WATER RESEARCH COMMISSION

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WATER FOOTPRINT AS AN INDICATOR OF SUSTAINABLE TABLE AND WINE GRAPE PRODUCTION

Report to the
Water Research Commission and Winetech

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WATER FOOTPRINT AS AN INDICATOR OF SUSTAINABLE TABLE AND WINE GRAPE PRODUCTION

Report

to the Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND AND RATIONALE

In recent years, the available water resources in the Western Cape have been severely constrained due to below-average rainfall, resulting in an extensive and prolonged drought. During the 2017 and 2018 grape production seasons in South Africa, very limited water was available for irrigation in the areas where table and wine grapes are extensively cultivated, making grape production, in some instances, nearly impossible. Most producers had to employ water conservation measures and, in some instances, vineyards were removed. Good rainfall over large parts of the Western Cape during the winters of 2018 and 2019 increased water availability, improving the conditions for grape production. However, severe drought conditions persist in many areas. The past and ongoing pressure on available water resources for agricultural production initiated renewed discussions on the sustainable and efficient use of water for crop production, as well as the crop water footprint as an indicator of sustainable water use. Whereas water use efficiency (often referred to as water productivity) typically refers to crops, indicating how much of a crop can be produced per unit of water, the water footprint provides a measure of the amount of water used to produce crops, goods or services. The water footprint can be expressed in different ways, for example, a litre of water used per kg of crop produced (ℓ/kg), or a litre of water used to produce a litre of wine (ℓ/ℓ). The water footprint considers both the direct and indirect water needed to produce a crop or product and is sometimes expressed in its colour components: green, blue and grey. A blue water footprint (WF_{blue}) typically refers to water "consumed" along the value chain of a product and therefore reflects the loss of water from a catchment, whereas a green water footprint (WF_{green}) refers to rainwater that has evaporated or is incorporated into a product and does not become runoff. A grey water footprint (WF_{grey}) refers to the volume of freshwater that is required to dilute polluted freshwater along a product supply chain for this water to meet the specified quality standards.

PROJECT AIM AND OBJECTIVE

Given the importance of the available water resources and their use in the production of table grapes and wine in South Africa, the WRC, together with the Wine Industry Network of Expertise and Technology (Winetech), co-funded research into the water footprint of wine and table grapes produced in South Africa. The focus of this study was on assessing the water footprint of table grapes and wine produced in selected production regions of the Western Cape as an indicator of sustainability. Access to large production databases, together with spatial estimates of crop water use (evapotranspiration) for a significant number of fields, allowed the estimation of water footprints for a wide spectrum of production conditions.

The project assessed the water footprint of table grapes and wine produced in South Africa and had the following objectives:

- Review how water footprint methodologies can be applied to table and wine grape production
- Apply the water footprint for selected and representative grape commodities and products, and make recommendations for improvements
- Develop and demonstrate a procedure whereby a Water Footprint Assessment (WFA) can be carried out utilising spatial datasets, and propose a set of guidelines that industries or organisations can follow when implementing the WFA within their organisations or industries
- Promote the benefits of a WFA to industries
- Build capacity and competence in WFA in the wine and table grape industries

Initially, this project was designed to be executed over a four-year period (2017 to 2021). However, in agreement with the WRC and Winetech, the project scope (and contract) was altered in March 2019 to enable the completion of the project at an earlier date (at the end of 2019).

This resulted in two main changes:

- A revised project scope, where the detailed economic valuation and sustainability assessment components of this project, which typically form part of a complete WFA, were removed

- A shortened project time frame to allow for the completion of the project at the end of 2019, while still meeting the set objectives outlined above

METHODOLOGY

A water footprint assesment, as per the Global Water Footprint Standard (GWFS) approach applied in this project, typically consists of four distinct phases:

- Setting the scope and goal(s) of the assessment
- Collecting data and performing the actual water footprint calculations
- Performing a sustainability assessment where the WFA is evaluated from an environmental, economic and social perspective
- Formulating response options and strategies.

