of the output product.

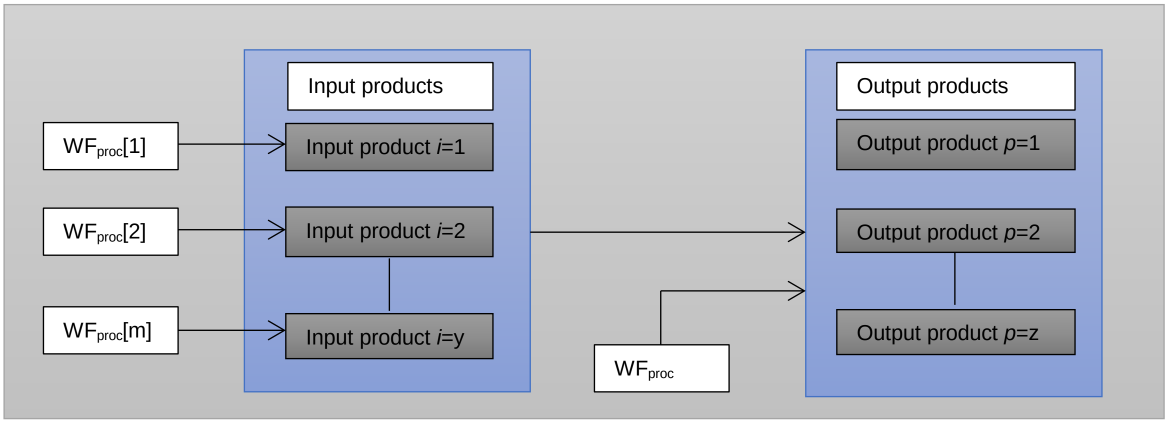

Figure 2.2: Schematic representation of the water footprint of various output products derived from several input products.

Source: Hoekstra *et al.* (2011)

In the case where a single product is produced from several input products, the water footprint of the output product is determined by summing the water footprints of all the input products utilised in producing the final product with the water footprint of the process step that converts these input products into the final product. However, in a situation where various output products are derived from a single-input product, the water footprint of this single-input product is allocated to the various output products on the basis of their respective value fractions. If one aims to calculate the water footprint of a particular product that is produced with various other output products from several input products, the water footprint of that particular output product is estimated by summing up all the water footprints of the input products. The quantity of the input product that eventually forms part of the output product is then estimated in order to determine how much of the water footprint of the input product becomes effectively embedded in the output product:

$$\left(\sum_{i=1}^{y}\frac{WF_{prod}[i]}{f_p[p,i]}\right). \qquad [2]$$

This value is then added to the water footprint of the processing step that transforms these input products into the various output products. The result is then divided amongst the several final products on the basis of their value fraction.

This latter case may be expressed mathematically as follows:

$$WF_{prod}[p] = \left(WF_{proc}[p] + \sum_{i=1}^{y} \frac{WF_{prod}[i]}{f_p[p,i]} \right) \times f_v[p] \quad [volume/time] \qquad [3]$$

Where:

$WF_{prod}[p]$ is the water footprint ($volume/mass$) of output product p;

$WF_{prod}[i]$ is the water footprint of input product i;

$WF_{proc}[p]$ is the process water footprint of converting several input products into the various output products ($volume/mass$);

$f_p[p,i]$ is the product fraction of output product p, i.e. the amount of output product p obtained per unit of input product i;

$f_v[p]$ is the value fraction of output product p, i.e. the ratio of the economic value of the output product under consideration to the average economic value of all the output products; and

The product fraction of an output product p ($f_p[p,i], \frac{mass}{mass}$) refers to the amount of output product ($w[p], mass$) that is produced per unit of the input product ($w[p], mass$). It may be calculated as follows:

$$f_p[p,i] = \frac{w[p]}{w[i]} \quad [-] \qquad [4]$$

The value fraction of an output product p ($f_v[p]$, monetary unit / monetary unit) is the ratio of the economic value of the output product under consideration to the average economic value of all the output products. It may be calculated as follows:

$$f_v[p] = \frac{price[p] \times w[p]}{\sum_{p=1}^{z} \left(price[p] \times w[p] \right)} \quad [-] \qquad [5]$$

Lastly, if one wants to determine the water footprint of a single-output product p that is derived from a single-input product i, the following equation becomes relevant:

$$WF_{prod}[p] = WF_{proc}[p] + \frac{WF_{prod}[i]}{f_p[p,i]} \quad [volume/time] \qquad [6]$$

Regarding the product fraction of an output product p ($f_p[p,i]$), it is important for one to identify the particular process applied in transforming the input product i into the output product p. This is because product fractions are greatly dependent on the processes involved in manufacturing the output product. Value fractions, on the other hand, should be derived from an aggregate price taken over five years or more.

2.4 VARIOUS WAYS OF QUANTIFYING WATER USE FOR WATER FOOTPRINT ASSESSMENTS

According to Sala *et al*. (2013), there are three main methods that are used to determine a water footprint. These approaches include the volumetric water footprint approach, stress-weighted life cycle assessment approach, and the impact assessment approach. The volumetric approach involves an analysis of the volume of freshwater consumption related to the production of a good or service. The stress-weighted approach assesses both the volume of freshwater utilised in an activity as well as the implications thereof. The impact assessment approach makes use of an inventory analysis to assess the volume of water consumed by a particular activity and highlights the implications that emerge in response to the level of water use. These approaches are discussed in more detail in the following section.

2.4.1 CONSUMPTIVE WATER-USE BASED VOLUMETRIC WATER FOOTPRINT APPROACH

Hoekstra (2003) pioneered the volumetric water footprint approach. The Water Footprint Network (WFN) (Hoekstra *et al*., 2009) adopted this approach. In their manual titled "The Water Footprint Assessment Manual: State of the Art", the WFN published an all-inclusive manual that Hoekstra *et al*. (2009) claimed would be subject to further modification, as was done in their second edition titled "The Water Footprint Assessment Manual: Setting the Global Standard" (Hoekstra *et al*., 2011). Figure 2.5 is a graphical representation of the components of a water footprint as described by Hoekstra *et al*. (2011).

Figure 2.3 shows three different types of water footprints in two distinct groups. In one group, all three water footprints are classified as direct water use and in another all three are classified as indirect water use. The blue and green water footprints in both groups (direct water use and indirect water use) are acknowledged as the consumptive water use, whereas the grey water footprint is viewed as the volume of water required to assimilate the load of pollutants in the water body, thus returning the water body to ambient water quality standards.

Non-consumptive water use, also referred to as return flow, does not form a part of the total water footprint because it is available for reuse in the system. Return flow is that part of the blue water that is available for reuse within the same basin and season.

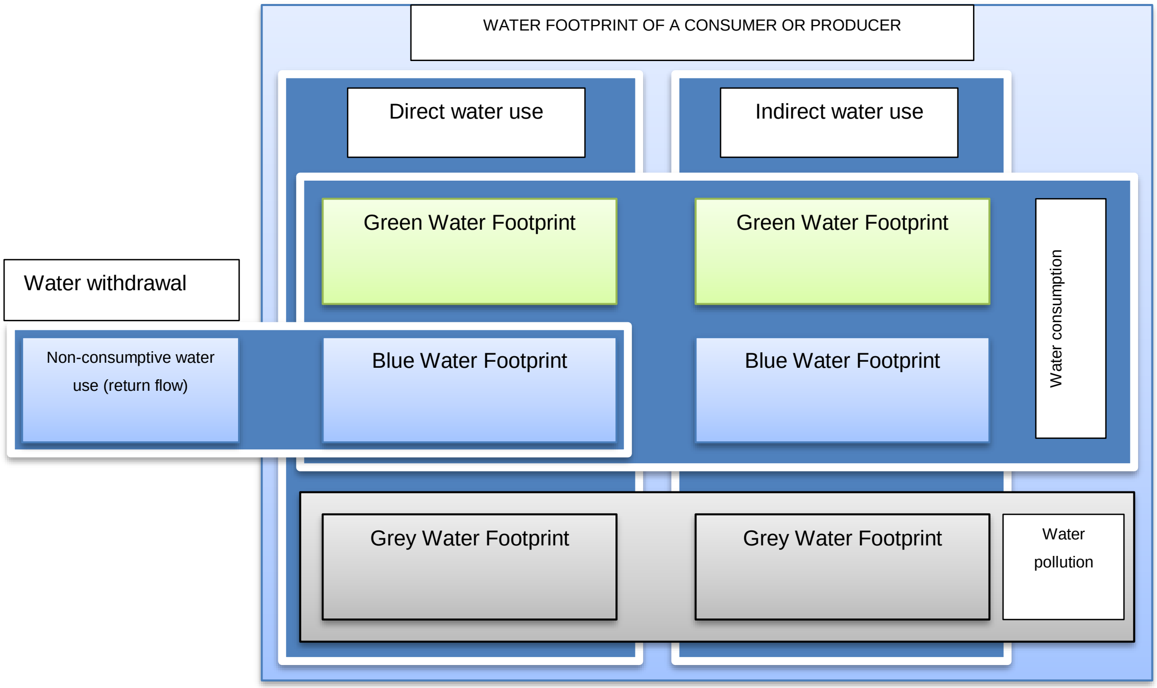

Figure 2.3: Schematic representation of the various components of a water footprint

Source: Hoekstra *et al*. (2011)

The volumetric water footprint approach distinguishes between three sources of water, namely blue, green, and grey water. It is important to note that the impacts and costs associated with a blue, green, and grey water footprint differ (Aldaya, Allan and Hoekstra, 2009). It is on this basis that one should comprehend each type of water footprint in its entirety.

2.4.1.1 BLUE WATER FOOTPRINT

The blue water footprint gives a measure of the degree of consumptive use of fresh surface water and groundwater. Groundwater can be divided further into flowing groundwater and fossil groundwater. The consumptive use of water is acknowledged as the following:

- Evaporation of irrigation water (including transpiration);
- The incorporation of water into a product (physical water content of the product);
- The movement of water from the initial catchment area to a different catchment area or to the sea; and/or

- Water that does not return to the same catchment area within the same period as it was abstracted.

Water evaporation is the common form of consumptive use compared to the other three components. Given the total volume of water available in a particular period, the blue water footprint indicates the volume of water that is consumed from the available water and thus provides the basis for determining the total volume of water available after consumption.

The blue water footprint is calculated as follows (Hoekstra *et al*., 2011):

$$WF_{proc,blue} = Blue\ Water\ \ Evaporation + Blue\ Water\ \ Incorporation + Lost\ \mathrm{Re}turn\ Flow$$
$$[volume/time]$$

2.4.1.2 GREEN WATER FOOTPRINT

Green water is precipitation that occurs on land. However, it is only limited to that precipitation that does not form part of runoff or replenishes groundwater reserves. Green water is the precipitation that remains in or above soil. In some instances it exists temporarily above plant material. As with blue water, green water is subject to evaporation or transpiration by plants (Hoekstra *et al.*, 2011). Green water above soil or plant material is more vulnerable to evaporation owing to the relatively high exposure to the heating effects of the sun. Thus the rate of loss of green water by means of evaporation varies depending on the locality of the green water. It is green water in soil that is lost through transpiration by plants, primarily because it is this green water that is in the vicinity of the plants' root systems.

The green water footprint refers to the total volume of green water that is evaporated from land or transpired by plants during the growth period of the plants. It also accounts for green water that is incorporated into the harvested crop (Hoekstra *et al*., 2011). However, this value is embedded within the volume of green water that is transpired by the plant. The green water footprint may be mathematically expressed as follows:

$WF_{proc,\ green}$ = Green Water Evaporation + Green Water Incorporation [volume/time]

One must note that the “Green Water Transpiration” has not been clearly expressed in the above equation for calculating the green water footprint in a process step. This variable is represented by the variable termed “Green Water Evaporation” in the above equation (Hoekstra *et al*., 2011).

2.4.1.3 GREY WATER FOOTPRINT

The grey water footprint is an indicator of the volume of freshwater necessary to reduce the degree of pollution in a water body. This reduction is equivalent to the volume of water required to return the water quality to its natural state. Existing ambient water quality standards require producers to maintain a grey water footprint that is in line with the ambient level of a river before production took place. The grey water footprint of a process step is determined by dividing the pollutant load (L, in mass/time) by the difference between the ambient water quality standard for that pollutant (C_{max}, in mass/volume) and the natural concentration of that pollutant in the water body being polluted (C_{nat}, in mass/volume). This calculation is illustrated by the following equation:

$$WF_{proc,grey} = \frac{L}{C_{\max} - C_{nat}} \quad [volume/time] \qquad [7]$$

The natural concentration of a water body is the concentration that is achieved if one does not consider the presence of waste material caused by human activity. It has been accepted as zero by Hoekstra *et al*. (2011). The second important function of a grey water footprint is to quantify the capacity of a water body to assimilate waste material. It does so by taking the difference between the ambient water quality standard of the pollutant and the natural concentration of that pollutant in the relevant water body. These two variables (ambient water quality standard of the pollutant and the natural concentration of the pollutant in the receiving water body) vary from one water body to another, even at the level of surface water and groundwater bodies. Nevertheless, one must appreciate that the ambient water quality standard of a pollutant in groundwater is informed by the degree of quality that drinking water should possess. Surface water, on the other hand, has a standard that is based on ecological considerations. Hence it is crucial for one to describe the ambient water quality standards and natural concentrations that inform their grey water footprint account. It is important to note that the grey water footprint is not an indicator of the volume of water that is polluted but rather communicates the degree of water pollution by indicating the total volume of freshwater necessary to dilute waste material within the water body.

Water bodies may be polluted in various ways. Depending on the manner in which a water body is polluted, the load will be determined accordingly. In a situation where polluted water is disposed of directly into a surface water body, as is the case with point source water pollution, the pollutant load is determined by subtracting the product of the water volume of the abstraction and the actual concentration of the intake water (C_{act}, in mass/volume) from the product of effluent volume (Effl, in volume/time) and the concentration of the pollutant in the effluent (C_{eff}, in mass/volume). This is shown in the following equation:

$$WF_{proc,grey} = \frac{L}{C_{\max} - C_{nat}} = \frac{Effl \times C_{effl} - Abstr \times C_{act}}{C_{\max} - C_{\min}} \quad [volume/time] \qquad [8]$$

In the case of point source pollution, the pollutant load is regarded as the waste material that accumulates above that which already exists in the water body. It is only logical, therefore, that the freshwater taken from the water body is returned to the same water body with a higher concentration of pollution. Hence the load is more likely to be a positive value. However, the treatment of effluent before it is released back into the water body may result in a negative load. If such a result arises, the load is to be identified as zero. In the absence of the consumptive use of freshwater that is abstracted from a water body, the following equation for calculating the grey water footprint of a process step at a point source of water pollution becomes applicable:

$$WF_{proc,grey} = \frac{C_{effl} - C_{act}}{C_{\max} - C_{nat}} \times Effl \quad [volume/time] \qquad [9]$$

Determining the pollutant load in the case of diffuse sources of water pollution is a complex and time-consuming process. Nevertheless, models do exist to account for such complexities. A chemical application above or into soil may result in some of these chemicals entering groundwater reserves through leaching. A fraction of these chemicals may also flow into surface water by means of runoff. To address the challenge of determining the quantity of chemicals that make their way into blue water reserves, a simple model was developed. This model assumes that a particular set quantity of the chemical flows into groundwater or surface water. This is represented by the following equation:

$$WF_{proc,grey} = \frac{L}{C_{\max} - C_{nat}} = \frac{\propto \times Appl}{C_{\max} - C_{nat}} \quad [volume/time] \qquad [10]$$

The fraction of applied chemicals that enter the mentioned blue water reserves are represented by $\propto$, whereas $Appl$ represents the chemicals that are applied above or into soil. One should bear in mind that this equation is a default method of calculating the grey water footprint of a process step in the case of diffuse sources of water pollution, and that other methods also exist.

It is a known fact that the evaporation of water from a water body that lies exposed to the sun is an unavoidable process. This is also true for soil moisture. Despite the role of this process in counteracting the increasing temperature of water, it has a negative impact on the quality of the water remaining. As water evaporates from a water body or moisture from soil, the chemical concentration in the remaining water increases. This increase is equivalent to the volume of water evaporated (m^3) multiplied by the natural concentration of the chemical in the water body (C_{nat} in mass/m^3). Such an increase in the chemical concentration of the water body is also regarded as an increase in the grey water footprint. Thus it is determined by dividing the increase in the pollutant load by the ambient water quality standard. The additional volume of water required to assimilate the increase in the load of pollutants that have resulted from evaporation represents an additional grey water footprint that should be summed with a grey water footprint prior to evaporation to obtain the total grey water footprint.

In many instances, one may be confronted with a situation whereby various types of pollutants enter a particular water body as effluent. Whilst it is true that all the pollutants in the water body make up the grey water footprint of that water body, the grey water footprint does not account for the combined impact of pollutants. The dilemma is made worse when one has to decide whether to account for the grey water footprint of the effluent that enters a water body or the waste material in the water body itself at some downstream point. This challenge is presented by the fact that the grey water footprint does not account for any changes in the water quality that may occur along the water flow.

In light of the abovementioned scenarios, the waste material that accounts for the largest share of the grey water footprint may be used to represent the overall grey water footprint of that particular water body. Given the circumstances regarding the change in water quality as effluent flows along the water body and the inability of the grey water footprint indicator to account for such alterations, the grey water footprint of the effluent that enters the water body must be given preference in determining the grey water footprint of a water body (Hoekstra *et al*., 2011).

2.4.1.4 TOTAL WATER FOOTPRINT

The total water footprint is the final step in water footprint accounting. In the case of a product, a sufficient understanding of the value chain of that particular product will allow for a more accurate estimation of each of the three water footprint indicators and thus the total water footprint. Once the blue, green, and grey water footprint have been quantified, one can determine the total water footprint. Adding up the three types of water footprint indicators will yield the total water footprint. The total water footprint can be calculated with the following equation:

$$WF_{proc} = WF_{proc,\ blue} + WF_{proc,\ green} + WF_{proc,\ grey}\ [\text{volume/mass}] \qquad [11]$$

The accuracy of this result greatly depends on a basic understanding of the value chain of the relevant product.

2.4.2 STRESS-WEIGHTED WATER LIFE CYCLE ASSESSMENT APPROACH

According to Pfister, Koehler and Hellweg (2009), the stress-weighted water life cycle assessment (LCA) approach must be used as the foundation upon which a water footprint is determined. The life cycle inventory (LCI) phase should not only account for the volume of water consumption but also for the origin and type of water use (Pfister, Koehler and Hellweg, 2009). In contrast to the volumetric water footprint approach, the LCA approach conveys the region-specific effects of water consumption (Van der Laan *et al*., 2013).

Consumptive water use comprises all the freshwater withdrawals that are allocated to various watersheds, incorporated into the product, or evaporated (Pfister, Koehler and Hellweg, 2009). Pfister, Koehler and Hellweg (2009) were primarily concerned with this consumptive water use. Despite the fact that consumptive water use includes both blue and green water use, the LCA method suggested by Pfister, Koehler and Hellweg (2009) only accounts for the blue water footprint. This may be attributed to the fact that green water does not form part of environmental flows until it becomes blue water (Scheepers, 2015). Mila i Canals *et al*. (2008) and Pfister, Koehler and Hellweg (2009) presented alternative approaches to LCAs.

2.4.2.1 LIFE CYCLE ASSESSMENT APPROACH PROPOSED BY MILA I CANALS ET AL. (2008)

The Mila i Canals *et al.* (2008) approach assesses the consumption of freshwater resources at a river basin. It takes the source of water as well as the type of use of freshwater resources into account (Mila i Canals *et al.*, 2008). Regarding water sources, it distinguishes between blue and green water sources. The blue water sources consist of flow (river or lake), fund (aquifer), or stock (fossil) water, whereas freshwater use comprises evaporative and non-evaporative use. Non-evaporative use refers to water that returns to the freshwater source and may be reused. This approach recognises water that is released to a different freshwater source as a non-evaporative use (Jeswani and Azapagic, 2011). The approach of Mila i Canals *et al.* (2008) focuses on two impact pathways of freshwater consumption:

- Freshwater ecosystem impact (FEI); and
- Freshwater depletion (FD).

Freshwater ecosystem impact gives a description of how the ecosystem quality is affected by alterations in freshwater availability and water cycles caused by a shift in land use. A water stress index (WSI_{Mila}) is defined for each river basin. The water stress index is the ratio of the water withdrawal to the water available for human use after deducting the required amount of water to sustain the ecosystem (Mila i Canals *et al.*, 2008).

This may be calculated with the following formula:

WSI_{Mila} = Water use / (Water Resources Available - Ecological Water Requirement)

Changes in land use have a considerable impact on the availability of freshwater resources to users by greatly influencing the infiltration and evapotranspiration rate. Hence land use is a significant aspect in a Life Cycle Inventory Analysis (LCIA). Freshwater depletion explores the decline in long-term availability of groundwater which may be attributed to its use.

2.4.2.2 THE PFISTER, KOEHLER AND HELLWEG (2009) APPROACH

The Pfister, Koehler and Hellweg (2009) approach examines the water use of a watershed, with the main focus of this approach being the blue water use. It further distinguishes between three types of blue water use, namely in-stream water use, water consumption where water resources have become unavailable in the watershed, and water quality degradation. This approach recognises water that is released to a different watershed as being consumed (Jeswani and Azapagic, 2011).

In the Pfister, Koehler and Hellweg (2009) approach, emphasis is placed on three areas of protection, namely:

- human health;
- ecosystem quality; and
- resources.

Unsustainable water consumption may result in a detrimental impact on human health by giving rise to an inadequate water supply for irrigation, which in turn will promote malnutrition. Ecosystem quality is recognised as a function of water availability. Decreases in available freshwater supplies in ecosystems are accompanied by the degradation of vegetation and biodiversity, which lead to poor ecosystem quality.

2.4.3 HYDROLOGICAL WATER BALANCE METHOD

Deurer *et al*. (2011) proposed the hydrological water balance approach. The significant difference between the approach proposed by Hoekstra *et al*. (2011) and that of Deurer *et al*. (2011) is that, in the latter, all the components of the water balance are accounted for (Van der Laan *et al*., 2013). The hydrological water balance method as suggested by Deurer *et al*. (2011) makes use of both positive and negative water footprints. A positive water footprint entails that the total blue water consumption is greater than the total recharge of the water body, whereas a negative water footprint entails that the restoration of the blue water is greater than the total volume consumed or taken up from the water body. Thus a negative water footprint is indicative of sustainable water use (Deurer *et al*., 2011; Van der Laan *et al*., 2013).

2.4.4 RELATED RESEARCH ON WATER FOOTPRINT ASSESSMENTS IN THE GRAIN AND BROILER INDUSTRY

There are several WFA studies that have been published by various authors such as Ercin, Mekonnen and Hoekstra (2013), Mekonnen and Hoekstra, (2010), Sun *et al*. (2013), and others. This section will identify what was done, how it was done, and the findings thereof. The purpose of this paper is to investigate the water footprint of maize and broiler as derived products.

The water footprint of crop production is an inclusive indicator that can indicate water consumption types, volumes, and the effect on the environment (Sun *et al*., 2013). Sun *et al.* (2013) evaluated how climate change affected the crop water requirements and irrigation water requirements of maize production during the period 1978 to 2008. They investigated the extent to which the green, blue, and grey water footprints of maize production varied each year in response to climate change and the use of agricultural inputs. They also assessed the main factors that contributed to changes in the water footprint of maize production. Sun *et al.* (2013) used the non-parametric Mann-Kendall test to evaluate climatic factors, and the volumetric water footprint approach to water footprinting. They used correlation and path coefficient analyses to determine the relationship between the water footprint and its associated impact factors. They found that the crop water requirement increased by about 0.52 mm per annum, whereas the irrigation water requirement for maize tended to increase by about 2.86 mm per annum. These increases may be attributed to variations in climatic conditions, which exhibited an average trend of increasing temperatures and decreasing rainfall. The total water footprint and green water footprint exhibited decreasing trends, whereas the blue and grey water footprints showed increasing trends in response to the combined effect of climate variation and agricultural inputs. Sun *et al*. (2013) concluded that a decrease in effective precipitation would lead to a decrease in the green water footprint and an increase in the blue water footprint. Furthermore, an increase in agricultural inputs such as chemical fertilisers would lead to an increase in the grey water footprint (Sun *et al*., 2013).

