WATER FOOTPRINT AND ECONOMIC WATER PRODUCTIVITY OF CITRUS PRODUCTION: A COMPARISON ACROSS THREE RIVER VALLEYS IN THE EASTERN CAPE MIDLANDS

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ABSTRACT

South Africa is a semi-arid, water scarce country. The nation has suffered a spate of severe droughts in several regions in recent years, which have significantly impacted the country's economy. Global warming, population growth, and rising demand for water intensive products are only expected to intensify water supply problems in the future. The agricultural industry is the largest consumer of water in South Africa, accounting for the majority of total surface water withdrawals. As such, the agricultural sector is faced with complex and difficult management decisions in the face of a potential water supply crisis.

The water footprint (WF) and economic water productivity (EWP) of citrus production across three river catchments located in the Eastern Cape Midlands (situated in the vicinity of the settlements of Adelaide, Cookhouse and Fort Beaufort respectively) were calculated and compared. In the long-term average (LTA), blue WF weighted across all three regions accounted for the greatest proportion of total WF (53%), followed in turn by green and grey WF (30% and 17% respectively). LTA blue and grey WF was lowest in the Adelaide region, while green WF was smallest in the Fort Beaufort region. Blue, green and grey WF were found to be greatest in the Cookhouse region. LTA EWP was greatest in the Fort Beaufort region and smallest in the Adelaide region.

Of all variety groups assessed, lemons were found to have the lowest LTA crop water use and blue, green and grey WF when considering citrus production averaged across all three study regions. Satsumas has the second smallest LTA blue, green and grey WF, followed by navels, mid-season mandarins, and finally, late mandarins. Lemons had the greatest LTA EWP of all varieties, followed in turn by satsumas, late mandarins, mid-season mandarins and navels. Blue crop water use was consistently lowest in the designated wet year and highest in the dry year. However, this same trend was not necessarily true for WF findings.

WF and EWP are useful indicators of water use which can be used to help guide complex water management decisions. However, these indicators are single-factor productivity measures applied in a multi-factor environment. It is therefore important that factors outside of water use are considered when making water management decisions. Moreover, it is important to examine the impact that the various components making up WF and EWP have on the resultant figures, rather than merely considering the superficial results themselves. Factors such as CWU, orchard maturity, crop choice, potential yield, climate, irrigation system, economic return, water allocation and water availability should all be taken into account.

Keywords: water footprint, economic water productivity, citrus production, sustainability, economic indicators, water management, water allocations.

DECLARATION

I, Lindsay Alice Diana Danckwerts, hereby declare that this thesis is my own original work, and that it has not been submitted for a degree to any university other than Rhodes University, Grahamstown, South Africa.

Lindsay A.D. Danckwerts
Grahamstown
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LIST OF ABBREVIATIONS

AR	application rate
ARC-ISCW	Agricultural Research Council – Institute for Soil, Climate and Water
CF	carbon footprint
CGA	Citrus Growers Association
COGTA	Ministry of Cooperative Governance and Traditional Affairs
CRI	Citrus Research International
CMA	catchment management agency
c_{max}	maximum acceptable concentration
CMS	catchment management strategy
c_{nat}	natural background concentration
CWU	crop water use
DAFF	Department of Agriculture, Forestry and Fisheries
DEA	Department of Environmental Affairs
DIP	delivered in port
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EC	Eastern Cape
EF	ecological footprint
EIA	Environmental Impact Assessment
ET	evapotranspiration
EWP	economic water productivity

FAO	Food and Agricultural Organization of the United Nations
FC	Field capacity
GDP	gross domestic product
GHG	greenhouse gas
GWP	global warming potential
IIMI	International Irrigation Management Institute
IOA	input-output analysis
ISO	International Organisation for Standardisation
ITC	International Trade Centre
IMF	International Monetary Fund
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LSRV	Lower Sundays River Valley
LTA	long-term average
MAP	mean annual precipitation
NWA	National Water Act
NWRS	National Water Resource Strategy
REW	Readily evaporable water
SA	South Africa
SANBI	South African National Biodiversity Institute
SARB	South African Reserve Bank
SARS	South African Revenue Service
SAWS	South African Weather Service

STATSSA	Statistics South Africa
SFP	single factor productivity
UN	United Nations
UNEP/SETAC	United Nations Environment Programme and the Society of Environmental Toxicology and Chemistry
USD	United States Dollar
WF	water footprint
WFA	water footprint assessment
WFN	Water Footprint Network
WP	water productivity
WRC	Water Research Commission
WMA	water management area
WSI	water stress index
WUA	water user association
WWF	World Wide Fund for Nature
ZAR	South African Rand

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CHAPTER 1
INTRODUCTION

1.1. Context of the Study

South Africa is classified as a water scarce country, experiencing sporadic and unreliable rainfall and a highly variable climate (DEA, 2011; DWS, 2018a). In recent years the country has suffered a spate of severe droughts, and it is expected that climate change will only exacerbate the incidence and intensity of droughts in the future (WRC, 2016a; DWS, 2018a). In 2016 the World Wide Fund for Nature (WWF) reported that South Africa had experienced the loss of "billions of Rands and thousands of jobs over the last year of drought" (WWF-SA, 2016: 2). In early 2018, large areas of the nation were still suffering from drought, with the Western, Eastern and Northern Cape Provinces classified as disaster areas (COGTA, 2018; Macharia, 2018). Agriculture is the largest consumer of water in South Africa, accounting for approximately 55% of total surface water withdrawals (DWS, 2018a). As such, the agricultural sector is faced with tough management decisions in the face of a potential water supply crisis.

From an agricultural standpoint, there are a number of tools that can inform and guide difficult water management decisions. Water productivity (WP) is one such tool. Introduced in the mid-1990s by David Seckler, the then Director General of the International Irrigation Management Institute (IIMI), agricultural WP was developed as an alternative to classical efficiency methods, which failed to account for return flows of irrigation water (Seckler, 1996; Scheierling *et al.*, 2016; Giordano *et al.*, 2017). Although various interpretations and approaches for its calculation exist, WP can simply be described as the amount of output that is produced per unit of water used (Barker *et al.*, 2003). Output can refer to the actual mass of production, or to its gross value – resulting in physical and economic WP respectively (Seckler *et al.*, 2003; Giordano *et al.*, 2017). WP remains a commonly used and popular method in current literature, as seen in articles by Chouchane *et al*. (2015); Grassini *et al.* (2015); Deryng *et al.* (2016); Giordano *et al.* (2017); Kang *et al.* (2017); and Paredes *et al.* (2017).

Another useful tool that can be used to inform decision makers is water footprint (WF). Described as a 'comprehensive indicator of freshwater use' (Hoekstra *et al.,* 2011: 23), the

WF of a product expresses the total volume of freshwater that is consumed in order to produce that product, throughout its entire production process (Hoekstra *et al.,* 2011). Developed by Arjen Hoekstra in the early 2000s (Hoekstra and Hung, 2002; Hoekstra *et al.,* 2011), the concept has achieved growing popularity, and continues to be used within a number of applications (as demonstrated in articles by Pahlow *et al.*, 2015; Munro *et al*., 2016; Zhuo *et al.,* 2016; Harding *et al.,* 2017; Gerbens-Leenes *et al*., 2018; and Marston *et al.,* 2018).

A distinguishing feature of the WF indicator versus many other water management indicators is that WF differentiates between blue, green and grey water consumption (Chapagain & Tickner, 2012). The definitions for blue and green WF are fairly intuitive: blue WF denotes the consumption of ground and surface water, and green WF conveys the consumption of rainwater (not including run off) (Hoekstra *et al.,* 2011). Grey WF signifies pollution and represents the 'volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards' (Hoekstra *et al.,* 2011: 24). Within the framework of crop production, WP is essentially the inverse of WF (in its cumulative blue and green form) – with WP describing the amount of production per unit of total consumptive water use (CWU), and WF describing the total CWU resulting from a certain production process (Amarasinghe & Smakhtin, 2014).

Although these WP and WF indicators are attractive in their simplicity, their major drawback is that they are single-factor productivity (SFP) indices, being applied in a multi-factor environment (Scheierling *et al.,* 2016; Giordano *et al.,* 2017). Rational decision makers at the farm-level have other considerations outside of water. As such, WP and WF provide an incomplete representation of the economic, political and environmental setting that confronts the agricultural sector (Rijsberman 2006; Wichelns 2015a, Wichelns, 2015b; Giordano, *et al*., 2017). Maximising WP is therefore a misplaced strategy – a fitting strategy should rather be to optimise WP (Wichelns, 2015a).

Water policy in South Africa is primarily guided by The National Water Act (NWA) (Act 36 of 1998), the purpose of which is to assure that South Africa's water resources are 'protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner, for the benefit of all persons' (NWA, 1998: 10). The central guiding principles of the act are sustainability, equality and efficiency (DWAF, 1998; DWA, 2013). It should be noted that these principles are potentially dichotomous and contradictory, especially set against the backdrop of water scarcity, competition for resources, budget limitations and the urge for economic growth and development of job creation (Conradie, 2002; Perret, 2002; Hassan & Crafford, 2006; Munro *et al.,* 2016). The National Water Resource Strategy (NWRS) is the instrument used to specify the strategies, goals, procedures and guidelines that need to be undertaken to achieve the objectives of the NWA and is responsible for the institutional arrangements required to achieve the purposes of the act (DWAF, 1998).

As of the 2016/2017 season, the citrus fruit was the second largest horticultural production category in terms of gross value of production, after deciduous and other fruits (DAFF, 2018a). Most of citrus production is exported and as such the industry contributes significantly to foreign exchange earnings within the country (DAFF, 2017a). In fact, in terms of value, citrus industry exports make up the largest proportion of South African agricultural export products (DAFF, 2018a; DAFF, 2018b). Furthermore, the industry employs a significant amount of labour, requiring large work forces in orchards and pack houses, as well as additional personnel for transport and other supply chain needs (DAFF, 2017a). According to their report on the South African citrus market value chain, DAFF estimates that the citrus industry directly provides above 100 000 jobs and supports over one million households (when including employment required for supply chain services) (DAFF, 2017a).

One of the greatest constraints and limiting factors of citrus production is water supply (Varhmeijer *et al.,* 2015). Citrus orchards require reliable and consistent irrigation in order to be effectively productive (Taylor & Gush, 2014; Vahrmeijer *et al.,* 2015). The industry is also limited by the time horizon inherent in citrus production – trees take a minimum of three years to become commercially productive, and their commercial lifespan is generally between 18-30 years (Alexander, 2015), making it difficult for producers to change their crop holdings. Citrus production also requires large capital outlay well in advance of making positive financial returns. As such, citrus production is an unfeasible investment without reliable water supply (Vahrmeijer *et al.,* 2015).

The study area encompasses primary citrus production within the Eastern Cape Midlands, specifically between three river basins – namely the Kat River, Koonap River and Fish River basins. Citrus production within these three river basins takes place under differing water supply schemes. Participant producers in the Fish River valley and upstream of the settlement in the Kat River valley have access to a state scheme water entitlements (commonly referred to as ‘water rights’), while producers assessed in the vicinity of the Koonap River basin and downstream of the settlement in the Kat River valley are registered water users, reliant on state verifications certifying the extent of lawful water utilisation (DWS, 2014).

1.2. Problem Statement

Climate change and the onset of global warming have resulted in access to freshwater becoming increasingly challenging, particularly in already water scarce areas. South Africa is no exception, with a spate of severe droughts experienced in recent years exacerbating water supply challenges throughout the country. Agriculture is the largest consumer of water in South Africa and as such faces increasingly complex water management decisions in the face of a potential supply-side crisis. The citrus industry in South Africa is faced with these same issues. Citrus production is highly water intensive, with access to consistent and reliable water supply posing one of the primary limiting factors to growth and development within the industry. Water footprint and water productivity indicators are two tools which may be used to help inform difficult water management decisions. They provide a valuable starting point from which to assess and compare various strategies for water consumption and allocation, and provide a basis from which to examine the associated incentives for efficient water utilisation.

1.3. Goals of the Research

The goals of this research project can be broken down into two parts:

i. To calculate and compare the water footprint and economic water productivity of primary citrus production over three river catchment areas, namely the Koonap, Kat and Fish River valleys.

ii. To explain reasons for differences in water footprint and economic water productivity across the three valleys, and to determine the implications of these differences in the context of water management.

The overarching aim of the research may then be said to be to identify the most efficient system of citrus production within these three river valleys, in terms of water footprint and economic water productivity respectively, and to identify and analyse the reasons behind these outcomes.

1.4. Research Method

The research undertaken in this project took a positivist approach. In order to calculate the WF and economic WP (EWP) of primary citrus production over the Koonap, Kat and Fish River valleys, various information needed to be collected. Data collection took place by means of interviews with various role players within the local industry, as well as from various secondary sources. Role players included farmers from 10 farms across the three valleys, as well as the local pack house and citrus marketing company. Information about irrigation and water use practices, crop characteristics, chemical applications and operational figures was obtained via these interviews with local role players. Information such as climate statistics, rainfall records and water quality data were obtained from secondary sources.

The WF of each orchard and variety on the subject farms within the three valleys was calculated using the methods outlined in the Water Footprint Assessment Manual, which sets out the global standard for WF assessments (Hoekstra *et al.,* 2011). As shown in the manual, the total WF of growing a crop or tree is the sum of the blue, green and grey WF of that crop or tree. The blue and green WF of growing a crop or tree is calculated as the ratio of blue and green Crop Water Use (CWU) (respectively) to crop yield (measured in tons per hectare) (Hoekstra *et al.,* 2011). Grey WF for growing crops and trees is calculated as the critical load divided by the difference between the maximum acceptable concentration and the natural concentration, then divided by the crop yield (Hoekstra *et al.,* 2011).

CWU is the daily evapotranspiration (ET) accumulation over the full growing cycle of the tree, where evapotranspiration refers jointly to the processes of evaporation and transpiration (Hoekstra *et al.,* 2011). The Water Footprint Assessment Manual suggests the use of the CROPWAT model to measure ET (Hoekstra *et al.,* 2011), a tool developed by the Land and Water Development Division of the FAO (FAO, 2018a). SAPWAT3 is a similar tool, developed by the Water Research Commission specifically for application in South Africa (Van Heerden, 2015). The newly introduced SAPWAT4 is an updated, improved version of SAPWAT3 (van

Heerden & Walker, 2016; van Heerden, 2017), and was used in this research project in order to calculate ET and crop water requirements. Like CROPWAT, SAPWAT4 is based on the methods put forward in the FAO Irrigation and Drainage Paper 56 by Allen *et al.* (1998).

After calculation of the WF, the EWP of citrus across the three river valleys was calculated. EWP is calculated by dividing the gross value of output by CWU (Giordano *et al.,* 2017; Amarasinghe & Smakhtin, 2014). CWU had already been estimated for the purposes of WF accounting, and the information required to calculate the gross value of output was collected from the local citrus marketing company used by farmers from the three valleys. The total WF, as well as its blue, green and grey components was then compared within and across the three river valleys. EWP was also compared within and across the river valleys, and then analysed in comparison to the WF in each valley.

1.5. Outline of the Thesis

This chapter provides an introduction to this research project, presenting a brief overview of the context, objectives and methods utilised. In Chapter 2, the literature relating to the concepts of WF, WP and EWP are discussed. The background to South Africa's agricultural sector and citrus industry are described in Chapter 3, along with an overview of the study area and a summary of the legislation surrounding water resources and management. A detailed description of the methods utilised in this research is provided in Chapter 4, while the results obtained are presented and discussed in Chapter 5. Finally, Chapter 6 lays out conclusions and recommendations drawn from this research, as well as opportunities for further research.

CHAPTER 2
LITERATURE REVIEW

2.1. Introduction

With the advent of global warming, water scarcity is expected to increase across the globe, effecting areas previously unimpacted by water supply concerns, and escalating the degree of scarcity in already water-stressed regions (Hoekstra and Mekonnen, 2011; Damania *et al*., 2017). Coupled with these supply-side concerns, demand for water is expected to increase in line with rising population levels and growing demand for water intensive products (Mekonnen and Hoekstra, 2012; Hoekstra and Wiedmann, 2014; Damania *et al*., 2017; Marston *et al*., 2018). Water is a valuable input in industry and production, as well as a basic human right. Water resources (particularly blue water resources) have associated opportunity costs, and choices need to be made for its allocation in order to optimise economic, social and ecological consumption levels (Chapagain and Tickner, 2012; Amarasinghe and Smakhtin, 2014; Wichelns, 2015a).

Water footprint and water productivity are two broad approaches which can be utilised to help guide water management strategies. This chapter comprises a review of the literature surrounding these concepts. First, the background and development of the water footprint concept is described, followed by a breakdown of the conceptual framework and a summary of case studies which have utilised the concept. This is followed by a description of the development, conceptual framework and application of the water productivity concept.

2.2 Background and Development of the WF Concept

The WF concept builds on previous developments introduced with the aim of assessing the environmental impact of humanity and its various associated activities and processes (Hoekstra, 2009). These developments include life cycle assessments, ecological footprint, as well as other members of the 'footprint family' (Hoekstra, 2009; Reddy *et al.*, 2014). Although there are similarities between WF and these previously introduced concepts, differences exist both in methodological approaches and applicability (Fang *et al.*, 2016). Sub-sections 2.2.1 to

2.2.3 describe these concepts and their contribution to the development of WF, while section 2.2.4 provides an overview of the WF concept itself.

2.2.1 Life Cycle Assessments

Life cycle assessments (LCAs) first emerged in the late 1960's and early 1970's as a method to analyse the environmental impact of a process or product throughout the entire supply chain – or 'life-cycle' – of that product or process (Hunt and Franklin, 1996; Berger and Finkbeiner, 2010; Kounina *et al.*, 2013). The establishment of the framework was set against the backdrop of mounting uncertainty concerning the sustainability of material and energy resource requirements for production or service processes (Guinée *et al.*, 2011; Reddy *et al.*, 2014). A pioneer of the comprehensive 'cradle-to-grave' approach, LCAs forged the way for water footprints, and in fact all footprint indices.

LCAs became a popular tool used by companies for analysing the impact of industrial processes. In 1969, a study done for Coca-Cola which paved the way for future LCAs to examine the environmental effect of the production of different types of beverage containers, accounting for the impact of the use of the various necessitated resources (Hunt and Franklin, 1996; Guinée *et al.*, 2011). Following this, the approach gained increasingly widespread recognition, and was termed 'Resource and Environmental Profile Analysis' (REPA) in the USA and 'Ecobalance' in Europe (Hunt and Franklin, 1996; Guinée *et al.*, 2011; Reddy *et al.*, 2014). In the early 1990s, an international standard for LCA methodologies was established, incorporated in the International Standards Organisation (ISO) 14000 series, ensuring that the various promotional assertions made by companies would be founded on uniform and consistent calculation methods (Klöpffer, 1997; Guinée *et al.*, 2011; Reddy *et al.*, 2014; Pfister *et al.*, 2017). The specific standards governing LCA "principles and framework" and "requirements and guidelines" are ISO 14040 and 14044 respectively[1] (Guinée *et al.*, 2011; ISO, 2006 a, b; Pfister *et al.*, 2017).

Originally, LCAs did not include the assessment of water inputs used throughout production or process life-cycles (Reddy *et al.*, 2014; Berger and Finkbeiner, 2010). However, within the

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[1] These ISO standards were initially published in the 1990s, with their most recent update taking place in 2006 (Guinée *et al.*, 2011; Pfister *et al.*, 2017).

last decade the integration and assessment of the environmental impacts of water consumption within the LCA framework has been the subject of much interest and attention (Pfister *et al.*, 2009; Berger and Finkbeiner, 2010; Ridoutt and Pfister, 2010; Kounina *et al.*, 2013; Hellweg and Milà i Canals, 2014; Boulay *et al.*, 2015; Verones *et al.*, 2017; Boulay *et al.*, 2018). In 2014, ISO 14046 was published, specifying the standards for water footprint assessments using LCAs (ISO, 2014). Recently, Boulay *et al.* (2018) published a consensus-based method for water scarcity footprint calculation consistent with ISO 14046, which evaluates the potential depravation of water consumers[2].

While LCAs are not expressed as footprints, they have played a significant role in the development of the concept. Their 'cradle-to-grave' approach, which comprehensively accounts for environmental impacts throughout the production or service process, establishes LCAs as a clear precursor to water footprints.

2.2.2 The "Footprint Family"

Water footprint is part of a suite of indicators commonly referred to as the "footprint family", which describe the impact that humanity has on various aspects of the environment (Galli *et al.*, 2012; Fang *et al.*, 2014, Hoekstra and Wiedmann, 2014). Introduced in the early 1990s, ecological footprint is the original member of the footprint family (Wackernagel and Rees, 1998; Fang *et al.*, 2014), and a number of complementary footprint indicators soon followed (Fang *et al.*, 2014; Fang *et al.*, 2016). These include, but are not limited to the water footprint, the carbon footprint, the energy footprint, the material footprint, the nitrogen footprint and the biodiversity footprint (Čuček *et al.*, 2012; Hoekstra and Wiedmann, 2014; Fang *et al.*, 2014).

Unfortunately, there is no universal footprint, since the different applications and methods associated with various footprint indicators diverge substantially (Fang *et al.*, 2016). No individual indicator can wholly encompass the environmental impact of humanity, and, as such, various footprint indicators need to be viewed in conjunction to obtain a complete picture (Galli *et al.*, 2012; Hoekstra and Wiedmann, 2014). Fang *et al.* (2016) demonstrated the diversity and complexity that embodies the footprint family by conducting a bi-word

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[2] Water consumers refer both to human and ecosystem users (Boulay *et al.*, 2018).

bibliometric analysis of literature containing the word “footprint”. Ecological footprint, carbon footprint, water footprint and LCA were found to be most prevalent keywords linked to “footprint” in the literature (Fang *et al.*, 2016).

The ‘ecological footprint’ (EF) was the first member of the footprint family to be developed (Hoekstra, 2009; Kitzes *et al.*, 2009; Reddy *et al.*, 2014; Fang *et al.*, 2016). The concept arose against the backdrop of various efforts to estimate the carrying capacity of the planet for humankind (Wackernagel and Rees, 1998; Fang *et al.*, 2013). However, in contrast to classic carrying capacity theory (which quantifies the population that may conceivably be sustained by a specified amount of resources (Wackernagel and Rees, 1998; Fang *et al.*, 2013)), ecological footprint represents the volume of resources that need to be appropriated for a specified human pursuit. Initially expressed as ‘the amount of ecologically productive land and water required to supply a specific activity with resources consumed and carbon dioxide (CO_2) generated’ (Fang *et al.*, 2014: 510), it has since been modified to indicate the volume of bio-productive land employed to enable the production and waste assimilation of consumed resources, taking into account the resource management systems and technologies that are customarily employed (Bastianoni *et al.*, 2012; Fang *et al.*, 2014).

Put simply, EF measures the demand that humanity has on the regenerative capacity of the earth (Galli *et al.*, 2012; Galli *et al.*, 2016). In a similar manner to LCA, EF comprehensively considers the environmental impacts of resource consumption from production through to waste disposal and absorption (Kitzes *et al.*, 2009; Fang *et al.*, 2014; Reddy *et al.*, 2014). However, it should be noted that EF does not traditionally incorporate water in terms of its consumption or expenditure[3] (another similarity to LCA) (Reddy *et al.*, 2014).

Carbon footprint (CF) typically refers to the quantity of greenhouse gas (GHG) emissions (measured by mass) that are both directly and indirectly produced by an activity, product or entity[4] (Galli *et al.*, 2012; Reddy *et al.*, 2014). The indicator emerged in scientific literature in the early 2000s and is believed to have stemmed from the concept of global warming

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[3] Although EF does not consider water consumed during production, it does include the expanse of the fishing area that is used for food acquisition (Reddy *et al.*, 2014).

[4] Alternatively, it may be interpreted as the area of bio-productive land and water needed to absorb emissions of carbon dioxide caused by humanity (Reddy *et al.*, 2014). This interpretation of carbon footprint is an ecological footprint sub-indicator (much like energy footprint).

potential (GWP)[5] (Høgevold, 2003 in Čuček *et al.*, 2012; Fang *et al.*, 2013). CF can be employed across broadly differing contexts, capable of indicating the emissions of whole populations, single individuals, companies, governments, industry sectors, organisations or specific processes and products (Wiedmann and Minx, 2008; Galli *et al.*, 2012; Fang *et al.*, 2013). CF is arguably the most well-known member of the "footprint family", having gained popularity in light of increasing focus and concern surrounding climate change (Wiedmann and Minx, 2008; Fang *et al.*, 2014).

The scope of carbon footprints and water footprints differ in the sense that carbon emissions are globally significant (Reddy *et al.*, 2014; Kanemoto *et al.*, 2016), while the impact of water consumption is most often relatively localised (Reddy *et al.*, 2014). However, CFs comprehensively account for emissions throughout the entire supply chain, both directly and indirectly, echoing the LCA and WF approach (Wiedmann and Minx, 2008; Fang *et al.*, 2014; Reddy *et al.*, 2014).

2.2.3 Virtual Water

Virtual water was developed in a completely different context to LCA and the footprint family and is not an indicator of environmental impact (Reddy *et al.*, 2014). Rather, it was introduced as a possible means to tackle water scarcity in the Middle East through the importation of the "virtual" water that is embedded in goods and services (Allan, 1997; Hoekstra, 2009; Reddy *et al.*, 2014). Developed in the early 1990s, virtual water is defined as the quantity of water needed to create a product or service, taking into account the water used both directly and indirectly throughout the entire production supply chain (Allan, 1997; Hoekstra, 2009; Hoekstra *et al.*, 2011). Strongly associated with WF, virtual water distinguished itself from classic water resource management theory in that it considers water use over and above direct withdrawals of water (Reddy *et al.*, 2014; Hoekstra *et al.*, 2011).

Virtual water presents the trade of food in terms of water use, effectively demonstrating how water "flows" and is transferred between countries through the international trade of food

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[5] GWP refers to the volume of GHGs that impact global warming and climate change (Čuček *et al.*, 2012).

products (Reddy *et al.*, 2014). The concept thus provides useful insight into the relative benefits of producing food in various countries.

The designation of “virtual water” has been deemed ambiguous and confusing by some, as it can create the mistaken impression that the term denotes the trade of water rather than food (Reddy *et al.*, 2014). In fact, virtual water is the actual water used to produce foodstuffs, and in the case of food crops, virtual water can be considered tantamount to the crop water requirement (Reddy *et al.*, 2014).

2.2.4 Water footprint

The notion of ‘water footprint’ (WF) was introduced by Arjen Hoekstra in 2002 as a solution to the call for a water use indicator that was consumption based (Hoekstra and Hung, 2002; Hoekstra, 2003). WF is a measure of comprehensive water consumption, factoring in both direct and indirect water use (Hoekstra, 2009; Hoekstra *et al.*, 2011). The WF concept is associated closely with the concept of virtual water, also known as embedded water (Allan, 1997; Hoekstra, 2009; Galli *et al.*, 2012). However, in contrast to virtual water, WF differentiates water consumption based on origin (whether that be rainwater or surface and groundwater) and incorporates an indication of polluted volumes (Hoekstra *et al.*, 2011). WF may therefore be separated into three distinct components – namely blue, green and grey.

Blue WF constitutes the utilization of surface and groundwater (i.e. blue water), insofar as that utilization results in the depletion of available blue water within the relevant catchment region, and does not constitute return flows (Hoekstra *et al.*, 2011). Green WF indicates rainwater (i.e. green water) consumption, and does not include run-off (Hoekstra *et al.*, 2011). Grey water footprint represents polluted water and is described as “the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards” (Hoekstra *et al.*, 2011: 2). Thus, WF distinguishes itself from the archetypical barometer of water consumption, ‘water withdrawal’, in that it: a) comprises indirect as well as direct water use; b) incorporates green and grey water, rather than merely blue water; and c) omits any return flows (i.e. that portion of applied blue water which is not consumed) (Hoekstra *et al.*, 2011).

One should note that measures of WF do not provide an indication of the significance or intensity of the impact that water use and pollution have on the pertinent setting (Hoekstra *et al.*, 2011). Merely, WF values provide a broader context from which to scrutinise the relationship between consumers or producers and the consumption of water and may therefore be used to stimulate and guide dialogue with regards to water allocation and the appraisal of socio-economic and environmental circumstances.

WF can be assessed for products and services, for consumer groups, or for producers (Hoekstra *et al.*, 2011; Zhang *et al.*, 2017). 'Consumers' may be defined as broadly as entire regions or nations, or as narrowly as specific individuals, while producers may include businesses, organisations and productive sectors (Galli *et al.*, 2012; Zhang *et al.*, 2017). This is elaborated upon further in section 2.4.

The development of WF assessment methodological standards have simultaneously taken place from two perspectives: the Water Footprint Network (WFN) WF assessment approach (Hoekstra *et al.*, 2011); and the LCA approach, more recently published by the International Organisation for Standardisation, in the form of ISO 14046 (ISO, 2014). WF may be found via a top-down, input-output analysis (IOA) approach, or by a bottom-up component-based approach (Hoekstra, 2009; Van Oel *et al*., 2009; Feng *et al*., 2011; Hoekstra *et al*., 2011; Fang *et al.*, 2014; Zhang *et al.*, 2017). The top-down and bottom-up approaches and the various methods developed for the calculation of WF are discussed in more detail in section 2.3.1.

2.3 Conceptual Framework and Components of Water Footprint

WF accounts for both direct and indirect freshwater appropriation by consumers, producers, products or services (Hoekstra *et al.*, 2011; Chapagain and Tickner, 2012). The indicator is multidimensional and is capable of differentiating water use according to source, as well as providing an indication of water pollution, identified according to contaminant (Hoekstra *et al.*, 2011; Chapagain and Tickner, 2012). WF is generally expressed volumetrically and may be termed in litres or cubic meters per tonne or per year (Chapagain and Tickner, 2012; Lovarelli *et al*., 2016).

The WF of a product is defined as the quantity of freshwater consumed throughout the production process of that product, considered across the entire supply chain (Hoekstra *et* *al.*, 2011). The WF of consumers or producers refers to the freshwater appropriated by the products and services utilised by those consumers or producers, throughout the complete supply chain, and including both consumed and polluted water (Hoekstra *et al.*, 2011; Chapagain and Tickner, 2012). It is important to specify that WF relates to freshwater, as global freshwater resources are scarce, while water in general is not (Hoekstra, 2009).

The components making up WF may be expressed both geographically and temporally, and are designated by colour: namely blue, green and grey WF (Hoekstra *et al.*, 2011; Chapagain and Tickner, 2012). It is important to consider the influence of each distinct component of total WF separately, as blue, green and grey WF are defined differently and have divergent implications (Lovarelli *et al*., 2016).

Blue WF refers to water consumption from ground or surface freshwater resources, excluding return flows (i.e. water that is returned to the source) (Hoekstra *et al.*, 2011; Hoekstra, 2014; Chenoweth *et al.*, 2014). Blue WF includes water incorporated into products, as well as the volume evapotranspired during production (i.e. water lost due to the processes of evaporation and transpiration) (Hoekstra *et al.*, 2011; Hoekstra, 2014). Blue water also accounts for water losses to other catchments or to the sea (Hoekstra *et al.*, 2011; Hoekstra, 2014). In contrast with green water, blue water resources may be utilised for a variety of purposes, and thus the opportunity cost of blue water has been considered greater than that of green water in many instances (Chapagain *et al.*, 2006; Hoekstra, 2009; Lovarelli *et al*., 2016).

Green WF indicates the consumptive rainwater use by products, services, consumers or producers (Hoekstra *et al.*, 2011; Hoekstra, 2014). Green WF comprises rainwater that is incorporated into products, as well as that which is lost due to evapotranspiration, and is especially pertinent in the agricultural and forestry industries (Hoekstra, 2014). As is the case with blue WF, runoff is excluded from green WF (Hoekstra *et al.*, 2011). The notion of 'green water' was originally introduced in the 1990s, with the intention of differentiating between the contributions of precipitation water and irrigation water to total plant water consumption (Falkenmark, 1995 in Pfister *et al.*, 2017). When the WF concept was originally introduced green water was not accounted for, despite being included in virtual water definitions (Hoekstra and Hung, 2002). However, this was primarily due to a lack of obtainable data relating to green water consumption on a national basis (Hoekstra and Hung, 2002), and green water has since been incorporated into standardised WF methodologies.

Grey WF is an indicator of the contamination of freshwater by pollutants and is defined as ‘the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards’ (Hoekstra *et al.*, 2011: 2). The grey component of WF does not represent actual water utilisation during the production process, but rather the theoretical volume of water that is required to return water quality to that which existed prior to contamination resulting from production (Chapagain and Tickner, 2012; Lovarelli *et al*., 2016). Grey WF was not initially included as a component of WF (Hoekstra and Hung, 2002; Chenoweth *et al*., 2014), and was originally introduced by Chapagain *et al.* (2006), who referred to it as ‘dilution water.’

The inclusion of both green and grey water in WF accounts has been the subject of some criticism (Chenoweth *et al.*, 2014). Some attest that blue and green water consumption cannot be easily separated, and that accounting for both may result in double counting (Pfister *et al.*, 2017). Grey WF is criticised for not representing actual consumptive water use or addressing the costs involved with the treatment of polluted water (Chenoweth *et al.*, 2014). Further criticisms of WF are included in section 2.3.2.

2.3.1 Different WF Methods

a. Introduction

WF has its conceptual roots in virtual water and can be calculated either by means of a top-down or bottom-up approach (Hoekstra, 2009; Van Oel *et al*., 2009; Feng *et al*., 2011; Hoekstra *et al*., 2011; Fang *et al.*, 2014). The top-down approach is an input-output analysis (IOA) approach, while bottom-up methodologies involve the analysis of the specific processes involved in production (Feng *et al*., 2011). Regardless of which approach is utilised, various methodologies for the assessment of WF have been developed, with international standards published by two organisations: the Water Footprint Network (WFN), which defines WF in volumetric terms (Hoekstra *et al.*, 2011; Pfister *et al.*, 2017); and the International Standardisation Organisation, which published ISO 14046 for the assessment of WF based on life cycle assessments (LCA), and focuses on the environmental impacts of water use (Vanham and Bidoglio, 2013; ISO, 2014; Pfister *et al.*, 2017).

b. Top-down versus Bottom-up Approaches to WF Calculation

WF calculation may take place by means of two primary approaches - namely the top-down and bottom-up approaches[6] (Hoekstra, 2009; Van Oel *et al.*, 2009; Feng *et al.*, 2011; Hoekstra *et al.*, 2011; Fang *et al.*, 2014). The top-down approach, founded on input-output analysis (IOA) (Feng *et al.*, 2011; Chenoweth *et al.*, 2014; Fang *et al.*, 2014), calculates the WF of national consumption by accounting for total water consumption in a country, including all virtual water imports, and excluding all virtual water exports[7] (Chenoweth *et al.*, 2014; Hoekstra, 2009). A balance-based approach, the top-down method provides an expeditious means of national water footprint assessment, allowing for relatively swift calculation (Hoekstra, 2009). The more conventional bottom-up approach considers water consumption item-by-item and is calculated as the sum of consumers' direct and indirect WF (in the case of national WF calculation, consumers refer to the relevant nation's population) (Hoekstra *et al.*, 2011). Direct WF is consumption of water for personal use (i.e. for home and garden use), and indirect WF is the water that is utilized to produce the items and services consumed (Feng *et al.*, 2011; Hoekstra *et al.*, 2011). A country's indirect WF is computed by multiplying a nation's consumption of goods and services by those goods' and services' corresponding water requirements throughout their supply chains (Hoekstra, 2009; Chenoweth *et al.*, 2014). When multiple products are produced from any single primary product, double counting is avoided by proportionally dividing water consumption between the relevant manufactured products in terms of value (Hoekstra, 2009; Chenoweth *et al.*, 2014).

The bottom-up method was the initial approach employed in WF analysis (Chenoweth *et al.*, 2014). However, although a practicable method for national WF accounting, the approach has been deemed most appropriate for WF calculations of products and processes, or consumers on a smaller than national scale, such as businesses and individuals (Hoekstra, 2009; Fang *et*

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[6] These approaches resemble the two primary methods used in EF calculations: the component-based, bottom-up approach; and the top-down, compound calculation method (Hoekstra, 2009; Feng *et al.*, 2011).

[7] Note that WF assessments were originally introduced for national water consumption analysis (Hoekstra and Hung, 2002).

al., 2016). The top-down approach is generally considered appropriate for national water footprint calculations, or for regions with accurate national and provincial-level statistics (Fang *et al.*, 2016; Galli *et al*., 2016), and has been employed for this purpose in several publications. Examples include: the calculation of the WF of national tourism in Spain (Cazcarro *et al.*, 2014); an evaluation of Liaoning province energy supply WF in China (Okadera *et al.*, 2015); and multi-regional input-output (MRIO) analyses of WF in China (Zhang and Anadon, 2014; Deng *et al.*, 2016); Italy (Ali *et al.*, 2018) and across the globe (Acquaye *et al.*, 2017).

In theory, WF calculations using the top-down and bottom-up approaches should yield the same result (Van Oel *et al*., 2009; Hoekstra *et al*., 2011), but this is often not the case (Feng *et al*., 2011). The data-intensive bottom-up method is sensitive to the reliability and consistency of data (Hoekstra, 2009; Galli *et al.*, 2016). Top-down calculation will be impacted by delays between the utilization of water during production and the actual consumption of that product, as well as changes to product stocks (particularly those which are water-intensive) throughout the year of calculation (Van Oel *et al*., 2009; Hoekstra *et al*., 2011). Furthermore, countries which engage in high levels of trade comparative to production are sensitive to relatively minor variations in import and export data, as demonstrated by Van Oel *et al.* (2009), who conducted a case study of external WF of the Netherlands using both the top-down and bottom-up approaches (Van Oel *et al*., 2009; Hoekstra *et al*., 2011).

International standards for water footprint accounting, regardless of whether the bottom-up or top-down approach is used, have been developed and are governed by two separate institutions: The Water Footprint Network (WFN) (Hoekstra *et al.*, 2011; Fang *et al.*, 2014) and the International Organisation for Standardisation under ISO 14046 (Ridoutt and Huang, 2012; ISO, 2014; Fang *et al.*, 2014).

c. Water Footprint Assessments – the WFN Approach

The initial standard developed for calculating WF was the Water Footprint Assessment (WFA) approach, founded on the concept introduced by Hoekstra and Hung in 2002, and established and maintained by the Water Footprint Network (WFN) (Hoekstra *et al.*, 2011). The objective of WFA is to investigate the way products and activities interact with water scarcity and pollution, and to provide insight for improved water-related sustainability for these products and processes (Hoekstra *et al*., 2011). WFA encompasses the calculation of the WF of a producer, consumer, product or process, or the spatio-temporal enumeration of the WF of a stipulated geographic region; the appraisal of environmental, economic and social sustainability; and finally, the development of a response strategy (Hoekstra *et al*., 2011). It is important to note that although WF assessments supply useful insight into potential response strategies, they do not prescribe explicit directives for action (Hoekstra *et al*., 2011; Manzardo *et al*., 2016).

A WFA is divided into four steps:

i. *Establishment of goals and scope*

   The appearance of a WFA relies on the relevant objectives and scope of that assessment (Hoekstra *et al.*, 2011). WFA can be incredibly diverse, capable of assessing water consumption on a national or global scale, or of a specific product or single step in a process. It is therefore important that the precise goals and scope of the assessment are clearly specified. The level of detail involved in a WFA will largely depend on the purpose of the undertaking – for instance, a WFA with the goal of setting WF reduction targets within a policy framework will require a significantly greater degree of detail than a WFA aiming to increase awareness levels regarding water consumption (Hoekstra *et al.*, 2011).

   The scope of a WFA identifies the boundaries of the assessment, specifying what needs to be included or excluded in the pursuit. The scope needs to be defined for each of the accounting, sustainability assessment, and response formulation phases of a WFA (Hoekstra *et al.*, 2011). The scope of accounting indicates the time interval and spatio-temporal level included in the analysis; the inclusion of blue, green, or grey WF calculations; the extent of the supply chain to be encompassed; the inclusion of direct or indirect WF; and so on (Hoekstra *et al.*, 2011). The scope of the sustainability assessment is dependent on whether the assessment takes a geographic outlook or considers sustainability from a consumer, producer, process or product viewpoint. The sustainability assessment of the former considers the sustainability of an area's aggregated WF, while the latter perspective examines the contribution that the WF of a consumer, producer, process or product has to the global WF of humanity, as well as the impact it has on the combined WF of a specific catchments or river basin (Hoekstra *et al.*, 2011). The scope of WFA response formulation identifies those whom action should be taken by, whether they be governments, companies, consumers, etc. (Hoekstra *et al*., 2011).

ii. *WF accounting*

This step encompasses the quantification of water appropriation within the context of a WFA. The foundation of all WF accounts is the WF of a process – the WF of products, consumers, consumer groups, producers, producer groups, and the WF within a specific geographic area can all be broken down into the WFs of the various processes making them up (Hoekstra *et al.*, 2011). For instance, a consumer's WF is the aggregated WF of all products consumed, and the WF of each of those products is the sum of the WFs of the various processes performed during their production. The WF of a certain region can be calculated by the addition of the WFs of the processes that occur within that area (Hoekstra *et al.*, 2011).

The accounting phase includes the calculation of blue, green, and/or grey WF. Further details regarding the calculation of these three WF elements have been described in Chapter 4.

iii. *WF sustainability assessment*

WF sustainability assessments are essentially intended to weigh human appropriation of water against the amount that the environment can sustainably maintain (Hoekstra *et al.*, 2011). It involves the comparison of WF to resources of freshwater that are available and accessible for consumption. Straightforward as that may appear, WF sustainability assessments can be significantly more complex – impacts of water use to be considered may be both direct and indirect; sustainability may differ substantially for blue, green or grey WF; and the scope of sustainability to be assessed may be environmental, economic or social. (Hoekstra *et al*., 2011).

iv. *WF response formulation*

In this step, findings from the accounting phase and sustainability assessment are used to establish a suitable response strategy. The WFA approach does not explicitly recommend specific courses of action (Hoekstra *et al.*, 2011). However, it does provide a list of possible response options (though this list is not comprehensive).

Throughout the process, each of the phases may be revisited and redefined, with outcomes of each step potentially impacting the others (Hoekstra *et al*., 2011). The four phases of the WFA framework are a guideline and not a directive, and as such, all four steps need not necessarily be incorporated in a WFA study (Hoekstra *et al*., 2011).

d. Life Cycle Assessment

An alternative approach to the WFN method of assessment is the life cycle assessment (LCA) approach (Lovarelli *et al*., 2016; Manzardo *et al*., 2016). LCA is a cradle-to-grave methodology used to assess the impacts that processes and products have on the environment (Berger and Finkbeiner, 2010; Manzardo *et al*., 2016), and has been standardised in ISO 14040 and 14044, which respectively set out the “principles and framework” and “requirements and guidelines” for the method (ISO, 2006a,b; Pfister *et al.*, 2017).

The impacts of water consumption have not classically been included in LCA methodologies and studies (Kounina *et al.*, 2013; Chenoweth *et al*., 2014). The LCA approach for assessing water footprints, developed subsequent to the WFA method and arose through the introduction in scientific literature of LCA techniques incorporating freshwater inventory analysis (Milà i Canals *et al*., 2009; Bayart *et al*., 2010; Boulay *et al.*, 2011) and freshwater consumption impact categories (Milà i Canals *et al*., 2009; Pfister *et al.*, 2009, Bayart *et al*., 2010; Kounina *et al.*, 2013). This led to the method ultimately being standardised by the International Organisation for Standardisation through ISO 14046, which lays out the “principles, requirements and guidelines” for WF assessments within the LCA framework (ISO, 2014; Fang *et al.*, 2014; Manzardo *et al*., 2016). Note that WF of a product within the LCA framework represents the potential water-related environmental impacts of that product from cradle-to-grave (Manzardo *et al*., 2016).

In a similar manner to the approach developed by the WFN, LCA is comprised of four broad steps:

i. *Establishment of goals and scope*

   This step incorporates specification of the impact assessment method to be used, as well as the identification of the spatial details and scope of the assessment (Pfister *et al.*, 2017).

ii. *Life cycle inventory (LCI) assessment*

   This step encompasses the assessment of environmental exchanges, known as inventory flows (in the case of water-related LCA this refers to freshwater use and pollution) throughout the life-cycle of the relevant product or process (Pfister *et al.*, 2017).

iii. *Life cycle impact assessment (LCIA)*

   In the context of WF assessments, LCIA is the evaluation of potential freshwater scarcity and degradation related environmental impacts based on the results of the LCI assessment (Pfister *et al.*, 2017). Potential impact measures within LCIA are commonly split into “midpoint” and “endpoint” metrics, where the former refers to the possible impacts at the “midpoint” level of the cause-effect chain, and the latter refers to impacts at the “endpoint” of the cause-effect chain. In the context of WF studies, water scarcity would be a “midpoint” metric, while potential negative impacts to the well-being of consumers or degradation to the environment from water utilization are examples of “endpoint” metrics (Pfister *et al.*, 2017).

iv. *Interpretation*

   Interpretation of the results may result in modifications to the goal and scope of the LCA, and thus the LCI and LCIA phases of the assessment. The LCA approach is iterative in nature, with the interpretation of the outcomes of each phase potentially impacting the others (Pfister *et al.*, 2017).