This research focused on the first two aspects and was designed to be executed in two phases. The two main phases included the following:

- A WFA method development phase where historical data was used
- A WFA method application where data for the 2018/19 season was used

Case studies

Due to the extent of grape cultivation across multiple provinces in South Africa and the data requirements to perform a WFA, such an assessment was only done for selected case studies for the table and grape industries. The case studies were designed in consultation with the table grape and wine industries. Case studies were only undertaken in three production regions each for the table grape and wine industries. For wine, the Coastal, Breede River Valley and Olifants River Valley regions were used, and for table grapes, the Berg River Valley, Hex River Valley and Olifants River Valley regions were included. The water footprints of table grapes and wine were calculated at packhouse level and cellar level for table grapes and wine, respectively. For table grapes, the water footprints were expressed as water use per kilogram of table grapes produced. The estimates are also shown in water use per 4.5 kg carton equivalent of table grapes produced, for industry reference. The water footprint of table grapes calculations include all direct water uses from grape production in the vineyard up to the packing of grapes in the packhouse, but prior to final cool storage. It includes WF_{green}, WF_{blue} and WF_{grey} at field level and WF_{blue} at packhouse level. The WF_{grey} at packhouse level was not considered. For wine, the water footprints are expressed as water use per litre of wine produced. For knowledge dissemination to the public, the water footprint values were also converted and are shown as water use per 750 mℓ bottle of wine produced. The water footprint of wine considered all direct water uses from grape production in the vineyard up to the winemaking process, but prior to bottling. This includes WF_{green}, WF_{blue} and WF_{grey} at field level and WF_{blue} and WF_{grey} at cellar level. The water footprint of wine was only determined for producer cellars. The water footprint of table grapes focused on grapes produced conventionally, i.e. not under nets. The GWFS approach was used as the basis for developing an improved methodology for WFA. The use of remote sensing (RS)-derived information and large datasets formed a major focus of this study.

Data used

Multiple datasets, captured in both spatial and non-spatial formats, were considered, and include information on table and wine grape production, as well as wine production, the position of fields considered in the study (i.e. field boundaries), field or block-specific information (e.g. block size, cultivar, rootstock, trellis system, planting date and planting density), spatial evapotranspiration (ET) from various sources, rainfall data, field-level chemical spray and fertilizer records, packhouse and cellar water use, and water quality records for cellars and the environment. The period under consideration for the water footprint estimation spanned 1 August 2018 to 31 July 2019 and data was sourced for this period.

The green, blue and grey water use (WU_{green}, WU_{blue}, WU_{grey}) at field level was first calculated, after which the respective water use values were divided by the production data (yield in t/ha) to give field-level water footprint values.

In very simple terms, the field-level WU_{green} (or ET_{green}) was calculated from (monthly) spatial FruitLook evapotranspiration and effective rainfall (P_{eff}) data, summed to annual totals. The field-level WU_{blue} (annual total) consisted of two components, which were calculated in two steps: as the difference between the annual ET and annual total WU_{green} or ET_{green}, and from typical chemical spray applications at farm level (summarised in a lookup table), determined by the production region in which the field is situated, the cultivar considered, as well as the size of the field in hectares. The WU_{grey} was calculated considering fertilizer chemical components or pollutants (summarised in a lookup table), production classes and region, and the size of the field. The water use estimates were converted to field level WF_{green}, WF_{blue} and WF_{grey} estimates, using the field-specific grape production or crop yield data. The field level WF_{total}, in turn, was calculated as the sum of these respective water footprint components.

In order to provide the complete water footprint estimate at packhouse and cellar levels, the water footprint (based on blue and grey water use) at this production level was added to the field-level WF_{total}. Only the WU_{blue} contribution was considered for table grapes (based on observations), but for wine at cellar level, both the WF_{blue} (based on actual observations) and WU_{grey} (based on a lookup table) were included.

MAIN FINDINGS

This study determined the water footprint of table grapes and wine produced in three important production regions, all situated in the Western Cape. The potential of integrating large spatial datasets with large production databases and lookup tables for use in the water footprint calculations was explored and illustrated. This provided a novel approach to determine the water footprint of table grapes and wines, accounting for all the water use components (blue, green and grey) considered across the production process (field and packhouse or cellar level).

Research aspects showed the progress made in using RS data to delineate field boundaries, in crop type mapping and to determine whether nets are present. It highlights the challenges still faced in applying these activities operationally. It also highlighted research into the impact of nets on crop water use. It further collated participants' information and industry recommendations pertaining to field-level chemical spray and fertilizer application into lookup tables for use in the WF_{blue} and WF_{grey} calculations.