Mekonnen and Hoekstra (2010) estimated the green, blue, and grey water footprint of global crop production for the period 1996 to 2005. The water footprints of crop production were determined using the volumetric water footprint approach. A grid-based dynamic water balance model and CROPWAT 8.0 were used to calculate crop water use. Mekonnen and Hoekstra (2010) found that the global water footprint associated with crop production during the period from 1996 to 2005 was 7 404 billion m^3 per year, which comprised 78% green, 12% blue, and 10% grey water footprints. This suggests that green water contributes greatly to global crop production. Blue water is found to be high in arid and semi-arid areas. Despite grey water accounting for the smallest share of the total water footprint, it is important to note that it is only associated with nitrogen fertilisation.

Mekonnen and Hoekstra (2014) determined a global water footprint benchmark for several crops worldwide. They calculated the green, blue, and grey water footprints of the crops on a five-by-five foot area using a dynamic water balance and crop yield model. In determining the components of a water footprint for each crop, they followed the volumetric water footprint approach. Regarding the grey water footprint component, they assessed nitrogen fertilisation levels, leaching-runoff fractions of nitrogen, as well as ambient water quality standards for nitrate. The water footprint benchmarks were developed and evaluated at a grid-level spatial resolution. They grouped countries according to their income in order to evaluate differences in water footprints between developing and industrialised countries. They divided the world into four categories based on climate using the Köppen-Geiger climate classification in order to examine how water footprints varied across different climatic regions. Mekonnen and Hoekstra (2014) found that the consumptive water use of maize (m^3/tonne) varied across the globe, and they therefore divided the water use into percentiles. The consumptive water use of maize was 754 m^3/tonne in the 50^{th} percentile, with a global average of 1 028 m^3/tonne. According to Mekonnen and Hoekstra (2014), if the global green and blue water footprints were reduced to the 50^{th} percentile, there would be a 35% reduction in the consumptive water use. The grey water footprint of maize production in the 50^{th} percentile was 171 m^3/tonne, with a global average of 194 m^3/tonne. If the grey water footprint of all the countries in the world could be reduced to the 50^{th} percentile, there would be a 23% decline in water pollution (Mekonnen and Hoekstra, 2014). At the 50^{th} percentile, the reduction in water pollution translates to a 23% increase in water availability worldwide (Mekonnen and Hoekstra, 2014). Mekonnen and Hoekstra (2014) concluded that the water footprint benchmark values may be used for comparison with the water footprint in a particular region or may be used as a reduction target. Given the considerable increase in water availability, the global benchmarks are attractive water footprint reduction targets for crop farmers.

Maize is used in the food industry as a sweetener to manufacture high-fructose maize syrups (HFMS) and to produce ethanol (Gerbeens-Leenes and Hoekstra, 2009). About three-quarters of the ethanol produced worldwide is used as a fuel (Worldwatch Institue, 2007). The United States of America (USA) was the leading manufacturer of ethanol derived from maize in 2005 (Gerbens-Leenes and Hoekstra, 2009). According to the FAO (2008), ethanol production in the USA contributes about 43% to global bio-ethanol production. In 2019, the demand for maize in the USA for the purpose of producing ethanol is anticipated to increase to approximately 40% of total maize production (Gerbens-Leenes and Hoekstra, 2009). Producing ethanol by dry milling requires about 1 735 litres of water per tonne of maize (Gerbens-Leenes and Hoekstra, 2009). In contrast, wet milling consumes about 1 921 litres per tonne of maize (Gerbens-Leenes and Hoekstra, 2009). Hence producing ethanol by dry milling rather than wet milling would save 186 litres of water per tonne of maize. About 95% of the ethanol produced globally is derived from crops such as maize (Gerbens-Leenes and Hoekstra, 2009). Maize is the second most suitable crop for sugar and ethanol production in the world (Gerbens-Leenes and Hoekstra, 2009). The global average water footprint of HFMS 55 in particular is 1 125 m^3/tonne, and for ethanol derived from maize it is 1 910 litre/litre (Gerbens-Leenes and Hoekstra, 2009). However, in the USA alone, maize has the lowest water footprint associated with producing sugar and ethanol (Gerbens-Leenes and Hoekstra, 2009). The average water footprint of HFMS 55 and ethanol derived from maize starch in the USA is

720 m^3/tonne and 1 220 litre/litre respectively. The maize products mentioned above primarily owe the degree of their water footprints to the maize water requirement and yields realised (Gerbens-Leenes and Hoekstra, 2009). Crop water requirement is a function of crop type, climate, and soil characteristics. Yields, on the other hand, have an inverse relationship with the water footprint (Gerbens-Leenes and Hoekstra, 2009). In other words, assuming that water use remains constant, increasing yields per ha will effectively reduce the water footprint per tonne of maize. In South Africa, the total water footprint of ethanol derived from maize is 4 264 litre/litre. It is comprised 3 879 litres of green water, 79 litres of blue water, and 306 litres of grey water per litre of ethanol (Mekonnen and Hoekstra, 2010). Alternatively, the water footprint of ethanol production may be expressed as 182 m^3/GJ ethanol (Mekonnen and Hoekstra, 2010). This is composed of 166 m^3 green water, 3 m^3 blue water, and 13 m^3 grey water per GJ ethanol (Mekonnen and Hoekstra, 2010).

Mekonnen *et al.* (2015) evaluated the sustainability, efficiency, and equity of water use in Latin America and the Caribbean. Their aim was to create an awareness of water use from a production and consumption perspective. Their analysis was based on a geographic WFA, and followed the volumetric water footprint approach. The grey water footprint focused on nitrogen. They used the three pillars of sustainability approach as suggested by Hoekstra (2013; 2014) to evaluate the sustainability, efficiency, and equitability of water allocation and use. Maize production accounts for one of the highest green water footprints, third largest blue water footprint, and the highest grey water footprint in Latin America and the Caribbean (Mekonnen *et al*., 2015). Despite its relatively low economic water productivity (EWP) of 0.10 US$/$m^3$ (Mekonnen *et al*., 2015), maize production accounts for a considerable share of freshwater consumption in Latin America and the Caribbean. Mekonnen *et al*. (2015) recommended the productive and efficient use of green water in rain-fed agriculture in order to increase production and minimise the demand for blue water resources, especially in water-scarce areas. They also recommended that there should be communication with small farmers, river basin managers, and policy makers, as well as readily available water data at the river basin level. Regarding the grey water footprint, Mekonnen *et al*. (2015) suggested that fertiliser applications should be optimised and the discharge of untreated water from the domestic sector must be reduced in order to lower nutrient pollution. It is therefore important to devise methods of increasing the productivity of green water and lowering the grey water footprint and to establish a platform for river basin managers to communicate water data to policy makers and farmers.

Mekonnen and Hoekstra (2014) measured the water footprint of Kenya related to national production and consumption for the period 1996 to 2005, as well as the virtual water export and import of Kenya. Their aim was to evaluate the relationship between water consumption within Kenya and its international trade. Mekonnen and Hoekstra (2014) quantified the green, blue, and grey water footprint using the volumetric water footprint approach. The total water footprint of crop production in Kenya during 1996 to 2005 consisted of 97% green water, 1% blue water, and 2% grey water (Mekonnen and Hoekstra, 2014). Mekonnen and Hoekstra (2014) identified maize as the crop with the highest total water footprint related to crop production. Maize production accounted for 38% of the total water footprint (6 794 million m^3/year; 6 688 million m^3 green water, 11 million m^3 blue water, and 96 million m^3 grey water) related to crop production (Mekonnen and Hoekstra, 2014). Despite the high total water footprint of maize production, maize has a lower water footprint per tonne than various other crops. The water footprint of maize per tonne is 2 746 m^3; 2 703 m^3/tonne is green water, 4.4 m^3/tonne is blue water, and 39 m^3/tonne is grey water (Mekonnen and Hoekstra, 2014). Maize, coffee, and potato production account for more than 150 million m^3 of nitrogen fertiliser that leaches from crop fields.

According to Mekonnen and Hoekstra (2014), the EWP of maize production in Kenya is 0.09 US$/$m^3$. Given the expected growth in the population from an estimated 9 725 million in 2050 to 11 213 million in 2100 (United Nations (UN), 2015), as well as the changing consumption patterns, the blue water resources will drop from an estimated 316 m^3 per capita in 2050 to 192 m^3 per capita in 2100. This is quite low considering that an adequate diet requires about 1 000 m^3/year per capita (Falkenmark, Rockström and Karlberg, 2009). To avoid decreases in water availability per capita in the short to medium term, Mekonnen and Hoekstra (2014) suggested that water productivities should be enhanced. As a long-term solution to dealing with water scarcity in Kenya, Mekonnen and Hoekstra (2014) proposed that water prices should be based on full marginal cost to encourage farmers to produce crops with a relatively higher EWP, the use of water-saving technologies, and educating water users about the implications of using freshwater resources unsustainably. Mekonnen and Hoekstra (2014) also recommended that Kenya should import water-intensive agricultural products and export less water-intensive agricultural commodities. In addition to the production of crops with a high EWP, Mekonnen and Hoekstra (2014) recommended that these crops must preferably be produced from green water. A large contribution to addressing water scarcity lies in the productive use of green water. Increasing maize yields per ha will promote the productive use of green water by lowering the green water use per tonne of maize. Attention must also be paid to changes in the population size and consumption patterns in South Africa over time to estimate changes in blue water per capita. It will also be informative to quantify the extent to which maize production contributes to changes in blue water per capita.

Ercin *et al.* (2013) examined the allocation of freshwater in France and analysed the extent to which production affected the country's state of water supply. They measured the volume of freshwater used in the production of products destined for export and the impact thereof. Ercin *et al.* (2013) investigated the degree to which France relies on virtual water imports, as well as the impact thereof on the exporting country. They followed the volumetric water footprint approach to quantify water use in France. Ercin *et al.* (2013) found that agricultural production made up 89% (80 Gm^3/year) of the total water footprint of production in France. Crop production accounted for 82% of the total water footprint of national production (Ercin *et al.,* 2013). The water footprint of maize production was determined as 14% of the total water footprint of agricultural production (Ercin *et al.*, 2013). Maize production accounted for the largest share of the blue and grey water footprints related to crop production. The blue water footprint of maize production accounted for 50% of the total blue water footprint of crop production, while the grey water footprint of maize production contributed 30% to the grey water footprint of crop production (Ercin *et al.*, 2013). However, the green water footprint of maize production made up only 10% of the total green water footprint associated with crop production (Ercin *et al.*, 2013). Thus maize production accounts for the third largest share of the green water footprint of crop production in France.

France is a net importer of virtual water. Crop products constitute 69% of the virtual water export (Ercin *et al.*, 2013). The green water footprint of exported goods is 70%, the blue water footprint is 11%, and the grey water footprint is 18% (Ercin *et al.*, 2013). Maize products make up 9% of the green water footprint of the goods exported to foreign nations, 17% of the blue water footprint, and 10% of the grey water footprint (Ercin *et al.*, 2013). Maize production, amongst others, contributes considerably to the water scarcity experienced in various river basins at different times of the year (Ercin *et al.*, 2013). This water scarcity has certain implications for the biodiversity in the vicinity of the river basins

(UNEP, 2008). An identification of maize products whose water footprints contribute significantly to water scarcity can assist in devising effective methods to address the issue in the relevant river basins (Ercin *et al.*, 2013). Linkages between products purchased by consumers and water scarcity in a relevant region is the basis on which Ercin *et al.* (2013) recommended that a consumer product policy may be part of a water policy. Consumer product policies are policies such as product labeling, product transparency, tariffs or taxes, and quotas (Ercin *et al.*, 2013). An assessment of the origins of a product water footprint at the level of a local watershed is imperative for acquiring accurate comprehension of the implications that may arise in response to the magnitude of a country's water footprint (Ercin *et al.*, 2013). In South Africa, the blue and grey water footprint of maize production must be compared to the blue and grey water footprint of other field crops. The contribution of maize production to the water scarcity of river basins must be quantified and assessed. Broilers are derived maize products and as such their production should be assessed in terms of water use to ascertain the extent of their contribution to water scarcity. Consumer product policies will go a long way in communicating the degree of water scarcity to the final consumer.

Zeng *et al*. (2012) conducted a water footprint assessment of the Heihe River Basin located in northwest China to determine the water footprint of the basin and evaluate its sustainability. Zeng *et al*. (2012) used the volumetric water footprint approach to conduct this water footprint assessment. They used the CROPWAT model to estimate the effective rainfall and irrigation of crops. Zeng *et al*. (2012) found the blue water footprint to be unsustainable in the Heihe River Basin. The agricultural sector constituted 96% and crop production 92% of the total water footprint of agricultural production in this basin (Zeng *et al*., 2012). Maize production assumed an 11.1% share of the water footprint of crop production in the Heihe River Basin (Zeng *et al*., 2012). Maize thus had the second largest consumptive water footprint. Zeng *et al*. (2012) proposed optimising the crop planting pattern in order to ensure sustainable water use. Considering the contribution of green water to agricultural production, particularly crop production, which is the largest consumer of green water, Zeng *et al*. (2012) recognised the efficient use and management of green water resources as a prerequisite for improving the water management of a river basin and addressing food security.

Mekonnen and Hoekstra (2012) conducted a global assessment of the water footprint of farm animal products. They took into consideration differences in production systems, feed composition and countries. Their aim was to conduct an all-inclusive global assessment of the water footprint of farm animal products by determing the water footprint of farm animals and their derived animal products following a particular production system in a particular country for the period 1996 to 2005. They followed the volumetric water footprint approach. They found that the blue and grey water footprints associated with grazing systems are smaller than those resulting from industrial systems. They suggest that it is more water efficient to use crop products as a calorie, fat, or protein source rather than animal products. The study found that animal products in industrial systems have the largest blue and grey water footprints compared to grazing and mixed systems. However, the water footprint of chicken products in industrial systems is not consistent with the general finding because they had the lowest blue and grey water footprints compared to grazing and mixed systems.

Gerbeens-Leenes, Mekonnen and Hoekstra (2013) examined the results of Mekonnen and Hoekstra (2012). Their objective was to identify the main contributing factors to the water footprint of meat. In their study, they distinguished between poultry, pork and beef, developed and developing countries, as well as different production systems, and took their differences into consideration. The study followed the volumetric water footprint approach. The study found the main contributing factors to be food conversion efficiency, feed composition (ratio of concentrates to roughages), and the origin of the feed. According to Gerbeens-Leenes *et al*. (2013), the food conversion efficiency refers to the amount of feed that is required to produce a unit of meat. They found that the feed conversion efficiency increases from grazing to mixed to industrial systems because less feed is required to produce a unit of meat as the animals move from grazing to mixed to industrial systems. They found that the high feed conversion efficiency of poultry in industrial systems results in smaller green, blue, and grey water footprints compared to grazing systems in the United States, China, Brazil, and the Netherlands. However, the mixed and industrial poultry systems in the United States and the Netherlands have similar green, blue, and grey water footprints. Broilers were found to have the highest feed conversion efficiencies. This contributed to a low broiler water footprint. Nevertheless, the more concentrated broiler feed in industrial systems increased the blue and grey water footprints of poultry. In Brazil, relatively large green water footprints were observed for poultry whilst small total water footprints were seen in the Netherlands due to their efficient systems.

Ibidhi *et al.* (2017) analysed freshwater consumption and land use as well as greenhouse gas emissions for sheep and chicken meat production under different farming systems from 1996 to 2005. The chickens followed the industrial system. The sheep followed the agro-pastoral system using cereal crop residues (APCR), the agro-pastoral system using barley (APB), and the pastoral system using barley (PB). The water footprint assessment was carried out using the volumetric water footprint network approach. The green, blue, and grey water footprints of a chicken carcass were reported as 4 535 litres/kg, 8.7 litres/kg, and 200 litres/kg respectively, with a total water footprint of 4 746 litres/kg. The green, blue, and grey water footprints of a sheep carcass following an APCR system was reported at 10 012 litres/kg, 138 litres/kg, and 124 litres/kg respectively, with a total water footprint of 10 273 litres/kg. The green, blue and grey water footprints of a sheep carcass following an APB system were reported at 15 170 litres/kg, 113 litres/kg, and 151 litres/kg respectively, with a total water footprint of 15 434 litres/kg. The green, blue, and grey water footprints of a sheep carcass following a PB system were reported at 19 357 litres/kg, 113 litres/kg, and 151 litres/kg respectively, with a total water footprint of 19 621 litres/kg. It was found that the total water footprint of chicken meat is two to four times smaller than for sheep meat. However, the grey water footprint component was larger for chickens than for sheep. Interestingly, the broiler land and carbon footprint were also found to be relatively smaller. The large part of the broiler and sheep water footprints was associated with the feed. Broiler feed was mainly imported, therefore the broiler water footprint was largely outside of Tunisia. They concluded that the water, land, and carbon footprints become small if the feed conversion efficiency is high and the feed is produced productively.

2.4.5 DISCUSSION

The volumetric water footprint approach accounts for the green, blue, and grey water footprint. The LCA approach differs from the volumetric water footprint approach in that it conveys region-specific effects of water consumption. It also accounts for only the blue water footprint. The hydrological water balance method, on the other hand, differs in that it includes all the components of the water balance.

South Africa is a net exporter of maize. This means that there is a high demand for local maize. This translates into a greater demand for domestic freshwater resources. The pressure on local freshwater supplies is limited by net imports of wheat, soybean, and sunflower seed into the country. It is thus clear that a considerable amount of South African maize is produced for the foreign market.

The agricultural sector bears the greatest potential with respect to increasing the productivity of freshwater use. This is primarily because it accounts for the largest share of freshwater consumed compared to all other economic sectors. The average maize yields under irrigation conditions amount to about 10 t/ha. Under dryland conditions, maize yields of about 3 to 4 t/ha are harvested (Johannesburg Stock Exchange (JSE), 2013). The importance of irrigation is seen in the way it promotes higher yields. Increasing freshwater productivity in irrigated agriculture will give rise to surplus water available for reallocation to areas of water deficit. Higher yields obtained through irrigation will in turn reduce the water footprint per tonne of maize.

Enhancing freshwater productivity, as suggested by Mekonnen and Hoekstra (2014), in maize production as well as in broiler production and processing, may avoid decreases in water availability per capita in the short to medium term. As a long-term solution to dealing with water scarcity in South Africa, the proposal of Mekonnen and Hoekstra (2014) that water prices should be based on full marginal cost may be adopted in the policies of the country. Regarding Mekonnen and Hoekstra's (2014) recommendation to import water-intensive agricultural products and export less water-intensive agricultural commodities, the recommendation should not be applicable to commodities that are produced in areas outside hotspots. Maize production in the Orange-Riet Irrigation Scheme primarily occurs under irrigation conditions. As such, producing crops solely from green water will defeat the purpose of the scheme. Nevertheless, moving crops with high EWP to areas suitable for rain-fed crop production may be an alternative for achieving Mekonnen and Hoekstra's (2014) recommendation of producing crops with high EWP from green water. In order to limit the pressure on the Orange, Modder, Riet, and Lower Riet rivers, Mekonnen *et al*. (2015) called for the productive and efficient use of green water in rain-fed agriculture. This would ensure that the demand for the blue water supply in the Orange-Riet Irrigation Scheme is kept to a minimum. The proposal of Zeng *et al*. (2012) to optimise the crop planting pattern would ensure sustainable water use in the Orange-Riet Irrigation Scheme. Regarding the grey water footprint, optimising fertiliser applications, as suggested by Mekonnen *et al*. (2015), would lower nutrient pollution in the scheme.

Maize products owe a large part of their water footprints to the maize water requirement and yields realised (Gerbens-Leenes and Hoekstra, 2009). Crop water requirement is a function of crop type, climate, and soil characteristics (Gerbens-Leenes and Hoekstra, 2009). Yields, on the other hand, have an inverse relationship with the water footprint (Gerbens-Leenes and Hoekstra, 2009). In other words, assuming that water use remains constant, increasing yields per ha would effectively reduce the water footprint per tonne of maize. An identification of maize products whose water footprints contribute significantly to water scarcity can assist in devising effective methods to address the issue in relevant river basins (Ercin *et al.*, 2013). Linkages between products purchased by consumers and water scarcity in a relevant region are the basis upon which Ercin *et al.* (2013) recommended that consumer product policy may be part of a water policy. An assessment of the origins of the water footprint of maize products at the level of a local watershed is imperative for acquiring an accurate comprehension of the implications that may arise in response to the magnitude of the Orange River basin water footprint.

It is interesting to note that the crop water requirement is not a constant or universal figure. It changes over time in response to a changing environment (Sun *et al*., 2013), and it differs from one region to another. The challenge therefore is to not only address the increase in demand for freshwater associated with the expected growth of 2.3 billion people globally, between 2009 and 2050 (FAO, 2009), but also to consider the changing crop water demand. Ours is more complicated than that. Whether it is satisfied by blue water or green water is of little significance to the consumer. This fact is clearly evident in the study conducted by Sun *et al*. (2013), in which they noted a situation where an overall decrease in the green water footprint associated with maize production was accompanied by a general increase in the blue water footprint. In effect, the total water footprint reduced. This suggests that one should strive to increase the productivity of water, which will in turn reduce the demand for freshwater. It also entails that green water constitutes a major portion of the total water footprint.

Furthermore, the lack of a proportional increase in blue water to the decrease in green water is an alarming incident that raises the following questions:

- Is it that the decrease in green water is that which may be classified as unproductive such that the increase in blue water use would only substitute the productive portion of green water?
- Is it that the blue water is not sufficient to substitute all green water that is absent?

The former question should serve to indicate that there is room for improvement regarding green water use. The latter question must make one conscious of human dependence on an unreliable source of water (green water), given the issue of climate change. Although the grey water footprint is in most cases to date lower than the consumptive water footprint, it is by no means any less important. Grey water contributes to a total water footprint and its reduction entails an increase in freshwater availability. One must appreciate the nature of grey water as an unintended consequence as it stems from a production activity. The challenge regarding grey water is to reduce it whilst maintaining, if not increasing, production. In achieving this objective, Chapagain and Orr (2010) suggested that highly mobile crop nutrients (nitrogen) be applied in soil at a level slightly lower or equal to crop uptake. A decrease in the amount of nitrogen that leaches into the soil will contribute to a reduction in grey water. Hence less water will be required to assimilate the load of pollutants and return the water quality to ambient water quality standards, thus effectively reducing the total water footprint of maize production in the scheme.

In contrast to other animal products identified by Mekonnen and Hoekstra (2012), chicken products following an industrial system have a lower blue and grey water footprint than those produced under a grazing and/or mixed system. Therefore, in addition to crop products, it may also be water efficient to consume chicken products from an industrial system as a calorie, fat and protein source as opposed to other animal products identified by Mekonnen and Hoekstra (2012). Gerbeens-Leenes, Mekonnen and Hoekstra (2013) identified industrial broiler systems as a more water-efficient system in comparison to grazing and mixed systems. Nevertheless, their study also shows that the system can be improved on to obtain greater efficiency in water use. This is observed in how small total water footprints were achieved in the Netherlands due to their efficient systems. Ibidhi *et* *al.* (2017) showed that producing broilers in industrial systems results in a relatively lower water, land, and carbon footprint.

The literature that has been reviewed indicates that several studies have been done internationally following the volumetric water footprint approach. The volumetric water footprint approach has been used successfully to achieve the objectives of various studies around the world. Thus the approach may be suitable for assessing the water footprint of maize and associated broiler production in South Africa.