These four phases making up WF LCAs were initially laid out in the original LCA international standards (ISO 14040 and 14044) and were adapted to concentrate specifically on water scarcity and pollution in ISO 140406 (Pfister *et al.*, 2017).

The methodology for Water Use in LCA (WULCA) has been the focus of much attention (Boulay *et al.*, 2015; Manzardo *et al.*, 2016; Pfister *et al.*, 2017; Boulay *et al.*, 2018). The United Nations Environmental Programme (UNEP) and the Society of Environmental Toxicology and Chemistry's (SETAC) joint international life cycle initiative (referred to as the UNEP-SETAC WULCA initiative) has attempted to develop a consistent framework and consensus-based approach for LCA water scarcity footprint calculation (Boulay *et al.*, 2015; Boulay *et al.*, 2018). The WULCA initiative has successfully reached a consensus on water scarcity indexing within the WF LCA framework (Boulay *et al.*, 2015; Pfister *et al.*, 2017). In 2018 the group presented a consensus characterisation model for water scarcity footprints in line with ISO 14046 (Boulay *et al.*, 2018), which evaluates the potential impacts resulting from water consumption based on the available water remaining (AWARE) and assesses the consequent potential deprivation to humans and ecosystems once demand has been met (Boulay *et al.*, 2018).

Influential methods previously developed based on LCA include the freshwater ecosystem impact (FEI) and freshwater depletion (FD) method (Milà i Canals *et al.*, 2009); the stress-weighted water footprint method (Ridoutt and Pfister, 2010); and the water impact index method (Bayart *et al.*, 2014). In the FEI and FD method, Milà i Canals *et al.* (2009) recognised the need for LCI to explicitly account for changes in land use (which may lead to altered water availability), as well as blue and green evaporative and non-evaporative water. FEI and FD were established as the major impact pathways that needed to be focused upon, with FEI indicators portraying existing utilisation of water in terms of the available resource volume, and FD addressing potential water resource scarcity resulting from freshwater being utilised at a faster rate than it is capable of being renewed (Milà i Canals *et al.*, 2009).

The Stress-Weighted Water Footprint approach developed by Ridoutt and Pfister (2010) integrated characterisation factors relating to water-stress into the assessment method and allowed the potential contribution of various production and system processes to water scarcity to be quantifiably evaluated and contrasted. The Water Stress Index (WSI) introduced by Pfister *et al.* (2009) was utilised to find location-specific water stress characterisation factors, and water utilization at each stage of production or system lifecycles were weighted according to the appropriate characterisation factor (Ridoutt and Pfister (2010).

The water impact index method introduced by Bayart *et al.* (2014) proposes a single WF indicator which incorporates issues relating to the volume of utilised freshwater, freshwater scarcity, as well as water quality. The method is LCA-based, and utilises the water balance method, weighting flows according to water scarcity and quality indices (Bayart *et al.*, 2014).

e. WFA versus LCA

From a broad perspective, the WFA approach (i.e. the WFN approach) and the LCA approach for assessing WF are similar: both provide quantitative indicators relating to water resources (Boulay *et al.*, 2013, Pfister *et al.*, 2017), are useful indicators of water scarcity and water-use hotspots (Jefferies *et al.*, 2012; Manzardo *et al.*, 2016; Pfister *et al.*, 2017), and indirectly promote the preservation of water resources (Chapagain and Tickner, 2012; Boulay *et al.*, 2013; Lovarelli *et al.*, 2016). Both methodological approaches are comprised of four steps, and both adopt a cradle-to-grave approach (Hoekstra *et al.*, 2011; Pfister *et al.*, 2017). However, WFA and LCA differ significantly in terms of functional relevance, methodological development, and communication of results (Pfister *et al.*, 2017). Indeed, WFA and LCA WF results are not comparable indices (Boulay *et al.*, 2013).

The WFA approach emerged as a water resource management tool and was developed to aid management of freshwater resources in terms of sustainable, equitable and efficient allocation (Boulay *et al.*, 2013; Hoekstra, 2016; Manzardo *et al.*, 2016). The WFA approach provides an indication of freshwater resource appropriation and water use efficiency, expressed in physical terms (Hoekstra, 2016; Manzardo *et al.*, 2016; Pfister *et al.*, 2017). In contrast, the LCA approach provides an indicator of potential water-related environmental impacts, quantifying and weighting the potential effect of water deprivation and pollutant emissions on human health, ecosystems and the depletion of resources (Boulay *et al.*, 2013; Pfister *et al.*, 2017).

The term WF was coined by Hoekstra and Hung (2002), and stems from the concept of virtual water. The volumetric, WFA approach was developed from this platform, and the methodological guidelines standardised globally by the WFN (Hoekstra *et al.*, 2011). The LCA-based WF assessment approach arose from the desire to incorporate water resources and the potential impacts of water use into LCA (Pfister *et al.*, 2017), which in time lead to the publication of ISO 14046, which specifically provides international standards for LCA-based WF assessments (ISO, 2014; Pfister *et al.*, 2017).

Although an international standard for LCA WF assessments exits, ISO 14046 allows certain freedoms regarding methodological approach and does not provide detailed directives for WF accounting (Fang *et al.*, 2014; Pfister *et al.*, 2017). This has resulted in the development of multiple approaches and methodologies for LCA-based WF assessments (Milà i Canals *et al.*, 2009; Ridoutt and Pfister, 2010; Bayart *et al.*, 2014; Fang *et al.*, 2014; Pfister *et al.*, 2017; Boulay *et al.*, 2018). This methodological freedom allows for the development of new and innovative approaches (Pfister *et al.*, 2017), but also results in a lack of analogous or comparable results across studies. However, work has been done to reach a consensus-based methodology (Boulay *et al.*, 2015; Pfister *et al.*, 2017; Boulay *et al.*, 2018). In contrast, the international standard for WFAs published by the WFN provides much more detail regarding methodology (Fang *et al.*, 2014; Pfister *et al.*, 2017), leading to greater coherence between WFAs carried out based on this approach.

WF results arising from the WFA approach may be expressed as single-score indicators, made up of blue, green and grey water components, and expressed in terms of physical water appropriation (Hoekstra *et al.*, 2011; Pfister *et al.*, 2017). In contrast, an array of indicators may emerge from an LCA (Pfister *et al.*, 2017). Instead of a physical indicator of water appropriation, WF outputs resulting from LCA-based assessments represent weighted potential environmental impacts pertaining to water, and are indicators of water scarcity (Pfister *et al.*, 2017).

The LCA approach has been criticised for not explicitly accounting for green and grey water (Hoekstra, 2016). By not including green water, LCA-based WF assessments ignore the impact of green-water scarcity, and do not acknowledge that both blue and green water have the potential to be scarce (Hoekstra, 2016). Proponents of the LCA approach have defended this by asserting that green water would be appropriated by natural vegetation regardless of human intervention, and thus does not significantly impact the environment (Pfister *et al.*, 2017). The inclusion of green and grey water in LCA-based WF assessments may also result in double-counting, since the environmental impacts of green and grey water related factors, such as eutrophication, toxicity and land-use, are already accounted for (Pfister *et al.*, 2017).

Potential synergies between the two methodological approaches have been put forward, in which the two approaches may benefit from one another (Jefferies *et al.*, 2012; Boulay *et al.*, 2013). For instance, some scarcity indicators utilised in the LCA approach bear similarities with the WFA blue water scarcity indicator, and efforts could be made to develop a common indicator capable of being used in either approach (Boulay *et al.*, 2013). In addition, The WFA approach would benefit from the extensive databases utilised in LCA, since similar data is generally required for both approaches (Jefferies *et al.*, 2012; Boulay *et al.*, 2013). Another potential area where the WFA approach may benefit from LCA is in terms of the sustainability assessment, specifically as relates impact assessment methodologies utilised within the LCA approach (Boulay *et al.*, 2013).

Despite some high-level similarities between the WFA and LTA approaches, the methodological development, interpretation and application of the two approaches differ substantially (Boulay *et al.*, 2013; Hoekstra, 2016; Pfister *et al.*, 2017). Neither approach is necessarily better than the other, and choice of appropriate approach should be determined by the objectives and scope of the relevant assessment to be undertaken.

2.3.2 Criticisms Surrounding the WF Concept

Criticisms have been raised regarding various aspects of WF. Amongst these is the fact that diverging approaches and methodologies have arisen for the assessment of WF, with no general consensus having been reached regarding a universally appropriate methodological standard or application for WF (Vanham and Bidoglio, 2013; Chenoweth *et al.*, 2014; Hoekstra, 2016; Pfister *et al.*, 2017). These various approaches and methodologies have been discussed in section 2.3.1. The quantity and quality of data required for WF assessments has also resulted in some criticism (Vanham and Bidoglio, 2013; Chenoweth *et al.*, 2014; Reddy *et al.*, 2014). Broad-scale assessments, such as those of countries or certain regions, usually involve some wide-ranging assumptions having to be made regarding climatic and spatio-temporal data (Chenoweth *et al.*, 2014; Reddy *et al.*, 2014). WF assessments of complex products and systems may require a copious amount of inputs from a diverse array of locations in order to be evaluated, and as such the reliability and consistency of data may be in doubt. This calls into question the quality and value of WF comparisons across products and regions (Vanham and Bidoglio, 2013; Chenoweth *et al.*, 2014; Reddy *et al.*, 2014).

Another criticism of WF is that the indicator does not provide a complete picture of the inherent costs and benefits involved in water use (Chenoweth *et al.*, 2014; Wichelns, 2015a). Factors such as opportunity costs, water-scarcity conditions and the socio-economic environment are not adequately addressed (Chapagain and Tickner, 2012; Wichelns, 2015a). Without considering outside factors, a high WF in a water-scarce area may indicate to decision makers the necessity to reduce water use. However, numerous livelihoods may be dependent on activities resulting in that elevated WF, and it would in fact be largely detrimental to the economy and well-being of the population to terminate said activities (Reddy *et al.*, 2014). Furthermore, the local economy may be unable to absorb workers into other sectors of the economy (Gawel and Bernsen, 2013). Critics attest that this exclusion of critical information relating to the benefits and costs of water use from WF indicators translates to limited policy value (Chenoweth *et al.*, 2014; Reddy *et al.*, 2014; Wichelns, 2015a).

With respect to virtual water and virtual water trading it has been proposed that international trade can take place in such a way as to reduce global water resource utilisation (Hoekstra and Hung, 2002; Hoekstra, 2009; Reddy *et al.*, 2014). However, countries trade products and services which are made up of multiple inputs over and above water; they do not trade virtual water (Wichelns, 2015a). It has been argued that water scarcity and quality are predominantly local concerns which need to be addressed in a regional setting, and that the concept of virtual water trading ignores political, economic, legal, cultural, and other locally-relevant factors (Gawel and Bernsen, 2013; Chenoweth *et al.*, 2014; Wichelns, 2015a). It has consequently been asserted that WF does not conform with or align to other members of the footprint family, such as carbon or ecological footprints, which provide a global indicator of the impact of human activity on environmental resources (Gawel and Bernsen, 2013; Wichelns; 2015a).

At a local scale, the importance of differentiating between surface and groundwater water resources has been asserted, as there are substantial differences in the potential impacts related to water use from each source (Dumont *et al.*, 2013; Zoumides *et al.*, 2013; Chenoweth *et al.*, 2014). WF does not customarily account for water use from these two water sources separately, with both forming part of blue WF (Hoekstra *et al.*, 2011). Traditional water resource management tools take these separate blue water resources into consideration, from which critics have inferred that WF is not useful as a water management tool at the local level (Chenoweth *et al.*, 2014; Reddy *et al.*, 2014; Perry, 2014). However, as the WF concept has evolved, some studies have begun making the distinction between surface and groundwater sources of blue water – for instance, an assessment of the WF of production in the United States has distinguished between the two blue water resources (Marston *et al.*, 2018).

The fact that WF indicators take the form of a single volumetric quantity signifying the consumptive water requirements of a process or product is an attractive and convenient notion, but can be misleading (Reddy *et al.*, 2014) The fact that the indicator only considers a single input in a multi-factor environment can easily be overlooked (Reddy *et al.*, 2014; Wichelns, 2015a). It is therefore important to remember to take into consideration the environmental and socio-economic context in which water appropriation takes place (Chapagain and Tickner, 2012; Reddy *et al.*, 2014; Wichelns, 2015a).

Critics do however recognise that the WF concept has resulted in significantly improved awareness with regards to the water requirement of products and services and has stimulated discussion surrounding the issue water scarcity (Chenoweth *et al.*, 2014; Lovarelli *et al*., 2016). WF combines a vast amount of data into a single indicator, and although this may lead to some misinterpretation, it has provided a useful tool that has broadened the understanding of freshwater use.

2.4 Water Footprint Case Studies

This section summarises various case studies in which WF has been evaluated on a national, regional and river basin scale. WF studies carried out for specific industries, companies, and individual products have also been described.

2.4.1 The Water Footprints of Nations, Regions and River Basins

A country's WF is made up of both an internal and external component – the consumption of internal water resources; and the consumption of external resources, which are typically appropriated through the import of foreign goods and services (i.e. virtual water imports) (Hoekstra, 2009). The WF of a nation can thus supply an estimation of virtual water flows resulting from international trade (Chenoweth *et al.*, 2014).

Hoekstra and Mekonnen (2012) estimated the WF of humanity by quantifying the WF of consumption and production of nations across the globe. High resolution blue, green and grey WF components were calculated for the period of 1996-2005 for each nation, and the international trade of industrial and agricultural commodities was assessed in order to evaluate virtual water trade between nations (Hoekstra and Mekonnen, 2012). The average annual total global WF of production was found to be 9 087 billion m^3/annum, with green WF making up the largest share of this figure (74%), followed in turn by grey WF (15%) and blue WF (11%) (Hoekstra and Mekonnen, 2012). The global average WF of consumption was found to be 1 385 m^3/capita/annum (Hoekstra and Mekonnen, 2012).

Several countries were found to depend greatly on virtual water imports, and thus on external water resources, with production of exported goods and services accounting for approximately 20% of the total global WF of production (Hoekstra and Mekonnen, 2012). Agricultural production was found to account for the vast majority of global WF, at 92% of the average figure. However, only 19% of the agricultural component of global WF was attributed to exported production, while 41% of the industrial sector's WF component comprised exported production (Hoekstra and Mekonnen, 2012). China, India and the United States had the highest estimated WF of production of the assessed nations, together making up roughly 38% of the total global figure (Hoekstra and Mekonnen, 2012). In terms of the WF of consumption, countries with large populations had the highest total WF values, which is to be expected. However, looking at the WF of consumption per capita is more meaningful. In terms of developed countries, the United States, Portugal and Spain had a relatively high average WF per capita figures, while the UK, Japan and Germany's WF per capita figures were low in relation to that of other countries (Hoekstra and Mekonnen, 2012). The WF per capita of developing countries tended to vary by a much greater degree than that of developed nations.

Pahlow *et al.* (2015) conducted a WF assessment of South Africa for the periods of 1996-2005. Total WF of production was found to be 58 853 million m^3/annum, which amounts to 0.6% of the total global figure found by Hoekstra and Mekonnen (2012). Green WF constituted the largest portion of total South African WF (making up 78% of the total figure), followed in turn by blue and grey WF (at 12.1% and 9.9% respectively) (Pahlow *et al.*, 2015). The portion of total WF attributed to crop production was substantial, constituting roughly 75% of the total figure (Pahlow *et al.*, 2015). The per capita average WF of consumers in South Africa was found to be lower than the global average figure found by Hoekstra and Mekonnen (2012), at 1 255 m^3/annum. In terms of sustainability, concerns were raised regarding the blue water scarcity experienced in several river basins in the country for protracted periods during the year (Pahlow *et al.*, 2015). In addition, grey WF results lead to levels of contamination across South African river basins being deemed unsustainable (Pahlow *et al.*, 2015).

Various additional country-specific WF studies have taken place. Marston *et al.* (2018) estimated the WF of production in the United States for a wide variety of industries and goods produced across the nation for the period of 2010-2012. Country-average as well as spatially defined, state-specific figures are provided in a publicly available database (Marston *et al.*, 2018). Surface and groundwater resources are differentiated, with separate blue WF results provided for these two water sources (Marston *et al.*, 2018). The green WF of agricultural crops is separated into that of rainfed and irrigated production. The study is as yet the most comprehensive WF assessment of its kind across the globe and allows consumers and producers alike to broaden their awareness of water consumption throughout the supply chain (Marston *et al.*, 2018).

Other WF studies which have been carried out on a national scale include: an assessment of the water footprints of the Netherlands and Morocco (Hoekstra and Chapagain, 2006); a study estimating the blue water footprint of industry, agriculture, households and water management in the Netherlands (Hoekstra *et al.*, 2012); a global assessment of the water footprint of sweeteners and bio-ethanol (Gerbens-Leenes and Hoekstra, 2012); an assessment of the efficiency, equitability and sustainability of water consumption and pollution in the regions of Latin America and the Caribbean (Mekonnen *et al.*, 2015a); a global assessment of the consumptive water footprint of electricity and heat (Mekonnen *et al.*, 2015b); and a study of the location-adjusted blue WF of beef production in South Africa (Harding *et al.*, 2017), amongst others. In addition, country water footprint profiles have been conducted by the Water Footprint Network for the Netherlands Ministry of Foreign Affairs for seven sub-Saharan countries, namely Benin, Ethiopia, Ghana, Kenya, Mali, Mozambique and Rwanda (WFN, 2016a-g).

Although WF analyses were initially carried out at a national level, the focus soon shifted to include basin-level WF assessments. Hoekstra and Mekonnen (2011) assessed blue water scarcity of river basins across the globe by comparing estimated monthly blue water footprint to blue water availability for a total of 405 river basins from 1996-2005. Close to half the river basins assessed experienced severe water scarcity for at least one month annually, while more than half of the basins' environmental flow requirement was not met for a minimum of one month per year (Hoekstra and Mekonnen, 2011). Weighted average global water scarcity across all basins was found to be 85% (Hoekstra and Mekonnen, 2011).

Other basin level WF case-studies have been carried out: Vanham and Bidoglio (2014) assessed the WF of production and consumption relating to agriculture across 365 European river basins from 1996-2005. In addition, WF was also analysed for only those agricultural products appropriate for a 'healthy' diet, as well as for a vegetarian diet. River basins such as the Thames, Seine and Rhine were found to be net virtual water importers, while basins located in the Baltic region, Western France and the Iberian Peninsula were net virtual water exporters (Vanham an Bidoglio, 2014). The WF of consumption was found to decrease under 'healthy' and vegetarian diets. Dumont *et al.* (2013) analysed the blue and green WF of the Guadalquivir basin in Spain, with blue WF stemming from groundwater receiving particular attention. It was found that the groundwater component of blue WF had increased over the period of 1997 to 2008, largely attributed to recent agricultural developments with high levels of groundwater dependence (Dumont *et al.*, 2013). The blue WF of crops and blue water scarcity in the Yellow River basin in China was assessed by Zhuo *et al.* (2016) on an annual and monthly basis across the period of 1961-2009. WF of crops was found to have increased in recent years, and moderate or severe blue water scarcity was experienced by the basin for more than half the year. Severe blue water scarcity was faced by roughly 50% of the basin area year-round, even in periods of relatively high rainfall (Zhuo *et al.*, 2016).

2.4.2 The Water Footprint of Companies

Several companies have quantified the WF of their operations in order to gain a better understanding of their water appropriation along the supply chain (Chapagain and Orr, 2010; SABMiller *et al.*, 2010; Coca-Cola Europe, 2011; Sikirica, 2011; Unger *et al.*, 2013). It has been proposed that businesses can utilise WF as a tool to identify and reduce operational and business risks as they relate to water, and to increase production efficiency (SABMiller *et al.*, 2010; Coca-Cola Europe, 2011; Chenoweth *et al.*, 2014). However, it is important that businesses remember to consider factors outside of water, such as the well-being of those employed in potentially water-intensive areas further down the supply-chain (Chenoweth *et al.*, 2014).

SABMiller quantified the WF of their beer value chain as it related to their operations in the Czech Republic and South Africa (SABMiller and WWF-UK, 2009). They acknowledged the need to consider a broader set of contextual factors than the volumetric WF results alone. The South African WF per litre of beer was found to be considerably greater than that of beer produced in the Czech Republic, largely due a greater proportion of agricultural inputs in South Africa depending on irrigation water, as well as climatic differences between the two nations (SABMiller and WWF-UK, 2009). However, in terms of the proportion of total water consumption at each stage of the value chain, results between the two countries were found to be similar (SABMiller and WWF-UK, 2009). This work was expanded upon in 2010 when the WF of beer was calculated for SABMiller operations in Peru, Tanzania, Ukraine and South Africa (SABMiller *et al.*, 2010). WF was found to vary significantly across countries, with the local context considerably impacting results.

Similarly, the Coca-Cola company has also undertaken WF analyses, both of its final products, such as a Coca-Cola drink (TCCC and TNC, 2010); and for inputs such as refined sugar from sugar beets (Coca-Cola Europe, 2011). The total WF of a 0.5 litre Coca-Cola drink in a PET bottle produced in a Dutch bottling plant was found to be 35 litres, with the green WF accounting for 43% of the total figure, followed in turn by grey WF (34%) and blue WF (23%)

(TCCC and TNC, 2010). The majority of the green and blue WF of the drink was attributed to the production of sugar beets. The WF of sugar beets (assessed in Europe) varied depending on location and climate, with the largest component of total WF found to be green WF, since sugar beets in Europe are primarily rain-fed (Coca-Cola Europe, 2011).

Amongst others, additional company evaluations of WF which have been carried out include: an analysis of the WF of Nestlé's 'Bitesize Shredded Wheat' (Chapagain and Orr, 2010); a WF assessment of bananas and pineapples by Dole Food, (Sikirica, 2011); a WF assessment by the Tata Group, including the WF of Tata Chemicals, Tata Motors, Tata Power, and Tata Steel (Unger *et al.*, 2013); and a WF assessment of the of FMO Entrepreneurial Development Bank's agribusiness portfolio (Chico and Zhang, 2015).

2.4.3 The Water Footprint of Products

WF has been quantified for a wide variety of products across the globe, prompting an increased awareness of the consumptive water use inherently included in goods and services (Chenoweth *et al.*, 2014; Lovarelli *et al.*, 2016). An understanding of the water use of a product throughout its supply chain also allows consumers and producers to identify potential areas for improving water use efficiency and sustainability (Reddy *et al.*, 2014; Lovarelli *et al.*, 2016). However, as previously noted, it is important that contextual considerations outside of water use, such as economic, social and environmental circumstances, are considered when basing decisions on WF (Reddy *et al.*, 2014; Chenoweth *et al.*, 2014; Wichelns, 2015a).

Global water use is predominantly appropriated by the agricultural sector (Ridoutt and Pfister, 2010; Chenoweth *et al.*, 2014), and as such WF is most significant for agricultural products and products which utilise agricultural products in their supply chain (Reddy *et al.*, 2014). Mekonnen and Hoekstra (2011a) quantified the WF of crops and derived crop products over the period of 1996-2005. Blue, green and grey WF were specified for 126 crops across the globe, as well as for upwards of 200 derived crop products. The total WF of crop production across the globe was found to be 7 404 billion m^3/annum, largely attributed to the green WF component (78%), followed by blue WF (12%) and grey WF (10%) (Mekonnen and Hoekstra, 2011a). The global WF of wheat, rice and maize production accounted for 38% of the total figure. Variation between the WF of crops within each crop category and across the various production regions was observed. WF was typically larger for low-yield crops and crops for which only a small portion of biomass is harvested; and accordingly, global average WF per ton was particularly high for rubber, nuts, spices, tobacco, tea and coffee (Mekonnen and Hoekstra, 2011a). The global average WF of food crops was relatively high for pulses, oil crops, cereals and fruits (ranging from 1 000-4 000 m^3/ton), and relatively smaller for sugar crops, vegetables, roots and tubers (ranging from 200-400 m^3/ton) (Mekonnen and Hoekstra, 2011a).

The global WF of farm animal products was assessed by Mekonnen and Hoekstra (2012) for the period of 1996 to 2005, both in terms of water use per ton and per unit of nutritional value. The WF of farm animal products was found to be consistently greater than that of crop products with similar nutritional characteristics, largely due to the quantity of feed crops consumed by animals (Mekonnen and Hoekstra, 2012; Chenoweth *et al.*, 2014). Total global WF of animal production was found to be 2 422 billion m^3/annum, and 98% of this figure is attributed to animal feed, with drinking, feed-mixing, and service water consumption responsible for a comparatively negligible proportion (Mekonnen and Hoekstra, 2012). The majority of the WF of animal feed consists of the grazing component (38%), followed in turn by the maize and fodder crop components (17% and 8% respectively) (Mekonnen and Hoekstra, 2012). It was found that approximately a third of the total animal product WF figure was attributed to the production of beef cattle. In addition, the blue and grey WF of industrial production of animal products was generally greater than that of grazing or mixed-system based production. It was found that vegetarian diets had a significantly lower WF than animal product-based diets, and a policy shift promoting dietary change towards crop-based products was predicted in order to manage water demand in the future (Mekonnen and Hoekstra, 2012).

The WF of agricultural products has been assessed in numerous additional studies – in a literature review of the WF of agricultural products, Lovarelli *et al.* (2016) listed 73 studies that have taken place between the periods of 2002 and 2016, both on a local and global scale. In the South African arena, Munro *et al.* (2016) assessed the WF of citrus production in the Lower Sundays River Valley in an average, wet and dry year, utilising the WFN WFA approach. It was found that, of the assessed citrus cultivars, lemons' blue and combined blue and green

WF was smallest, and that lemons were more economically efficient in terms of financial return and labour requirements than other varieties (Munro *et al.*, 2016). Water scarcity was not encountered for citrus production, though infrastructural and institutional scarcity did exist in the region. In the dry year it was found that nitrogen-related grey WF was unsustainable (Munro *et al.*, 2016).

Another South African WF study relating to agricultural products was conducted by Harding *et al.* (2017), who analysed the location-adjusted blue WF of beef production across the country. A top-down LCA-based approach was utilised, and the WSI was used to find local impacts for water management areas (WMAs) throughout South Africa. The blue WF found for beef production, unadjusted by location, was found to be 437 litres per kilogram, while adjusted blue WF varied from 105 to 2820 equivalent litres per kilogram, illustrating the impact of site-effect (Harding *et al.*, 2017). Similar to results found by Mekonnen and Hoekstra (2012), the portion of beef production WF attributed to feed typically accounted for the majority of the result. An environmental hotspot as allied to water-related impacts was identified in the central interior of the country (Harding *et al.*, 2017).

The WF of industrial products was quantified by Mekonnen and Hoekstra (2011b), along with that of agricultural products, in their analysis of the global blue, green and grey WF of production and consumption. Global WF, quantified from 1996-2005, was predominantly attributed to production of agricultural products, making up 92% of the total figure (Mekonnen and Hoekstra, 2011b). WF is most applicable for industries which rely on agriculturally derived inputs and is not particularly pertinent for industries in which water use does not play a significant role in the supply-chain (Reddy *et al.*, 2014).

2.5 Water Productivity: Development, Conceptual Framework and Applications

The concept of agricultural water productivity (WP) was proposed by Seckler[8] (1996) as a suitable alternative to classical irrigation and water use efficiency indices, which were criticised for not taking into account the potential for water reuse (i.e. return flows), and were

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[8] The then Director General of the International Irrigation Management Institute (IIMI, officially recognized as the International Water Management Institute (IWMI) since 2000 (Giordano *et al.*, 2017).

thus deemed unsuitable as tools for water management strategies at the basin-level (Seckler, 1996; Giordano *et al*., 2017). Seckler (1996) argued that measures of agricultural WP were more appropriate indicators for use in the development of water management strategies targeting real water savings and efficiency gains. This sparked a change in water management research, adjusting the focus towards WP and basin management rather than irrigation efficiency and irrigation system performance (Rijsberman, 2006; Giordano *et al*., 2017). In the twenty plus years since the concept's inception, the notion of agricultural WP has progressed and remained the focus of much research and investigation within the agricultural water management domain (Rijsberman, 2006; Chouchane *et al.*, 2015; Grassini *et al.*, 2015; Giordano *et al.*, 2017; Kang *et al.*, 2017; Paredes *et al.*, 2017).

In broadest terms, WP indicates a ratio of production output per unit of water used (Giordano *et al.*, 2017). Both the denominator and numerator may be interpreted in various ways, depending on the scope, scale and intended use of the productivity measure. Water use may refer to the volume of water applied, the volume of water withdrawn or consumptive water use (CWU) (Amarasinghe and Smakhtin, 2014; Giordano *et al.*, 2017). Production is usually measured either physically or economically for WP calculations, with physical production referring to the physical mass of output, such as yield or biomass, and economic production referring to the output value in monetary terms, typically conveyed in terms of gross value of production (Pereira *et al.*, 2012; Giordano *et al.*, 2017). When assessing crop production, physical WP calculated using CWU is essentially the inverse of combined blue and green WF (Amarasinghe and Smakhtin, 2014).

Production may also be expressed in other ways in WP calculations. For example, 'Standardised Gross Value of Production' (SGVP) may be used as the numerator in the ratio of economic WP (EWP) (Molden, 1997; Mainuddin and Kirby, 2009; Karimi *et al*., 2011; Rebelo *et al.*, 2014; Sharma *et al.*, 2015). SGVP is used as an alternative to conventional economic production, allowing for the comparison of productivities across diverse backgrounds of crop and food production by employing world prices (Molden, 1997; Sharma *et al.*, 2015). SGVP is calculated by first using local prices to convert crop yield into that of a major traded crop, and then converting the resultant physical production volume into economic production using the traded crop's world price (Molden, 1997; Sharma *et al.*, 2015). Another alternative is to measure production in terms of nutritional value (Sharma *et al.*, 2015; Giordano *et al.*, 2017).

For example, Renault and Wallender (2000) calculated the nutritional water productivity of main crops and food products in California by measuring production output in terms of energy (kilocalories), protein and calcium content. It was found that animal products were less productive in terms of water use than crop products, and that a balanced vegetarian diet requires substantially less water per capita per day than an animal product-based diet (Renault and Wallender, 2000). This echoes the findings by Mekonnen and Hoekstra (2012) in their global assessment of the water footprint of farm animal products.

Four key ‘pathways’ have been identified for improving WP at the basin level (Molden *et al*., 2007; Giordano *et al*., 2017). The first is to improve productivity per unit of CWU, which may be achieved by optimising crop choice, irrigation systems, and inputs unrelated to water. The second is to reduce non-productive blue water consumption, remembering to consider ecological water use requirements and other potential water consumers (Molden *et al*., 2007). This may be achieved by decreasing evapotranspiration (ET), salinization and unrecoverable runoff and percolation. Thirdly, the potential of un-utilised water resources can be explored, taking into account potential environmental impacts and downstream consumers. The final pathway is to transfer water resources between and within sectors, reallocating supply towards more productive consumers (Molden *et al*., 2007; Giordano *et al*., 2017).

WP and the parallel notion of improved food production at equivalent or reduced levels of water consumption (colloquially referred to as ‘more crop per drop’) has become a popular concept, particularly for addressing the issues of food security, water scarcity, and environmental sustainability (Sharma *et al.*, 2015; Giordano *et al*., 2017). However, WP is a single factor productivity (SFP) measure in an environment in which a wide array of factors play a role, and it is important to investigate the costs and benefits of improved WP before pursuing a related water management strategy (Wichelns, 2015b; Giordano *et al*., 2017). In order to avoid undesirable consequences, socio-economic and ecological factors need to be accounted for before action is taken to increase WP (Rijsberman 2006; Molden *et al*., 2007; Wichelns 2015b; Giordano *et al*., 2017). Rather than simply aiming to improve WP, a more suitable strategy may be to optimise WP, taking into account the broader set of factors which may be impacted (Wichelns, 2015b).

WP has remained relevant since its initial conception and has been utilised in numerous case studies: Grassini *et al.* (2015) evaluated yield gaps and the physical WP of soybean production in the western United States Corn Belt and found that WP could be increased by refining and improving farming practices. Deryng *et al.* (2016) assessed how rising carbon dioxide (CO_2) levels associated with climate change impact global crop WP. It was found that, by 2080, increased CO_2 atmospheric concentrations will result in higher crop WP, with levels increasing by between 10-38%, depending on crop type[9]. Kang *et al.* (2017) investigated opportunities for enhancing agricultural WP in order to achieve greater food security in China.

EWP was quantified by Chouchane *et al.* (2015) for main crops produced in Tunisia. Average EWP for rain-fed and irrigated agriculture was found to be fairly similar, with the rain-fed figure slightly exceeding that of irrigated crops. Tunisia's estimated EWP of crop production was found to be lower than that found in Spain (equated to approximate US dollars), at 0.32 US\$/m^3 and approximately 0.35 US\$/m^3 respectively (Chouchane *et al.*, 2015). Paredes *et al.* (2017) analysed both the physical and economic WP of malt barley, finding that delays in sowing the crop corresponded with higher WP and EWP indices in drought, dry and wet years. When considering water-scarce conditions, it was concluded that farmers needed to find a balance between yield, water use, and EWP objectives (Paredes *et al.*, 2017). In South Africa, Munro *et al.* (2016) quantified both the physical and economic WP of citrus production in the Lower Sundays River Valley. Lemons were found to have the highest physical WP of the assessed cultivars, while navel oranges had the lowest. Lemons also had the highest EWP across cultivars (Munro *et al.*, 2016).

2.6 Synopsis

Water footprint and water productivity are two concepts which can be used as tools to help guide water management decisions in an environment of increased water scarcity and rising demand. This chapter discusses the literature surrounding these two concepts. The development, conceptual framework, and application of water footprint and water productivity are described, and criticisms surrounding the two concepts are reviewed.

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[9] Increasing CO_2 concentrations due to global warming are predicted to result in increased photosynthesis, and thus in lower crop water use (Deryng *et al.*, 2016).

Following this literature review, Chapter 3 will address the background to this research project, including global and local water scarcity issues, the citrus industry in South Africa, and the site-specific characteristics of the research area in which this case study will take place.

CHAPTER 3
CONTEXT AND BACKGROUND

3.1. Introduction

This chapter provides background and context to this research project, beginning with a brief description of the issue of water scarcity on both a global and national scale. The South African agricultural sector is described, followed by a summary of the country's citrus industry and its contribution to the nation's economy. A synopsis of the study region is then provided, including a description of citrus production in the region, as well as the water-supply structure, climate, and vegetative biomes characterising the area. Finally, a brief overview of the legislation surrounding water use and management in South Africa is provided.

3.2. Water Scarcity

Throughout history, availability of water has been strongly linked to economic activity (Damania *et al.*, 2017). With rising population growth and the impacts of climate change beginning to be felt, water scarcity has become a growing concern on a global scale. Rainfall is predicted to become increasingly erratic, and water scarcity is expected to emerge in previously unimpacted areas, while worsening in regions already suffering from a dearth of water (Hoekstra and Mekonnen, 2011; Damania *et al.*, 2017). In 2015, the United Nations (UN) highlighted the need for sustainable water management in their 2030 Agenda for Sustainable Development. Specifically, Sustainable Development Goal (SDG) 6.4 aims to "by 2030 substantially increase water use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity," (UN, 2015: 18). This echoes the sentiments of former UN Secretary General Kofi Annan, who called for a "Blue Revolution" directed at improving the productivity of water usage and achieving "more crop per drop" (2000:61).

South Africa has not been immune to the rising challenges relating to water availability. A semi-arid country, South Africa has been classified as water scarce, and climate change is expected to intensify water supply problems, particularly in the western part of the country (DWS, 2018a). Average annual rainfall in South Africa is approximately 450mm, in contrast to the global average of 860mm, and the country furthermore experiences large fluctuations in precipitation. Severe droughts have been experienced in recent years, with the government declaring a national disaster in early 2018 based on the drought experienced in the southern and western parts of the country (COGTA, 2018; DWS, 2018a; Macharia, 2018). Prolonged drought conditions were experienced throughout 2018 in several isolated regions across the country, including areas in the Eastern Cape, Western Cape, Limpopo, KwaZulu Natal and the Northern Cape (SAWS, 2018).

3.3. The South African Agricultural Sector

Agriculture in South Africa uses the largest proportion of the country's water resources. The sector is responsible for approximately 55% of the country's total surface water use, with the majority of this utilised for irrigation purposes (DWS, 2018a; FAO, 2016). In terms of water footprint, agriculture accounts for 94.7 % of the country's total WF of 58 853 million m^3 per annum, with irrigated agriculture's blue WF accounting for approximately 10.1% of the total figure (Pahlow *et al.*, 2015). Roughly a third of South Africa's crops are produced under irrigation, with irrigated agriculture occupying just 1.5% of South Africa's arable land (DWS, 2018a). Moreover, only a small proportion of the landmass in South Africa is arable, at approximately 12%. The growth and development of the country's agricultural industry is greatly influenced and limited by water availability, or more appropriately, water scarcity (DWA, 2013).

The agricultural sector in South Africa contributes to food security, is a valuable earner of foreign currency, and contributes substantially to the country's employment (DAFF, 2018b). The sector employs and supports approximately 8.5 million people, both directly and indirectly (DWA, 2013), with the majority of employment taking place in rural areas. Agriculture's contribution to GDP is approximately 2.2% (DAFF, 2018b), which seems trivial considering the proportion of water utilised by the industry. However, this figure does not provide a full representation of the impact of the industry on the country's economy. If the GDP contribution of sectors that are strongly linked to agriculture (such as agribusinesses) are accounted for, the total contribution is much greater, and was calculated to be roughly 7% of GDP in 2010 (Greyling, 2015).

In addition, in terms of multipliers, the agricultural sector has relatively strong backward linkages to other sectors in the South African economy, with increases in demand for agricultural products strongly influencing other sectors' outputs and contribution to GDP (Greyling, 2015). Agriculture in South Africa has been estimated to have a backward linkage factor of 2.14 on other sectors' GDP, and a forward linkage factor of 1.81 (i.e. higher prices in the agricultural sector impact prices in other sectors by a factor of 1.81) (Greyling, 2015). Backward linkages refer to the agricultural sector's demand from other sectors for inputs such as implements, machinery, fertiliser and chemicals. On the other hand, forward linkages are formed by the supply of agricultural products as inputs within other sectors (Davis *et al.*, 2002; DAFF, 2018b).

Agricultural production in South Africa was valued at R281 370 million for the year 2017/18[10], which was an increase of 4.7% on the previous year (DAFF, 2018b). Animal products make up approximately 47% of the total value, followed by horticultural products at 28%, and field crops at 25% (DAFF, 2018a). About 11% of South Africa's exports in 2017 were attributed to agricultural products in terms of value (SARS, 2017; DAFF, 2018a). Relatively high value exported agricultural products included fresh or dried citrus; wine; fresh or dried grapes; fresh or dried apples, pears and quinces; and maize (DAFF, 2018a).

3.4. The South African Citrus Industry

Citrus accounts for approximately 25% of the gross value of total horticultural production across the country (DAFF, 2018a; DAFF, 2018b), occupying 77 708 hectares of South African arable land (CGA, 2018). In terms of total crop production, citrus accounts for close to 15% of gross value; while it makes up for approximately 7% of the value of total agricultural production (DAFF, 2018a; DAFF, 2018b). The majority of citrus fruit produced in South Africa is exported (78%) (CGA, 2018), and citrus exports constitute the greatest proportion of the country's agricultural exports in terms of export value (DAFF, 2018a; DAFF, 2018b). In fact, South Africa is the second biggest exporter of fresh and dried citrus fruit across the globe (only surpassed by Spain), accounting for approximately 10% of world exports, and is the largest exporter in the Southern Hemisphere (ITC, 2018). The citrus industry in South Africa is therefore a valuable importer of foreign currency, exporting roughly 1 758 thousand tonnes

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[10] For the year 1 July 2017 to 30 June 2018

of fruit in 2017 (Agrihub, 2018) at a total value of approximately R18 670 million (DAFF, 2018a).

South African export of citrus has taken place since the early 1900s, and a citrus growers co-operative exchange was established in 1926 in order to co-ordinate and support citrus exports (Sippel, 2006). This co-operative was referred to as the Citrus Exchange, and later known as Outspan International. By 1966 all citrus exports fell under the 'Outspan' brand, and were exclusively channelled through the Citrus Board, which controlled marketing and distribution of all South African citrus exports (Sippel, 2006). This continued until 1997, when the deregulation of all fruit industries in South Africa took place, allowing for the registration of multiple export agents (CGA, 2018). This prompted the formation of the Citrus Growers Association of Southern Africa (CGA), which promotes market access, research, and transformation in the citrus industry, and is funded by a statutory levy on all growers who export citrus fruit (CGA, 2018).

The citrus industry is highly labour intensive, requiring a substantial number of labourers on farms and in packhouses. Upwards of 100 000 people are directly employed in the industry, and when indirect employment in the supply-chain is considered, an estimated million households are reliant on the industry for income (DAFF, 2017a).

Citrus varieties can be classified into four broad variety categories, namely oranges, lemons and limes, soft citrus (i.e. mandarins) and grapefruit (DAFF, 2017a). There are numerous cultivars which constitute each of these variety classifications. Oranges may be sub-categorised into two variety groups, namely valencia oranges and navel oranges (Bijzet, 2006a; CGA, 2018). Soft citrus includes multiple cultivars which may broadly be categorised into satsuma, clementine, and mandarin hybrid species (Bijzet, 2006a). Mandarin hybrids include nova and late mandarin cultivars. Valencia oranges make up the greatest proportion of all variety groups produced in the country, accounting for 37% of total production, followed by navel oranges (21%), soft citrus (i.e. mandarins) (17%), lemons and limes (15%), and finally grapefruit (10%) (CGA, 2018).

Figure 3.1 shows the gross value per ton of exported fresh oranges, soft citrus, grapefruit and lemons for the period of 2008-2017 (CGA, 2018). The US dollar (USD) to South African Rand (ZAR) exchange rate is also shown (SARB, 2018), which illustrates the correlation between returns for exported production and the rand value of foreign currency. Over the ten-year period, soft citrus and lemon gross returns per ton were consistently higher than those for oranges and grapefruit, except for 2009, when the return for lemons dropped and was exceeded by that of oranges. Prior to 2014, soft citrus returns typically exceeded those of lemons. Apart from 2017, when the return for both varieties was very similar, lemons' return per ton has tended to exceed that of soft citrus in recent years.

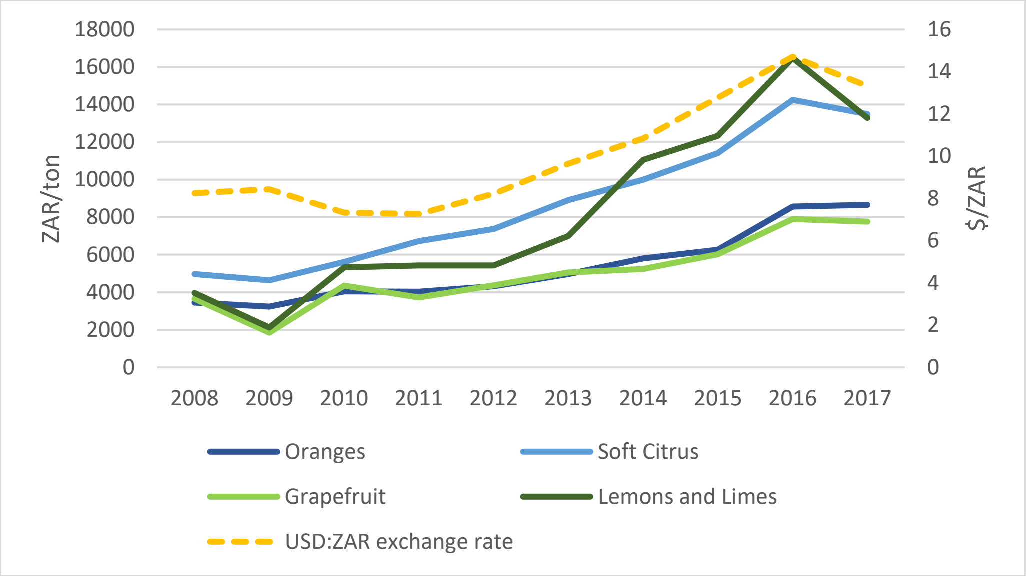

Figure 3.1: Gross Value Per Ton of South African Citrus Exports, and the US Dollar to Rand Exchange Rate (USD:ZAR): 2008-2017

Source: CGA (2018); SARB (2018)

Citrus in South Africa is chiefly cultivated in three provinces, with 42% of the country's production taking place in Limpopo, 26% in the Eastern Cape, and 17% in the Western Cape (CGA, 2018). In the Eastern Cape, the three main production regions are the Eastern Cape (EC) Midlands (which is the study area of this project), the Lower Sundays River Valley, and Patensie (DAFF, 2017a). The climate in the Eastern and Western Cape regions is cooler than that in the North and East of the country (DAFF, 2017a). This cooler climate makes these two regions more suitable for the production of soft citrus, 70% of which is produced across the two provinces (Bijzet, 2006b; DAFF, 2017a; CGA, 2018). Other varieties which are suited to this relatively cool climate are navel oranges and lemons (Bijzet, 2006b; DAFF, 2017a). Valencia oranges may be produced within warmer microclimates situated in these provinces. In contrast, the warmer climate in Limpopo and Mpumalanga is more suitable for the production of grapefruit and valencia oranges (Bijzet, 2006b; DAFF, 2017a). The Eastern Cape produces approximately 47% of the lemons and limes cultivated across the country; 40% of navel oranges; 30% of soft citrus; 15% of valencia oranges; and only 2% of grapefruit.

