WATER FOOTPRINT OF WHEAT AND DERIVED WHEAT PRODUCTS IN SOUTH AFRICA

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Submitted in accordance with the requirements for the degree

MAGISTER SCIENTIAE AGRICULTURAE

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DECLARATION

I, Matohlang Pascalina Mohlotsane, hereby declare that

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DEDICATION

This dissertation is dedicated to my parents, Velesita and Paul Mohlotsane, for every sacrifice they endured to provide me with this opportunity.

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ABSTRACT

The main objective of this study was to assess the water footprint of wheat in South Africa, an important input in the wheat-bread value chain. The water footprint of flour, and that of bread, was calculated to determine the total water footprint of bread along the wheat-bread value chain in South Africa. Water productivities at each stage of production within the wheat-bread value chain were also determined. The study was conducted as a case study of the Vaalharts region. Farm-level data were obtained from Van Rensburg *et al.* (2012). A commercial processor with both a mill and bakery was used for collecting data at the processing level of the value chain.

Water footprint assessment (WFA) is emerging as an important sustainability indicator in the agricultural sector. The water footprint concept takes a consumptive perspective to freshwater use that links production to final consumption by consumers. This study employed the Global Water Footprint Network Standard approach (GWFNS) to calculating the volumetric blue and green water footprint along the wheat-bread value chain. The GWFS considers three different types of water: blue water, which is all the surface and groundwater consumed along the value chain; green water, which is rainwater that does not become runoff; and grey water, which is the volume of freshwater required to assimilate pollutants to ambient levels.

The results indicate that the water footprint indicator for wheat production at Vaalharts was 991.12 m^3.tonne^{-1}; of this 788.01 m^3.tonne^{-1} originates from surface water and groundwater (blue water footprint) and 203.12 m^3.tonne^{-1} from effective rainfall (green water footprint). The water footprint of flour and bread was 0.073 m^3.tonne^{-1} and 0.459 m^3.tonne^{-1} respectively. The total water footprint of the processing stage was 0.532 m^3.tonne^{-1}. The total water footprint of bread along the wheat-bread value chain was 991.84 m^3.tonne^{-1}, which is a combination of farm-level (wheat) and processing (mill and bakery) data.

The water productivity assessment followed the water footprint assessment, where the value added to water was quantified along the wheat-bread value chain. This was achieved by calculating the economic water productivity (EWP) of wheat, flour, and bread, followed by the value added by the water footprint of wheat, flour, and bread along the wheat-bread value chain. The EWP of wheat, flour, and bread was 4.18ZAR.m^3, 0.079ZAR.m^3, and 0.038ZAR.m^3 respectively. Value added by the water footprint of this value chain was 11.52ZAR.m^3, which consisted of 4.0ZAR.m^3 value added from the farm level and 7.49ZAR.m^3 from the processing level.

The total water footprint of wheat in Vaalharts is 61% lower than the global average. Approximately 79% of the water footprint of wheat was from absorbed surface and groundwater (irrigated water), which indicates a high dependency on surface and groundwater for wheat production in the Vaalharts region. Effective rainfall contributed only 21% of the total water footprint, which leaves room for possible increased usage. At the processing stage, 86% of the total water footprint in the processing stage of bread along the wheat-bread value chain was from the bakery and only 14% from the milling process. It is concluded that the amount of water used at farm level is the largest contributor to the total water footprint of bread along the wheat-bread value chain (99.95%), while processing is only accountable for 0.056%.

For economic productivities, more income is generated per cubic metre of water used from wheat than any other product along the wheat-bread value chain. Due to the high contribution of wheat in this value chain, it is a conclusion that is easily understood. Value added to water encompasses the value added to the product throughout its value chain (in monetary terms) multiplied with the water footprint of the product at different nodes of production throughout the product's value chain. Total value added to water from the water footprint assessment of the wheat-bread value chain is ZAR11.43 per kilogram. About 65% of this value is from the processing level and only 35% from farm level. This means higher income is received per cubic metre of water used in the processing level of the wheat-bread value chain than from the farm level. The result is similar to the value added per cubic metre of the water footprint of bread along the wheat-bread value chain.

Despite the fact that the water footprint of wheat along the wheat-bread value chain contributes 99.95% of the overall footprint in this value chain, the income received per cubic metre of water footprint used for wheat along this value chain is only 35% (4.0ZAR.m^3) of value added to the value chain.

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LIST OF ABBREVIATIONS

ADP	Abiotic depletion potential
CWMA	Catchment water management area
CWU	Crop water use
DAFF	Department of Agriculture, Forestry and Fisheries
DEA	Department of Environmental Affairs
DWA	Department of Water Affairs
ET	Evapotranspiration
EWP	Economic water productivity
EWR	Ecological water requirement
FD	Freshwater depletion
FEI	Freshwater ecosystem impact
GDP	Gross domestic product
GWFNS	Global Water Footprint Network Standard
LCA	Life cycle assessment
LCI	Life cycle inventory
NAMC	National Agricultural Marketing Council
NDP	National Development Plan
VF	Variation factor
WA	Water availability
WFA	Water footprint assessment
WFN	Water Footprint Network
WSI	Water stress index
WTA	Water usage to water availability [ratio]
WU	Water usage
WUA	Water User Association
WWF	World Wide Fund [for Nature]
ZAR	South African Rand

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Approximately 70% of the world is covered with water, of which only 2.5% is freshwater, which is mostly embedded in glaciers, ice caps, or at great depths underground (Gleick, 1998). Freshwater is a renewable resource but considering its availability in terms of unit per time per region, the reality of the limitations of this resource cannot be ignored (Jefferies *et al*., 2012).

South Africa is the 30th driest country in the world (Department of Water Affairs (DWA), 2013). Located in a predominantly semi-arid part of the world, South Africa receives average rainfall of 450 mm per annum, which is approximately half of the global average of 860 mm per annum (Department of Environmental Affairs (DEA), 2008). The agricultural sector is the largest user of freshwater in South Africa (Department of Agriculture, Forestry and Fisheries (DAFF), 2014). This sector accounts for 60% for freshwater use, while about 40% of exploitable runoff is used for irrigated agriculture (Backeberg and Reinders, 2009). Field and forage crops are the largest users of freshwater (Ray *et al*., 2013). Considering the close relation of these crops to food security and the eradication of poverty, it is realised that water availability is not only a limiting factor in agricultural production but also a key contributor to rural socioeconomic development (Hoekstra *et al*., 2012; World Wide Fund (WWF), 2013).

The agricultural sector contributes less than 3% to South Africa’s gross domestic product (GDP) (DAFF, 2012). Looking at water as an economic good, this contribution does not coincide with the allocation and use of freshwater resources in South Africa (DWA, 2013). The large use of freshwater in agriculture is inefficient and ineffective in sustaining socioeconomic development (DWA, 2012). This enhances the need for innovative water management systems that incorporate the use of freshwater resources in a sustainable, socioeconomic manner as the water footprint assessment method does.

The concept of “water footprint”, as introduced by Hoekstra (2003), is an indicator of direct and indirect appropriation of freshwater resources, which ultimately accounts for the total volume of freshwater that is used to produce a product measured along its full supply chain (Hoekstra *et al.,* 2011). This assessment takes a consumptive perspective to freshwater and links production to final consumption by consumers (Bulsink, Hoekstra and Booij, 2009).

The components of a water footprint are specified graphically and temporally (Aldaya, Munoz and Hoekstra, 2010). This assessment consists of blue, green, and grey water footprints (Bulsink *et al.,* 2009). The blue water footprint refers to the volume of surface and groundwater consumed or evaporated as a result of the production of a good along the supply chain of that product (Aldaya and Hoekstra, 2010), as well as losses that occur when water returns to a different catchment area. The green water footprint refers to the rainwater consumed, evapotranspired, and incorporated into a crop (Chapagain and Orr, 2009). The grey water footprint of a product refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards (Hoekstra and Mekonnen, 2011). As such, the grey water footprint is the volume of freshwater required to reduce pollutants to ambient levels, and therefore considers the impact of water pollution.

1.2 PROBLEM STATEMENT

Agriculture is the largest freshwater user; accounting for 99% of global consumption in terms of the green and blue water footprint (Hoekstra and Mekonnen, 2012). Global freshwater withdrawals have increased nearly sevenfold in the past century, and with a growing population, coupled with changing diet preferences, water withdrawals are expected to continue to increase and South Africa is no exception (Orlowsky *et al*., 2014). Hoekstra and Chapagain (2008) showed that visualising the amount of water use in producing products can further increase understanding of the global character of freshwater – a concept that is explored in a water footprint assessment (WFA).

Internationally, WFA is emerging as an important sustainability indicator in the agricultural sector, as well as the agricultural food-processing industry (Ruini *et al*., 2013). Ruini *et al.* (2013) conducted a WFA of Barilla pasta production based on the life cycle assessment (LCA) approach. In Italy, Aldaya and Hoekstra (2010) conducted a WFA according to the Water Footprint Assessment Manual of Hoekstra *et al.* (2011) on Italian wheat and bread. Similarly, Sundberg (2012), Neubauer (2012), Cao, Wu and Wang (2014), and Mekonnen and Hoekstra (2014) conducted a WFA of wheat and bread in Sweden, Hungary, China, and Tunisia respectively, where different production states were calculated and national averages taken. Mekonnen and Hoekstra (2010) conducted a WFA of wheat globally; from this assessment a benchmark for irrigated as well as rain-fed wheat was established.

The WFAs reported above focused only on the environmental impact of water and not the economic aspects thereof. Although he did not conduct a WFA of wheat in South Africa, Scheepers (2015) calculated the WFA of lucerne's dairy value chain, where he linked the economic valuation of water to the Global Water Footprint Network Standard (GWFNS) approach in order to determine where along the respective value chain the most value was added to water.

WFA has been accepted internationally and is widely used as a tool to assess the sustainable use of water. In the South African wheat industry, the use thereof is limited. There is currently no scientific information on water footprints available to inform sustainable water use behaviour. Considering the importance of this industry in the South African economy, a WFA would effectively guide policy makers in formulating appropriate strategies to guide freshwater use and assist irrigation farmers' water use behaviour to becoming more sustainable.

1.3 AIMS AND OBJECTIVES

The aims of this study are to explore the water footprint of wheat along the wheat-bread value chain in South Africa, as well as to conduct a water productivity assessment in order to quantify the value added to water along the wheat-bread value chain. This will inform water management and policy makers of appropriate strategies and sustainability targets along the selected value chain.

The two sub-objectives used to achieve the main objective are as follows:

Sub-objective 1: To determine the volumetric water footprint of wheat and bread as derived wheat products along the wheat-bread value chain.

Sub-objective 2: To quantify the value of water along the wheat-bread value chain in order to identify areas along the chain where most attention is required. This was expressed in South African rands per cubic metre of water (ZAR/m^3).

1.4 THE SCOPE OF THE STUDY

Due to the geographical and climatic variation within South Africa, this study was based on case studies. The Vaalharts Irrigation Scheme was used as a case study for the production of wheat, while bread processing was based on one of the major national bread processors. The WFA of the case study was conducted, focusing mainly on the calculation of the water footprint and the economic valuation or water.

1.5 CHAPTER LAYOUT

The context and scope of the study were set out in the commencement of this chapter. A detailed explanation of the rationale for investigating water use along the South African wheat-bread value chain was provided, followed by the aims and objectives of this study.

After setting the scene for this study, the literature that guided the manner in which the aims and objectives are achieved were discussed. Chapter 2 investigates the South African water situation, as well as the relevance of the South African wheat industry from an economic and social perspective.

Following the justification of investigating the water use of the wheat-bread value chain, the theoretical framework of the WFA is discussed in detail. The concept, together with the various methods of calculating the water footprint, is assessed. A concluding section on water footprinting specifically evaluates wheat-related water use research.

In the final portion of Chapter 2, the economic valuation of the water footprint is addressed. The rationale for adding the economic valuation of the water footprint is explained, after which relevant research findings are weighed against one another. After evaluating the different methods in the literature review chapter, the methods used to achieve the aims and objectives are discussed.

Chapter 3 explains the chosen methods in detail, followed by an introduction to the data.

The results of the study are calculated and interpreted in Chapter 4. The water footprints of the various steps of the wheat-bread value chain in the case study are calculated individually before they are added together to determine the final water footprint of producing bread along the wheat-bread value chain. In the final sections, the water productivities of the wheat-bread value chain are investigated.

The summary, conclusions, and recommendations are discussed in Chapter 5. A summary of the first chapter is given to set the scene for the research findings. This is followed by the findings in the final section, where the recommendations that originate from the research are discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter consists of discussions of the South African water situation, the wheat industry, as well as the theoretical concept of WFA, where different methods of water footprint accounting are evaluated. The discussion then shifts to related research on WFA and derived wheat products globally, followed by an economic valuation of the water footprint concept. This chapter is then concluded with relevant discussions on the implications of the literature for this research.

2.2 SOUTH AFRICA'S WATER SITUATION

A significant amount of water is used in food production, and with current production, consumption, and environmental trends, water availability is gaining prominence as a stumbling block to global agricultural production (WWF, 2011; 2013). Mukheibir (2005) investigated the Southern African water situation and highlighted climate change, uneven distribution of rainfall, and inefficient administration of water resources as major uncertainties that could be detrimental to agricultural growth within these regions.

South Africa, in global terms, is the 30th driest country in the world and is deemed water scarce and water limited (Mukheibir, 2005). Only 12% of the total area of the country is considered arable, with as little as 3% viewed as "truly fertile" (DWA, 2013). South Africa has a supply potential of 1 100 m^3 per person per year, while the global average is 1 700 m^3 per person per annum (DAFF, 2012). According to the DAFF (2008), South Africa is approaching complete utilisation of available surface water yields, which is a threat to the 54.96 million people who reside in this country. The World Bank (2016) estimates that South Africa has a 1.58% population growth per annum; therefore trends of increased urbanisation, industrialisation, and pressure on water resources for food production will increase.

Groundwater is common in aquifers, which range widely in capacity, size, and depth. Groundwater flow follows surface topography and often interacts closely with surface water. Aquifers are concentrated in the eastern, northeastern, and western parts of South Africa, where our most exploited groundwater also occurs (Mukheibir, 2005).

Erratic runoff due to unpredictable rainfall patterns, large-scale inter-basin transfer, high levels of evaporation and transpiration, and shallow dam basins are amongst the many reasons why most catchment water management areas (CWMAs) are in a deficit, with water requirements exceeding availability (DWA, 2012). Groundwater plays an important role in South Africa. About 20% of extractable groundwater occurs in major aquifers that could be utilised on a larger scale. Due to the limitations of dryland production and truly fertile land, approximately 40% of exploitable runoff in South Africa is used by irrigated agriculture.

Figure 2.1 illustrates how South Africa's freshwater resources are distributed within the economy. Irrigated agriculture is accountable for two-thirds of the country's available water (63%), followed by urban usage (14%), and commercial use (13%). The challenge is that South Africa is a water-scarce country, therefore this substantial water use must be beneficial to the country's economic growth. According to the DAFF (2012), this is not a reality because South Africa's agricultural sector makes the lowest direct contribution to the GDP per million cubic metres of water, and is also the smallest direct employer per million cubic metres of water (WWF, 2015; Nieuwoudt, Backeberg and Du Plessis, 2004). In relation to the objectives of the National Water Act (No. 36 of 1998) of achieving sustainable and efficient use of water by all South Africans, agriculture is water inefficient.

According to the National Development Plan (NDP) (2004), South Africa's largest communities are found in rural areas and irrigated agriculture in these areas contributes significantly towards poverty alleviation through job creation and increased economic productivity. Allocation of freshwater to irrigated agriculture therefore holds substantial social and rural economic development benefits for South Africa. The National Water Act (Act No 36 of 1998) also recognises that the ultimate aim of water resource management is to achieve the sustainable use of water for the benefit of all users.

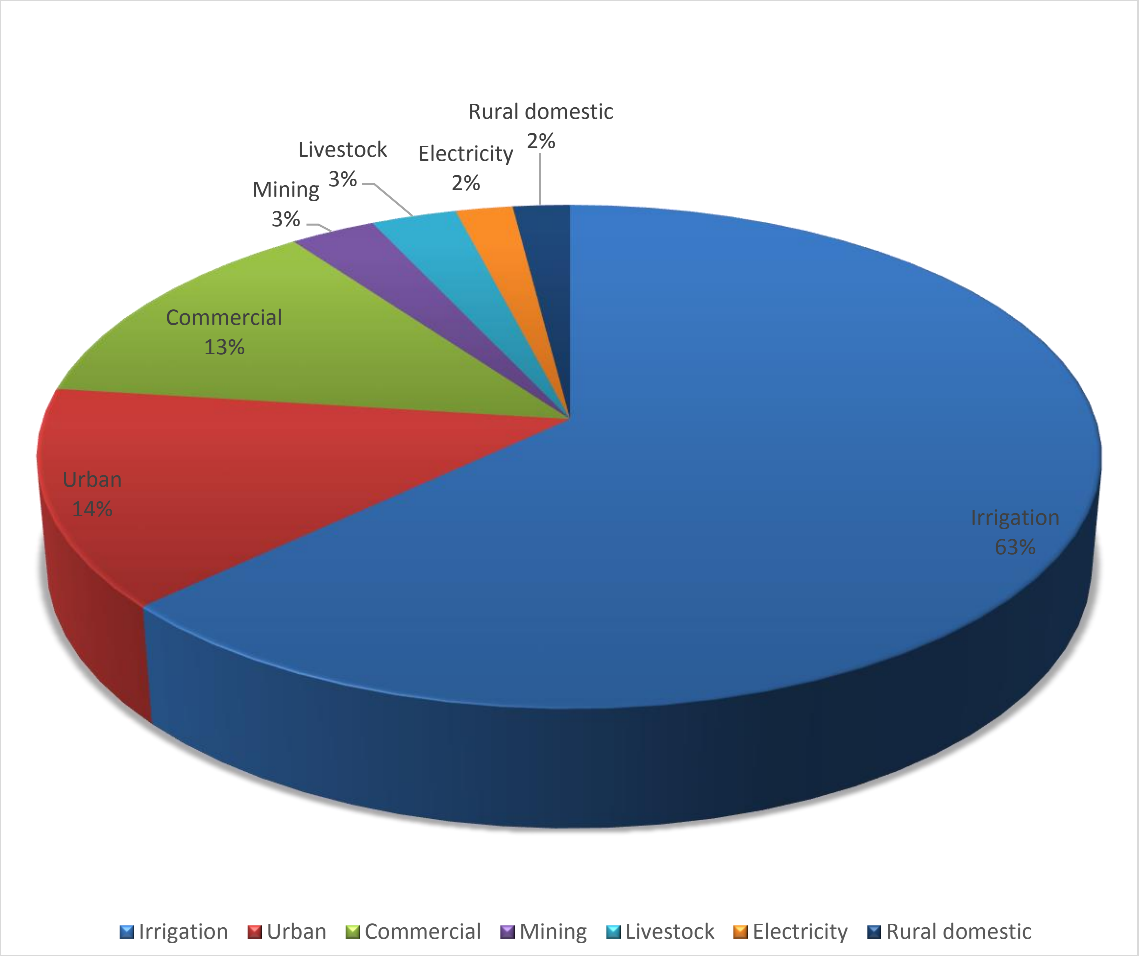

Figure 2.1: Freshwater distribution amongst the major sectors in South Africa's economy

Source: WWF (2013)

According to the National Water Resource Strategy (2012), 66% of the mean annual runoff is captured by the 320 major dams spread throughout the country (WWF, 2011). Nevertheless, 98% of South Africa's ground and surface water is already allocated, leaving little to no room for increased extraction (DWA, 2012). This could cause conflict amongst the different sectors in South Africa, especially those with higher direct socioeconomic contributions to the country's growth (WWF, 2015). At the same time, if this water is moved to these sectors, it would cause a great threat to food security (WWF, 2011).