There is a relationship between the green and blue water components of the water footprint. There is also a relationship between fertiliser use, yields, the grey water footprint, and the total water footprint. Green water availability determines the blue water requirement. An increase or decrease in the green water footprint must be accompanied by an appropriate decrease or increase in the blue water footprint to meet the freshwater needs of the particular production process. High yields obtained through the use of fertilisers are accompanied by higher grey water footprints. Nevertheless, higher yields result in lower total water footprints.

Despite the arid or semi-arid conditions seen in countries like South Africa, the world relies more on green water for crop production compared to blue water. The extent of the reliance differs from one region to another based on the prevailing climatic conditions. Maize is a water-intensive crop with a relatively lower economic water productivity.

The water footprint of maize production at farm level accounts for a large share of the total water footprint of maize products such as broilers. Generally, livestock following an industrial production system have a higher blue and grey water footprint than those following grazing and/or mixed systems. However, broilers following industrial systems tend to have lower blue and grey water footprints than those following grazing and mixed systems. This is attributed to the high feed conversion efficiency of broilers.

In light of the recommendations described in the section on related research, this study seeks to establish sustainable water use in maize and broiler production by identifying the various ways in which freshwater can be used productively in irrigated agriculture, particularly in the Orange-Riet Irrigation Scheme. It also seeks to determine the extent to which poultry production contributes to water scarcity in the Orange River basin. The following section investigates the value of water from an economic perspective within the maize industry in South Africa.

2.5 ECONOMIC VALUE OF WATER IN SOUTH AFRICA'S AGRICULTURAL SECTOR

The value of water in the agricultural sector is best described by comparing it to the value of water in other economic sectors.

2.5.1 THE IMPORTANCE OF WATER IN SUPPORTING INCOME AND CREATING JOBS

2.5.1.1 CONTRIBUTION OF ECONOMIC SECTORS TO GROSS DOMESTIC PRODUCT PER UNIT OF WATER

The agricultural sector contributes R1.50 to the gross domestic product (GDP) per cubic metre of water that it consumes. It is followed by mining with R39.50, eco-tourism with R44.40, and the industrial sector with a staggering R157.40/m^3 of water (Nieuwoudt, Backeberg and Du Plessis, 2004). From an income perspective, the agricultural sector is clearly the most inefficient user of freshwater.

2.5.1.2 CONTRIBUTION OF ECONOMIC SECTORS TO JOB CREATION

The agricultural sector generates far less employment per cubic metre of water use compared to the industrial sector. About 108 jobs are created in the agricultural sector per one million m^3 of water. This figure is extremely low when one considers the 4 269 jobs created in the industrial sector per one million m^3 of water. The mining sector, on the other hand, creates about 150 jobs per one million m^3 of water that it consumes (Nieuwoudt *et al*., 2004). Nevertheless, when one considers the employment created within the agricultural sector on the basis of "per value of agricultural products", a different conclusion is reached. Agricultural output worth R1 million is associated with the creation of 24 jobs. This is a higher level of employment compared to the mining and manufacturing sectors that yield 10.9 and 9.0 jobs per R1 million worth of output respectively (Nieuwoudt *et al*., 2004).

2.5.1.3 CONTRIBUTION OF IRRIGATION TO AGRICULTURAL PRODUCTION

The role and significance of irrigated agriculture in the agricultural sector should not be assessed on the basis of its relatively low share of cultivated land, which in Tunisia amounts to 7% (Chouchane *et al*., 2013). At least 35% of the total production in Tunisia's agricultural sector may be attributed to irrigated agriculture. Furthermore, irrigated agriculture consumes more than 80% of the total water withdrawn in Tunisia (Chouchane *et al*., 2013). In South Africa, only 10% of maize production occurs under irrigation. However, irrigated maize yields 5.28 t/ha to 6.10 t/ha more than under rain-fed conditions. Therefore irrigation contributes to higher crop output.

2.5.1.4 FOOD PRODUCTION VERSUS WATER SCARCITY AS A DRIVER FOR PRODUCTIVITY

As the supply of water diminishes, water users increasingly promote the productive use of water (Chouchane *et al*., 2015). This is unfortunate because it entails that water users wait to experience the impact of water scarcity before supporting the efficient use of freshwater resources. The productive use of water should be based on the contribution of freshwater to food production rather than on water scarcity. Nevertheless, Chouchane *et al.* (2015) suggested that both scarcity and the contribution of water to food production encourage the wise use of water resources.

2.5.1.5 WATER PRODUCTIVITY

Water productivity (WP) is defined as the amount of output derived per unit of water consumed (Chouchane *et al*., 2015). Freshwater productivity can be broken down such that it highlights the source of freshwater that is of relevance. In the case of rain-fed agriculture, one must refer to green WP. Surprisingly, under irrigation conditions, both the green and blue WP are important. This is evident in the reality that under irrigation conditions, rainfall does occur. In other words, green water is consumed in combination with blue water, or at least during the same production period. Hence the terms green WP and blue WP become relevant in irrigated agriculture.

2.5.1.6 *WATER PRODUCTIVITY IN IRRIGATED AGRICULTURE*

In the context of irrigated agriculture, green WP refers to the ratio of the yield that is realised from green water consumption in the absence of blue water to the green water footprint of that particular activity. Furthermore, the blue WP is the ratio of the increase in yield associated with blue water consumption to the water footprint of that particular activity (Hoekstra, 2013). Physical WP refers to the ratio of agricultural output to the volume of water consumed (Chouchane *et al*., 2015).

2.5.1.7 *ECONOMIC WATER PRODUCTIVITY OF CROP PRODUCTION*

Economic water productivity (EWP) is the value realised per unit of water use (Chouchane *et al*., 2015). The economic productivity of water use is better defined once the water consumption of a particular crop is established. In this case, water use is expressed in terms of monetary unit/m^3, rather than tonne/m^3 or kg/ℓ (Hoekstra *et al*., 2011). An EWP (R/m^3) is the product of physical WP (kg/m^3) and crop value (R/kg). Chouchane *et al*. (2015) found that the EWP in rain-fed agriculture (0.35 US$/m^3) was higher than in irrigated agriculture (0.32 US$/m^3). They also found that the economic land productivity (ELP) in irrigated agriculture was greater than in rain-fed agriculture.

In light of the above findings, they concluded that there was a direct relationship between irrigation and the ELP (R/ha). Regarding EWP (R/m^3), Chouchane *et al*. (2015) went on to state that one cannot raise the EWP (R/m^3) by applying more irrigation. However, irrigation should be increased for crops with a high EWP and for which the difference between ELP in rain-fed and irrigated agriculture is high. This will allow one to benefit from the increase in EWP associated with such crops, as well as from the increase in ELP. This is a viable alternative where market conditions exist and crops with low EWP may be imported from other countries (FAO, 2012). Schyns and Hoekstra (2014) calculated the EWP for a variety of crops. They found that crops that accounted for the highest consumptive use of freshwater were associated with the lowest EWP, which ranged from 0.02 US$/m^3 for almonds to 0.08 US$/m^3 for wheat. Tomatoes, on the other hand, had an EWP that was 22 times higher than that of wheat. In semi-arid countries such as Morocco and South Africa, the productive use of freshwater must be a national priority. Hence, in addition to the factors that are considered in deciding which crops to produce (national strategy regarding food security and demand for crops), the EWP of a crop must also be taken into account.

2.5.1.8 GREEN VERSUS BLUE WATER PRODUCTIVITY

In Africa, green water contributes more to crop production than blue water. Morocco is a typical example, where 77% of its water footprint is green water (Schyns and Hoekstra, 2014). It is thus clear that the solution to lowering the blue water footprint lies in the productive use of green water. Rainwater harvesting is essential in ensuring blue water availability in times when there is no precipitation to meet the immediate needs of freshwater. This statement, however, becomes controversial when there is considerable evaporation of freshwater from reservoirs that ultimately increases the blue water footprint of a particular production process. This is true for Morocco, where evaporation losses contribute 13% to the blue water footprint of the country (Schyns and Hoekstra, 2014).

2.5.2 DISCUSSION ON THE ECONOMIC VALUE OF WATER IN THE AGRICULTURAL SECTOR

According to Mekonnen *et al*. (2014), the demand for freshwater will increase in the next couple of years in response to the rising demand for food, fibre, and biofuel crops. Sustainable economic growth and development, energy production, and food security depend heavily on the availability of freshwater (KPMG and Small Enterprise Development Agency (SEDA), 2012). However, considering the degree of dependence of a nation's economy on freshwater resources, the economic value of water does not appropriately convey the value of water (KPMG and SEDA, 2012). As the demand for freshwater rises amongst the various sectors in an economy, at a particular point local freshwater reserves may be insufficient to satisfy the demand. This may compromise food security, as evident in the fluctuating global food prices (KPMG and SEDA, 2012). About 8% of South Africa's rainfall becomes runoff (KPMG and SEDA, 2012). About 17% of captured or stored freshwater is released unintentionally into the environment due to degraded infrastructure that does not have the capacity to hold water sufficiently (KPMG and SEDA, 2012). The increase in the demand for water can be accommodated by using freshwater resources in a sustainable manner. This sustainability may be acquired by increasing the productivity of water in the agricultural sector.

Freshwater is a valuable resource and it must be treated as such. In dealing with the issue of water, it is important for one to acknowledge the influence that one source of water has on the use of another. The productive use of green water will lower the pressure on blue water resources. It is also important for one to appreciate the differences in the water consumption of crops produced in different river basins owing to the different climatic conditions in each river basin. The phenomenon of climate change will thus introduce changes in the known water consumption of crops produced in various river basins. Furthermore, the productivity of one crop with respect to water use varies from another. This variation may be attributed to the characteristics of each crop. In deciding which crop to produce, the EWP of a crop must be considered. An increase in irrigation increases ELP (R/ha). Increasing the ELP for crops with a high EWP is an effective way of promoting freshwater productivity in irrigated agriculture. The productive use of water has the potential to lower costs and thus increase income.

From an income perspective, the agricultural sector is clearly the most inefficient user of freshwater. Regarding employment created by the sector, the benefits derived from water are in one view undesirable, whilst in another satisfactory. The agricultural sector yields insignificant jobs per unit of water use relative to other sectors. However, when one considers the value of the agricultural product, the agricultural sector employs more workers than other sectors. An agricultural product is a good that has a water footprint of its own. With an agricultural product, the total volume of water used rather than per unit water consumed becomes relevant. Hence the focus shifts from water to the product itself. Thus the employment associated with the product is the number of jobs created along the value chain of the product. It is this employment that is said to be higher than in other economic sectors.

2.6 CONCLUSIONS FROM THE LITERATURE AND THE IMPLICATIONS FOR THIS RESEARCH

Maize is an important crop in South Africa. It is a major feed grain and a staple food for the majority of South Africans. It contributes approximately 46.1% to the gross value of field crops. The Free State is the major maize production region in South Africa. While rainfed maize production is still dominating in South Africa, irrigated maize production is becoming increasingly important in order to meet the increased demand for maize, especially by the animal feed industry. Broiler production by far accounts for the largest share of feed sales in South Africa. Feed sales associated with broiler production have increased by 34.45% for the period 2005 to 2013. Maize is a main ingredient in animal feed and makes up about 60% of the feed for broiler chicks and 59.32% of the feed for broiler chickens. Broilers make a marked contribution to South Africa's economy and to South Africa's animal feed industry.

While the maize and broiler industries are considered important from an economic perspective, both industries are also documented to be major water users. Thus, it is important to understand the pressure placed by the maize and broiler industries on the scarce freshwater resources in order to ensure the sustainable use of the scarce resource in South Africa.

The volumetric water footprint approach is preferred over the LCA approach because it accounts for the green, blue, and grey water footprints. It is also preferred over the hydrological water balance method because it demands less data for quantifying the green and blue water footprints. Therefore, for the purposes of this study and for the abovementioned reasons, the volumetric water footprint approach is the preferred methodology of this study.

A water footprint is a useful indicator to determine how much of available freshwater is made unavailable through consumption. A WFA can be applied to any activity that uses or relies on freshwater.

The maize-broiler value chain is more in line with the chain summation approach. Several inputs are used to produce maize; however, attention is only given to water and fertiliser. Various inputs are used to produce broilers but the relevant input is maize. Broilers are intended for only one output product, namely chicken meat.

Water footprint assessments have been applied on a global scale. The issue of water scarcity is a global crisis with varying degrees of severity between regions; it is therefore not unique to South Africa. Many of the recommendations made in other countries are applicable to the South African context. It is interesting to note that green and blue water can substitute each other to promote sustainability.

The agricultural sector is a water-intensive sector. Nevertheless, productivity can be achieved by enhancing the ELP for crops with a higher EWP. It is inefficient in terms of income obtained per unit of water used and employs less people per unit of water used compared to other sectors. However, in terms of the total volume of water used along the value chain of an agricultural product, the sector accounts for one of the highest employment levels compared to several other sectors.

CHAPTER 3

METHODS AND DATA

3.1 INTRODUCTION

Chapter 3 focuses on the methodology and data that were used to address the aim and objectives of the study. In Chapter 2 it was established that the volumetric water footprint approach is the most suitable methodology for the purposes of this study.

3.2 METHOD

The volumetric water footprint approach has been identified as the method of choice for the purposes of this study. This approach comprises four phases that explicitly guide the procedure for conducting a WFA. The first phase involves setting the goals and scope of the study. Phase 2 comprises water footprint accounting. This is followed by a water footprint sustainability assessment in Phase 3, and finally a response formulation in Phase 4.

3.2.1 STAGE 1: FORMULATING GOALS AND SCOPE

3.2.1.1 GOALS OF A WATER FOOTPRINT ASSESSMENT

Each WFA study has a unique purpose. This purpose will in turn demand attention to various aspects that will inevitably make up the scope of the study. Hence one must first identify the goal of a WFA. Once the goal has been established, the foundation upon which the scope will emerge will be set.

The data for this study were acquired from experiments documented by Van Rensburg *et al.* (2012), as well as from a broiler-producing company. The broiler company procures its feed elsewhere but produces and processes their broilers on-site. For the purposes of this study, all the components of the water footprint will be considered for maize production but only the blue water footprint will be considered for broiler production and processing.

The processes that account for a considerable share of the water footprint in the value chain are identified as feed production and broiler production and processing. Both the direct and indirect water footprints will be considered because the water footprint of the feed is an indirect water footprint of the broiler-producing firm. Accounting for both the direct and indirect water footprints will achieve the aim of the study. In analysing the sustainability of the maize-broiler value chain, only the blue water footprint will be considered. It will be assessed based on the water availability in the Orange River basin. The study will only focus on the environmental aspect of sustainability. The study intends to inform maize and broiler producers and processors as well as policy makers about the environmental impact of using water to produce maize and broilers at a certain time of the year. Producers and processors are anticipated to respond by taking the recommendations of this study into consideration as they perform their activities. Policy makers are expected to consider the findings of this study as they amend or draft policies.

3.2.2 STAGE 2: WATER FOOTPRINT ACCOUNTING

Blue Water Footprint (volume/time)

$$WF_{proc,\ blue} = \text{Blue Water Evaporation} + \text{Blue Water Incorporation} + \text{Lost Return Flow}\ [\text{volume/time}] \qquad [12]$$

The blue water footprint of the process of growing a crop is expressed as the volume of water consumption per unit of time. However, when divided by the yield, the units change to the volume of water consumed per tonne. It is important to note that the water footprint of a consumer, producer, or a particular area is always expressed in terms of the volume of water consumed per unit of time since there is no “yield” to be realised in such cases. Time may be expressed per day, month, or year, depending on the study.

Blue Water Evaporation
This comprises the water that may be used through evapotranspiration, evaporate during storage (e.g. artificial water reservoirs, dams, harvested rainwater, etc.), transport (e.g. open canals), processing (e.g. evaporation of heated water that is not recollected), and collection and disposal (e.g. from drainage canals and from wastewater treatment plants).

Blue Water Incorporation

The volume of blue water that is incorporated into the crop or product.

Lost Return Flow

The part of the return flow that is not available for reuse within the same catchment within the same period of withdrawal, either because it is returned to another catchment (or discharged into the sea) or because it is returned in another period of time.

Green Water Footprint (volume/time)

$WF_{proc,\ green}$ = Green Water Evaporation + Green Water Incorporation [volume/time] [13]

Green Water Evaporation

The evaporation of rainwater stored in soil or temporarily positioned on the surface of soil or vegetation.

Green Water Incorporation

Absorption of freshwater derived from the top soil or soil surface into the crop.

Grey Water Footprint (volume/time)

$$WF_{proc,\, grey} = \frac{L}{c_{\max} - c_{nat}} \quad [volume/time] \qquad [14]$$

The pollutant load (L) is the mass of the substance that is released into a water body at a particular time. The maximum concentration (c_{max}) refers to the highest level of the pollutant load that is considered acceptable in a given water body, while the natural concentration (c_{nat}) is the mass of the substance present in a water body in the absence of human influence, interference, or activity.

3.2.2.1 WATER FOOTPRINT OF GROWING A CROP

The total water footprint (WF_{proc}) of the process of growing a crop is calculated as follows:

$$WF_{proc} = WF_{proc,\,green} + WF_{proc,\,blue} + WF_{proc,\,grey} \quad [m^3 / tonne] \tag{15}$$

Hence, WF_{proc} is the sum of the green, blue, and grey water footprints of the process of growing a crop.

The green water footprint ($WF_{proc,\ green}$) of the process of growing a crop is calculated as follows:

$$WF_{proc,\,green} = \frac{CWU_{green}\,(m^3/ha)}{Y\,[ton/ha]} \quad [m^3 / tonne] \tag{16}$$

Hence, $WF_{proc,\ green}$ is the green crop water use (CWU_{green}) measured in m³/ha divided by the yield (Y) measured in tonne/ha.

$$CWU_{green} = 10 \times \sum_{d=1}^{1gp} ET_{green} \quad [m^3 / ha] \tag{17}$$

ET_{green} is the evapotranspiration of green water. Factor 10 is a standard used to convert water depths in millimetres into water volumes per land surface in m³/ha. The equation d = 1 illustrates that green water evapotranspiration is calculated from the “first day of planting”. 1gp represents the day of harvest, thus it entails measuring evapotranspiration for the entire length of the crop-growing period in days. Hence the CWU_{green} is the sum of the evapotranspiration experienced by the crop over the growing period, from planting to harvest.

The blue water footprint of the process of growing a crop is calculated as follows:

$$WF_{proc,\,blue} = \frac{CWU_{blue}}{Y} \quad [m^3 / tonne] \tag{18}$$

Hence, $WF_{proc,\ blue}$ is the blue crop water use (CWU_{blue}) measured in m^3/ha divided by the yield (Y) measured in tonne/ha (Hoekstra *et al*., 2011).

$$CWU_{blue} = 10 \times \sum_{d=1}^{1gp} ET_{blue} \quad [m^3/ha] \tag{19}$$

ET_{blue} is blue water evapotranspiration. The CWU_{blue} works on the same basis as the CWU_{green}. The only difference is that ET_{blue} is used instead of ET_{green} (Hoekstra *et al*., 2011).

The grey water footprint ($WF_{proc,\ grey}$) of the process of growing a crop is calculated as follows:

$$WF_{proc,\,grey} = \frac{L}{(C_{\max} - C_{nat})} = \frac{(\propto \times AR)}{(C_{\max} - C_{nat})} \left(volume/time\right) \tag{20}$$

$$WF_{proc,\,grey} = \frac{(\propto \times AR)\,/\,(C_{\max} - C_{nat})}{Y} \quad \left(m^3\ /\ tonne\right) \tag{21}$$

AR is the chemical application rate to the field per ha (kg/ha). $\propto$ represents the leaching-runoff fraction. C_{max} is the maximum acceptable concentration of the pollutant (kg/m^3). C_{nat} is the natural concentration for the pollutant considered (kg/m^3). Y represents crop yield (tonne/ha).

The $WF_{proc,\ grey}$ calculates the volume of solution that is leached into the soil. It then divides it by the increase in the chemical concentration of the water source into which the chemicals (e.g. salts) were deposited. This quotient is then further divided by the yield to determine the $WF_{proc,\ grey}$ in m^3/tonne. Note that the pollutants are mainly fertilisers, pesticides, insecticides, and herbicides. Subtracting C_{nat} from C_{max} indicates the amount of pollutant that has been applied. It is important to note with regard to the grey water footprint that one only considers the pollutant that accounts for the largest contribution to the grey water footprint (Hoekstra *et al*., 2011).

3.2.2.2 *WATER FOOTPRINT OF A PRODUCT*

According to Hoekstra *et al.* (2011), the water footprint of a product is the total volume of freshwater that is utilised both directly and indirectly to produce the product. It comprises three components, namely the green, blue, and grey water footprints. A water footprint accounts for the volume and type of consumptive water use, as well as when and where that water is used.

There are two methods of calculating the water footprint of a product: the chain summation approach and the stepwise accumulative approach. The chain summation approach can only be used when a production system produces one output product. Hence this study follows the chain summation approach.

3.2.2.3 *ANIMAL PRODUCT WATER FOOTPRINT*

The water footprint of an animal product comprises a direct water footprint and an indirect water footprint (Mekonnen and Hoekstra, 2010). The direct water footprint is associated with drinking water and service water used (Mekonnen and Hoekstra, 2010). The indirect water footprint is the water that is linked to the feed (Mekonnen and Hoekstra, 2010). According to Mekonnen and Hoekstra (2010), the water footprint of an animal product may be expressed as follows:

$$WF_{chicken} = WF_{feed} + WF_{drink} + WF_{service} \qquad [m^3/year/chicken] \text{ or } [m^3/chicken] \qquad [22]$$

$WF_{chicken}$ is the total water footprint associated with the production of a tonne of chicken meat. WF_{feed} is the total water footprint associated with producing chicken feed. WF_{drink} is the water that the chickens drink during their production and is associated with a blue water footprint. $WF_{service}$ is the water used to create and sustain a hygienic environment suitable for chicken production. $WF_{service}$ has a blue and a grey water footprint.

It is more appropriate to express the water footprint of broiler chickens in terms of m^3/chicken (Mekonnen and Hoekstra, 2010). However, the water footprint of layer chickens is best described as m^3/year/chicken (Mekonnen and Hoekstra, 2010). The component of the water footprint of a chicken that is associated with chicken feed is calculated as follows:

$$WF_{feed} = \frac{\sum_{p=1}^{n}(Feed[p] \times WF^{*}_{prod}[p]) + WF_{mixing}}{Pop*} \qquad [23]$$

Feed [*p*] represents the yearly quantity of the feed ingredient *p* that is consumed by a chicken and is expressed in terms of tonne/year. $WF^{*}_{prod}[p]$ is the water footprint of the feed ingredient *p*, which is expressed in terms of m^3/tonne. WF_{mixing} is the water footprint of mixing the chicken feed and is expressed in terms of m^3/year/chicken. *Pop** is the number of slaughtered broiler chickens per year. The water footprint of the feed ingredient *p* may be calculated as follows:

$$WF^{*}_{prod}[p] = \frac{P[p] \times WF_{prod}[p] + \sum_{n_e} T_i[n_{e,}\, p] \times WF_{prod}[n_{e,}\, p]}{P[p] + \sum_{n_e} T_i[n_e, p]} \qquad [24]$$

P [*p*] is the quantity of the feed product produced in a country per year and it is expressed in terms of tonne/year. $T_i[n_e,p]$ is the amount of feed product *p* that is imported from an exporting nation n_e and it is expressed in terms of tonne/year. $WF_{prod}[p]$ is the water footprint of the feed product *p* when it is produced in the nation under review and it is expressed in terms of m^3/tonne. $WF_{prod}[n_{e,p}]$ is the water footprint of the feed product *p* when it is produced in the exporting nation n_e and it is expressed in terms of m^3/tonne.

The amount and composition of feed consumed is a function of animal type, the production system, as well as the country in which production takes place. The differences in climatic and agricultural practices between different countries make the water footprint of feed crops different from one country to another. The total feed consumed by a certain animal following a production system in a country may be calculated as follows:

$$Feed = FCE \times P \qquad [25]$$

Feed represents the total quantity of an animal's feed intake (tonne/year). *FCE* is the feed conversion efficiency of the animal (kg dry mass of feed/kg of product). *P* is the total quantity of product produced by an animal, for instance meat produced by broiler chickens or the total quantity of eggs produced by layer chickens. The term "feed conversion efficiency" is used to describe the quantity of feed an animal must consume to produce a unit product (Mekonnen and Hoekstra, 2010). Low FCE suggests that an animal is an efficient user of feed.