Two major threats to the citrus industry identified in DAFF's annual profile of the South African citrus market value chain (2017a) are the availability and cost of irrigation water, and the impact of climate change. Citrus trees require water on a regular basis throughout the year, with flowering, fruit set, yield, internal quality and fruit size all highly sensitive to water stress (Mostert, 2006; Taylor and Gush, 2014). As such reliability of water supply is an important aspect of any citrus producing enterprise. Citrus trees require between 850 and 1000 mm of water per annum, with more than 50% of this requirement theoretically falling between the months of November and February (Mostert, 2006; Taylor and Gush, 2014).

The citrus industry in South Africa also faces other threats and challenges, such as pests and diseases; increased protectionism and non-tariff barriers from importing countries; and variation in the exchange rate of foreign currency (DAFF, 2017a). Decision makers therefore need to base their actions on a wider array of factors than simply water supply.

3.5. Study Region

The EC Midlands is one of the three primary citrus producing regions within the Eastern Cape (DAFF, 2017a; CGA, 2018). The region primarily produces soft citrus (at approximately 46% of estimated 2018 export production), navels (31%) and lemons (21%) (Brooke, 2018). Valencia oranges only make up approximately 2% of production in the area, and grapefruit production is negligible (Brooke, 2018). Figure 3.2 illustrates the estimated export volumes of various variety groups produced in the EC Midlands for the period spanning 2012 to 2018. Quantities are expressed in 15kg carton equivalents[11].

As can be seen in Figure 3.2, soft citrus volumes have gradually increased over the years, eventually overtaking navel production in the area. This illustrates newly planted soft citrus orchards coming into production and their increasing yield as they mature. Citrus production is growing in the Eastern Cape, and in 2017 the province had the highest proportion of new plantings in the country, consisting primarily of lemons and soft citrus (CGA, 2018).

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[11] Fresh citrus is typically packaged and exported in 10-15kg cartons (although not exclusively). 15kg cartons are widely used, and citrus export volumes are generally expressed in 15kg carton equivalents.

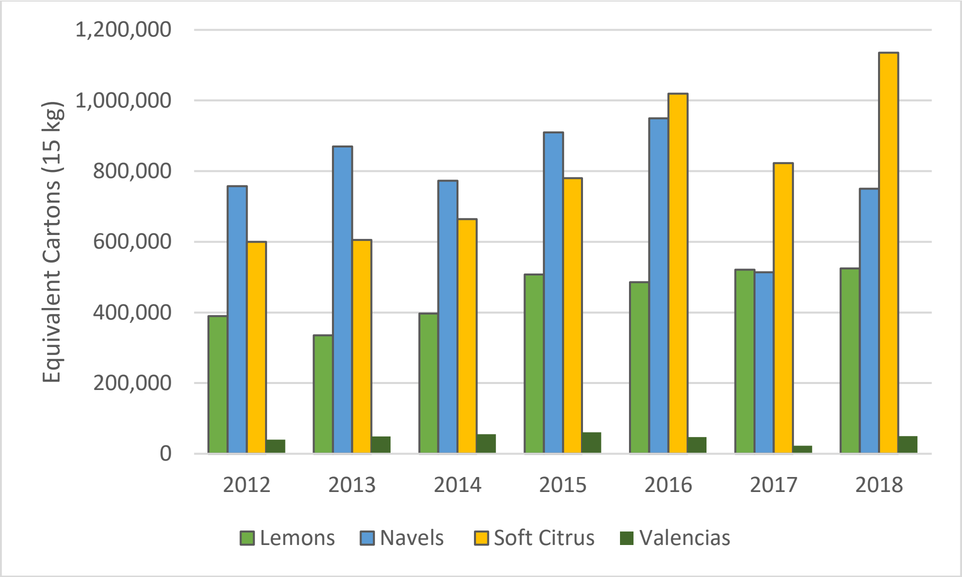

Figure 3.2: Estimated Export Citrus Production in the Eastern Cape Midlands: 2012-2018

Source: Brooke (2018).

The specific study region for this project is located across three river valleys in the EC Midlands, namely the Koonap, Kat, and Great Fish River valleys, with study sites situated in the vicinity of the towns of Adelaide, Fort Beaufort and Cookhouse respectively. The study region falls within the Mzimvubu-Tsitsikamma WMA. The study region, along with the approximate locations of the specific study sites, are illustrated in Figure 3.3.

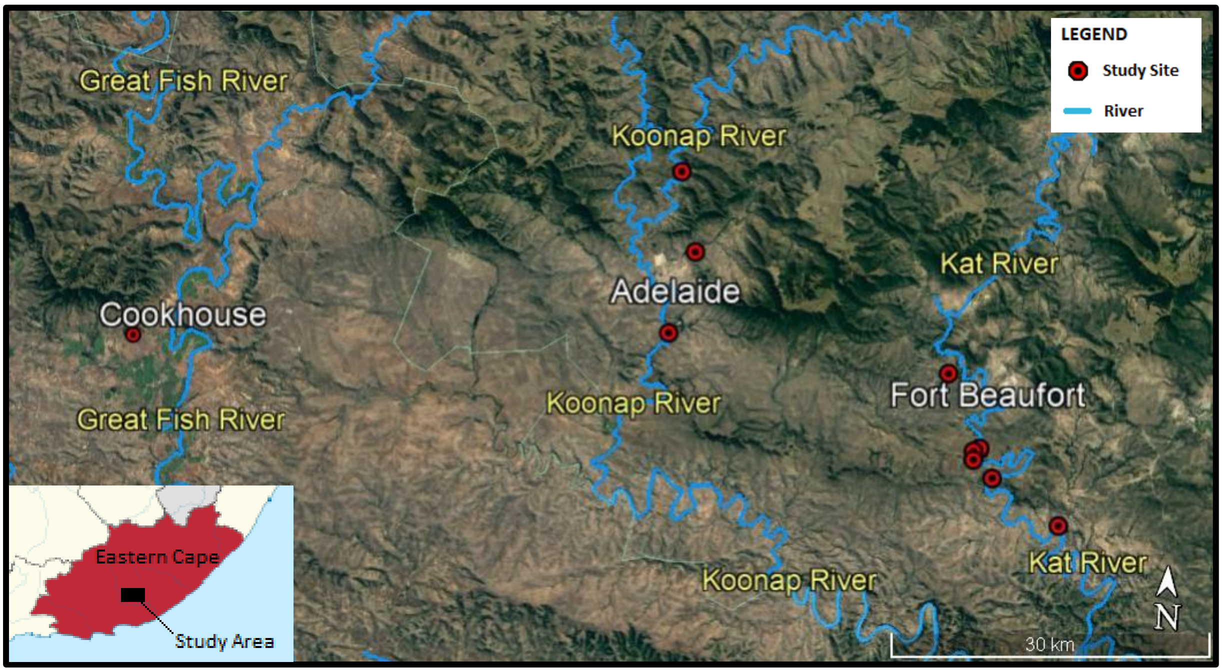

Figure 3.3: Map of Study Area within the Eastern Cape Midlands
Source: Created using Google Earth (2018) and supporting data from DAFF (2017b).

3.5.1. Water Supply Structure

The study site on the Great Fish River, in the vicinity of Cookhouse, as well as that which is upstream of Fort Beaufort (on the Kat River) have state water entitlements (commonly referred to as ‘water rights’) of 12 500 m^3/ha/annum and 10 900 m^3/ha/annum respectively (DWS, 2014). These entitlements stem from the development of state water schemes, which holders of water rights have access to. The schemes in question are the Orange-Fish Transfer Scheme and the Kat River Dam. Farms with scheme-supplied water entitlements (hereafter referred to as water rights) generally have relatively reliable access to water. Water allocations for holders of water entitlements are typically specified in terms of permitted extraction volume per hectare, defined for a specific area of land.

The assessed citrus farms situated in the Koonap River Valley (i.e. the Adelaide region) and downstream of Fort Beaufort on the Kat River are required to register as water users, needing to periodically apply for certificates of verification of the ‘extent and lawfulness of water use’ in terms of section 35 of the NWA (1996). These verification certificates lay out the volume of water that farmers are permitted to utilise as determined by the Department of Water and Sanitation (DWS), both in terms of withdrawals for irrigation and storing of water. In contrast to water users with access to state schemes, these water users (hereafter referred to as registered water users) are typically reliant on natural flows and environmental factors for water supply.

Registered water users’ allocated volume is not transferrable and is linked to a specified erf. Similarly, water rights (i.e. scheme entitlements) are linked to title deeds, though they do not appear on these documents. Theoretically, these entitlements may be transferred between title deeds, subject to statutory approval. However, since the introduction of the NWA in 1996, it has not typically been the practice of government to approve such transfers (Knott, 2018). The fact that water rights are typically non-tradable, and the comparably high reliability of water supply generally characterising scheme entitlements, mean that land linked to water rights is commonly valued substantially higher than land without access to such schemes. It should be noted that short-term leases or transfers of water rights between title deeds within the same scheme have been permitted (Knott, 2018). Water allocations are not guaranteed, and may be reduced, or even completely detached, by state authority (NWA, 1998). For instance, during the drought experienced in 2018, water allocations in the Langkloof Irrigation Area in the Langkloof Valley of the Eastern Cape were reduced to 20% of their normal level[12] (Jansen, 2018; Jansen, 2019).

Water rights within schemes are defined for a certain area of land per title deed, and if water use per hectare is lower than the specified volume, water users may extend water use across a greater area of land on that same property, provided that total water use remains within the maximum bounds of that specified for the entitlement (Knott, 2018). Farms with linked water rights are therefore incentivised to utilise less water per hectare, as the unused proportion of the per-hectare water allocation may be used for expanded production[13]. Alternatively, farmers may obtain permission to temporarily lease excess water (i.e. the proportion of the water allocation which is unused) to other farms within the same scheme. Farmers with water rights are therefore incentivised to utilise water as efficiently as possible.

Registered water users are limited by the inconsistency of water availability and flows. These water users are not necessarily incentivised to utilise water efficiently, particularly in times of plenty (i.e. periods with no water shortages). However, when planning orchards, farmers need to consider likely water availability in dry years and consider the incidence and likelihood of water-scarcity. Farmers are therefore incentivised limit cultivation to a level such that water requirements are sustainable both in wet and dry years. Both registered water users and water users with scheme rights are charged for water use. Scheme charges are typically higher, due to the higher level of maintenance required.

Certain registered water users in the vicinity of Fort Beaufort may occasionally purchase water releases from the Kat Dam, which ease water availability challenges during times of scarcity. The feasibility of a dam to be constructed upstream of the settlement in the Adelaide region (known as the Foxwood Dam) has been investigated by the DWS (2015). Such an undertaking has the potential to alter water supply systems and infrastructure in the Adelaide region, specifically for farms downstream of the settlement.

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[12] Since increased to 40% of normal allocation in early 2019 (Jansen, 2019).

[13] Provided that required permissions (such as environmental impact assessment (EIA) approvals) are granted.

3.5.2. Climate

The Eastern Cape is the second largest province in South Africa, and its long coastline and large expanse result in highly variable climatic conditions across the province (Bijzet, 2006a). However, some generalisations can be made. Winters across the entire region are typically cool to cold, with moderate frost in some areas. Summers are generally warm to hot, and rainfall typically takes place in summer months (Bijzet, 2006a). In the study region specifically (i.e. the EC Midlands), historical rainfall typically varies between 300 and 700 mm/annum, with an average annual rainfall of roughly 450-500mm (ARC-ISCW, 2018). Along with much off the rest of South Africa, the EC Midlands has suffered from recurring and severe droughts in recent years (Brooke, 2018; SAWS, 2018).

The climate in the region is suited to the production of soft citrus varieties, navel oranges, and lemons (which are the variety groups predominantly grown in the area) (Bijzet, 2006a; Brooke, 2018). The EC Midlands are positioned at a higher altitude than other production regions in the Eastern Cape (i.e. Patensie and the Lower Sundays River Valley). The region is also located more inland than other producing regions in the Eastern Cape, and this, coupled with its higher altitude, results in the area having a more continental climate than other regions, experiencing relatively cold nights coupled with warm to hot day time temperatures (Sparks, 2018). These diurnal fluctuations in temperature are understood to favour colour development and high internal sugar levels in citrus, and particularly in soft citrus (Bijzet, 2006 a, b; Sparks, 2018). These climatic characteristics typically result in high quality fruit being produced in the region. However, the area does not necessarily achieve the yield volumes obtained in more sub-tropical environments, and the cooler night temperatures experienced also result in a higher risk of frost (Sparks, 2018).

3.5.3. Biomes and Vegetation Characteristics

South Africa has 9 biomes made up of 435 vegetation units (Rutherford *et al.*, 2006a; Rutherford and Mucina, 2006). Apart from the desert biome, all biomes in South Africa occur in the Eastern Cape (Rutherford *et al.*, 2006a). The study sites assessed in this project fall within three of these biome categories – namely Grassland, Savanna and Albany Thicket biomes, with some study sites located in marginal areas, on the border of different biome categories (SANBI, 2012). In the Fort Beaufort region, the vegetation surrounding the study site upstream of the settlement is categorised as Bhisho Thornveld, which is a Savanna vegetation unit (Rutherford *et al.*, 2006b; SANBI, 2012). Downstream of the settlement, farms' vegetation is either categorised as Bhisho Thornveld or Great Fish Thicket (an Albany Thicket vegetation unit) (Hoare *et al.*, 2006; SANBI, 2012). In the Adelaide region, the vegetation unit upstream of the settlement is classified as Great Fish Thicket, while downstream is Bedford Dry Grassland, as is the vegetation in the vicinity of the Cookhouse study site (Mucina *et al.*, 2006; SANBI, 2012).

Bedford Dry Grassland and Great Fish Thicket occur in the vicinity of all three river valleys, while Bhisho Thornveld is only present in the vicinity of Fort Beaufort. Bedford Dry Grassland and Bhisho Thornveld both typically occur on undulating plains, though the latter may also occur on moderately steep slopes (Mucina *et al.*, 2006; Rutherford *et al.*, 2006b). Bedford Dry Grassland is characterised by loamy or clay loam soils, and dry, open grassland with scattered woodland vegetation (Mucina *et al.*, 2006). Rainfall generally occurs in late summer or spring, and frost may occur on between 3-31 days per annum. Similar to the Bedford Dry Grassland vegetation unit, Bhisho Thornveld soils are typically loamy, though they can vary substantially across regions (Rutherford *et al.*, 2006b). Environmental conditions also differ across areas characterised by this vegetation unit, as its distribution is relatively extensive. Predominantly summer rain is experienced, with average inland mid-summer daily maximum temperatures of 28^{o}C, and mid-winter minimum temperatures averaging 3^{o}C inland (Rutherford *et al.*, 2006b).

The Great Fish Thicket vegetation unit, which forms part of the Albany Thicket biome, generally occurs on steep slopes, and is typified by shallow clayey soil (Hoare *et al.*, 2006). Rainfall usually occurs in late spring and late summer/early autumn, though precipitation may occur year-round. Frost days range from zero in coastal areas to over 60, depending on location (Hoare *et al.*, 2006). Average July minimum daily temperatures are 0^{o}C inland (9^{o}C in coastal areas); and average January daily maximum temperatures range from 30^{o}C inland to 26^{o}C in coastal areas respectively (Hoare *et al.*, 2006).

Other vegetation units in the vicinity of the study region include Albany Broken Veld (Nama-Karoo biome); Eastern Cape Escarpment Thicket (Albany Thicket); Southern Mistbelt Forest; Amathole Montane Grassland; and Karoo Escarpment Grassland (SANBI, 2012).

3.6. Overview of South African Water Policy

Water policy in South Africa is principally governed by the National Water Act (NWA) (Act No. 36 of 1998) and the Water Services Act (Act No. 108 of 1997). The Water Services Act primarily lays out municipal rules for water services, such as the supply of potable water and water sanitation services (DWAF, 1998). In contrast, the NWA addresses policy surrounding water resources, laying out regulations for their use, protection, development, conservation, control and management in a sustainable, equitable manner which is universally beneficial (NWA, 1998). The NWA has its foundations in the Constitution (Act 108 of 1996), which specifies that South Africans have the right to sufficient and safe water, requires that the environment be safeguarded for current and future generations, and states that government is the custodian of water resources in the country (DWAF, 1998).

The fundamental principles guiding the NWA are sustainability, equality and efficiency (DWAF, 1998; DWA, 2013). International best practices for water resource management were used as a basis for the NWA (Bourblanc, 2017). Though very progressive, the principles of the NWA are potentially contradictory in the South African context, particularly when considering water scarcity conditions, competition for resources, developmental limitations, and the economic growth and unemployment challenges faced in this country (Conradie, 2002; Perret, 2002; Munro *et al.*, 2016; Bourblanc, 2017).

The National Water Resource Strategy (NWRS) is the instrument through which the objectives of the NWA are implemented. The NWRS, required by the legislation to be formally reviewed at regular intervals, provides the 'framework' through which both national and regional water resource management activities are carried out (NWA, 1998). The second edition of the NWRS, published in 2013, specifically expresses its purpose to regulate South Africa's water resources in such a manner as to advance the country's growth and socio-economic development, in circumstances which it states differ substantially to those transpiring during the development of the first edition of the NWRS in 2004 (DWA, 2013).

In order to regulate national water resources at a regional level, the NWRS has specified separate water management areas (WMAs) across the country (DWA, 2013), each of which are required to have a distinct catchment management strategy (CMS) for the 'protection, use, development, conservation, management and control of water resources' within that particular catchment (NWA, 1998: 9), and which lays out the water allocation plan for that WMA. Catchment management agencies (CMAs) in each WMA are responsible for the development of that region's CMS, ensuring that strategies involve participation and contribution from local stakeholders, and that they are in line with the NWRS and national legislation (NWA, 1998; DWA, 2013).

At the sub-CMA level, the NWA also regulates Water User Associations (WUAs). The majority of WUAs originate from irrigation boards formed prior to the NWA (DWAF, 1998). WUAs have no powers in terms of water management decisions unless appointed by the local CMA or Minister of Water and Sanitation (DWAF, 1998; NWA, 1998). WMAs may be founded by water users who wish to work together regarding water-related activities relating to irrigation water use; effluent and waste water management; environmental protection; and recreational water use, amongst others (DWAF, 1998).

In terms of the applicability of WF tools in policy, Reddy *et al.* (2014b) propose that an analysis of national WF could assist with water allocation decisions between strategic water users (such as agricultural entities) and municipalities. However, WF at a basin or catchment level is considered more useful. CMAs are required to consider the interests of local stakeholders, and knowledge regarding the WF of various entities within catchments can assist with water management decisions (Reddy *et al.*, 2014b). Activities relating to WF allowed for in the NWRS include water offsetting and water trading, though the concepts need to be fine-tuned in terms of operational feasibility (DWA, 2013).

3.7. Synopsis

This chapter provides background and context to this research project. Water scarcity across the globe and in South Africa is briefly discussed. This is followed by a description of the South African agricultural sector and citrus industry. An overview of the study region is provided, including a synopsis of citrus production in the region, and a description of the water supply structure, climate, and vegetative biomes present in the region. This chapter is followed by a description of the methods utilised to conduct the research undertaken in this project.

CHAPTER 4
RESEARCH METHOD

4.1 Data collection

In order to evaluate blue, green and grey water footprint, calculate economic water productivity and assess sustainability a variety of data sources were required. As far as possible, local data was utilised. Primary data was collected through personal interviews with farmers and representatives of the local citrus packhouse and marketing co-operative (see Appendix 1)[14]. In addition to primary data obtained, several secondary data sources were utilised. The data sources made use of in this project are detailed alongside the various methods in which they were applied in sections 4.2 to 4.6 below. A summary of the data used, and corresponding data sources may be found in Appendix 2.

Farm interviews took place for ten farms located across the Kat, Koonap, and Fish River valleys. Six of these farms are situated in the vicinity of the town of Fort Beaufort (located in the Kat River Valley), three in the vicinity of Adelaide (located in the Koonap River valley); and one on the Fish River in the vicinity of Cookhouse. All participating farms are members of and utilise a collective packhouse and marketing co-operative situated in Fort Beaufort, from which additional information was obtained.

4.2 Water Footprint Accounting: An Overview

The Water Footprint Assessment Manual (Hoekstra *et al.*, 2011) provides specific guidelines for calculating the blue, green and grey WF of the process of growing a crop or tree. The method described in the manual applies to annual as well as perennial crops and is therefore suitable for calculating the WF of citrus production (as citrus is a perennial crop).

Total WF of the process of growing a crop or tree is made up of the green, blue and grey WF of that process (see Equation 1), expressed in volume of water per mass (Hoekstra *et al.*, 2011). For the purposes of this project, all WFs will be expressed in m^3/tonne.

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[14] Interview questions for the research were approved by the Rhodes University Research Ethics Committee.

$$WF_{proc} = WF_{proc,green} + WF_{proc,blue} + WF_{proc,grey} \tag{1}$$

The green WF of a process ($WF_{proc,green}$) is an indicator of the green water appropriated during that process (i.e. the precipitation water appropriated). For agricultural crops this includes green water evaporation from fields and orchards and green water incorporation into the crop (Hoekstra *et al*., 2011). Similarly, blue WF of a process ($WF_{proc,blue}$) indicates the consumptive use of blue water during that process (i.e. the appropriation of surface and ground water), and encompasses blue water evaporation, incorporation, and lost return flows (Hoekstra *et al*., 2011). In order to estimate green and blue water appropriation, crop-specific properties and climate, soil and irrigation data were used to estimate evapotranspiration by means of a crop model. The volume of water incorporated into the crop is typically negligible in comparison to the volume of evaporated water (in general in the region of 0.1% of evaporated water) (Hoekstra *et al*., 2011), and as such this component of consumptive water use was not included in calculations.

The grey WF of a process ($WF_{proc,grey}$) indicates the extent of water pollution connected to that process, expressed broadly in terms of the quantity of water needed to dilute contaminants to the point that their concentration is no longer harmful (Hoekstra *et al*., 2011; Franke *et al*., 2013). Allowable pollutant levels are determined by ambient water quality standards. Typically, a number of pollutants may be applied during agricultural processes, be they in the form of fertilizers, pesticides or insecticides. Only the most critical pollutant (the pollutant which requires the largest volume of water to assimilate its load) is accounted for. Grey WF calculations were conducted based on fertilizer applications (in the form of nitrogen, phosphorous and potassium) directly to the soil, with only the most critical of these pollutants finally being accounted for.

Blue, green and grey water footprints were calculated for various citrus enterprises across three river valleys in the Eastern Cape Midlands, situated in the proximity of the towns of Cookhouse, Adelaide and Fort Beaufort respectively. The variety groups (i.e. cultivar groups) for which the water footprints were calculated were lemons, oranges, satsumas, mid-season mandarins and late mandarins. Since water footprints may differ substantially over time and under varying climatic conditions, the method utilized by Munro *et al*. (2016) whereby water footprint is assessed and compared across an average year (using long term average data), a wet year and a dry year was applied.

4.3 Blue and Green Water Footprint Accounting

Blue and green WF calculations were conducted based on the guidelines put forward by Hoekstra *et al*. (2011) for calculating the water footprint of growing a crop or tree. Blue water footprint was calculated by dividing the blue component of crop water use across the complete growing period (CWU_{blue}), by the yield produced (expressed in tonnes/ha). Similarly, green WF was calculated by dividing the green component of crop water use (CWU_{green}) by yield.

$$WF_{proc,blue} = \frac{CWU_{blue}}{Yield} \qquad [m^3/tonne] \qquad (2)$$

$$WF_{proc,green} = \frac{CWU_{green}}{Yield} \qquad [m^3/tonne] \qquad (3)$$

CWU_{blue} and CWU_{green} respectively indicate the amount of irrigation and rainwater lost to evaporation in the field during the growing period, and CWU is accordingly calculated as the sum of daily evapotranspiration across the length of the growing period (LGP) of the crop. Since citrus is perennial, the growing period continues throughout the year. Equations 4 and 5 show the formulae used to calculate CWU_{blue} and CWU_{green}. ET_{blue} and ET_{green} refer to blue and green evapotranspiration respectively. The sum of daily ET across the growing period is multiplied by ten in order to convert water measured in millimetres to water measured into m^3/ha (Hoekstra *et al*., 2011).

$$CWU_{blue} = 10 \times \sum_{d=1}^{LGP} ET_{blue} \qquad [m^3/ha] \qquad (4)$$

$$CWU_{green} = 10 \times \sum_{d=1}^{LGP} ET_{green} \qquad [m^3/ha] \qquad (5)$$

For perennial crops, Hoekstra *et al*. (2011) notes that the annual average evapotranspiration and the average annual yield over the tree's entire lifespan should be used, so that differences across the various stages of tree maturity can be accounted for. Citrus trees have an expected lifespan of approximately 25-30 years, depending on variety (Malan, 1991). During farmer interviews the existence of several orchards closer to 40 years old were indicated. Historical data availability extending to that period was highly limited. An alternative method utilised by Munro *et al*. (2016) was instead applied, whereby CWU was calculated for citrus trees within different age groups, and then weighted according to the proportion of trees within each age group.

Munro *et al.* (2016) made use of two age groups for citrus trees, namely young (0-5 years) and mature (6 years and older.) In general, citrus trees take three or more years after being planted to produce marketable fruit, after which potential yield increases steadily until trees reach maturity (Malan, 1991; Alexander, 2015). Figure 4.1 illustrates how potential yield changes with tree age, expressed as a percentage of the maximum potential yield achievable at tree maturity.

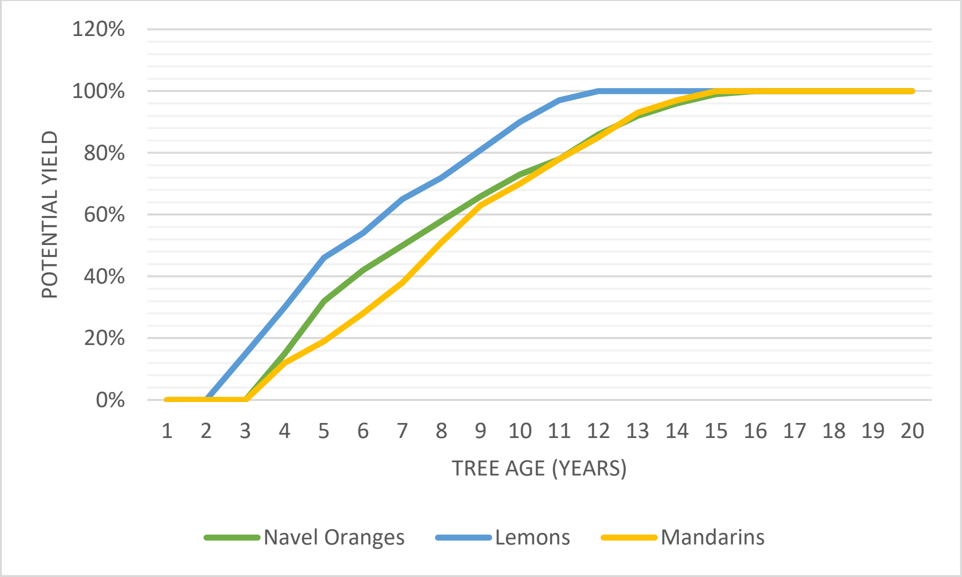

Figure 4.1: Potential Yield Percentage According to Tree Age for Navel Oranges, Lemons and Mandarins

Source: Malan (1991).

In general, trees do not reach their maximum potential yield until 12 to 15 years after planting date, and yield volumes change substantially from age at first productive harvest until maturity. Citrus trees were therefore categorised into three broad age groups, namely young, intermediate and mature. These age group classifications, laid out in Table 4.1 below, are based on the potential yield characteristics of citrus at various stages of maturity (supplied by Malan, 1991). Note that mandarins encompass satsumas, mid-season mandarins and late-mandarins. Young trees were categorised as those aged 0-3 years, with an average potential yield of 0-5% (essentially non-productive trees) (Malan, 1991). Trees categorised into the intermediate age group were those with an approximate potential yield of between 15 and 75% of maximum potential yield, and an average potential yield of roughly 50% (Malan, 1991). Mature trees were categorised as those with a potential yield percentage of above 75%.

Table 4.1: Age Group Classification of Navel Oranges, Lemons and Mandarins based on Potential Yield

Age Classification	**Tree Age (Years)**		
	Navel Oranges	**Lemons**	**Mandarins**
Young	0-3	0-3	0-3
Intermediate	4-10	4-8	4-10
Mature	11+	9+	11+

Once calculations for CWU_{blue} and CWU_{green} were completed for young, intermediate and mature variety groups produced on each farm and within each river valley, weighted CWU_{blue} and CWU_{green} were calculated based on the proportion of trees falling within each age group. Weighted CWU_{blue} and CWU_{green} were then used for blue and green WF calculations, computed for a long-term average (LTA) year, as well as for a representative 'wet' and 'dry' year. Yield data for WF calculations was obtained from the local citrus co-operative packhouse, which is used exclusively by all participant farms. LTA yield was calculated using averaged yield data across the last ten years (2008-2017). WF calculations for a 'wet' and 'dry' year used yield figures from the designated 'wet' and 'dry' years respectively.

4.3.1 Evapotranspiration

Evapotranspiration refers to water loss by means of the dual processes of evaporation from the soil surface and crop transpiration (Allen *et al*., 1998). Evaporation is primarily determined by the amount of solar radiation reaching soil in which crops are grown. As crops grow and foliage and ground cover become more substantial, less water is lost due to evaporation, and transpiration becomes increasingly responsible for water appropriation.

The direct calculation of evapotranspiration using empirical formulas is challenging and expensive (Hoekstra *et al*., 2011). It is more common for ET to be estimated indirectly via models founded on the underlying formulas, using local climate, soil and crop-specific input data. ET was estimated using SAPWAT4, a program developed by the Water Research Commission (WRC) in South Africa to estimate crop water and irrigation requirements. The SAPWAT4 program is based on FAO drainage report No.56 (Allen *et al*., 1998), which lays out guidelines and procedures for the computation of evapotranspiration (van Heerden, 2017). The program adheres strictly to the recommendations contained in the FAO report (van Heerden & Walker, 2016).

In order to estimate crop water requirements, SAPWAT4 calculates crop evapotranspiration (ET_c) by relating the reference evapotranspiration (ET_o) to the relevant crop in question by means of its crop coefficient (K_c) (van Heerden & Walker, 2016). ET_o indicates the rate of ET from a standardised reference surface or vegetation (typically grass) that has access to adequate water supply (Allen *et al*., 1998). ET_o accounts for the impact of weather parameters, such as temperature, radiation, wind speed and humidity, but is not influenced by crop-specific characteristics or management and environmental factors. The internationally accepted standard method for the calculation of ET_o is the FAO Penman-Monteith equation (van Heerden & Walker, 2016). The equation is published and recommended for use in the FAO drainage report No. 56 (Allen *et al*., 1998), and is accordingly employed by SAPWAT4.

The crop coefficient (K_c) represents the differences between crops in terms of evapotranspiration. K_c links ET_o to ET_c by accounting for aerodynamic resistance and crop canopy disparities of the crop in question from the reference crop (Allen *et al*., 1998). Crop evaporation and transpiration change as the crop develops, adjusting through the various stages of crop growth, and the crop coefficient changes accordingly. The four crop growth stages utilised by Allen *et al*. (1998), and thus by SAPWAt4 are the initial stage, the crop development stage, the mid-season stage, and finally, the late season stage. These four stages were defined for primary citrus production and are described in section 4.3.2 (c). K_c for these four stages is combined and then utilised to estimate the crop water requirement.

K_c may be expressed as a single coefficient or divided into two separate components which individually express the effects of transpiration and evaporation respectively (Allen *et al*., 1998). Equation 6 expresses the single crop coefficient approach for the calculation of ET_c, while equation 7 shows the dual crop coefficient approach. K_{cb} represents the basal crop coefficient, which describes plant transpiration, while K_e is the soil water evaporation coefficient, which indicates soil surface evaporation (Allen *et al*., 1998).

$$ET_C = K_c \times ET_o \tag{6}$$

$$ET_C = (K_{cb} + K_e) \times ET_o \tag{7}$$

The dual crop coefficient approach is used by SAPWAT4 (van Heerden & Walker, 2016). The approach is more appropriate than the single crop coefficient approach for irrigation scheduling in real-time and for high frequency water application (such as micro-irrigation) (Allen *et al*., 1998). Weather data is used to find K_e, while the K_{cb} of the relevant crop is dependent on the duration of its various growing periods (van Heerden & Walker, 2016).

ET_{blue}, and thus CWU_{blue}, were found utilising SAPWAT4 irrigation requirement results, including losses due to irrigation system inefficiencies, but excluding runoff and percolation losses. SAPWAT4 determines effective rainfall (P_{eff}) by taking into account rainfall intensity and the soil water balance (van Heerden *et al*., 2009; van Heerden, *et al* 2014 in Munro, 2015). ET_{green} was therefore obtained from P_{eff}, which was found for each variety group grown within the three river valleys.

4.3.2 SAPWAT4

SAPWAT was developed in the late 1990s as a computer program used to estimate irrigation requirements and establish scheduling strategies, specifically catering to Southern African requirements (Crosby and Crosby, 1999). Subsequent to the initial development of the program, FAO Irrigation and Drainage Paper No. 56 (hereafter referred to as FAO 56) was published, presenting guidelines for crop water requirement calculations, and providing what has since become the established approach for evaluating crop evapotranspiration (Allen *et al*., 1998; WRC, 2016b). In 2008, a reprogrammed version of SAPWAT was launched, known as SAPWAT3, developed in accordance with the guidelines published in the FAO 56, and making use of the recommended Penman-Monteith approach described therein (van Heerden & Walker, 2016). SAPWAT4, introduced in 2016, is an upgraded version of SAPWAT3, developed using the same principles and guidelines (van Heerden & Walker, 2016; van Heerden, 2017). The objectives for the development of SAPWAT4 were to enhance functionality, to update the data incorporated in the program, and to upgrade the program in line with technological upgrades in computer software (van Heerden & Walker, 2016).

In order to estimate crop water requirements, or crop evapotranspiration using SAPWAT4, various data inputs are required. These include weather and soil data, crop characteristics, as well information regarding irrigation practices.

a) Weather and Climate Data

In order to find daily reference ET (ET_o) by means of the Penman-Monteith equation, SAPWAT4 requires weather data, which may be specified on either a daily or monthly basis. SAPWAT4 allows weather data to be manually added[15]. Daily weather data was obtained from the Agricultural Research Council (ARC-ISCW, 2018) for weather stations located in the near vicinity of each study site. These records were then converted to monthly data, and the long-term average (LTA) mean monthly data was manually added for each of the three locations, calculated over a period of thirteen years, from 2005 to 2017. This time period was chosen due to availability of reliable and complete weather data. Mean monthly values were also included for a “dry” year and a “wet” year, as per the method applied in the WFA of citrus production conducted in the Lower Sundays River Valley in South Africa (Munro *et al.*, 2016). Due to an indexing problem discovered in SAPWAT4 (van Heerden, 2018), manual appending of weather data had to be completed in SAPWAT3, with loaded weather data then incorporated into SAPWAT4 through the program file directory.

A year in which all three river valleys received relatively high rainfall was designated as the “wet” year. This representative “wet” year was not necessarily that for which each valley received the most rainfall. Similarly, a year which was dry across all three river valleys was chosen for the representative “dry” year, and was not necessarily the year which received the least rainfall in each valley over the 13 year period (i.e. between 2005 and 2017). This was done in order to allow easy comparison across the three valleys, ensuring that other non-climatic factors that might come into play over various years did not unduly impact comparisons. The designated wet year was 2011, and 2009 was selected as the representative

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[15] SAPWAT4 also provides pre-loaded weather data for selected weather stations across the country. However, the weather stations for which data was provided by the ARC-ISCW (2018) were in closer vicinity to the study sites, and data provided was more current. Hence manual appending of data into SAPWAT4 was the chosen method.

dry year. Table 4.2 shows the mean annual precipitation (MAP) over 13 years (2005-2017), as well as the annual precipitation for the representative wet and dry years.

Table 4.2: Mean Annual Precipitation (2005-2017), and Annual Precipitation in a Wet and Dry Year (mm)

Weather Station	**MAP** (mm)	**Wet Year (2011)** (mm)	**Dry Year (2009)** (mm)
Klipfontein (Cookhouse)	389	533	283
Adelaide PP (Adelaide)	495	646	363
Winterberg (Fort Beaufort)	479	626	382

Source: ARC-ISCW (2018).

The mean monthly weather station data elements loaded into the program for a “wet”, “dry” and LTA year were maximum and minimum temperature (^{o}C); maximum, minimum and average humidity (%); average wind speed (m/s); and radiation (MJ/m^{2}/day). Total monthly rainfall (mm), MAP (mm) and number of rainfall events were also included, along with weather station location (longitude and latitude).

SAPWAT4 makes use of the Köppen-Geiger international climate classification system, which is based on temperature and rainfall levels (van Heerden & Walker, 2016). Manually loaded weather data is therefore used by the program to classify each of the three study sites by climatic category over a “wet”, “dry” and LTA year.

b) Crop characteristics

SAPWAT4 requires crop-specific data in order to calculate ET_c from ET_o and the K_c. SAPWAT4 makes use of a dual crop coefficient approach, in which K_c is broken down the basal crop coefficient (K_{cb}) and the soil water evaporation coefficient (K_e) (see equation 7). K_{cb} describes plant transpiration and specific information regarding the crop in question helps to inform this coefficient. K_e, which indicates soil surface evaporation, is also dependant on crop factors such as foliage and canopy cover, which impact the amount of moisture which is evaporated from the soil.

Crop data was manually added for young, intermediate and mature citrus tree varieties, categorised into five broad variety groups. These variety groups are ‘lemons’, ‘oranges’, ‘satsumas’, ‘mid-season mandarins’ and ‘late mandarins.’ Mandarin varieties (also known as easy-peelers or soft citrus) were broken down into three distinct groups rather than one comprehensive category due to the substantial disparity in harvest periods and crop growth stages that exist across these varieties[16]. Satsumas are a mandarin variety that is harvested early in the citrus season; mid-season mandarins, which include clementine and nova varieties, reach maturity mid-way through the season; and late-mandarins are picked near the end of the season. Oranges refer primarily to navel orange varieties (including navelates and cara-caras). Valencia orange varieties (such as taroccos) were not separately accounted for, as these volumes are relatively insignificant, comprising less than 1% of total bin deliveries across the last ten years of citrus production.

The crop data required by SAPWAT4 includes yield potential; crop height; salinity threshold, leaf resistance, rooting depth for the initial and mid-season crop growth stages; allowed depletion fraction for the initial, mid-season and late-season crop growth stages; yield-response factors; duration of each crop growth stage (the initial, crop-development, mid-season and late-season stages); the basal crop-coefficient (K_{cb}) in the initial, mid-season and late-season stages; and the start of season date.

K_c values determined in numerous citrus growing regions across the world have been shown to vary substantially (Gush & Taylor, 2014). Gush and Taylor (2014) found that transpiration crop coefficients in four citrus orchards found in different citrus growing locations in South Africa also differed considerably. It was therefore decided to make use of the K_{cb} values for citrus provided in FAO 56 (Allen *et al*., 1998), as this publication is internationally accepted as the appropriate guideline for finding crop water requirements (van Heerden, 2017). Moreover, the K_{cb} figures provided in FAO 56 lie roughly within the range of transpiration crop coefficients found by Gush and Taylor (2014) for citrus grown in South Africa. Initial, mid-season, and late-season K_{cb} values for citrus trees without ground cover were used[17], applying figures for trees with 70%, 50% and 20% canopy cover for mature, intermediate and young trees respectively[18]. Data sources for the additional crop data required by SAPWAT4 are laid out in Table 4.3.

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[16] Appendix 3 shows typical harvest periods for various varieties based on bin deliveries to the local packhouse and data obtained from de Villiers & Joubert (2006) and CRI (2015).

[17] Farmer interviews revealed that weeds and other ground cover beneath trees are removed/sprayed.

[18] Appendix 5 shows canopy cover for trees of different ages

Table 4.3: Crop Data Inputs Required by SAPWAT4 and Corresponding Data Sources

Data Input	**Data Source**
Yield potential	Malan, 1991; corroborated by farmer interviews
Crop height	Farmer interviews
Salinity threshold	Allen *et al*., 1997 (default SAPWAT4 values used for citrus)
Leaf resistance	Default SAPWAT values for citrus[19]
Rooting depth	Farmer interviews; de Villiers & Joubert (2006); Malan, 1991
Allowed depletion fraction	Farmer interviews; Allen *et al*., 1997
Yield response factor	Allen *et al*., 1997 (default SAPWAT4 values used for citrus)
Crop growth stage durations	The sources and method used to determine the duration of each crop growth stage is detailed in section 4.4.2 (c) below.
Crop coefficients (K_{cb})	Allen *et al*., 1997
Start of season date	Farmer interviews; Alexander (2015)

c) Crop Growth Stages

Crop evapotranspiration (ET_c) is dependent on the development and growth pattern of that crop. As recommended by FAO 56 (Allen *et al*., 1998), SAPWAT4 breaks this development pattern down into four stages, namely the initial stage, the crop development stage, the mid-season stage, and the late season stage (van Heerden, 2017; van Heerden & Walker, 2016).

FAO 56 shows that the initial, crop-development and late season stages are markedly short for perennial crops, and particularly for evergreen trees (such as citrus) (Allen *et al*., 1998).[20] The longest stage for perennials (as well as for many annual crops) is the mid-season stage (Allen *et al*., 1998). The term 'citrus season' denotes the period from the start of flower initiation until harvest, and in South Africa typically extends from August until July (despite harvesting of some of the later cultivars taking place in September and October) (CRI, 2015). Flower initiation refers to the cellular differentiation of vegetative buds to flower buds (de Villiers & Joubert, 2006). This stage of the phenological cycle is imperceptible to the naked

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[19] Based on recommendation of SAPWAT4 developer (van Heerden, 2018).

[20] In fact, the figure demonstrating the proportion of the various stages throughout the growing season in FAO 56 (Allen *et al*., 1998: 94) evidently shows the initial, crop-development and late season stages to be nil for evergreen trees. This figure may be seen in Appendix 6.

eye (Alexander, 2015), and takes place approximately a month before the first flowers are perceptible on the tree (de Villiers & Joubert, 2006).

For perennial crops the 'initial stage' of crop growth is the period from 'greenup' date (the start of new leaf growth) until approximately 10% ground cover (Allen *et al*., 1998). As citrus trees are evergreen, this period is not obviously discernible. However, when providing typical ranges for the four stages of growth, the FAO guidelines for computing crop water requirement (Allen *et al*., 1998) include a brief, non-zero period for the initial phase for citrus crops, and consequently this phase cannot be completely disregarded. It is therefore assumed to be a short period of 15 days taking place at the commencement of the new season (i.e. August).

The 'crop development' stage is the growth period that takes place from a 10% level of ground cover until effective full cover, typically at the initiation of flowering (Allen *et al*., 1998). This period is analogous to the flower induction phase within the citrus phenological cycle. Farmer interviews indicated that flowering in the region typically commences from early to mid-September, with full bloom occurring at the end of September or early October. The crop development stage is therefore assumed to take place from mid-August (after the initial phase is complete) until mid-September.

The mid-season stage is the longest growth stage for perennial crops and refers to the period spanning from effective full cover (or the initiation of flowering) until the start of maturity, where maturity can often be signalled by leaf senescence or the 'browning' of fruit (Allen *et al*., 1998). Since citrus trees are evergreen the end of this phase cannot simply be indicated by leaf ageing. However, it is possible to estimate the maturity period of citrus trees from the citrus fruit growth curve, which is divided into three distinct phases, namely cell division (Stage I), cell enlargement (Stage II), and fruit maturation (Stage III) (Figure 4.2) (Bain, 1958; Verreynne, 2009). Similar to that of other fruits, the curve depicting these stages of citrus fruit growth is approximated by a sigmoidal curve (Verreynne, 2009; Monselise, 1986). Cell division (Stage I) is the phase in which the cell composition of the fruit increases, and typically takes place from flowering until fruitlet drop, with increase in fruit size mainly attributed to growth in the thickness of the fruit peel (Bain, 1958; Alexander, 2015). Stage II (cell enlargement) is characterised by rapid fruit growth, with increases in fruit size resulting chiefly from pulp growth (Bain, 1953; Alexander, 2015). Fruit maturation, which takes place in Stage III, is the phase in which ripening takes place. Fruit continues to grow in this stage, but at a much slower rate than observed in Stage II (Bain, 1953; Alexander, 2015). The maturation phase may therefore be estimated via scrutinization of the fruit growth curves of various citrus varieties.