In order to achieve sustainable agricultural management, it is important to consider the amount of water required for sustaining human life (Kang, Khan and Ma, 2009), as well as ecological water requirements, meaning that the broader prospects of water, i.e.

ethical and cultural, cause a further increase in water demand (Kang *et al.,* 2009; DWA, 2012).

South Africa is quickly reaching a point where all financially viable freshwater resources are fully utilised (DAFF, 2011). In light of social and economic inequality, it is important to realise that there are different experiences of water scarcity by South Africans; the poor are mostly faced with unreliable water supply and come from communities mostly affected by drought and flooding, and these are also the communities where large-scale farming activities occur (DEA, 2008), while the other end of society is under a false sense of water security. This highlights the importance of education and communication to create awareness of water issues (DEA, 2008).

It is also important that economic growth targets are not achieved at the expense of ecological sustainability (Kang *et al*., 2009). Effective management of water resources therefore requires a holistic approach that links both socioeconomic development and ecological water requirements.

2.3 THE WHEAT INDUSTRY IN SOUTH AFRICA

Prior to 1998, when the government controlled the markets and specified production and consumption of agricultural commodities, wheat production was high and increased each year (National Agricultural Marketing Council (NAMC), 2015). After 1998, markets were open and producers were allowed to trade and market their goods internationally, which left them with many opportunities and exposed them to unfamiliar risks. Consumption and preferences of wheat-based products continued to grow, whilst local wheat production declined (NAMC, 2015; DAFF, 2012, 2016).

According to the DAFF (2015), South Africa is divided into 36 crop production regions with wheat planted in 32 of these regions. This makes wheat the largest winter cereal crop produced in South Africa. The industry has 3 200 to 4 000 producers spread over an average of 510 000 ha of land. *Triticum aestivum*, also known as bread wheat, is the most produced cultivar. Approximately 60% of the total quantity of wheat flour and meal is used for the production of bread and the remaining percentage is shared by cereal, rusks, and biscuits. Of the areas planted with wheat, 80% is in dryland conditions, while the remaining 20% is irrigated. An inductive environment for wheat production is cool and moist, and for harvesting warm and dry, making winter rainfall areas ideal for wheat production. Wheat is planted mainly from mid-April to mid-June and mid-May to end-July in the winter rainfall and summer rainfall areas respectively (DAFF, 2015). Sufficient residual soil moisture is necessary for wheat production (Purchase, Hatting and Van Deventer, 2000).

Wheat production, as well as wheat-based products, in South Africa is focused on end consumers and the value of the industry is high in terms of its contribution to food security. Bread consumption in South Africa is estimated at 2.8 billion loaves per year, which is equivalent to 62 loaves per person per year, with a noticeable difference in preference and consumption amongst the provinces (DAFF, 2011). The NAMC (2009) reported that 1 tonne of bread flour produces 2 278 and 2 135 loafs of brown and white bread of 700 g respectively, and that 1 tonne of wheat has an extraction rate of 0.87 tonnes for brown flour and 0.76 tonnes for white flour. In other words, once a tonne of wheat goes through the four stages of the milling process in the case of white and brown bread, 0.76 and 0.84 tonnes of flour are extracted. Brown bread has a higher extraction rate because some of the bran removed in the mill process is added back to the process at the last stages of milling. Although not considered in this study, whole-wheat flour has a 100% extraction rate because all the by-products of the wheat are added back to the flour (Mueen-ud-Din *et al*., 2010).

2.3.1 WHEAT PRODUCTION AND CONSUMPTION LEVELS

South Africa produces between 1.5 and 2 million tonnes of wheat per year. According to the Crop Estimate Committee, in 2014 the overall area planted with wheat was 0.87% lower than previous production seasons (47 6570 ha) and the smallest area planted with wheat to date (NAMC, 2015). Figure 2.2 is a graphical representation of wheat production with exact contributions from each province representing the average wheat production levels for the past decade. The Western Cape (winter rainfall), Free State (summer rainfall), and Northern Cape (irrigation) account for 81% of the overall production. In 2015, these areas were spread over 310 000, 80 000, and 36 000 ha respectively, and are expected to increase slightly for the 2016 production season. North West, KwaZulu-Natal, Limpopo, Mpumalanga, and Eastern Cape account for 17.7% of production, while Gauteng accounts for less than 1% of the overall production; yet Gauteng is accountable for 80% of overall wheat consumption in the country.

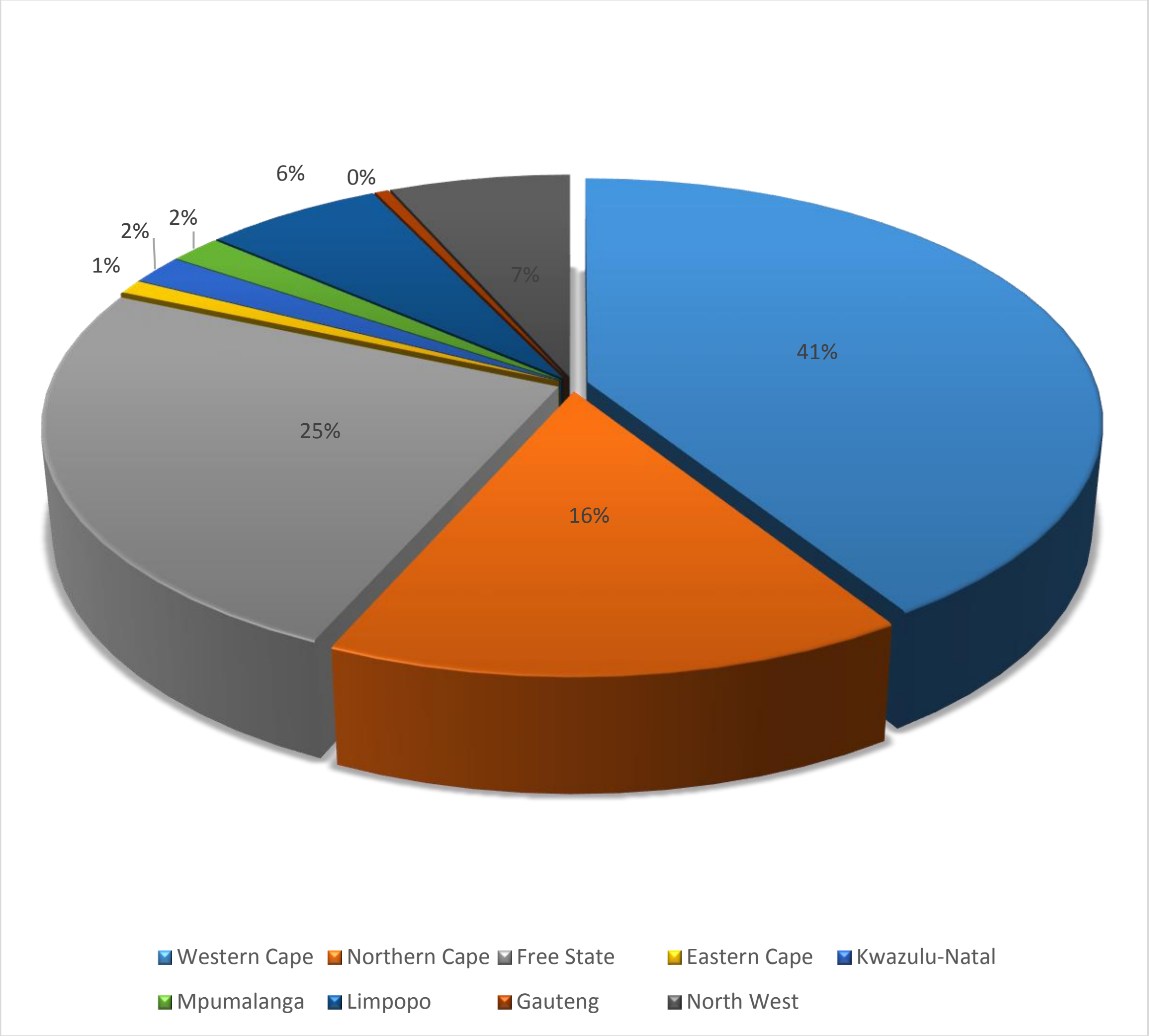

Figure 2.2*: Wheat production areas in South Africa by provinces*

Source: Adjusted from Crop Estimate Committee (2016)

At the 1996 World Food Summit it was established that food security exists when all people at all times have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life (Food and Agriculture Organization (FAO), 2008). Wheat is the second most important cereal in South Africa, and is also a key player in the reduction of poverty, food insecurity, and malnutrition. When comparing the nutritional content of major staple foods per 100 g serving, wheat contained the highest proportion of fibre, protein, calcium, zinc, copper, magnesium, and vitamin E.

The demand for wheat-based products is high. More than 60% of the wheat consumed in South Africa is imported (DAFF, 2012). This is realised by the gap between local production and consumption levels (WWF, 2016). Figure 2.3 presents the local wheat production, consumption, and import levels in the past decade. Even though import levels were quite high from 2005 to 2013, they still remained below local production levels. In 2014 and 2015, wheat imports were above local production, and according to the Bureau for Food and Agricultural Policy (2015), this is expected to be the case for the next decade. There is a high volume of trade in agricultural commodities worldwide, which indicates growth in international dependencies of food supply (Hoekstra and Chapagain, 2007).

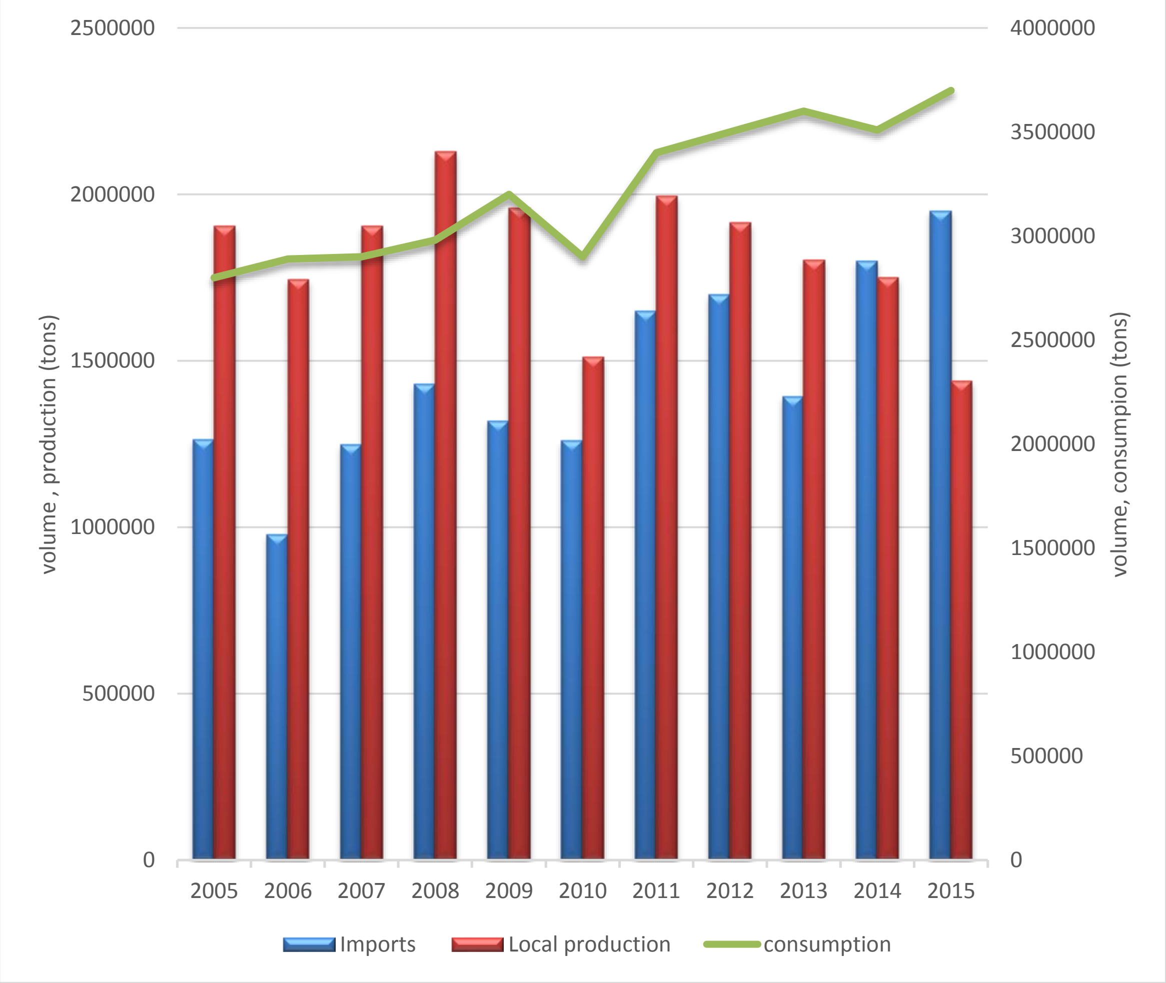

Figure 2.3: Local wheat production, consumption and imports 2004-2015

Source: DAFF (2015)

The price of bread in South Africa has increased by 63% in the past decade. Recent depreciation of the rand led to higher cost of imported wheat and affected the affordability of wheat-based products for poor consumers. Local producer prices for wheat are influenced by international market prices and until domestic production exceeds domestic demand, this will not change. According to Mekonnen and Hoekstra (2010), water scarcity evokes a dependency on the import of water-intense goods, which creates a direct relationship between water scarcity and water dependency. This is an indication of a strong correlation between water availability and quantity of imported commodities.

2.3.2 Wheat value chain

The South African wheat industry is highly concentrated (DAFF, 2012). Four large millers own 87% of the market power and most are vertically intergrated, which contributes to managing risks along this supply chain (NAMC, 2015). On-farm wheat production employs about 28 000 people across the country, and the milling industry employs around 3 800 people, with further skilled job opportunities throughout the value chain (DAFF, 2012). Figure 2.4 is a flow diagram of the wheat market value chain, which starts with research in biotechnology and ends with consumers.

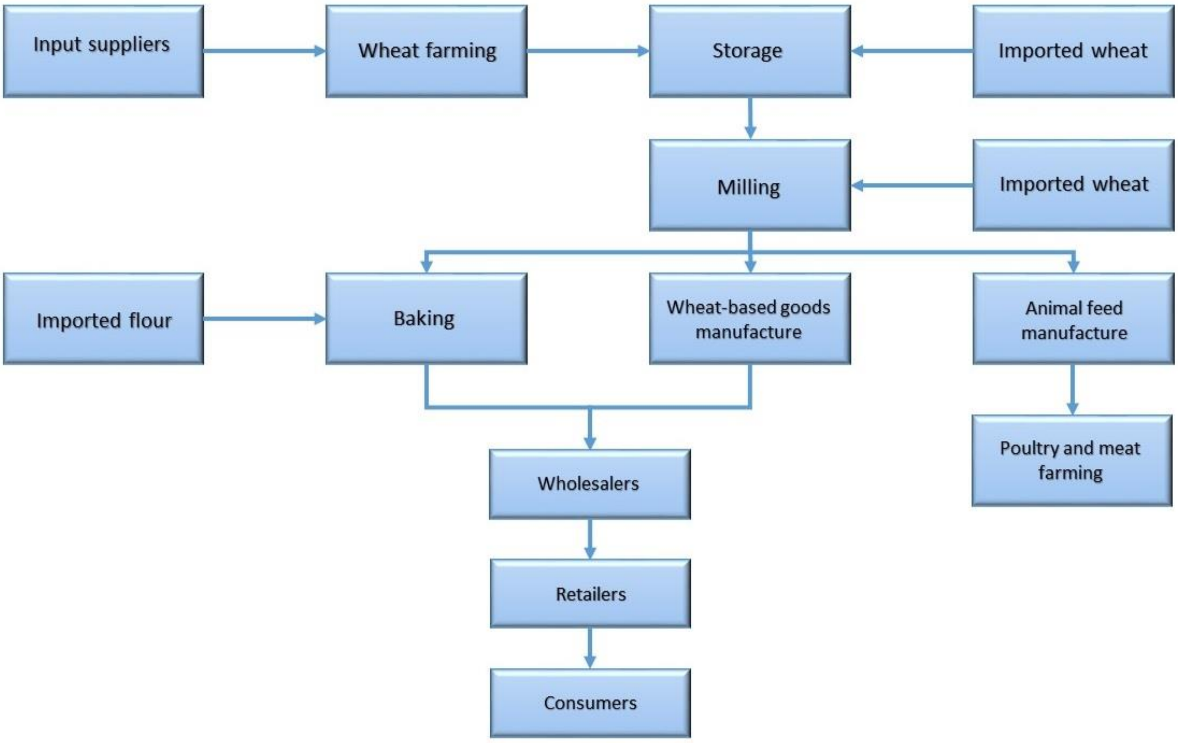

Figure 2.4: Wheat market value chain

Source: DAFF (2015)

The wheat market value chain (see Figure 2.4) begins with research in biotechnology where seed quality, climate predictions, soil quality, and consumer needs are studied. This process is followed by input suppliers of seed, fertiliser, trucks, etc. in order to carry out the planting process. Cooperatives are put together in this phase, where inputs are shared and distributed among the different groups. Once the crop is harvested, it is stored according to different grades and a small portion is exported or stored until the desired selling price is reached.