In collating the data required for the WFA of table grapes and wine, the main challenge faced was the lack of easily accessible data required for water footprint calculations. This challenge explained why few studies of this nature have been conducted successfully in South Africa and for the table grape and wine industries, and why existing studies focused on single or a few fields. Systems to manage wine grape and wine production are only available to customers and do not currently contain a full spatial dimension, therefore making integration with RS datasets tedious.

As with all systems, the accuracy of the data captured in these systems is fully reliant on the customers. To our knowledge, there are no inbuilt accuracy checks within these systems. No single table grape data management system is used in South Africa. Therefore, easy access to production data is limited, which complicates data integration for multiple farms or packhouses. Here too, the data does not have a spatial dimension, and linking the field data to RS data involves numerous steps and checks.

Despite increased pressure on available water in South Africa, the water use at field, farm and packhouse level is still not widely measured. Therefore, alternative approaches had to be explored to come up with an estimate of water use in the production of grapes. Where water use data is available, it will often include all uses for multiple fields or the entire farm. Therefore, the use of spatial ET data and region-specific lookup tables, derived as part of this project, was explored, with the latter providing a summary of valuable data.

Considering the above, this research highlighted the complexities of investigating the water footprint of extensive areas, involving thousands of field records in the case studies for table grape and wine production in South Africa. This explains why many water footprint studies, which involve an entire production process, and all components that contribute to the water footprint process, often focus on one or a few fields. The study results show that a vast quantity of new knowledge can be created using an alternative and innovative approach of using large databases, RS data and lookup tables. It further illustrates the large variations that are often present in water footprint estimates which are a direct result of the wide range of production conditions encountered in South Africa.

Considering the WF_{total} for table grapes, the following important observations were made:

- In this study, data from more than 200 cases was considered and represented the wide range of production conditions typical of the Western Cape, including large production ranges (up to 64 t/ha), a large number of cultivars, low annual rainfall (less than 345 mm/year) and a median export fraction of 67% for the 2018/19 season, representing a production season that is less than ideal.
- The WF_{total} for table grapes showed the small or negligible contribution of the WF_{blue} from the packhouse (under 1% or 0.76 ℓ/kg) to the WF_{total}; with the field-level WF_{total} therefore contributing to 99% of the estimates. It is noted that this is in the absence of WF_{grey} at packhouse level, which will contribute to the WF_{total}.
- The WF_{total} for table grapes ranged between 500 and 714 ℓ/kg, with a median value of 619 ℓ/kg, considering the data from all areas. The highest WF_{total} was calculated for grapes produced in the Berg River Valley. The results reflect the fields and season studied.
- Variation in the WF_{total} was observed between cultivars. For the cultivars investigated in more detail, the highest median WF_{total} was calculated for Prime and the lowest for Sugranineteen (Scarlotta Seedless®). These results reflect the fields and season studied.
- For all areas studied, the WF_{blue} (field level plus packhouse) contributed most to the WF_{total} (more than 70%). The WF_{grey} contributed to about 20% of the WF_{total}.
- The resultant WF_{total} for table grapes directly reflects the fields considered in this study, the conditions experienced during the 2018/19 season and the quality of the table grapes produced during this season.

Considering the WF_{total} for wine, the following were important observations and findings:

- The WF_{total} of wine was calculated for three production regions of the Western Cape and considered data from more than 3,600 vineyards across these regions for the 2018/19 production season. The data that was considered represented a wide range of production conditions – with wine grape yields of up to 79 t/ha, data from 37 cultivars considered, a large range in age (two to 100 years) and rainfall in the production regions (61 to 608 mm/year).

- The median WF_{total} for wine (field level plus cellar), considering the data from all areas, was 863 ℓ/ℓ. The largest WF_{total} for wine was calculated for the Coastal Region (1,325 ℓ/ℓ), with the field-level water use and water footprint contributing to 86% of the WF_{total} of wine. The lowest WF_{total} for wine was for the Breede River Valley (641 ℓ/ℓ), with an 88% contribution from the field-level water footprint to this estimate. The Olifants River Valley saw the greatest contribution of the cellar-level WF_{grey} to the WF_{total} of wine at 21%. It should be noted that, for the latter, the cellar level WF_{grey} presents an estimated worst-case scenario or maximum value.
- Wine grape yield strongly influenced the field-level WF_{total} for wine grapes and therefore the WF_{total} of wine. For wine grape production of less than 5 t/ha, the field level WF_{total} increased exponentially to values higher than 1,600 ℓ/kg.
- Differences in the field-level WF_{total} were observed between cultivars. Of eight important cultivars considered, the field-level WF_{total} was highest for Cabernet Sauvignon (1,131 ℓ/kg or 1,467 ℓ/ℓ) and lowest for Colombar (345 ℓ/kg or 450 ℓ/ℓ).
- At field level, the WF_{blue} contributed greatly to the WF_{total} of wine (more than 83%), with a larger contribution of the WF_{green} in the Coastal Region (27%). The WF_{grey} was not insignificant and contributed most in the Coastal Region (19%).
- Converting the WF_{total} of wine to a 750 mℓ unit yielded a median value for all the fields considered of 647 ℓ of water for 750 mℓ of wine.