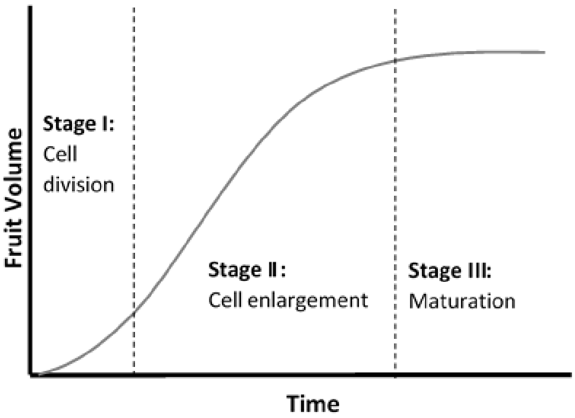
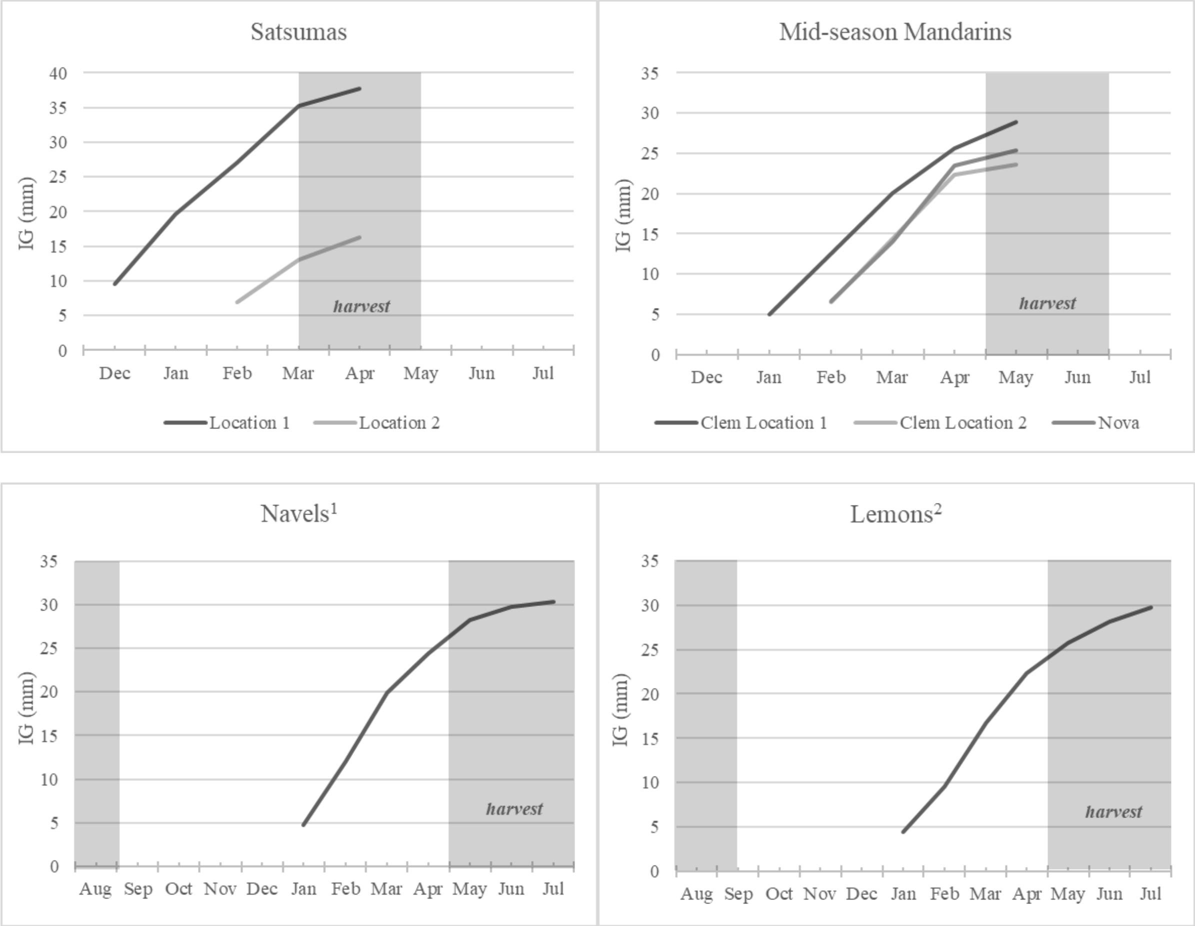


Figure 4.2: Citrus fruit growth over time

Source: Bain (1958); Verreynne (2009).

Verreynne (2010) obtained historical fruit growth data for three consecutive years in Citrusdal and Swellendam, which show monthly incremental growth (expressed in millimetres fruit diameter) for various varieties. The cumulative growth for satsumas, mid-season mandarins, navels and lemons is shown in Figure 4.3. Harvesting periods for the varieties are also shown, which were obtained from farmer interviews and the local packhouse. As can be seen, harvesting of some varieties continues into the initial and crop-development stage (during August and September). Unfortunately, no growth figures were available for late mandarin varieties. However, considering the harvesting period for late mandarins, it can be assumed that the fruit growth curve is similar to that of mid-season mandarins, merely delayed by approximately 1.5 months. It should be noted that the growth curves presented stem from data obtained in citrus producing regions within the Western Cape, while the harvesting periods are those of the study region (i.e. the Eastern Cape Midlands). The regions may be considered comparable as both the Western Cape and the midlands of the Eastern Cape are considered cold production regions (de Villiers & Joubert, 2006). Maturity in cold production regions occurs later than in more tropical, warmer climates (such as Mpumalanga and Limpopo), and harvest periods are longer (de Villiers & Joubert, 2006).

The mid-season stage for each variety was therefore estimated by taking into account the relevant growth curves and harvest periods. Where harvest periods appear to take place prior to a decrease in the rate of growth in fruit size, maturation was assumed to begin at the time of harvest. The maturity phase for late mandarin varieties was assumed to begin 6 weeks after that of mid-season varieties. The late season stage of crop growth takes place from the start of maturity until harvest, or until the date of 'planting' for perennial crops (such as citrus) (Allen *et al*., 1998), which is taken to be start of the new citrus season.



[1] Harvest period includes late navels/navelates

[2] Fruit growth curve is for Eureka lemons, while harvest period includes all lemon varieties harvested by local citrus co-operative farmers. However, majority of lemons grown in the study area are the Eureka variety.

Figure 4.3: Typical harvest periods and cumulative monthly incremental growth (IG) based on historical data from 3 consecutive years (mm) for Satsumas, Mid-season Mandarins, Navels and Lemons

Source: Verreynne, 2010; farm interviews; data from local citrus co-operative

Crop stages throughout the growing season for each cultivar were thus estimated for each variety group, taking into account the FAO guidelines and definitions for each stage (Allen *et al*., 1998), growth curves for various cultivars, as well as harvesting periods and other information provided by farmers and the local packhouse. These estimated stages are laid out in Table 4.4.

Table 4.4: Estimated Crop Growth Stages for Various Citrus Variety Groups (Days)

Crop Growth Stage	**Days per Growth Stage**				
	Navels	**Satsumas**	**Mid-season Mandarins**	**Late Mandarins**	**Lemons**
Initial	15	15	15	15	15
Crop Development	30	30	30	30	30
Mid-Season	228	182	228	274	228
Late Season	92	138	92	46	92
Total	365	365	365	365	365

d) Soil Data

Soil evaporation is dependent on the amount of exposed soil un-protected by canopy cover, as well as the frequency that soil is wetted (Steduto *et al*., 2012; Allen *et al*., 1998; van Heerden & Walker, 2016) In order to calculate the soil water evaporation coefficient (K_e) and estimate crop water requirements, SAPWAT4 requires various data inputs relating to soil characteristics. This data includes soil type (i.e. soil texture); effective depth; field capacity (FC); wilting point; evaporation depth; readily evaporable water (REW); infiltration; soil salinity and irrigation water salinity.

In order to determine soil type the percentage of clay, silt and sand in the soil were used to find the relevant soil texture by means of the soil texture triangle, which is provided in the SAPWAT4 program (see Appendix 7) An approximate clay, silt and sand content of the soil in each of the three study sites was attained through farmer interviews, an interview with a local soil scientist often consulted by the local citrus farmers (Fry, 2018), and past soil surveys that have been conducted in the surrounding area (Hartmann *et al*., 1979; Baard *et al*., 1978; Geers *et al*., 1984). A 'sandy clay loam' soil texture was determined as the predominant soil type in all three study areas.

Based on certain soil textures, Allen *et al*. (1998) and Allen *et al*. (2005) provide recommended values for field capacity, wilting point and REW. However, recommendations are not available for a 'sandy clay loam' soil texture, and values from FAO 56 and its supporting document were therefore unavailable. As such, typical field capacity and wilting point values were instead obtained from Saxton and Rawls' (2006) soil water characteristic estimates by texture. If one considers the FAO 56 recommended REW values for 'sandy loam' and 'clay' soil textures, the overlapping array from both ranges is between 8-10mm (Allen *et al*., 1998; Allen *et al*., 2005). Zeleke and Wade (2012) made use of the median of these values for 'sandy clay loam' soil. Accordingly, a REW value of 9mm was used for the purposed of this project. Default SAPWAT4 values across pre-loaded soil texture types were used for effective depth, evaporation depth and infiltration. Soil salinity and irrigation water salinity were obtained from data provided by the local citrus co-operative, as well as from local soil expert (Fry, 2018).

e) Field and Irrigation Data

In addition to weather, crop and soil data, SAPWAT4 requires irrigation and field-specific data in order to find irrigation requirements. Cultivated and irrigated hectares for each farm and study region were added, obtained from tree census data and farm interviews. Young, intermediate and mature orchards of each variety group were added for each farm and for each of the three regions, for a dry, wet and LTA year. Newly developed orchards (i.e. those planted on previously undeveloped land) were excluded, as they may not have been present during the designated wet and dry year and can skew LTA results.

The information required by SAPWAT4 regarding irrigation system is system type; design application; system efficiency; evenness of distribution of irrigation water over irrigated field (DU); and wetted area. Type of irrigation system was obtained from farmer interviews, and default SAPWAT4 values were used for the remaining variables. Information detailing management of irrigation was also required – specifically the irrigation timing and application strategy for each crop growth stage. Irrigation timing refers to whether irrigation scheduling takes placed based on the passing of a fixed interval of days, depletion of readily available water (RAW), or whether irrigation occurs by means of infield rainwater harvest. Options for irrigation application in each stage include refilling to below field capacity (FC) or irrigating to a fixed depth. These irrigation management details were obtained via farmer interviews.

Once all required data had been included into SAPWAT4 for each farm and river valley, specifying young, intermediate and mature orchards of each variety group across a wet, dry and LTA year, the relevant calculations were completed by the program. Outputs include monthly and total ET_c and ET_o, irrigation requirements, and effective rainfall. Graphs depicting crop coefficients (K_c, K_e and K_{cb}), as well as the water balance (showing deficit to FC, RAW and wilting point) across the growing period were also produced.

4.4 Grey Water Footprint Accounting

Grey WF expresses the amount of freshwater necessary to alleviate water pollution to such a point that pollutant loads reach non-detrimental levels. Grey WF calculations were based on the guidelines provided in the WF Assessment Manual (Hoekstra *et al.*, 2011), supplemented by the Tier 1 supporting guidelines for grey WF accounting (Franke *et al.*, 2013). Hoekstra *et al.* (2011) describe grey WF of growing a crop or tree as the pollutant load (L) divided by the difference between the maximum acceptable concentration (c_{max}) and the natural background concentration (c_{nat}), all divided by the crop yield (measured in tonnes/ha) (equation 8).

$$WF_{proc,grey} = \frac{L/(c_{max} - c_{nat})}{Yield} \qquad [m^3/tonne] \qquad (8)$$

Water pollution resulting from citrus production takes place in the form of diffuse contamination. Rather than pollutants being directly emitted into the water body, as is the case with point sources of water pollution, pollution occurs through soil application of chemicals (such as fertilizers and pesticides) (Hoekstra *et al.*, 2011). Accordingly, the water body receives only a portion of the applied chemicals, which have diffused through the soil.

The WF assessment manual (Hoekstra *et al.*, 2011) recommends a three-tier approach for estimating diffuse pollutant loads, with each successive tier increasing in complexity and exactness (Franke *et al.*, 2013; Chukalla *et al.*, 2018). The Tier 1 approach is the most practicable of these, with higher tiers requiring increasingly advanced data and modelling techniques (Franke *et al.*, 2013)[21]. The most feasible option, the Tier 1 approach provides an

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[21] Tier 1 is the most commonly used approach, followed by Tier 2 and then Tier 3, which has been very rarely applied (Franke *et al.*, 2013; Chukalla *et al.*, 2018). The first study to have used the Tier 3 approach was published by Chukalla *et al.* in mid-2018.

adequate indication of water pollution using accessible data, and is the method applied to estimate pollutant load in this study.

In order to find the diffuse pollutant load (L) by means of the Tier 1 approach, the chemical load applied to the soil, or more specifically, the per hectare chemical application rate to the field (AR) is multiplied by a leaching-runoff fraction (α), which is the portion of the chemical load which eventually leaches into freshwater bodies (Hoekstra *et al.*, 2011; Franke *et al.*, 2013) (equation 9). Equation 9 may then be substituted into equation 8 to reach the formula for grey WF of growing a crop or tree displayed in equation 10.

$$L = \alpha \times AR \tag{9}$$

$$WF_{proc,grey} = \frac{(\alpha \times AR)/(c_{max} - c_{nat})}{Yield} \qquad [m^3/tonne] \tag{10}$$

The data and methods used to find the leaching run-off fraction, chemical application rate, maximum acceptable concentration, and the natural background concentration are described in sections 4.4.1 to 4.4.4 below. Grey WF was calculated using these variables for an LTA, 'wet' and 'dry' year, employing the relevant yield volumes obtained from the local citrus packhouse used by citrus farmers in the study area. The Grey WF of participant farms across all three river valleys was found for each variety group.

According to the WF assessment manual and Tier 1 guidelines, grey WF should be evaluated separately for each chemical applied to the soil, with the largest grey WF resulting from these separate calculations then deemed the overall grey WF (i.e. the most critical pollutant is accounted for, and no other) (Hoekstra *et al.*, 2013; Franke *et al.*, 2013). Grey WF was therefore estimated separately for nitrogen, phosphorous and potassium soil applications[22], which were identified as the primary chemical applications to soil for citrus production in the region.

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[22] The WF assessment manual (Hoekstra *et al.*, 2011) and the Tier 1 supporting guidelines (Franke *et al.*, 2013) provide a method for the calculation of the grey WF of pollutants applied directly to soil (either by hand or via irrigation), and not applied in the form of foliar sprays. Therefore, only applications of chemicals directly to soil were accounted for. Since only fertilizers were applied directly to soil, pesticides and insecticides were not included in grey WF calculations.

4.4.1 The Leaching Run-Off Fraction

When chemicals are applied to soil, only a portion of these contaminants reach water bodies (i.e. diffuse water pollution occurs). This fraction of chemical load eventually leaching into freshwater sources is known as the leaching run-off fraction (α). This leaching run-off fraction is dependent on several influencing factors, which can be separated into three categories: environmental conditions; management practices; and the physical-chemical properties of the applied chemical (Franke *et al.*, 2013). The leaching run-off fraction will therefore vary from site to site, depending on variations in these properties. Moreover, the specific factors impacting the leaching run-off fraction within each of these categories depends on the chemical substance applied.

The tier 1 supporting guidelines provide tables for various chemical substances or substance groups, containing the relevant influencing factors, which may be used to determine the impact of each of these factors on the leaching run-off fraction (Franke *et al.*, 2013). Each table assigns a weight to each impacting factor, which is determined by the importance and influence of that factor. The sum of the weights assigned to each factor within each chemical group add up to 100. In addition to weights, scores of between 0 and 1 for each influencing factor are shown on the tables. The appropriate score is allotted based on the state or condition of each specified factor. As nitrogen, phosphorous and potassium soil applications were considered in this study, separate tables were used for each of these chemicals. Appendices 8 shows these tables, along with the relevant scores which were allotted for each influencing component.

Once the scores for each influencing factor are determined, they can be combined with the weights of each factor to find the leaching run-off fraction (α). Equation 11 shows the formula used to find α using the applicable scores (s) and weights (w) for each factor i. The minimum and maximum leaching run-off fraction for each chemical group (α_{min} and α_{max} respectively) were obtained from the Tier 1 grey WF guidelines (Franke *et al.*, 2013). The final α value determined lies between the α_{min} and α_{max}.

$$\alpha = \alpha_{min} + \left[\frac{\sum_i s_i \times w_i}{\sum_i w_i}\right] \times (\alpha_{max} - \alpha_{min}) \tag{11}$$

4.4.2 Application Rate

Chemical application details were obtained from farmer interviews for the various citrus varieties produced. The level of detail supplied differed substantially across interviews. Most commonly an estimated 'NPK'[23] application volume was supplied, with only some farmers supplying more detailed application records. It was indicated that the majority of chemical applications to soil were for fertilization purposes, typically providing nutrients in the form nitrogen, phosphorous and potassium (or chemical compounds incorporating these chemicals) to the soil. Pesticides and insecticides were typically applied via foliar sprays. Since Tier 1 guidelines provide procedures for calculating grey water footprint from chemical applications to soil (Franke *et al*., 2013), these foliar applications were not accounted for.

Considering the information provided by farmers, and the level of detail provided therein, it was decided to only consider applications of nitrogen (N), phosphorous (P) and potassium (K) when assessing grey WF. In the instances of detailed chemical application records being provided, volumes of nitrogen, phosphorous and potassium were not explicitly provided. Rather, the application volumes of the chemical compounds containing these nutrients were supplied. Chemical compounds applied included urea, limestone ammonium nitrate, phosphoric acid and potassium sulphate. Conversion factors were applied to the quantities provided to obtain the legitimate N, P and K application volumes.

Identical chemical application rates were utilised for LTA, 'dry' and 'wet' years, since it was indicated that application did not alter substantially year-on-year and based on the nature of the data obtained through farmer interviews.

4.4.3 Maximum Acceptable Concentration

The maximum acceptable concentration (c_{max}) of a contaminant refers to the ambient water quality standards for that contaminant (Hoekstra *et al*., 2011; Franke *et al*., 2013). Grey WF indicates the amount of ambient water that is needed to dilute pollutants back to their natural background concentrations (c_{nat}). Therefore, ambient water quality standards are recommended rather than other standards, such as those governing drinking or irrigation water quality (Hoekstra *et al*., 2011). Ambient water quality standards are those which

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[23] Representing total nitrogen (N), phosphorous (P) and potassium (K) volumes applied throughout the season.

express the maximum permissible concentrations of chemical pollutants in freshwater bodies.

As recommended by Hoekstra *et al*. (2011) and Franke *et al*. (2013), national water quality standards were used to determine c_{max} for nitrogen, phosphorous and potassium. South African Water Quality Guidelines for Aquatic Ecosystems were utilised to obtain ambient water quality standards for nitrogen and phosphorous (DWAF, 1996a). No standards exist for potassium concentrations within aquatic ecosystems in South Africa (DWAF, 1996a), and no c_{max} value for potassium is recommended by the Tier 1 supporting guidelines for grey WF accounting[24] (Franke *et al*., 2013). Potassium standards were therefore obtained from South African Water Quality Guidelines for Domestic Water Use (DWAF, 1996b). Potassium standards are primarily based on aesthetic effects (a bitter taste occurs when potassium concentration exceeds the target water quality range), and high concentrations are otherwise relatively harmless (DWAF, 1996b).

Despite ambient water quality standards for potassium being unavailable, calculations were carried out using domestic water quality guidelines for South Africa (DWAF, 1996b). However, it should be noted that resulting grey WF figures merely indicate the volume of water required to assimilate potassium back to concentrations suitable for domestic consumption. Grey WF evaluations using domestic water quality standards for potassium will not have any meaningful implications for aquatic ecosystem health and ambient water pollution levels.

The maximum acceptable concentrations used for nitrogen and phosphorous are those which maintain concentrations below those which indicate hypertrophic conditions. South African Water Quality Guidelines for Aquatic Ecosystems (DWAF, 1996a) provide standards for both ammonia and inorganic nitrogen. Ammonia is a reduced form of inorganic nitrogen, which is made up of individual concentrations of nitrite (NO_2^-), nitrate (NO_3^-) and ammonia (NH_3 + NH_4^+) (DWAF, 1996a). Since ammonia is a component of inorganic nitrogen, standards for inorganic nitrogen were utilised to obtain c_{max}. Maximum acceptable concentrations utilised were 10 mg/l for inorganic nitrogen; 0.25 mg/l for phosphorous; and 50 mg/l for potassium.

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[24] The Tier 1 supporting guidelines (Franke *et al*., 2013) provide a list of recommended c_{max} values to use when local ambient water quality standards are unavailable, compiled from European, Canadian and American water quality guidelines for aquatic ecosystems. (EU, 2013; CCME, 2013 & US-EPA, 2013 in Franke *et al*., 2013: 29-32)

4.4.4 Natural Background Concentration

The natural background concentration (c_{nat}) is the concentration of each 'contaminant' that would be present in the absence of human disturbance (Hoekstra *et al.*, 2011). Tier 1 supporting guidelines for grey WF accounting (Franke *et al.*, 2013) recommend the use of local water quality records to obtain c_{nat}. There are three potential approaches which may be used to obtain natural background concentrations from local data: i. utilising concentrations present upstream of pollutant sources; ii. making use of historical water quality data that precedes the instigation of potentially contaminating activities; and iii. using concentrations at pristine reference sites located in the near vicinity of the study site (i.e. from separate water bodies) (Franke *et al.*, 2013).

The favoured approach is to use concentrations obtained from unimpacted water bodies in the region, such as from headwaters or other sites located upstream (EC, 2011 in Franke *et al.*, 2013: 37). According to Hoekstra *et al.* (2011: 45), it is permissible to assume that c_{nat} equates to concentrations present in 'more or less pristine rivers.' However, historical figures need to be used if water bodies have been impacted by human activities (Hoekstra *et al.*, 2011).

Water quality data was obtained from the Department of Water and Sanitation (DWS, 2018b) for various testing sites upstream of citrus producing locations on the Fish, Koonap and Kat Rivers. As far as possible, efforts were made to ensure that selected water quality testing sites were located upstream of known potentially impactful activities. In order to determine whether concentrations from these selected sites were suitable to be used for c_{nat}, a nitrogen to phosphorous ratio was calculated. South African (SA) water quality guidelines for aquatic ecosystems (DWAF, 1996a) indicate that nitrogen and phosphorous concentrations need to be considered together in order to assess their impact on aquatic ecosystems. Water bodies with an N:P ratio less than 10 are classified as 'impacted' systems (eutrophic or hypereutrophic in nature), while a ratio of between 25 and 40 or higher indicates that water bodies are 'unimpacted' (DWAF, 1996a). This method was utilised to determine whether sample sites were suitable to be used to obtain natural background concentrations, with unimpacted ecosystems assumed to be 'pristine.'

The resultant N:P ratios, along with the natural background concentrations used are shown in Table 4.5. As can be seen, N:P ratios across the utilised water quality testing sites for the Koonap and Fish Rivers indicate that these sites are unimpacted. The ratio for the Kat River falls just below the designated 'unimpacted' range. However, since the figure falls short by such as small margin, the water quality testing sites used for the Kat River were also assumed to be suitable to find c_{nat}.

Average nitrogen, phosphorous and potassium concentrations were utilised across three suitable testing sites on the Koonap River, and two testing sites on both the Kat and Fish Rivers. Based on the SA aquatic ecosystem water quality guidelines (DWAF, 1996a), summer nitrogen and phosphorous concentrations were utilised, averaged over time.

Table 4.5: C_{nat} for Koonap, Kat and Fish Rivers, obtained from mean concentrations present at utilised water quality testing sites & average N:P ratio for each river

	Inorganic Nitrogen[a] (mg/l)	**Phosphorous[b] (mg/l)**	**Potassium (mg/l)**	**N:P Ratio**
C_{nat}: Koonap River	0.246	0.008	1.687	31.62
C_{nat}: Kat River	0.270	0.011	2.378	24.42
C_{nat}: Fish River	0.739	0.022	2.087	34.38

[a] Based on guidelines provided by DWAF (1996a), Inorganic N concentrations were calculated from DWS (2018b) water quality data for average summer ammonium, nitrate and nitrite concentrations, and with ammonia contribution estimated via DWAF (1996a) determination table, using average PH (DWS, 2018b) and assuming temperature of 20°C.

[b] In order to determine phosphorous concentrations, the relevant conversion factor (Oram, 2014) was applied to phosphate concentrations obtained from DWS (2018b) water quality data.

Source: DWS (2018b); DWAF (1996a); Oram (2014).

4.5 Total Water Footprint

Once blue, green and grey WF had been calculated for citrus production in each river valley and for each producing farm, total WF was calculated for each site by adding individual blue, green and grey WF components at each site. Calculations were completed for each variety group produced in the region.

4.6 Water Productivity

Water productivity broadly refers to a ratio of output to the quantity of water utilised to produce that output (Giordano *et al.*, 2017). Output may be measured in physical or economic terms (Pereira, 2012; Giordano *et al.*, 2017). In the context of crop production, physical water productivity and cumulative blue and green water footprint ($WF_{blue,green}$) are essentially inverse functions of one another (Amarasinghe & Smakhtin, 2014). Both physical water productivity (WP) and economic water productivity (EWP) were assessed for the purposes of this project.

WP and EWP were calculated using a denominator of combined blue and green CWU ($CWU_{blue,green}$), and were assessed for each variety group produced across each farm and across each river valley as a whole. Yield was obtained from the local citrus co-operative utilised by the participant farmers. Calculations were carried out using a long-term average (LTA) yield, calculated over a ten-year period (2008-2017), as well as for a representative wet and dry year.

Economic water productivity (EWP) was calculated by dividing the economic value of production by the yield produced (equation 13). In order to determine the value of production, yield was multiplied by average real Delivered in Port (DIP) price[25]. Average annual DIP price per variety was obtained from the local citrus co-operative for the years 2008-2017. The average real DIP across all ten years was utilised to find LTA EWP, while the average annual DIP occurring in the relevant corresponding year was used for the 'wet' and 'dry' year calculations.

$$WP = \frac{Yield}{CWU_{blue,green}} \qquad (tonnes/m^3) \qquad (12)$$

$$EWP = \frac{Economic\ Value\ of\ Production}{CWU_{blue,green}} \qquad (R/m^3\ or\ \$/m^3) \qquad (13)$$

DIP prices from the local citrus co-operative were obtained in South African Rand (ZAR) format. Since the majority of citrus produced in the region is exported, and payment is received in foreign currency, the relevant currency exchange rate has an impact on ZAR value. It was therefore decided to conduct two sets of EWP calculations – one where economic value

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[25] DIP refers to the price inclusive of delivery to port. Typically, growers pay for land transport to port, from which point the relevant export agent takes ownership (Brooke, 2011). DIP prices were used rather than prices in alternative trade term format due to data availability.

of production was expressed in ZAR value, and one where production was expressed in terms of a representative foreign currency – United States Dollars (USD). Historical exchange rates obtained from the South African Reserve Bank (SARB, 2018) were used to convert ZAR-value DIP prices received from the local packhouse into USD. Both ZAR and USD prices were converted to real values using Consumer Price Index (CPI) figures obtained from Statistics South Africa (STATSSA, 2018) and the International Monetary Fund (IMF, 2018) respectively.

4.7 Ethical Considerations

Research carried out for the purposes of this project abided by the requirements and standards of the Rhodes University research ethics policy. The methodology and procedures through which participants were asked to take part were approved by the Department of Economics Research Ethics Committee and the Rhodes University Ethical Standards Committee. Participants in the study were informed of the purpose of the research, as well as the intended use of the information that they were asked to provide. Participants were fully appraised of the voluntary nature of their participation and were aware that they had the right to withdraw at any time. The identity of all participants remained strictly confidential. Care was taken to ensure that any offense or harm to participants was avoided, and participants' rights, privacy and anonymity were respected and observed at all times.

4.8 Synopsis

The research methods utilised to achieve the objectives of this project have been described in this chapter. Details regarding the collection of data are included, followed by an explanation of the methods used to find blue and green CWU and WF. The procedures and resources used to find grey WF, as well as its various components, are then described. Finally, the methods used to calculate WP and EWP are laid out. Following this chapter, Chapter 5 describes the results found using these research methods.

CHAPTER 5
RESULTS

5.1 Introduction

This chapter details the results obtained through the course of the research. Characteristics of the assessed farms are described, including orchard and variety details, irrigation strategies and systems, and water withdrawal allocations. CWU of citrus production across the three valleys is then expressed, followed by blue, green, grey and total WF. Finally, WP and EWP for variety groups produced across the study region are described.

5.2 Farm Characteristics

Data was obtained from ten citrus farms located across the Koonap, Kat and Fish River valleys, situated in the vicinity of the towns of Adelaide, Fort Beaufort and Cookhouse respectively. Three farms were located in the Adelaide district, six in the surrounding area of Fort Beaufort, and one in the vicinity of Cookhouse. The total area of cultivated citrus assessed across the three valleys amounted to 605 hectares, with size varying from 110 hectares on the largest farming unit assessed to 15 hectares on the smallest. The study area on each farm was not necessarily the same as farm size – most farms do not exclusively produce citrus, with stock farming and avocado production taking place in conjunction with citrus production. Furthermore, newly developed orchards comprising immature, as-yet unproductive trees were excluded[26]. Non-productive orchards have zero yields and would thus result in an undefined and meaningless WF result (i.e. CWU divided by zero).

5.2.1 Orchard and Variety Details

Figure 5.1 shows the size of the study area utilised for each farming unit across the three valleys. The variety group making up the majority of production in terms of cultivated hectares across the three valleys was navels at 36% of total production, followed by late mandarins, lemons, mid-season mandarins and finally satsumas. The variety split for citrus cultivation across the three valleys, as well as for each valley individually is shown in Figure

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[26] This only refers to orchards planted on previously uncultivated land. Orchards which were replanted once trees came to the end of their lifespan were considered (but not if the variety was not present across the LT, wet and dry years).

5.2 below. As orchards get older and reach their anticipated lifespan, so they are replaced with new plantings. These plantings do not necessarily consist of the same variety, and cultivated area may vary between plantings. Accordingly, the area of cultivated citrus differs slightly in the designated wet and dry year (2011 and 2009 respectively) (see Appendices 10.1 and 10.2).

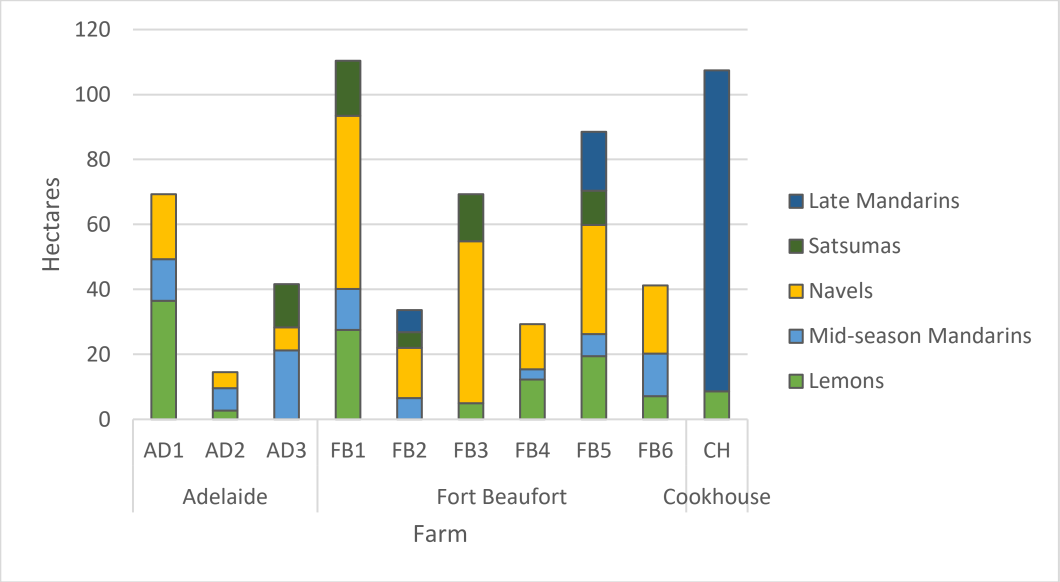

Figure 5.1: Hectares by Variety and Per Farm Across the Adelaide, Fort Beaufort and Cookhouse Regions

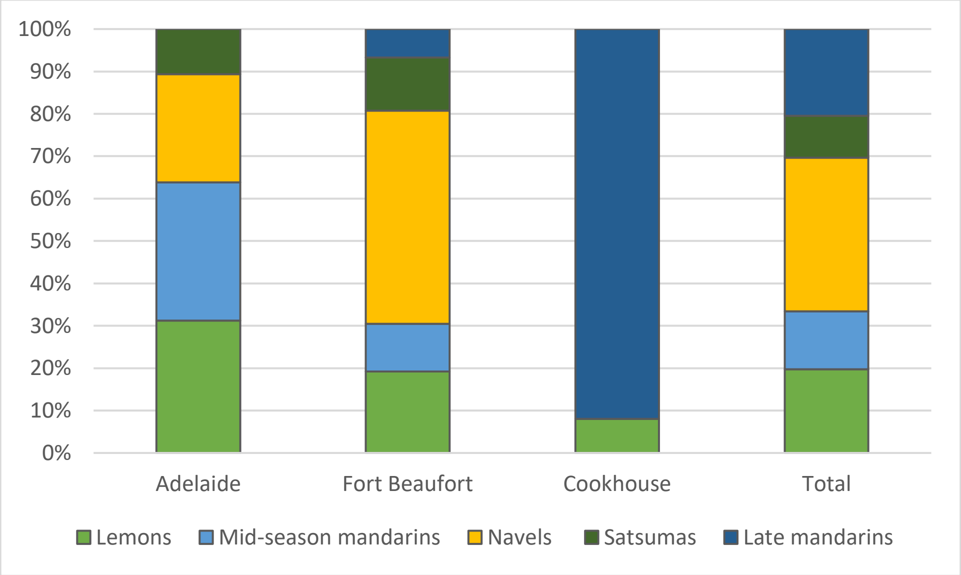

Figure 5.2: The Proportion of Each Variety Group Grown in Each River Valley and Across the Three Valleys as a Whole.

a. Adelaide

The area of cultivated citrus assessed in the Adelaide region (Koonap River valley) totals 125.5 hectares across three farms, ranging from 15 to 69 hectares in size. Varieties grown in the region are lemons, mid-season mandarins, navels and satsumas. Lemons and mid-season mandarins each make up approximately a third of production in the area, followed by navels (25% of production) and satsumas at (11% of production) (see Figure 5.2). The Koonap valley produces the majority of mid-season mandarins across assessed production throughout the three valleys.

b. Fort Beaufort

All five variety groups (lemons, navels, satsumas, mid-season mandarins and late mandarins) are produced within this region and were assessed across a cultivated area of 372 hectares. The largest citrus producing region considered, the Kat River valley produced the most navels, lemons and satsumas in terms of cultivated hectares out of the three assessed regions[27]. The average size of participant farms in the area was 62 hectares, ranging from 29 to 110 hectares. The proportion of each variety group produced in the region is shown in Figure 5.2.

c. Cookhouse

The area of cultivated citrus assessed in the Cookhouse region was 107 hectares. The majority of production in the area consists of late mandarins, with a smaller volume of lemons also produced. However, it should be noted that this project did not include major recent developments in the region that would have increased the proportion of lemons to approximately one third of production, if included, and would have resulted in Cookhouse being the largest lemon producing region of the three areas considered in terms of cultivated hectares.

5.2.2 Age Distribution

Age classifications were based on yield potential figures for each variety (Malan, 1991) across the lifespan of a hypothetical tree. 'Young' trees are those which have not yet reached an

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[27] New developments have been excluded. If recently established orchards in the Cookhouse region had been included, lemon plantings in the Fish River valley would be the largest across the three valleys.

economically productive stage, ranging from 0-3 years in age. 'Intermediate trees' were classified as those producing a positive yield, but not yet approaching full potential production (producing on average 50% of maximum potential yield, with yields ranging from 15-75% of potential). For orange and mandarin variety groups, intermediate trees fall between the ages of 4 and 10 years. Lemons reach full productivity sooner than oranges and mandarins (Malan, 1991), and thus intermediate lemons ranged from 4-8 years in age. 'Mature' plantings were those capable of achieving 75% or more of their maximum potential yield. Mature lemons were classified as those 9 years or older, while all other variety groups were labelled mature at 10 years of age or above.

On average across all varieties and across all three river valleys, 10.5% of trees were young trees; 24.5% were classified as intermediate; and 65% were mature. Orchards tended to be older in the Fort Beaufort region, with 80% of trees in the area classified as mature. The majority of orchards cultivated in the surrounds of Adelaide were also mature, with just over half of all trees falling in this category. Citrus production in the Cookhouse region was initiated relatively recently in comparison to the other two valleys, and the age distribution is indicative of this, with approximately 61% of trees in the area classified in the intermediate age group (see Appendix 11).

Lemon and navel orchards tend to be older, with the proportion of mature trees across the three valleys lying in the order of 80-90%. Late-mandarin orchards are generally younger, with only 30% of trees classified as mature. Both late-mandarin and mid-season mandarin orchards have the highest percentage of young trees, at roughly 20% of plantings. Refer to Appendix 12 for more detailed age distribution per variety across all three valleys. The age breakdown per valley by variety is presented in Appendix 13.

5.2.3 Irrigation Systems and Strategies

The majority of orchards were irrigated by means of drip irrigation systems, with 63% of all orchards across the three river valleys using drippers and 37% utilising micro irrigation. Young and intermediate orchards were predominantly irrigated by drip irrigation systems (approximately 85% across both age groups), while an equal proportion of mature trees were irrigated via dripper and micro systems respectively. This indicates a trend towards drip irrigation as time goes by.

Half of the interviewed farmers indicated a combination of dripper and micro systems being utilised. Four farms exclusively employed dripper systems (two in the Adelaide district, and one each in the Fort Beaufort and Cookhouse districts), and only one farm's irrigation system consisted entirely of micro sprinklers (located in the Fort Beaufort region).

Most farmers made use of probes to determine irrigation timing and application, thereby basing their irrigation strategy on depletion of readily available water (RAW) in the soil. Two farmers made use of pre-set irrigation schedules, which vary with season and tree maturity. However, both these farmers based their irrigation schedules on crop evapotranspiration and crop water requirements and indicated that scheduling was therefore also roughly based on depletion of RAW.

5.2.4 Water Allocations

Out of the ten farms assessed in this study, two qualified for scheme-linked state water entitlements, (typically referred to as 'water rights'), while the remaining eight were registered water users in possession of verification certificates laying out the extent and lawfulness of their water use, in accordance with section 35 of the NWA (1996) (see section 3.5.1). Farms with water rights included one located in the vicinity of Fort Beaufort (upstream of the settlement) and the farm situated in the Cookhouse area. The farm located in the Cookhouse region is permitted to extract 12 500 m^3/ha/annum from the Fish River (Orange Fish Sundays WUA, Boschberg river canal) (DWS, 2014), and the farm located upstream of Fort Beaufort is allocated 10 900 m^3/ha/annum (DWS, 2014), which may be extracted from the Kat River.

Six of the remaining farmers provided an indication of their permitted withdrawal volume; three from Adelaide, and three from Fort Beaufort. Some farmers provided this information in the form of total allocated volume across the property, while others provided their allocation in terms of cubic meters per hectare. On average, registered water users were permitted to extract 9306 m^3/ha/annum in the Adelaide region and 6980 m^3/ha/annum in the Fort Beaufort region. However, it should be noted that these were the volumes resulting from dividing total water allocation for the farm by only the area of cultivated citrus on that farm. All farmers in the Fort Beaufort and Adelaide regions indicated that other farming activities were undertaken on their farms, such as stock farming or avocado production.

However, stock farming requires substantially less water than cultivated citrus, and those who indicated the existence of other irrigated crops (such as avocados) provided water allocations in per hectare terms.

5.3 Crop Water Use

5.3.1 Blue Crop Water Use

ET_{blue} was found using gross irrigation requirements obtained from SAPWAT4 calculations, including losses due to irrigation system inefficiencies, but excluding runoff and percolation losses. Blue crop water use (CWU_{blue}) was then calculated from ET_{blue} (equation 4 in Chapter 4) and weighted according to the proportion of trees of each variety within in each age group (young, intermediate and mature). Figure 5.3 shows the weighted CWU_{blue} and yield per hectare for variety groups grown in each river valley over the long term, and for a representative wet and dry year (2011 and 2009 respectively).

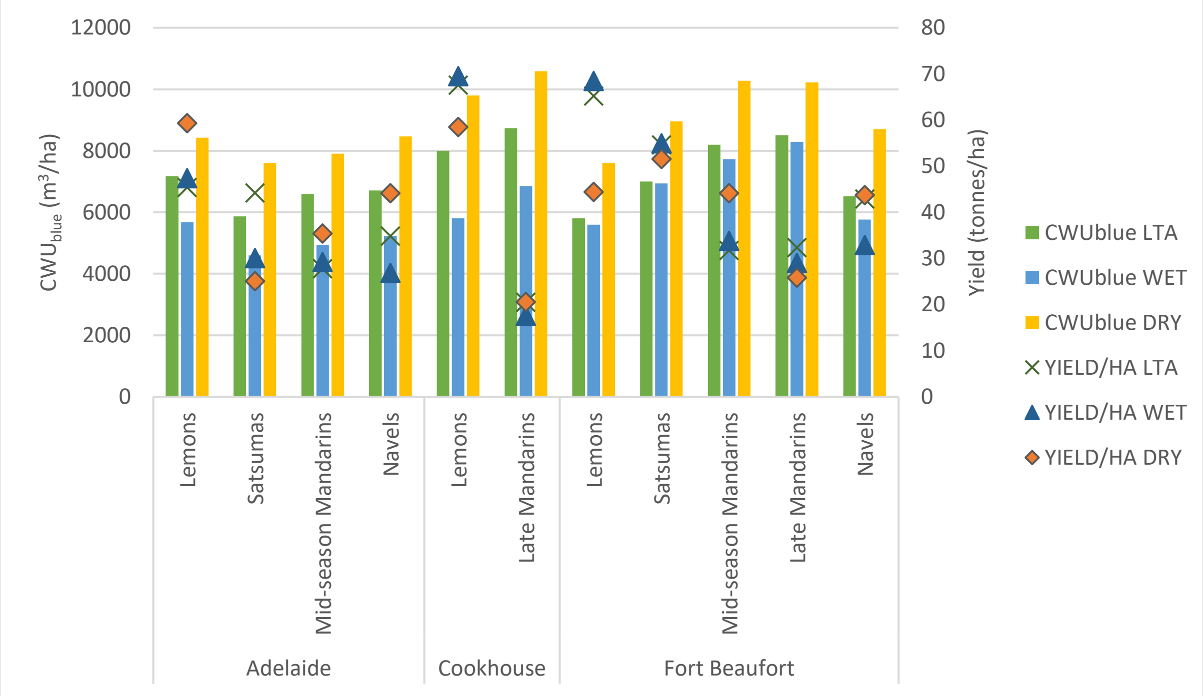

Figure 5.3: CWU_{blue} (m^3/ha) and Yield (tonnes/ha) for Citrus Production in the Adelaide, Cookhouse and Fort Beaufort Production Regions.

As expected, CWU_{blue} across all three valleys were highest in the dry year and lowest in the wet year. Since green water emanates from precipitation, higher rainfall will lead to a greater proportion of total CWU stemming from green water, and vice versa. When jointly considering all three citrus producing valleys together, late mandarins had the highest CWU_{blue} across the LTA, wet and dry years, followed by mid-season mandarins in the LTA and dry years, and satsumas in the wet year. In the LTA, wet and dry years, lemons had the lowest CWU_{blue}, followed by navels.

When comparing the valleys in which citrus production was assessed, CWU_{blue} averaged across varieties was highest in the Cookhouse region in the LTA, wet, and dry years, followed by the Fort Beaufort region. Adelaide had the lowest average CWU_{blue} across the LTA, wet and dry years. The variation in CWU_{blue} between variety groups was highest in the Fort Beaufort region, followed in turn by Adelaide and then Cookhouse in the LTA. In the wet and dry years Adelaide had the lowest variation in CWU_{blue} between cultivars. It should be noted that Fort Beaufort was the only area in which all five variety groups were assessed, so it is not surprising that the region demonstrated the greatest variation between varieties. However, four of the five variety groups were assessed in the Adelaide area, and variation between variety groups was substantially lower than that exhibited in Fort Beaufort. On the other hand, the deviation from the mean of CWU_{blue} between LTA, wet and dry years was lowest in Fort Beaufort for all varieties (followed by Adelaide and then Cookhouse).

In the Adelaide region CWU_{blue} ranged from 5 868 to 7 172 m^3/ha (LTA figures). The variety with the smallest CWU_{blue} across the LTA, wet and dry years in the Adelaide region was satsumas, followed by mid-season mandarins. In the LTA and wet year, lemons had the highest CWU_{blue}, while in the dry year of CWU_{blue} of navels exceeded that of lemons. In Cookhouse the CWU_{blue} of late mandarins was higher than that of lemons, with late mandarins' CWU_{blue} ranging from 8 738 to 10 592 m^3/ha across the LTA, wet and dry years; and lemons' CWU_{blue} ranging from 5 800 to 9 800 m^3/ha.

In the Fort Beaufort region LTA CWU_{blue} ranged from 5 800 to 8 507 m^3/ha. The variety group with the highest CWU_{blue} in the region in the LTA and wet years were late mandarins, followed in turn by mid-season mandarins, satsumas and navels. In the dry year mid-season mandarins' CWU_{blue} just exceeded that of late mandarins. In contrast to those produced in the Adelaide region, lemons produced in Fort Beaufort had the lowest CWU_{blue} throughout the LTA, wet and dry years. A greater proportion of lemon orchards were mature in the Fort Beaufort region than in Adelaide. Although younger orchards require less water per tree (Malan, 1991;

Mostert, 2006), canopy cover is smaller, and a greater proportion of soil per hectare is exposed to sunlight. Moreover, it has been hypothesised that transpiration per unit leaf area is greater for younger trees than for mature trees (Ryan & Yoder, 1997; Ryan *et al*., 2000; McDowell *et al*., 2002; Moore *et al*., 2004).