Milling consists of four main processes:

1. *Sorting*, where wheat is passed through a cleaning process to remove coarse impurities and stored according to quality determined by the protein content and gluten quality of the wheat.
2. *Cleaning*, where impurities are removed and grain is sorted in different sized grinders.
3. *Tempering/Conditioning*, during this stage the wheat is soaked in water to make it softer in order to remove the outer bran coating. In this step the moisture content of the wheat is increased to about 12%.
4. *Gritting and milling*, where flour is created. This includes the removal of bran and grinding of endosperm to make flour, which is then enriched or fortified.

From the milling stage, the produce is moved to either bakeries, wheat-based good manufacturing, or animal feed manufacturers. Approximately 60% of the wheat flour (the rest is bran and meal) is used to produce bread. The remaining percentage comprises wheat-based products such as cereal and biscuits, and a small portion is sold to animal manufacturers for animal feed.

Freshwater resources are said to have a global character, where exported commodities increase local water use and scarcity, and imported water-intense commodities ease the pressure on local water resources and water security (Hoekstra, 2015 Mekonnen and Hoekstra, 2010). To further explore this concept, it is important to quantify the amount of water used in the production of agricultural products, as well as the extent to which water use is sustainable.

2.4 THEORETICAL FRAMEWORK

2.4.1 THE WATER FOOTPRINT CONCEPT

The water footprint is an indicator of freshwater use. It includes both the direct and indirect water use of a consumer or product. Hoekstra *et al.* (2011) emphasised that the water footprint is regarded as a comprehensive indicator of freshwater use and should be used along with traditional and restricted measures of water withdrawal. The aim of the water footprint is to investigate the sustainability of freshwater use, which is achieved by comparing the water footprint with freshwater availability (Mekonnen and Hoekstra, 2010).

The concept of the water footprint provides an appropriate framework of analysis to find the link between the consumption of agricultural goods and the use of water resources. The water footprint is an indicator of indirect and direct appropriation of freshwater resources, thus referring to the total volume of freshwater that is used to produce a product, measured along the full supply chain with the aim of investigating the sustainability of freshwater use. This is achieved by comparing the water footprint with freshwater availability (Hoekstra and Mekonnen, 2011; Hoekstra *et al*., 2012). Internationally, the water footprint concept is understood as described by Hoekstra *et al*. (2011) and the LCA.

The water footprint concept is multidimensional and considers all the water used according to the sources from which the water is extracted and the volumes of freshwater required to assimilate polluted water to ambient levels. According to the water footprint concept of Hoekstra *et al.* (2011), the water footprint is therefore divided into three different categories: blue, green, and grey water footprints.

- *Blue water footprint* refers to the surface and groundwater that are consumed along the value chain of a product, and consumptive use of this water refers to the loss of surface or groundwater from a catchment. The losses can occur through incorporation into a product, evaporation, or when the water returns to a different catchment or the sea (Hoekstra *et al.*, 2011).
- *Green water footprint* refers to rainwater that is evaporated or incorporated into a product and does not become runoff. Similar to blue water, the loss can occur through incorporation into a product (Hoekstra *et al.*, 2011).
- Polluted water needs vast quantities of freshwater to assimilate the load of pollutants to acceptable standards. *Grey water* footprint refers to the volume of freshwater that is required to dilute polluted freshwater along a product supply chain in order for this water to meet specified quality standards once again (Hoekstra *et al.*, 2011).

Hoekstra *et al*. (2011) described different types of water footprints that can be assessed to determine the impact of human behaviour on sustainable water use.

There are a number of different entities for which a water footprint analysis can be performed. Determined by the scope of analysis, these entities include the water footprint of a process step, product, consumer, group of consumers, business, business sectors, or within a specified geographical area (Hoekstra *et al*., 2011):

- Water footprint of a product is the total volume of freshwater used, directly or indirectly, to produce a product. It is determined by considering the water consumption and pollution in all the steps or processes (amount of freshwater that is consumed, evapotranspired, or incorporated into the product) of the production chain. A product water footprint indicates how much pressure that product puts on freshwater resources. It can be measured in cubic metres of water per tonne of production. The water footprint of a product is a multidimensional indicator as it does not only refer to the virtual water of a product but also to the type of water that was used (green, blue, or grey) and where and when the water was used.
- Water footprint of a consumer is defined as the total volume of freshwater used and polluted for the production of goods and services used by consumers. The water footprint of a group of consumers is equal to the sum of the water footprints of individual consumers. The water footprint of a consumer is calculated by adding the direct water footprint of the individual and his or her indirect water footprint.
- Water footprint of a geographical area is defined as the total volume of freshwater used and polluted within the boundaries of the area. The area can include catchments and river basins, a province, a state or nations, or any other hydrological or administrative spatial unit. The water footprint within a geographically delineated area is calculated as the sum of the process water footprint of all water-using processes in that area.
- Water footprint of business, also known as organisational or corporate water footprint, is defined as the total volume of freshwater that is used directly or indirectly to run and support a business. It consists of two main components; operational (direct) and supply chain (indirect), which represents the water footprint of a business as the volume of freshwater consumed or polluted due to the business' own operations, and water footprint of a business as the volume of freshwater consumed or polluted to produce all the goods and services that form part of the inputs of production of the business.

When dealing with the water footprint of a company or cooperation's water footprint, it is important to distinguish between operational and supply chain water footprint due to policy issues because a company has direct and indirect control over its operational and supply chain footprints.

Although both the GWFA and LCA approaches can be used to investigate the water footprint for bread along the wheat-bread value chain in South Africa, the guidelines of the ISO 14046 must also be kept in mind in the reporting of the water footprint indicator. ISO 14046 is strongly based on the LCA, and it is for this reason that both methods will be discussed.

2.4.2 LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is an applied environmental tool that measures various environmental indicators caused by products (Berger and Finkbeiner, 2010; 2011). This assessment consists of four phases that analyse the stages/cycles of a product from the acquisition of raw material to the disposal of the final product. These stages are as follows: goal and scope of assessment, water footprint inventory analysis, water footprint impact assessment, and, lastly, interpretation of results. The LCA analyses the environmental impact related to water and not the economic or social impact thereof (Boulay, Hoekstra and Vionnet, 2013).

The LCA does not directly account for the green water footprint (Ridoutt and Pfister, 2010). The LCA assumes that green water is directly related to occupation of land and is accounted for elsewhere in the LCA. Similarly, the grey water footprint is also not included since deterioration of water quality is dealt with by means of other impact categories such as eutrophication or freshwater eco-toxicity (Ridoutt and Pfister, 2009; Jefferies *et al.*, 2012). The LCA approach can be conducted as a standalone approach or can be included in a wider environmental assessment (Ridoutt and Pfister, 2010). According to Berger and Finkbriner (2010), green water is important in the production of crops, and not including this assessment in the water footprint accounting stage does not give an accurate measure of the water used.

2.4.3 ISO 14046

The aim of this international standard is to ensure a form of consistency between different methodologies. This is achieved by standardising the terminology used in the calculations and reporting of the various methods. ISO 14046 (2014) does not prescribe which methodology one should use for the calculation of a water footprint, but rather serves as a guideline of what to include in a comprehensive WFA. According to this international standard, the term “water footprint” can only be used to describe the result of a comprehensive impact assessment. A water footprint is, in other words, the quantification of potential environmental impacts related to water.

According to this analysis, ISO 14046 (2014) is based on the LCA approach, which identifies potential environmental impacts associated with water use. A WFA conducted according to this international standard must be compliant with ISO 14044 and the four phases of an LCA, which include the definition of the goals and scope of analysis and the water footprint inventory analysis. Once the inventory analysis has been completed, the water footprint impact assessment is conducted. Only then can the results be interpreted.

2.5 METHODS FOR WATER FOOTPRINT ACCOUNTING

Jordaan *et al*. (2014) summarised a number of methods that are available to calculate water footprint. These methods are:

1. Consumptive water-use based volumetric water footprint proposed by the Water Footprint Network (WFN) (Hoekstra *et al*., 2011).
2. The LCA, which only accounts for blue water footprint, based on the theory that green water use cannot be separated from the occupation of land and which is accounted for elsewhere in LCA.
3. Milà i Canals *et al.* (2008) considered green and blue water resources; blue water is further classified as groundwater (fund), fossil groundwater (stock), and rivers (flow).
4. Lastly, Deurer *et al*. (2011) suggested the use of the hydrological water balance method. This approach determines blue, green, and grey water footprints annually on a local scale. The approach characterises the hydrological system by indicating all in- and outflows and storage changes.

2.5.1 CONSUMPTIVE WATER-USE BASED VOLUMETRIC WATER FOOTPRINT

This method was developed by Hoekstra *et al.* (2011) and endorsed by the WFN. The Water Footprint Assessment Manual was the first comprehensive manual published by the WFN containing the methodology to calculate the impact that communities, individuals, businesses, and production processes have on water resources. Figure 2.5 shows the three different types of water footprints that this method calculates.

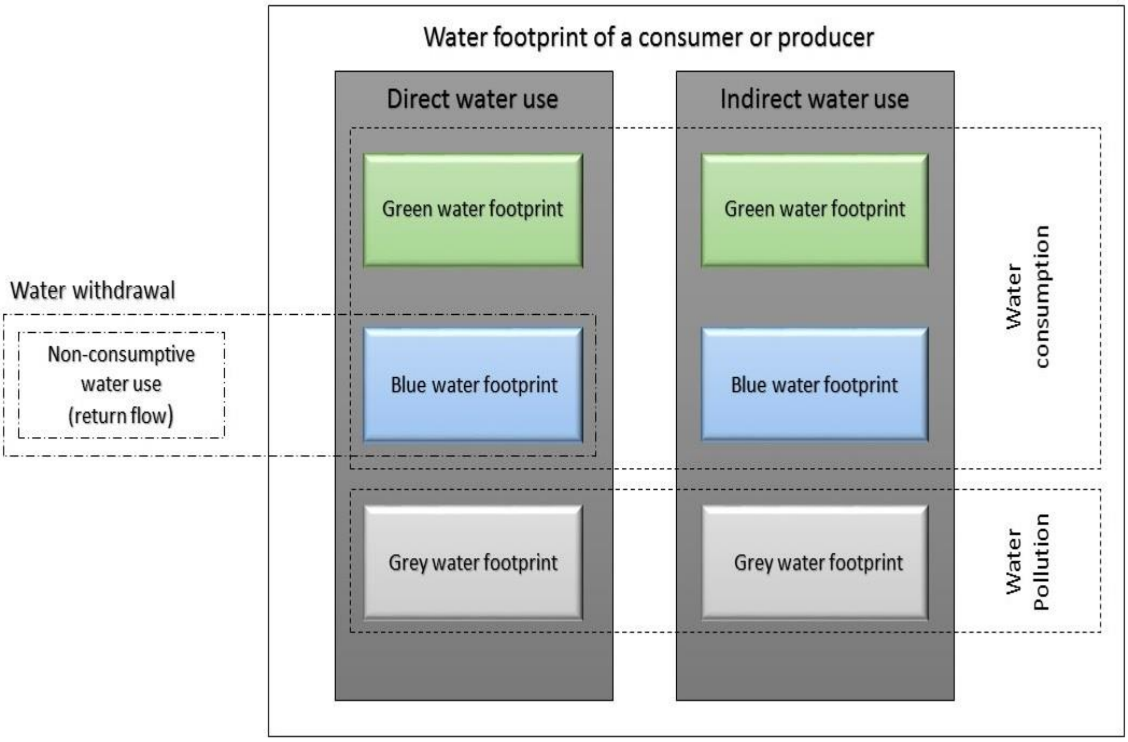

Figure 2.5*: Schematic representation of a water footprint as per the GWFNS*
Source: Hoekstra *et al*. (2011)

The GWFNS approach suggests a clear distinction between the direct and indirect water use, as well as different types of water footprints. It shows that the return flow, which is the non-consumptive part of water withdrawals, is included in the footprint. It further illustrates that the water footprint concept includes consumptive blue and green water footprints that do not become runoff or returns to the original catchment, as well as the grey water footprint that accounts for polluted water; this is for both direct and indirect water use.

The calculations of this method are done according to the three distinct sources of the water, namely blue, green, and grey water.

2.5.1.1 BLUE WATER FOOTPRINT

The blue water footprint accounts for all the surface and groundwater consumed along the value chain of a product. Hoekstra *et al.* (2011) demonstrated that the blue water footprint is an indicator of fresh surface or groundwater that is used up. Such consumptive use of the blue water refers to the following cases:

1. Evaporated water;
2. Water that is incorporated into a product;
3. Water that does not return to the original catchment (including water transfers); and/or
4. Water that does not return to the same catchment during the same period (abstracted during periods of limited supply and returned in times of excess supply).

Evaporation is often found to be the most significant component of blue water consumption and therefore consumptive use is often equated to evaporation. Other components, however, should be included in the consumptive use whenever relevant. Consumptive use does not imply that the water vanishes from the hydrological cycle; instead this means that it is not immediately available for alternative use. The equation to calculate the blue water footprint, as suggested by Hoekstra *et al.* (2011), is as follows:

$$WF_{proc,blue} = \text{Blue Water Evaporation} + \text{Blue Water Incorporation} + \text{Lost Return Flow} \quad (1)$$

2.5.1.2 GREEN WATER FOOTPRINT

The green water footprint accounts for rainwater that does not become runoff but is evapotranspired or incorporated into a product. Green water is further explained as rainwater stored in the soil, which is only available for vegetation growth and transpiration. Hoekstra *et al.* (2011) concluded that the green water footprint is the total volume of rainwater consumed during a production process. They further emphasised the importance of the green water footprint for agricultural and forestry production, where the green water footprint refers to the total rainwater evapotranspiration (ET) from the fields, together with the water incorporated into the harvested crop. The equation to calculate the green water footprint, as suggested by Hoekstra *et al.* (2011), is as follows:

$$WF_{proc,green} = \text{Green Water Evaporation} + \text{Green Water Incorporation} \quad (2)$$

In agriculture, green water consumption can be physically measured or it can be estimated with a model suitable for estimating the ET of a specific crop based on input data on soil, crop, and climate characteristics.

2.5.1.3 GREY WATER FOOTPRINT

Polluted water needs high quantities of freshwater to dilute the load of pollutants to acceptable standards. This volume of freshwater needed to reduce the pollutants to ambient levels is considered to be the grey water footprint. The volumetric-based grey water footprint does not include an indicator of the severity of the environmental damage of the pollution, but is simply a method to include the volume of water required to reduce the pollution to acceptable norms. Hoekstra *et al.* (2011) formulated the calculation of the grey water footprint as follows:

$$WF_{proc,grey} = \frac{L}{c_{max} - c_{min}} \qquad (3)$$

The “*L*” in the equation is the pollutant load (in mass/mass) that is discharged into the water body. This load is divided by the difference between the ambient water quality standard for that pollutant (the maximum acceptable concentration c_{max} (in mass/mass) and the natural concentration in the receiving water body, c_{nat} (in mass/mass)).

According to the WFN method, a distinction should be made between direct and indirect water use. Direct water use is the water that is actually used at a specific point in a value chain. A consumer’s direct water footprint is the water that the consumer uses in his or her daily life. The indirect water footprint is usually much larger than the direct water footprint. This is because the indirect water footprint includes all the water used to produce all the products that are consumed by the end consumer. For a business or a product, the greatest portion of the water usage is found in the supply chain (Hoekstra *et al*., 2011), thus in the value-adding activities before the product reaches the business.

Two alternative approaches could be applied in the consumptive water-use based volumetric water footprint. The approaches are the chain-summation approach and the stepwise accumulative approach (Hoekstra *et al*., 2011) and are discussed in more detail below.

<u>The chain-summation approach</u>

Figure 2.6 is a schematic representation of this approach. Such cases rarely exist in practice where one can simply divide the total water usage by the production quantity.

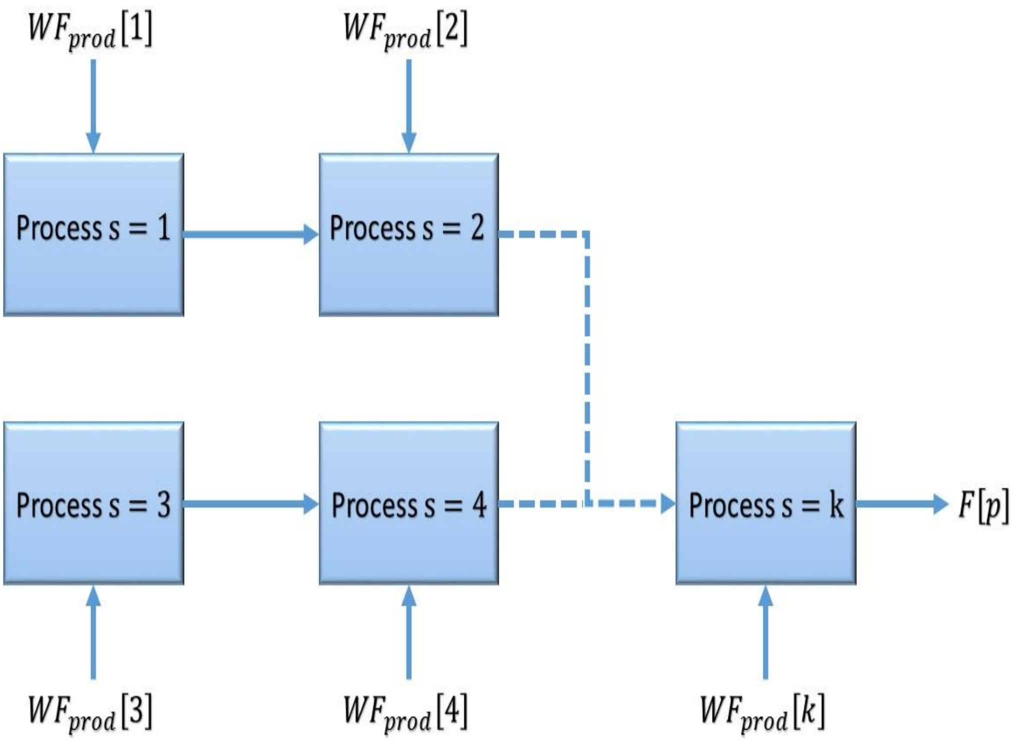

Figure 2.6*: Chain summation approach*

Source: Hoekstra *et al*. (2011)

The calculation of the water footprint of a production system with a single output can be explained in terms of the water footprint of product *p* ($WF_{prod}[p]$) (volume/mass). The calculated water footprint is equal to the sum of the relevant process water footprints divided by the production quantity of product *p* ($P[p]$), or:

$$WF_{prod}[p] = \frac{\sum_{s=1}^{k} WF_{proc}[s]}{P[p]} \qquad [volume/mass] \qquad (4)$$

$WF_{proc}[s]$ is the process water footprint of process step *s* as indicated in Figure 2.6, and therefore calculated for each process step along the complete value chain of the product.