It can be concluded that this study successfully calculated the water footprint of table grapes and wine in different production regions of the Western Cape using spatial data, large production datasets and lookup tables, providing an innovative approach to water footprint assessment. This study was successfully completed despite the amended study scope and an earlier completion date. The result successfully illustrated how large numbers of field-level water footprint estimates can be integrated into final water footprint estimates to show the range in production and water footprints related to a production unit like a table grape packhouse or wine cellar. The water footprint results for the 2018/19 season provide a new and extensive knowledge base, which can be used to build onto in future WFA studies for table grapes and wine production in South Africa.

RECOMMENDATIONS

General

This study successfully calculated the water footprint of table grapes and wine in different production regions of the Western Cape using spatial data, large production datasets and lookup tables. It illustrated how large numbers of field-level water footprint estimates can be integrated into final water footprint estimates to show the range in production and water footprints related to a production unit like a packhouse or cellar. Although the water footprint results provide a basis for future WFAs for table grapes and wine production, the water footprint results only provide insight into the water footprint for the 2018/19 season and the specific fields considered.

Water footprint benchmarking

To derive water footprint benchmarking values for both these industries and specific production regions or cultivars, it is proposed that water footprints are calculated for more production seasons to account for the impact of climate variation and crop production responses to such climate variation. The results from multi-seasonal estimates should be used to set benchmarking standards, considering industry and regional sustainability aspects.

Data contributions to the water footprint assessment process

It is recommended that research continues to improve the data inputs required for a WFA. This project demonstrated the value of remote sensing and earth observation for WFAs. It is proposed that research into field boundary delineation, crop type mapping and assessing the impact of nets used in crop production on available remote sensing data continues.

Determining ET_{blue} and ET_{green} at field level with a high accuracy, across a large scale and using remote sensing, remains a research challenge. Models require parameterisation with large quantities of field data that are not readily available. Future research on this topic should be conducted.

The grey water footprint calculated in this research is the first step towards gaining insight into the impact of pollution associated with the production of table grapes and wine on the water resource in the selected study areas. Further research is required to obtain more accurate leaching fractions of the soil in the fields in the study areas under consideration in order to obtain more accurate pollution levels for calculating the grey water footprint. Further research is also required into the impact of certain actions (such as water purification) as a response strategy to decrease the WF_{grey} at wine cellars.

Sustainability assessment

While calculating the water footprint is an important step of the WFA process, further research is required to assess the degree of sustainability with which the resources are used in table grape and wine production from an environmental, economic and social perspective. Research into the environmental sustainability is required to determine whether enough water is available to meet environmental flow requirements after the water has been used for table grape and wine production. From an economic perspective, economic water productivities must be explored to determine the economic returns from the use of freshwater to produce table grapes and wine in the selected regions. From a social perspective, equitable access to the scarce resource is crucial and needs to be ensured.

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- Numerous table grape producers and exporters situated in the Western Cape for the data contributions (production and other contributions), field maps and background information provided to aid in data interpretation.
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LIST OF SYMBOLS AND ABBREVIATIONS