Navels' CWU_{blue} were the most similar across the valleys in which they are produced (Adelaide and Fort Beaufort) for all three years assessed (LTA, wet and dry). Late mandarins also had fairly similar CWU_{blue} values across valleys in LTA and dry years, though greater variation was displayed in the wet year. Mid-season mandarins' CWU_{blue} varied the most across valleys.

As was the case for CWU_{blue} considered for each citrus producing area, CWU_{blue} at the farm level was highest in the dry year. For the most part, LTA CWU_{blue} was higher than that in the wet year on the farm level, with some exceptions where the figure for the wet year exceeded the that of the LTA by a small margin. Although actual precipitation in the designated wet year exceeded precipitation in the LTA and dry year, in some instances in the Fort Beaufort region, effective rainfall (P_{eff}) in the LTA exceeded that occurring in the wet year (see Figure 5.4 and Table 4.2).

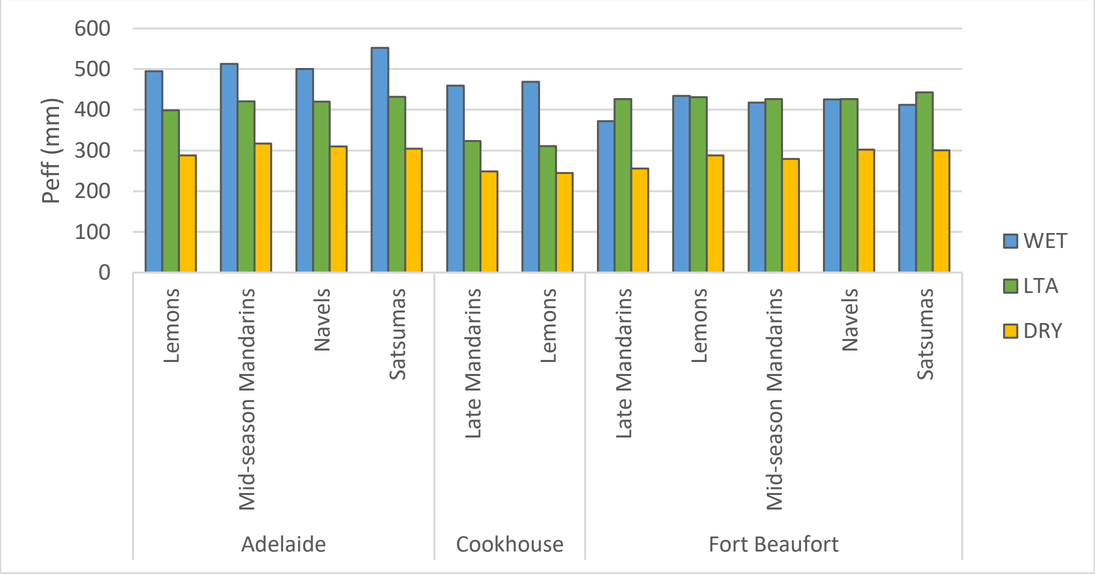

Figure 5.4: Weighted Effective Rainfall for Varieties Produced on Farms in the Adelaide, Cookhouse and Fort Beaufort Regions for a LTA, Wet and Dry Year.

In the LTA and dry years, the farm assessed in Cookhouse, which has state water rights, had the second greatest weighted average CWU_{blue} across varieties, and yet was ranked fourth lowest in the wet year. In contrast, the other farm assessed in possession of water rights (located in the vicinity of Fort Beaufort) had the third and fifth lowest CWU_{blue} in the LTA and dry year respectively, and the fourth highest in the wet year. In other words, the farm with water rights in the Fort Beaufort region had relatively low CWU_{blue} in the LTA and dry years, and relatively high CWU_{blue} in the wet year, while the opposite was true for the farm with water rights located in the vicinity of Cookhouse. The relationship between CWU_{blue} and the holding of water rights is therefore inconclusive, and a larger sample of water-rights holders would need to be evaluated in order to construe meaningful implications. Factors outside of water allocation structure have played a role in these two farms' divergent CWU_{blue} results. For instance, Fort Beaufort received roughly 20% more rainfall than Cookhouse in the long term. Moreover, late mandarins, which have been found to have the highest CWU_{blue} across the study regions, make up the majority of citrus production assessed in the Cookhouse region, while no late mandarins were produced on the farm with water rights located in the Fort Beaufort vicinity. Differences between LTA, dry and wet year results may also be attributed to factors such as the maturity of assessed orchards during the relevant year, as water use varies with tree age.

Due to differences in irrigation efficiencies, per hectare irrigation losses where typically larger for micro irrigated orchards than those irrigated via dripper systems, except for lemons, where drip-system irrigation losses were occasionally marginally larger than those occurring in micro irrigated orchards. Irrigation losses also tended to be higher for younger orchards. CWU_{blue} was similarly generally higher for micro irrigated orchards (with some exceptions). The difference between drip and micro irrigated orchards' CWU_{blue} was largest for satsumas and mid-season mandarins, with the weighted average CWU_{blue} of micro irrigated orchards exceeding that of drip irrigated orchards by roughly 20-30%. CWU_{blue} of micro and drip irrigated orchards differed the least for navels and lemons[28]. The weighted average CWU_{blue} of navels irrigated by micro sprinklers exceeded that of drip-irrigated orchards by approximately 5%, while micro irrigated lemons' CWU_{blue} surpassed that of drip irrigated lemons, though by a very small margin (roughly 1% difference). However, when comparing valleys, it is only in the in the Adelaide region where drip irrigated CWU_{blue} of lemons surpassed that of micro irrigated orchards – the opposite is true in the Fort Beaufort region[29].

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[28] All assessed late mandarins where irrigated via dripper systems and could therefore not be compared to micro irrigated production.

[29] All lemons produced in the Cookhouse region were irrigated via dripper systems.

Most lemon orchards under drip irrigation in the Adelaide region were not yet mature, while all lemons irrigated via dripper system in the Fort Beaufort region were mature. Micro irrigated lemon orchards in both valleys were also mature.

5.3.2 Green Crop Water Use

Green CWU was calculated from ET_{green} using equation 5 (see Chapter 4). ET_{green} was obtained from P_{eff}, which was found for each variety group grown within the three river valleys using SAPWAT4. SAPWAT4 determines P_{eff} by taking into account rainfall intensity and the soil water balance (van Heerden *et al*., 2009; van Heerden, *et al* 2014 in Munro, 2015). CWU_{green} for each variety assessed in the three river valleys can be seen in Figure 5.5 for LTA, wet and dry years. CWU_{green} is typically smaller than CWU_{blue} across the study region, which is unsurprising, considering the water scarce nature of the region and the irrigation intensive nature of citrus production. As expected, CWU_{green} is generally largest in the designated wet year, followed in turn by the LTA and dry years. However, there are a few exceptions where CWU_{green} in the LTA exceeds CWU_{green} in the wet year. As discussed in section 5.3.1 above, this is attributed to LTA P_{eff} exceeding P_{eff} in the wet year in some instances, despite the wet year receiving the greater actual precipitation throughout.

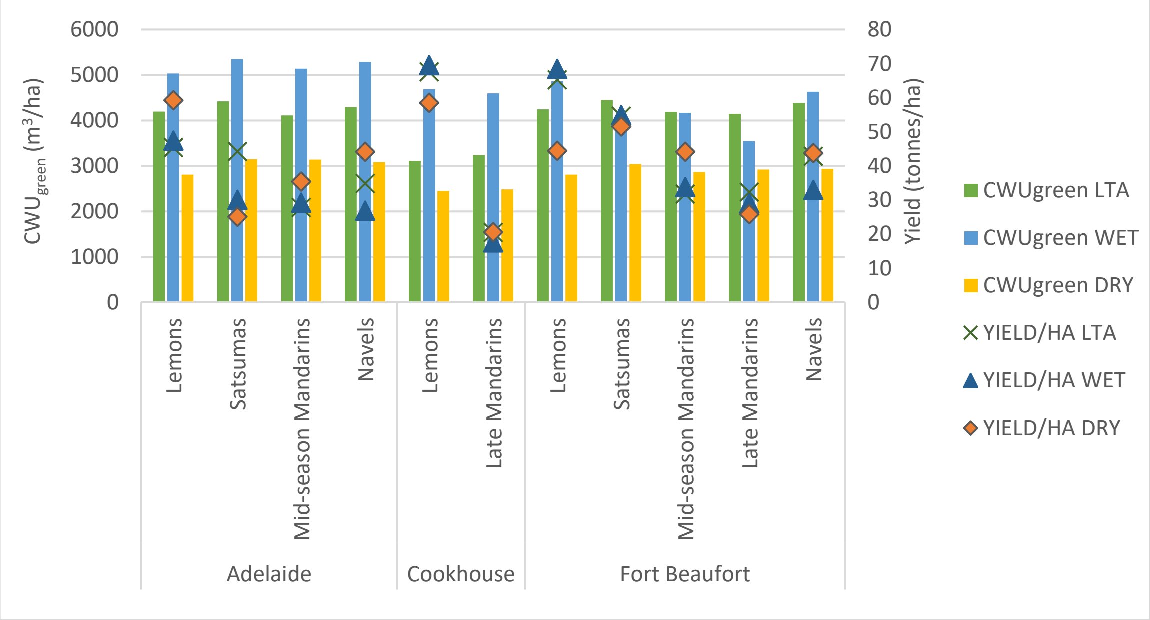

Figure 5.5: *CWU_{green} (m^3/ha) and Yield (tonnes/ha) for Citrus Production in the Adelaide, Cookhouse and Fort Beaufort Production Regions.*

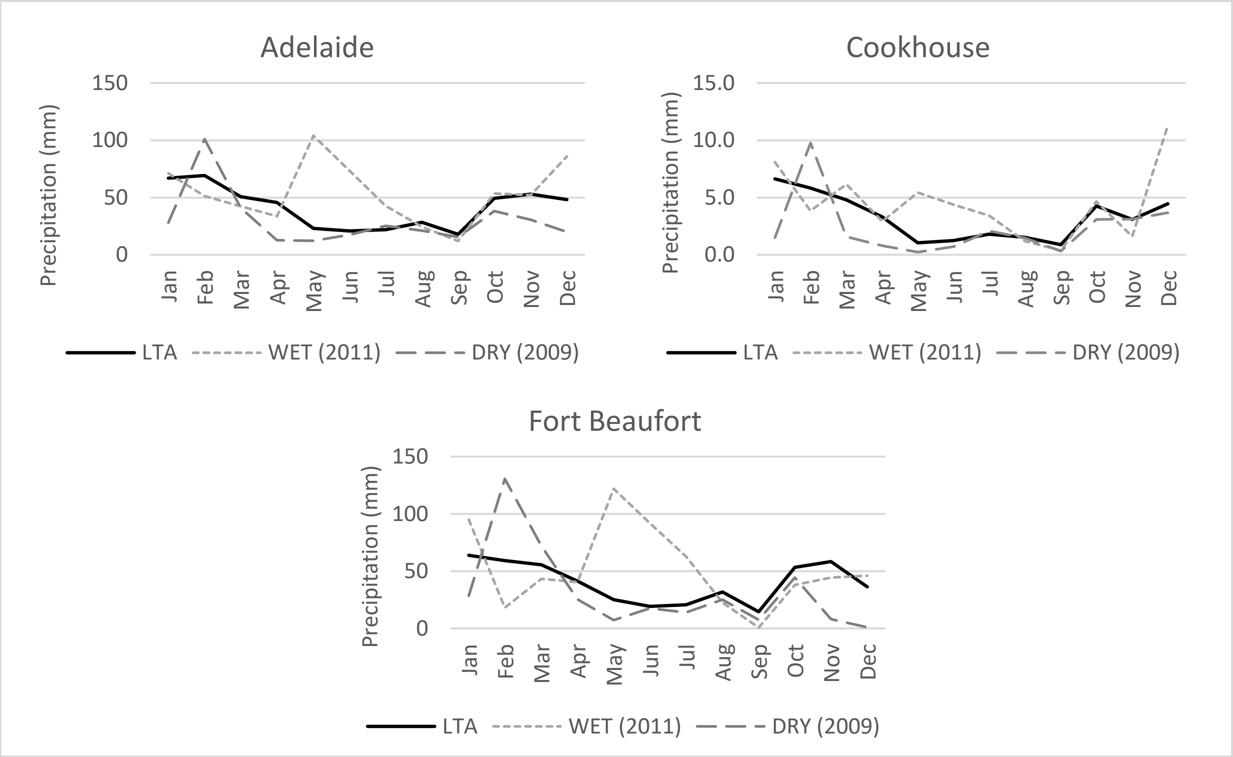

Figure 5.6: Monthly historical precipitation (mm) in Adelaide, Cookhouse and Fort Beaufort

Source: ARC-ISCW (2018)

In the LTA and dry years satsumas had the highest CWU_{green} averaged across the study region, while late mandarins and lemons had the smallest CWU_{green}. In the wet year lemons had the highest CWU_{green}, followed in turn by navels, mid-season mandarins, late mandarins and satsumas. Disparities in CWU_{green} between the LTA, wet and dry years may be attributed to the timing and intensity of rainfall in the wet and dry and year in comparison to the LTA. For example, there was an unusual spike in rainfall in May in the wet year in all three regions, which may have resulted in a higher than usual lemon CWU_{green} (see Figure 5.6).

Averaged across all varieties, LTA CWU_{green} was highest in Fort Beaufort, followed by Adelaide and then Cookhouse. Adelaide had the highest CWU_{green} in the designated wet and dry years, while Fort Beaufort and Cookhouse had the smallest CWU_{green} in the wet and dry years respectively. The Cookhouse region demonstrated the most similar CWU_{green} between varieties, followed in turn by Adelaide and Fort Beaufort. As was the case with CWU_{blue}, CWU_{green} for each variety grown varied the least between the LTA, wet and dry years in the Fort Beaufort region, followed by the Adelaide and Cookhouse regions respectively.

CWU_{green} in the Adelaide region ranged from 4 111 to 4 422 m^3/ha in the LTA and was highest for satsumas for each of the LTA, wet and dry years. Mid-season mandarins had the lowest CWU_{green} in the LTA, while lemons had the smallest figure for the wet and dry years. Similarly, satsumas in the Fort Beaufort region also had the largest CWU_{green} in the LTA and dry years. Late mandarins had the smallest CWU_{green} in the LTA and wet years. While lemons had the highest CWU_{green} in the wet year, they also possessed the smallest value for the dry year. LTA CWU_{green} in the Fort Beaufort region ranged from 4 148 to 4 445 m^3/ha. In the Cookhouse region LTA CWU_{green} ranged from 3 110 to 3 236 m^3/ha. Late mandarins in the Cookhouse region had a higher CWU_{green} than lemons in all but the wet year, where the opposite was true. As before, the disparities in CWU_{green} year-on-year may largely be attributed to variation in rainfall patterns and intensity.

At the farm level, the highest CWU_{green} in the LTA and wet years were exhibited in the Fort Beaufort region, while a farm in the vicinity of Adelaide possessed the largest CWU_{green} in the dry year. The farm in the Cookhouse region had the lowest CWU_{green} in the LTA and dry years, but the fourth highest in the wet year. In contrast, the second farm with scheme water entitlements (i.e. water rights), which is in the Fort Beaufort area, had the second and fifth highest CWU_{green} in the LTA and dry years, and the 3rd lowest CWU_{green} in the wet year.

5.3.3 Total Crop Water Use and Theoretical Water Use

The theoretical annual water requirement of citrus varies between 850 and 1000 mm/annum, equivalent to 8 500 and 10 000 m^3/ha/annum (Mostert, 2006), with over 50% of this annual requirement utilised between November and February (Mostert, 2006; Taylor & Gush, 2014). Total monthly blue and green CWU ($CWU_{blue,green}$) for citrus produced in each of the three study regions is shown in Figure 5.7 and compared to the theoretical monthly water requirements of citrus provided by Mostert (2006) (benchmark 1) and Netterville (1996) (benchmark 2). Monthly $CWU_{blue,green}$ in the three valleys follow a similar pattern to that of the benchmarks, with water use highest in the summer months. Roughly 40-45% of annual $CWU_{blue,green}$ was found to have been utilised between November and February.

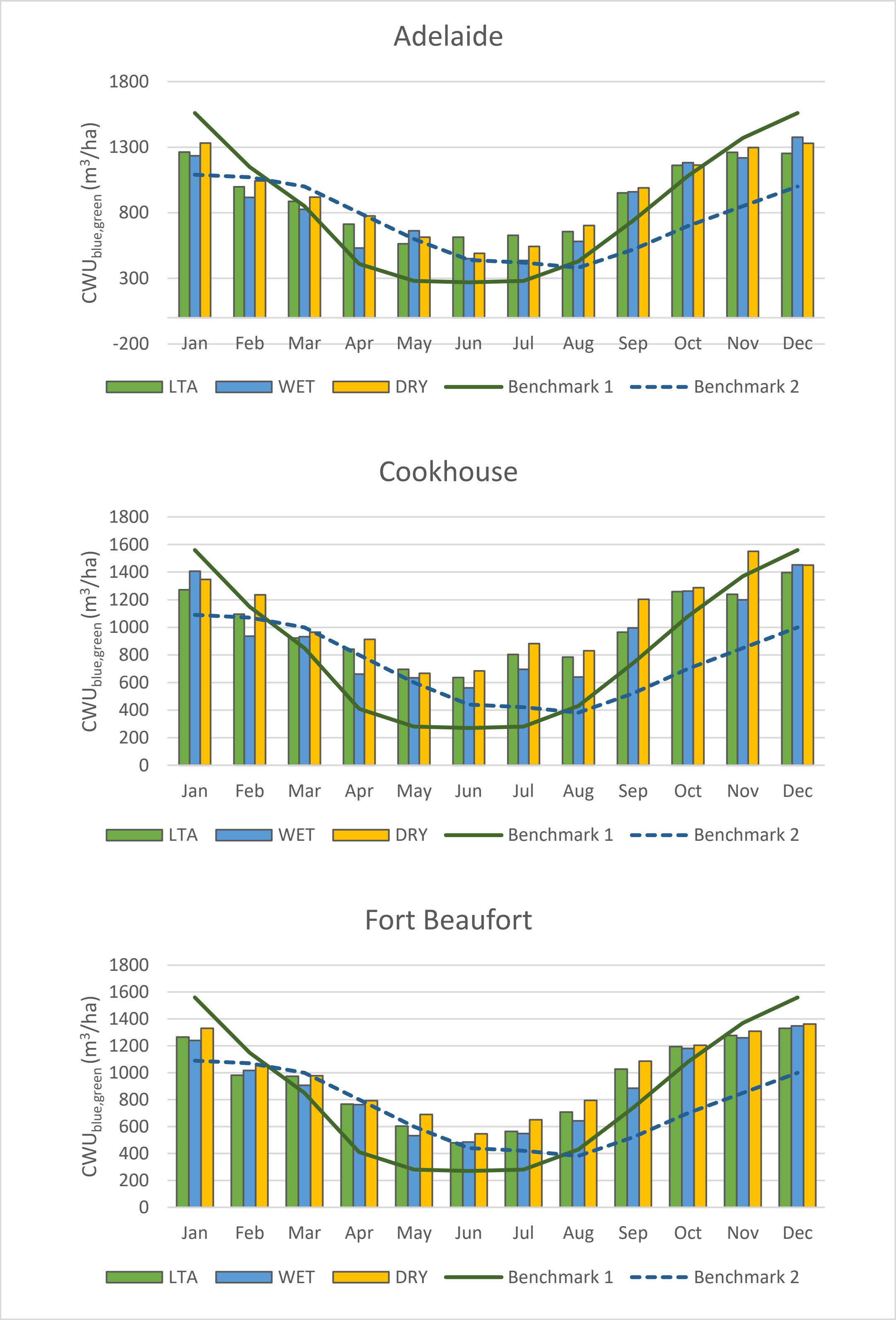

Figure 5.7: Weighted Monthly CWU$_{blue,green}$ (m^3/ha) for Citrus Production in the Adelaide, Cookhouse and Fort Beaufort Production Regions Benchmarked Against Theoretical Water Requirement

Source: Netterville (1996); Mostert (2006); Own calculations

Total blue and green CWU ($CWU_{blue,green}$) calculated for orchards in the three river valleys generally exceeded 10 000 m^3/ha/annum. This can partially be attributed to the inclusion of irrigation system losses. However, it is largely due to the over-estimation of water use by young citrus trees: Young trees theoretically require approximately 35% of the water that is needed by mature trees (Mostert, 2006). However, ET_c found for young trees was on average roughly 1.4 times larger than that of mature trees. As recommended in the WF Assessment manual (Hoekstra *et al*., 2011), ET (both blue and green) (measured in mm, equivalent to litres/m^2) was multiplied by 10 in order to convert the volume measured to meters cubed per hectare, and CWU. This method was applied to orchards regardless of age group.

However, younger trees occupy a smaller area per cultivated hectare than mature trees. If one assumes 1000 trees per hectare[30], and that young trees' soil surface of leaf canopy is 2.5m^2 per tree (as indicated by Netterville (1996)), young trees would occupy 25% of a cultivated hectare. If ET_c for young trees is generally 1.4 times that of mature trees, and young trees occupy 25% of the area occupied by mature trees, young orchards' ET_c per hectare should be 35% that of mature trees (1.4 multiplied by 25%), and ET_c would more appropriately be multiplied by 3.5 than 10 to find CWU measured in m^3 per hectare. This corresponds with the theoretical water use of young trees in relation to that of mature trees.

If one assumes that $CWU_{blue,green}$ results provide a realistic picture, only the farms with scheme-linked state water rights were permitted to withdraw an adequate volume of water to meet crop water requirements (and only marginally in the case of the farm in the Fort Beaufort region). Registered water users would in this case need to rely on additional water sources, such as bore holes, on-farm stored water, and, in the Fort Beaufort region, purchasing water which is sporadically released from the Kat Dam. However, as discussed, it is believed that $CWU_{blue,green}$ requirements found in this research were over-estimated.

These results highlight the importance of state water supply scheme development, which, coupled with the allocation of linked water rights, lead to greater availability and reliability of water for agricultural enterprises. This in turn has the potential to lead to economic growth and increased employment, particularly for high-value, employment-rich agricultural

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[30] This is a conservative figure – tree censuses obtained for the study region indicated that the number of trees per hectare in the study region was often less than this.

industries (such as the citrus industry). The development of new state water supply schemes would also increase water security for domestic needs in the local vicinity. However, the development of new schemes is both expensive and time consuming. Nevertheless, the potential for such schemes has been explored. For instance, the DWS (2015) has investigated the feasibility of a dam to be built upstream of Adelaide (Foxwood Dam), the construction of which would substantially alter the water supply structure of farmers in the region.

5.4 Yield

Yield per hectare for each variety group produced in each of the river valleys assessed are shown in Figures 5.8 and 5.9. As expected, yield per hectare was positively correlated with tree maturity. Lemons had the highest proportion of mature trees across the three valleys and demonstrated consistently high yield per hectare across the three regions. Late mandarins, which had the smallest proportion of mature trees across the study area, had the lowest average yield per hectare. Maturity is not the only contributing factor - varieties have varying potential yields (Malan, 1991), shown in Figure 5.8. Lemons and satsumas have the highest potential yield amongst the variety groups assessed, and, as anticipated, demonstrated correspondingly high yields per hectare in LTA, wet and dry years (lower satsuma yields per hectare in the Adelaide region can be attributed to the comparatively young age of trees in the area).

None of the realised yields achieved the maximum potential figures (as provided by Malan (1991) and farm interviews). However, quoted potential yield per hectare (shown in Figure 5.8) is that which is achievable by mature trees. If the potential yield is weighted by the proportion of that potential yield which is achievable by trees within each age group (young, intermediate and mature) (Malan, 1991), a more realistic adjusted potential yield per hectare is produced, which are more meaningful when considering the orchards of differing age groups which exist within the three valleys. These adjusted yields per hectare are shown in Figure 5.8, along with the actual realised yield per hectare for each variety within each of the three river valleys.

Figure 5.8: Yield per Hectare (tonnes/ha) of Citrus Produced in the Adelaide, Cookhouse and Fort Beaufort Regions, Benchmarked Against Potential and Adjusted Potential Yield.

Source: Malan (1991); Farmer interviews; Local Citrus Co-Operative

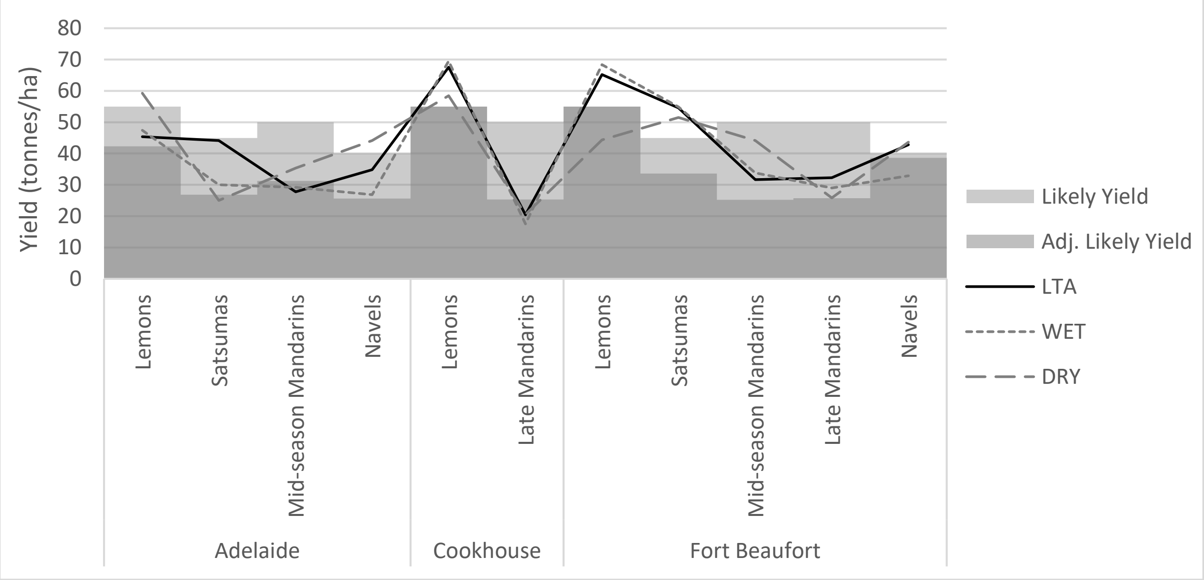

Figure 5.9: Yield per Hectare (tonnes/ha) of Citrus Produced in the Adelaide, Cookhouse and Fort Beaufort Regions, Benchmarked Against 'Likely' and Adjusted 'Likely' Yield.

Source: Malan (1991); Farmer interviews; Local Citrus Co-Operative

When comparing yields to the adjusted potential yield per hectare, figures fell on average within roughly 30% of the adjusted potential across all three valleys. Along with 'potential production' per hectare, a 'likely production' estimate is also available (Malan, 1991) and 'target' production figures were supplied by a representative from the local citrus co-operative. Likely and target production is generally lower than the maximum potential production. The crop load produced by a citrus tree is inversely related to fruit size (de Villiers and Joubert, 2006). Achieving maximum potential yield may therefore result in undesirably small fruit, and consequently farmers may intentionally manipulate production in order to achieve a desired balance between preferred marketable fruit size and quantity of fruit produced. When considering LTA production against likely or target production (adjusted according to age group capacity to achieve likely production), the realised yield per hectare within each river valley is generally very close to the 'likely' figure, and often exceeds it (see Figure 5.9).

In the Adelaide region, satsuma LTA yield per hectare lay very close to the adjusted potential yield, differing by approximately 1%. Navel production also came close to adjusted potential yield per hectare, falling short by less than 10%. Lemon and mid-season mandarin per hectare LTA yields were both approximately 25% lower than the adjusted potential. Lemon, navel and satsuma LTA yield per hectare all exceeded adjusted 'likely' production, while mid-season mandarin production lay approximately 10% below this benchmark. In the Cookhouse region lemon production exceeded adjusted 'likely' figures and was roughly 15% lower than potential production. Late mandarin production fell short of both adjusted potential and 'likely' yields. In the Fort Beaufort area, late mandarin and mid-season mandarin LTA yield per hectare exceeded adjusted potential yield, with satsuma production closely approaching the adjusted potential, falling short by 3%. Lemon and navel LTA yields per hectare were respectively 19% and 26% short of the adjusted potential figure. The per hectare LTA yield of all varieties produced in the Fort Beaufort region exceeded adjusted 'likely' production.

5.5 Water Footprint

This section describes blue, green, grey and total WF results. Blue, green and grey WF were calculated by dividing CWU_{blue}, CWU_{green}, and the pollutant load (L) respectively by yield per hectare in LTA, wet and dry years. Total WF was found by summing these blue, green and grey WF components.

5.5.1 Blue Water Footprint

Blue water footprint (WF_{blue}) found for citrus produced in the Adelaide, Cookhouse and Fort Beaufort regions in LTA, wet and dry years is shown in Figure 5.10. As expected, WF_{blue} in the designated dry year typically exceeded that found in the wet year. However, WF_{blue} in the dry year did not necessarily always exceed WF_{blue} over the LTA, and LTA WF_{blue} did not necessarily exceed WF_{blue} in the wet year. Water footprint is influenced by yield per hectare, which is in turn influenced by tree maturity. Moreover, as discussed in section 5.3.1, in some instances P_{eff} in the LTA exceeded that occurring in the wet year (despite actual precipitation in the designated wet year consistently exceeding LTA rainfall), which impacts WF_{blue} through CWU_{blue}.

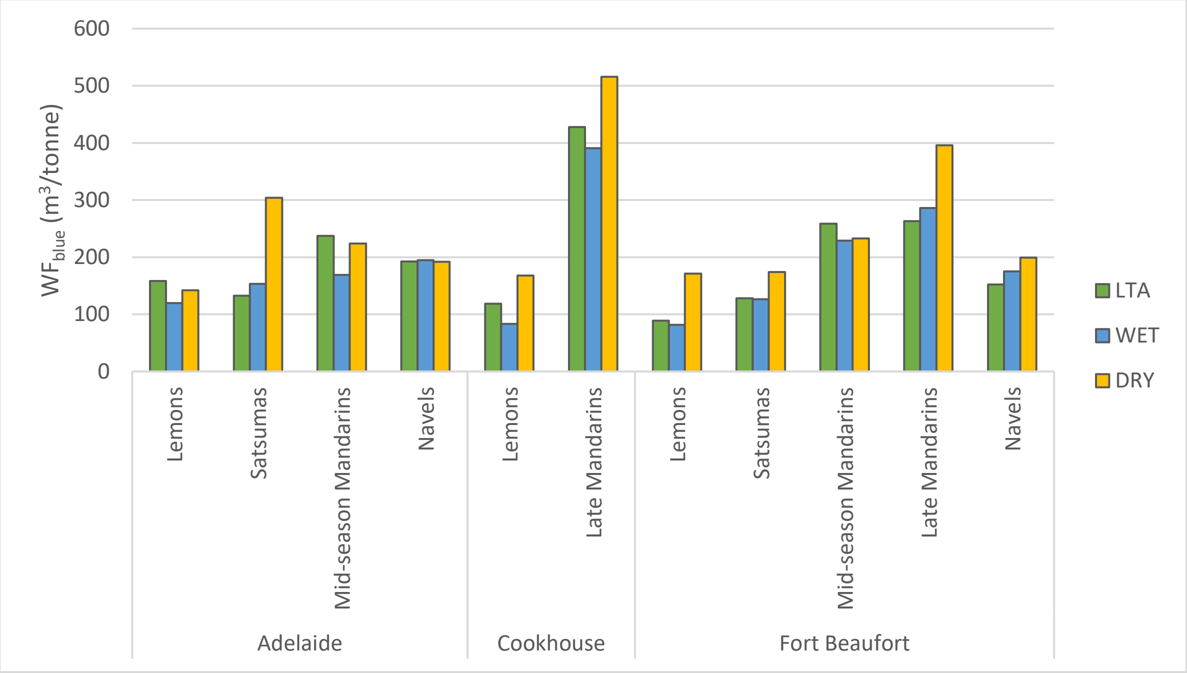

Figure 5.10: WF_{blue} (m^3/tonne) of Citrus Produced in the Adelaide, Cookhouse and Fort Beaufort Regions

Across all three valleys considered together lemons had the lowest WF_{blue} in the LTA, wet and dry years. Late mandarins had the highest WF_{blue} across the LTA, wet and dry years, followed in turn by mid-season mandarins, navels and satsumas in the LTA and wet years. In the dry year, the average WF_{blue} of satsumas across the study regions exceeded that of mid-season mandarins, largely due to the elevated WF_{blue} of satsumas in the Adelaide region the dry year.

When jointly considering varieties in each valley, Cookhouse had the largest WF_{blue} across LTA, wet and dry years. Joint WF_{blue} in Fort Beaufort surpassed that of Adelaide in the LTA but was smaller in the Fort Beaufort region in the wet and dry years. The Adelaide region displayed the least variation between WF_{blue} of variety groups grown in the area in the LTA, wet and dry years, while Cookhouse had the greatest variation between varieties' WF_{blue}.

In the Adelaide region WF_{blue} ranged from 133 to 238 m^3/tonne in the LTA. Mid-season mandarins had the greatest LTA WF_{blue} in the region, and the second greatest WF_{blue} in the wet and dry years. Mid-season mandarins' WF_{blue} was exceeded by that of navels in the wet year and satsumas in the dry year. The WF_{blue} of lemons was consistently low (ranked lowest in the wet and dry years and second lowest in the LTA). Satsumas has a relatively low WF_{blue} in the LTA and dry years but displayed the highest WF_{blue} of all varieties assessed in the region in the dry year. A large proportion of the satsumas assessed in the Adelaide region were not mature in the dry year, and yield per hectare was accordingly lower in that year. CWU_{blue} of satsumas grown in Adelaide in the dry year was also substantially higher than that in the LTA and wet years. WF_{blue} of navels in the LTA, wet and dry years were strikingly similar in the Adelaide region, deviating from each other by only 1%.

In the Cookhouse region the WF_{blue} of late mandarins was significantly higher than that of lemons in each of the LTA, wet and dry years. In contrast to the lemons grown in the area, a large proportion of late mandarins were in the 'young' and 'intermediate' age groups. Yield per hectare was accordingly lower, conforming with the lower potential yield of immature trees (as specified by Malan, 1991). In addition, potential production of mature lemons is higher than that of late mandarins, at 80 and 60 tonnes per hectare respectively (Malan, 1991; interviews with local citrus co-operative representative). Moreover, the CWU_{blue} of late mandarins was higher than that of lemons throughout the LTA, wet and dry years. It is therefore unsurprising that the WF_{blue} of lemons was consistently and substantially lower than that of late mandarins in the Cookhouse region.

In the Fort Beaufort region LTA WF_{blue} ranged between 89 and 263 m^3/tonne. WF_{blue} was highest for late mandarins across the LTA, wet and dry years, followed in turn by mid-season mandarins, navels, satsumas and lemons. As was the case in the Cookhouse region, late mandarins produced in Fort Beaufort had consistently high CWU_{blue} values (the highest CWU_{blue} of assessed varieties in the LTA and wet years, and the second highest in the dry year, when mid-season mandarins' CWU_{blue} just surpassed that of late mandarins). Moreover, a large proportion of the late mandarins grown in the area had not yet reached maturity. Late mandarin yield per hectare was ranked lowest in the Fort Beaufort area in the wet and dry years and was ranked second lowest in the LTA. Mid-season mandarins also had a large proportion of young and intermediate trees, and consistently high CWU_{blue} values in the LTA, wet and dry years. High WF_{blue} figures for late and mid-season mandarins in the region were therefore to be expected. In contrast, lemons and satsumas produced in the Fort Beaufort area both had high yields per hectare (and correspondingly high potential yields) in comparison to other varieties, with the majority of trees having reached maturity. In addition, both lemons and satsumas had comparatively low CWU_{blue} values across the LTA, wet and dry years, leading to lower WF_{blue} results for these two variety groups.

At the farm level WF_{blue} followed a similar pattern to WF_{blue} assessed across each valley: WF_{blue} was generally lowest for lemons and satsumas, and highest for late mandarins and mid-season mandarins, varying according to CWU_{blue} and the proportion of young, intermediate and mature orchards in production. The farm with the lowest WF_{blue} (averaged across varieties) varied across years, located in the Fort Beaufort region in the LTA and the Adelaide region in the wet and dry years. Cookhouse had the highest farm level WF_{blue} in all three LTA, wet and dry years. The other farm with scheme-linked water rights, located in the Fort Beaufort region, had only the fifth highest WF_{blue} in the LTA, but was ranked second and third in the dry and wet years respectively.

Weighted average WF_{blue} at the farm level was greater for micro irrigated production than drip irrigated production for lemons in the LTA, wet and dry years; for satsumas and mid-season mandarins in the LTA and wet years; and for navels in the wet year. However, weighted average WF_{blue} of drip irrigated production was greater for satsumas and mid-season mandarins in the dry year, and for navels in the LTA and dry years. Although WF_{blue} of micro irrigation surpassed that of drip irrigation more often than not, the lack of conformity with the ranking of CWU_{blue} of drip and micro irrigated orchards implies that yield per hectare has a skewing effect on the apparent impact of irrigation system on WF_{blue}.

5.5.2 Green Water Footprint

CWU_{green} of variety groups assessed within the three study regions were divided by the relevant yield per hectare in order to find WF_{green} in the LTA, wet and dry years. As expected, WF_{green} was generally largest in the wet year and smallest in the dry year, with some exceptions (see Figure 5.11). As shown in Figure 5.4 (section 5.3.1) LTA P_{eff} for some variety groups assessed in the Fort Beaufort region exceeded P_{eff} in the wet year, despite actual precipitation remaining greater in the wet year.

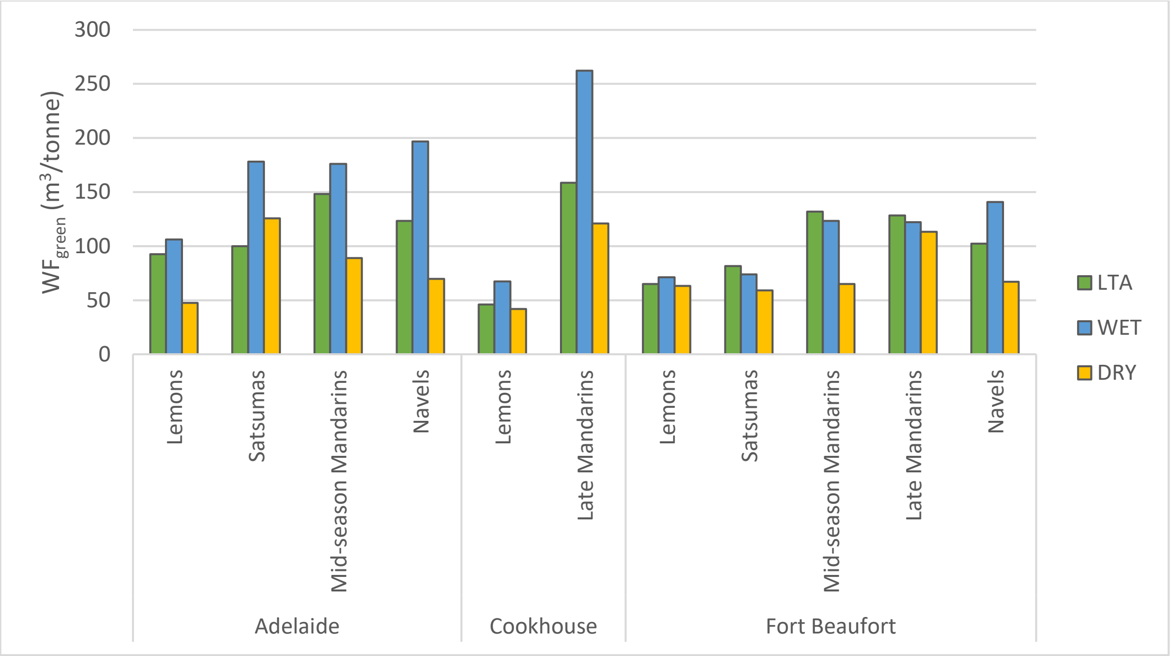

Figure 5.11: WF$_{green}$ (m^3/tonne) of Citrus Produced in the Adelaide, Cookhouse and Fort Beaufort Regions

Across all three valleys, weighted average WF$_{green}$ was greatest for late mandarins in the LTA, wet and dry years, and smallest for lemons. Mid-season mandarins' WF$_{green}$ was ranked second highest, followed in turn by navels and satsumas in the LTA and wet years. In the dry year, the WF$_{green}$ of satsumas exceeded that of navels. When comparing the joint WF$_{green}$ averaged across all varieties produced within each valley, Cookhouse had the largest weighted WF$_{green}$ in the LTA, wet and dry years, followed by Adelaide and Fort Beaufort respectively.

In the Adelaide region WF$_{green}$ ranged from 92 to 148 m^3/tonne in the LTA. Lemons consistently had the lowest WF$_{green}$ in the region in the LTA, wet and dry years. However, no other parallel rankings were exhibited. In the LTA, mid-season mandarins had the highest WF$_{green}$, followed in turn by navels and satsumas. In the wet year mid-season mandarins' WF$_{green}$ was exceeded by that of navels and satsumas. In the dry year the WF$_{green}$ of late mandarins were highest, followed by mid-season mandarins and then navels. CWU$_{green}$, and thus WF$_{green}$, is highly dependent on precipitation, and varying rainfall patterns and intensity in the wet and dry years result in variation from the LTA.

In the Fort Beaufort region LTA WF$_{green}$ ranged from 65 to 132 m^3/tonne. Lemons had the lowest WF$_{green}$ in the area in the LTA and wet years, followed by satsumas. Apart from this, the WF_{green} ranking of varieties assessed in the Fort Beaufort region differed year on year, as was the case in the Adelaide region. In the LTA, mid-season mandarins had the highest WF_{green}, followed by that of late mandarins and navels. In the wet year navels' WF_{green} was ranked the highest, with mid-season mandarins and late mandarins ranked second and third respectively. In the dry year, the WF_{green} of late mandarins was greatest, followed in turn by navels, mid-season mandarins, lemons and satsumas. In the Cookhouse region late mandarins' WF_{green} was higher than that of lemons throughout the LTA, wet and dry years, which was unsurprising considering the consistently higher yield per hectare of lemons in the region compared to that of late mandarins. Lemons have a greater potential yield than late mandarins, and a relatively large proportion of the late mandarins produced in the Cookhouse region were not yet mature. LTA WF_{green} in the Cookhouse region ranged from 46 m^3/tonne for lemons to 158 m^3/tonne for late mandarin.

At the farm level, Cookhouse had the highest weighted average WF_{green} in the LTA, wet and dry years. In contrast, the Fort Beaufort farm in possession of water rights linked to a state scheme had the third lowest WF_{green} in the long term and was ranked second and fourth lowest in the dry and wet years respectively. This is not surprising, considering the disparity in rainfall between the Cookhouse and Fort Beaufort regions. In the LTA a farm in the Fort Beaufort region had the lowest WF_{green}, while in the wet and dry years farms in the Adelaide region had the lowest ranking WF_{green}.

5.5.3 Grey Water Footprint

Grey water footprints were found for varieties produced across the three valleys by dividing grey water by yield per hectare, where grey water is calculated as the pollutant load (L) divided by the difference between the maximum acceptable concentration (c_{max}) and natural background concentration (c_{nat}) of chemicals (see equation 10 in Chapter 4). Since water pollution resulting from citrus production is diffuse in nature (i.e. chemicals are applied to soil rather than directly to the water bodies), chemical application to the soil was multiplied by a leaching-runoff fraction (α) in order to find L. Separate calculations were carried out for nitrogen (N), phosphorous (P) and potassium (K) soil applications, with the most critical pollutant finally being accounted for[31]. The most critical pollutant is that which requires the largest volume of freshwater to assimilate its load.