The stepwise accumulative approach

A more generic approach to calculate the water footprint of a product is the stepwise accumulative approach that is indicated in Figure 2.7. In production systems with complex input and output combinations, the water footprint can only be calculated by using the proportional water footprints of the varying inputs. If the production system depicted is considered, the water footprint of product *p* can be calculated as follows:

$$WF_{prod}[p] = \left(WF_{proc}[p] + \sum_{i=1}^{y} \frac{WF_{prod}[i]}{f_p[p,i]}\right) \times f_v[p] \tag{5}$$

$WF_{prod}[p]$ is the water footprint (volume/mass) of output product *p* and the water footprint of input *i* is represented by $WF_{prod}[i]$. The process water footprint of the processing step is denoted by $WF_{proc}[p]$ and it transforms the *y* input products into the *z* output products. The $f_p[p,i]$ parameter is known as the “product function”, while $f_v[p]$ is a “value function”. The value function of input *p*, $f_v[p]$, is defined as the ratio of the market value of the input products in relation to the aggregated market value of all the output products (from *p*=1 to *p*=*z*):

$$f_v[p] = \frac{price[p] \times w[p]}{\sum_{p=1}^{z}(price[p] \times w[p]} \tag{6}$$

In the above equation, *price* [*p*] represents the price of output product *p* (monetary unit/mass). The summation in the denominator is done over all *z* (the output products) that are produced in the considered production process.

Output product *p*’s product function is defined as the quantity of the output product (*w*[*p*], mass) that is produced per quantity of input product (*w*[*i*], mass):

$$f_p[p,i] = \frac{w[p]}{w[i]} \qquad [mass/mass] \tag{7}$$

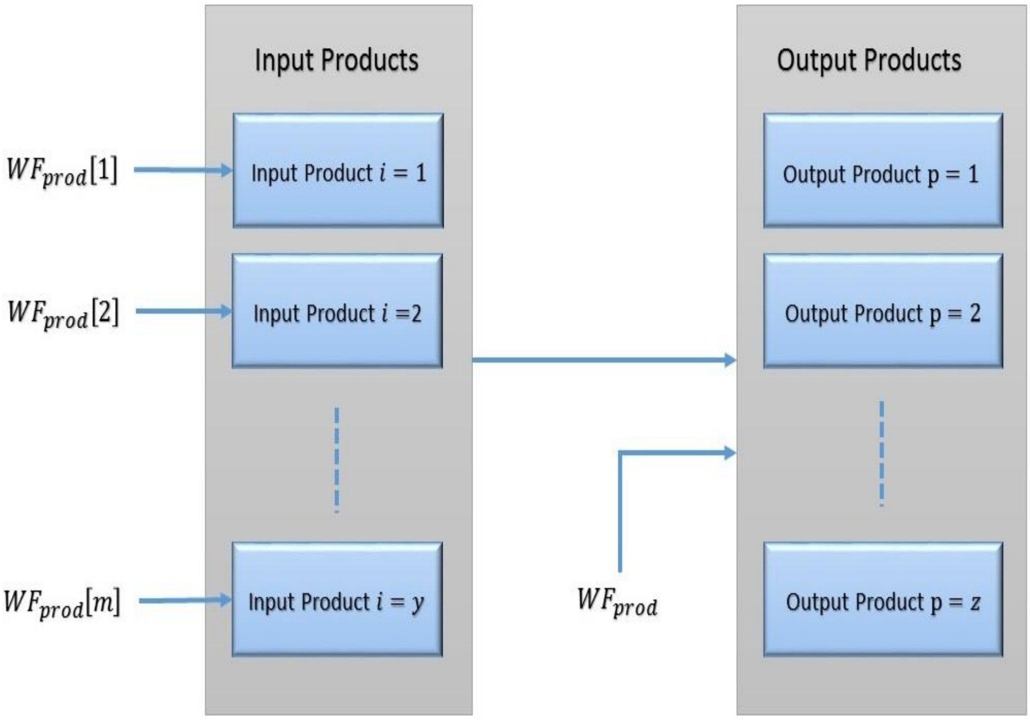

Figure 2.7: The stepwise accumulative approach

Source: Hoekstra *et al*. (2011)

2.5.1.4 WATER FOOTPRINT ASSESSMENT AS PER THE GLOBAL WATER FOOTPRINT STANDARDS OF WATER FOOTPRINT NETWORK APPROACH

A WFA, as per the GWFNS, is divided into four distinct phases which add more transparency to the methodology and help stakeholders to understand the process. The first phase involves setting the scope and goal(s) of the assessment. This step is important because it will determine how the assessment will be approached. The second phase is where data are collected and actual calculations are made. The third phase involves a sustainability assessment where the WFA is evaluated from an environmental, economic, and social perspective. The fourth phase is a conclusion of the first three, as well as the formulation of response options and strategies (Hoekstra *et al*., 2011).

Phase 1: Setting goals and a scope

When a WFA is performed, it is important to clarify the purpose of the study because this has a great impact on the execution of the assessment.

First, it is critical to know the type of footprint one is interested in because this will dictate the methodology to be followed in the study. Then it is important to determine by which entity the water footprint will be completed. Once the entity is known, the following questions will have to be answered:

1. Should all three types of water footprints be included?
2. Where along the supply chain should the analysis be conducted?
3. For which period should the WFA be made (e.g. specific year)?
4. Should a direct or indirect water footprint be used?

Phase 2: Water footprint accounting

The actual calculation of the water footprint takes place in this phase. The production process of a product is broken down into several process steps to simplify the calculations of total water usage. This is done by applying either the chain summation or stepwise accumulation approach. The total green, blue, and grey water footprint is determined, and, by adding the different water types, the total water footprint is derived.

Total water footprint

After the different types of water footprints are calculated for a process, they are simply added together to determine the total process water footprint (Hoekstra *et al*., 2011):

$$WF_{proc} = WF_{proc,blue} + WF_{proc,green} + WF_{proc,grey} \quad (volume/mass) \tag{8}$$

Phase 3: Sustainability assessment

This phase is dependent on the scope and goal(s) of the assessment. It is important to keep in mind that the sustainability of a consumer or product water footprint will depend on the geographical context of the product; in other words, the location of each process would be identified within a product's value chain. Once this is done, it is easier to distinguish between processes that take place in different geographical areas, and whether water is used in a sustainable manner in each of those areas (Jordaan *et al.*, 2014).

Sustainability has been defined differently by researchers over time. This study follows the definition of Gleick (1998) and Siche *et al*. (2008), who stated that sustainability is ensuring that the needs of the present generation are met without compromising the ability of future generations to meet their own needs. Sustainability is used with increased frequency in economic, social, and environmental dimensions (Hoekstra, 2015). From these definitions it is clear that sustainability requires a fundamental change in how we think about water, the use thereof, as well as preservation at a regional and, ultimately, a global level (Gleick, 1998). There is a strong relationship between available water resources and the ability to produce food (Brown and Matlock, 2011). In terms of sustainability, the volumetric water footprint of a product is the amount of water required to produce the product at a specific location at a specific time (Hoekstra, 2015), which highlights the importance of water availability at that specific location and time. Water availability is expressed as the difference between natural runoff (water that flows in a river) and environmental flow requirements. Natural runoff is estimated by adding estimates of actual runoff plus estimates of water volumes already consumed (Hoekstra and Mekonnen, 2011). Environmental flow requirements were estimated based on the presumptive standard for environmental flow protection proposed by (Hoekstra and Mekonnen, 2011). Blue water scarcity is defined as the ratio of blue water footprint (consumptive water) to blue water availability, Blue water availability could be further explained as and could be further explained as natural runoff minus the environmental concept (flow requirements) (Hoekstra and Mekonnen, 2011).

Phase 4: Response formation

After the goals and scope of the study are set and the respective water footprints are calculated and interpreted in terms of sustainability, one is able to formulate appropriate responses strategies.

2.5.2 LIFE CYCLE ANALYSIS BY PFISTER *ET AL*. (2009)

Pfister, Koehler and Hellweg (2009) indicated that the stress-weighted water LCA approach should be used as a base for calculating the water footprint. They further explained that in the life cycle inventory (LCI) phase, the quantities of water used are often reported, but the water source and type of use should ideally also be included.

According to the LCA method, consumptive water use includes all the freshwater withdrawals that are transferred to different watersheds, incorporated into the products, or lost due to evaporation. In this method, they use the term “degradative use” to describe the change in water quality that is released back to the original water body.

Pfister *et al.* (2009) focused on the consumptive water use and hence virtual water was of importance to them. Virtual water consists of all the water evaporated during production and incorporated into products, and thus includes both blue and green water.

However, according to the LCA method proposed by Pfister *et al.* (2009), only the blue virtual water footprint is considered because green water does not contribute to environmental flows until it becomes blue water. Green water is thus only accessible through the occupation of land. It is comparable to soil and solar radiation that cannot be separated from occupation of land (Jordaan *et al*., 2014).

The LCA method of Pfister *et al*. (2009) makes use of the virtual water database developed by Chapagain and Hoekstra (2004) in order to obtain the volume of water used to produce the relevant products. Once this is done, the water stress index (WSI) is determined. The WSI is a measure to determine whether freshwater withdrawal exceeds the water body's replenishment (after the volume of water used to produce the product is known). It is based on the water usage (WU) to water availability (WA) ratio (WTA). In order to calculate the WSI, the WaterGAP2 global model is used. This WaterGAP2 global hydrological water availability model is based on data from 1961 to 1990 and therefore gave an annual average water availability. Such data, however, do not allow for short periods of severe water stresses. This led to the annual data only being used to calculate the WTA and a variation factor (VF) was introduced to the model in order to provide for monthly variation in precipitation. Storage facilities (dams) reduce the variation in water supply and therefore regulate catchments require a reduced variation factor (Jordaan *et al.*, 2014).

Pfister *et al.* (2009) suggested the following equations to calculate the WTA in regulated and unregulated catchments:

$$\text{WTA}_{Regulated\ Catchments} = \sqrt{VF} \times \frac{WU}{WA} \tag{9}$$

$$\text{WTA}_{Non-regulated\ Catchments} = VF \times \frac{WU}{WA} \tag{10}$$

$$VF = e^{\sqrt{\ln(S_{Month})^2 + \ln(S_{Year})^2}} \tag{11}$$

VF is defined as the aggregated measure of dispensation of the multiplicative standard deviation of the annual S_{Year} and monthly S_{Month} precipitation (Pfister *et al*., 2009).

Pfister *et al.* (2009) used the WTA to calculate the WSI, but because the WSI is not linear in terms of WTA, they had to modify the WSI to a logistic function. This allowed them to achieve continuous values between 0.01 and 1.

$$WSI = \frac{1}{1+e^{-6.4WTA(\frac{1}{0.01}-1)}} \qquad (12)$$

From this equation, 0.01 represents the minimum value of the WSI. At this point, any water withdrawal will have at least marginal local impact. The maximum value of the WSI is 1 and indicates extreme water stress.

2.5.3 LIFE CYCLE ANALYSIS APPROACH PROPOSED BY MILÀ I CANALS *ET AL.* (2008)

Milà i Canals *et al*. (2008) proposed an adapted "life cycle analysis" water footprint methodology that differentiates between the two main impact pathways. These pathways are freshwater ecosystem impacts (FEIs) and freshwater depletion (FD). (Jordaan *et al.,* 2014).

Suggested calculation of the WSI is as follows:

$$\text{WSI} = \frac{Water\ Use}{(Water\ Resources\ Available - Ecological\ Water\ Requirement\ )} \qquad (13)$$

or:

$$\text{WSI} = \frac{WU}{(WR-EWR)} \qquad (14)$$

This calculation results in a much more accurate indication of the water available for further human use after allowing for the ecological water requirement (EWR).

The volume is added to the blue water consumption, and the total is then multiplied with the WSI as the characterisation factor.

Depleted freshwater is calculated using an abiotic depletion potential (ADP) formula that is adapted to accommodate the possibility of regeneration of water resources (Milà i Canals *et al*., 2008). The adapted ADP model is as follows:

$$ADP_i = \frac{ER_i - RR_i}{(R_i{}^2)} \times \frac{R_{Sb}{}^2}{DR_{Sb}} \qquad (15)$$

or:

$$ADP_i = ER_i - RR_i\left(R_i{}^2\right)^{-1} \times R_{sb}{}^2(DR_{sb})^{-1} \qquad (16)$$

Where:

- *i* = relevant water resource

- Sb = reference resource
- ER_i = resource *i*'s extraction rate
- RR_i = resource *i*'s regeneration rate
- R_i = resource *i*'s ultimate reserve
- R_{Sb} = reference resource's ultimate reserve
- DR_{Sb} = reference resource's de-accumulation rate

2.5.4 HYDROLOGICAL WATER BALANCE METHOD

The hydrological water balance method introduced by Deurer *et al.* (2011) was loosely based on the method developed and refined by Hoekstra *et al.* (2011) and considers all components of the water balance, not just the water consumption (Jordaan *et al*., 2014).

The calculation of the water footprint, according to this model, considers all the components of a water balance. These components include inflows, outflows, and storage changes. The green water footprint calculation according to the water balance method is as follows:

$$\Delta\, Green\, Water = D^r + ET^r + R^r - RF \tag{17}$$

Where:

- ET^r = Evapotranspiration under rain-fed conditions
- RF = Effective rain through fall or the rainfall minus water intercepted by plants
- D^r = Drainage under rain-fed conditions
- R^r = Runoff under rain-fed conditions

The blue water footprint calculation according to the water balance method is as follows:

$$\Delta\, Blue\, Water = D^r + D^{ir} + R^r + R^{ir} - IR \tag{18}$$

Where:

- D^r = Drainage under rain-fed conditions
- D^{ir} = Difference between drainage under rain-fed and irrigated conditions
- R^r = Runoff under rain-fed conditions
- R^{ir} = Difference between runoff under rain-fed and irrigated conditions
- IR = Annual irrigation water used

Grey water is calculated according to the method used by Hoekstra *et al*. (2011) and included in the total water footprint.

2.6 RELATED RESEARCH ON WATER FOOTPRINT ASSESSMENT OF WHEAT AND DERIVED WHEAT PRODUCTS

The amount of water used in the world is ultimately linked to final consumption by consumers. The water footprint of a product is the exact amount of water required to produce the product throughout its value chain. Wheat is grown on more land area than any other commercial crop, making it one of the most widely cultivated cereal grains globally, and the second most produced cereal, followed by rice (Mekonnen and Hoekstra, 2010). The global water footprint in relation to consumption of agricultural crops is given as 7 404 $Gm^3.year^{-1}$. Wheat is accountable for 15% of this consumption (1 088 $Gm^3.year^{-1}$), which is also the largest proportion for a single crop. Approximately 82% of this consumption is from domestic production, excluding most of the African, Southeast Asian, Central American, and Caribbean countries which rely strongly on external water resources for agricultural crop consumption (Hoekstra and Mekonnen, 2010a; 2010b). Mekonnen and Hoekstra (2010) took a high-resolution approach to estimating the water footprint of wheat and determined the global water footprint of wheat production of rain-fed and irrigated wheat as 1 805 $m^3.tonne^{-1}$ on an average yield of 2.5 $tonne.ha^{-1}$, and 1 868 $m^3.tonne^{-1}$ on an average yield of 3.3 $tonne.ha^{-1}$. The global average water footprint of wheat is 1 830 $m^3.tonne^{-1}$ at an average yield of 2.7 $tonne.ha^{-1}$. Blue water accounted for 50% of the total water used in irrigated wheat.

Hoekstra and Mekonnen (2010a; 2010b) realised that the average yield is directly proportional to water use and that the green water footprint generally has low opportunity cost compared to blue water. They concluded that low yields in green water footprint should be increased in order to lower the footprint and address negative externalities in the blue water footprint as this will reduce the need for blue water usage. Mekonnen and Hoekstra (2010) reported that the water footprint of irrigated agriculture is 30% higher than in rain-fed agriculture, even though the consumptive water use, which includes both green and blue water, was found to be the same. The difference is due to ET as well as yields being higher for irrigated wheat.

Mekonnen and Hoekstra (2010) concluded that the water footprint of a crop was largely dependent on agricultural management processes that the farmer can control rather than the agro-climate under which the crop is grown. They went further to calculate the water footprint of the products produced by crops and found wheat flour to have a water footprint of 1 849 $m^3.tonne^{-1}$ (1 292 $m^3.tonne^{-1}$ green, 347 $m^3.tonne^{-1}$ blue, and 210 $m^3.tonne^{-1}$ grey) and bread 1 608 $m^3.tonne^{-1}$ (1 124 $m^3.tonne^{-1}$ green, 301 $m^3.tonne^{-1}$ blue, and 183 $m^3.tonne^{-1}$ grey).

Chouchane *et al*. (2013) conducted an assessment of the water footprint of crop production, grazing, animal water supply, industrial production, and domestic water supply of Tunisia. Due to the major contribution of crop production to the total water footprint of Tunisia, Chouchane *et al*. (2013) calculated the water footprints of the total production of wheat and barley, as well as per tonne of crop. The water footprints of wheat and barley produced in Tunisia were found to be 2 560 $m^3.tonne^{-1}$ and 3 820 $m^3.tonne^{-1}$ respectively. Compared to the global average water footprints of wheat (1 830 $m^3.tonne^{-1}$) and barley (1 420 $m^3.tonne^{-1}$), Tunisia may have scope to decrease the respective water footprints.