3.2.2.4 TOTAL WATER FOOTPRINT

The blue water footprint of the maize-broiler value chain will comprise the blue water footprint of farm-level irrigated maize and chicken production. At the processor level, the blue water footprint will include that of processing maize into chicken feed and processing broiler chickens into final products for consumers, as well as the blue water utilised for cleaning and sanitation at the processing plants.

Green water in the maize-broiler value chain only plays a role during farm-level maize production, thus the green water footprint will only be calculated for maize production. There is no green water use at farm-level broiler chicken production, neither is green water used during the processing of chickens.

3.2.3 STAGE 3: WATER FOOTPRINT SUSTAINABILITY ASSESSMENT

3.2.3.1 SUSTAINABILITY OF THE WATER FOOTPRINT OF A PRODUCT, PROCESS, AND RIVER BASIN

The WFA involves comparing the water footprint of maize and broiler production with blue water availability in the Orange River basin during the summer months. As mentioned earlier, the study will focus on the environmental aspect of sustainability and then quantify the extent to which production impacts the environment.

In assessing the sustainability of broiler production, this study will consider the sustainability of various process steps that are involved in producing broiler meat. These processes include maize and broiler production, as well as the slaughtering and processing of broilers. If the water footprint of any of the process steps is unsustainable, the water footprint of broiler meat will also be unsustainable. Maize and broiler production, as well as broiler slaughtering and processing, may be found to be unsustainable if the process occurs at a time of the year when the total water footprint of the Orange River basin is unsustainable. It may also be unsustainable if, given the current water footprint of the process, it is not possible to lower the freshwater use. The sustainability of the maize-broiler value chain will be assessed based on the monthly blue water scarcity method proposed by Hoekstra and Mekonnnen (2011).

3.2.3.2 ENVIRONMENTAL SUSTAINABILITY CRITERIA FOR IDENTIFYING ENVIRONMENTAL HOTSPOTS

The water footprint in a catchment is considered environmentally sustainable if the environmental freshwater requirements are satisfied and the degree of water pollution is below the waste assimilation capacity. If, however, the water footprint in a catchment is environmentally unsustainable, an environmental hotspot will develop. The hotspot can be quantified by determining the green water scarcity, blue water scarcity, and/or the extent of water pollution. An environmental hotspot occurs when the green water scarcity, blue water scarcity, and/or the extent of water pollution are beyond 100%. Regarding the blue water footprint, one must assess whether there is a reduction in blue water in response to the water footprint such that the reduction goes beyond a certain environmental threshold. The green, blue, or grey water footprint can have a direct influence on the occurrence of environmental hotspots. The blue water footprint will be explored in the following discussion.

Environmental sustainability of the blue water footprint

The aggregate blue water footprint in a particular catchment is equal to the sum of all the blue water footprints of the processes that occur in the catchment. When the blue water footprint at a certain time in a particular catchment is greater than the blue water availability at that time and in that catchment, a hotspot will develop during that time and in that catchment area. The blue water availability (WA_{blue}) in a catchment x in period t may be calculated as follows:

$$WA_{blue}[x,t] = R_{nat}[x,t] - EFR[x,t] \qquad \text{[volume/time]} \qquad [26]$$

WA_{blue} is the blue water availability, R_{nat} is the natural runoff, and EFR is the environmental flow requirement.

According to the above equation, the total blue water availability in catchment x during period t is equal to the natural runoff minus the EFR. In the case where the blue water footprint is greater than the blue water availability, the surplus freshwater is derived from environmental freshwater flows, thus rendering the blue water footprint unsustainable. The EFRs are estimated based on the volume and timing of freshwater flows necessary to support freshwater and estuarine ecosystems and human livelihoods that depend on these ecosystems.

Figure 3.1 demonstrates the relationship between the blue water footprint and availability, as well as the EFRs. It is important to note that the total blue water available is equal to the blue water remaining from the runoff after the EFR has been satisfied. According to Figure 3.1, from January to mid-April and during the second half of September to December, the blue water footprint is sustainable. However, from May towards the end of September, the blue water footprint is unsustainable. The blue water footprint is not sustainable in the latter period because a fraction of the blue water intended for the purpose of meeting the EFR is redirected for another use.

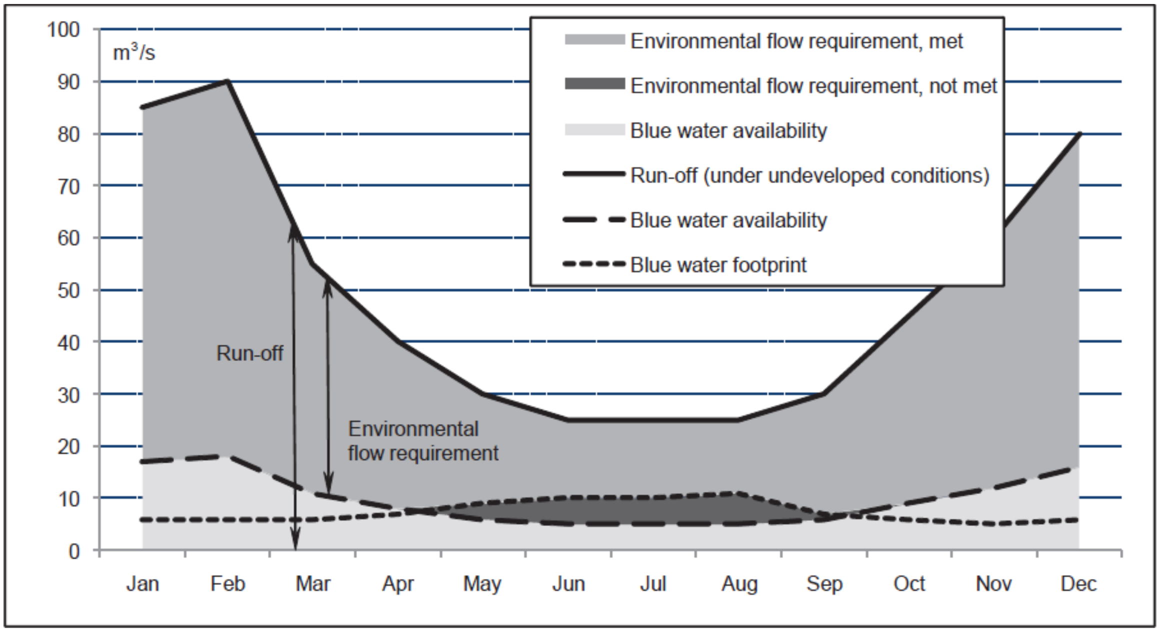

Figure 3.1: Example of annual blue water footprint versus blue water availability
Source: Hoekstra *et al.* (2011)

Environmental flow requirements (EFRs) are determined by subtracting the natural runoff from the blue water availability. The natural runoff is the sum of the actual runoff and the blue water footprint within the catchment. There are two criteria for assessing the environmental sustainability of the blue water footprint in a catchment or river basin. Firstly, in any given month, the blue water footprint may not be sustainable from an environmental point of view if the blue water footprint within the catchment is greater than the blue water availability. Such a situation compromises the EFRs as freshwater or runoff that is meant to satisfy the EFRs is utilised for a different purpose. Secondly, one may examine the implications on groundwater reserves and the volume of freshwater in lakes in a catchment that arise in response to the blue water footprint. The blue water scarcity (WS_{blue}) in a catchment *x* in period *t* may be calculated as follows:

$$WS_{blue}[x,t] = \frac{\sum WF_{blue}[x,t]}{WA_{blue}[x,t]} \quad [-] \qquad [27]$$

WS_{blue} is the blue water scarcity, WF_{blue} is the aggregate blue water footprint, and WA_{blue} is the blue water availability. According to the above equation, the blue water scarcity in a catchment *x* in period *t* is equal to the quotient of the sum of the blue water footprints to the blue water availability in catchment *x* in period *t*. The blue water footprint is a physical concept in that it measures the difference between the utilised and available freshwater resources. It is also an environmental concept because it takes the EFRs into consideration.

3.3 DATA

This study analyses the water footprint of the maize-broiler value chain, with focus on broiler chickens. The study considers production from farm level to processor right through to retail level. Secondary data on the water requirement for maize production were obtained from Van Rensburg *et al.* (2012). The general objective of Van Rensburg *et al.* (2012) was to formulate methods for controlling irrigation-induced salinity on the farms located in the Orange-Riet and Vaalharts irrigation schemes. However, for the purposes of this study, only the Orange-Riet Irrigation Scheme will be considered.

As mentioned in Chapter 2, maize is the major input used as feed in the production of broiler chickens. Therefore, data on the water requirements for maize production at farm level are essential. Data on water used during the processing of maize to produce chicken feed are also necessary. Thus water use data for a commercial poultry farm and poultry processor have a considerable contribution towards this study. These data were acquired from a chicken-processing facility by means of questionnaires and interviews with senior management.

3.3.1 WATER USE DATA ON MAIZE PRODUCTION

3.3.1.1 LOCATION AND LAYOUT OF THE ORANGE-RIET IRRIGATION SCHEME

The research area is the Orange-Riet Irrigation Scheme. A large area of the Orange-Riet Irrigation Scheme is located in the Free State within the confines of the Orange River and the Riet River and extends marginally into the Northern Cape (Van Rensburg *et al.*, 2012). The Orange-Riet Irrigation Scheme is managed within the Riet/Modder and Vanderkloof sub-areas of the Upper Orange Water Management Area (Van Rensburg *et al.*, 2012).

The Orange-Riet Transfer Scheme is in the Free State province. It allows for the flow of freshwater from the Vanderkloof Dam through the Orange-Riet Canal and into the Riet River catchment.

Figure 3.2 is a graphic illustration of the position of the Orange-Riet Irrigation Scheme in South Africa. It is evident from Figure 3.2 that the scheme is primarily located in the Free State province.

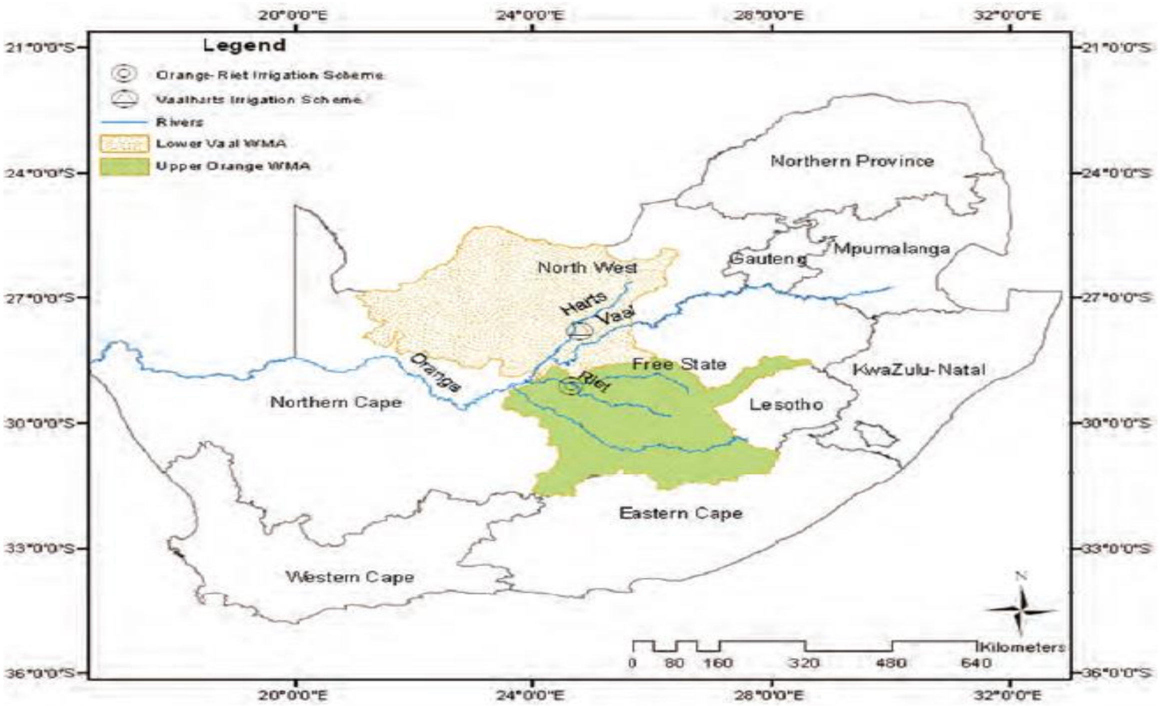

Figure 3.2: Geographic position of the Orange-Riet Irrigation Scheme in South Africa
Source: Van Rensburg *et al.* (2012)

Figure 3.3 provides a more detailed description of the Orange-Riet Irrigation Scheme. The Vanderkloof Dam serves as a source of water for the Orange-Riet Irrigation Scheme (Van Rensburg *et al.*, 2012). As freshwater flows from the Vanderkloof Dam along the Orange-Riet canal section, about 3 970 ha are irrigated. In the Riet River Settlement section, 8 045 ha are irrigated and 637 ha are irrigated in the Scholtzburg section of the Orange-Riet Irrigation Scheme (Van Rensburg *et al.*, 2012). Excess and drainage water from the settlement section flow into the Riet River, which in turn flows across the Ritchie and Lower Riet sections of the Orange-Riet Irrigation Scheme where 97 ha and 3 938 ha are irrigated respectively (Ninham Shand, 2004).

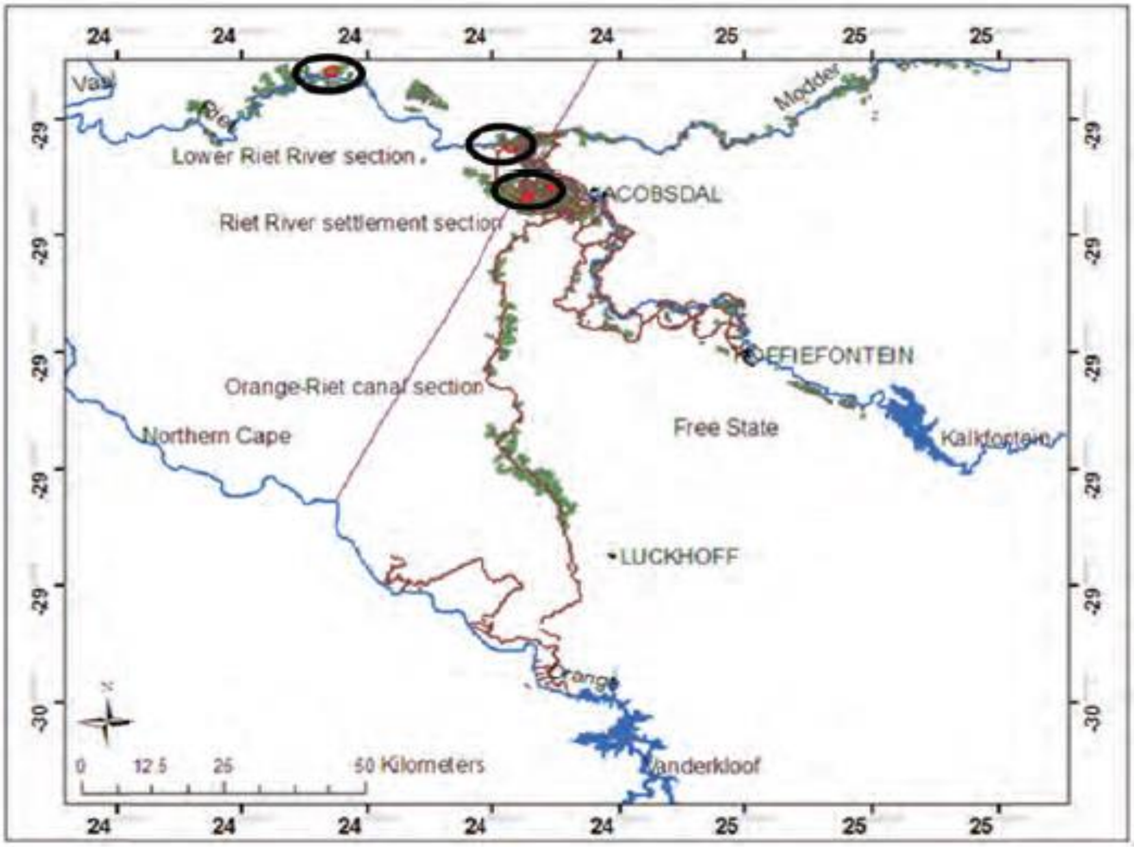

Figure 3.3: Graphical description of the Orange-Riet Irrigation Scheme

Source: Van Rensburg *et al.* (2012)

3.3.1.2 LOCATION AND LAYOUT OF MEASURING POINTS

Van Rensburg *et al.* (2012) set up 30 measuring points in such a manner that they could consider differences in bio-physical conditions at root zone scale, namely irrigation water qualities, soil types, crops, irrigation systems, soils with artificial drainage, as well as different managers of the various sites. The measuring points had 4 m × 4 m dimensions in the crop fields where they were established. Two measuring points were set up in fields with artificial drainage systems. One measuring point was established on the drainage line, whilst another was set up away from the drainage line. The distance between the two measuring points depended on the line spacing and type of drainage system. At each measuring point, two neutron access tubes (2 000 mm), one piezometer (perforated 63 mm PVC tubes and 3 000 mm deep), and a rain gauge were installed. Measurements were taken over four seasons (two winters and two summers) from July 2007 to June 2009.

This study focuses on areas identified by Van Rensburg *et al.* (2012) as measuring points or4, or5, or18, and or20. The occurrence of maize cultivation in these areas is the fundamental basis upon which these measuring points were selected. Measuring points or4 and or5 are located in site 1. Measuring points or18 and or20 are located in site 14. The Orange River serves as the water source for site 1. Blended water (a mixture of water that originates from the Orange, Modder, Riet, and Lower Riet rivers and drainage water) serves as the water source for site 14. Measuring points at site 14 have neither a water table nor a drainage system. Measuring points at site 1 have a water table. Measuring point or4 has a drainage system but measuring point or5 does not.

3.3.1.3 CLIMATE

The mean maximum and minimum temperature as well as the mean evapotranspiration and rainfall for different months of the year in the Orange-Riet Irrigation Scheme are expressed in Table 3.2. The annual mean maximum temperature in the scheme is 25.58 °C. The mean maximum temperature for each of the summer months (October to February) is greater than the mean maximum temperature per annum. As autumn sets in, the temperatures begin to fall gradually. The mean minimum temperature in the scheme is 8.5 °C per annum. The mean minimum temperature for each winter month (May to July) is less than the mean minimum temperature in the scheme per annum. As spring sets in, the temperatures begin to rise. The total mean evaporative demand in the scheme is 1 741 mm. The mean evaporative demand for the summer months is about 965 mm. This is 55.43% of the total evaporative demand. As autumn approaches, the mean evaporative demand declines. The mean evaporative demand for the winter months is about 251 mm. This is 14.42% of the total mean evaporative demand. As spring approaches, the mean evaporative demand increases. The total mean rainfall in the scheme is 397 mm, while the mean rainfall for the summer months is about 239 mm (60.2%).

3.3.1.4 WATER QUALITY

The natural concentration of nitrate in the groundwater is less than 3 mg NO3-N/l of freshwater (Bouchard, Williams and Surampalli, 1992). The natural background concentration of dissolved inorganic nitrogen (ammonium-nitrogen, nitrate-nitrogen, and nitrite-nitrogen) at Oranjedraai is 0.348mg/ℓ of freshwater (DAFF, 2009). Nitrate-nitrogen accounts for 0.30mg/ℓ of the dissolved inorganic nitrogen concentration at Oranjedraai (DAFF, 2009). Such a relatively high concentration of nitrate-nitrogen in freshwater renders it an appropriate contaminant that should receive considerable attention.

Koning, Roos and Grobbelaar (2000) analysed the nitrate-nitrogen as well as phosphate-phosphorous concentration in the upper part of the Modder River within the boundaries of the Rustfontein Dam, Mazelspoort Barrage, Klein Modder River, and the Modder River just before Sannaspos. The water samples from the Modder River were taken every two weeks from February 1996 to December 1997. Koning *et al.* (2000) found the mean nitrate-nitrogen concentration in the Modder River to be 230µg/ℓ. It was also found that the flow of water from the Klein Modder River increases the nitrate-nitrogen levels of the Modder River by 171% (Koning *et al.*, 2000). The Klein Modder River is subject to anthropogenic pollution and as such its contribution to nitrate-nitrogen levels in the Modder River should be deducted from the nitrate-nitrogen concentration in the Modder River. Thus the mean nitrate-nitrogen concentration in the Modder River is 134.5029µg/ℓ of freshwater. The mean global natural background concentration of nitrate-nitrogen in rivers is 100µg/ℓ (Koning *et al.*, 2000). Franke, Boyacioglu and Hoekstra (2013) suggested a natural background concentration of 0.1mg NO_3-N/ℓ of freshwater. According to Nordin and Pommen (2009), the maximum allowable nitrogen concentration must be 10 mg NO_3-N/ℓ of freshwater. This maximum is set to protect the health of human life. Franke *et al.* (2013) suggested a maximum allowable nitrogen concentration of 13 mg NO_3-N/l of freshwater.

Grey water footprint at measuring points or18 and or20:

The leaching-runoff fraction

The leaching-runoff fraction is estimated using the following method:

$$\alpha = \alpha_{\min} + \left[\frac{\sum_i s_i \times w_i}{\sum_i w_i} \right] \times \left(\alpha_{\max} - \alpha_{\min} \right) \qquad [28]$$

s_i is the score of each factor and w_i is the weight of the factor, and the maximum and minimum leaching-runoff fractions are represented by α_{max} and α_{min} respectively. Table 3.1

depicts the minimum and maximum leaching-runoff fractions that are required to estimate the leaching-runoff fraction at the measuring points.

Table 3.1: Minimum and maximum leaching-runoff fractions for nitrogen

α_{min}	α_{max}
N	N
0.01	0.25

Source: Franke *et al.* (2013)

The leaching-runoff fraction at measuring points or18, or20, or4 and or5

Table 3.2 is a guideline for determining the leaching-runoff fraction of nitrogen. It distinguishes between environmental factors and agricultural practice. The environmental factors consist of atmospheric nitrogen deposition, soil texture, and natural drainage as well as precipitation. The agricultural practice comprises nitrogen fixation, application rate, plant uptake, and management practice. In determining the leaching-runoff fraction, a weight is assigned to each factor. The weights ranged from 5 to 15. Natural drainage and plant uptake received the lowest weights. Soil texture and precipitation were assigned the highest weights.

Table 3.2: The score of each factor and the associated weight for the case of nitrogen at measuring points or18, or20, or4 and or5

Category	**Factor**		**Score (s_i)**		**Weight (w_i)**	
			or18 and or20	or4 and or5	or18 and or20	or4 and or5
Environmental factors	Atmospheric input	N-deposition (g N.m^{-2}.yr^{-1})	0.5	0.5	10	10
	Soil	Texture (relevant for leaching)	0	1	15	15
		Texture (relevant for runoff)	0	1	10	10
		Natural drainage (relevant for leaching)	0	0.33	10	10

		Natural drainage (relevant for runoff)	1	0.67	5	5
	Climate	Precipitation (mm)	0	0	15	15
Agricultural practice	N-fixation (kg/ha)		0.5	0.5	10	10
	Application rate		217	215	10	10
	Plant uptake		359.694	413.775	5	5
	Management practice		0.33	0.33	10	10

Source: Van Rensburg *et al*. (2012)

The maize season at measuring points or18 and or20 commenced in October and ended in May 2008. This was a period of eight months. Rainfall over this period was 361 mm. Both N-deposition from the atmosphere and N-fixation are unknown, therefore they are each assigned a score of 0.5, as suggested by Franke *et al.* (2013). The soil is clayey with no drainage system, hence the soils are poorly drained. Nitrogen fertilisation was applied at 217 kg/ha. The management practice was good because a yield of 13.32 $t.ha^{-1}$ was achieved in the area. At this yield level, the Fertilizer Society of South Africa (FSSA, 2007) suggested that 199.83 kg N/ha were taken up by the crop.