[p]	Product
[s]	Process step
AR	Application rate
ARC	Agricultural Research Council
Bio	Biomass production
BioWUE	Biomass water use efficiency
Ca	Calcium
C_{act}	Actual concentration
Cat	Category
C_{max}	Maximum concentration
C_{nat}	Natural concentration
CEC	Crop Estimates Consortium
Cl	Chloride
COD	Chemical oxygen demand
CWMA	Catchment Water Management Area
CWU	Crop water use
DAAC	Distributed Active Archive Centre
DAFF	Department of Agriculture, Forestry and Fisheries
DSTV	Diurnal surface temperature variation
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
ET	Evapotranspiration
ET_c	Crop evapotranspiration
ET_{act}	Actual evapotranspiration
ET_b	Blue water use fraction of evapotranspiration
ET_{def}	Evapotranspiration deficit
ET_o	Reference evapotranspiration
EVI	Enhanced Vegetation Index
FAO	Food and Agricultural Organisation
Fe	Iron
FL	FruitLook
f_p	Product function
f_v	Value function
GDP	Gross domestic product
GIS	Geographical information systems
GWFS	Global Water Footprint Standard
HRVI	High-Resolution Vegetation Index
ISO	International Standards Organization
K	Potassium
K_c	Crop coefficient
kg	Kilograms
kg/ha	Kilogram per hectare
kg/ℓ	Kilogram per litre
kg/m^3	Kilogram per cubic meters
K_s	Stress coefficient
ℓ	Litre
ℓ/kg	Litre per kilogram

ℓ/ℓ	Litres of water per litres of product
LAADS	Atmosphere Archive and Distribution System
LAI	Leaf Area Index
LCA	Life cycle assessment
LiDAR	Light detection and ranging
LRVI	Low-resolution vegetation index
m^3	Cubic meter
m^3/t	Cubic meter per ton
m^3/year	Cubic meter per year
Max	Maximum value
MCC	Méthode Cap Classique
Mg	Magnesium
mg/ℓ	Milligrams per litre
Min	Minimum value
mℓ	Millilitre
METRIC	Mapping Evapotranspiration with High Resolution and Internalised Calibration
MLR	Multiple linear regression
Mn	Manganese
N	Nitrogen
Na	Sodium
N/A	Not available or Not applicable
NASA	National Aeronautics and Space Administration
NDVI	Normalised Difference Vegetation Index
NGO	Non-governmental organization
N_{plant}	Nitrogen in plant
N_{top}	Nitrogen at the top of the plant
OLS	Ordinary least-squares
P	Phosphate
PBR	Plant bioregulator
P[p]	Production quantity of product
$P\_(_{eff(dec))}$	Effective rainfall for the month of December
P_{eff}	Effective rainfall
PL	Pollutant load
P_{tot}	Total monthly rainfall
ppha	Plant density in plants per hectare
R^2	Coefficient of determination
RFR	Random forest regressor
RMSE	Root mean square error
RS	Remote sensing
S	Sulphate
SASEV	South African Society for Enology and Viticulture
SATI	South African Table Grape Industry
SAVI	Soil-adjusted Vegetation Index
SAWIS	South AfricaN Wine Industry Information and Systems
SPASM	Soil-Plant-Water-Atmosphere System Model
SPOT	*Satellite Pour l'Observation de la Terre*
SVM	Support vector machine
SWNZ	Sustainable Winegrowing New Zealand
t	Tonnes of grape production

T	Transpiration
t/ha	Ton per hectare
TDS	Total dissolved solids
USDA	United States Department of Agriculture
USDA SCS	United States Department of Agriculture Soil Conservation Service
VIVA	Valutazione Impatto Viticoltura Sull'ambiente
VI	Vegetation Index
VITT	Vegetation Index/Temperature Trapezoid
WaPOR	Water Productivity Open-Access Portal
WCCC	Western Cape Crop Census
WCDoA	Western Cape Department of Agriculture
WF	Water Footprint
WF_{total}	Sum of water footprint components
WFA	Water Footprint Assessment
WF_{blue}	Blue water footprint component
WF_{green}	Green water footprint component
WF_{grey}	Grey water footprint component
WFN	Water footprint network
WF_{prod}	Water footprint of a product
WF_{proc}	Water footprint of a process
Winetech	Wine Industry Network of Expertise and Technology
WO	Wine of Origin
WOSA	Wines of South Africa
WRC	Water Research Commission
WU	Water use
WU_{blue}	Blue water use component
$WU_{bluelookupvalue}$	Blue water use lookup value
WUE	Water use efficiency
WU_{green}	Green water use component
WU_{grey}	Grey water use component
WU_{grey}	Grey water use lookup value

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

In recent years, the available water resources in the Western Cape have been severely constrained due to below-average rainfall and extensive and prolonged drought. During the 2017 and 2018 grape production seasons in South Africa, the water available for irrigation in the areas where table and wine grapes are extensively cultivated was severely curtailed, making grape production, in some instances, nearly impossible. Most producers had to employ water conservation measures and, in extreme cases, vineyards were removed. Goudriaan et al. (2019) illustrated the severity of the impact of this drought on grape production in the Olifants River Valley region during this period using remote sensing data.