In Iran, Ababaei and Etedali (2014) found the average water footprint of rain-fed wheat production to be 3 071 $m^3.tonne^{-1}$, which ranged from 1 595 $m^3.tonne^{-1}$ to 4 906 $m^3.tonne^{-1}$. For irrigated wheat, the average water footprint was 3 188 $m^3.tonne^{-1}$, which ranged from 2 249 $m^3.tonne^{-1}$ to 5 056 $m^3.tonne^{-1}$. The variation of Iran's water footprint is high and necessary means should be taken to reduce it, as well as to decrease the overall water footprint of wheat.

Ahmed and Ribbe (2011) explored the green and blue water footprints of rain-fed and irrigated crops in Sudan. Interestingly, they also considered the impact of different rainwater harvesting techniques on the water footprint of the products. Among the irrigated crops, Ahmen and Ribbe (2011) considered cotton, sorghum, groundnut, and wheat. The water footprints of the crops were found to be about 11 000 $m^3.tonne^{-1}$, 3 000 $m^3.tonne^{-1}$, 5 000 $m^3.tonne^{-1}$, and 5 500 $m^3.tonne^{-1}$ respectively. The results also showed that using rainwater harvesting techniques substantially decreased the water footprint of rain-fed sorghum in Sudan.

Aldaya and Hoekstra (2010) used the WFN approach to calculate the water footprint of pasta and pizza magarita in Italy. They found that 72% of durum wheat and bread wheat becomes semolina and bread flour respectively. Both constitute 88% of the total value of mill products, and the rest is attributed to bran and germ. To calculate the water footprint of flour, Aldaya and Hoekstra (2010) multiplied the WF_{wheat} by the value fraction divided by extraction rate (786 × 0.88/0.72) = 605 $m^3.tonne^{-1}$, further expressed as 154 $m^3.tonne^{-1}$ green, 202 $m^3.tonne^{-1}$ blue, and 368 $m^3.tonne^{-1}$ grey water. A similar process was followed for semolina (1 574 × 0.88/0.72) = 1 924 $m^3.tonne^{-1}$, further expressed as 914 $m^3.tonne^{-1}$ green, 642 $m^3.tonne^{-1}$ blue, and 368 $m^3.tonne^{-1}$ grey water.

Similar to Aldaya and Hoekstra (2010), Neubauer (2012) calculated the water footprint required to produce 1 kg of bread in Hungary. She found the water footprint of wheat to be 1 267.5 $m^3.tonne^{-1}$ and the Hungarian flour conversion rate to be 0.76 kg from 1 kg of wheat. Due to lack of data, the author estimated the value fraction of the resulting flour base on an Italian example as 0.88, meaning that 88% of the total value of a mill product is flour. Neubauer (2012) calculated the water footprint of flour by multiplying the water footprint of wheat with the value fraction divided by flour conversion rate (1 267.5 × 0.88/0.76) = 1 468 $m^3.tonne^{-1}$, and further expressed this water as a combination of green, blue, and grey water. She also concluded that there was no difference between the water footprint of flour and that of bread, due to a lack of regional share of bread production, yet concluded that 1 014 litres of water is required for 1 kg of bread.

Ruini *et al*. (2013), in a case study of a pasta-producing company, conducted a WFA of the wheat-pasta value chain using the LCA approach and concluded that the water footprint of pasta ranged from 1 336 $m^3.tonne^{-1}$ to 2 847 $m^3.tonne^{-1}$, and the water footprint of pasta at the processing stage was between 1.34 $m^3.tonne^{-1}$ and 2.85 $m^3.tonne^{-1}$, which is 1% to 4% of the total water footprint of pasta along the wheat-pasta value chain.

Sundberg (2012), using the WFA approach by Hoekstra *et al.* (2011), conducted a WFA of winter wheat production in Sweden, and also considered derived wheat products along their respective value chains. The products included wheat flour and macaroni. Wheat flour had a conversion rate of 76.72%. The water footprint of wheat flour at the mill was found to be 1.15 $m^3.tonne^{-1}$ and included in this footprint was the footprint of transport, processing, supply chain (wheat), and energy use. The water footprint along this value chain was realised by taking the annual total water use in each step and dividing it by the annual production in the relevant step. The results indicated that 12 156 000 kg of flour was produced per annum and the water used throughout the flour value chain was 27 897 886 m^3, giving a water footprint of 1.15 $m^3.tonne^{-1}$. The supply chain had a 99% contribution to this value chain, while processing accounted for only 1%.

Based on the above discussion, it is evident that the water footprint of wheat differs significantly between countries and regions within these countries. The global water footprint of wheat is given as 1 830 $m^3.tonne^{-1}$, and 1 849 $m^3.tonne^{-1}$ and 1 608 $m^3.tonne^{-1}$ of flour and bread respectively. Aldaya *et al.* (2010) emphasised with the study in Italy that different production regions within a country can have different water footprints for the same crop. However, the study did not suggest ways to increase yield and production where the water footprint was below the global average. Ababaei and Etedali (2014) showed the importance of separating the irrigated and rain-fed wheat production but also did not give an economic assessment and response formation of their findings.

Aldaya and Hoekstra (2010) and Neubauer (2012) calculated the water footprint of wheat and derived wheat products using the mill and flour extraction rate per 1 kg of wheat, which yielded a high water footprint value for flour, bread, and pasta. Ruini *et al*. (2013) and Sundberg (2012), on the other hand, instead calculated the water footprint of wheat and derived wheat products along their respective value chains. Ruini *et al*. (2013) and Sundberg (2012) calculated the water footprint at cultivation (farm) level and processing level, as well as the proportion of these footprints to the products' overall water footprint. This approach provided a more detailed understanding of the areas in a product's value chain where much attention should be focused on lowering the water footprint of the product. This allows processers to make better informed decisions about their suppliers. Much emphasis is placed on the volumetric water footprint rather than on the sustainability of water use, and response formulation was not clear. Overall, the relevant research indicated that there is a substantial difference in the water footprint of wheat across different countries, regions within a country, rain-fed or irrigated wheat, as well as between wheat-based products and the same product along their respective value chains.

To conclude this section, Aldaya and Hoekstra (2010) stated that conducting a WFA of a product's supply chain will be useful for practitioners in the agro-food industry who wish to improve the environmental performance of their final product over its full supply chain and in so doing influence their raw material suppliers who are often the bearers of 95% of the footprint incurred by agro-processors.

2.7 ECONOMIC VALUATION OF WATER FOOTPRINT

2.7.1 VALUATION FOR ECONOMIC CONTRIBUTION

Water supply in sufficient quality and quantity is a critical input to South Africa's economic growth and employment creation (DWA, 2012). Irrigated agriculture accounts for about 60% of available water resources in South Africa and is a major role player in the South African economy (DAFF, 2015). This sector is specifically mentioned in the NDP as a focus area to contribute towards economic development in South Africa (National Planning Commission, 2013). The impacts of water use in a supply chain have often been overlooked but are increasingly subjected to critical observation by businesses, society, and the government (Crafford *et al.* 2004). Due to this, companies are changing the way they address water and are increasingly promoting sustainable water management outside their guidelines to reduce and alleviate water-related risks and impacts of raw material along the value chain of products, particularly in processed foods (Scheepers, 2015).

Agricultural market linkages such as the earner of foreign exchange, provider of food, buyer and seller of inputs to the manufacturing sector, and key drivers of agribusinesses such as co-ops, food processers, distributers, and trade shows indicate that agriculture is prominent in South Africa's economic growth. By using multipliers to estimate the indirect impact on the economy, primary agriculture has a backward linkage of 2.14, meaning that an increase of R1 million in the demand of agricultural output will cause a R2.14 million increase in agri-related manufacturing sectors (Geyling, 2015; Tergenna, 2010). According to Mekonnen and Hoekstra (2010), when compared to the majority of crops, wheat has a low economic water productivity (EWP) (Euro/m^3) and is accountable for 15% of global consumption (Hoekstra and Mekonnen, 2010a; 2010b). It is therefore important to analyse the extent to which water should be allocated to irrigated wheat production in water-scarce regions and in so doing, quantify the value added to water resources along the wheat-bread value chain. Based on this discussion, the next section examines the economic valuation of water footprints.

According to Hoekstra (2015), the three pillars under wise freshwater allocation are sustainable (environmental), efficient (economic), and equitable (social) water use; while the focus of water footprint research is mainly on the environmental impact of water. It is therefore important that researchers consider economic and social aspects in line with the WFA. Hoekstra *et al.* (2011) considered environmental, economic, and social aspects of the water footprint; however, the scope of economic and social analysis is relatively small. Inclusion of economic analysis is in terms of EWP, where the EWP is calculated by multiplying the physical productivity of a product with the price of the product in order to attain the value of the marginal product of the agri-food product with respect to water. Economic water productivity has also been used to relate water to nutrition, welfare, jobs, and the environment (Molden *et al*., 2009). According to Molden (2007), high EWP can alleviate poverty in two ways: first by increasing water use on targeted interventions for nutrition and income generation, and secondly, by use of the multiplier effect on food security, employment, and income.

Aldaya *et al*. (2010) calculated the EWP of blue water of cotton, wheat, and rice in Central Asia as expressed in market price (US\$.tonne^{-1}) per cubic metre of water consumed. According to Aldaya *et al.* (2010), in Central Asia the agricultural sector is accountable for 90% of water use, and cotton, wheat, and rice (selected crops for their study) amount to about 75% of agricultural sector water use. The average water footprints of cotton, rice, and wheat production in Central Asia were calculated at 4 642 m^3.tonne^{-1},
4 284 m^3.tonne^{-1}, and 2 652 m^3.tonne^{-1} respectively. Interestingly, the EWP of blue water for the three crops was 0.5US\$/m^3, 0.18US\$/m^3, and 0.07US\$/m^3 respectively. Thus, the crops with the highest water footprints were also found to have the highest EWP in terms of blue water. No production costs were included throughout the value chain; therefore the value added to water is not known.

Chouchane *et al*. (2015) placed a significant amount of focus on the economic aspect of the water footprint in Tunisia. In addition to calculating the water footprints of different crops (bio-physical focus), EWP (amongst others) was also calculated for the different crops, which was done in two steps. First, the physical water productivity (kg/m^3) was calculated for each crop by dividing the crop yield (in kg) by the green, blue, and grey water footprints (in m^3) of the crops. In the second step, the economic productivity (US\$/m^3) of the crops were calculated by multiplying the physical water productivity (kg/m^3) of each crop with the product price of the particular crop (in US\$/kg). The EWP of the different crops were found to range from 0.03US\$/m^3 (olives) to 1.08US\$/m^3 (tomatoes). The economic productivity provided an indication of the income that was generated per cubic metre of green, blue, and grey water footprint, with no cost included.

Similar to Chouchane *et al*. (2015), Zoumides *et al*. (2014) included EWP when assessing the water footprint of crop production and supply utilisation in Cyprus. Zoumides *et al*. (2014) found that the EWP of blue water in Cyprus (2009 prices) ranged between 0.89€/m^3 and 1.15€/m^3 in the period 1995 to 2009. In turn, the economic productivity of green water ranged between about 0.22€/m^3 and 0.45€/m^3 for the same period. Thus, per cubic metre of blue water that is used in the production of the selected crops, more income is generated compared to a cubic metre of green water. Changing water use behaviour in Cyprus to decrease the pressure on blue water resources may thus have a significant impact on the country's economy. Similar to the cases described by Aldaya *et al.* (2010) and Chouchane *et al*. (2013), the reported EWP in Zoumides *et al.*'s (2014) study refers to the income that is generated per cubic metre of water applied; no costs were considered.

The stated research focused on the economic productivity of products based on the physical productivity, price, and the water footprint of the product. The cost of production along the product value chain was not included and none of the research studies focused on economic crop productivity of South Africa.

In respect to direct and indirect economic benefits realised in backward and forward sectoral linkages to production activities, Crafford *et al.* (2004) analysed the social, economic, and environmental direct and indirect costs and benefits of water use in irrigated agriculture and forestry. More specifically, Crafford *et al.* (2004) considered plantation forestry, irrigated sugarcane, and irrigated subtropical fruit in the Crocodile River catchment. Value added (the difference between proceeds from new production minus the cost of intermediate inputs bought from other sectors) was used as a proxy measure of economic benefit. The results from the economic impact analysis showed that the direct value added per cubic metre of water ranged between 1.8ZAR/m^3 and 2.6ZAR/m^3 of water for the forest plantations, 1.3ZAR/m^3 for sugarcane, and 3.2ZAR/m^3 to 8.7ZAR/m^3 for subtropical fruit, and for the indirect linkages, value added per cubic metre of water ranged between 19.9ZAR/m^3 and 32.1ZAR/m^3 of water for the forest plantations, 9.9ZAR/m^3 for sugarcane, and 3.2ZAR/m^3 to 8.9ZAR/m^3 for subtropical fruit. Crafford *et al.*'s (2004) results also showed that the fruit trees created the most employment benefits per cubic metre of water used. Crafford *et al*. (2004) concluded that their findings showed the impact of the length of the specific value chain on the economic benefits along the value chain, and the importance of also considering indirect economic impact when making decisions regarding water allocation.

Scheepers (2015), following the methodology of Crafford *et al.* (2004) and Jordaan and Grové (2012), calculated the value added to water along the South African lucerne-dairy value chain during an assessment of the water footprint and the value of water used in the lucerne-dairy value chain. The gross margin was used as the value added at the farm gate. The price that the processor paid for raw milk varied with the quality of the milk and the distance it had to be transported. At the time, the average price paid for milk with 3.3% protein and 4% fat was [1]4.75ZAR per litre. The processing facility had two outputs with different value added along the value chain from processing to retail. These products were explored individually. The one-litre bottles were sold to the retailer at 10.40ZAR per unit, while the processor received 25.90ZAR for a three-litre bottle of processed milk. At retail level, the milk was sold at 14.95ZAR for a one-litre unit and 35.95ZAR for a three-litre bottle.

The results of Scheepers' (2015) study indicated that by packaging the processed milk in a bottle with a capacity of one litre, a total value of 11.72ZAR was added per litre of milk. This value comprised processing, where 5.65ZAR is added, retailers, with 4.55ZAR value added per litre, and farmers adding only 1.52ZAR per litre of milk. With the three-litre bottles it was found that only 8.75ZAR of value was added per litre. This value was comprised of processing, where 3.88ZAR was added, retailers with 3.35ZAR value added per litre, and from the farmers value added was similar to that of the one-litre packaging, at 1.52ZAR per litre of milk. The total value added to water (in ZAR/m^3) is derived by the total value added to milk (in ZAR/kg) multiplied by the water footprint of milk (in m^3/kg). Value added to water for one litre of milk was 11.81ZAR/m^3 and for the three-litre milk units 8.82ZAR/m^3. Scheepers (2015) concluded that milk sold in one-litre bottles added the greatest value per litre of milk (thus also per kilogram), while the same quantity of water was used in the production thereof. It therefore makes sense that the value chain of milk packaged in bottles with a volume of one litre add significantly more value to the water than the larger containers' value chain.

The approach and findings of Scheepers (2015), which followed the methodology of Crafford *et al*. (2004) and Jordaan and Grové (2012), thus provided good insight that may guide the assessment of the sustainability of respective value chains of field and forage crops.

2.8 CONCLUSION

South Africa is water stressed and water limited, with water requirements that exceed water availability. The South African agricultural sector, despite being the smallest

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[1] Exchange rate 2015: 12.76ZAR per 1USD.

contributor to the GDP and the smallest employer, uses 63% of available freshwater resources. Therefore this water has to be employed in the most equitable, efficient, and effective way possible. Wheat is grown on more land area than any other crop globally and in South Africa it is the largest winter crop cereal. About 60% of the total quantity of wheat flour and wheat meal is used to produce bread, with consumption of 2.8 billion loaves per annum. Therefore the water footprint of bread in South Africa would inform stakeholders and consumers of the sustainability, socioeconomic contribution, and value of water used for bread along the wheat-bread value chain in South Africa.

According to ISO 14046 (2014), a water footprint is the quantification of potential environmental impacts related to water and is based on the LCA approach, which indicates environmental impact. A WFA conducted according to this international standard must be compliant with and include the four phases of an LCA, and only after the completion of these assessments can the results be interpreted. The LCA neglects green water accounting based on the notion that green water use cannot be separated from the occupation of land, the impact of which is accounted for elsewhere in LCA. The LCA is not a comprehensive approach to WFA and because ISO 14046 is based on this approach, it too is not a comprehensive WFA method.

The GWFS method accounts for blue, green, and grey water footprints, while the LCA only accounts for the blue water footprint. Milà i Canals *et al.* (2008) considered both green and blue water resources and classified blue water as fund (groundwater), stock (fossil groundwater), and flow (rivers). The hydrological water balance method determines blue, green, and grey water footprints annually on a local scale. Although in the green water footprint, water that becomes runoff is included at the same time as blue water footprint drainage under rain-fed conditions, which would be runoff from the green water footprint, which is already accounted for in the previous assessment, and which makes this method inaccurate. In conclusion, the WFN approach is thus by far the best method to use.

Related research established that the water footprint of wheat differed significantly between countries, regions within countries, rain-fed and irrigated wheat. The water footprint of a product and of similar products along the value chain also differ. It was also established that the water footprint along a value chain has a larger proportion of farm-level (crop cultivation) water footprint to process (mill and bakery) water footprint on the WF_{bread}, which is why it is important to consider the economic valuation of this process in terms of ZAR/m^3 of produce to determine if the large amount of water at cultivation is proportional to value added to the final product. The sustainability assessment and response formation are the most important aspects of a WFA, or else the message of this approach is lost.

The South African milling industry makes up a total capital investment of about R3 billion through the production of wheat flour, wheat meal, and bran – making this industry crucial for rural economic development; however, this same industry is built on a crop known to have low economic productivity per unit of water used (Mekonnen and Hoekstra, 2010; WWF, 2016). It is therefore important to quantify the water footprint of bread along the wheat-bread value chain in order to advise and enlighten policy makers of whether the investment of already scarce freshwater resources in this industry is justified.