The first maize season at measuring points or4 and or5 commenced in December 2007 and ended in July 2008 the following year. This was a period of eight months. Rainfall over this period was 262 mm. Both N-deposition from the atmosphere and N-fixation are unknown, therefore they are each assigned a score of 0.5 as suggested by Franke *et al.* (2013). The soil is sandy with no drainage system at the fields in the vicinity of measuring point or5. Nevertheless, lands that were covered by measuring point or4 had a drainage system, hence the soils are moderately to imperfectly drained. Nitrogen fertilisation was applied at 215 kg/ha. The management practice was good because a yield of 15.33 $t.ha^{-1}$ was achieved in the area. At this yield level, the FSSA (2007) suggested that 413.775 kg $N.ha^{-1}$ were taken up by the crop.

The leaching-runoff fraction of nitrogen is as follows:

$$\alpha = \alpha_{\min} + \left[\frac{\sum_i s_i \times w_i}{\sum_i w_i} \right] \times \left(\alpha_{\max} - \alpha_{\min} \right) \qquad [29]$$

$$\alpha = 0.01 + \left[\frac{0.5\times10+0\times15+0\times10+0\times10+1\times5+0\times15+0.5\times10+0.67\times10+0.33\times5+0.33\times10}{10+15+10+10++5+15+10+10+5+10} \right] \times \left(0.25-0.01\right)$$

$$\alpha = 0.01 + \left[\frac{26.65}{100} \right] \times 0.24$$

$$\alpha = 0.01 + 0.2665 \times 0.24$$

$$\alpha = 0.07396$$

Therefore, the leaching-runoff fraction of nitrogen at measuring points or18 and or20 is 7.40%.

$$\alpha = 0.01 + \left[\frac{0.5\times10+1\times15+1\times10+0.33\times10+0.67\times5+0\times15+0.5\times10+0.67\times10+0.33\times5+0.33\times10}{10+15+10+10+5+15+10+10+5+10} \right] \times \left(0.25-0.01\right)$$

$$\alpha = 0.01 + \left[\frac{53.3}{100} \right] \times 0.24$$

$$\alpha = 0.01 + 0.533 \times 0.24$$

$$\alpha = 0.13792$$

Therefore, the leaching-runoff fraction of nitrogen at measuring points or4 and or5 is 13.79%.

Table 3.3 is a summary of the leaching-runoff fractions and application levels of nitrogen at measuring points or18, or20, or4, and or5. The leaching-runoff fractions of nitrogen at measuring points or18 and or20 are estimated at 7.40%. At measuring points or4 and or5 the leaching-runoff of nitrogen is 13.79%. Van Rensburg *et al.* (2012) reported the nitrogen application at measuring points or18 and or20 at 217 kg/ha. They reported the nitrogen application for measuring points or4 and or5 at 215 kg/ha.

The grey water footprint associated with nitrogen fertilisation per ha at measuring points or18 and or20 is calculated as follows:

$$GWF_N = \frac{0.07396 \times 217kg}{13mg.l^{-1} - 0.1mg.l^{-1}}$$

$$GWF_N = \frac{16.04932kg}{12.9mg.l^{-1}}$$

$$GWF_N = \frac{16049320mg}{12.9mg.l^{-1}}$$

$$GWF_N = \frac{1244133.333\,l}{1000}$$

$$GWF_N = 1244.13m^3 / ha$$

The grey water footprint associated with nitrogen fertilisation per ha at measuring points or4 and or5 in season 1 is estimated as follows:

$$GWF_N = \frac{0.13792 \times 215kg}{13mg.l^{-1} - 0.1mg.l^{-1}}$$

$$GWF_N = \frac{29.6528kg}{12.9mg.l^{-1}}$$

$$GWF_N = \frac{29652800mg}{12.9mg.l^{-1}}$$

$$GWF_N = \frac{2298666.667l}{1000}$$

$$GWF_N = 2298.67m^3 / ha$$

3.3.1.5 DATA ACQUISITION

Data on rainfall, irrigation, soil water content, water table depth, drainage from artificial drainage systems where applicable, electrical conductivity of irrigation water, water table and drainage, and fertiliser application were taken from Van Rensburg *et al*. (2012).

3.3.1.6 LOCATION AND DESCRIPTION OF MEASURING POINTS OR18 AND OR20

Figure 3.4 indicates the geographic location of measuring points or18 and or20. They are both located in the valley bottom of a farm located in the Lower Riet River section of the Orange-Riet Irrigation Scheme. These measuring points are situated on a 42-ha centre pivot irrigation scheme. The soil form in this area is Valsrivier Aliwal (Soil Classification Working Group, 1991). The Valsrivier Aliwal soil form comprises various horizons with unique characteristics of its own. At a depth of 0 mm to 300 mm from the soil surface lies the dark-brown Orthic A with 41% clay. It is followed by a dark-brown B1 horizon with 43% clay which extends to 900 mm. The dark-brown B2 consists of 46% clay and is situated at a depth of 900 mm to 1 200 mm directly beneath the B1 horizon. An unspecified C horizon concludes the profile. It reaches depths beyond 1 500 mm and consists of 50% clay. A strong, coarse, angular, and blocky structure with clay cutans, slickensides, and lime concretions are marked features of the profile. The B2 and C horizons are characterised by blue, black, brown, red, and white mottles. The centre pivots in the vicinity of measuring points or18 and or20 have a uniformity coefficient, distribution uniformity, application efficiency, and system efficiency of 93%, 92%, 97%, and 88% respectively. It is on this basis that Van Rensburg *et al.* (2012) declared that the irrigation systems are in a good condition. A drainage system has been constructed in the area to address water logging. The drainage water is released into a storage dam, where it is mixed with water from the Lower Riet River and reused to irrigate crops at the measuring sites.

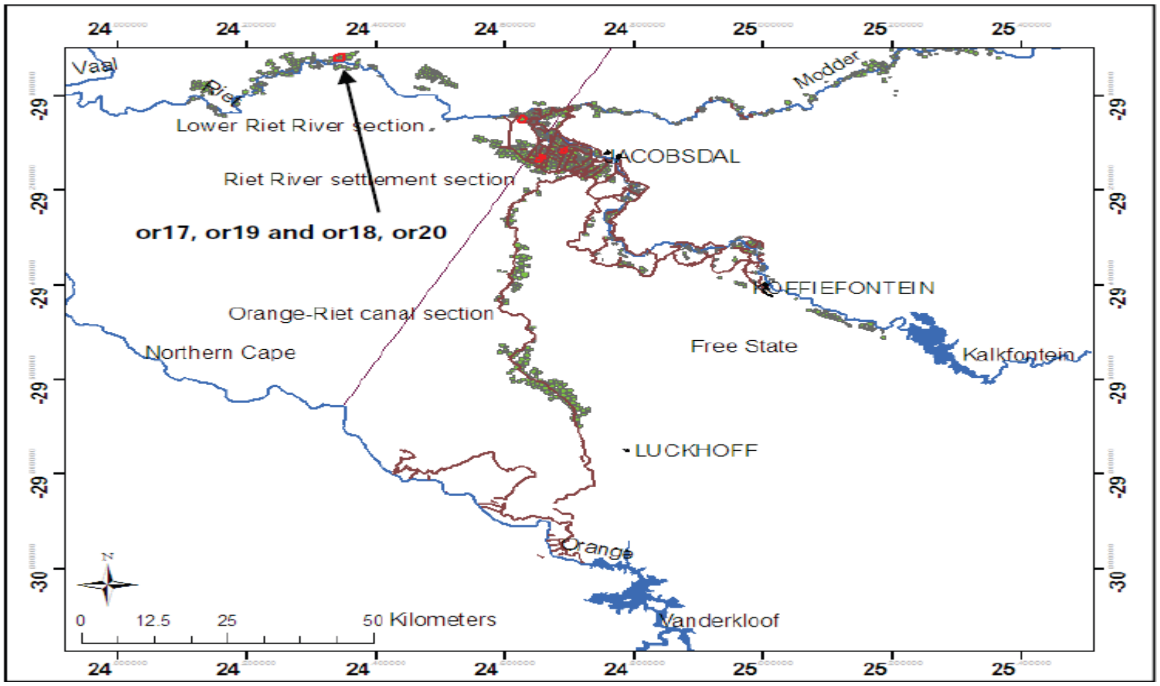

Figure 3.4: Geographic position of measuring points or18 and or20 within the Lower Riet section of the Orange-Riet Irrigation Scheme

Source: Van Rensburg *et al.* (2012)

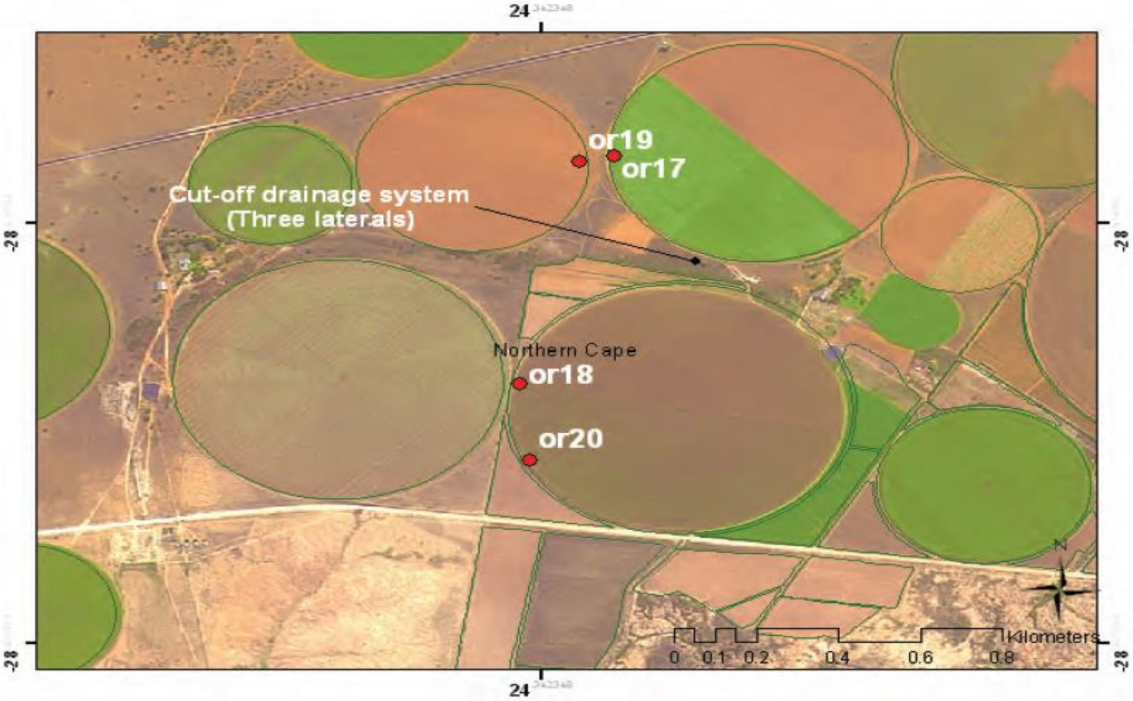

Figure 3.5: Position of measuring points or18 and or20 on the irrigated fields of the Valsrivier Aliwal soil form in the Lower Riet section of the Orange-Riet Irrigation Scheme.

Source: Van Rensburg *et al.* (2012)

3.3.2 LOCATION AND DESCRIPTION OF MEASURING POINTS OR4 AND OR5

Measuring points or4 and or5 are positioned on a 30-ha centre pivot in the settlement section of the Orange-Riet Irrigation Scheme. These two measuring points occupy a soil classified as the Hutton soil from of the Ventersdorp family (Soil Classification Working Group, 1991). The profile is characterised by four diagnostic horizons, namely Orthic A with 4% clay (0 mm to 300 mm), red apedal B1 with 8% clay (300 mm to 600 mm), red apedal B2 with 10% clay (600 mm to 1500 mm), and an unspecified C with 10% clay (+1 500 mm) (Van Rensburg *et al.*, 2012). The A, B1, B2, and C horizons have an apedal massive structure. The A and B1 horizons are grouped in the fine sandy textural class. In contrast, the B2 and C horizons are grouped into the fine loamy sand class. The measuring points or4 and or5 have an internal drainage system, which comprises a single lateral installed at a depth of 1 800 mm in the centre of the field.

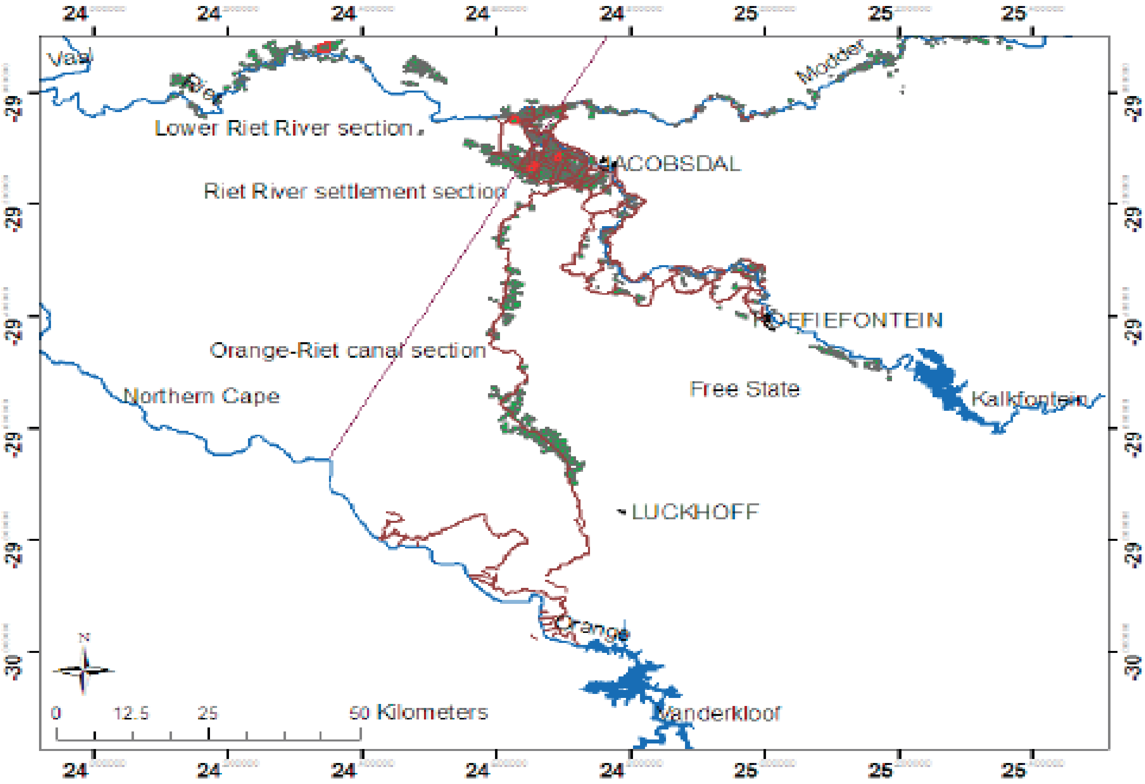

Figure 3.6: Geographical position of measuring points or4 and or5 at the Riet River settlement section of the Orange-Riet Irrigation Scheme

Source: Van Rensburg *et al.* (2012)

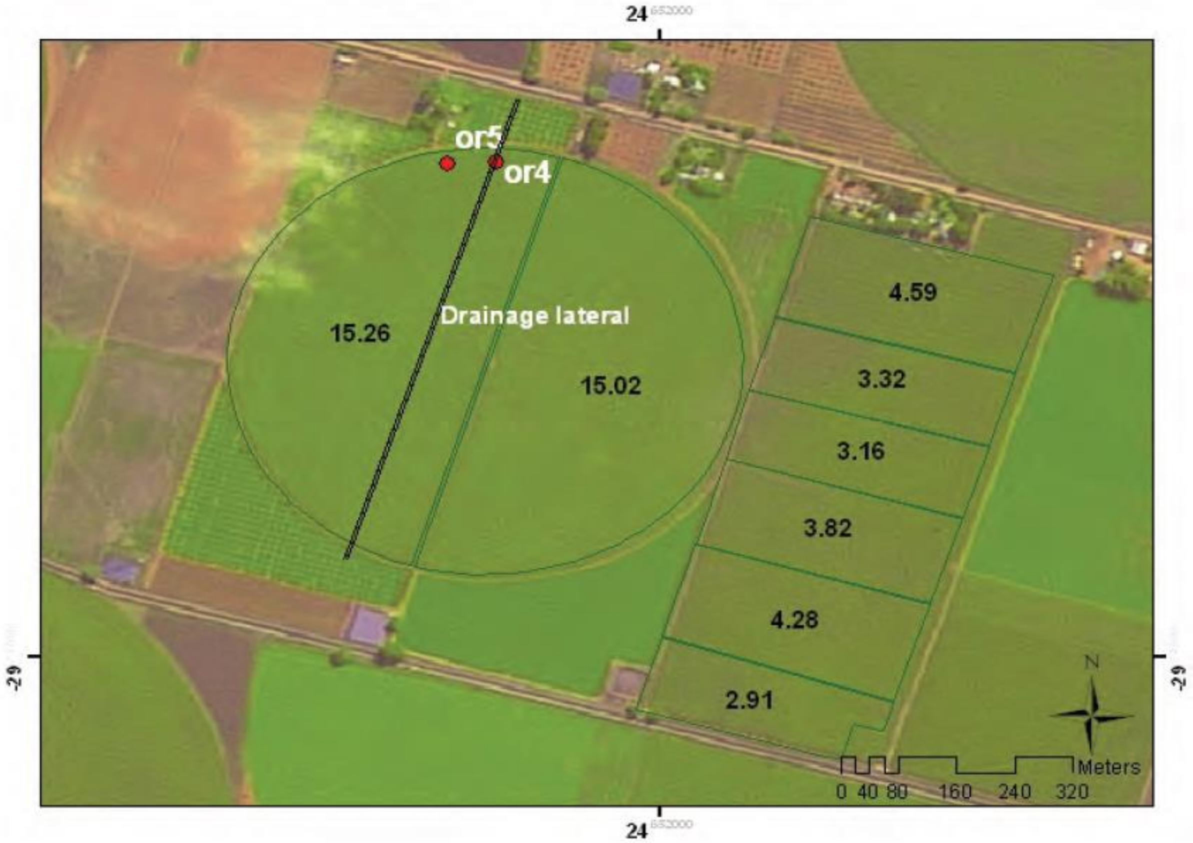

Figure 3.7: Location of measuring points or4 and or5 on the irrigated fields at the Riet River settlement section of the Orange-Riet Irrigation Scheme

Source: Van Rensburg *et al.* (2012)

Grey water footprint

Table 3.3: Nitrogen and phosphorous removal by maize per one tonne of marketable product

Maize	N	P	K
Grain only	15	3	3.5
Whole plant	27	4.5	20

Source: FSSA (2007)

The whole plant represents the entire crop, excluding the roots (FSSA, 2007).

3.3.3 WATER USED TO PRODUCE CHICKEN MEAT

Figure 3.8 illustrates an industrial production system that is followed by the broiler farm studied in this research. The broiler farm is located in the eastern Free State. The farm produces 101 465 broilers per day. Broilers are grown to reach 0.00185 tonnes. Therefore, the farm produces 187.71 tonnes of broilers per day. The farm has 950 broiler houses in total. The broilers are relatively less mobile, they are bred to grow at a higher rate, and they are slaughtered at an earlier age. Their feed ration comprises maize, full-fat soya, soya oilcake, and sunflower oilcake. Their diet is divided into pre-starter, starter, grower, finisher, and post-finisher. Maize accounts for the highest percentage in all phases of their diet, followed by soya oilcake and sunflower oilcake. The feed is produced locally using conventional practices, mainly under irrigation conditions. Ultimately, the FCE, the water footprint of the feed, the water footprint associated with drinking, and other on-farm activities yield the water footprint of chicken meat.

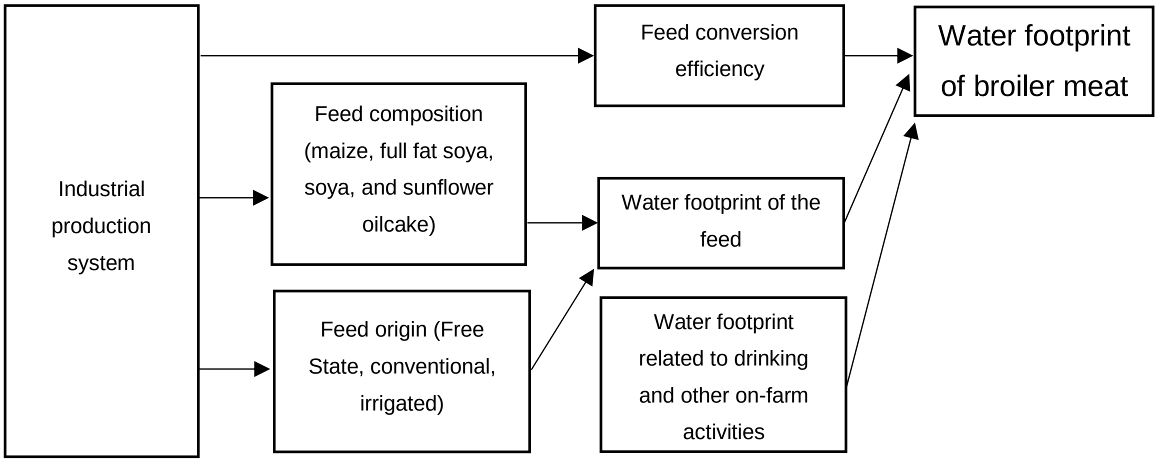

Figure 3.8: Factors influencing the water footprint of chicken meat

Source: Gerbens-Leenes *et al*. (2013)

3.3.3.1 FARM-LEVEL WATER USE FOR BROILER PRODUCTION

Water usage: Feed production

According to Hoekstra (2014), the largest share of the water footprint of animal products is attributed to the production of animal feed. Mekonnen and Hoekstra (2010) found that animal feed production accounts for 98% of the water footprint of animal products.

Nevertheless, the feed composition has a marked impact on the contribution of animal feed to the total water footprint of animal products. Feed concentrates have a larger water footprint than roughages (grass, crop residues, and fodder crops) (Gerbens-Leenes and Hoekstra, 2011). In fact, Hoekstra (2014) found that the water footprint of concentrates is five times greater than that of roughages. Thus animal feed with a higher proportion of concentrates contributes to a larger water footprint of animal products than feed with a higher proportion of roughages. It is thus critical to quantify the water footprint of chicken feed. As previously mentioned, Mekonnen and Hoekstra (2010) suggested equation [23] as an appropriate method for calculating the water footprint of chicken feed.

Table 3.4 is a summary of the total water footprint of a tonne of soya and sunflower oilcake production in South Africa's Free State province. It was derived from Mekonnen and Hoekstra (2010). The green water footprint is the largest component in the water footprint of soya and sunflower oilcake. It makes up 98.44% of the total water footprint per tonne of soya oilcake produced and 96.08% of the total water footprint per tonne of sunflower oilcake produced. The consumptive water footprint is greater than the grey water footprint in both cases. The consumptive water footprint of soya oilcake is more than double the consumptive water footprint of sunflower oilcake. Nevertheless, the grey water footprint of sunflower oilcake is four times greater than the grey water footprint of soya oilcake.