Good rainfall during the winters of 2018 and 2019 over large parts of the Western Cape increased the water availability in many areas, thereby improving the conditions for grape production. However, severe drought conditions persist in many areas. The past and ongoing pressure on available water resources for agricultural production initiated renewed discussions on the sustainable and efficient use of water for crop production, as well as the crop water footprint as an indicator of sustainable water use. Whereas water use efficiency, also referred to as water productivity, typically refers to crops, indicating how much of a crop can be produced per unit of water (e.g. in kg/m^3), the water footprint provides a measure of the amount of water used to produce crops, goods or services. The water footprint can be expressed in different ways, for example, a litre of water used per kg of crop produced (ℓ/kg), or the litres of water used to produce a litre of wine (ℓ/ℓ). The water footprint considers both direct and indirect water used to produce a crop or product and is sometimes expressed in its colour components: green, blue and grey.

The focus of this study was on assessing the water footprint of table grapes and wine produced in selected production regions of the Western Cape as an indicator of sustainability. Access to large production databases, together with spatial estimates of crop water use (evapotranspiration) for a significant number of fields, allowed for the estimation of water footprints for a wide spectrum of production conditions typical of the Western Cape.

The importance of water, as well as the importance of the table grape and wine industries in South Africa, are described in more detail in the next sections. These sections also provide an overview of the use of the water footprint as an indicator of the sustainable use of water. The project's aim and objectives are then stated.

1.1.1 The importance of water in South Africa

Water is essential for all life on earth. This resource is becoming increasingly limited, but it is still not widely recognised that there is a finite supply of water. Growing water scarcity and misuse of freshwater pose serious threats to sustainable development (FAO, 1993). Competition among the different users (agriculture, industry and settlements) of a limited water supply is already constraining development efforts in many countries. With growing populations and economies, the competition for the limited water supply will likely intensify, along with conflicts among water users (FAO, 1993), as was the case during the 2017 and 2018 drought in the Western Cape. The demand for more water for domestic, agricultural and industrial use is increasing the pressure on the equitable distribution of water among these different users and industries, but it also requires increasing efficiencies in their utilisation of water.

Agriculture is highly dependent on a safe, secure and adequate water supply throughout the production season. Worldwide, it is estimated that more than two-thirds of the water withdrawn from the earth's rivers, lakes and aquifers is used for irrigated agriculture (FAO, 1993). Proper agricultural water management is therefore necessary for food security, poverty reduction and environmental protection (World Bank, 2005).

Agriculture is burdened by numerous demands: to provide more food for consumers and materials for industries, to create and increase incomes and wealth in rural areas (and, in doing so, reduce poverty among rural people), and to contribute to the sustainability of natural resources and the environment. The challenge is to utilise water sustainably within an integrated approach (World Bank, 2005).

The sustainable use of water is particularly challenging in South Africa, given that it is a semi-arid country with an average annual rainfall of about 450 mm, well below the world average of about 860 mm/year. As such, South Africa is recognised as a water-stressed country. Furthermore, water availability across the country is not uniform, with an uneven spatial and temporal distribution of rainfall: 43% of the rain falls on 13% of the land (DWA, 2010), typically within a period of four to five months. Available water in South Africa is mainly from surface water, with groundwater contributing approximately 10% of the volume. It is estimated that the combined total water requirement for all user sectors for 2000 was 13,280 million m^3/year, with the requirement for irrigation being 7,836 million m^3/year, or roughly 60% of the total water requirement (DWA, 2010).

Most wine grapes are produced in the Western Cape, which has a Mediterranean climate. Rainfall occurs mainly in winter when grapevines require little water, and summer rainfall is infrequent and inadequate to support grape crop production. It is estimated that about 80% of the 110,200 ha of wine grape vineyards require irrigation during the hot, dry summers (SAWIS, 2004, in Myburgh, 2006). The irrigation amount and frequency vary greatly over production areas, climate and soils. Some wine grapes are produced in the summer rainfall area of South Africa, e.g. in the semi-arid Lower Orange River regions, where the annual precipitation is less than 200 mm. Such low rainfall is inadequate to sustain viticulture and these areas remain highly dependent on irrigation. Efficient water use for wine production is an important environmental consideration (Myburgh, 2006).