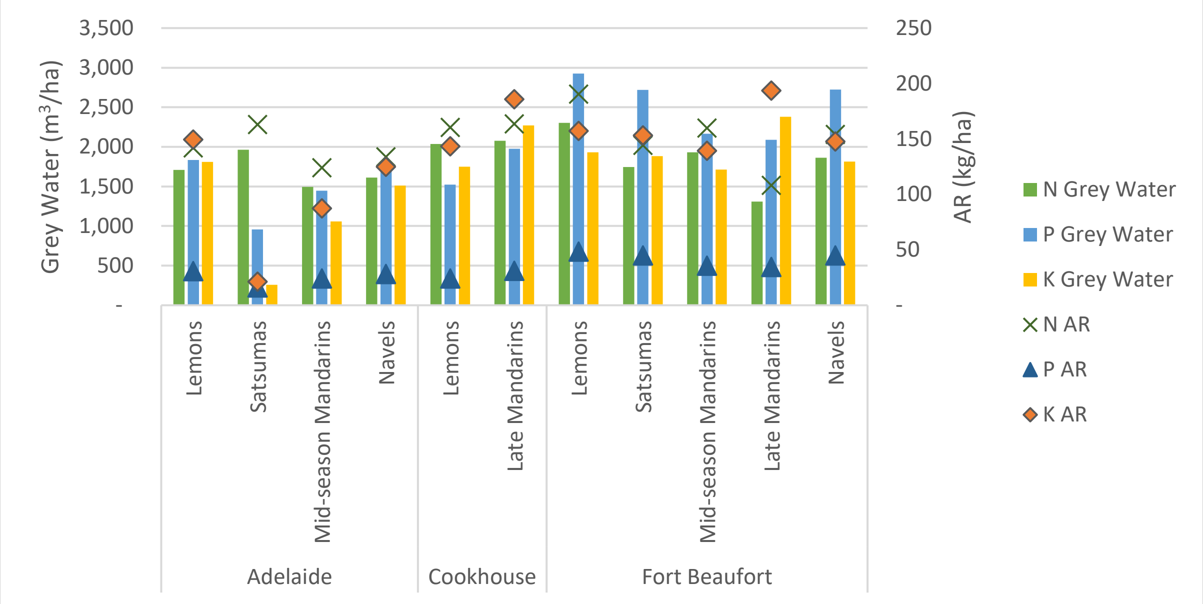

Figure 5.12: N, P and K Application Rates (kg/ha per annum) and Grey Water (m^3/ha) of Citrus Produced in the Adelaide, Cookhouse and Fort Beaufort Regions

Weighted application rates for N, P and K in each valley and the resultant volume of grey water are shown in Figure 5.12. P application rates tended to be substantially lower than those of N and K, with the exception of average K applied to satsuma orchards in the Adelaide region, which is similarly low. This is primarily due to relatively low K application by one farm in particular in the Adelaide region, on which the fertigation method for K involves daily daylight fertigation (i.e. fertigation via enriched water, delivered by means of drip irrigation during daylight hours), as well as an annual K-Humate application, which together are understood to increase the uptake efficiency of K (according to farm interviews). It is important to note that all K application rates are based on leaf and soil analyses, and that a relatively lower AR of K is not indicative of lower uptake levels by plants. Rather, a higher K AR is considered unnecessary due to suitable levels of K found in soil and leaf samples. The farm in question utilises similar K ARs across all varieties produced. However, weighted across the valley, the impact is only visible for satsuma production as the enterprise is the sole

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[31] In fact, only the most critical of N and P was accounted for (and these were generally the most critical), as K calculations were carried out using c_{max} obtained from domestic water quality guidelines, rather than ambient standards. Domestic guidelines are largely based on aesthetic standards, since even large concentrations of K are relatively harmless (DWAF, 1996b).

satsuma-producer assessed in the region. At the farm level chemical AR varied substantially – N application ranged from 75-250 kg/ha; P from 11-50 kg/ha; and K from 21-245 kg/ha.

The WF_{grey} for varieties produced in the three valleys in the LTA, wet and dry years are shown in Figure 5.13 These WF_{grey} values are those for the most critical pollutant, only considering N and P (i.e. the highest of the resultant WF_{grey} calculated for N and P). Since K calculations were carried out using domestic rather than ambient water quality standards, K WF_{grey} results indicate the volume of freshwater required to return K concentrations to levels suitable for domestic consumption (which are largely based on acceptable aesthetic levels, as high concentrations of K are relatively harmless (DWAF, 1996b)). K-specific WF_{grey} calculations were therefore not ultimately considered for the final WF_{grey} result, as they have no implication for the condition of aquatic ecosystems.

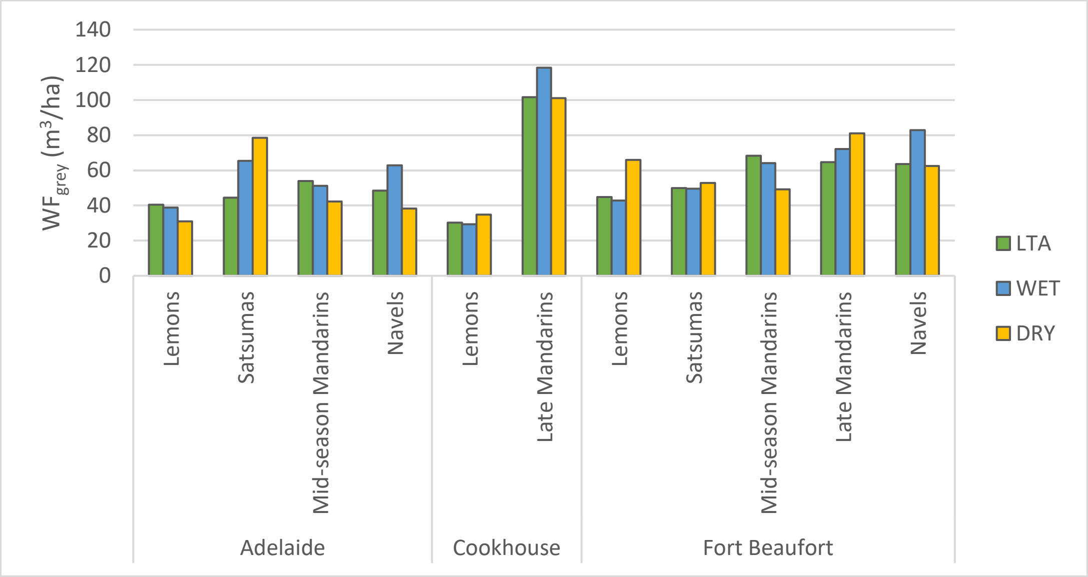


Figure 5.13: WF_{grey} (m^3/tonne) of Citrus Produced in the Adelaide, Cookhouse and Fort Beaufort Regions

Across the LTA, wet and dry years N was the most critical pollutant in the case of mid-season mandarins and satsumas produced in the Adelaide region, and for late mandarins and lemons produced in Cookhouse. P was most critical for the remaining varieties produced in the study regions. If taken into account, K would have been the most critical contaminant for late mandarins produced in the Cookhouse and Fort Beaufort regions in the LTA, wet and dry years, and for lemons in the Cookhouse region in the dry year. Note that the most critical contaminant is that which has the greatest contaminant-specific WF_{grey} (i.e. the contaminant which requires the largest amount of freshwater in order to be diluted back to natural background concentrations) (Franke *et al.*, 2013). It is not necessarily the contaminant which has the highest AR, being more dependent on the proximity of the pollutant load to the maximum acceptable concentration.

When comparing WF_{grey} of valleys (weighted across varieties), Cookhouse had the greatest WF_{grey} in the LTA, wet and dry years, followed by Fort Beaufort, with Adelaide consistently having the lowest WF_{grey} of the three valleys. Adelaide did indeed have a smaller WF_{grey} than Fort Beaufort for lemons, navels, mid-season mandarins and satsumas. However, Cookhouse lemons had the smallest WF_{grey} across all three valleys. Cookhouse's overall WF_{grey} was adversely affected by the markedly high WF_{grey} of late mandarins produced in the area, which were highest across all varieties in all three valleys in the LTA, wet and dry years. Late mandarin's grey water in the area (for N, which was most critical) was not particularly high relative to grey water of other varieties produced across the three valleys, at 2076 m^3/ha. The elevated late mandarin WF_{grey} is therefore primarily due to the relatively low yield per hectare of late mandarins, which in turn resulted from the relatively high proportion of immature late mandarin trees in the region. On the other hand, lemons in the area had a relatively high yield per hectare (lemons have a higher potential yield and were predominantly mature), which resulted in a low WF_{grey}, despite their grey water volume being higher than the weighted average (at 2038 m^3/ha).

In the Adelaide region lemons consistently had the lowest WF_{grey} of varieties produced in the area, at 40, 39 and 31 m^3/tonne in the LTA, wet and dry years respectively. Mid-season mandarins had the greatest WF_{grey} in the LTA, at 54 m^3/tonne; while satsumas' WF_{grey} was highest in the wet and dry years, at 65 and 79 m^3/tonne respectively. As discussed, WF_{grey} in the Cookhouse region was highest for late mandarins and lowest for lemons throughout the LTA, wet and dry years. Late mandarin's WF_{grey} in the area ranged from 101 m^3/tonne in the dry year, to 118 m^3/tonne in the wet year. In contrast, lemons WF_{grey} ranged from 29 to 35 m^3/tonne in the wet and dry years respectively.

In the Fort Beaufort region lemons had the lowest WF_{grey} in the LTA and wet years (at 45 and 43 m^3/tonne respectively), while mid-season mandarins had the lowest figure in the dry year (at 49 m^3/tonne). Satsumas had the second lowest WF_{grey} throughout the LTA, wet and dry years, ranging from 59 to 53 m^3/tonne. The highest WF_{grey} was that of mid-season mandarins in the LTA (at 68 m^3/tonne); navels in the wet year (at 83 m^3/tonne); and late mandarins in the dry year (at 81 m^3/tonne). Variations in rankings across the LTA, wet and dry years can largely be attributed to varying yields per hectare.

The variety with the greatest weighted average WF_{grey} across valleys was late mandarins in the LTA, wet and dry years, followed in turn by mid-season mandarins, navels, satsumas and lemons in the LTA. In the wet year, late mandarins' WF_{grey} was followed respectively by that of navels, mid-season mandarins, satsumas and finally lemons. In the dry year navels' WF_{grey} was also ranked second greatest, but the WF_{grey} of satsumas exceeded that of mid-season mandarin and lemons, with mid-season mandarins having the lowest WF_{grey}.

5.5.4 Total Water Footprint

In order to find total WF (WF_{total}) the blue, green and grey WF components were combined, as per equation 1 in Chapter 4. When considering all three regions together as a whole, late mandarins had the highest WF_{total} in the LTA (629 m^3/tonne), as well as in the wet and dry years. Late mandarins' LTA WF_{total} was followed in turn by that of mid-season mandarins, navels and satsumas. Lemons consistently had the lowest WF_{total} in the LTA, wet and dry years (232 m^3/tonne in the LTA). For all varieties, WF_{blue} weighted across the three valleys accounted for the greatest proportion of WF_{total} in all years (53% across varieties in the LTA), followed by WF_{green} (30%) and WF_{grey} (17%).

Figure 5.14 shows the WF_{total} of the various cultivars assessed across the three river valleys, as well as their blue, green and grey components, across the LTA, wet and dry years. Of the varieties produced across the study regions, late mandarins grown in the Cookhouse area had by far the largest WF_{total} across the LTA, wet and dry years. In contrast, lemons produced in the Cookhouse region had the smallest WF_{total} in the LTA and wet years, and the second lowest in the dry year (exceeding the WF_{total} of lemons produced in the Adelaide region by only a small margin). In general, the blue component of WF was larger than the green component, and WF_{green} was larger than WF_{grey}.

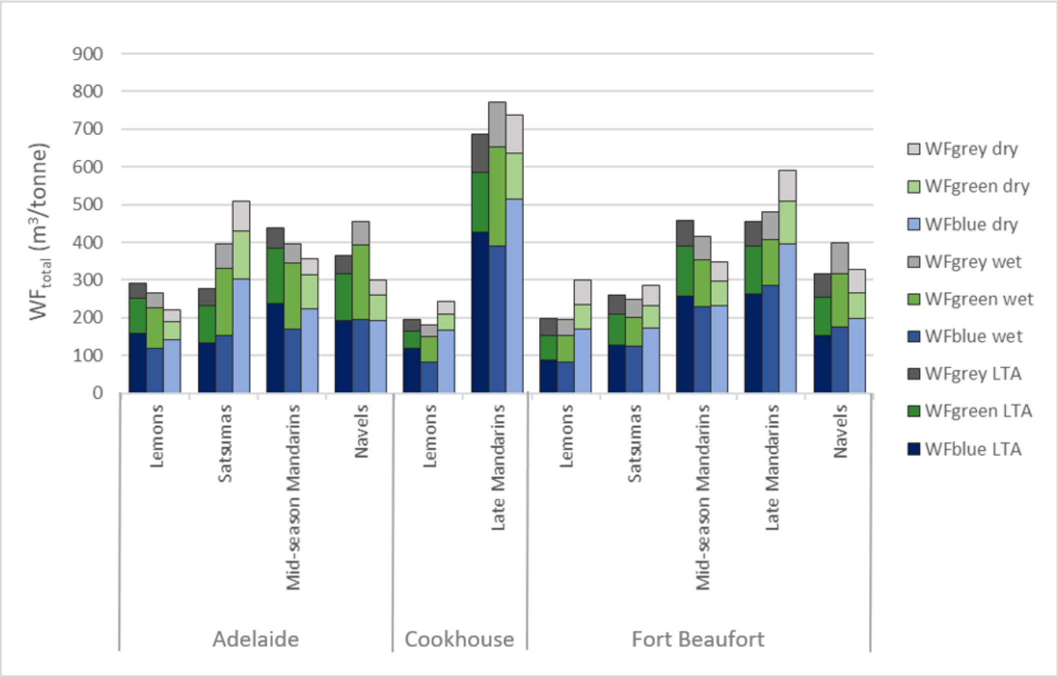


Figure 5.14: WF$_{total}$ (m^3/tonne) of Citrus Produced in the Adelaide, Cookhouse and Fort Beaufort Regions, with Blue, Green and Grey Components

In the Fort Beaufort region, the WF$_{total}$ of late and mid-season mandarins were consistently higher than that of other varieties across the LTA, wet and dry years. Late mandarins' WF$_{total}$ ranged from 456 to 590 m^3/tonne, while that of mid-season mandarins ranged from 347 to 459 m^3/tonne. Lemons' and satsumas' WF$_{total}$ were typically ranked lowest, with lemons WF$_{total}$ ranging from 196 to 300 m^3/tonne and satsumas WF$_{total}$ ranging from 250 to 286 m^3/tonne.

In the Adelaide region lemons had a consistently low WF$_{total}$, ranked second lowest in the LTA and smallest in the wet and dry years (at 291, 265 and 220 m^3/tonne respectively). Other varieties' WF$_{total}$ varied more substantially across the LTA, wet and dry years, with satsumas' WF$_{total}$ ranging from 277 to 508 m^3/tonne; mid-season mandarins' WF$_{total}$ ranging from 355 to 440 m^3/tonne; and navels' figure ranging between 300 and 455 m^3/tonne. As previously noted, in the Cookhouse region the WF$_{total}$ of late mandarins exceeded that of lemons throughout the LTA, wet and dry years, with late mandarins' WF$_{total}$ ranging from 688 to 771 m^3/tonne, and lemons' WF$_{total}$ ranging from 180 to 245 m^3/tonne.

When considering varieties grouped together within valleys, Cookhouse had the largest WF$_{total}$ of the three valleys in the LTA, wet and dry years. This is unsurprising, considering the elevated WF_{total} of late mandarins produced in the region. Fort Beaufort had the lowest weighted average WF_{total} in the LTA and wet years, while Adelaide's was smallest in the dry year.

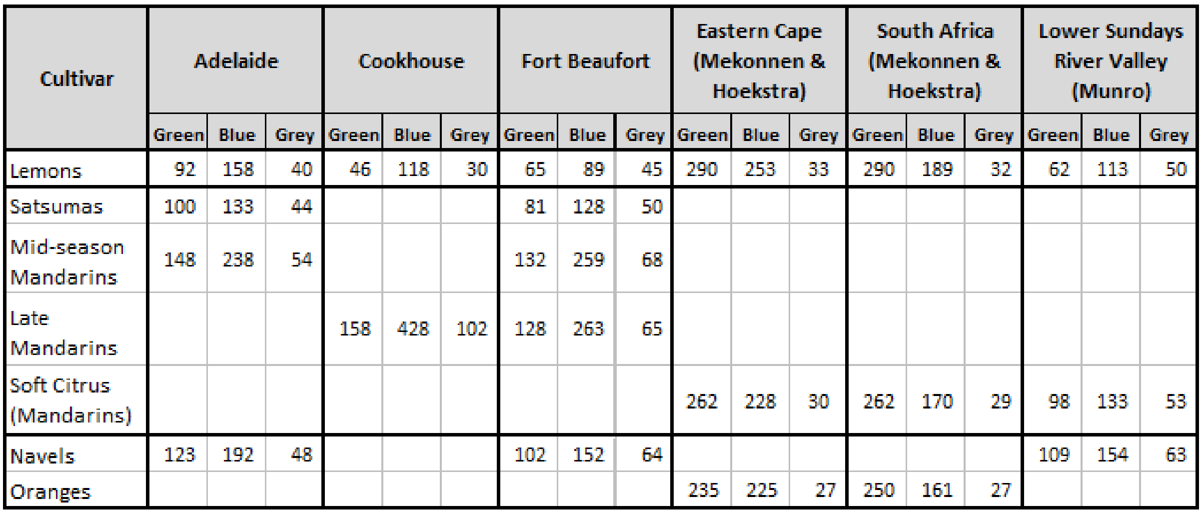
At the farm level, WF_{total} of farms located in the Adelaide region ranged from 355 to 530 m^3/tonne in the LTA; from 273 to 405 m^3/tonne in the designated wet year; and from 273 to 449 m^3/tonne in the dry year (weighted across varieties). In the Fort Beaufort region, the weighted WF_{total} of farms ranged from 286 to 424 in the LTA; from 290 to 443 m^3/tonne in the wet year; and from 325 to 491 m^3/tonne in the dry year. Both farms with state water entitlements (i.e. water rights) had relatively high WF_{total} figures: the WF_{total} of the Cookhouse farm was highest across the three valleys; while the farm with a water provision located in the Fort Beaufort region had the third highest WF_{total} of all farms across the three valleys in the LTA, and the second highest in the dry year, at 424 and 491 m^3/tonne respectively (in the wet year the WF_{total} of the farm in the vicinity of Fort Beaufort was only fifth highest, at 384 m^3/tonne).

5.5.5 Benchmarking Water Footprint Results

The water footprint of citrus in South Africa has previously been estimated by Mekonnen & Hoekstra (2010) and by Munro *et al*. (2016). Mekonnen and Hoekstra (2010) evaluated the blue, green and grey WF of citrus in each province of South Africa as well as for the country as a whole. Munro *et al*. (2016) assessed citrus production in the Lower Sundays River Valley (LSRV), located in the Eastern Cape Province. Table 5.1 provides a summary of the WF figures found in these two studies, as well as results from this research.

WF_{green} found by Mekonnen and Hoekstra (2010) for citrus produced in the Eastern Cape (EC) and South Africa (SA) consistently exceeded that found in this study for each variety group in the Adelaide, Cookhouse and Fort Beaufort regions in the LTA. In general, LTA WF_{blue} in this study was lower than that found by Mekonnen and Hoekstra (2010), except for mid-season mandarins and late mandarins across valleys. In addition, the WF_{blue} of oranges found for South Africa as a whole (Mekonnen and Hoekstra, 2010) was lower than that of navels in the Adelaide region, though the WF_{blue} of oranges in the EC exceeded that of Adelaide navels. LTA WF_{grey} found in this study was generally higher than that found in the EC and SA by Mekonnen and Hoekstra (2010), with the exception of lemons in the Cookhouse region. LTA WF_{total} was largely smaller in this study than that found by Mekonnen and Hoekstra (2010), apart from that of late mandarins produced in the Cookhouse region.

Table 5.1: LTA Green, Blue and Grey WF Results Benchmarked Against Findings by Mekonnen & Hoekstra (2010) and Munro et al. (2016)



Cultivar	Adelaide			Cookhouse			Fort Beaufort			Eastern Cape (Mekonnen & Hoekstra)			South Africa (Mekonnen & Hoekstra)			Lower Sundays River Valley (Munro)		
	Green	Blue	Grey	Green	Blue	Grey	Green	Blue	Grey	Green	Blue	Grey	Green	Blue	Grey	Green	Blue	Grey
Lemons	92	158	40	46	118	30	65	89	45	290	253	33	290	189	32	62	113	50
Satsumas	100	133	44				81	128	50									
Mid-season Mandarins	148	238	54				132	259	68									
Late Mandarins				158	428	102	128	263	65									
Soft Citrus (Mandarins)										262	228	30	262	170	29	98	133	53
Navels	123	192	48				102	152	64							109	154	63
Oranges										235	225	27	250	161	27			

Source: Mekonnen and Hoekstra (2010); Munro et al. (2016)

When comparing results from this study to those found by Munro *et al* (2016) for citrus produced in the LSRV, it was found that LTA WF$_{green}$ in this study generally exceeded that in the LSRV, except in the case of lemons produced in the Cookhouse region, and satsumas and navels produced in Fort Beaufort. Similarly, LTA WF$_{blue}$ in this study exceeded that found by Munro *et al* (2016), except for the WF$_{blue}$ of satsumas produced in the Adelaide region, and that of lemons, satsumas and navels in the Fort Beaufort region. On the other hand, LTA WF$_{grey}$ found in this study was smaller than that found by Munro *et al*. (2016), with the exception of mid-season mandarins' and late mandarins' WF$_{grey}$ across all three valleys, as well as that of navels produced in Fort Beaufort. LTA WF$_{total}$ found by Munro *et al*. (2016) was greater than that found in this study for lemons, satsumas and navels produced in the Fort Beaufort region; lemons produced in the Cookhouse region; and satsumas produced in Adelaide. LTA WF$_{total}$ exceeded that found by Munro *et al*. (2016) for lemons and navels produced in the Adelaide region and for mid-season mandarins and late mandarins across valleys.

5.6 Water Productivity and Economic Water Productivity

5.6.1 Water Productivity

Water productivity (WP) was found by dividing yield per hectare by combined blue and green CWU ($CWU_{blue,green}$). The WP found for the varieties produced across the three river valleys are shown in Figure 5.15 (in kilograms per m^3). WP is the inverse of combined blue and green WF. The WP approach looks at water use in terms of volume of production per unit of water use, while WF considers the quantity of water used to produce a certain volume of production.

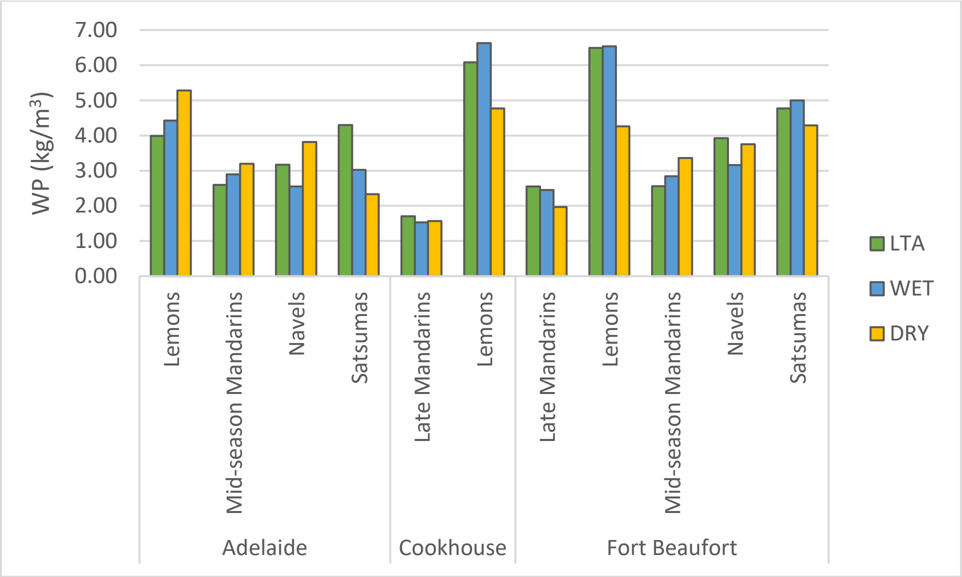


Figure 5.15: WP (kg/m^3) of Citrus Produced in the Adelaide, Cookhouse and Fort Beaufort Regions

WP of citrus varieties grown across the three regions ranged from 1.5 to 6.6 kg/m^3. Average weighted WP across valleys was greatest for lemons, followed in turn by satsumas, navels, mid-season mandarins and finally late mandarins in each of the LTA, wet and dry years. In the Adelaide region LTA WP ranged from 4.3 kg/m^3 for satsumas to 2.6 kg/m^3 for mid-season mandarins. Lemons had the largest WP in the wet and dry years, at 4.4 and 5.3 kg/m^3 respectively. In the wet year the variety with the smallest WP in the Adelaide region was navels (at 3.8 kg/m^3), while satsumas had the lowest WP in the dry year (2.3 kg/m^3), in stark contrast to the LTA.

In the Cookhouse region the WP of lemons exceeded that of late mandarins in all three wet, dry and LTA years. In the wet year, Cookhouse possessed the highest and lowest WP across all three valleys for lemons (with a WP of 6.6 kg/m^3) and late mandarins (1.5 kg/m^3) respectively. In the Fort Beaufort region WP was highest for lemons in the LTA and wet years, at 6.5 kg/m^3 in both cases. In the dry year the WP of satsumas matched that of lemons at 4.3 kg/m^3. Late mandarins had the lowest WP across the LTA, wet and dry years (ranging from 2 to 2.6 kg/m^3), followed in turn by mid-season mandarins and navels. For all varieties considered together, Fort Beaufort had the highest WP in the LTA and wet years, while WP in Adelaide was highest in the dry year. Cookhouse had the lowest WP across the LTA, wet and dry years.

Farms in Fort Beaufort held the position of having the highest weighted average WP across varieties in the LTA and wet years, while the farm with the greatest WP in the dry year was located in Adelaide. Cookhouse consistently had the lowest weighted average WP in the LTA, wet and dry years, with values ranging from 1.8 to 2 kg/m^3. Although lemons produced in the Cookhouse region had relatively high WP values, late mandarins' WP was low, and, in terms of hectares, late mandarin production far exceeds lemon production in the assessed Cookhouse region. The other farm with state scheme water rights, located in the Fort Beaufort region, did not have similar weighted WP values to Cookhouse, with values ranging from 3.6 to 4.9 kg/m^3 in the LTA, wet and dry years.

In instances where certain varieties were irrigated solely (or close to solely) with either drippers or micro sprinklers, it was possible to compare irrigation systems across farms. Lemons, satsumas and navels irrigated via dripper systems were consistently more productive (in terms of WP) than those with micro irrigation. The weighted average WP of mid-season mandarins irrigated via drippers was also higher than that of those which were micro-irrigated in the LTA and wet years (though the opposite was true in the dry year). All late mandarins assessed were drip-irrigated, and therefore no comparison could take place. As drip irrigated orchards were largely found to use water more productively than micro irrigated orchards, decision makers concerned with water savings and efficient water usage should consider a move towards drip irrigation systems. However, the cost of such a conversion also needs to be considered, and the water saving advantages of switching must be weighed against these costs. It was found that newer orchards were most typically irrigated via dripper system, and orchards irrigated via micro systems tended to be older. Farmers therefore have shown a tendency to opt for the more water-efficient dripper system when developing new orchards.

5.6.2 Economic Water Productivity

The economic WP (EWP) of citrus production was found by multiplying yield per hectare of each variety group by the average annual real DIP (i.e. 'Delivered in Port') price per tonne of each variety, and dividing the resultant figure by $CWU_{blue,green}$. EWP presents water use in terms of the gross economic return per unit of $CWU_{blue,green}$. EWP is essentially the inverse of economic $WF_{blue,green}$, if economic $WF_{blue,green}$ is deemed the volume of blue and green water expended to achieve a certain economic value of production.

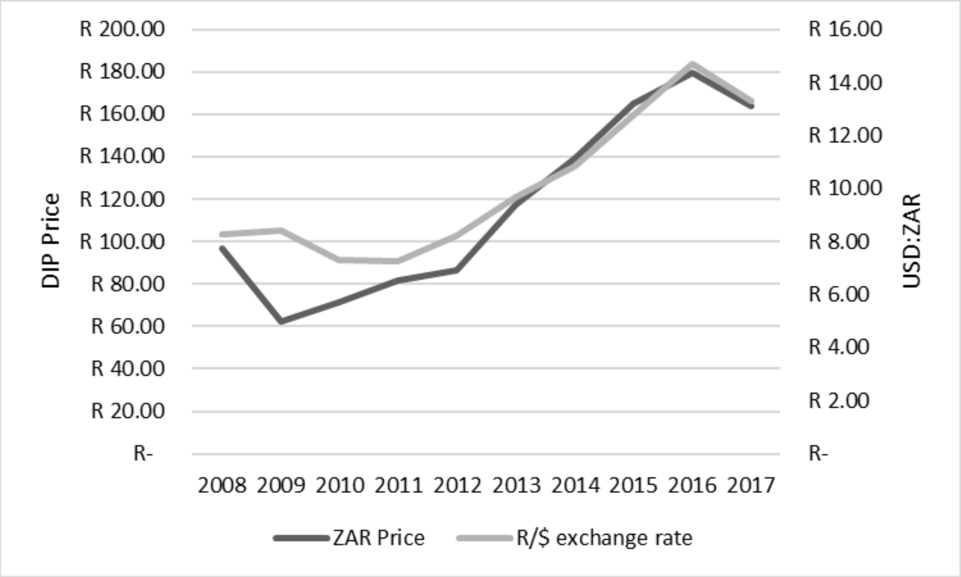


Figure 5.16: Average ZAR Prices Received for Citrus and USD:ZAR Exchange Rate: 2008-2017

Source: Local citrus co-operative and SARB (2018)

EWP was calculated for variety groups produced in each river valley using average real DIP prices both in terms of South African Rands (ZAR) and US Dollars (USD). Prices were obtained from the local citrus co-operative in ZAR terms. However, the majority of citrus produced in the area is exported, and payment for fruit is received in foreign currency which is then exchanged for ZAR. Foreign currency exchange rates can therefore be expected to significantly impact the ZAR price. As payments for exported fruit are typically (though not exclusively) received in USD, it was decided that USD would be an appropriate foreign currency in which to assess EWP. As is illustrated in Figure 5.16, there was a strong positive correlation between average DIP prices in ZAR terms (obtained from the local citrus co-operative) and the USD:ZAR exchange rate (obtained from the South African Reserve Bank (SARB, 2018) between 2008 and 2017. Historical exchange rates (SARB, 2018) were therefore used to convert ZAR prices into USD. Real ZAR and USD prices were found using Consumer Price Index (CPI) statistics from Statistics South Africa (STATSSA, 2018) and the International Monetary Fund (IMF, 2018) respectively.

Between the years of 2008 and 2017 late mandarins consistently had the highest annual average real DIP price, followed by lemons in 2008, 2010, and from 2014 to 2017 (as well as in the LTA). Mid-season mandarin prices exceeded those of lemons in 2009, 2011, 2012, and 2013 (and thus exceeded lemon prices in the designated dry and wet years). Navel prices were lowest in all years except 2008 and 2017, when satsuma prices were lower.

Figure 5.17 illustrates EWP found across the three assessed river valleys, presented in both ZAR and USD terms. Across all three valleys, weighted average EWP in the LTA and wet year was highest for lemons, followed in turn by satsumas, late mandarins, mid-season mandarins and navels. In the dry year satsumas had the greatest EWP, followed by mid-season mandarins, lemons, late mandarins and navels respectively.

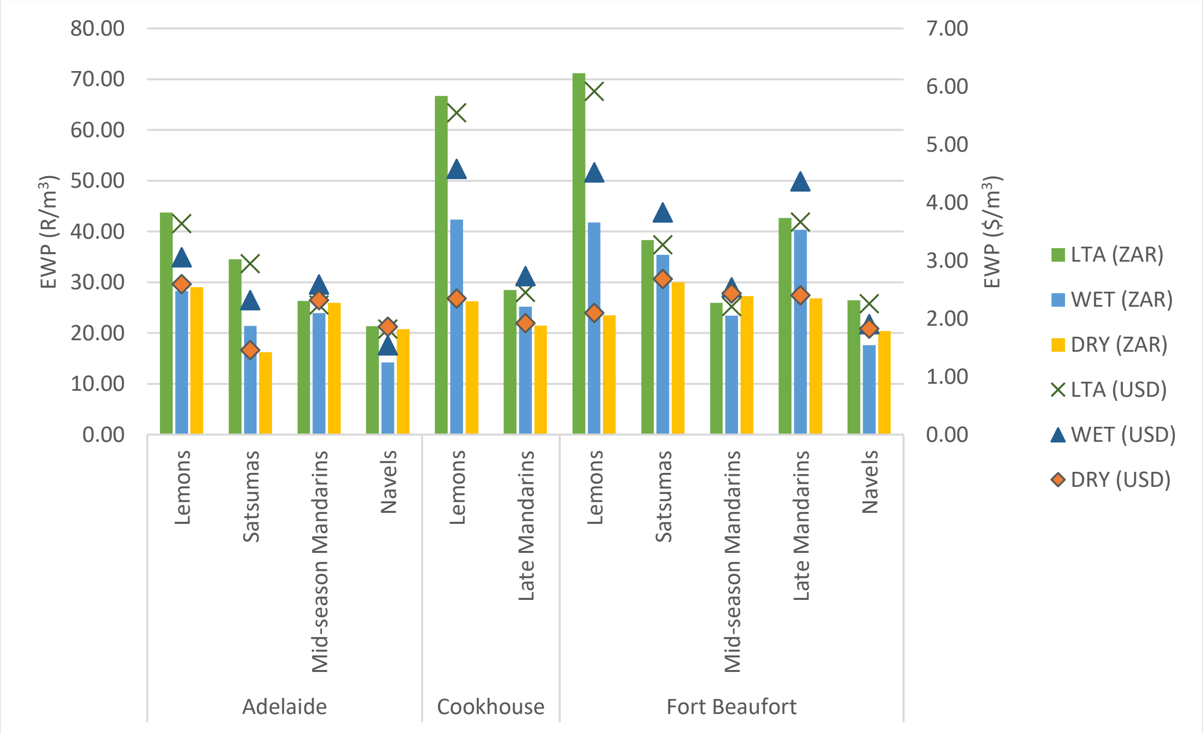


Figure: 5.17: EWP of Citrus Produced in the Adelaide, Cookhouse and Fort Beaufort Regions

In the Adelaide region lemons had the greatest EWP of all varieties across LTA, wet and dry years, ranging from R28.27/m^3 in the wet year to R43.77/m^3 in the LTA (or, in USD terms, from \$2.59/m^3 in the dry year to \$3.64/m^3 in the LTA). Lemons' EWP was followed by that of satsumas in the LTA, while mid-season mandarins were ranked second greatest in the wet and dry years (in both ZAR and USD terms). Navels' EWP was smallest in the LTA and wet years, at R21.33/m^3 (\$1.82/m^3 in USD terms) and R14.20/m^3 (\$1.54/m^3) respectively. In the dry year satsumas had the lowest EWP, at R16.26/m^3 in ZAR terms and \$1.45/m^3 in USD terms. Mid-season mandarins' EWP showed the least variation between the LTA, wet and dry years, while the EWP of satsumas varied the most.

In the Cookhouse region lemons' EWP was consistently higher than that of late mandarins. In ZAR terms lemons' EWP ranged from R26.25/m^3 in the dry year to R66.69/m^3 in the LTA, and from \$2.34/m^3 (dry year) to \$5.54/m^3 (LTA) in USD terms. The EWP of late mandarins in the region ranged from R21.48/m^3 (or \$1.92/m^3 in real USD terms) to R28.48/m^3 (or \$2.73/m^3). The margin between lemon and late mandarin EWP in the Cookhouse region was smaller than that observed in WP results (as well as in WF_{blue} and WF_{green} results), especially in the wet and dry years. The impact of late mandarins' lower yield in the region (due in part to the relatively large proportion of immature trees) is substantially alleviated in EWP measures by the high returns received for late mandarins in contrast to other varieties.

EWP in the Fort Beaufort region was highest in the LTA and wet years for lemons, at R71.18/m^3 and R41.78/m^3 respectively (or \$5.91/m^3 and \$4.52/m^3 in USD terms), followed in turn by late mandarins and satsumas. In the dry year, the EWP of satsumas was greatest (at R30/m^3 or \$2.68/m^3), while lemon EWP was ranked second to last. In the LTA, the EWP of mid-season mandarins was lowest, at R25.98/m^3 in ZAR terms and \$2.20/m^3 in USD. Navels had the smallest EWP in the wet and dry year, at R17.60/m^3 and R20.42/m^3 respectively (\$1.90/m^3 and \$1.82/m^3 in USD terms). Rankings of varieties in the Adelaide, Cookhouse and Fort Beaufort regions were identical for EWP expressed in ZAR and USD terms.

The EWP of lemons produced in the Cookhouse and Fort Beaufort regions were much higher than that in the Adelaide region in the LTA and wet years. This is likely due to the greater proportion of younger trees in the Adelaide region in comparison to the other two valleys, which results in a lower potential yield per hectare. Yield per hectare was roughly 30% lower in Adelaide than in the Fort Beaufort and Cookhouse regions in the wet and LTA years (in the dry year Adelaide had a greater yield per hectare than the other two valleys, though by a smaller margin). Satsumas' EWP were similar across valleys in the LTA, but much lower in the Adelaide region in the wet and dry years, which had a larger proportion of immature trees than the other valley. Similarly, a larger proportion of late mandarins in the Fort Beaufort region were mature than those in Cookhouse, and accordingly, the EWP of the variety was higher in Fort Beaufort than in Cookhouse. The EWP of mid-season mandarins were fairly similar across valleys, as was the case for navels' EWP.

When considering weighted EWP across varieties assessed in each valley, Fort Beaufort had the highest value in the LTA and wet years (R37.4/m^3 and \$3.16/m^3 in ZAR and USD terms respectively) but was exceeded by Adelaide in the dry year (at R24.75/m^3 and \$2.21/ m^3). Although Cookhouse had the lowest EWP in the dry year (R21.84/m^3 and \$1.95/m^3), the region had the second greatest joint EWP in the LTA and wet years, at R31.36/m^3 (\$2.68/m^3 in USD terms) and R26.51/m^3 (\$2.87/m^3) respectively. This contrasts with WP (weighted across varieties), which was lowest in each of the LTA, wet and dry years in the Cookhouse region (and WF_{blue} and WF_{green}, which were both greatest in the Cookhouse region in LTA, wet, and dry years when weighted across variety groups). This elevated ranking in the Cookhouse region's EWP (in contrast to its WP) can be attributed to the relatively high value crops grown in the region. Only late mandarins and lemons were assessed in the Cookhouse region, and these two varieties generally received the highest economic return per tonne of production for the period of 2008 to 2017.

At the farm level, farms' joint EWP across varieties tended to be positively correlated with the proportion of mature trees, as well as with the proportion of higher-value variety groups in production. The EWP of the two farms with a state water rights (one in Cookhouse and one in Fort Beaufort) were similar, varying by approximately 3% in the LTA and wet years, and 13% in the dry year.

5.7 Discussion

As indicators of water use, WF and WP are useful decision-making tools. However, it is important to note that they are single-factor productivity measures applied in a multi-factor environment, and that decision makers at the farm level must also consider factors outside of water use (Scheierling *et al.*, 2016; Giordano *et al.*, 2017). In addition, it is important to examine the various components making up WF, WP and EWP indices in order to obtain a more complete picture. Rather than minimising WF (and maximising WP and EWP), the aim should be to achieve optimal WF, WP and EWP (Wichelns, 2015a), considering situational variables and on-farm objectives.

Instead of solely considering superficial WF, WP and EWP values, factors such as CWU, potential yield, economic return, climate, water availability and water allocation should also be taken into account. The ideal scenario would be to cultivate high value crops that have a relatively low CWU and high potential yield. However, when this is not possible, farmers must decide whether to prioritise high value crops, such as late mandarins and mid-season mandarins, despite their high CWU; or alternatively to cultivate varieties with high yield potential, such as satsumas and lemons. Optimising crop choice links back to the first of the four 'key pathways' for improving WP as identified by Molden *et al*. (2007) (as discussed in section 2.5), which involves increasing yield per unit of water consumption[32].

In the LTA, lemons had the smallest WF_{total} of all varieties produced in the Fort Beaufort and Cookhouse regions, and the second lowest WF_{total} in Adelaide (exceeding satsumas' WF_{total} by a small margin). Similarly, the variety's $CWU_{blue,green}$ was lowest of assessed cultivars in the Fort Beaufort and Cookhouse regions (though it was ranked highest in Adelaide). Lemons have the highest potential yield of the varieties assessed across the three valleys (80 tonnes/ha) and are also a high value crop in relation to other varieties (in terms of LTA DIP prices). Lemons' LTA EWP (in both ZAR and USD terms) was highest across varieties produced in each of the three valleys. However, lemons are more cold- and frost-sensitive than mandarins and oranges (Bijzet, 2006), deeming them unsuitable for production in some locations within the three river valleys.

As with lemons, satsumas have a high yield potential in relation to other varieties (75 tonnes/ha). Satsumas had the lowest $CWU_{blue,green}$ in the Adelaide region and fairly average $CWU_{blue,green}$ in the Fort Beaufort region. The variety also had the smallest LTA WF_{total} in Adelaide and the second smallest in the Fort Beaufort region. However, the LTA DIP price for

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[32] Though these key pathways were identified for the improvement of WP at basin-level (Molden *et al*., 2007; Giordano *et al*., 2017), they may be applied to a certain extent at the farm-level and are useful for the identification of strategies aimed at optimising WP.

satsumas was on the lower end of the scale in relation to that of other varieties. Satsumas' LTA EWP (in both ZAR and USD terms) was second highest in the Adelaide region and average in Fort Beaufort.

Late mandarins had the highest LTA WF_{total} across the three valleys, as well as the highest $CWU_{blue,green}$. The potential yield of late mandarins is amongst the lowest of the assessed varieties (60 tonnes/ha). However, late mandarins are a high value crop relative to other varieties and obtained the highest LTA DIP price/tonne by a substantial margin. This resulted in a higher LTA EWP for late mandarins (second highest in the Fort Beaufort and Cookhouse regions). Late mandarins are therefore a desirable crop for profit maximising farmers, provided that an adequate and reliable water supply is available. However, despite their relatively high return, late mandarins may not be an appropriate option for farms with a high probability of facing extended periods of reduced water availability, as may occur during protracted droughts.

When considering and comparing WF and WP results across the three valleys, it is important to take into account the age profile of fruit in production. Potential yield is highly dependent on tree maturity – younger trees are not capable of producing the same volume of yield as mature trees, which leads to WF of young trees typically being higher, and WP being lower. Moreover, as previously discussed, $CWU_{blue,green}$ results for young trees were found to be unduly elevated. $CWU_{blue,green}$ and WF_{total} weighted across varieties in each valley were highest for the Cookhouse region in the LTA, wet and dry years. However, this is not necessarily due to site-effect: Cookhouse had the highest proportion of immature trees of all three valleys (across all varieties). It is therefore useful to compare results pertaining to mature orchards. Lemons, for instance, were largely mature in the Cookhouse and Fort Beaufort regions, and $CWU_{blue,green}$ and $WF_{blue,green}$ was greater for this variety in Cookhouse than in Fort Beaufort, which can more reliably be attributed to factors outside of maturity (such as site-effect, management practice, etc.).

Fort Beaufort had the largest proportion of mature trees of the three assessed valleys. Despite this, weighted $CWU_{blue,green}$ in the Adelaide region was lowest across the LTA, wet and dry years, which can also be attributed to site-specific characteristics rather than age-profile. However, the higher yield potential of the more mature trees came into play when comparing weighted $WF_{blue,green}$ across the three valleys, which was lowest in the Fort Beaufort region in the LTA and wet years. It is interesting to note that late mandarins and mid-season mandarins, which typically had high WF values, were predominantly in the young and intermediate age groups across all valleys. It is therefore possible that results would differ for older orchards of these varieties, and with return per tonne amongst the highest across cultivars (in terms of LTA DIP prices), late mandarins and mid-season mandarins may potentially be of greater long-term desirability for profit-maximising farmers than presumed at first glance.

Drip irrigation systems were utilised for approximately 63% of the assessed orchards across the three valleys, while micro irrigation systems were used for the remainder. Dripper systems were largely found to be more efficient than micro systems: irrigation losses were typically greater for micro irrigation systems; CWU_{blue} was consistently found to be lower for drip irrigated orchards; and orchards irrigated via dripper systems typically had greater LTA WP. Citrus enterprises aiming to improve water use efficiency should therefore consider switching to drip irrigation systems. However, it is important for decision makers to weigh the water saving advantages of drippers against the financial burden of changing irrigation systems. Opportunity costs need to be considered, with the short-term monetary costs involved evaluated against and compared to the long-term benefits of a more efficient system. Irrigation system choice can be linked to the first two 'key pathways' for improving WP identified by Molden *et al*. (2007), which are: a. to improve yield per unit of CWU; and b. to decrease non-productive water consumption. Productivity per unit of CWU can be increased by utilising more efficient irrigation systems (i.e. drip versus micro systems); and non-productive water consumption may be decreased by reducing irrigation system losses due unrecoverable runoff (which was generally found to be lower for dripper systems).

A comparison of farms with state scheme water rights versus registered water users did not yield particularly conclusive results. Although WF_{total} for water rights holders were fairly high in relation to that of other assessed farms, results were not similar when comparing CWU. As only two farms with state water rights were assessed, additional sample sites are required in order to draw more meaningful conclusions with respect to water use differences between farms with differing water supply structures. It is noted, however, that holdings in possession of water rights, which typically have greater reliability of water supply, are able to cultivate land for citrus with a greater degree of certainty regarding future irrigation water availability, even in periods of relative scarcity. Water rights are not guaranteed, however, and may be reallocated or reduced by government in accordance with the NWA (1996). For example, in 2018 water rights quotas were reduced by 80% in the Langkloof Valley in the Eastern Cape as a result water scarcity stemming from protracted drought (Jansen, 2018). In contrast to water rights holders, registered water users are largely reliant on environmental flows for water supply (as no state water schemes have been developed), and accordingly need to ensure that available water is used as efficiently as possible during periods of water scarcity.