Table 3.4: Water footprint of soya and sunflower oilcake

Broiler Feed	**WF**	**WFgreen**	**WFblue**	**WFgrey**
	m^3/tonne			
Soya oilcake	2434	2396	29	9
Sunflower oilcake	1199	1152	10	37

Source: Mekonnen and Hoekstra (2010)

Drinking water of chickens

The volume of water a chicken drinks depends on several factors. Kratzer *et al.* (1994) identified environmental temperature, relative humidity, diet composition, rate of growth or egg production, and the efficiency of kidney absorption of water as factors which influence the freshwater intake of a chicken. Kratzer *et al.* (1994) quantified the water consumption of a broiler chicken at an environmental temperature of 21 °C. According to Kratzer *et al.*

(1994), the volume of freshwater a broiler chicken drinks increases by 7% for every 1 °C in temperature above 21 °C. One can conclude that as the chicken gets older, the volume of water that it drinks on average per week increases. For a broiler chicken, the increase is variable until the chicken is four weeks old. From five weeks old, the broiler chicken maintains a more constant increase in water intake per week.

Williams, Tabler and Watkins (2013) investigated the water consumption of broiler chickens. The objective was to establish whether or not there is a variation in the volume of water broiler chickens drink over time. The broiler chickens for the periods 1991 (Period 1), 2000 to 2001 (Period 2), and 2010 to 2011 (Period 3) were housed in four commercial broiler houses at the University of Arkansas Applied Broiler Research Farm. During Periods 1, 2, and 3, each house was allocated an average of 18 800, 20 600, and 20 590 chicks respectively. The number of chicks per 0.09 m^2 was 0.85, 0.78, and 0.78 in Periods 1, 2, and 3 respectively. An in-house water meter for poultry water lines was used to capture the volume of water the chickens drank per day. This was done for each house. Digital scales on feed bins were used to measure how much feed the chickens ate each day, and this was also done for each broiler house. In Period 1, the broilers consumed 140.32 litres of water and 8.85 kilograms of feed per 1000 chickens. In Period 2, the broilers consumed 160.54 litres of water and 9.72 kg of feed per 1000 chickens. In Period 3, the broilers consumed 190.48 litres of water and 11.30 kg of feed per 1000 chickens. This suggests that the broilers consumed more water and feed from Period 1 to Period 2 with the highest consumption levels reported in Period 3. Given the increasing demand for freshwater and feed in broiler production over the years, it is important to use water sustainably for the production of broilers and broiler feed.

Service water of chicken

The broiler farm produces 101 465 broilers per day. Each broiler weighs 0.00185 tonnes. Therefore the farm produces 187.71 tonnes of broilers per day. The farm reported that they use 2 800m^3 of water per broiler house per year and has 950 broiler houses in total. Therefore the volume of water used at the broiler farm for the purposes of drinking, cleaning, and service water was determined as 38.82 m^3 per tonne of broilers produced as shown below:

$$BWF_{FARM} = \frac{(2800m^3 \, per \; year \times 950 \, broiler \; houses)/365 \; days}{101465 \, broilers \; per \; day \times \left(1.85kg \; per \, broiler \; /1000\right)}$$

$$BWF_{FARM} = \frac{7287.67 \, m^3 \, per \; day}{187.71 \, tonnes \; per \; day}$$

$$BWF_{FARM} = 38.82 \, m^3$$

3.3.3.2 PROCESSOR LEVEL WATER USE FOR BROILER CHICKENS

The broiler abattoir uses 0.01m^3 to slaughter and process a chicken. It is assumed that the slaughtering and processing of broilers each account for 50% of the volume of water used at the abattoir. Each chicken is slaughtered at 0.00185 tonnes. The abattoir slaughters 286.75 tonnes per day. Therefore the volume of water used to slaughter a tonne of broilers at the abattoir is 2.70m^3. The processing of a tonne of broilers uses 3.76 m^3 of water. This includes service water. The broiler firm sources 53 535 broilers from external farmers so that it slaughters and processes 155 000 broilers. It is determined as follows:

$$BWF_{ABATTOIR\,(SLAUGHTERING)} = \frac{(0.01m^3 \;\, per \, broiler \; / \, 2) \times (155000 \, broilers)}{0.00185 \, tonnes \times 155000 \, broilers}$$

$$BWF_{ABATTOIR\,(SLAUGHTERING)} = \frac{775m^3}{286.75 \, tonnes}$$

$$BWF_{ABATTOIR\,(SLAUGHTERING)} = 2.70m^3 \;\, per \, tonne$$

$$BWF_{ABATTOIR\,(PROCESSING)} = \frac{(0.01m^3 \;\, per \, broiler \; / \, 2) \times (155000 \, broilers)}{0.00133 \, tonnes \times 155000 \, broilers}$$

$$BWF_{ABATTOIR\,(PROCESSING)} = \frac{775m^3}{206.15 \, tonnes}$$

$$BWF_{ABATTOIR\,(PROCESSING)} = 3.76m^3 \;\, per \, tonne$$

3.3.4 ORANGE RIVER BASIN SUSTAINABILITY ASSESSMENT

The source of freshwater for maize production in the Orange-Riet Irrigation Scheme is mainly irrigation water. Furthermore, the chicken abattoir and processing facility rely on blue water to meet their process water requirements. Both practices have an associated grey water footprint. Both the scheme and the processing firm fall within the Orange River basin. It is for these reasons that the focus of this study is to assess the sustainability of the Orange River basin according to the sustainability of the blue water footprint as well as the grey water footprint.

Hoekstra and Mekonnen (2011) measured the blue water scarcity of the Orange River basin on a monthly basis for the period 1996 to 2005. They estimated the blue water scarcity by dividing the blue water footprint of the basin by the blue water availability in the catchment. Blue water availability was taken as the difference between the natural runoff and EFRs. The natural runoff is the sum of the actual runoff and the total blue water footprint of the basin. The blue water scarcity of the Orange River basin was classified into four categories based on the degree of scarcity. A low blue water scarcity, moderate blue water scarcity, significant blue water scarcity, and severe water scarcity have a blue water scarcity value less than 100%, 100% to 150%, 150% to 200%, and greater than 200%, respectively.

3.3.5 ECONOMIC WATER PRODUCTIVITY

Quantifying the economic productivity of water use (EWP) along the maize-broiler value chain is critical. It forms the basis upon which one may contrast the economic returns per unit of water used among various other alternative uses. For the purposes of this study, the focus will be on the EWP of the poultry processors. The EWP will be determined by taking the ratio of the retail price per tonne of chicken (R) and the water footprint of a tonne of chicken (V). This will result in the economic returns per unit of water (in m^3) used to produce chicken. This may be expressed as follows:

$$EWP = \frac{R}{V} \qquad [30]$$

CHAPTER 4

RESULTS

4.1 INTRODUCTION

This chapter expresses and discusses the calculations of the green, blue, and grey water footprints at each stage of the maize-broiler value chain. The total water footprint of a tonne of chicken meat is then established by summing the water footprint components at each stage of the value chain accordingly. This is followed by a calculation of the EWP of chicken.

4.2 THE WATER FOOTPRINT OF MAIZE PRODUCTION

The water footprint of maize production describes the total freshwater use per unit of maize produced. Total freshwater refers to the sum of the volume of rainfall and irrigation water consumed during the growth of the maize. It also includes water reservoirs, whose quality is degraded by chemicals applied during the course of maize production. One site where the water footprint of maize production was measured consisted of measuring points or18 and or20; another site consisted of measuring points or4 and or5. Both sites are located in the Orange-Riet Irrigation Scheme. Measuring points or18 and or20 are discussed in the next section.

4.2.1 THE WATER FOOTPRINT OF MAIZE PRODUCTION AT MEASURING POINTS OR18 AND OR20

Table 4.1 describes the biophysical data at measuring points or18 and or20. The yield of maize was obtained from Van Rensburg *et al*. (2012). The soil form at the measuring points is a Valsrivier soil form with a Silt-plus-clay percentage, a mean volumetric soil water content, and soil depth of 65.67%, 0.33 mm.mm^{-1}, and 2 000 mm respectively. Maize evapotranspiration for the production period was 507 mm.

Table 4.1: Biophysical data of measuring points or18 and or20

	Yield ($kg.ha^{-1}$)	Silt-clay (%)	θs (mm.mm-1)	Soil Depth (mm)	∆W (mm)	ET (mm)
Average	13322	65.67	0.33	2000	31	507

Source: Van Rensburg *et al*. (2012)

4.2.1.1 BLUE AND GREEN WATER FOOTPRINT

Table 4.2 illustrates the level of water use at measuring points or18 and or20. The evapotranspiration of maize produced at the measuring points was 589 mm. The rainfall in the area for the period of maize production was 199 mm. Despite an irrigation requirement of 390 mm, the farmers irrigated the maize fields with 496 mm. About 31 mm of the excess irrigation water was stored in the soil, whilst 75 mm was lost from the potential root zone through upward or downward drainage. The rainfall and irrigation together totaled 695 mm for the maize production period. It can be deduced from Table 4.2 that the maize farmers in the vicinity of measuring points at Orange-Riet Irrigation Scheme over-irrigated by 106 mm.

Table 4.2: Summary of water use data at the measuring points or18 and or20 at Orange-Riet Irrigation Scheme

	ET crop (mm)	R (mm)	I (mm)	IR (mm)	R+I (mm)
Average	589	199	496	390	695

Source: Van Rensburg *et al*. (2012)

Table 4.3 is a summary of the consumptive water use at measuring points or18 and or20. It shows the green and blue water footprint of maize production to be 149.38 m^3/tonne and 292.75 m^3/tonne respectively. The consumptive water footprint of maize production amounts to 442.13 m^3/tonne.

Table 4.3: Summary of the green and blue water footprints of producing maize in the Orange-Riet Irrigation Scheme at measuring points or18 and or20

ET crop	ET green	ET blue	CWU	CWU green	CWU blue	Yield	WF	WF green	WF blue
mm/period			**m^3/ha**			**tonne/ha**	**m^3/tonne**		
589	199	390	5890	1990	3900	13.32	442.13	149.38	292.75

Source: Van Rensburg *et al*. (2012)

4.2.1.2 GREY WATER FOOTPRINT

The grey water footprint associated with nitrogen at measuring points or18 and or20 is summarised as follows:

$$GWF = \frac{L}{c_{\max} - c_{\min}} [volume / time] \tag{31}$$

Table 4.4 is a summary of the leaching-runoff fractions and application levels of nitrogen at measuring points or18 and or20. The leaching-runoff fraction of nitrogen at measuring points or18 and or20 is estimated at 7.40%. Van Rensburg *et al*. (2012) reported the nitrogen application in the area at 217 kg/ha.

Table 4.4: Variables necessary for estimating the pollutant load for nitrogen at measuring points or18 and or20

Nutrient	Pollutant load	
N	α	Application (kg/ha)
	7.40 %	217

Source: Van Rensburg *et al*. (2012)

Table 4.5 describes the grey water footprint at measuring points or18 and or20. The grey water footprint per ha was found to be 1 244.13 m^3/ha. At a yield of 13.32 tonne/ha, the grey water footprint was found to be 93.39 m^3/tonne.

Table 4.5: Summary of the grey water footprint at or18 and or20

GWF_N	Yield	GWF_N
m^3/ha	**tonne/ha**	**m^3/tonne**
1244.13	13.32	93.39

Source: Van Rensburg *et al*.(2012)

4.2.1.3 DISCUSSION

The maize yield at measuring points or18 and or20 was 13.32 tonne/ha. At this yield level, the blue water footprint was found to be the highest at 292.75 m^3/tonne. It was followed by a green water footprint of 149.38 m^3/tonne. The grey water footprint was by far the lowest at 93.39 m^3/tonne. As a result, the distribution of water footprint components indicated that the blue water footprint made up the majority of the total water footprint, while the grey water footprint was the lowest. The blue water footprint made up 54.67% of the total water footprint. It was followed by the green and grey water footprints, which made up 27.89% and 17.44% of the total water footprint respectively.

4.2.2 THE WATER FOOTPRINT OF MAIZE PRODUCTION AT MEASURING POINTS OR4 AND OR5

Table 4.6 describes the biophysical data at measuring points or4 and or5. The yield of maize was obtained from Van Rensburg *et al*. (2012). The soil form at the measuring points is a Hutton soil with a Silt-clay percentage, mean volumetric soil water content, and soil depth of 11%, 0.35 $mm.mm^{-1}$, and 2 000 mm respectively. Maize evapotranspiration for the production period was 693 mm.

Table 4.6: Biophysical data of measuring points or4 and or5 at Orange-Riet Irrigation Scheme

	Yield ($kg.ha^{-1}$)	Silt-clay (%)	θs (mm.mm-1)	Soil Depth (mm)	∆W (mm)	ET (mm)
Average	15325	11	0.35	2000	45	693

Source: Van Rensburg *et al*. (2012)

4.2.2.1 BLUE AND GREEN WATER FOOTPRINTS

Table 4.7 indicates that the evapotranspiration of maize produced in the vicinity of measuring points or4 and or5 was 740 mm. The rainfall in the area for the period of maize production was 262 mm. Despite an irrigation requirement of 478 mm, the farmers irrigated the maize fields with 344 mm, which is 134 mm less than the actual irrigation requirement. The build-up of a water table over time made up for the under-irrigation because it supplemented the irrigation. The rainfall and irrigation together totaled 606 mm for the maize production period. Table 4.7 shows that the maize farmers in the vicinity of measuring points or4 and or5 at Orange-Riet Irrigation scheme under-irrigated by 134 mm. However, the maize was not under water stress due to a water table that had risen to high levels over time.

Table 4.7: Summary of water use data at the measuring points or4 and or5 at the Orange-Riet Irrigation Scheme in season 1

	ET crop (mm)	**R (mm)**	**I (mm)**	**IR (mm)**	**R+I (mm)**
Average	740	262	344	478	606

Source: Van Rensburg *et al*. (2012)

Table 4.8 shows that at a yield level of 15.33 tonne/ha, the green and blue water footprints of maize production are 170.96 m^3/tonne and 258.40 m^3/tonne respectively. The consumptive water footprint of maize production is 395.43 m^3/tonne. There is under-irrigation of approximately 87.44 m^3 for each tonne of maize produced. Since Van Rensburg *et al*. (2012) indicated that this water was evapotranspirated by the crop, the researcher assumed that this water was stored in the soil as groundwater and thus formed part of the blue water footprint. Hence the true blue water footprint is 258.40 m^3/tonne. This makes it the highest water footprint component, accounting for 40.83% of the total water footprint per tonne of maize production.

Table 4.8: Summary of the green and blue water footprints of producing maize in the Orange-Riet Irrigation Scheme at measuring points or4 and or5 in season 1

ET crop	ET green	ET blue	CWU	CWU green	CWU blue	Yield	WF	WF green	WF blue
mm/period			m³/ha			tonne /ha	m³/tonne		
740	262	344	7400	2620	3440	15.33	429.36	170.96	258.40

Source: Van Rensburg *et al*. (2012)

4.2.2.2 GREY WATER FOOTPRINT

The grey water footprint associated with nitrogen at measuring points or4 and or5 is summarised as follows:

$$GWF = \frac{\alpha \times Appl}{c_{\max} - c_{\min}} [volume/time] \quad [32]$$

Table 4.9 is a summary of the leaching-runoff fractions and application levels of nitrogen at measuring points or4 and or5. The leaching-runoff fraction of nitrogen was estimated at 13.79%. Nitrogen application was reported at 215 kg/ha. These values are necessary for determining the pollutant load of nitrogen.

Table 4.9: Variables necessary for estimating the pollutant load for nitrogen and phosphorous at measuring points or4 and or5

Nutrient	Pollutant load	
N	α	Application
	13.792%	215 kg/ha

Source: Van Rensburg *et al*. (2012)

Table 4.10 describes the grey water footprint at measuring points or4 and or5. The grey water footprint per ha was found to be 1 244.13 m^3/ha. At a yield of 13.32 tonne/ha, the grey water footprint was found to be 93.39 m^3/tonne.

Table 4.10: Summary of the grey water footprint at or4 and or5

GWF_N	Yield	GWF_N
m^3/ha	**tonne/ha**	**m^3/tonne**
2299.35	15.33	149.99

Source: Van Rensburg *et al*. (2012)

4.2.2.3 DISCUSSION

The maize yield at measuring points or4 and or5 was 15.33 tonne/ha. At this yield level, the blue water footprint was found to be the highest at 258.40 m^3/tonne. It was followed by a green water footprint of 170.96 m^3/tonne. The grey water footprint was the lowest at 149.99 m^3/tonne. Hence the distribution of water footprint components showed that the blue water footprint made up the majority of the total water footprint, while the grey water footprint was the lowest. The blue water footprint made up 35.47% of the total water footprint. It was followed by the green and grey water footprints, which made up 27.01% and 23.70% of the total water footprint respectively. However, about 13.82% of the consumptive water footprint of each tonne of maize produced is not accounted for.

4.2.3 THE TOTAL WATER FOOTPRINT OF MAIZE PRODUCTION

Table 4.11 is a summary of the total water footprint of maize production in the Orange-Riet Irrigation Scheme. The average yield between the two sites is 14.32 t/ha. The total water footprint of maize production in the Orange-Riet Irrigation Scheme is taken as the average of the water footprint at measuring points or18 and or20, and or4 and or5. The mean water footprint of maize production is therefore 584.19 m^3/tonne. The consumptive water footprint amounts to 462.50 m^3/tonne, whilst the grey water footprint associated with nitrogen fertilisation is 121.69 m^3/tonne. The blue water footprint makes up 47.17% of the total water footprint of maize production in the Orange-Riet Irrigation Scheme. It is followed by the green water footprint, which accounts for 32% of the total water footprint. Grey water contributes 20.83% to the total water footprint.

Table 4.11: The total water footprint at Orange-Riet Irrigation Scheme

	WF_{maize}	WF_{green}	WF_{blue}	WF_{grey}	Yield
	m^3/tonne				t/ha
Mean	584.19	186.92	275.58	121.69	14.32

Source: Van Rensburg *et al*. (2012)

4.3 THE WATER FOOTPRINT OF BROILER PRODUCTION

The water footprint of broiler production describes the total volume of freshwater used to produce a tonne of chicken meat.

4.3.1 BLUE WATER FOOTPRINT OF BROILER PRODUCTION

This study focuses on the water used in maize and broiler production, as well as the water used in slaughtering and processing broilers to produce chicken meat.
The blue water footprint of broiler production is estimated as follows:

$$BWF_{FARM} = \frac{(2800m^3 \; per\; year \times 950 \, broiler\; houses)/365\; days}{101465\, broilers\;\; per\; day \times \left(1.85kg\; per\, broiler\; /1000\right)}$$

$$BWF_{FARM} = \frac{7287.67\, m^3\, per\; day}{187.71 tonnes\;\; per\; day}$$

$$BWF_{FARM} = 38.82\, m^3\; /\, tonne$$

The farm uses about 7 287.67 m^3 of water to produce 101 465 broilers a day. At a broiler final weight of 1.85 kg, the broiler farm’s blue water footprint amounted to 38.82 m^3/tonne. The blue water footprint of slaughtering and slaughtering broilers at the abattoir is estimated as follows:

$$BWF_{ABATTOIR\,(SLAUGHTERING)} = \frac{(0.01m^3\;\; per\, broiler\; /\, 2)\times(155000\, broilers)}{0.00185\, tonnes \times 155000\, broilers}$$

$$BWF_{ABATTOIR\,(SLAUGHTERING)} = \frac{775m^3}{286.75\, tonnes}$$

$$BWF_{ABATTOIR\,(SLAUGHTERING)} = 2.70m^3\;\; per\, tonne$$

The abattoir uses 775 m^3 of water to slaughter 155 000 broilers a day. At a broiler weight of 1.85 kg, the abattoir's blue water footprint of slaughtering a tonne of broilers is 2.70m^3/tonne. The blue water footprint of processing broilers at the abattoir is estimated as follows:

$$BWF_{ABATTOIR\,(PROCESSING)} = \frac{(0.01m^3 \;\; per\, broiler\, /\, 2) \times (155000\, broilers)}{0.00133\, tonnes \times 155000\, broilers}$$

$$BWF_{ABATTOIR\,(PROCESSING)} = \frac{775m^3}{206.15\, tonnes}$$

$$BWF_{ABATTOIR\,(PROCESSING)} = 3.76m^3 \;\; per\; tonne$$

The abattoir uses 775 m^3 of water to process 155 000 broiler carcasses per day. At a carcass weight of 1.33 kg, the blue water footprint for processing the broiler carcass was 3.76 m^3/tonne. Blue water is the main source of freshwater for broiler production.

Table 4.12 is a summary of the volume of water used to produce a tonne of chicken meat. It distinguishes between the volume of water used at the farm, abattoir, and processing plant. Water use is the highest at the farm. The water footprint of maize production has been estimated at 584.19 m^3/tonne. The broiler farm uses 1.04 tonnes of maize, 0.29 tonnes of soya oilcake, and 0.10 tonnes of sunflower oilcake to produce one tonne of broilers. Therefore, the water footprint associated with the broiler feed per tonne of broilers produced is equivalent to the product of the maize, soya oilcake, and sunflower oilcake water footprint per tonne and the tonnes of maize, soya oilcake, and sunflower oilcake consumed by a tonne of broilers, respectively. Hence the feed water footprint of a tonne of broilers is 1 430.33 m^3. The abattoir and processing plant have a smaller water footprint. The total volume of water used to produce one tonne of chicken is the sum of the volume of water used on the broiler farm, abattoir, and processing plant, as well as the water footprint associated with the maize feed. In total, water used along the three segments of the broiler value chain amounts to 1475.61 m^3 per tonne of chicken produced. Water that has been used at the broiler farm, abattoir, and processing plant is released into the nearby veld. This water forms part of the grey water footprint of chicken production. About 97% of the water footprint of a tonne of chicken meat is attributed to broiler feed. This is well in line with the findings of Mekonnen and Hoekstra (2010), who established that animal feed accounts for 98% of the water footprint of animal products.

Table 4.12: Total water footprint per tonne of broilers produced, slaughtered, and processed

	Farm		**Abattoir**	**Processing plant**	**Total**
	Excluding feed	**Broiler feed**	**Broilers**	**Carcasses**	
m^3 per tonne	38.82	1430.33			
	1469.15		2.70	3.76	1475.61

The total water footprint associated with the production of a tonne of chicken meat is made up of a green, blue, and grey component. The green water footprint is 1 001.66 m^3/tonne of chicken meat produced. This is 67.88% of the total water footprint of a tonne of chicken. The blue and grey water footprints are 341.27 m^3 and 132.71 m^3 per tonne of chicken produced, respectively. The blue water footprint makes up 23.13% and the grey water footprint contributes 9% to the total water footprint of chicken production. The green water footprint makes up more than half of the total water footprint.

4.4 ECONOMIC WATER PRODUCTIVITY

Economic water productivity (EWP) is the economic value obtained per unit of water utilised (Chouchane *et al*., 2015). Table 4.13 is a description of the average retail prices of chicken meat for 2015, depending on whether it is whole chicken or chicken portions, and whether they are fresh or frozen. For the period of 2015, the average retail prices of fresh whole chicken, fresh chicken portions, and frozen chicken portions were R39 560, R51 210, and R28 980 per tonne respectively. To produce a tonne of chicken meat, about 1 475.61 m^3 of water is used. The EWP of producing a tonne of fresh, whole chicken meat is R26.83. When producing a tonne of fresh chicken portions, the EWP is approximately R34.73. The production of a tonne of frozen chicken portions has an EWP of R19.65. Thus more EWP is derived from producing fresh chicken portions than frozen chicken portions.

Table 4.13: Average chicken retail prices

Chicken	**Retail price**		**EWP**
	R/kg	**R/tonne**	**R/m^3**
Whole chicken: fresh	39.56	39560	26.83
Chicken portions: fresh	51.21	51210	34.73
Chicken portions: frozen	28.98	28980	19.65

Source: South African Poultry Association (2016)

4.5 SUSTAINABILITY ASSESSMENT

The Orange-Riet Irrigation Scheme falls in the Orange River basin. Figure 4.1 is a graphical representation of the blue water scarcity of the Orange River basin. Low blue water scarcity is a condition where water availability exceeds water usage such that the ratio of the water footprint to water availability is less than 1 or 100%. This ratio is known as the water scarcity index. As the water footprint increases relative to the water availability, until such a point where it is equal to water availability, a water scarcity index of 100% is reached. An increase in water usage beyond this point would render the blue water scarcity index moderate. Moderate blue water scarcity ranges from 100% to 150%. Further demand for freshwater above a scarcity level of 150% but below 200% is in a significant phase. Severe blue water scarcity indices are reached at scarcity levels exceeding 200%.