CHAPTER 3

METHODS AND DATA

3.1 INTRODUCTION

Chapter 3 is a discussion of the methods and data used in order to achieve the aims and objectives outlined in Chapter 1 of this study. The water footprint methodology that best suits the goals and scope of this study is elaborated upon. In Chapter 2, it was determined that the WFN approach is best aligned with the goals and scope of this study, and in this chapter the application of the method is explored. Once the total water footprint methodology is explained, the located study area as well as data utilised in the study are discussed.

3.2 METHODS

After evaluating the different water footprint accounting methods in Chapter 2, it was decided that the consumptive water-use-based volumetric water footprint method of the WFN best fits the scope of this study. The methodology in this chapter and the calculations in Chapter 4 are based on the guidelines of the Water Footprint Assessment Manual (Hoekstra *et al.,* 2011).

According to this framework, a WFA consists of four phases. The first phase involves setting the scope and goals of the assessment. The second phase is the water footprint accounting, where the volumetric water footprint indicator is calculated throughout the value chain. The third phase is a sustainability assessment in which the WFA is evaluated from an environmental, social, and economic perspective. The fourth phase is the response formulation where policy recommendations are made.

3.2.1 PHASE 1 – SETTING THE GOALS AND SCOPE

In Phase 1 the goals and scope of this analysis are set. This is where the steps to be taken throughout the study are conceptualised.

- Water footprint assessment can be performed for a number of entities. This study has analysed the water footprint of a product, i.e. bread along the wheat-bread value chain. The products included in this value chain were wheat, flour, and bread.

- To calculate the footprints, the total volume of freshwater directly and indirectly used to produce bread, wheat, and flour was considered, as well as the yield at each stage of production.
- The nature of this assessment is such that the products along the value chain became inputs in the next production stage. Therefore, the assessment followed the guidelines of the stepwise accumulation approach.

For the chosen entity, the following was included in the study;

- The analysis include consumptive water footprint, i.e. green and blue water consumed, evapotranspired, and incorporated into the various products along the wheat-bread value chain.
- The total water footprint of the value chain was the addition of all the water footprints from the different products. Therefore includes all direct and indirect water used throughout the value chain.
- Data period: Fluctuations in water availability and supply within and across years is a reality and consequently the water footprint vary with the time chosen. It is therefore important to state whether one is calculating the water footprint in a specific year, an average over several years, or for a number of years.
- Truncation of the supply chain: All types of footprinting face the truncation issue where one needs to determine where along the supply chain to truncate the analysis. With Water footprinting, there is no generally accepted guidelines for what to include in the study. Hoekstra *et al.* (2011), however, suggested the importance of inclusion of all water usages that contribute “significantly” to the overall water footprint. It is common practice not to include the water footprint of labour, as this could lead to a never-ending cycle of accounting, as well as the problem of double counting. In South Africa, the use of biofuels and hydropower is fairly limited, especially in the agricultural sector, therefore these are also excluded from the study.
- Due to the nature of data used in this study, grey water was not considered and therefore the grey water footprint will not be calculated in the analysis.

This study acknowledges that 60% of wheat consumption is imported, but focuses on local wheat production for bread and the impact thereof on South Africa’s freshwater resources.

3.2.2 PHASE 2 – WATER FOOTPRINT ACCOUNTING

The objective of this phase is to calculate the volumetric water footprint of bread along the wheat-bread value chain. For this purpose, this study conducted a WFA of a product (along a process step). This was determined by considering the water consumption in each step of the production process. A product water footprint indicates how much pressure a product puts on freshwater resources. It can be measured in cubic metres of water per tonne of production. The water footprint of a product is a multidimensional indicator that not only refers to the virtual water of a product, but also refers to the type of water that was used (green, blue) and to where and when the water was used. The wheat-bread value chain was comprised by a crop water footprint for wheat production and a product water footprint for flour (from a mill) and bread (from a bakery). These water footprints were then added together to obtain the total water footprint of bread along the wheat-bread value chain. The production process of the product was broken down into several process steps in order to simplify the calculation of the total water usage.

For the purpose of this study, the stepwise accumulation approach was used. In production systems with complex input and output combinations, the stepwise approach can be used to calculate the water footprint of a product by using the proportional water footprints of the varying inputs. This is a more generic approach to calculate the water footprint of a product and because the output of one product in this value chain is the input of the next product, this approach best suits the expected outcome of this study, which estimates the water footprint for different output products such as wheat, flour, and bread to conceptualise the water footprint of bread along the wheat-bread value chain. The water footprint of product *p* will be adapted from equation (5) as specified in Section 2.4.1.3.

3.2.2.1 THE WATER FOOTPRINT OF WHEAT

The primary product of this assessment is wheat, and the water footprint of wheat will be calculated following the WFN approach by Hoekstra *et al.* (2011), similar to Mekonnen and Hoekstra (2010), Aldaya and Hoekstra (2010), Ahmed and Ribbe (2011), Sundberg (2012), Chouchane *et al*. (2013), and Ababaei and Etedali (2014).

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

$$WF_{wheat} = WF_{wheat,blue} + WF_{wheat,green} + WF_{wheat,grey} \quad [volume/mass] \tag{19}$$

$WF_{wheat,blue}$ is the blue crop water footprint, which refers to the total amount of surface and ground water that evaporates and is incorporated into the product and does not become runoff, from the field over the total length of the crop's growing period. $WF_{wheat,green}$ refers to the total rainwater that evaporates and is incorporated into the product and does not become runoff. $WF_{prod,grey}$ is the total amount of water required to remove pollutants and return water to its ambient form.

The total amount of irrigated (ground or surface) water that evapotranspired over the total length of the crop's growing period, $WF_{wheat,blue}$ ($m^3.tonne^{-1}$) is calculated as the blue component in crop water use CWU_{blue} ($m^3.ha^{-1}$) divided by the crop yield ($tonne.ha^{-1}$). Similarly, the total volume of rainwater that evapotranspired from the field during the same period, $WF_{wheat,green}$ ($m^3.tonne^{-1}$), is calculated in a similar fashion:

$$WF_{prod,blue} = \frac{CWU_{blue}}{Y} \quad [volume/mass] \tag{20}$$

$$WF_{prod,green} = \frac{CWU_{green}}{Y} \quad [volume/mass] \tag{21}$$

Blue and green crop water use, *CWU* ($m^3.ha^{-1}$), is the sum of the daily ET (*ET*, mm/day) over the complete growing period of the crop:

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue} \quad [volume/area] \tag{22}$$

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green} \quad [volume/area] \tag{23}$$

ET_{blue} and ET_{green} represent the blue and green water ET respectively. The water depths are converted from millimetres to volumes per area or $m^3.ha^{-1}$ by using the factor 10. Summation is done over the complete length of the growing period (*lgp*) from day one to harvest (Hoekstra *et al.,* 2011).

3.2.2.2 WATER FOOTPRINT OF A PROCESSOR

The water footprint of flour and bread was calculated following the logic of Sundberg (2012), who used the WFN approach to conducted a WFA of winter wheat as well as derived wheat products along their respective value chains, and Ruini *et al.* (2013), who may not have used the WFA approach but rather the LCA approach, conducted a WFA of pasta along the wheat-pasta value chain. As affirmed in Chapter 2, Sundberg (2012) and Ruini *et al.* (2013) focused on calculating the water footprint of derived wheat products along the respective supply chains by calculating the water used in each production node and dividing it by the quantity of products produced at that node. These footprints were then added to determine the final water footprint of end products along that supply chain in order to highlight the importance of the direct and indirect water use of a given product.

3.2.2.3 MILL

For the total water footprint of flour, the volume of water used in the mill to produce the flour is quantified and divided by the quantity of flour produced:

$$WF_{flour,mill} = \frac{total\ volume\ of\ water\ in\ mill\ (m^3)}{quantity\ of\ flour\ milled\ (ton)} \tag{24}$$

3.2.2.4 BAKERY

Similar to the water footprint of flour, the total water footprint of bread is the volume of water used in the bakery divided by the quantity of flour produced:

$$WF_{bread,bakery} = \frac{total\ volume\ of\ waterin\ backery\ (m^3)}{quantity\ of\ flour\ milled\ (ton)} \tag{25}$$

3.2.2.5 TOTAL WATER FOOTPRINT

The final blue water footprint is an indicator of the total amount of surface and ground water that evaporated along the wheat-bread value chain, or that was incorporated into the final product. This is the one type of water that is realised on both crop production and processing level of the respective value chains and is expected to be the largest contributor to the total water footprint realised at the end of this assessment. The case study is on irrigated winter wheat planted in a summer rainfall region, therefore it is expected that the green water footprint will be quite low considering that no green water is used in the processing stage of the assessment. The final calculated green water footprint is an indicator of the total amount of rainwater that was evapotranspired by the crop and incorporated into the crop along the wheat-bread value chain.

The total water footprint of bread along the wheat-bread value chain is realised by adding the respective water footprint along this value chain:

$$WF_{bread} = WF_{wheat} + WF_{flour,mill} + WF_{bread,bakery} \quad volume/mass \tag{26}$$

3.2.3 PHASE 3 – WATER PRODUCTIVITIES ASSESSMENT: QUANTIFYING THE VALUE OF THE WATER

The value added to water along the wheat-bread value chain was calculated in terms of EWP. The EWP was calculated at each node of production in order to determine which of the process steps along the value chain contribute the highest and lowest EWP. The steps followed in calculating EWP are as follows.

1. The *physical water productivity* ($m^3.kg^{-1}$) of each product along the wheat-bread value chain was calculated. This was done by taking the yield at each production node and dividing it by the respective crop water use in the case of wheat, and total water used in the case of flour and bread. These values are given in $m^3.tonne^{-1}$ and therefore will be converted to $m^3.kg^{-1}$ by dividing the values by 1 000.

2. *Value added* along the value chain (in $ZAR.kg^{-1}$). Once the physical water productivity for each production node is known, value added at each node can be calculated. This was done following the logic of Jordaan and Grové (2012) and Scheepers (2015). Value added will be calculated using the following equation:

   $$V_{ic} = \sum_i Vic \tag{27}$$

   Where V_i represents the value added at process step i of value chain c and is derived as:

   $$V_{ic} = PS_{ic} - PP_{ic} \tag{28}$$

The parameters of the equation are as follows:

- V_c = Value added along value chain c
- V_{ic}= Value added at process step i of value chain c
- PS_{ic}= Selling price at process step i of value chain c
- PP_{ic}= Purchase price at process step i of value chain c

The purchase price of each product at the beginning of the production node as well the selling price at the end of each node is known. Due to the fact that wheat has no direct purchase price, the gross production value (in ZAR.ha^{-1}) divided by the yield (in tonne.ha^{-1}) was used as the value added at farm level. In the case of flour, the value added was sourced from the industry and was taken as the price of flour per tonne. The cost and sale price of bread is known.

3. Once the value added at each production node was known, the EWP was determined by multiplying the physical water productivity by the respective value added. Economic water productivity was presented in ZAR.kg^{-1}.

This assessment enabled the comparison of water usage and economic productivity of the water along the wheat-bread value chain.

In order to calculate the EWP along the wheat-bread value chain, data was sourced from Chapter 3 of the Wheat-Bread Value Chain from a general report of the Food Price Monitoring Committee (2003) led by the National Development Agency and the DAFF.

Included in this report was the average wheat-to-brown-and-white-bread supply chain for the period February 2000 to December 2002, where all the production costs and income received at each node of production, as well as when the products moved to the next node, were known. The values were adjusted to 2016 prices using the 2016 consumer price index. These data was only used for flour-bread along the value chain. In the case of wheat, this study used the Producer Price Framework for Irrigation Wheat for the 2016/2017 production year by Grain SA. This report includes all the production costs and income received for wheat produced in the Northern Cape at different yields.

3.2.4 PHASE 4 – RESPONSE FORMULATION

This is the final step in a WFA, where responses are formulated according to the different assessments performed in the previous phases. This phase combines the individual assessments and attempts to give a more holistic analysis of the water footprint of a selected product, in order to inform water users towards improving water use behaviour. The response formulation is further explored in Chapter 5 of this study.

3.3 DATA

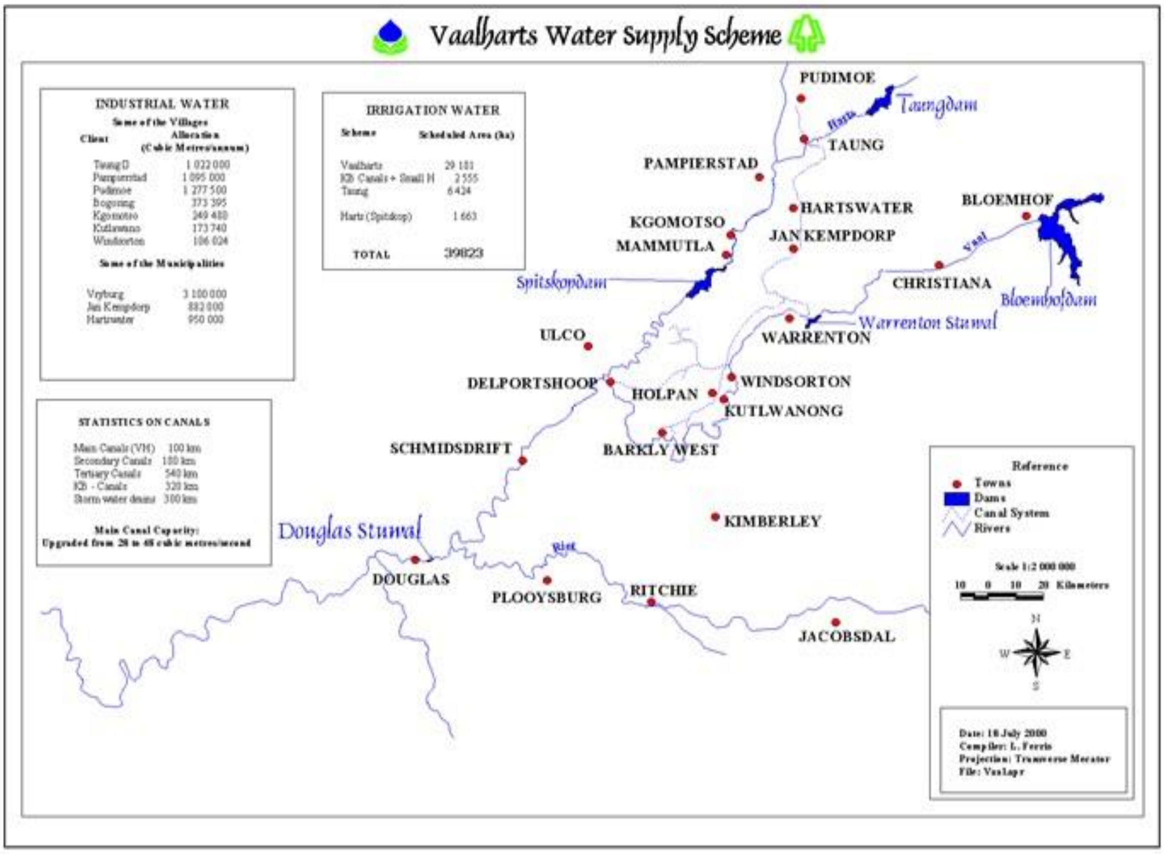
The scope of this study covers a case study of the water footprint of bread along the wheat-bread value chain. Secondary data on water use for the production of wheat were obtained from van Rensburg *et al.* (2012), who, among other things, looked at the management of salinity on field crops where wheat was included.

Once the wheat is produced, it becomes an important input for bread production, and the link between the wheat and bread value chains is made. Therefore, water data for a commercial mill and bakery (processor) were needed. The data were collected through a questionnaire sent to the managers of one of the leading wheat-processing agri-businesses in South Africa.

3.3.1 LOCATION AND LAYOUT

South Africa has 19 catchment water management areas (CWMAs), equipped with agencies that manage water resources by coordinating water-related activities within their jurisdiction (DWA, 2008; Mukhuibir, 2005; Van Rensburg *et al*., 2012). Irrigated water within the respective CWMA is managed by Water User Associations (WUAs), which regulate the daily supply of irrigated water to farms and also the channels water uses to reach the respective farms. Lastly, the farmer manages the on-farm irrigation, where efficiency is crucial to the entire system.

For the purpose of this study, the Vaalharts irrigation schemes managed by the CWMA of the Upper Orange and Lower Vaal, as well as the WUA of the Vaalharts region were used. These schemes are spread across the Free State, as well as parts of the Northern Cape (Van Rensburg *et al*., 2012). Figure 3.1 illustrates the layout of the Vaalharts Irrigation Scheme.



INDUSTRIAL WATER

Some of the Villages

Client	Allocation (Cubic Metres/annum)
Taung D	1 022 000
Pampierstad	1 095 000
Pudimoe	1 277 500
Bogosing	373 395
Kgomotso	249 480
Kutlwano	173 740
Windsorton	106 024
Some of the Municipalities	
Vryburg	3 100 000
Jan Kempdorp	882 000
Hartswater	950 000

IRRIGATION WATER

Scheme	Scheduled Area (ha)
Vaalharts	29 181
KB Canals + Small H	2 555
Taung	6 424
Harts (Spitskop)	1 663
TOTAL	39823

STATISTICS ON CANALS

Main Canals (VH)	100 km
Secondary Canals	180 km
Tertiary Canals	540 km
KB - Canals	320 km
Storm water drains	300 km

Main Canal Capacity:
Upgraded from 28 to 48 cubic metres/second

Date: 18 July 2000
Compiler: L. Ferris
Projection: Transverse Mercator
File: Vaalapr

Figure 3.1: Layout of the Vaalharts Irrigation Scheme

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

The Vaal River (largest tributary of the Orange River) is the main supplier of water to the Vaalharts Irrigation Scheme, with the Warrenton Weir just upstream of Warrenton diverting water into the Vaalharts main canal. This main canal in turn supplies the North, West, Taung, and Klipdam-Barkley canals that convey the water to Vaalharts, Barkley-West, Spitskop, and Taung sections. The total licensed areas for irrigation in the sections are 29 181 ha, 2 555 ha, 1 663 ha, and 6 424 ha respectively. In order to convey the irrigation water to the licensed areas, the system comprises 1 176 km of concrete-lined canals, together with 314 km of additional concrete-lined drainage canals to convey stormwater and subsurface drainage water out of the irrigation scheme through to the Harts River (Van Rensburg *et al*., 2012; Muller and Van Niekerk, 2016).