5.8 Synopsis

This chapter described and discussed the results found during the research. Farm characteristics across the three assessed regions are expressed, followed by CWU results; blue, green and grey WF findings; and finally, WP and EWP results. The chapter following contains concluding remarks, summarising the methods applied, outcomes, and recommendations ensuing from the research.

CHAPTER 6
CONCLUSION

6.1 Introduction

The objective of this research was to calculate and compare the WF and EWP of citrus production across three river catchments located in the Eastern Cape Midlands, namely the Koonap, Kat and Fish River Valleys. The overarching aim was to identify the most efficient systems and practices in use, in terms of WF and EWP, and to analyse and explain differences in these indices. In order to achieve these objectives, the literature surrounding the concepts of WF, WP and EWP was explored. In addition, the background of the South African citrus industry, as well its economic, environmental, and operational context were investigated. Following this, WF, EWP, and the various components making up these two indices were evaluated for participant citrus producing enterprises located across the three valleys. Results were then compared and assessed in order to draw conclusions regarding efficient water usage practices in the context of citrus production in the Eastern Cape Midlands.

6.2 Summary and Conclusions

6.2.1 Background and Literature Review

Water is an invaluable and often indispensable commodity for industry, the environment, and society. Despite this, access to freshwater has become increasingly challenging, with the onset of global warming exacerbating the frequency and duration of drought in already water scarce areas (Hoekstra and Mekonnen, 2011; Damania *et al*., 2017). In addition, rising population levels have increased pressures on global water resources while the demand for water intensive products is on the rise (Mekonnen and Hoekstra, 2012; Hoekstra and Wiedmann, 2014; Damania *et al*., 2017; Marston *et al*., 2018). South Africa is classified as a water scarce country, characterised by a highly variable, semi-arid climate, which is distinguished by sporadic and unreliable rainfall (DEA, 2011; DWS, 2018a). Severe droughts have been experienced across the country in recent years, and water supply challenges have come to be considered the ‘new normal’. As a result, increasingly complex and difficult water management decisions must be made, with associated opportunity costs having to be considered in order to optimise economic, social and ecological water consumption.

Water footprint and water productivity indicators are two tools which may be used to help inform difficult water management decisions. Building on the concepts of LCA, EF, and other 'footprint' indicators which measure the impact of humanity on environmental resources, the concept of WF was introduced as an indicator of consumptive water use, accounting for both direct and indirect water appropriation (Hoekstra *et al.,* 2011). WF can be defined for both consumers and products and services, and has been applied extensively within the arena of agricultural research (Mekonnen and Hoekstra, 2011a; Mekonnen and Hoekstra, 2012; Lovarelli *et al*., 2016; Munro *et al*., 2016; Harding *et al.,* 2017). In the context of crop production, physical WP is essentially the inverse of combined blue-green WF. Agricultural WP defines water use in terms of the output that is produced per unit of water used, where output may be defined physically or economically (Pereira *et al*., 2012; Giordano *et al*., 2017). The notion of improved agricultural WP, often referred to as 'more crop per drop,' has gained international popularity in the discussion surrounding issues of water scarcity, food security and environmental sustainability (Sharma *et al*., 2015; Giordano *et al*., 2017).

Agriculture is the largest consumer of water in South Africa, utilising approximately 55% of total surface water resources (DWS, 2018a) and accounting for an estimated 94.7% of the country's total WF (Pahlow *et al*., 2015). The industry is an important contributor to food security in South Africa and plays a significant role in the nation's employment. Approximately 8.5 million people are employed or supported by the sector (both directly and indirectly), which amounts to roughly 15% of the country's total population (DWA, 2013). Though the agricultural industry's direct contribution to GDP is relatively trivial (2.2%) (DAFF, 2018b), when considering multipliers linked to the industry, the sector's performance is found to strongly impact the GDP of other sectors (Greyling, 2015).

Citrus production in South Africa accounts for roughly 25% of the country's gross value of horticultural production (DAFF, 2018a; DAFF, 2018b). The majority of citrus produced in South Africa is exported (CGA, 2018), and the industry is thus a valuable importer of foreign currency. In terms of export value, citrus exports make up the greatest proportion of the nation's agricultural exports (DAFF, 2018a; DAFF, 2018b). The citrus industry is highly labour intensive, and it is estimated that over one million households are reliant on the industry for income (both directly and indirectly, taking into account supply chain services). However, citrus production is also highly water intensive, and water supply is the primary limiting factor to growth and development within the industry (DWA, 2013; Vahrmeijer *et al*., 2015).

6.2.2 Research Method

WF and its constituent blue, green and grey components were calculated using the WFN approach, as laid out in the 'Water Footprint Assessment Manual' (Hoekstra *et al*., 2011), supplemented by the accompanying Tier 1 supporting guidelines for grey WF accounting (Franke *et al*., 2013). Blue and green WF were calculated by dividing the respective blue and green components of CWU by crop yield. In contrast, WP was found by dividing yield by combined blue and green CWU, with EWP utilising the gross value of crop yield as the numerator. Grey WF was estimated by dividing the pollutant load (L) resulting from citrus production by the difference between c_{max} and c_{nat}, and then dividing the resultant figure by the crop yield.

Calculations were carried out over five citrus variety groups (navel oranges, lemons, satsumas, mid-season mandarins, and late-mandarins) produced across ten farms located throughout the three valleys. Three of these farms were located in the vicinity of the settlement of Adelaide (in the Koonap River Valley), six in the region of Fort Beaufort (Kat River Valley), and one in the vicinity of Cookhouse (Fish River Valley). WF, WP and EWP indices were calculated for a ten-year LTA period (2008-2017), as well as for a designated wet and dry year (2011 and 2009 respectively).

6.2.3 Results, Discussion and Conclusions

It was found that citrus production in the Cookhouse region typically had the greatest CWU, WF_{blue}, WF_{green} and WF_{total} across the three valleys, when weighted across all variety groups in production. The region also had the lowest WP of the three valleys. However, the EWP of citrus production in Cookhouse was second greatest across the three valleys in the LTA and wet years (though the indicator was still lowest in the dry year). Cookhouse has a warmer climate and lower mean annual rainfall than the other two assessed regions, which had an elevating impact on the CWU (and thus blue and green WF) of citrus production in the area. However, the varieties assessed in the Cookhouse region were lemons and late mandarins, which were typically the two highest returning crops produced across the three valleys. These superior returns resulted in higher ranking EWP figures in relation to the other water-use indices assessed.

Adelaide had the lowest CWU, weighted across varieties, of the three assessed regions. However, this lower CWU did not necessarily translate to the region having the lowest WF across the study areas. The Adelaide region's LTA WF_{blue} was indeed lowest of the three valleys, but in the designated wet and dry years WF_{blue} was lowest in the Fort Beaufort region. Moreover, WF_{green} was lowest in the Fort Beaufort region across the LTA, wet and dry years, as was the case for WF_{total} in the LTA and wet years. This demonstrates the impact that yield and, indirectly, orchard maturity have on WF indices. Fort Beaufort had the greatest proportion of mature trees across the three valleys. Tree maturity is positively correlated with yield potential (Malan, 1991), and this translated to lower WF results in the Fort Beaufort area. Yield similarly impacted WP and EWP in the region, both of which were highest for citrus production in Fort Beaufort in the LTA and wet years (though these indices were highest in the Adelaide region in the dry year).

WF_{grey} was lowest in the Adelaide region when weighted across all produced variety groups, and highest in the Cookhouse region. These results are due in part to participant farmers' chemical application rates and strategies, and partly to yield figures. The Cookhouse region had the smallest proportion of mature trees of the three assessed regions, which meant that yield (which is positively correlated to tree maturity) was lower, translating to higher WF_{grey} results. On the other hand, average chemical application rate was smallest in the Adelaide region, which lead to lower WF_{grey} results. Chemical AR is typically based on concentrations found in leaf and soil analyses, and thus nutrient rich soils result in lower fertilisation applications. However, management-specific chemical application strategies also play a role, and new and innovative application methods can result in reduced levels of application, and thus to potentially lower associated costs. The development and trial of such strategies is therefore in the best interest of decision makers, both from an environmental and a financial standpoint.

When considering citrus production across all three valleys as whole. It was found that the blue, green, grey and total WF of the assessed variety groups was typically lowest for lemons, followed by that of satsumas. In contrast, the WF of late mandarins and mid-season mandarins was generally found to be relatively high, while navel oranges WF results were average across the assessed varieties. Lemons and satsumas have the highest potential yield of the assessed variety groups, and the impact of this can be seen in the WF results. In addition, lemons' CWU was lowest of all the varieties, while the CWU of late mandarins and mid-season mandarins was typically relatively high, further influencing WF results. When considering EWP results, lemons were typically the most productive of all varieties. Satsumas also had relatively high EWP results, despite the relatively low prices earned for this variety. The impact of economic return was most significant for late mandarins and navels. Late mandarins LTA return was relatively high, which resulted in higher EWP figures for the variety than obtained for navels and mid-season mandarins. Navels, on the other hand, had the lowest EWP of all varieties, with the lowest LTA return across varieties.

WF, WP and EWP found for varieties produced throughout the three regions varied, impacted by factors such as orchard maturity, yield, water use, climate, and economic return. Irrigation systems utilised also impacted results, with CWU_{blue} typically lower for drip irrigated orchards than for those utilising micro irrigation systems. Irrigation losses due to runoff and percolation were also generally found to be smaller in the case of dripper systems. Astute decision makers concerned with using water as efficiently as possible should therefore utilise drip rather than micro systems. However, the water savings benefits associated with drip systems need to be weighed against the costs linked to switching to and installing dripper systems. It was observed that more newly developed orchards, such as those in the Cookhouse region, typically utilised dripper systems.

A comparison of state scheme water rights holders' CWU, WF and WP figures versus those found for registered water users did not lead to conclusive results being drawn regarding differences in water use patterns. Additional sample sites with access to state water rights are required to draw more meaningful conclusions. However, certain observations regarding the water use (and water saving) incentives associated with the two allocation structures can be drawn. Water rights are defined in terms of volume of water per hectare for a certain area of land per title deed (which is generally smaller than the entirety of land covered by the deed). Water rights holders are incentivised to use water efficiently, as any un-utilised portion of the per-hectare water allocation may be used for areas of the holding over and above the area specified in the water allocation. Efficient users of water may therefore extend the cultivated area of land on their holding, provided they do not exceed their total water allocation. Alternatively, permission may be obtained to temporarily lease any unused portion of the allocated water entitlement. Water rights holders are not without water supply related risks, however, as the state is able reduce or reallocate water entitlements in accordance with the NWA (1996). Water rights may be reallocated to benefit emerging enterprises, or may be reduced during periods of protracted drought, as occurred in the Langkloof Valley in the Eastern Cape in late 2018, when water rights quotas were temporarily reduced to 20% of their normal level (Jansen, 2018).

Registered water users are largely reliant on environmental flows for access to water (as no state schemes have been developed supplementing water supply). Decision makers must therefore carefully think about using existing water as efficiently as possible, since water supply is not guaranteed or reliable. It is important to note that registered water users' water allocation does not guarantee water supply. Allocations merely specify the quantity of water that is permitted to be extracted, if it is available. In times of plenty, when water supply is more than sufficient, registered water users are not necessarily incentivised to use water sparingly. However, the potential for and likelihood of periods water scarcity needs to be taken into account by decision makers.

WF, WP and EWP are useful indicators of water use which may be used to help guide difficult water management decisions. However, it is important to note that WF and WP indices are SFP measures applied in a multi-factor environment. Rather than minimising WF or maximising EWP, the goal should be to optimise these indices, taking into account situational economic, social and environmental variables. Moreover, it is important to consider the impact of the various components making up and effecting these indices when assessing results. Factors such as CWU, orchard maturity, crop choice, potential yield, climate, irrigation system, economic return, water allocation and water availability all play a role.

The optimal scenario in terms of crop choice would be to cultivate high value crops with low CWU and high yield potential. This is not always an option, however, and decision makers need to decide whether to prioritise crops with high economic returns, despite their high CWU, or to cultivate crops with high yield potentials and low CWU, though economic return may be lower for these varieties. Late mandarins and mid-season mandarins are examples of high value crops with relatively high water requirements, and these may be suitable for profit-maximising farmers with secure and reliable access to sufficient water. Water supply is never guaranteed, however, and farmers also need to consider the risks of diminished water availability and the potential reduction of water allocations, which may occur as a result of protracted droughts, state strategies to improve ecological flow, or the reallocation of water resources towards emerging farmers. Satsumas and lemons have relatively low CWU requirements and have comparably high potential yields. These varieties may thus be a wiser choice for farmers with water supply concerns. In addition to having a relatively high yield potential and low CWU, lemons also received high returns in relation to other varieties. However, lemons are frost sensitive, and are therefore unsuitable to be grown in many locations in the Eastern Cape Midlands.

6.3 Recommendations

Opportunities for future research include widening the project scope to include a more comprehensive assessment of WF and EWP across the three catchment areas, evaluating all types of agricultural production that takes place in the region rather than merely citrus. Assessment across a greater number of agricultural enterprises would allow for a more thorough analysis of the factors impacting water use indices and provide a more meaningful starting point for discussions and recommendations surrounding complex water management decisions. In addition, an assessment of a larger sample of enterprises with attached water rights, as well as a greater number of registered water users, would allow for a more reliable and valid comparison of supply structure linked water use practices. In the context of the citrus industry, research could be expanded to include citrus production on a wider scale, with WF and EWP assessed across a larger area, such as the Eastern Cape Province or South Africa.

REFERENCES

ACQUAYE, A., FENG, K., OPPON, E., SALHI, S., IBN-MOHAMMED, T., GENOVESE, A. and HUBACEK, K., 2017. Measuring the Environmental Sustainability Performance of Global Supply Chains: A Multi-Regional Input-Output Analysis for Carbon, Sulphur Oxide and Water Footprints. *Journal of Environmental Management* 187: 571-585.

AGRICULTURAL RESEARCH COUNCIL – INSTITUTE FOR SOIL, CLIMATE AND WATER (ARC-ISCW), 2018. *Weather Station Data: Daily Report*.

AGRIHUB, 2018. *Citrus Weekly Exports: Week 47 (2018).* [Online]. Available: http://www.agrihub.co.za/reports/ [Accessed 01 December 2018].

ALEXANDER, C., 2015. *Plant Manipulation Level 2: Apply Plant Manipulation Methods*. Hillcrest: The Citrus Academy.

ALI, Y., PRETAROLI, R., SOCCI, C. and SEVERINI, F., 2018. Carbon and Water Footprint Accounts of Italy: A Multi-Region Input-Output Approach. *Renewable and Sustainable Energy Reviews* 81: 1813-1824.

ALLAN, J.A., 1997. *'Virtual water': a long term solution for water short Middle Eastern economies?* London: School of Oriental and African Studies, University of London.

ALLEN, R.G., PEREIRA, LS, RAES, D and SMITH, M, 1998. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements.* FAO Irrigation and Drainage Paper No. 56. Rome: Food and Agriculture Organization.

ALLEN, R.G., PEREIRA, LS, SMITH, M, RAES, D and WRIGHT, JL, 2005. FAO-56 Dual Crop Coefficient Method for Estimating Evaporation from Soil and Application Extensions. *Journal of Irrigation and Drainage Engineering* 131 (1): 2-13.

AMARASINGHE, U.A. and SMAKHTIN, V., 2014. Water Productivity and Water Footprint: Misguided Concepts or Useful Tools in Water Management and Policy? *Water International* 39 (7): 1000-1017.

ANNAN, K., 2000. *'We the Peoples': The Role of the United Nations in the 21st Century.* New York: United Nations Department of Public Information.

BAARD, C.R., DU PREEZ, G., VAN DER RYST, A.C., VAN AARDT, C., DE KOCK, G.C., BRANDT, D.J. and VILJOEN, J., 1978. *'n Grond- en Watertafelondersoek in Golden Valley Besproeiingsbied.* Pretoria: Department van Landbou.

BAIN, J.M., 1958. Morphological, Anatomical, and Physiological Changes in the Developing Fruit of the Valencia Orange, Citrus Sinensis (L) Osbeck. *Australian Journal of Botany* 6 (1): 1-23.

BARKER, R., DAWE, D. and INOCENCIO, A., 2003. Economics of water productivity in managing water for agriculture. In: Kijne, J.W., Barker, R., Molden, D.J. (eds.). *Water productivity in agriculture: Limits and opportunities for improvement*. Wallingford: CABI Publishing; Colombo: International Water Management Institute (IWMI).

BASTIANONI, S., NICCOLUCCI, V., PULSELLI, R.M. and MARCHETTINI, N., 2012. Indicator and Indicandum: "Sustainable Way" vs "Prevailing Conditions" in the Ecological Footprint. *Ecological Indicators* 16: 47-50.

BAYART, J., BULLE, C., DESCHÊNES, L., MARGNI, M., PFISTER, S., VINCE, F. and KOEHLER, A., 2010. A Framework for Assessing Off-Stream Freshwater use in LCA. *The International Journal of Life Cycle Assessment* 15 (5): 439-453.

BAYART, J., WORBE, S., GRIMAUD, J. and AOUSTIN, E., 2014. The Water Impact Index: A Simplified Single-Indicator Approach for Water Footprinting. *The International Journal of Life Cycle Assessment* 19 (6): 1336-1344.

BERGER, M. and FINKBEINER, M., 2010. Water Footprinting: How to Address Water use in Life Cycle Assessment? *Sustainability* 2 (4): 919-944.

BIJZET, Z., 2006a. Cultivar Characteristics. In: de Villiers, E.A. and Joubert, P.H. (eds). *The Cultivation of Citrus*. Nelspruit: ARC-Institute for Tropical and Subtropical Crops.

BIJZET, Z., 2006b. Climatic Requirements. In: de Villiers, E.A. and Joubert, P.H. (eds). *The Cultivation of Citrus*. Nelspruit: ARC-Institute for Tropical and Subtropical Crops.

BOULAY, A., BARE, J., BENINI, L., BERGER, M., LATHUILLIÈRE, M.J., MANZARDO, A., MARGNI, M., MOTOSHITA, M., NÚÑEZ, M. and PASTOR, A.V., 2018. The WULCA Consensus Characterization Model for Water Scarcity Footprints: Assessing Impacts of Water Consumption Based on Available Water Remaining (AWARE). *The International Journal of Life Cycle Assessment* 23 (2): 368-378.

BOULAY, A., BARE, J., DE CAMILLIS, C., DÖLL, P., GASSERT, F., GERTEN, D., HUMBERT, S., INABA, A., ITSUBO, N. and LEMOINE, Y., 2015. Consensus Building on the Development of a Stress-Based Indicator for LCA-Based Impact Assessment of Water Consumption: Outcome of the Expert Workshops. *The International Journal of Life Cycle Assessment* 20 (5): 577-583.

BOULAY, A., BOUCHARD, C., BULLE, C., DESCHÊNES, L. and MARGNI, M., 2011. Categorizing Water for LCA Inventory. *The International Journal of Life Cycle Assessment* 16 (7): 639-651.

BOULAY, A., HOEKSTRA, A.Y. and VIONNET, S., 2013. Complementarities of Water-Focused Life Cycle Assessment and Water Footprint Assessment. *Environmental Science and Technology* 47 (21): 11926-11927.

BOURBLANC, M., 2017. State transformation and policy networks: The challenging implementation of new water policy paradigms in post-apartheid South Africa. *Water Alternatives*, 10 (2): 303-321.

BROOKE, M., 2011. Export Costs beyond the farm gate: Part 1 of 4. *SA Fruit Journal* 10 (2): 17.

BROOKE, M., 2018. *Citrus Export Production Estimates and Forecast Projections: An Analysis for Foreseeable Conditions iro Logistics*. Citrus Growers Association. [Online]. Available: https://ppecb.com/wp-content/uploads/2018/04/2018-Citrus-Export-Production-Estimates-and-Forecast-Projections.pdf [Accessed 20 October 2018].

CAZCARRO, I., HOEKSTRA, A.Y. and CHÓLIZ, J.S., 2014. The Water Footprint of Tourism in Spain. *Tourism Management* 40: 90-101.

CHAPAGAIN, A.K. and ORR, S., 2010. *Water Footprint of Nestlé's 'Bitesize Shredded Wheat'.* [Online]. Available: https://waterfootprint.org/media/downloads/Nestle-2010-Water-Footprint-Bitesize-Shredded-Wheat.pdf World Wide Fund for Nature, [Accessed 09 October 2018].

CHAPAGAIN, A.K. and TICKNER, D., 2012. Water Footprint: Help or Hindrance? *Water Alternatives* 5 (3): 563.

CHAPAGAIN, A.K., HOEKSTRA, A.Y., SAVENIJE, H. and GAUTAM, R., 2006. The Water Footprint of Cotton Consumption: An Assessment of the Impact of Worldwide Consumption of Cotton Products on the Water Resources in the Cotton Producing Countries. *Ecological Economics* 60 (1): 186-203.

CHENOWETH, J., HADJIKAKOU, M. and ZOUMIDES, C., 2014. Quantifying the Human Impact on Water Resources: A Critical Review of the Water Footprint Concept. *Hydrology and Earth System Sciences* 18 (6): 2325-2342.

CHICO, D. and ZHANG, G. (2015) *Water Footprint Assessment of FMO's Agribusiness* Portfolio. *Towards halving the footprint in the sugar supply chain.* The Water Footprint Network.

CHOUCHANE, H., HOEKSTRA, A.Y., KROL, M.S. and MEKONNEN, M.M., 2015. The Water Footprint of Tunisia from an Economic Perspective. *Ecological Indicators* 52: 311-319.

CHUKALLA, A.D., KROL, MS and HOEKSTRA, A.Y., 2018. Grey Water Footprint Reduction in Irrigated Crop Production: Effect of Nitrogen Application Rate, Nitrogen Form, Tillage Practice and Irrigation Strategy. *Hydrology and Earth System Sciences* 22 (6): 3245-3259.

CITRUS GROWERS ASSOCIATION (CGA), 2018. *About us: Citrus Growers Association of Southern Africa.* [Online]. Available: http://www.cga.co.za/page.aspx?ID=3242 [Accessed: 20 June 2018].

CITRUS RESEARCH INTERNATIONAL (CRI), 2015. *Citrus Postharvest Series Module 3: Citrus Varieties.* [Online]. Available: http://www.citrusresourcewarehouse.org.za/home/document-home/learning-aidsand-resources/ca-citrus-av-series-learning-material/citrus-post-harvest-series/1125-cphs-learning-material-module-03-citrus-varieties [Accessed 20 August 2018].

COCA-COLA EUROPE (2011) *Water footprint sustainability assessment: Towards sustainable sugar sourcing in Europe.* Brussels: Coca-Cola Europe.

COETZEE, J.G.K., 2007. *CRI Production Guidelines: Fertilisation.* Stellenbosch: Citrus Research International (CRI).

CONRADIE, B, 2002. *The value of water in the Fish-Sundays scheme of the Eastern Cape*. WRC Report No. 987/1/02. Pretoria: Water Research Commission.

CROSBY, C.T. and CROSBY, CP, 1999. *A computer program for establishing irrigation requirements and scheduling strategies in South Africa.* WRC Report No. 1999/264. Pretoria: Water Research Commission.

ČUČEK, L., KLEMEŠ, J.J. and KRAVANJA, Z., 2012. A Review of Footprint Analysis Tools for Monitoring Impacts on Sustainability. *Journal of Cleaner Production* 34: 9-20.

DAMANIA, R., DESBUREAUX, S., HYLAND, M., ISLAM, A., MOORE, S., RODELLA, A., RUSS, J. and ZAVERI, E., 2017. *Uncharted Waters: The New Economics of Water Scarcity and Variability.* Washington DC: International Bank for Reconstruction and Development; The World Bank.

DAVIS, B., REARDON, T., STAMOULIS, K. AND WINTERS, P., 2002. *Promoting farm/non-farm linkages for rural development: case studies from Africa and Latin America*. Rome: Food and Agriculture Organization of the United Nations (FAO).

DE VILLIERS, E.A. and JOUBERT, P.H., 2006. *The Cultivation of Citrus*. Nelspruit: ARC-Institute for Tropical and Subtropical Crops.

DENG, G., MA, Y. and LI, X., 2016. Regional Water Footprint Evaluation and Trend Analysis of China—based on Interregional Input–output Model. *Journal of Cleaner Production* 112: 4674-4682.

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF), 2017a. *A Profile of the South African Citrus Market Value Chain*. Pretoria.

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF), 2017b*. Water quality data exploration tool: layers*. [Online]. Available: http://www.dwa.gov.za/iwqs/wms/data/000key2data.asp [Accessed 05 September 2018].

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF), 2018a. *Abstract of Agricultural Statistics 2018*. Pretoria.

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF), 2018b. *Economic Review of the South African Agriculture: 2017/18*. Pretoria.

DEPARTMENT OF ENVIRONMENTAL AFFAIRS (DEA), 2011. *National Climate Change Response White Paper.* Pretoria.

DEPARTMENT OF WATER AFFAIRS (DWA), 2013. *National Water Resource Strategy* (Second Edition). [Online]. Available: http://www.dwa.gov.za/documents/Other/Strategic%20Plan/NWRS2-Final-email-version.pdf [Accessed 06 February 2018].

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF), 1996a. *South African Water Quality Guidelines. Volume 7: Aquatic Ecosystems.*

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF), 1996b. S*outh African Water Quality Guidelines (second edition). Volume 1: Domestic Use.*

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF), 1998. *Guide to the National Water Act.* Pretoria: Department of Water Affairs and Forestry.

DEPARTMENT OF WATER AND SANITATION (DWS), 2014. *The Development of a Comprehensive Water Conservation and Water Demand Management Strategy and Business Plan for the Fish to Tsitsikamma Water Management Area*. Report No. P WMA 15/000/00/2012/2/2.

DEPARTMENT OF WATER AND SANITATION (DWS), 2015. *Feasibility Study for Foxwood Dam (WP10580): Koonap River Hydrology.* DWS Report P WMA 15/Q92/00/2113/7.

DEPARTMENT OF WATER AND SANITATION (DWS), 2018a. Strategic Overview of the Water Sector in South Africa 2018. [Online]. Available: http://www.dwa.gov.za/downloads/WS/Macro_Planning_Products/STRATEGIC%20OVERVIEW%20OF%20WATER%20SERVICES/2018_May_A6_SOWSSA_HQ.pdf [Accessed 02 November 2018].

DEPARTMENT OF WATER AND SANITATION (DWS), 2018b. *National Water Management System data.* [Online]. Available: www.dwa.gov.za/iwqs/wms/data/Q_reg_WMS_nobor.htm [Accessed 01 May 2018].

DERYNG, D., ELLIOTT, J., FOLBERTH, C., MÜLLER, C., PUGH, T.A., BOOTE, K.J., CONWAY, D., RUANE, A.C., GERTEN, D. and JONES, J.W., 2016. Regional Disparities in the Beneficial Effects of Rising CO 2 Concentrations on Crop Water Productivity. *Nature Climate Change* 6 (8): 786.

DISTRIBUTED ACTIVE ARCHIVE CENTRE FOR BIOCHEMICAL DYNAMICS (DAAC), 2014. *Global Gridded Soil Phosphorus Distribution Maps at 0.5-degree Resolution.* [Online]. Available: https://daac.ornl.gov/SOILS/guides/Global_Phosphorus_Dist_Map.html [Accessed 29 September 2018].

DUMONT, A., SALMORAL, G. and LLAMAS, M.R., 2013. The Water Footprint of a River Basin with a Special Focus on Groundwater: The Case of Guadalquivir Basin (Spain). *Water Resources and Industry* 1: 60-76.

FANG, K., HEIJUNGS, R. and DE SNOO, G., 2013. The Footprint Family: Comparison and Interaction of the Ecological, Energy, Carbon and Water Footprints. *Revue De Métallurgie–International Journal of Metallurgy* 110 (1): 77-86.

FANG, K., HEIJUNGS, R. and DE SNOO, G.R., 2014. Theoretical Exploration for the Combination of the Ecological, Energy, Carbon, and Water Footprints: Overview of a Footprint Family. *Ecological Indicators* 36: 508-518.

FANG, K., SONG, S., HEIJUNGS, R., DE GROOT, S., DONG, L., SONG, J. and WILOSO, E.I., 2016. The Footprint's Fingerprint: On the Classification of the Footprint Family. *Current Opinion in Environmental Sustainability* 23: 54-62.

FENG, K., CHAPAGAIN, A., SUH, S., PFISTER, S. and HUBACEK, K., 2011. Comparison of Bottom-Up and Top-Down Approaches to Calculating the Water Footprints of Nations. *Economic Systems Research* 23 (4): 371-385.

FOOD AND AGRICULTURE ORGANISATION OF THE UNITED NATIONS (FAO), 2018a. *CropWat*. [Online]. Available: http://www.fao.org/land-water/databases-and-software/cropwat/en/ [Accessed 21 March 2018].

FOOD AND AGRICULTURE ORGANISATION OF THE UNITED NATIONS (FAO), 2018b. *GeoNetwork.* [Online]. Available: www.fao.org/geonetwork. [Accessed 29 September 2018].

FOOD AND AGRICULTURE ORGANISATION OF THE UNITED NATIONS (FAO), 2016. *South Africa.* [Online]. Available: http://www.fao.org/nr/water/aquastat/countries_regions/ZAF/print1.stm [Accessed 12 February 2018].

FRANKE, N.A., BOYACIOGLU, H and HOEKSTRA, AY, 2013. *Grey water footprint accounting: Tier 1 supporting guidelines.* Delft: UNESCO-IHE Institute for Water Education.

FRY, M., 2018. Personal communication. 18 July.

GALLI, A., GIAMPIETRO, M., GOLDFINGER, S., LAZARUS, E., LIN, D., SALTELLI, A., WACKERNAGEL, M. and MÜLLER, F., 2016. Questioning the Ecological Footprint. *Ecological Indicators* 69: 224-232.

GALLI, A., WIEDMANN, T., ERCIN, E., KNOBLAUCH, D., EWING, B. and GILJUM, S., 2012. Integrating Ecological, Carbon and Water Footprint into a "Footprint Family" of Indicators: Definition and Role in Tracking Human Pressure on the Planet. *Ecological Indicators* 16: 100-112.

GAWEL, E. and BERNSEN, K., 2013. What is Wrong with Virtual Water Trading? on the Limitations of the Virtual Water Concept. *Environment and Planning C: Government and Policy* 31 (1): 168-181.

GEERS, B.C., GRUNDLING, H. and ELLIS, F., 1984. *Grondondersoek na Gedeeltes van Vyftien Besproeiingsplase in die Groot- en Kleinvisriviervalleie vir Aansoek om Waterregte te Koop.* Navorsinginstituut vir Grond en Besproeiing Verslag Nr. 1037/8/84. Pretoria: Department van Landbou.

GERBENS-LEENES, W. and HOEKSTRA, A.Y., 2012. The Water Footprint of Sweeteners and Bio-Ethanol. *Environment International* 40: 202-211.

GIORDANO, M., TURRAL, H., SCHEIERLING, S.M., TRÉGUER, D.O. and MCCORNICK, P.G., 2017. *Beyond More Crop per Drop: evolving thinking on agricultural water productivity. IWMI Research Report 169*. Colombo: International Water Management Institute (IWMI); Washington DC: The World Bank.

GRASSINI, P., TORRION, J.A., YANG, H.S., REES, J., ANDERSEN, D., CASSMAN, K.G. and SPECHT, J.E., 2015. Soybean Yield Gaps and Water Productivity in the Western US Corn Belt. *Field Crops Research* 179: 150-163.

GREYLING, J., 2015. *A look at the contribution of the agricultural sector to the South African economy.* Grain SA. [Online]. Available: https://www.grainsa.co.za/a-look-at-the-contribution-of-the-agricultural-sector-to-the-south-african-economy [Accessed 02 November 2018].

GUINÉE, J.B., HEIJUNGS, R., HUPPES, G., ZAMAGNI, A., MASONI, P., BUONAMICI, R., EKVALL, T. and RYDBERG, T., 2011. Life Cycle Assessment: Past, Present, and Future. *Environmental Science and Technology* 45 (1): 90-96.

GUSH, M.B. and TAYLOR, N.J. 2014. *The water use of selected fruit tree orchards (Volume 2): Technical report on measurements and modelling*. WRC REPORT NO. 1770/2/14. Gezina: Water Research Commission.

HARDING, G., COURTNEY, C. and RUSSO, V., 2017. When Geography Matters. A Location-Adjusted Blue Water Footprint of Commercial Beef in South Africa. *Journal of Cleaner Production* 151: 494-508.

HARTMANN, M.O., HALL, L.R., DU PLOOY, F.J., VAN DEVENTER, J.H.A. and SMITH-BAILLIE, A.L., 1979. *Soil survey of the Kat River Basin between Fort Beaufort and the Kat River*

Dam. Technical Communication No. 157. Pretoria: Department of Agricultural Technical Services

HASSAN, R. and CRAFFORD, J., 2006. Environmental and economic accounts for water in South Africa. In: Lange, G. and Hassan, R. (eds.). *The Economics of Water Management in Southern Africa: an Environmental Accounting Approach*. Cheltenham: Edward Elgar Publishing Limited.

HELLWEG, S. and MILÀ I CANALS, L., 2014. Emerging Approaches, Challenges and Opportunities in Life Cycle Assessment. *Science* 344 (6188): 1109-1113.

HOARE, D.B., MUCINA, L., RUTHERFORD, M.C., VLOK, J.H.J., EUSTON-BROWN, D.I.W., PALMER, A.R., POWRIE, L.W., LECHMERE-OERTEL, R.G., PROCHEŞ, S.M., DOLD, A.P. AND WARD, R.A., 2006. Albany Thicket Biome. In: Mucina, L. and Rutherford, M.C. *The Vegetation of South Africa, Lesotho and Swaziland.* Pretoria: South African National Biodiversity Institute.

HOEKSTRA, A.Y. and CHAPAGAIN, A.K., 2006. *The Water Footprints of Morocco and the Netherlands*. Water Research Report Series No. 21. Delft: UNESCO-IHE.

HOEKSTRA, A.Y. and HUNG, P.Q., 2002. *Virtual Water Trade. A Quantification of Virtual Water Flows between Nations in Relation to International Crop Trade.* Value of Water Research Report Series No 11. Delft: IHE Delft.

HOEKSTRA, A.Y. and MEKONNEN, M., 2011. *Global Water Scarcity: The Monthly Blue Water Footprint Compared to Blue Water Availability for the World's Major River Basins.* Value of Water Research Report Series No.53. Delft: UNESCO-IHE.

HOEKSTRA, A.Y. and MEKONNEN, M.M., 2012. The Water Footprint of Humanity. *Proceedings of the National Academy of Sciences* 109 (9): 3232-3237.

HOEKSTRA, A.Y. and WIEDMANN, T.O., 2014. Humanity's Unsustainable Environmental Footprint. *Science* 344 (6188): 1114-1117.

HOEKSTRA, A.Y., 2003. *Virtual water trade: Proceedings of the international expert meeting on virtual water trade*. Value of Water Research Report Series No 12. Delft: IHE Delft.

HOEKSTRA, A.Y., 2009. Human Appropriation of Natural Capital: A Comparison of Ecological Footprint and Water Footprint Analysis. *Ecological Economics* 68 (7): 1963-1974.

HOEKSTRA, A.Y., 2014. Sustainable, Efficient, and Equitable Water use: The Three Pillars Under Wise Freshwater Allocation. *WIREs Water* 1 (1): 31-40.

HOEKSTRA, A.Y., 2016. A Critique on the Water-Scarcity Weighted Water Footprint in LCA. *Ecological Indicators* 66: 564-573.

HOEKSTRA, A.Y., BOOIJ, M., HUNINK, J. and MEIJER, K., 2012. *Blue Water Footprint of Agriculture, Industry, Households and Water Management in the Netherlands: An Exploration of using the Netherlands Hydrological Instrument.* Value of Water Research Report Series No 58. Delft: UNESCO-IHE.

HOEKSTRA, A.Y., CHAPAGAIN, A.K., ALDAYA, M.M. and MEKONNEN, M.M., 2011. *The Water Footprint Assessment Manual*. London: Earthscan.

HUNT, R.G. and FRANKLIN, W.E., 1996. LCA—How it Came About. *The International Journal of Life Cycle Assessment* 1 (1): 4-7.

INTERNATIONAL MONETARY FUND (IMF), 2018. *Prices, Production and Labour Selected Indices*. [Online]. Available: http://data.imf.org/regular.aspx?key=61545849 [Accessed 18 October 2018].

INTERNATIONAL ORGANISATION FOR STANDARDISATION (ISO), 2006a. *ISO 14040:2006.* [Online]. Available: https://www.iso.org/standard/37456.html [Accessed 06 September 2018].

INTERNATIONAL ORGANISATION FOR STANDARDISATION (ISO), 2006b. *ISO 14044:2006.* [Online]. Available: https://www.iso.org/standard/38498.html [Accessed 06 September 2018].

INTERNATIONAL ORGANISATION FOR STANDARDISATION (ISO), 2014. *ISO 14046:2014.* [Online]. Available: https://www.iso.org/standard/43263.html [Accessed 06 September 2018].

INTERNATIONAL TRADE CENTRE (ITC), 2018. *Trade Map – International Trade Statistics*. [Online]. Available: https://www.trademap.org/tradestat/Country_SelProduct_TS.aspx?nvpm=1%7c%7c%7c%7c%7c0805%7c%7c%7c4%7c1%7c1%7c2%7c2%7c1%7c2%7c1%7c1 [Accessed 12 November 2018].

JANSEN, C., 2018. 80% water restriction, despite full farm dams, of grave concern to Langkloof topfruit farmers. *FreshPlaza.* 31 October. [Online]. Available: https://www.freshplaza.com/article/9037990/water-restriction-despite-full-farm-dams-of-grave-concern-to-langkloof-topfruit-farmers/ [Accessed 10 December 2018].

JANSEN, C., 2019. Langkloof topfruit starts on a positive note. *FreshPlaza.* 01 February. [Online]. Available: https://www.freshplaza.com/article/9068524/langkloof-topfruit-starts-on-a-positive-note/ [Accessed 04 February 2019].

JEFFERIES, D., MUÑOZ, I., HODGES, J., KING, V.J., ALDAYA, M., ERCIN, A.E., MILÀ I CANALS, L. and HOEKSTRA, A.Y., 2012. Water Footprint and Life Cycle Assessment as Approaches to Assess Potential Impacts of Products on Water Consumption. Key Learning Points from Pilot Studies on Tea and Margarine. *Journal of Cleaner Production* 33: 155-166.

KANEMOTO, K., MORAN, D. and HERTWICH, E.G., 2016. Mapping the Carbon Footprint of Nations. *Environmental Science and Technology* 50 (19): 10512-10517.

KANG, S., HAO, X., DU, T., TONG, L., SU, X., LU, H., LI, X., HUO, Z., LI, S. and DING, R., 2017. Improving Agricultural Water Productivity to Ensure Food Security in China Under Changing Environment: From Research to Practice. *Agricultural Water Management* 179: 5-17.

KARIMI, P., MOLDEN, D. and BASTIAANSSEN, W., 2011. Mapping crop water productivity in the Nile basin through combined use of remote sensing and census data. *ICID 21st International Congress on Irrigation and Drainage.* Tehran: International Commission on Irrigation and Drainage, ICID 21st Congress.

KITZES, J., GALLI, A., BAGLIANI, M., BARRETT, J., DIGE, G., EDE, S., ERB, K., GILJUM, S., HABERL, H. and HAILS, C., 2009. A Research Agenda for Improving National Ecological Footprint Accounts. *Ecological Economics* 68 (7): 1991-2007.

KLÖPFFER, W., 1997. Life Cycle Assessment-from the Beginning to the Current State. *Environmental Science and Pollution Research* 4 (4): 223-228.

KNOTT, B., 2018. Personal Communication. 22 October.

KOUNINA, A., MARGNI, M., BAYART, J., BOULAY, A., BERGER, M., BULLE, C., FRISCHKNECHT, R., KOEHLER, A., MILÀ I CANALS, L. and MOTOSHITA, M., 2013. Review of Methods Addressing Freshwater use in Life Cycle Inventory and Impact Assessment. *The International Journal of Life Cycle Assessment* 18 (3): 707-721.

LIN, D., WACKERNAGEL, M., GALLI, A. and KELLY, R., 2015. Ecological Footprint: Informative and evolving–A Response to Van Den Bergh and Grazi (2014). *Ecological Indicators* 58: 464-468.

LOVARELLI, D., BACENETTI, J. and FIALA, M., 2016. Water Footprint of Crop Productions: A Review. *Science of the Total Environment* 548: 236-251.

MACHARIA, J., 2018. South Africa declares drought a national disaster. *Reuters.* 13 February. [Online]. Available: https://www.reuters.com/article/us-safrica-drought-dayzero/south-africa-declares-drought-a-national-disaster-idUSKBN1FX1BI [Accessed 23 October 2018].

MAINUDDIN, M. and KIRBY, M., 2009. Spatial and Temporal Trends of Water Productivity in the Lower Mekong River Basin. *Agricultural Water Management* 96 (11): 1567-1578.

MALAN, T., 1991. The Economics of Citrus Production. In: Netterville, R.M. (ed). *Production Guidelines for Export Citrus. Volume I: Citriculture – Establishment*. Hennopsmeer: South African Co-Operative Citrus Exchange.

MANZARDO, A., MAZZI, A., LOSS, A., BUTLER, M., WILLIAMSON, A. and SCIPIONI, A., 2016. Lessons Learned from the Application of Different Water Footprint Approaches to

Compare Different Food Packaging Alternatives. *Journal of Cleaner Production* 112: 4657-4666.

MARSTON, L., AO, Y., KONAR, M., MEKONNEN, M.M. and HOEKSTRA, A.Y., 2018. High-Resolution Water Footprints of Production of the United States. *Water Resources Research* 54 (3): 2288-2316.

MCDOWELL, N.G., PHILLIPS, N., LUNCH, C., BOND, B.J. and RYAN, M.G., 2002. An Investigation of Hydraulic Limitation and Compensation in Large, Old Douglas-Fir Trees. *Tree Physiology* 22 (11): 763-774.

MEKONNEN, M. and HOEKSTRA, A.Y., 2010. *The green, blue and grey water footprint of crops and derived crop products. Volume 2: Appendices.* Value of Water Research Report Series No 47. Delft: UNESCO-IHE.

MEKONNEN, M. and HOEKSTRA, A.Y., 2011b. *National Water Footprint Accounts: The Green, Blue and Grey Water Footprint of Production and Consumption.* Value of Water Research Report Series No 50. Delft: UNESCO-IHE.

MEKONNEN, M.M. and HOEKSTRA, A.Y., 2011a. The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products. *Hydrology and Earth System Sciences* 15 (5): 1577-1600.

MEKONNEN, M.M. and HOEKSTRA, A.Y., 2012. A Global Assessment of the Water Footprint of Farm Animal Products. *Ecosystems* 15 (3): 401-415.

MEKONNEN, M.M., GERBENS-LEENES, P.W. and HOEKSTRA, A.Y., 2015b. The Consumptive Water Footprint of Electricity and Heat: A Global Assessment. *Environmental Science: Water Research and Technology* 1 (3): 285-297.

MEKONNEN, M.M., PAHLOW, M., ALDAYA, M.M., ZARATE, E. and HOEKSTRA, A.Y., 2015a. Sustainability, Efficiency and Equitability of Water Consumption and Pollution in Latin America and the Caribbean. *Sustainability* 7 (2): 2086-2112.

MILÀ I CANALS, L., CHENOWETH, J., CHAPAGAIN, A., ORR, S., ANTÓN, A. and CLIFT, R., 2009. Assessing Freshwater use Impacts in LCA: Part I—inventory Modelling and

Characterisation Factors for the Main Impact Pathways. *The International Journal of Life Cycle Assessment* 14 (1): 28-42.

MINISTRY OF COOPERATIVE GOVERNANCE AND TRADITIONAL AFFAIRS (COGTA), 2018. *The outcomes of the Inter-Ministerial Task Team meeting on Drought and Water Scarcity held on 30 January 2018.* Media Briefing Statement. [Online]. Available: http://www.dwa.gov.za/Communications/PressReleases/2018/MS%20-%20The%20outcomes%20 of%20the%20Inter-Ministerial%20Task%20Team%20meeting%20on%20Drought%20and%20 Water%20Scarcity%20held%20on%2030%20January%202018.pdf [Accessed 21 March 2018].

MOLDEN, D., 1997. *Accounting for water use and productivity.* SWIM Paper 1. Colombo: International Irrigation Management Institute (IIMI).

MOLDEN, D., OWEIS, T.Y., STEDUTO, P., KIJNE, J.W., HANJRA, M.A., BINDRABAN, P.S., BOUMAN, B.A.M., COOK, S.J., ERENSTEIN, O. and FARAHANI, H., 2007. Pathways for Increasing Agricultural Water Productivity. In: Molden, D. (ed). *Water for Food Water for Life: A Comprehensive Assessment of Water Management in Agriculture.* London: Taylor and Francis AS.

MONSELISE, S.P., 1986. *Handbook of fruit set and development*. Boca Raton: CRC press.

MOORE, G.W., BOND, B.J., JONES, J.A., PHILLIPS, N. and MEINZER, F.C., 2004. Structural and Compositional Controls on Transpiration in 40-and 450-Year-Old Riparian Forests in Western Oregon, USA. *Tree Physiology* 24 (5): 481-491.