The monthly magnitude of water availability (WA), water footprint (WF), and water scarcity (WS) in the basin are depicted in Figure 4.1. The water footprint exceeds the water availability from June to November, resulting in water scarcity during this period. The water scarcity during this time reaches moderate to severe levels, such that water use during this period is considered unsustainable. Nevertheless, the degree of unsustainability in the Orange River basin from June to November varies from moderate to severe. June marks the beginning of a moderate blue water scarcity. It becomes significant in July and severe from August to September. As October approaches, the blue water scarcity drops down to moderate levels and maintains those levels until the end of November. Low levels of blue water scarcity are reported from December to May. Nevertheless, 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. Therefore, it underestimated blue water availability in the Orange River basin and was not a true reflection of the basin's water endowment throughout the year.

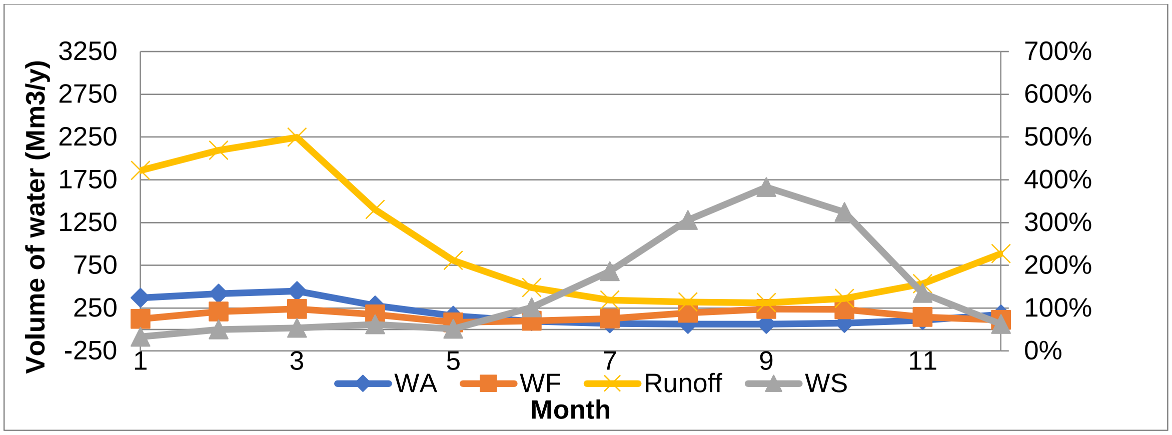

Figure 4.1: Monthly blue water scarcity of the Orange River basin

Source: Hoekstra and Mekonnen (2011)

Maize production at measuring points or18 and or20 commenced in October and harvesting was done in May. At measuring points or4 and or5, maize was planted in December and harvested in July. Thus maize production is moderately unsustainable during June, October, and November, and is significantly unsustainable in July. The maize water requirement increases gradually from planting, and diminishes as it reaches its physiological maturity stage. Hence considerable maize water requirement occurs during a period of low blue water scarcity. Ultimately, maize, soybean, and sunflower are summer crops and are largely produced during the summer months when blue water scarcity is low. Chicken production occurs throughout the year. Given that 97% of the water footprint of broiler production is attributed to feed, broiler production may be considered sustainable.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This study was concerned with the implications of broiler production on freshwater availability. It evaluated the sustainability of maize production in the Orange-Riet Irrigation Scheme and chicken meat produced by a broiler company located in the Free State. It does not necessarily claim to represent South Africa's entire broiler industry as there are differences in the production systems that various companies use. The following conclusions arise from the analysis of the results of this study:

According to the DWA (2013), South Africa's water usage comprises 77% surface water, 9% groundwater, and 14% reuse of return flows. South Africa's annual surface water supplies are estimated at 49 billion m^3. Given the annual fluctuations in surface water availability, the country can only guarantee the availability of 10.24 billion m^3 of surface water each year. This is a concerning issue because about 9.5 billion m^3 of water is needed to meet the freshwater demand of the total ecological reserve. Nevertheless, groundwater availability is estimated at 5 billion m^3 per year, with an annual consumption of 2 billion m^3. This limited volume of freshwater has to be distributed such that it does not fall short of the country's registered water usage, currently reported at 15 to 16 billion m^3 per year. More than 60% of the total water consumption is attributed to agricultural irrigation. Despite its high level of water consumption, irrigated agriculture has an important role to play in promoting food security. As such, maize is an important ingredient in broiler feed. It forms 60% of broilers' diet and the broiler industry thus relies heavily on maize. Such reliance on the product of a water-intensive industry, particularly irrigated agriculture, in a semi-arid South Africa, warrants the use of tools to investigate the sustainability of maize production. The WFA is a reliable indicator for assessing the sustainability with which freshwater is used for broiler production in South Africa.

There is an abundant and increasing use of WFAs in the world. However, South Africa falls behind in that respect, as seen in its limited local applications of WFAs. To the author's knowledge, there has been no assessment of the water footprint of the South African maize-broiler value chain, thus there is a lack of scientific water footprint information to effectively guide water use in the South African maize and broiler industries.

This study aimed to assess the water footprint of the South African broiler industry in terms of a derived product of maize that is used as feed for broiler chickens. First, the volumetric water footprint indicator was calculated for the maize-broiler value chain. Thereafter the degree of sustainability was determined. Lastly, the EWP was assessed to gain insight into the economic returns that were generated from using freshwater in the maize-broiler value chain.

The results showed that, in both sites of the study area, the blue water footprint of maize production is greater than the green water footprint of maize production. The blue water footprint accounted for most of the consumptive water footprint. Even in the total water footprint, which is meant to be representative of the whole scheme, the blue water footprint accounts for almost 60% of the consumptive use of freshwater and more than double the grey water footprint. This suggests that there is great reliance on blue water in the Orange-Riet Irrigation Scheme. The grey water footprint associated with nitrogen fertilisation accounts for about 17% of the water footprint at measuring points or18 and or20, and approximately 24% of the water footprint at measuring points or4 and or5. The total grey water footprint (GWF_N) makes up 21% of the total water footprint in the Orange-Riet Irrigation Scheme, thus the grey water footprint accounts for a significant share of the total water footprint of maize production in the scheme. This suggests that there is great potential for lowering the total water footprint by reducing the total grey water footprint. Hence special attention must be paid to addressing blue water consumption, as well as minimising the leaching and runoff of nitrogen into blue water.

Despite the large blue water footprint of maize production in the Orange-Riet Irrigation scheme and the 60% share of maize in broiler feed, the results show that the green water footprint accounts for 67.88% of the total water footprint of producing a tonne of chicken meat. The blue and grey water footprint account for 23.13% and 9%, respectively. Soybean and sunflower oilcake have a much higher green water footprint compared to their blue water footprint. This has caused the green water footprint of producing a tonne of chicken meat to be higher than the blue water footprint. Therefore, the water footprint of soybean and sunflower oilcake have had a greater impact in “shaping” the green, blue, and grey water footprint of the water footprint of producing a tonne of chicken meat. Therefore the significance of broiler feed ingredients in the water footprint of broilers does not only lie in their share of the feed but also in how large their individual water footprints are.

The water footprint of chicken production varies from the farm to abattoir to the processing plant. About 97% of the farm-level water footprint of broiler production per tonne of broilers is attributed to broiler feed. This entails that other uses of water on the farm account for less than 3% of the water footprint of on-farm broiler production. The slaughtering of broilers makes up 0.18% of the volume of water used to produce a tonne of chicken, whilst processing contributes 0.25%. Together, the slaughtering and processing of chickens account for 0.43% of the total water footprint of producing a tonne of chicken.

The irrigation and nitrogen fertilisation of maize for broiler feed account for the greatest share of the water footprint of producing a tonne of chicken meat. Farmers in the Orange-Riet Irrigation Scheme typically plant maize in December when the blue water scarcity index of the Orange River basin is low. As mentioned in the previous chapter, 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. Therefore, farmers in the scheme may be regarded as sustainable.

The economic value derived per unit of water used depends on the type of chicken product produced. Chicken meat sold fresh yields higher economic returns per unit of freshwater than frozen chicken meat. In terms of fresh chicken, a tonne of chicken portions yields more economic returns per unit of water consumed than a tonne of whole chicken. Therefore, the EWP is higher for chicken portions that are sold fresh.

South Africa’s water resources are limited. Irrigation puts pressure on freshwater but ensures an adequate supply of broiler feed. Nevertheless, production is sustainable. To increase the economic productivity of water, value must be added to broilers through processing.

5.1.1 SUSTAINABILITY ASSESSMENT

Despite maize production extending past the end of the maize marketing year, farmers generally do not irrigate maize in June and July. These two months form part of the harvesting season. Nevertheless, farmers in the region normally plant maize in December, when water use in the Orange River basin is sustainable. The sustainability of broiler production largely depends on the sustainability of maize production. Broiler production thus is found to be sustainable because maize production is sustainable.

5.2 RECOMMENDATIONS

5.2.1 RECOMMENDATIONS FOR WATER USERS

Maize farmers should:

- irrigate towards the later hours of the day to avoid moisture losses through evaporation;
- optimise their in-row spacing to achieve sufficient ground cover in order to avoid evaporation losses of soil moisture;
- make use of efficient irrigation scheduling techniques to be more informed about their water requirements;
- divide their nitrogen fertilisation into several smaller applications according to the soil’s nitrogen content and maize growth stages. This will limit the amount of nitrogen that leaches into the soil or flows with runoff and thus effectively reduce the grey water footprint;
- make use of rainwater harvesting to increase their blue water reserves and reduce the pressure on blue water sources;
- add mulch above the planted area to retain soil moisture and reduce runoff;
- clear the field of weeds to reduce unnecessary soil moisture losses; and
- optimise the fertiliser-water relationship for maximum yields.

5.2.2 RECOMMENDATIONS FOR POLICY MAKERS

Policy makers may:

- implement the polluter-pays principle and use the money to return the water body to ambient water quality standards;
- allocate water according to the yield a farmer intends on producing;
- tax farmers on every kilogram of nitrogen fertiliser that they purchase and use the money to improve the water quality in the region; and
- give companies that purchase maize in the scheme an incentive because it is produced sustainably. An incentive may be in the form of tax relief on their water bill.

5.2.3 RECOMMENDATIONS FOR FURTHER RESEARCH

Researchers may:

- conduct a sustainability assessment with local, context-specific data to obtain 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;
- investigate the water footprint of broilers and take into consideration all or most of the ingredients in broiler feed for a more accurate assessment;
- include the end consumer and account for the indirect water footprint associated with packaging;
- conduct an assessment on the water footprint of different broiler cuts to give an idea of the impact of each cut on each pillar of sustainability. They may also determine the EWP of each cut to identify which cut has the highest EWP;
- assess the social and/or economic sustainability of the maize-broiler value chain;
- conduct a WFA of layers to allow for the comparison between the impact of layer production and broiler production; and
- place this study in the wider South African broiler production context, to gain a national picture of the water footprint associated with broiler production.

5.3 LIMITATIONS OF THE STUDY

The study assumed:

- broiler producers source their maize from the Orange-Riet Irrigation scheme, and
- that slaughtering and processing at the abattoir each account for 50% of abattoir water use.

REFERENCES

ADVANCED PURIFICATION ENGINEERING CORP. 2015. *Nitrate (nitrate nitrogen) in drinking water.* Available at: http://www.freedrinkingwater.com/water-education2/79-nitrate-nitrogen.htm [Accessed: 20 December 2015].

ANIMAL FEED MANUFACTURERS ASSOCIATION (AFMA), (2007). *Chairman's report 2006/2007*. Available at: http://www.afma.co.za/afma-chairmans-report/?cp_afma-chairmans-report=1 [Accessed: 19 November 2016]

ANIMAL FEED MANUFACTURERS ASSOCIATION (AFMA), (2008). *Chairman's report 2007/2008*. Available at: http://www.afma.co.za/afma-chairmans-report/?cp_afma-chairmans-report=1 [Accessed: 19 November 2016]

ANIMAL FEED MANUFACTURERS ASSOCIATION (AFMA), (2010). *Chairman's report 2009/2010*. Available at: http://www.afma.co.za/afma-chairmans-report/?cp_afma-chairmans-report=1 [Accessed: 19 November 2016]

ANIMAL FEED MANUFACTURERS ASSOCIATION (AFMA), (2011). *Chairman's report 2010/2011*. Available at: http://www.afma.co.za/afma-chairmans-report/?cp_afma-chairmans-report=1 [Accessed: 19 November 2016]

ANIMAL FEED MANUFACTURERS ASSOCIATION (AFMA), (2012). *Chairman's report 2010/2011*. Available at: http://www.afma.co.za/afma-chairmans-report/?cp_afma-chairmans-report=1 [Accessed: 19 November 2016]

ANIMAL FEED MANUFACTURERS ASSOCIATION (AFMA), (2013). *Chairman's report 2010/2011*. Available at: http://www.afma.co.za/afma-chairmans-report/?cp_afma-chairmans-report=1 [Accessed: 19 November 2016]

ANIMAL FEED MANUFACTURERS ASSOCIATION (AFMA), (2014). *Chairman's report 2010/2011*. Available at: http://www.afma.co.za/afma-chairmans-report/?cp_afma-chairmans-report=1 [Accessed: 19 November 2016]

ALDAYA, M.M., ALLAN, J.A. AND HOEKSTRA, A.Y. 2009. *Strategic importance of green water in international crop trade. Ecological Economics* 69(2010): 887-894. Available at: http://waterfootprint.org/media/downloads/Aldaya-Allan-Hoekstra-2010_1.pdf [Accessed: 29 October 2016]

ALDAYA, M.M. AND HOEKSTRA, A.Y. 2010. *The water needed for Italians to eat pasta and pizza. Agricultural Systems* 103(2010): 351-360. Available at: http://waterfootprint.org/media/downloads/Aldaya-Hoekstra-2010.pdf [Accessed: 25 June 2016]

ALLAN, J.A. 1998. Virtual water: a strategic resource. Global solutions to regional deficits. *Groundwater* 36(4): 545-546. Available at: http://onlinelibrary.wiley.com/doi/10.1111/j.1745-6584.1998.tb02825.x/epdf [Accessed: 02 May 2015].

BALOYI, R.T., BELETE, A., HLONGWANE, J.J. AND MASUKU, M.B. 2012. Technical efficiency in maize production by small-scale farmers in Ga-Mothiba of Limpopo province, South Africa. *African Journal of Agricultural Research* 7(40): 5478-5482. Available at: http://www.academicjournals.org/AJAR [Accessed: 07 March 2015].

BEZUIDENHOUT, J. 2013. *Agriculture in South Africa*. Available at: http://www.capeland.co.za/articles/69-agriculture-in-south-africa [Accessed: 03 February 2016].

BOUCHARD, D.C., WILLIAMS, M.K. AND SURAMPALLI, R.Y. 1992. *Nitrate contamination of groundwater: Sources and potential health effects*. Available at: file:///C:/Users/Phoka/Downloads/waternet.0031621%20(1).pdf [Accessed: 21 December 2015].

BROUWER, C. AND HEIBLOEM, M. 1986. *Irrigation water management: Irrigation water needs.* Available at: http://www.fao.org/docrep/s2022e/s2022e00.htm#Contents [Accessed: 09 May 2017].

CAMARGO, J.A., ALONSO, A. AND SALAMANCA, A. 2004. Nitrate toxicity to aquatic animals: A review with new data for freshwater invertebrates. *Chemosphere* 58(2005): 1255-1267. Available at: http://www.waterboards.ca.gov/water_issues/programs/tmdl/records/region_2/2008/ref2426.pdf [Accessed: 04 December 2015].

CHAPAGAIN A.K. AND ORR, S. 2010. *Water footprint of Nestle's 'Bitesize Shredded Wheat'*. Available at: http://waterfootprint.org/media/downloads/Nestle-2010-Water-Footprint-Bitesize-Shredded-Wheat.pdf [Accessed: 28 August 2016]

CHOUCHANE, H., HOEKSTRA, A.Y., KROL, M.S. AND MEKONNEN, M.M. 2013. *The water footprint of Tunisia from an economic perspective.* Value of water research report series No. 61. Enschede, The Netherlands: UNESCO-IHE. Available at: http://waterfootprint.org/media/downloads/Report61-WaterFootprintTunisia_1.pdf [Accessed: 13 June 2016]

CHOUCHANE, H., HOEKSTRA, A.Y., KROL, M.S. AND MEKONNEN, M.M. 2015. The water footprint of Tunisia from an economic perspective. *Ecological Indicators* 52(2015): 311-319. Available at: http://waterfootprint.org/media/downloads/Chouchane-et-al-20151.pdf [Accessed: 13 June 2015].

CROP ESTIMATES COMMITTEE (CEC), 2005. *Calculated final area and crop figures of summer crops: 2004/05 production season.* Available at: http://www.sagis.org.za/cec_reports_2005.html [Accessed: 02 January 2017].

CROP ESTIMATES COMMITTEE (CEC), 2006. *Calculated final crop figures of summer crops: 2005/06 production season.* Available at: http://www.sagis.org.za/cec_reports_2006.html [Accessed: 02 January 2017].

CROP ESTIMATES COMMITTEE (CEC), 2007. *Calculated final area and crop production figures of maize and sorghum: 2006/07 production season.* Available at: http://www.sagis.org.za/cec_reports_2007.html [Accessed: 02 January 2017].

CROP ESTIMATES COMMITTEE (CEC), 2008. *Commercial summer crops: calculated final area and crop production figures - 2007/08 production season*. Available at: http://www.sagis.org.za/CEC_2008_-_Nov_final_summer_crops.pdf [Accessed: 02 January 2017].

CROP ESTIMATES COMMITTEE (CEC), 2009. *Final area planted and crop production figures of commercial maize, sunflower seed, soya-beans, groundnuts and sorghum 2008/09 production season.* Available at: http://www.sagis.org.za/CEC_2009_-_Nov_(b).pdf [Accessed: 03 January 2017].

CROP ESTIMATES COMMITTEE (CEC), 2010. *Final area planted and crop production figures of commercial maize, sunflower seed, soya-beans, groundnuts and sorghum 2009/10 production season.* Available at: http://www.sagis.org.za/cec_reports_2010.html [Accessed: 03 January 2017].

CROP ESTIMATES COMMITTEE (CEC), 2011. *Final area planted and crop production figures of commercial maize, sunflower seed, soya beans, groundnuts and sorghum for 2011.* Available at: http://www.sagis.org.za/CEC_2011_-_Nov_(a).pdf [Accessed: 03 January 2017].

CROP ESTIMATES COMMITTEE (CEC), 2012. *Final area planted and crop production figures of commercial maize, sunflower seed, soya beans, groundnuts and sorghum for 2012.* Available at: http://www.sagis.org.za/CEC_2012_-_Nov.pdf [Accessed: 07 January 2017].

CROP ESTIMATES COMMITTEE (CEC), 2013. *Final area planted and crop production figures of commercial maize, sunflower seed, soya beans, groundnuts and sorghum for 2013.* Available at: http://www.sagis.org.za/cec_reports_2013.html [Accessed: 07 January 2017].

CROP ESTIMATES COMMITTEE (CEC), 2005. *Sagis monthly info/data.* Available at: http://www.sagis.org.za/smd2005(afreng).html [Accessed: 20 November 2016].

CROP ESTIMATES COMMITTEE (CEC), 2006. *Sagis monthly info/data.* Available at: http://www.sagis.org.za/smd2006(afreng).html [Accessed: 20 November 2016].

CROP ESTIMATES COMMITTEE (CEC), 2007. *Sagis monthly info/data.* Available at: http://www.sagis.org.za/smd2007(afreng).html [Accessed: 20 November 2016].

CROP ESTIMATES COMMITTEE (CEC), 2008. *Sagis monthly info/data.* Available at: http://www.sagis.org.za/smd2008(afreng).html [Accessed: 20 November 2016].

CROP ESTIMATES COMMITTEE (CEC), 2009. *Sagis monthly info/data.* Available at: http://www.sagis.org.za/smd2009(afreng).html [Accessed: 20 November 2016].

CROP ESTIMATES COMMITTEE (CEC), 2010. *Sagis monthly info/data.* Available at: http://www.sagis.org.za/smd2010(afreng).html [Accessed: 20 November 2016].

CROP ESTIMATES COMMITTEE (CEC), 2011. *Sagis monthly info/data.* Available at: http://www.sagis.org.za/smd2011(afreng).html [Accessed: 20 November 2016].

CROP ESTIMATES COMMITTEE (CEC), 2012. *Sagis monthly info/data.* Available at: http://www.sagis.org.za/smd2012(afreng).html [Accessed: 27 November 2016].

CROP ESTIMATES COMMITTEE (CEC), 2013. *Sagis monthly info/data.* Available at: http://www.sagis.org.za/smd2013(afreng).html [Accessed: 27 November 2016].

CROP ESTIMATES COMMITTEE (CEC), 2014. *Sagis monthly info/data.* Available at: http://www.sagis.org.za/smd2014(afreng).html [Accessed: 03 December 2016].

CROP ESTIMATES COMMITTEE (CEC), 2015. *Sagis monthly info/data.* Available at: http://www.sagis.org.za/page540.html [Accessed: 03 December 2016]

CROP ESTIMATES COMMITTEE (CEC). 2016. *Sagis monthly info/data*. Available at: http://www.sagis.org.za/smd2016(afreng).html [Accessed: 04 June 2017].

CROP ESTIMATES COMMITTEE (CEC), 2017. Sagis monthly info/data. Available at: http://www.sagis.org.za/smd2017(afreng).html [Accessed: 30 June 2017].

CROP ESTIMATES COMMITTEE (CEC), 2013. *Summer crops – Area planted and fifth production forecast: 2013*. Available at: http://www.daff.gov.za/doaDev/cropestimates/mediajune2013.pdf [Accessed: 08 June 2017].

CROP ESTIMATES COMMITTEE (CEC), 2017. *Summer crops – area planted and fifth production forecast: 2017.* Available at: http://www.sagis.org.za/cec_reports_2017.html [Accessed: 30 June 2017].

CROP ESTIMATES COMMITTEE (CEC), 2014. *Summer crops – area planted and final production estimate: 2014*. Available at: http://www.sagis.org.za/cec_reports_2014.html [Accessed: 07 January 2017].

CROP ESTIMATES COMMITTEE (CEC), 2015. *Summer crops – area planted and final production estimate*: *2015*. Available at: http://www.sagis.org.za/CEC-Sep-2015.pdf [Accessed: 07 January 2017].

CROP ESTIMATES COMMITTEE (CEC), 2016. *Summer crops – area planted and final production estimate: 2016*. Available at: http://www.sagis.org.za/cec_reports_2016.html [Accessed: 25 June 2017].

CROP ESTIMATES COMMITTEE (CEC), 2017. *Summer crops – Revised Area planted and first production forecast: 2017.* Available at: http://www.nda.agric.za/docs/Cropsestimates/Media%20Feb%202017.pdf [Accessed: 09 May 2017].

DEPARTMENT OF AGRICULTURE (DoA), 2003. *Maize production*. Available at: http://www.arc.agric.za/arc-gci/Fact%20Sheets%20Library/Maize%20Production.pdf [Accessed: 04 February 2015].

DEPARTMENT OF AGICULTURE: DIRECTORATE AGRICULTURAL STATISTICS. 2006. *Crops and Markets: First quarter 2006.* Available at: http://www.daff.gov.za/docs/statsinfo/Crops_0106.pdf [Accessed: 20 April 2015].

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF). 2016. *A profile of the South African maize market value chain*. Available at: http://www.nda.agric.za/doaDev/sideMenu/Marketing/Annual%20Publications/Commodity%20Profiles/field%20crops/Maize%20Market%20value%20Chain%20Profile%202016.pdf [Accessed: 25 June 2017].