The Vaalharts area is essentially bordered by two plateaus on the east and west sides of the Harts River Valley (Erasmus and Gombar, 1976), and the valley slopes towards the south. The low gradient of the Harts River, with no incising by the river itself, means that very little topographical changes can be observed within the valley. The general surface flow pattern tends to be towards the Harts River (Van Rensburg *et al*., 2012).

The Vaalharts Irrigation Scheme falls within a summer rainfall area, with thunder showers responsible for the majority of the rain during the summer months. Between November and April, the long-term rainfall for the area is normally more than 40 mm per month, with a mean of 59 mm. The long-term maximum temperature between November and March for Vaalharts is 31 °C, while the minimum temperatures vary between 14 °C and 17 °C. During the winter months, the maximum temperature is around 20 °C, with the mean minimum temperature just above 0 °C (Van Rensburg *et al*., 2012).

3.3.2 LAYOUT OF MEASURING POINTS

Wheat data were collected in an experimental manor over a period of three years. The area of the experimental site was 70 m x 35 m and was irrigated by means of a drip irrigation system. In the centre of this site, 30 round plastic containers (1.8 m in diameter and 1.8 m deep) were arranged in two parallel rows of 15 each, with their rims 5 cm above the bordering soil surface. A 10 cm layer of rock was placed in the base of each container and covered with a plastic mesh. One row of containers was filled with a homogenous yellow sandy soil and the other row with a red sandy loam soil to the same level as the soil in the surrounding field. An underground access chamber (1.8 m wide, 2 m deep, and 30 m long) allowed access to the inner walls of the containers. On the access chamber side, an opening at the bottom of each container was connected to a manometer and a bucket that was used to recharge and regulate the height of the water table treatments. Each container was also equipped with two neutron probe access tubes (Ehlers *et al.,* 2003).

It was decided to make use of actual measurements through a lysimeter trial, instead of estimations from water use models, to determine the water footprint of wheat. The experiment consisted of five treatments replicated three times and an average taken to represent each sample. Cultivars used were selected as widely used throughout all the central parts of the South Africa. Above-ground biomass was harvested when crops were dry by cutting it just above the soil surface (Ehlers *et al.*, 2003).

For the purpose of this study, only one of the five treatments was selected to represent the water footprint of wheat in the Vaalharts irrigation scheme.

3.3.3 PROCESSING STAGE

Data used in this study were obtained from one of the leading processing companies in South Africa, with an average of five mills and 15 bakeries nationwide. The company maintains an excellent recordkeeping system, which guarantees the authenticity of the results. The data acquired were of a single production year and were acquired with the use of a questionnaire (compiled in a clear and easy to understand manner) to obtain the necessary information in order to conduct a WFA of the processing stage within the wheat-bread value chain. The questionnaire (see Appendix A) made it possible to calculate the water footprint of flour and bread in order to determine where the largest contribution of the water footprint lies in the respective value chains. There was no differentiation between the different types of water. Therefore the data are a representation of the total water used in the processing stage. From the literature one expects the water footprint from the processing stage to contribute less than 1% to the overall water footprint of bread along the wheat-bread value chain. These footprints are later compared to the value added to water and the necessary conclusions made.

CHAPTER 4
RESULTS

4.1 INTRODUCTION

Chapter 4 is concerned with the results of the study, and consists of two sections. In the first section, the volumetric water footprint of wheat, flour, and bread along the wheat-bread value chain is reported. This is accomplished by first calculating the green and blue water footprints for each product throughout the value chain. Once completed, the total water footprint of bread along the wheat-bread value chain was established. The second section is the EWP, where the value added to water in each production stage as the product moves along the value chain was determined. This chapter is concluded with a discussion on the findings, as well as the impact they have on South Africa's freshwater resources.

4.1.1 GREEN AND BLUE WATER FOOTPRINTS OF WHEAT PRODUCTION

Due to similar climatic condition (i.e. Evapotranspiration) Table 4.1 is a summary of wheat production estimates recorded at the Vaalharts Irrigation Scheme. Wheat yield per hectare was found to be 9 010 kg. The cumulative ET was 869 mm, the effective rainfall 183 mm, surface water 286.33 mm, and groundwater 423.67 mm. Most often, water footprints are expressed in terms of water per unit of production and therefore it is sensible to express the blue water footprint in terms of cubic metres per tonne of output. In order to convert the water footprint into a spatio-temporal dimension, ET was converted to cubic metres per hectare, which is an indication of the blue crop water use (CWU_{blue}). The blue CWU must thus be divided by the yield expressed in tonnes per hectare to obtain the blue water footprint.

Similar to the blue water footprint, the same method employed by Aldaya and Hoekstra (2010) was used to calculate the green water footprint of wheat. Table 4.2 provides the water utilisation in wheat production. The effective rainfall (R) is ET_{green}. The blue water used was classified according to its source. Blue water used from the surface ($ET_{blue}S$) was 286.33 mm and the blue water from the ground ($-ET_{blue}G$) was 423.67 mm. CWU_{green} and CWU_{blue} were obtained by multiplying the relevant ET by 1 000. For example, (183 × 1 000) = 1 830, which is CWU_{green} for all the treatments. The CWU_{blue} was 6 860 $m^3.ha^{-1}$. This implies that the blue water utilised is substantially higher than the green water used.

The green water footprint WF_{green} of producing wheat is therefore 203.12 $m^3.tonne^{-1}$, which this is achieved by dividing CWU_{green} by the yield in ($m^3.ha^{-1}$). The total blue water footprint was estimated to be 788.01 $m^3.tonne^{-1}$.

Table 4.1: Summary of wheat data at the measuring points: Vaalharts Irrigation Scheme

CROP	**YIELD** *($kg.ha^{-1}$)*	**DM** *($kg.ha^{-1}$)*	**TOTAL BIOMASS** *($kg.ha^{-1}$)*	**CUM. ET** *(mm)*	**R** *(mm)*	**WUE** *(mm)*	**I+R** *(mm)*	**I** *(mm)*	**WT** *(mm)*
wheat	9 010	13 995	23 005	869	183	10.4	469.33	286.33	423.67

Source: Ehlers *et al.* (2003)

Table 4.2: Wheat water utilisation at Vaalharts Irrigation Scheme

CROP	**ET crop** *(mm)*	**ET green** *(mm)*	**ET Blue surface** *(mm)*	**ET Blue ground** *(mm)*	**CWU** *(m^3)*	**CWU** green *($m^3.ha^{-1}$)*	**CWU blue** *($m^3.ha^{-1}$)*
wheat	869	183	286.33	423.67	8 690	1 830	6 860

Source: Ehlers *et al.* (2003)

Table 4.3: Blue and green water footprints of wheat: Vaalharts Irrigation Scheme

Yield *($tonne.ha^{-1}$)*	**WF green** *($m^3.tonne^{-1}$)*	**WF_{blue} surface** *($m^3.tonne^{-1}$)*	**WF_{blue} ground** *($m^3.tonne^{-1}$)*	**Total WF** *$m^3.tonne^{-1}$)*
9.01	203.12	317.79	470.22	991.12

Source: Own calculations

Therefore the total water footprint of wheat, WF_{wheat}, is given as follows:

$$WF_{wheat} = WF_{wheat,blue} + WF_{wheat,green}$$

$$WF_{prod} = WF_{blue(surface+ground)} + WF_{,green}$$

$$WF_{wheat} = 788.01 + 203.12$$

$$WF_{wheat} = 991.12\, m^3.ton^{-1} \qquad volume/tonne \tag{29}$$

The total water footprint of wheat is calculated as 991.12 $m^{-3}.tonne^{-1}$, as indicated in Table 4.3. The blue water footprint accounts for the largest portion of the total water footprint. It is worth noting that the blue water utilised from the ground is higher than the blue water utilised from the surface. These results indicate that water tables, caused by over-irrigation over the years, are capable of contributing almost 50% of a crop's ET. This is achieved by under-irrigating the crop and also maximising the use of rainwater. Mekonnen and Hoekstra (2010) estimated the global water footprint of wheat, and concluded that the global average WF_{wheat} is 1 623 $m^3.tonne^{-1}$ (1 277 $m^3.tonne^{-1}$ green and 344 $m^3.tonne^{-1}$); of this total, blue water accounts for 50% of the total water used in irrigated wheat. Comparing this result to that of Mekonnen and Hoekstra (2010), it is evident that the water footprint of wheat in the Vaalharts Irrigation Scheme in South Africa is lower than the world average.

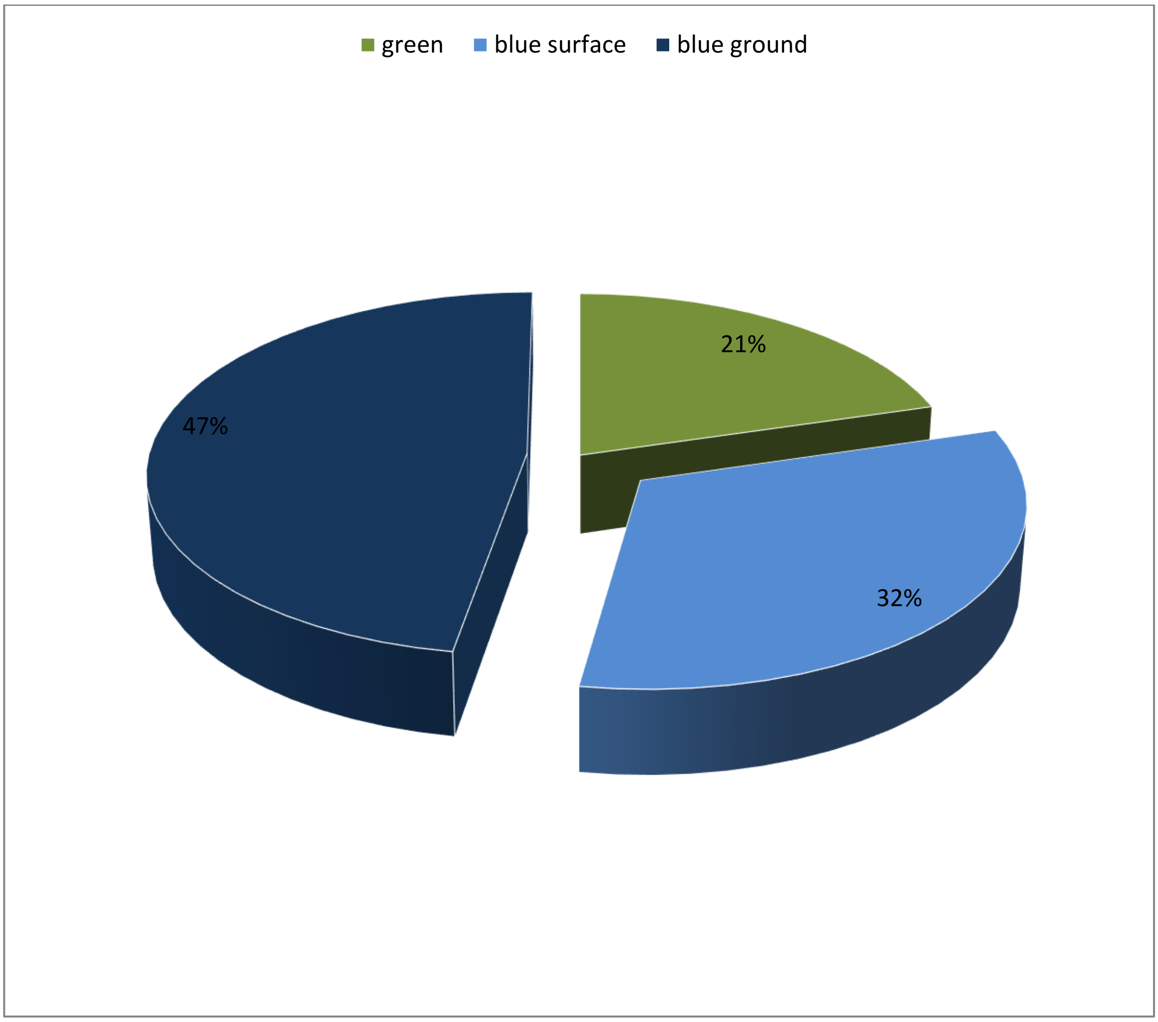


Figure 4.1: Proportional distribution of blue and green water footprints of wheat
Source: Own calculations

Figure 4.1 indicates the total water footprint of wheat in the Vaalharts region. Blue water contributes 79% of the footprint (29% higher than the world average). Although 47% of this contribution is from water tables, it does not dispute the high use of ground and surface water resources. The green water footprint accounts for 21% of total water use this could be due to low rainfall in this region.

4.1.2 Water footprint of the processors

Data used in this study were obtained from a leading mill and bakery in South Africa, which have an excellent recordkeeping system. The data are of a single production year. Table 4.4 presents the water use at the processing stage of the wheat-bread value chain, which represents a combination of both brown and white bread.

Table 4.4: Water use at the processing stage of the wheat-bread value chain (mill and bakery)

Parameter	Unit	Quantity
Milling stage		
Quantity of wheat	Tonne	767 545
Volume of water used	m^3	46 053
Quantity of flour	Tonne	632 348
Water footprint	$m^3.tonne^{-1}$	0.073
Bakery stage		
Quantity of bread produced	Tonne	379 803.33
Volume of water used	m^3	174 452
Water footprint	$m^3.tonne^{-1}$	0.459
Total water footprint processing	$m^3.tonne^{-1}$	0.532

Source: Own calculations

A total of 767 545 tonnes of wheat was milled in the processing plant. A tonne of wheat had an extraction rate of 82%. This resulted in 632 348 tonnes of flour. This rate is higher than that reported by Aldaya and Hoekstra (2011) for Italy, Hoekstra and Mekonnen's (2011) global average, Neubauer's (2012) 76% for Hungary, and Sundberg's (2012) 76.7% Sweden (the latter did not differentiate between white and brown bread). This extraction rate is similar to the findings of the NAMC (2009) for the flour extraction rate from wheat at a national level. Water use amounted to 46 053 m^3 per annum. This volume includes the total water used in processing and cleaning. The water footprint of a product or process is expressed as the volume of water used in the product divided by the product yield (Hoekstra et al., 2011). To obtain the water footprint of flour, the total annual water used in the mill for flour is divided by the annual flour production

(46 053 m^3 ÷ 63 234 tonnes) = 0.073 $m^3.tonne^{-1}$. When looking at bread production, 249 217 tonnes of flour are used in 15 bakeries per year (which is less than 40% of the total flour milled); the rest of the flour is sold to other bakeries and end consumers. About 552 039 728 loaves of bread are produced by this processer each year, which includes both 600 g and 700 g loaves, with a weighted average of 688 g per loaf. By multiplying the loaves with the weighted average and dividing this by a million results in 379 803.33 tonnes of bread produced per year. Similar to flour, the total annual water use in the bakery for the purpose of making bread was divided by the annual bread production (174 452 m^3 ÷ 379 803.33 tonnes) = 0.459 $m^3.tonne^{-1}$. The total water footprint of the processing stage is given by (0.073 + 0.459) = 0.532 $m^3.tonne^{-1}$. Approximately 1% of the mentioned water is used for other purposes and end up in the municipality's waste water systems.

Table 4.5: Summary of the water footprint of bread along the wheat-bread value chain in South Africa

Parameter	**Green water**	**Blue water**	**Total**
Volume of water used (m^3)	1830	6860	8690
Yield ($tonne$)	9.0	9.0	
WF ($m^3.tonne^{-1}$)	203.12	788.01	991.12
Volume of water used (m^3)	0	46053	46053
Quantity of flour produced ($tonne$)	632348	632348	632348
WF of flour	0	0.0728	0.0728
Volume of water used (m^3)	0	174452	174452
Quantity of bread produced ($tonne$)	379803.33	379803.33	3798033.33
WF of bread ($m^3.tonne^{-1}$)	0	0.459	0.459
Total WF of bread ($m^3.tonne^{-1}$)	190.62	745.39	991.84

Source: Own calculations

Table 4.5 gives a clearer view of the green and blue water used at each production node, as well as the total water used. Blue water had the highest contribution to the value chain, with 227 660.81 m^3 (99.2%), while green water contributed 1 830 m^3 (0.80%). This makes blue water resources a crucial role player in the wheat-bread value chain. The total volume of water used throughout this value chain in cubic metres is given by (8 960 + 46 053 + 174 452) = 229 490.81 m^3. The contribution to the total volume of water used in ascending order is as follows: crop production (3.9%), milling (20.1%), and baking (76.02%). If the analysis is interpreted at this point, it seems as if the most water is used at the last node of this value chain, which is not true. Therefore, water use cannot be expressed on its own but with the respective yields of that production. By doing so, the water footprint of the respective processes and the effect they have on water resources are obtained.

Therefore, the water footprint of bread along the wheat-bread value chain is calculated as follows:

$$WF_{bread} = WF_{wheat} + WF_{flour,mill} + WF_{bread,bakery}$$

$$WF_{bread} = 991.12\, m^3.tonne^{-1} + 0.073\, m^3.tonne^{-1} + 0.459\, m^3.tonne^{-1}$$

$$WF_{bread} = 991.84\, m^3.tonne^{-1} \qquad [volume/tonne] \tag{30}$$

According to Table 4.5, the water footprint of bread along the wheat-bread value chain was 991.84 $m^3.tonne^{-1}$; of this 991.12 $m^3.tonne^{-1}$ was wheat and 0.532 $m^3.tonne^{-1}$ processing, which is in accordance with the findings of Sundberg (2012). The crop production level contributes 99.95% to the water footprint of bread along the respective value chain, while processing (mill and bakery) contributes only 0.532%. Hoekstra and Mekonnen (2011) compiled the water footprint benchmark for wheat and derived wheat products and used the water footprint of wheat as a basis to calculate the water footprint of derived wheat products, based on a product and value fraction of 79% and 80% respectively for flour. They also concluded that 1 kg of flour was equal to 1.15 kg of bread. The water footprint of wheat was given as 1 830 $m^3.tonne^{-1}$, the water footprint of wheat flour is 1 639$m^3.tonne^{-1}$ (1 292 $m^3.tonne^{-1}$ green and 347 $m^3.tonne^{-1}$ blue), while that of bread is given as 1 425 $m^3.tonne^{-1}$ (1 124 $m^3.tonne^{-1}$ green and 301 $m^3.tonne^{-1}$ blue) (Hoekstra and Mekonnen, 2011). It is important to note that the authors' assessment was of a single product and not along the wheat-bread value chain.