Irrigation systems used in wine grape vineyards vary from full surface flood and overhead sprinklers (portable and permanent), to micro-sprinklers and drippers. Flood irrigation is primarily used on alluvial soils along rivers in the warm inland areas, whereas overhead sprinklers are used for low-frequency irrigation in the Coastal Region. Many newly established wine grape vineyards are developed under drip irrigation (Myburgh, 2006). Crop water use and irrigation requirements vary greatly for grapes. Bearing grapevines in the Coastal Region of the Western Cape require approximately 500 mm of water from September to April (Van Zyl and Van Huyssteen, 1984, in Myburgh, 2006), of which about 300 mm is contributed by rainfall, and the remainder is supplied either by irrigation or water stored in the root zone (Myburgh et al., 1996). All table grape vineyards in South Africa are irrigated because of low summer rainfall in the production regions (SAWIS, 2004, in Myburgh, n.d.). Grapevine water status does not only influence berry size and yield, but also the colour of red or black cultivars. The profitability of export table grapes depends largely on the time they reach the markets. This is determined by the rate of sugar accumulation and colour development in table grapes. For table grape production, it is critical that good irrigation strategies are followed to allow for optimum yield, berry ripening, export percentage, storage capability and eating quality (Myburgh, n.d.). Table grape production takes place under conventional methods, but also under netting. It is estimated that the production in the northern provinces is exclusively under netting and that approximately 80% of production in the Orange River area is taking place under netting. In the other areas, the percentage area under netting is substantially lower, ranging from 10 to 20%. The direct impact of netting on irrigation requirements is not known.

The economic importance of the production of grapes and derived grape products in South Africa, together with the fact that grape production is heavily dependent on scarce freshwater resources, emphasises the need to focus attention on how or to what extent grapes can be produced sustainably in South Africa.

1.1.2 The importance of grape and wine production in South Africa

South Africa has a dual agricultural economy, which includes a well-developed commercial farming sector, as well as a smaller-scale communal farming sector (WWF-SA, 2010). Together, commercial and small-scale farming are important contributors to the South African economy. The direct contribution of primary agriculture to the total gross domestic product (GDP) is relatively small as estimated in 2017 at approximately 2.2% (DAFF, 2018), but when considering value-adding activities along the complete agriculture food value chain, the contribution is estimated to be closer to 40%. The challenge in a country such as South Africa is for the economically important agricultural sector to operate within the context of water scarcity as described above.

When comparing agriculture to other sectors in South Africa, irrigated agriculture has both the lowest contribution to GDP and the fewest jobs created per million cubic metres of water (Nieuwoudt et al., 2004, in Jordaan et al., 2019). Considering only these measures, agriculture, in general, may be an inefficient user of the scarce freshwater resource in South Africa (Jordaan et al., 2019). Irrigated agriculture remains an important sector in providing employment and earning foreign exchange (WWF-SA, 2010). According to the National Development Plan, agriculture will remain important for future economic growth in South Africa (NPC, 2013, in Jordaan et al., 2019). The importance of agriculture lies in its economy-wide multiplier effects, multi-sector linkages and contribution to food security and the livelihoods of the rural poor (Jordaan et al., 2019).

The wine, table and raisin grape industries are important contributors to the South Africa economy. In South Africa, grapes are grown to be pressed, dried or directly consumed. Table grapes are intended for consumption while they are fresh, as opposed to grapes grown for wine production, juice production or for drying into raisins (DAFF, 2011), which require processing before the products can be consumed. Table grapes are among the most traded fruit types in the world. They are produced in areas with mild Mediterranean (e.g. Western Cape) and arid subtropical climates. The remainder is produced in the Northern Cape, Eastern Cape, Limpopo, Free State and Mpumalanga (DAFF, 2011). Table grapes are almost exclusively produced under irrigation. In South Africa, the largest table grape harvest since deregulation in 1997 was recorded during 2016/17. An estimated 304.088 tons of table grapes was produced, of which 90% (67.575 million of 4.5 kg carton equivalents) was exported. The area under table grape production in 2018 was an estimated 21,798 ha (SATI, 2019a), with table grapes grown in five production regions distributed across South Africa. An estimated 12 612 permanent and 62 208 seasonal workers are employed by this industry (SATI, 2019a). In 2016, it was estimated that the table grape industry contributed over R3 billion towards South Africa's GDP (Fin24, 2016).