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF). 2013. *Economic review of the South African agriculture*. Available at: http://www.senwes.co.za/Files/main_productsservices/agriservices/2014/Economic_Review_2013.pdf [Accessed: 09 April 2015].

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES, 2013. *Abstract of Agricultural Statistics*. Available at: http://www.nda.agric.za/docs/statsinfo/Abstact2013.pdf [Accessed: 19 June 2016].

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF). 2012. *Maize market value chain profile*. Available at: http://www.nda.agric.za/docs/AMCP/MaizeMVCP2011.pdf [Accessed: 14 July 2015].

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF). 2013a. *Pocket guide to South Africa 2012/2013.* Available at: http://www.gcis.gov.za/sites/www.gcis.gov.za/files/docs/resourcecentre/pocketguide/2012/03%20Agriculture.pdf [Accessed: 05 March 2015].

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF). 2013b. *Trends in the agricultural sector*. Available at: http://www.econostatistics.co.za/TrendsinSAAgriculture13.pdf [Accessed: 15 May 2015].

DEPARTMENT OF WATER AFFAIRS (DWA). 1964. *Report on the proposed Modder River government water work (Krugersdrift Dam)*. Available at: http://libguides.wits.ac.za/c.php?g=145429ANDp=951694 [Accessed: 09 October 2015].

DEPARTMENT OF WATER AFFAIRS (DWA). 2013. *Strategic Overview of the Water Sector in South Africa*. Pretoria: Department of Water Affairs. Available at: http://nepadwatercoe.org/wp-content/uploads/Strategic-Overview-of-the-WaterSector-in-South-Africa-2013.pdf [Accessed: 09 October 2015].

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF). 2009. *Water resource planning systems, Orange River: Assessment of water quality data requirements for water quality planning purposes. Resource Water Quality Objectives (RWQOs): Upper and lower Orange Water Management Areas (WMAs 13 and 14).* Report no. 5. Available at: https://www.dwa.gov.za/Dir_WQM/docs/RWQOsUpperandLowerOrangeReport5.pdf [Accessed: 22 December 2015].

DEURER, M., GREEN, S.R., CLOTHIER, B.E., AND MOWAT, A., 2011. *Can product water footprints indicate the hydrological impact of primary production? – A case study of New Zealand kiwifruit. Journal of Hydrology* 408(3-4): 246–256. Available at: http://www.sciencedirect.com/science/article/pii/S0022169411005336 [Accessed: 21 February 2016]

ERCIN, A.E., MEKONNEN, M.M. AND HOEKSTRA A.Y. 2013. *Sustainability of national consumption from a water resources perspective: The case study for France*. Enschede: The Netherlands. Available at: http://www.sciencedirect.com/science/article/pii/S0921800913000359 [Accessed: 21 November 2016].

FALKENMARK, M., ROCKSTRÖM, J. and KARLBERG, L. 2009. *Present and future water requirements for feeding humanity. Food Security* 1:59-69.

FERTILIZER SOCIETY OF SOUTH AFRICA (FSSA). 2007. *FSSA Fertilizer handbook*. Pretoria: Fertilizer Society of South Africa.

FOOD AND AGRICULTURE ORGANIZATION (FAO). 2009. *Global agriculture towards 2050*. Available at: http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf [Accessed: 01 February 2015].

FOOD AND AGRICULTURAL ORGANIZATION'S STATISTICAL DATABASE (FAOSTAT). 2014. *Land use area database*. Available at: http://faostat.fao.org/site/377/DesktopDefault.aspx?PageID=377#ancor [Accessed: 22 April 2015].

FRANKE, N.A., BOYACIOGLU, H. and HOEKSTRA, A.Y. 2013. *Grey water footprint accounting, Tier 1 supporting guidelines*. Value of Water Research Report Series No. 65. Delft, The Netherlands: UNESCO-IHE. Available at: http://waterfootprint.org/media/downloads/Report65-GreyWaterFootprint-Guidelines_1.pdf [Accessed: 10 December 2015].

GERBENS-LEENES AND HOEKSTRA 2009. *The water footprint of Sweeteners and bio-ethanol from sugar cane, sugar beet and maize*. Value of Water Research Report Series No. 38. Delft. The Netherlands: UNESCO-IHE. Available at: http://temp.waterfootprint.org/Reports/Report38-WaterFootprint-sweeteners-ethanol.pdf [Accessed: 21 October 2016]

GERBENS-LEENES, P.W., MEKONNEN, M.M. and HOEKSTRA, A.Y. 2011. *A comparative study on the water footprint of poultry, pork and beef in different countries and production systems*. Value of Water Research Report Series No. 55. Delft, The Netherlands: UNESCO-IHE. Available at: http://waterfootprint.org/media/downloads/Report55_1.pdf [Accessed: 10 November 2015].

GERBENS-LEENES, P.W., MEKONNEN, M.M. and HOEKSTRA, A.Y. 2013. The water footprint of poultry, pork and beef: A comparative study in different countries and production systems. *Water Resources and Industry* 1-2:25-36. Available at: http://waterfootprint.org/media/downloads/Gerbens-et-al-2013-waterfootprint-poultry-pork-beef_1.pdf [Accessed: 10 November 2015].

GLEICK, P.H. and IWRA, M. 1996. Basic water requirements for human activities: Meeting basic needs. *Water International* 21(2): 83-92. Available at: http://pacinst.org/wp-content/uploads/sites/21/2012/10/basic_water_requirements-1996.pdf [Accessed: 04 November 2015].

GLOBAL WATER PARTNERSHIP. 2012. *Water is finite and vulnerable resource*. Available at: http://www.gwp.org/en/The-Challenge/What-is-IWRM/IWRM-Principles/Water-is-finite-and-vulnerable-resource/ [Accessed: 04 February 2015].

HARTER, T. 2001. *Groundwater hydrology.* Available at: http://groundwater.ucdavis.edu/files/136254.pdf [Accessed: 15 May 2016]

HASNIP, N., VINCENT L. AND HUSSEIN, K. 1999. *Poverty reduction and irrigated agriculture.* Paper No. 1. Rome, Italy: International Programme for Technology and Reseacrh in Irrigation and Drainage. Available at: ftp://ftp.fao.org/docrep/fao/005/x1000e/x1000e00.pdf [Accessed: 21 November 2016]

HOEKSTRA, A.Y. (ed.). 2003. *Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade*. Delft, The Netherlands, 12 – 13 December 2002. Value of Water Research Report Series No.12. Delft, The Netherlands: UNESCO-IHE. Available at: www.waterfootprint.org/Reports/Report12.pdf [Accessed: 11 April 2015].

HOEKSTRA, A.Y. 2013. *Sustainable, efficient, and equitable water use: the three pillars under wise freshwater allocation*. Available at: http://waterfootprint.org/media/downloads/Hoekstra-2013-Sustainable-efficient-equitable-water-use.pdf [Accessed: 19 October 2016]

HOEKSTRA, A.Y. 2014. The hidden water resource use behind meat and dairy. *Animal Frontiers* 2(2): 3-8. Available at: https://www.animalsciencepublications.org/publications/af/articles/2/2/anfront_2_2_002 [Accessed: 10 November 2015].

HOEKSTRA, A.Y. AND CHAPAGAIN, A.K. 2008. *Globalization of Water: Sharing the Planet's Freshwater Resources*. Oxford, UK: Blackwell Publishing Ltd. Available at: http://eu.wiley.com/WileyCDA/WileyTitle/productCd-1405163356.html [Accessed: 02 January 2016].

HOEKSTRA, A.Y., CHAPAGAIN, A.K., ALDAYA, M.M. and MEKONNEN, M.M. 2009. *Water footprint manual: State of the art 2009*. Available at: http://waterfootprint.org/media/downloads/WaterFootprintManual2009.pdf [Accessed: 29 March 2015].

HOEKSTRA, A.Y., CHAPAGAIN, A.K., ALDAYA, M.M. and MEKONNEN, M.M. 2011. *The water footprint assessment manual: Setting the global standard*. Available at: http://waterfootprint.org/media/downloads/TheWaterFootprintAssessmentManual_2.pdf [Accessed: 06 February 2015].

HOEKSTRA, A.Y. and MEKONNEN M.M. 2011. *Global monthly water scarcity: Blue water footprints versus blue water availability for the world's major river basins*. Delft, The Netherlands: UNESCO-IHE. Available at: http://waterfootprint.org/media/downloads/Report53-GlobalBlueWaterScarcity.pdf [Accessed: 18 November 2015].

IBIDHI, R., HOEKSTRA, A.Y., GERBENS-LEENES, P.W. AND CHOUCHANE, H. 2017. Water, land and carbon footprints of sheep and chicken meat produced in Tunisia under different farming systems. *Ecological Indicators* 77:304-313. Available at: http://waterfootprint.org/media/downloads/Ibidhi-et-al-2017.pdf [Accessed: 10 May 2017]

ILISO CONSULTING. 2012. *Water reconciliation strategy study for the large bulk water supply systems: Greater Bloemfontein area*. *Final water quality assessment report.* Available at: https://www.dwa.gov.za/orange/Docs/Great%20Bloem%20Area/Water%20Quality%20Assessment.pdf [Accessed: 23 December 2015].

JESWANI, H.K. and AZAPAGIC, A. 2011. Water footprint: Methodologies and a case study for assessing the impacts of water use. *Journal of Cleaner Production* 19(2011): 1288-1299. Available at: http://www.buyteknet.info/fileshare/data/trabajo_modular/methodologies%20and%20a%20case%20study%20for%20assessing%20the%20impacts%20of%20water%20use.pdf [Accessed: 23 March 2015].

JOHANNESBURG STOCK EXCHANGE (JSE), 2013. *South African Futures Exchange (SAFEX) Commodity derivatives Market, Dealers Examination Material, Agricultural Products and Agricultural Derivatives.* Johannesburg: South African Institute of Financial Markets. Available at: www.jse.co.za [Accessed: 25 June 2015]

KONING, N., ROOS, J.C. AND GROBBELAAR, J.U. 2000. Water quality of the Modder River, South Africa. *African Journal of Aquatic Science* 25(1): 202-210. Available at: http://www.tandfonline.com/doi/pdf/10.2989/160859100780177992 [Accessed: 22 December 2015].

KPMG AND SMALL ENTERPRISE DEVELOPMENT AGENCY (SEDA). 2012.*Research on the performance of the agricultural sector*. Available at: http://www.seda.org.za/Publications/Publications/Research%20on%20the%20Performance%20of%20the%20Agriculture%20Sector.pdf [Accessed: 02 April 2015].

KRATZER, F.H., LATSHAW, J.D., LEESON, S.L., MORAN, E.T., PARSONS, C.M., SELL, J.L. AND WALDROUP, P.W. 1994. *Nutrient requirements of poultry*. 9th Revised Edition. Wahington, D.C.: National Academy Press. Available at: http://www.nap.edu/catalog/2114.html [Accessed: 11 November 2015].

MARGAT, F., FOSTER, S., AND DROUBI, A. 2006. *Non-renewable groundwater resources. A guidebook on socially-sustainable management for water-policy makers. Concept and importance of non-renewable resources.* Available at: http://unesdoc.unesco.org/images/0014/001469/146997e.pdf [Accessed: 18 May 2016]

MEKONNEN, M.M. AND HOEKSTRA, A.Y. 2010. *The green, blue and grey water footprint of farm animals and animal products.* Volume 1: Main Report. Value of Water Research Report Series, No. 48. Delft, The Netherlands: UNESCO-IHE. Available at: http://www.waterfootprint.org/Reports/Report50-NationalWaterFootprints-Vol1.pdf. [Accessed: 20 November 2015].

MEKONNEN, M.M. AND HOEKSTRA, A.Y. 2011. *National water footprint accounts: The green, blue and grey water footprint of production and consumption.* Volume 1: Main Report. Value of Water Research Report Series, No. 1(50). Delft, The Netherlands: UNESCO-IHE. Available at: http://waterfootprint.org/media/downloads/Report50-NationalWaterFootprints-Vol1.pdf [Accessed: 10 November 2015].

MEKONNEN, M.M. AND HOEKSTRA, A.Y. 2012. A Global Assessment of the Water Footprint of Farm Animal Products. *Ecosystems* (2012): 15:401-415. Available at: http://waterfootprint.org/media/downloads/Mekonnen-Hoekstra-2012-WaterFootprintFarmAnimalProducts.pdf [Accessed: 16 November 2016]

MEKONNEN, M.M. AND HOEKSTRA, A.Y. 2013. *Water Footprint Benchmarks for Crop Production.* Value of Water Research Report Series No.64. Enschede. the Netherlands: UNESCO-IHE. Available at: http://waterfootprint.org/media/downloads/Report64-WaterFootprintBenchmarks-CropProduction_1.pdf [Accessed: 21 July 2016]

MEKONNEN, M.M. AND HOEKSTRA, A.Y. 2014. Water footprint benchmarks for crop production: A first global assessment. *Ecological Indicators* 46:214-223. Available at: http://ac.els-cdn.com/S1470160X14002660/1-s2.0-S1470160X14002660-main.pdf?_tid=44aa6564-bdca-11e5-8ec4-00000aab0f27&acdnat=1453111393_eba5577c86717204_42d03c719f348682 [Accessed: 06 February 2015].

MEKONNEN, M.M., PAHLOW, M., ALDAYA, M.M., ZARATE, E. AND HOEKSTRA, A.Y. 2015. *Sustainability, Efficiency and Equitability of Water Consumption and Pollution in Latin America and the Carribean*. Available at: http://waterfootprint.org/media/downloads/Mekonnen-et-al-2015-WFA-LAC.pdf [Accessed: 23 April 2016]

MILÀ i CANALS, L., CHENOWETH, J., CHAPAGAIN, A.K., ORR, S., ANTÓN, A. AND CLIFT, R. 2008. Assessing freshwater use impacts in LCA: Part I – Inventory modelling and characterisation factors for the main impact pathways. *The International Journal of Life Cycle Assessment* 14(1): 28-42. Available at: http://link.springer.com/10.1007/s11367-008-0030-z [Accessed: 11 April 2015].

MILA i CANALS, L., CHENOWETH, J., CHAPAGAIN, A., ORR, S., ANTÓN, A. AND CLIFT, R. 2009. Assessing freshwater use impacts in LCA: Part I – Inventory modelling and characterisation factors for the main impact pathways. *International Journal of Life Cycle Assessment* 14(1): 28-42. Available at: http://epubs.surrey.ac.uk/763783/3/chenoweth%20assessing.pdf [Accessed: 15 March 2015].

MUNRO, S.A., FRASER, G.C.G., SNOWBALL, J.D. AND PAHLOW, M. (2015). Water footprint assessment of citrus production in South Africa: A case study of the Lower Sundays River Valley. *Journal of Cleaner Production* 135 (2016) 668-678. Elsevier. Available at: https://facultystaff.richmond.edu/~sabrash/110/Chem%20110%20Fall%202016%20Homework%20Articles/Water_footprint_assessment_of_citrus.pdf [Accessed: 18 November 2015]

NIEUWOUDT, W.L., BACKEBERG, G.R. AND DU PLESSIS, H.M. 2004. The value of water in the South African economy: Some implications. *Agrekon* 43(2): 162-183. Available at: http://ageconsearch.umn.edu/bitstream/9484/1/43020162.pdf [Accessed: 21 March 2015].

NINHAM SHAND (PTY) LTD. 2004. *Orange-Riet Water Users' Association water management plan*. Pretoria, South Africa: DWAF.

NORDIN, R.N. AND POMMEN, L.W. 2009. *Water quality guidelines for nitrogen (nitrate, nitrite and ammonia).* Canada: Water Stewardship Division, Ministry of Environment, Province of British Columbia. Available at: http://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/waterqualityguidesobjs/approved-wat-qual-guides/nitrogen/nitrogen-overview.pdf [Accessed: 19 December 2015].

ORAM, B. 2014. *Phosphates in the environment*. USA: Water Research Center. Available at: http://www.water-research.net/index.php/phosphates [Accessed: 20 December 2015].

ORANJE RIET WATER USER ASSOCIATION. 2012. *About us*. Available at: http://oranje-riet.co.za/index.php/about-us1 [Accessed: 17 March 2015].

PAHLOW, M., KROL, M.S. AND HOEKSTRA, A.Y. 2015. *Assessment of measures to reduce the water footprint of cotton farming in India*, Value of Water Research Report Series No. 68, UNESCO-IHE, Delft, the Netherlands. Available at: http://waterfootprint.org/media/downloads/Report68-WaterFootprintReduction-Cotton-India.pdf [Accessed: 29 May 2016]

PAHLOW, M., SNOWBALL, J. AND FRASER, G. 2015. Water footprint assessment to inform water management and policy making in South Africa. *Water SA* 41(3): 300-313. Available at: http://www.scielo.org.za/scielo.php?script=sci_abstract&pid=S1816-79502015000300002 [Accessed: 4 July 2016]

PFISTER, S., KOEHLER, A. AND HELLWEG, S. 2009. Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environmental Science & Technology* 43(11), 4098-4104. Available at: http://dx.doi.org/10.1021/es802423e [Accessed: 19 May 2015]

RICHARDS, L.A. (ed.). *Diagnosis and improvement of saline and alkaline soils*: *U.S. Salinity Laboratory Handbook 60*. Washington, USA: USDA. Available at: https://www.ars.usda.gov/ARSUserFiles/20360500/hb60_pdf/hb60complete.pdf [Accessed: 22 December 2015].

SALA, S., BIANCHI, A., BLIGNY, J.C., BOURAOUI, F., CASTELLANI, V., CAMILLIS, C.D., MUBAREKA, S., VANDECASTEELE, I. AND WOLF, M.A. 2013. *Water footprint in the context of sustainability assessment*. Available at: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC78032/lb-na-25781-en-n%20water%20footprint%20in%20the%20context%20of%20sustainability%20assessment.%20report%20on%20the%20application%20of%20life%20cycle%20based%20indicators%20of%20water%20consumption%20in%20the%20context%20of%20integrated%20sustainability%20impact%20analysis.pdf [Accessed: 23 September 2016]

SCHEEPERS, M. 2015. *Water footprint and the value of water used in the Lucerne-dairy*. Available at: http://scholar.ufs.ac.za:8080/xmlui/bitstream/handle/11660/1640/ScheepersME.pdf?sequence=1 [Accessed: 30 November 2016]

SCHYNS, J,F. AND HOEKSTRA, A.Y 2014. *The Added Value of Water Footprint Assessment for National Water Policy: A Case Study for Morocco*. Available at: http://waterfootprint.org/media/downloads/Schyns-Hoekstra-2014.pdf [Accessed: 21 February 2016]

SIWI STOCKHOLM INTERNATIONAL WATER INSTITUTE. 2008. *Professor John Anthony Allan, Great Britain.* Available at: http://www.siwi.org/prizes/stockholmwaterprize/laureates/professor-john-anthony-allan-great-britain/ [Accessed: 19 March 2015].

SMITH, L.E.D. 2004. Assessment of the contribution of irrigation to poverty reduction and sustainable livelihoods. *International Journal of Water Resources Development* 20(2): 243-257.

SOIL CLASSIFICATION WORKING GROUP. 1991. *Soil Classification, A Taxonomic System For South Africa*. Memoirs on the Agricultural Natural Resources of South Africa No. 15. A Report on a Research Project Conducted under the Auspices of the Soil and Irrigation Research Institute. Pretoria: The Department of Agricultural Development, Republic of South Africa.

SOUTH AFRICAN POULTRY ASSOCIATION. 2015. *Quarterly developing poultry farmers organisation stats: Report for the third quarter of 2015*. Available at: http://www.sapoultry.co.za/home/dpfo-intro.php [Accessed: 22 May 2016].

SOUTH AFRICAN POULTRY ASSOCIATION. 2016. *Key market signals in the broiler industry for the fourth quarter of 2015.* Available at: http://www.sapoultry.co.za/pdf-statistics/broiler-industry-key-market-signals.pdf [Accessed: 22 May 2016].

STATISTICS SOUTH AFRICA (STATS SA). 2014. *Mid-year population estimates 2014*. Available at: http://www.statssa.gov.za/publications/P0302/P03022014.pdf [Accessed: 21 March 2015].

SUN, S.K., WU, P.T., WANG, Y.B. AND ZHAO, X.N. 2013. Temporal Variability of Water Footprint for Maize Production: The Case of Beijing from 1978 to 2008. *Resour Manage* (2013)27: 24-47. Available at: http://link.springer.com/article/10.1007/s11269-013-0296-1 [Accessed: 22 October 2016]

THEUNISSEN P. 2005. *Can maize be grown profitably?* Bethlehem: Computus Management Bureau. Available at: http://www.computus.co.za/Artikels/Maize06.pdf [Accessed: 21 March 2015].

UNITED NATIONS, DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS, POPULATION DIVISION (2015). *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables*. Working Paper No. ESA/P/WP.241 Available at: https://esa.un.org/unpd/wpp/publications/files/key_findings_wpp_2015.pdf [Accessed: 19 November 2016]

UNITED NATIONS ENVIRONMENT PROGRAMME. 2008. Vital water graphics: An overview of the state of the world's fresh and marine waters. Available at: http://www.unep.org/dewa/vitalwater/article48.html [Accessed: 09 August 2016].

UNITED STATES DEPARTMENT OF AGRICULTURE FOREIGN AGRICULTURAL SERVICE. 2015. *Global agricultural information network report: The South African meat market*. Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/The%20South%20African%20meat%20market_Pretoria_South%20Africa%20-%20Republic%20of_9-15-2015.pdf [Accessed: 28 January 2017].

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY. 2015. *Harmful algal blooms*. Available at: https://youtube/G6F9uJMHzBs [Accessed: 21 December 2015].

VAN DER LAAN, M., LE ROUX, C.E., ANNANDALE, J.G., AND GUSH, M. 2013. *Literature review on different methodologies to determine the water footprint of vegetable and fruit products and the potential usefulness of this information*. Pretoria

VAN RENSBURG, L.D., DE CLERCQ, W.P., BARNARD, J.H. AND DU PREEZ, C.C. 2011. *Salinity guidelines for irrigation: Case studies from Water Research Commission projects along the Lower Vaal, Riet, Berg and Breede rivers*. Available at: http://www.scielo.org.za/ pdf/wsa/v37n5/v37n5a15.pdf [Accessed: 30 November 2015].

WILLIAMS, C.L., TABLER, G.T. AND WATKINS, S.E. 2013. *Comparison of broiler flock daily water consumption and water-to-feed ratios for flocks grown in 1991, 2000–2001, and 2010–2011*. Available at: https://academic.oup.com/japr/article/22/4/934/763754/Comparison-of-broiler-flock-daily-water [Accessed: 10 November 2015].

WORLD HEALTH ORGANIZATION (WHO). 2015. *Nitrate and nitrite in drinking water.* Background document for development of WHO guidelines for drinking-water quality. Available at: http://www.who.int/water_sanitation_health/dwq/chemicals/nitratenitrite2ndadd.pdf [Accessed: 21 December 2015].

WORLD WATER COUNCIL. 2004. *E-Conference synthesis: Virtual water trade – Conscious choices.* World Water Council Publication No. 2. Available at: http://www.worldwatercouncil.org/fileadmin/wwc/Programs/Virtual_Water/virtual_water_final_synthesis.pdf [Accessed: 21 March 2015].

ZENG, Z., LIU, J., KOENEMAN, P.H., ZARATE, E. AND HOEKSTRA, A.Y. 2012. *Assessing water footprint at river basin level: a case study for the Heihe River Basin in northwest China*. Available at: http://waterfootprint.org/media/downloads/Zeng-et-al-2012-WaterFootprint-HeiheBasin_1.pdf [Accessed: 24 July 2016]

ZIMMER, D. AND RENAULT, D. 2003: *Virtual water in food production and global trade: Review of methodological issues and preliminary results.* Available at: http://www.fao.org/nr/water/docs/virtualwater_article_dzdr.pdf