4.2 ECONOMIC WATER PRODUCTIVITY

The economic contribution of water is expressed in terms of EWP. This process consists of three steps:

1. Calculating physical water productivity;
2. Calculating value added; and
3. Calculating EWP.

Table 4.6 represents the physical water productivity of wheat, flour, and bread along the wheat-bread value chain. Physical water productivity is usually expressed in kg/m^3. The yield for the products was multiplied by 1 000 to change it from tonnes to kilogram. Table 4.6 indicates that wheat (grain) has the highest water productivity at 1.037 kg/m^3, followed by bread with 0.022 kg/m^3. Flour has the lowest water productivity of 0.014 kg/m^3.

Table 4.6: Physical water productivity of wheat, flour, and bread along the wheat-bread value chain

Parameters	Wheat	Flour	Bread
Physical water productivity			
Yield	9.010	632 348 tonnes	379 803.33 tonnes
Total water use	8690 m^3.ha^{-1}	46 053 m^3	17 447 m^3
Physical water productivity	1.037	0.014	0.022

Source: Own calculations

The second step in determining the EWP is calculating the value added to water at each stage of production. For wheat, the gross production value (in ZAR.ha^{-1}) divided by the yield (tonne.ha^{-1}) is taken as the value added to water. This value is given as 4 001.55ZAR.tonne^{-1}. Value added is usually expressed in ZAR/kg. This means that the value added to wheat is therefore given as 4.0ZAR.kg^{-1}. In the case of flour, no direct cost of buying was found. The selling price is taken as the value added, and this value is given as 5 700ZAR.tonne^{-1}. Converted to ZAR.kg^{-1}, this is amount is given as 5.7ZAR.kg^{-1} and taken as the value added at this production stage.

As for bread, the value added was calculated using equation (27) and (28) in Section 3.2.

The cost of bread is 6.56ZAR.kg^{-1} and the selling price is given as 8.29ZAR.kg^{-1}. By deducting the purchase from the selling price, value added is 1.73ZAR.kg^{-1}.

Table 4.7 illustrates the calculation of the EWP of wheat, flour, and bread along the wheat-bread value chain.

Table 4.7: The economic water productivity of wheat, flour and bread along the wheat-bread value chain

Parameters	Wheat	Flour	Bread
Economic water productivity			
Physical water productivity	1.037 kg.m^3	0.014 kg.m^3	0.022 kg.m^3
Value added	4.0ZAR.kg^{-1}	5.7ZAR.kg^{-1}	1.73ZAR.kg^{-1}
EWP	4.18ZAR.m^3	0.079ZAR.m^3	0.038ZAR.m^3

Average exchange rate for December 2016: US$1; 14.62ZAR

Source: Own calculations

Table 4.7 indicates that wheat has the highest EWP of 4.18ZAR.m^3, followed by flour and bread at 0.079ZAR.m^3 and 0.038ZAR.m^3 respectively.

Table 4.8: Summary of the value added to water for bread production along the wheat-bread value chain

Production nodes	Value added	Units
Farm level		
Wheat	4.0	ZAR/kg
Processing level		
Mill$_{\mathbf{Flour}}$ and **Bakery$_{\mathbf{bread}}$**	7.43	ZAR/kg
Total value added	11.43	ZAR/kg
Water footprint of bread along the value chain is given as $\mathbf{991.84\ m^3.tonne^{-1}}$ Therefore WF_{bread} = 0.99184 m^3/kg		
Production nodes	**Value added to water at each production node**	**Units**
Farm level		
Wheat	4.0	ZAR/m^3
Production level		
Mill$_{\mathbf{Flour}}$ and **Bakery$_{\mathbf{bread}}$**	7.49	ZAR/m^3
Total value added to water along the wheat-bread value chain	11.52	ZAR/m^3

Average exchange rate for December 2016: US$1; 14.62ZAR

Source: Own calculations

Table 4.8 is a summary of the value added at the different stages of production divided by the respective total water footprints at each stage. Table 4.8 indicates that the total value added by the water footprint of bread along the wheat-bread value chain is 11.52ZAR/m^3. The water footprint of wheat therefore has the lowest value added to water along the wheat-bread value chain.

4.3 DISCUSSION

The water footprint of wheat in the Vaalharts region was estimated at 991.12 m^3.tonne^{-1}. This value is about 61% lower than the world average of 1 622 m^3.tonne^{-1}(1 279 m. m^3.tonne^{-1} green water footprint and 343 m^3.tonne^{-1} blue water footprint). According to Hoekstra and Mekonnen (2010a; 2010b), the water footprint is largely determined by overall yields. The low footprint could be due to high yields attained by wheat producers in the Vaalharts region of 9.0 m^3.tonne^{-1}. This indicates that South African wheat producers are effective in production processes. Blue water accounts for 80% of the water footprint found in this study. Globally, blue water used in irrigated wheat contributes 50% of the footprint, which raises a red flag of possible overexploitation of ground and surface water resources in the Vaalharts region. Given the current blue water scarcity in South Africa, the high blue water usage should be a major concern for water users along the wheat value chain.

The South African wheat-to-flour extraction rate is higher than that of Italy, Hungary, and Sweden. This means that wheat loss in South Africa (in the process of converting wheat to flour) is closer to the mill fraction of flour (88%) stipulated by the FAO (Aldaya and Hoekstra, 2010). This could result in less wheat used in the mill to achieve the same yields. Wheat is accountable for 99.95% of the water footprint of bread along the wheat-bread value chain, while processing is only accountable for 0.56%. This highlights the importance of not just effective but also efficient water use in the production stages of crops. The water used at the farm level has the highest impact on sustainability, efficiency, and effectiveness of water used for the entire value chain. Processors should therefore be aware of the water footprint of their raw materials because this volume accounts for more than 99% of the water footprint of the products they produce. The water footprint of bread is 58% lower than the global average. When only considering the volumetric water footprint, this means that bread is produced with effective and efficient use of freshwater resources in South Africa.

When looking at water productivities, about 97% of the EWP of the wheat-bread value chain is from wheat, while only 0.117ZAR.m^3 is from the processing stage. However, when looking at the value added to water by bread along the wheat-bread value chain, the water footprint of wheat adds the lowest value to the value chain (35%), while the water footprint of the processors adds 75% value to the value chain (7.49ZAR.m^3)

Incorporation of the water footprint of bread production inputs such as yeast, sugar, salt, and eggs would give a more holistic assessment and would potentially increase the water footprint of bread along this value chain, as well as value added at the processing stage. Grey water footprint was not considered in this study.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1. BACKGROUND AND MOTIVATION

South Africa’s available freshwater resources are scarce and limited (Mukheibir, 2005), and irrigated agriculture accounts for the largest proportion (40% to 60%) of freshwater use (DWA, 2012). Meanwhile, agriculture has the lowest direct contribution (3%) to the country’s GDP (WWF, 2013). Coupled with climate change, uneven distribution of rainfall, and a 1.58% annual population growth, South Africa’s irrigated agriculture requires diverse and innovative management strategies for effective and efficient water use to ensure sustainable food production.

When looking at indirect economic impact (the multiplier effect), it is clear that agriculture is at the pivot of South Africa’s rural and economic development (Tergenna, 2010). An increase in demand for agricultural goods causes a R2.14 million increase to the economy through co-ops, agri-processors, distributors, and agricultural trade; not to mention the number of jobs spread throughout these linkages (Tergenna, 2010; Geyling, 2015). Similarly, an increase in demand for these goods means an increase in demand for freshwater resources, which has an impact on the entire industry.

Globally, wheat is grown on more land area than any other commercial crop, making it one of the most widely cultivated cereal grains (Mekonnen and Hoekstra, 2010). Wheat also accounts for the largest proportion of global agricultural consumption at 15% (Hoekstra and Mekonnen, 2010a; 2010b). Wheat is the second largest cereal crop produced in South Africa (Purchase *et al.*, 2000; DAFF, 2015). It is spread over approximately 460 000 ha and has a production level of between 1.4 to 2 million tonnes, while consumption is estimated at about 3.1 million tonnes per annum (DAFF, 2015). It is estimated that South Africans consume about 64 loaves of bread per person per annum, and approximately 60% of wheat flour is used to produce bread (DAFF, 2012). Therefore, the milling industry, which produces wheat flour, bran, and wheat meal, make up a total capital investment of about R3 billion in South Africa. The milling and baking industry and the retail sector are the main role players in the wheat-bread value chain.

Water footprint assessment is a relatively new concept that is globally recognised as an indicator of consumptive water use of a process step, product, business, and geographical area (Aldaya and Hoekstra, 2010). The GWFS approach by Hoekstra *et al.* (2011) offers a clear distinction between blue (ground and surface water consumed and evapotranspired and incorporated into a product), green (rainwater that is consumed, evapotranspired, and incorporated into a product), and grey (volume of water required to clean polluted water and return it to its original form) water footprints. The GWFS approach considers sustainable (environmental), efficient (economic), and equitable (social) water use to be the three pillars of wise freshwater allocation, which is a more holistic approach to WFAs (Hoekstra, 2014).

Performing a WFA of bread along the wheat-bread value chain is valuable in South Africa due to the fact that it not only compares volumetric water use to global benchmarks, but also economic valuation of water along value chains. This allows one to identify large water users along the value chain and to determine if consumption of bread as well as the price thereof reflects the pressure this product has on the already scarce water resources.

5.2 PROBLEM STATEMENT AND OBJECTIVES

Water footprint assessment is globally recognised for quantifying the volume of water required to produce a product, as well as to formulate a sustainability assessment of the product along its value chain. For this reason, many researchers have used this approach to compare and evaluate the sustainability of domestic and imported wheat, flour, and bread consumption, in order to develop better policies for freshwater use in a number of countries. Even so, much of the focus was on the volumetric footprint of the product as well as the environmental impact assessment of water, and not on the economic valuation of freshwater use.

Water footprint assessment is relatively new in South Africa, with only a few applications, and is seldom used to inform policy makers on sustainable water use behaviour, as well as farmers who are largely dependent on irrigation for crop production. In light of the economic contribution of bread along the wheat-bread value chain discussed in this study, South Africa stands to benefit from adopting the WFA approach to ensure sustainable water use, as well as to know the value added to water along the different nodes of production in order to inform policy makers and ensure wise water use behaviour in the wheat industry.

The main objective of this study was to explore the water footprint of irrigated wheat and derived wheat products in South Africa, in order to promote and ensure the sustainable use of freshwater resources in the South African wheat industry. This was also done in order to demonstrate how WFAs can be used to address sustainable economic as well as social concerns of water allocation along the wheat-bread value chain, and thereby informing water management and policy makers to identify appropriate strategies and sustainability targets. The two sub-objectives used to achieve the main objective were to first determine the volumetric water footprint of irrigated wheat and derived wheat products along the wheat-bread value chain, and secondly to perform an economic valuation of water use expressed in ZAR/m^3 of water along the value chain.

5.3 CONCLUSIONS

5.3.1 WATER FOOTPRINT OF WHEAT GRAIN

Based on the results, it is concluded that the total water footprint of irrigated wheat in the Vaalharts region is 991.12 $m^3.tonne^{-1}$. Of this footprint, groundwater accounts for 470.22 $m^3.tonne^{-1}$, surface water 317.79 $m^3.tonne^{-1}$, and water from effective rainfall 203.12 $m^3.tonne^{-1}$. Water usage in the supply chain of inputs for the production of wheat was not considered in the calculations. Water evaporated during transportation through canals and diversions and in storage in dams and reservoirs in the water footprint of wheat was not considered.

The total water footprint of irrigated wheat in Vaalharts is 61% lower than the global average; which depicts a certain level of efficiency in water use in the Vaalharts region. Approximately 79% of the water footprint of wheat was from absorbed surface and groundwater (irrigated water), which shows a high dependency on surface and groundwater for wheat production in the Vaalharts region. This is higher than the global average blue water footprint for irrigated wheat, which was found to account for only 50% of the total water footprint. According to Hoekstra *et al.* (2011), efficiency and sustainability should be interpreted in the context of water availability and as such the sustainability of the blue water consumption should be taken into consideration. Effective rainfall contributed only 21% of the total water footprint, which leaves room for possible increased usage.

5.3.2 WATER FOOTPRINT AT THE PROCESSING LEVEL (MILL AND BAKERY)

At the processing stage, it is concluded that the total water footprint of the processor is 0.53 m^3.$tonne^{-1}$. Of this footprint, wheat milling accounts for 0.073 m^3.$tonne^{-1}$, and the bakery accounts for 0.459 m^3.$tonne^{-1}$. This implies that 86% of the total water footprint in the processing stage of bread along the wheat-bread value chain is from the bakery and only 14% is from the mill process.

Given the total water footprint of bread along the wheat-bread value chain of 991.12 m^3.$tonne^{-1}$, it is concluded that 99.95% of the water footprint of bread along the wheat-bread value chain is from primary input (wheat production), while processing is only accountable for 0.056%. The water footprint of bread is 59% lower than the global average of bread. This shows a certain level of efficiency in the volumetric context of water usage. The findings show that the water footprint of wheat grain has a big impact on the overall water footprint of bread, which means that the blue water footprint is a major contributor of the water footprint of bread produced in South Africa.

5.3.3 ECONOMIC CONTRIBUTION OF WATER

The farm level accounts for 97% of the EWP along the wheat-bread value chain. Therefore, more income is generated per cubic metre of water used from wheat than any other product along the wheat-bread value chain. Given that 99.95% of the water footprint of bread along the wheat-bread value chain is from wheat, its easer to accept the results of the EWP of this value chain. Value added to water encompasses the value added to the product throughout its value chain (in monetary terms) multiplied by the water footprint of the product at different nodes of production throughout the product value chain. Total value added to water from the WFA of the wheat-bread value chain is 11.43ZAR /kg. About 65% of this value is from the processing level and only 35% is from the farm level. This means higher income is received per cubic metre of water used in the processing level of the wheat-bread value chain. This result is similar to the value added per cubic metre of water footprint of bread along the wheat-bread value chain.

Despite the fact that the water footprint of wheat along the wheat-bread value chain contributes 99.95% to the overall footprint in this value chain, the income received per cubic metre of water footprint used for wheat along this value chain is only 35% (4.0ZAR.m^3) of value added to the value chain.

Bread is an integral part of the South African diet, therefore the value added to water from wheat within the wheat-bread value chain does not reflect the importance of investing this resource in wheat production, which is also the most important part of the value chain in terms of the WFA. Therefore more attention has to be paid to increasing the value of water for wheat, as well as decreasing the water footprint of wheat by increasing yields.

5.4 RECOMMENDATIONS

5.4.1 RECOMMENDATIONS FOR WATER USERS

Wheat farmers in the Vaalharts region are efficient with water used in their production. This is shown by the low water footprint as compared to the global average. The low water footprint can be attributed to high wheat yields. It is therefore recommended that wheat farmers should adopt farm management practices that improve yields per hectare. For instance, wheat farmers should adopt high-yielding wheat cultivars, improve soil fertility, etc.

The higher utilisation of surface and groundwater in wheat production has negative implications for sustainability. In periods of drought or forced reallocation of freshwater resources to other sectors of the economy, wheat production in the Vaalharts irrigation scheme can potentially come to an abrupt stop due to the high dependency of the wheat industry on surface and groundwater. It is recommended that increased attempts should be made by farmers to maximise the use of green water in order to combat the negative externalities of blue water resources. Farmers can optimise rainfall by adopting rainwater-harvesting technologies.

Bread producers in South Africa are efficient in terms of water use. This is shown by the low water footprint compared to global averages. The study recommends that bread processors and bakers should adopt production practices that would further decrease their use of water by recycling water used in the processing stages. At the processing level, millers should strive to attain a higher wheat-to-flour conversion ratio and reduce wastage.

Any measures to increase or decrease efficiency in how water resources are employed at farm level have a 95.95% impact on the water footprint of bread along the wheat-bread value chain. It is recommended that stakeholders along the wheat-bread value chain should insist water footprint benchmarks to ascertain wheat suppliers who are water efficient. Stakeholders should require WFA information from wheat farmers as this water footprint largely determines the water footprint of their products.

A higher income is received, per cubic metre of water, from the use of wheat along the wheat-bread value chain. Therefore, ensuring sustainable water use behaviour for wheat production would have a strong economic contribution to stakeholders along the wheat-bread value chain.

In terms of value added to the water along the wheat-bread value chain, there is high economic impact per cubic metre of water used from processors and wholesalers.

Value added to water at the processing stage of the wheat-bread value chain should be increased in order to increase the economic contributions per cubic metre of water used.

5.4.2 RECOMMENDATIONS FOR POLICY MAKERS

Policy makers should better promote and implement guidelines on sustainable water use at farm level. This can be achieved by educating farmers of the current water scarcity situation in South Africa as well as campaigns on efficient water use practices.

Policy makers should set water footprint targets or benchmarks for the production of wheat, flour, and bread, as well as other food products in South Africa in order to help achieve the aim of the National Water Act (Act No 36 of 1998) which seeks to achieve the sustainable use of water for the benefit of all users.

5.4.3 RECOMMENDATIONS FOR FURTHER RESEARCH

Future research should consider blue water sustainability assessment in the Orange River basin in order to determine whether wheat farmers are sustainable in their blue water usage.

Further research should also consider the grey water footprint along the wheat-bread value chain, in order to better inform farmers and policy makers of the national grey water footprint of bread along the wheat-bread value chain.

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APPENDIX

Appendix A: Prepared questionnaire to acquire necessary data in order to perform a WFA at the processing stage of the wheat-bread value chain

Miller	
Volume (m^3/tonne) of water used per month/year?	
Volume of wheat milled per month/year?	
Volume (tonnes) of flour delivered per year?	
Volume of by-products ➢ Specify by products (tonne/year)	

Bakery	
Volume (m^3/tonne) of water used in bakery?	
Volume (tonnes) of flour used per year?	
Volume (tonnes) of bread produced per year?	
Selling price of bread (R/bread)?4	