MOSTERT, P.G., 2006. Irrigation Requirements. In: de Villiers, E.A. and Joubert, P.H. (eds). *The Cultivation of Citrus*. Nelspruit: ARC-Institute for Tropical and Subtropical Crops

MUCINA, L., HOARE, D.B., LÖTTER M.C., DU PREEZ P.J., RUTHERFORD, M.C., SCOTT-SHAW, C.R., BREDENKAMP, G.J., POWRIE, L.W., SCOTT, L., CAMP, K.G.T., CILLIERS, S.S., BEZUIDENHOUT, H., MOSTERT, T.H., SIEBERT, S.J., WINTER, P.J.D., BURROWS, J.E., DOBSON, L., WARD, R.A., STALMANS, M., OLIVER, E.G.H., SIEBERT, F., SCHMIDT, E., KOBISI, K. AND KOSE, L., 2006. Grassland Biome. In: Mucina, L. and Rutherford, M.C.

The Vegetation of South Africa, Lesotho and Swaziland. Pretoria: South African National Biodiversity Institute.

MUNRO, S.A., 2015. *A Water Footprint Assessment of Primary Citrus Production in The Lower Sundays River Valley Citrus Farms, Eastern Cape, South Africa.* Unpublished MSc thesis. Grahamstown: Dept of Economics, Rhodes University.

MUNRO, S.A., FRASER, G.C., SNOWBALL, J.D. and PAHLOW, M., 2016. Water Footprint Assessment of Citrus Production in South Africa: A Case Study of the Lower Sundays River Valley. *Journal of Cleaner Production* 135: 668-678.

NATIONAL WATER ACT NO 36 of 1998 (NWA) (South Africa). [Online]. Available: http://www.dwa.gov.za/Documents/Legislature/nw_act/NWA.pdf [Accessed 06 February 2018].

NETTERVILLE, R.M., 1996. *Production Guidelines for Export Citrus. Volume II: Citriculture – Cultural Practices.* Hennopsmeer: Outspan International.

OKADERA, T., GENG, Y., FUJITA, T., DONG, H., LIU, Z., YOSHIDA, N. and KANAZAWA, T., 2015. Evaluating the Water Footprint of the Energy Supply of Liaoning Province, China: A Regional Input–output Analysis Approach. *Energy Policy* 78: 148-157.

ORAM, B., 2014. *Conversion Factors for Water Quality*. Water Research Centre. [Online]. Available: https://www.water-research.net/index.php/conversion-factors-for-water-quality [Accessed 12 September 2018].

PAHLOW, M., SNOWBALL, J. and FRASER, G., 2015. Water Footprint Assessment to Inform Water Management and Policy Making in South Africa. *Water SA* 41 (3): 300-313.

PAREDES, P., RODRIGUES, G.C., DO ROSÁRIO CAMEIRA, M., TORRES, M.O. and PEREIRA, L.S., 2017. Assessing Yield, Water Productivity and Farm Economic Returns of Malt Barley as Influenced by the Sowing Dates and Supplemental Irrigation. *Agricultural Water Management* 179: 132-143.

PEREIRA, L.S., CORDERY, I. and IACOVIDES, I., 2012. Improved Indicators of Water use Performance and Productivity for Sustainable Water Conservation and Saving. *Agricultural Water Management* 108: 39-51.

PERRET, S.R., 2002. Water policies and smallholding irrigation schemes in South Africa: A history and new institutional challenges. *Water Policy* 4 (3): 283-300.

PERRY, C., 2014. Water Footprints: Path to Enlightenment, Or False Trail? *Agricultural Water Management* 134: 119-125.

PFISTER, S., BOULAY, A., BERGER, M., HADJIKAKOU, M., MOTOSHITA, M., HESS, T., RIDOUTT, B., WEINZETTEL, J., SCHERER, L. and DÖLL, P., 2017. Understanding the LCA and ISO Water Footprint: A Response to Hoekstra (2016) "A Critique on the Water-Scarcity Weighted Water Footprint in LCA". *Ecological Indicators* 72: 352-359.

PFISTER, S., KOEHLER, A. and HELLWEG, S., 2009. Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environmental Science and Technology* 43 (11): 4098-4104.

POTTER, P., RAMANKUTTY, N., BENNETT, E.M. and DONNER., S.D., 2011a. *Global Fertilizer and Manure: Nitrogen Fertilizer Application.* Palisades: NASA Socioeconomic Data and Applications Center (SEDAC). [Online]. Available: https://doi.org/10.7927/H4Q81B0R [Accessed 29 September 2018].

POTTER, P., RAMANKUTTY, N., BENNETT, E.M. and DONNER., S.D., 2011b. *Global Fertilizer and Manure: Africa Phosphorous Fertilizer Application.* Palisades: NASA Socioeconomic Data and Applications Center (SEDAC). [Online]. Available: http://sedac.ciesin.columbia.edu/data/set/ferman-v1-phosphorus-fertilizer-application/maps?facets=region:africa [Accessed 29 September 2018].

REBELO, L., JOHNSTON, R., KARIMI, P. and MCCORNICK, P.G., 2014. Determining the Dynamics of Agricultural Water use: Cases from Asia and Africa. *Journal of Contemporary Water Research and Education* 153 (1): 79-90.

REDDY, T., AMOS, M., BALETA, H. and PEGRAM, G, 2014b. *Water Footprints for Industry in South Africa. Volume II: Policy and Regulations.* WRC Report No. TT 617/14. Gezina: Water Research Commission.

REDDY, T., HASTINGS, E. and PEGRAM, G, 2014a. *Water Footprints for Industry in South Africa. Volume I: Literature Review: Applicability of Water Footprints in South Africa.* WRC Report No. TT 616/14. Gezina: Water Research Commission.

RENAULT, D. and WALLENDER, W.W., 2000. Nutritional Water Productivity and Diets. *Agricultural Water Management* 45 (3): 275-296.

RIDOUTT, B.G. and HUANG, J., 2012. Environmental Relevance—the Key to Understanding Water Footprints. *Proceedings of the National Academy of Sciences* 109 (22): E1424.

RIDOUTT, B.G. and PFISTER, S., 2010. A Revised Approach to Water Footprinting to make Transparent the Impacts of Consumption and Production on Global Freshwater Scarcity. *Global Environmental Change* 20 (1): 113-120.

RIJSBERMAN, F., 2006. More Crop Per Drop: Realigning a Research Paradigm. In: Giordano, M., Rijsberman, F. and Saleth, M. (eds). *More Crop Per Drop: Revisiting a Research Paradigm: Results and Synthesis of IWMI's Research, 1996-2005*. London: IWA Publishing; Colombo: International Water Management Institute (IWMI).

RUTHERFORD, M.C. and MUCINA, L., 2006. Introduction. In: Mucina, L. and Rutherford, M.C. *The Vegetation of South Africa, Lesotho and Swaziland.* Pretoria: South African National Biodiversity Institute.

RUTHERFORD, M.C., MUCINA, L. and POWRIE, L.W., 2006a. Biomes and Bioregions of Southern Africa. In: Mucina, L. and Rutherford, M.C. *The Vegetation of South Africa, Lesotho and Swaziland.* Pretoria: South African National Biodiversity Institute.

RUTHERFORD, M.C., MUCINA, L., LÖTTER, M.C., BREDENKAMP, G.J., SMIT, J.H.L., SCOTT-SHAW, C.R., HOARE, D.B., GOODMAN, P.S., BEZUIDENHOUT, H., SCOTT, L., ELLIS, F., POWRIE, L.W., SIEBERT, F., MOSTERT, T.H., HENNING, B.J., VENTER, C.E., CAMP, K.G.T., SIEBERT, S.J., MATTHEWS, W.S., BURROWS, J.E., DOBSON, L., VAN ROOYEN, N., SCHMIDT, E., WINTER, P.J.D., DU PREEZ, P.J., WARD, R.A., WILLIAMSON, S. AND

HURTER, P.J.H., 2006b. Savanna Biome. In: Mucina, L. and Rutherford, M.C. *The Vegetation of South Africa, Lesotho and Swaziland.* Pretoria: South African National Biodiversity Institute.

RYAN, M.G. and YODER, B.J., 1997. Hydraulic Limits to Tree Height and Tree Growth. *Bioscience* 47 (4): 235-242.

RYAN, M.G., BOND, B.J., LAW, B.E., HUBBARD, R.M., WOODRUFF, D., CIENCIALA, E. and KUCERA, J., 2000. Transpiration and Whole-Tree Conductance in Ponderosa Pine Trees of Different Heights. *Oecologia* 124 (4): 553-560.

SABMILLER and WWF-UK (2009) *Water footprinting: Identifying and addressing water risks in the value chain.* Woking: SABMiller; Glodalming: WWF-UK.

SABMILLER, GTZ and WWF (2010) *Water futures: Working together for a secure water future.* Woking: SABMiller; Glodalming: WWF-UK.

SAXTON, K.E. and RAWLS, WJ, 2006. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. *Soil Science Society of America Journal* 70 (5): 1569-1578.

SCHEIERLING, S., TREGUER, D.O. and BOOKER, J.F., 2016. Water productivity in agriculture: Looking for water in the agricultural productivity and efficiency literature. *Water Economics and Policy* 2 (3): 1-30.

SECKLER, D.W., 1996. *The new era of water resources management: from" dry" to" wet" water savings.* Colombo: IIMI.

SECKLER, D.W., MOLDEN, D. and SAKTHIVADIVEL, R., 2003. The concept of efficiency in water resources management and policy. In: Kijne, J.W., Barker, R., Molden, D. (eds.). *Water productivity in agriculture: Limits and opportunities for improvement*. Wallingford: CABI Publishing; Colombo: International Water Management Institute (IWMI).

SHARMA, B., MOLDEN, D. and COOK, S., 2015. Water use Efficiency in Agriculture: Measurement, Current Situation and Trends. In: Drechsel, P., Heffer, P., Magen, H., Mikkelsen, R. and Wichelns, D. (eds). *Managing Water and Fertilizer for Sustainable Agricultural Intensification.* Paris: International Fertilizer Industry Association.

SHEPPARD, S., LONG, J., SANIPELLI, B. and SOHLENIUS, G., 2009. *Solid/liquid partition coefficients (Kd) for selected soils and sediments at Forsmark and Laxemar-Simpevarp.* Stockholm: Swedish Nuclear Fuel and Waste Management Co.

SIKIRICA, N. (2011) *Water footprint assessment bananas and pineapples.* Driebergen: Dole Food Company, Soil and More International.

SIPPEL, A.D., 2006. The Origin of Citrus and its History in South Africa. In: de Villiers, E.A. and Joubert, P.H. (eds). *The Cultivation of Citrus*. Nelspruit: ARC-Institute for Tropical and Subtropical Crops.

SOUTH AFRICAN NATIONAL BIODIVERSITY INSTITUTE (SANBI), 2012. *Vegetation Map of South Africa, Lesotho and Swaziland*. [Online]. Available: http://bgisviewer.sanbi.org/Html5Viewer/Index.html?configBase=http://bgisviewer.sanbi.org/Geocortex/Essentials/REST/sites/Vegmap/viewers/National_Vegetation_Map_2009/virtualdirectory/Resources/Config/Defaultanduser=andextent=andlayerTheme= [Accessed 20 November 2018].

SOUTH AFRICAN RESERVE BANK (SARB), 2018. *Historical Exchange Rates*. [Online]. Available: https://www.resbank.co.za/Research/Rates/Pages/SelectedHistoricalExchangeAndInterestRates.aspx [Accessed 18 October 2018].

SOUTH AFRICAN REVENUE SERVICE (SARS), 2017. *Merchandise Trade Statistics: December 2017.* [Online]. Available: http://www.sars.gov.za/ClientSegments/Customs-Excise/Trade-Statistics/Pages/Merchandise-Trade-Statistics.aspx [Accessed 02 November 2018].

SOUTH AFRICAN WEATHER SERVICE (SAWS), 2018. *Drought Monitoring – December 2018.* [Online]. Available: http://www.weathersa.co.za/images/climate/pdf/CLS-CI-Drought%20Monitoring-2018-12.pdf [Accessed 05 December 2018].

SPARKS, I., 2018. Technical Manager, Kat River Citrus Co-Operative, Fort Beaufort. Personal communication. 25 October.

STATISTICS SOUTH AFRICA (STATSSA), 2018. *CPI History*. [Online]. Available: http://www.statssa.gov.za/?page_id=1854andPPN=P0141 [Accessed 18 October 2018].

STEDUTO, P., HSIAO, TC, FERERES, E and RAES, D, 2012. *Crop Yield Response to Water.* FAO Irrigation and Drainage Paper 66. Rome: Food and Agriculture Organization.

TAYLOR, N.J. and GUSH, M.B., 2014. *The water use of selected fruit tree orchards (Volume 1): Review of available knowledge.* WRC Report 1770/1/14. Gezina: Water Research Commission.

TCCC and TNC (2010) *Product water footprint assessments: Practical application in corporate water stewardship*. Atlanta: The Coca-Cola Company; Arlington: The Nature Conservancy.

UNGER, K., ZHANG, G. and MATHEWS, R. (2013). *Water Footprint Assessment Results and Learning: Tata Chemicals, Tata Motors, Tata Power, Tata Steel.* Tata Quality Management Services, International Finance Corporation, and Water Footprint Network.

UNITED NATIONS (UN), 2015. *Transforming Our World: The 2030 Agenda for Sustainable Development.* A/RES/70/1. [Online]. Available: www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1andLang=E [Accessed 15 February 2018].

VAHRMEIJER, J.T., ANNANDALE, J.G., GUSH, M.B., and TAYLOR, N.J., 2015. Citrus Water Use in South Africa. *Acta Horticulturae,* 1065: 1719-1724.

VAN HEERDEN, P.S. and WALKER, S., 2016. *Upgrading of SAPWAT3 as a Management Tool to Estimate the Irrigation Water Use of Crops, Revised Edition: SAPWAT4*. WRC Report No. TT 662/16. Gezina: Water Research Commission.

VAN HEERDEN, P.S., 2015*. Improvement of SAPWAT as an irrigation planning tool.* Unpublished PHD thesis. Bloemfontein: Department of Soil, Crop and Climate Sciences, Faculty of Natural and Agricultural Sciences, University of Pretoria.

VAN HEERDEN, P.S., 2017. SAPWAT4 Arrives. *SABI Magazine-Tydskrif* 9 (3): 34-39.

VAN HEERDEN, P.S., 2018. Personal communication. 27 August.

VAN HEERDEN, P.S., CROSBY, C.T., GROVÉ, B., BENADÉ, N., THERON, E., SCHULZE, R.E., and TEWOLDE, M.H., 2009. *Integrating and Updating of SAPWAT and PLANWAT to Create a Powerful and User-Friendly Irrigation Planning Tool.* WRC Report No. TT 391/08. Gezina: Water Research Commission.

VAN OEL, P.R., MEKONNEN, M.M. and HOEKSTRA, A.Y., 2009. The External Water Footprint of the Netherlands: Geographically-Explicit Quantification and Impact Assessment. *Ecological Economics* 69 (1): 82-92.

VANHAM, D. and BIDOGLIO, G., 2013. A Review on the Indicator Water Footprint for the EU28. *Ecological Indicators* 26: 61-75.

VANHAM, D. and BIDOGLIO, G., 2014. The Water Footprint of Agricultural Products in European River Basins. *Environmental Research Letters* 9 (6): 1-11.

VERONES, F., PFISTER, S., VAN ZELM, R. and HELLWEG, S., 2017. Biodiversity Impacts from Water Consumption on a Global Scale for use in Life Cycle Assessment. *The International Journal of Life Cycle Assessment* 22 (8): 1247-1256.

VERREYNNE, S., 2009. Fruit Size and Crop Load Prediction for Citrus. *South African Fruit Journal* 8 (5): 63-67.

VERREYNNE, S., 2010. Crop Manipulation: Fruit Size and Crop Load Prediction. In: *Integrated Production Guidelines: Volume II*. Citrus Research International (CRI).

VILELA, N., THEBALDI, M.S., LEAL, B.D.P., SILVA, A.V. & MARTINS, I.P., 2018. Transport Parameters of Potassium from Different Sources in Soil Columns. *Engenharia Agrícola* 38 (1): 135-141.

WACKERNAGEL, M. and REES, W., 1998. *Our ecological footprint: reducing human impact on the earth.* Canada: New Society Publishers.

WATER FOOTPRINT NETWORK (WFN), 2016a. *Country Water Footprint Profile: Ghana*. [Online}. Available: https://waterfootprint.org/en/resources/publications/corporate-water-footprint-publications/ [Accessed 10 November 2018]. Water Footprint Network for Ministry of Foreign Affairs of the Netherlands.

WATER FOOTPRINT NETWORK (WFN), 2016b. *Country Water Footprint Profile: Kenya*. [Online}. Available: https://waterfootprint.org/en/resources/publications/corporate-water-footprint-publications/ [Accessed 10 November 2018]. Water Footprint Network for Ministry of Foreign Affairs of the Netherlands.

WATER FOOTPRINT NETWORK (WFN), 2016c. *Country Water Footprint Profile: Mali.* [Online}. Available: https://waterfootprint.org/en/resources/publications/corporate-water-footprint-publications/ [Accessed 10 November 2018]. Water Footprint Network for Ministry of Foreign Affairs of the Netherlands.

WATER FOOTPRINT NETWORK (WFN), 2016d. *Country Water Footprint Profile: Mozambique*. [Online}. Available: https://waterfootprint.org/en/resources/publications/corporate-water-footprint-publications/ [Accessed 10 November 2018]. Water Footprint Network for Ministry of Foreign Affairs of the Netherlands.

WATER FOOTPRINT NETWORK (WFN), 2016e. *Country Water Footprint Profile: Rwanda*. [Online}. Available: https://waterfootprint.org/en/resources/publications/corporate-water-footprint-publications/ [Accessed 10 November 2018]. Water Footprint Network for Ministry of Foreign Affairs of the Netherlands.

WATER FOOTPRINT NETWORK (WFN), 2016f. *Country Water Footprint Profile: Benin*. [Online}. Available: https://waterfootprint.org/en/resources/publications/corporate-water-footprint-publications/ [Accessed 10 November 2018]. Water Footprint Network for Ministry of Foreign Affairs of the Netherlands.

WATER FOOTPRINT NETWORK (WFN), 2016g. *Country Water Footprint Profile: Ethiopia.* [Online}. Available: https://waterfootprint.org/en/resources/publications/corporate-water-footprint-publications/ [Accessed 10 November 2018]. Water Footprint Network for Ministry of Foreign Affairs of the Netherlands.

WATER RESEARCH COMMISSION (WRC), 2012. *WR 2012.* [Online]. Available: http://waterresourceswr2012.co.za/resource-centre/ [Accessed 29 September 2018].

WATER RESEARCH COMMISSION (WRC), 2016a. *Annual Report 2015/16.* [Online]. Available: http://www.wrc.org.za/Pages/KH_AnnualReports.aspx?dt=9&ms=66 [Accessed 31 May 2017].

WATER RESEARCH COMMISSION (WRC), 2016b. *SAPWAT Description*. [Online]. Available: http://sapwat.org.za/sapwat-description/ [Accessed 10 August 2018].

WEINZETTEL, J., STEEN-OLSEN, K., HERTWICH, E.G., BORUCKE, M. and GALLI, A., 2014. Ecological Footprint of Nations: Comparison of Process Analysis, and Standard and Hybrid Multiregional Input–output Analysis. *Ecological Economics* 101: 115-126.

WICHELNS, D., 2015a. Virtual Water and Water Footprints do not Provide Helpful Insight Regarding International Trade or Water Scarcity. *Ecological Indicators* 52: 277-283.

WICHELNS, D., 2015b. Water Productivity and Food Security: Considering More Carefully the Farm-Level Perspective. *Food Security* 7 (2): 247-260.

WIEDMANN, T. and MINX, J., 2008. A Definition of 'Carbon Footprint'. In: Pertsova, C.C. (ed). *Ecological Economics Research Trends*. Hauppauge, NY: Nova Science Publishers.

WORLD WIDE FUND FOR NATURE – SOUTH AFRICA (WWF-SA), 2016. *Water: Facts & Futures.* [Online]. Available: http://awsassets.wwf.org.za/downloads/wwf009_waterfactsandfutures_report_web__lowres_.pdf [Accessed 06 June 2017].

ZELEKE, K.T. and WADE, LJ, 2012. Evapotranspiration Estimation using Soil Water Balance, Weather and Crop Data. In: Irmak, A. (ed). *Evapotranspiration-Remote Sensing and Modelling.* Rijeka: InTech.

ZHANG, C. and ANADON, L.D., 2014. A Multi-Regional Input–output Analysis of Domestic Virtual Water Trade and Provincial Water Footprint in China. *Ecological Economics* 100: 159-172.

ZHANG, Y., HUANG, K., YU, Y. and YANG, B., 2017. Mapping of Water Footprint Research: A Bibliometric Analysis during 2006–2015. *Journal of Cleaner Production* 149: 70-79.

ZHUO, L., MEKONNEN, M.M., HOEKSTRA, A.Y. and WADA, Y., 2016. Inter-and Intra-Annual Variation of Water Footprint of Crops and Blue Water Scarcity in the Yellow River Basin (1961–2009). *Advances in Water Resources* 87: 29-41.

ZOUMIDES, C., BRUGGEMAN, A., ZACHARIADIS, T. and PASHIARDIS, S., 2013. Quantifying the Poorly Known Role of Groundwater in Agriculture: The Case of Cyprus. *Water Resources Management* 27 (7): 2501-2514.

APPENDICES

1. SAMPLE INTERVIEW QUESTIONS

1.1. Sample interview questions posed to participant farmers:

- Please provide your tree censuses from the last 10 years.
- What is your approximate crop height for each variety?
- What is your approximate skirt height for each variety?
- Are all your orchards ridged? If not, please specify (proportion/variety).
- What is the approximate rooting depth per variety/orchard?
- Please provide details of your irrigation scheme:
    - Does the farm in question have a state water scheme entitlement (i.e. does the farm have water rights)?
    - If yes – what is the water allocation?
    - If no – are you a registered water user? Is the water available sufficient to irrigate the area which is registered for water use? In your estimation, what is the proportion of years in which there is sufficient water available?
    - Do you make use of supplementary irrigation over and above scheme supply?
- Please provide irrigation details, specifically relating to:
    - System type (drip, microjet, etc)
    - Design application
    - Please describe your methods of scheduling irrigation (e.g. calendar method or probes)
- Please provide details of your fertilizer and chemical soil application – including names, active ingredients (% composition), and amount applied (kg/ha). Specifically, please provide details for nitrogen, phosphorous, metals, pesticide and insecticide application.
- Does active ground cover exist beneath trees, or is groundcover removed?
- How many permanent labourers do you typically employ? How many casual employees?

- Do you have any objection to your local packhouse providing me with details relating to your production activities (such as production records, export volumes, tree census data, water quality, etc)?

1.2. Interview questions posed to local citrus co-operative representatives:

Please provide data on the following:

- Tree census data from last 10 years for participant farms
- Production records for participant farms
- Average annual prices charged per variety group from 2008-2017
- Packout statistics
- The proportion of export and local market production
- Soil salinity records
- Water salinity records

2. Table of Data Inputs Utilised and Corresponding Sources

DATA INPUT	DATA SOURCE
Weather and Climate Data	ARC-ISCW, 2018
Yield Data	Local citrus co-operative
Crop Data	
Yield potential	Malan, 1991; corroborated by farmer interviews
Crop height	Farmer interviews
Rooting depth	Farmer interviews; Malan, 1991; de Villiers & Joubert, 2006
Allowed depletion fraction	Farmer interviews; Allen *et al.*, 1997
Crop growth stage durations:	
FAO guidelines and definitions	Allen *et al.,* 1998
Citrus phenological cycle	de Villiers & Joubert, 2006; Alexander, 2015
Citrus fruit growth curve	Bain, 1958; Verreynne, 2009; Alexander, 2015
Historical fruit growth data	Verreynne, 2010
Typical harvest periods	Farmer interviews; Local citrus co-operative; CRI, 2015
Crop coefficients (K_{cb})	Allen *et al.*, 1997
Start of season date	Farmer interviews; Alexander (2015)
Soil Data	
Soil texture	Farmer interviews; Hartmann *et al*. (1979); Baard *et al*. (1978); Geers *et al*. (1984); Fry (2018)
Field capacity (FC)	Saxton and Rawls (2006)
Wilting point	Saxton and Rawls (2006)
Readily evaporable water (REW)	Allen *et al*. (1998); Allen *et al*. (2005); Zeleke and Wade (2012)
Soil salinity	Local citrus co-operative; Fry (2018)
Irrigation water salinity	Local citrus co-operative; Fry (2018)
Field and Irrigation Data	
Orchard and variety details	Farmer interviews; Local citrus co-operative
Cultivated hectares	Farmer interviews; Local citrus co-operative
Age distribution of orchards	Farmer interviews; Local citrus co-operative
Irrigation system and practices	Farmer interviews
Water allocation structure	Farmer interviews
Grey WF	
Fertilizer application rate	Farmer interviews
c_{max}	DWAF, 1996a; 1996b
c_{nat}	DWS, 2018b
Leaching run-off fraction	Franke *et al*., 2013
EWP	
Average annual DIP prices 2008-2017	Local citrus co-operative
CPI	STATSSA, 2018; IMF, 2018
Historical USD:ZAR exchange rate	SARB, 2018

3. Typical Harvest Periods for Various Citrus Varieties

	Mar				**Apr**				**May**				**June**				**July**				**August**				**September**			
Variety	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Navels[1]									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨				
Satsumas			▨	▨	▨	▨	▨	▨	▨	▨																		
Clementines									▨	▨	▨	▨	▨	▨	▨	▨												
Nova													▨	▨	▨	▨												
Late Mandarins																	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	
Lemons									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		

[1] Includes Late Navels/Navelates

Source: de Villiers & Joubert (2006); CRI (2015); local citrus co-operative

4. Expected Lifespan and Potential Production of Navels, Lemons, Satsumas and Mandarins

	Navels	**Lemons**	**Satsumas**	**Mandarins**
Expected lifespan (years)	33	25	25	25
Potential production (mature trees) (tons/ha)	60	80	75	60

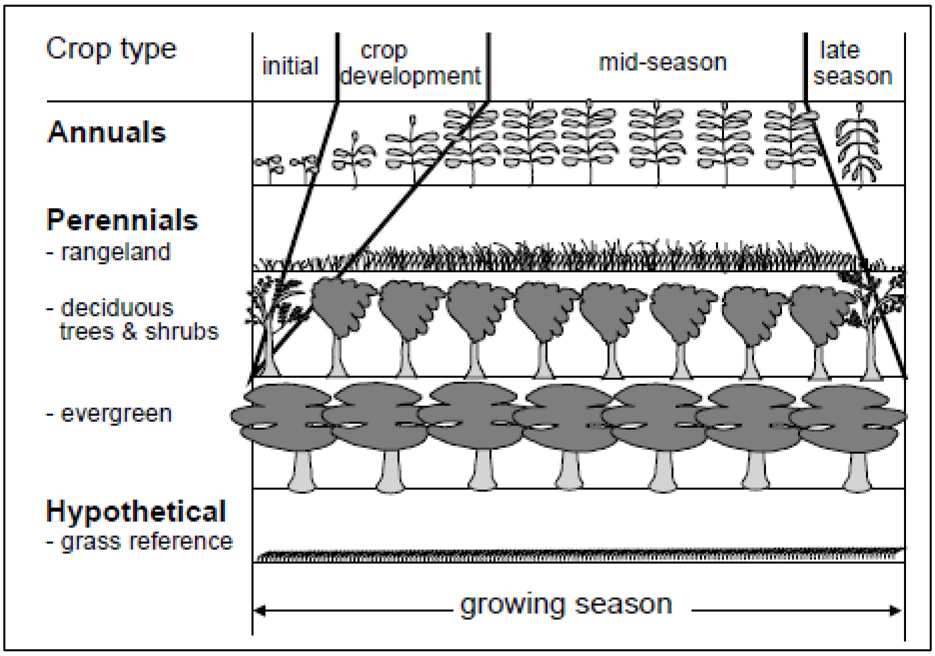
Source: Malan (1991)

5. Soil Surface Area of Leaf Canopy for Citrus Trees of Various Ages

	Tree age		
	Mature	**8 yrs.**	**3 yrs.**
Soil surface area of leaf canopy (m^2)	18	7.5	2.5
Approx. soil surface area of leaf canopy (%)	70-100%	50%	20%

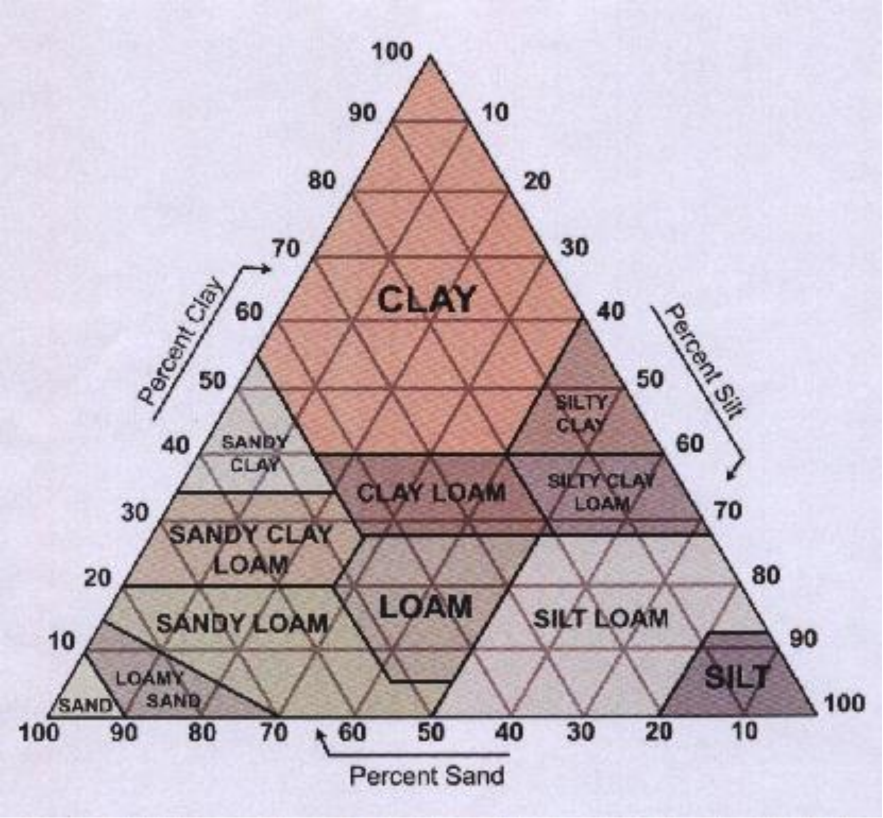
Source: Taylor and Gush (2017); Netterville (1996)

6. Figure Showing Crop Growth Stages for Annuals, Perennials and Hypothetical Reference Crop, obtained from Allen *et al*., (1998).



Source: Allen *et al*. (1998)

7. Soil Texture Triangle Obtained from SAPWAT4 Programme



Source: SAPWAT4 program

8. Tables utilised for the determination of leaching run-off potential

8.1. Nitrogen Leaching Run-Off Fraction

			Nitrogen						
Category	Factor		Leaching runoff potential	Very low	Low	High	Very high	**Score (s) x Weight (w)**	Source
			Score (s)	0	0.33	0.67	1		
			Weight (w)						
Environ-mental factors	Atmos-pheric input	N-deposition (g N/m^2/yr)	10	[✓ < 0.5]	> 0.5	< 1.5	> 1.5	**0**	Cleveland *et al*., 2013 in Franke *et al*., 2013.
	Soil	Texture[a] (relevant for leaching)	15	Clay	Silt [✓ 0.63]	Loam	Sand	**9.45**	Farm interviews; Hartmann *et al*., 1979; Baard *et al*., 1978; Geers *et al*., 1984.
		Texture[a] (relevant for runoff)	10	Sand	Loam [✓ 0,37]	Silt	Clay	**3.7**	Farm interviews; Hartmann *et al*., 1979; Baard *et al*., 1978; Geers *et al*., 1984.
		Natural drainage (relevant for leaching)	10	Poorly to very poorly drained	Moderately to imperfectly drained	[✓ Well drained]	Excessively to extremely well drained	**6.7**	FAO, 2018.
		Natural drainage (relevant for runoff)	5	Excessively to extremely well drained	[✓ Well drained]	Moderately to imperfectly drained	Poorly to very poorly drained	**1.65**	FAO, 2018.
	Climate	Precipitation (mm)	15	[✓ 0-600]	600-1200	1200-1800	> 1800	**0**	ARC-ISCW, 2018.
Agricul-tural practice	N-fixation (kg/ha)		10	0	> 0	< 60	[✓ > 60]	**10**	Farm interviews
	Application rate		10	Very low	Low	High	[✓ Very high]	**10**	Farm interviews; Potter *et al*., 2011a.
	Plant uptake (crop yield)		5	[✓ Very high]	High	Low	Very low	**0**	Coetzee, 2007.
	Management practice		10	Best	[✓ Good]	Average	Worst	**3.3**	Franke *et al*., 2013
								44.8	

[a] Soil type is sandy clay loam. Calculated score by proportioning percentage of sand, clay and silt making up sandy clay loam, as per soil texture triangle (Appendix 7).

α = 0.118

Note: Table based on determination tables provided by Franke *et al*. (2013).

8.2. Phosphorous Leaching Run-Off Fraction

			Phosphorus						
Category	Factor		Leaching runoff potential	Very low	Low	High	Very high	**Score (s) x Weight (w)**	Source
			Score (s)	0	0.33	0.67	1		
			Weight (w)						
Environ-mental factors	Soil	Texture[a] (relevant for runoff)	15	Sand	[✓ 0,37] Loam	Silt	Clay	**5.55**	Farm interviews; Hartmann *et al.*, 1979; Baard *et al.*, 1978; Geers *et al.*, 1984.
		Erosion	20	Low	[✓ Moderate]	High	Very High	**6.6**	WRC, 2012.
		P-Content (g P/m^2)	15	[✓ < 200]	200-400	400-700	> 700	**0**	Yang *et al.*, 2013 in Franke, 2013; DAAC, 2014.
	Climate	Rain Intensity	10	[✓ Light]	Moderate	Strong	Heavy	**0**	WRC, 2012; ARC-ISCW, 2018.
Agricul-tural practice	Application Rate		15	Very low	[✓ Low]	High	Very high	**4.95**	Farm interviews; Potter *et al.*, 2011b.
	Plant uptake (crop yield)		10	Very high	High	[✓ Low]	Very low	**6.7**	Coetzee, 2007.
	Management practice		15	Best	[✓ Good]	Average	Worst	**4.95**	Franke *et al.*, 2013.
								28.75	

[a] Soil type is sandy clay loam. Calculated score by proportioning percentage of sand, clay and silt making up sandy clay loam, as per soil texture triangle (Appendix 7).

α = 0.01

Note: Table based on determination tables provided by Franke *et al*. (2013).

8.3. Potassium Leaching Run-Off Fraction

Category	Factor		**Metals (used for Potassium)**					**Score (s) x Weight (w)**	Source
			Leaching runoff potential	Very low	Low	High	Very high		
			Score (s)	0	0.33	0.67	1		
			Weight (w)						
Chemical properties	Kd (L/kg)		30	> 1000	[✓ 1000-200]	200-50	< 50	**9.9**	Sheppard *et al*., 2009; Vilela *et al*., 2018.
Environ-mental factors	Soil	Texture[a] (relevant for runoff)	15	Sand	[✓ 0,37] Loam	Silt	Clay	**5.55**	Farm interviews; Hartmann *et al*., 1979; Baard *et al*., 1978; Geers *et al*., 1984.
		Erosion potential	20	Low	[✓ Moderate]	High	Very High	**6.6**	WRC, 2012.
	Climate	Rain Intensity	15	Heavy	Strong	Moderate	[✓ Light]	**15**	WRC, 2012; ARC-ISCW, 2018.
Manage-ment practice	Site manage-ment	Artificial drainage	20	[✓ Poorly to very poorly drained]	Moderately to imperfectly drained	Well drained	Excessively to extremely well drained	**0**	Feick *et al*., 2005 in Franke, 2013.
								37.05	

[a] a Soil type is sandy clay loam. Calculated score by proportioning percentage of sand, clay and silt making up sandy clay loam, as per soil texture triangle (Appendix 7).

α = 0.59

Note: Table based on determination tables provided by Franke *et al*. (2013).

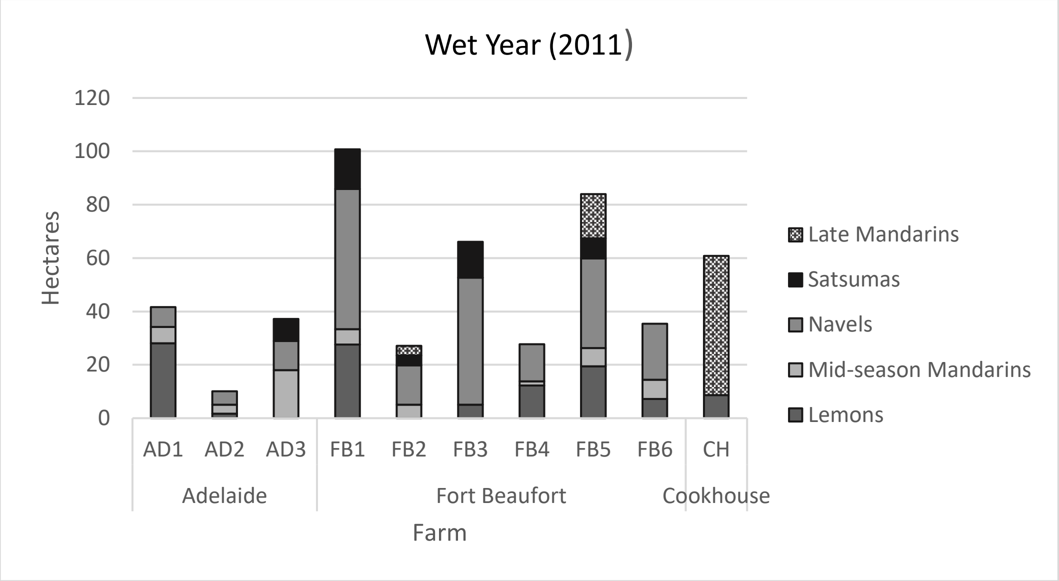
9. Water Quality Testing Sites Utilised

River	**Testing Site**	**Detail**	**Years**
Koonap River	Q92 102484	Koonap River at Frisch Gewaagd/Groenkop	1971-1982
	Q92 102485	Koonap River at Schurftekop	1971-1993
	Q92 102497	Koonap River at Frisch Gewaagd/Groenkop (New Weir (NCWQ))	1995-2018
Fish River	Q13 102439	At Katkop on Great Fish River (Groot-Visrivier) (NCMP)	1971-1993
	Q30 102450	At Rietfontyn Waaikraal on Great Fish River (NCWQ NCMP)’	1977-1997
Kat River	Q94 102494	Kat River Dam on Kat River: Down Stream Weir (NCWQ)	1972-2004
	Q94 102499	Weltevreden 760 - Kat River Dam on Katrivier: near Dam Wall (NCWQ) Q01	1971-2002

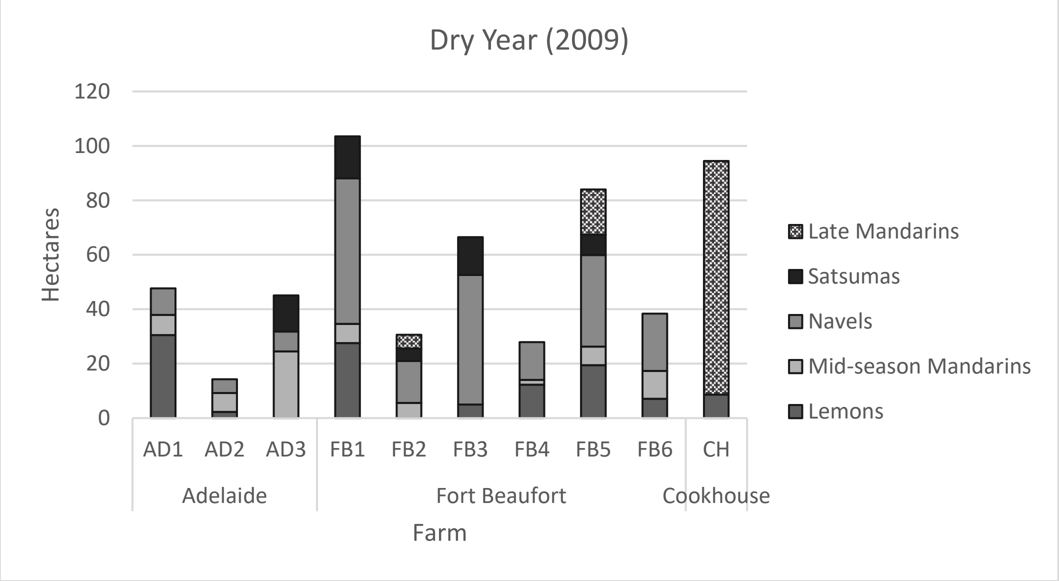
Source: DWS (2018b)

10. Hectares by Variety and Per Farm Across the Adelaide, Fort Beaufort and Cookhouse Regions: Wet and Dry Years

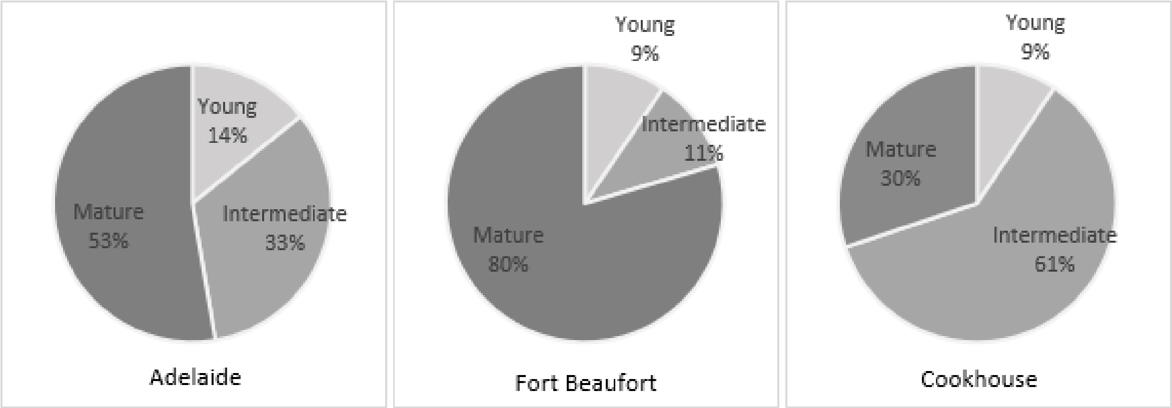
10.1. Wet Year



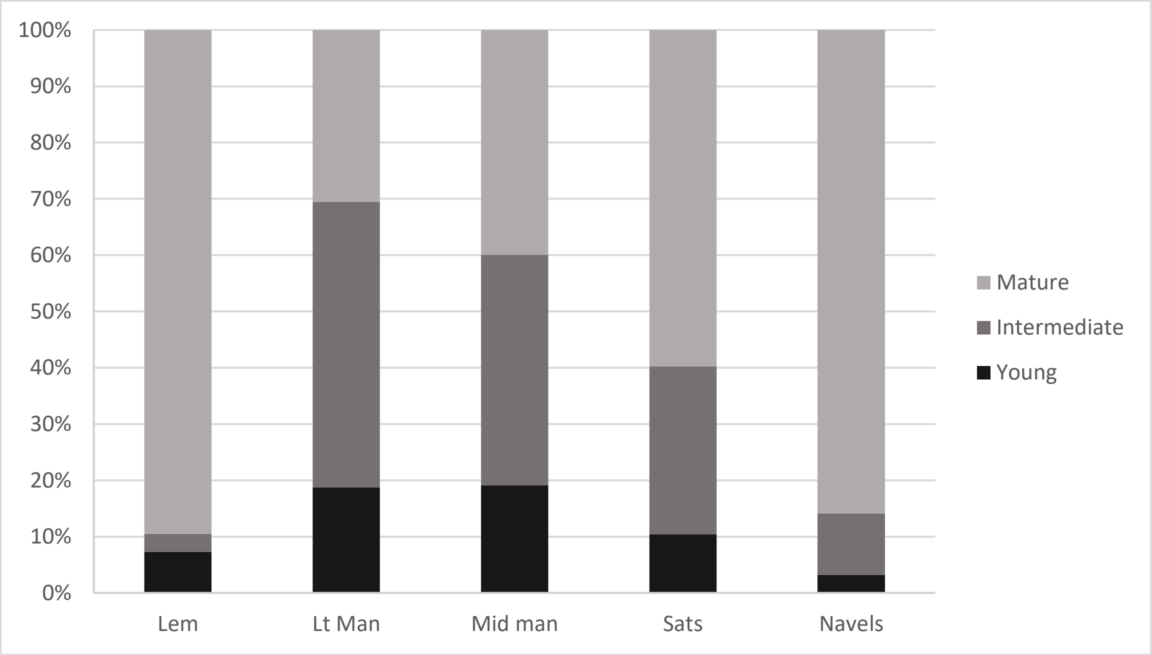
10.2. Dry Year



11. Proportion of young, intermediate and mature trees across all varieties for Adelaide, Fort Beaufort and Cookhouse



12. Proportion of mature, intermediate and young trees by variety across the entire study region.



13. Proportion of trees falling into each age group for each variety across each study region