Wine grapevines covered an area of 93,021 ha in 2018 (SAWIS, 2018). The wine industry encompasses more than the typical meaning of the word “wine”. Brandy (or wine for brandy/distilling wine) has always been an important contributor to the wine industry. More recently, grape juice and grape juice concentrate (for use in non-alcoholic beverages and not just for sweetening wine) have become more important. Grapes produced for the wine industry include wine (natural, fortified and sparkling), wine for brandy, distilling wine and grape juice and grape juice concentrate for use in wine and non-alcoholic products. Internationally, in 2018, South Africa ranked ninth in overall volume production of wine and produced 3.3% of the world’s wine (SAWIS, 2018). In 2018, the country's total annual harvest was 950 million litres (1,220,920 t), down from the 1,154.0 million litres in 2015. The 2018 harvest was also 15% smaller than the 2017 harvest (SAWIS, 2018). The 2018 harvest was said to be “…really challenging, due to a prolonged drought which some believe to be the worst in 100 years and accompanied by water restrictions and frost damage in some areas…” (Vinpro, 2018). According to a study commissioned by the South African Wine Industry Information and Systems (SAWIS), published in January 2015, some 290,000 people were employed both directly and indirectly in the wine industry in 2015, including farm labourers, and those involved in packaging, retailing and wine tourism.

The study estimated that, of the R36.1 billion GDP contributed by the wine industry to the regional economy, about R19.3 billion would eventually remain in and benefit the Western Cape (WOSA, 2018; Vinpro, 2015). Wine grapes are widely produced under irrigation, but areas where grapes are produced under rainfed conditions exist.

In the 2014/15 season, the production of raisins reached a record level of 63,000 tons. This was the result of favourable weather conditions, the expansion of the area planted and the diversion of wine grapes to raisin production, caused by low prices for wine grapes (Sikuka, 2015). The most recent statistics indicate that the production was 65,589 tons for 2018, up 4.1% from 2014 (Dried Fruit Technical Services, 2018). Most raisins produced in South Africa are exported, with a total of 55 675 tons exported in 2018 (85% of the total crop). The value of raisins marketed internationally in 2018 was estimated at R19 827/t or R1,903 million (Dried Fruit Technical Services, 2018). Raisins are mainly produced along the Orange River in the Northern Cape due to its ideal dry climate (Sikuka, 2015). In 2014, the area under raisin grape production reported by Hortgro (2014) was 14,317 ha in the Orange River Region and 1,519 ha in Namaqualand, respectively. The most recent statistics indicate 12,603 ha under raisin grape production in 2018, including the cultivars Thompson Seedless, Merbein Seedless, Corinth and Flame Seedless (Dried Fruit Technical Services, 2018), but excluding other table grape cultivars used for raisin production and included in the Hortgro statistics of 2014.

This study only focused on table grape and wine production in the Western Cape where most grapes are produced. Raisin production was excluded from the water footprint analysis.

1.1.3 Consumer awareness and sustainability

In recent years, wine sustainability has been growing very rapidly in popularity. Farmers, producers, marketers and research institutes in the wine industry seem to be interested and involved in making wine production more sustainable. It is not clear to what extent consumers pay attention to organic labels or value sustainable wines (Sogari et al., 2014). Some research has suggested that consumers are becoming increasingly concerned with the effects of conventional agricultural food production practices on human health and environmental wellbeing. A study conducted in New Zealand analysed whether environmentally sustainable practices in the vineyard would equate to advantages in the wine marketplace. The results indicated that consumers have a strong demand for wine produced through green production practices. Consumers believe that the quality of sustainable wine will be equal to or better than conventionally produced wine, and they are prepared to pay a higher price for such wine (Forbes et al., 2009).

Given the recent increase in consumer awareness and preference for sustainably produced products, more focus is placed on indicators that can measure and report on the degree of sustainability with which the products are produced. Therefore, for any study on sustainable agriculture, the question arises as to how agricultural sustainability can be measured. Some argue that the concept of sustainability is a “social construct” (David, 1989; Webster, 1999, in Hayati et al., 2010) that is yet to be made operational (Webster, 1997, in Hayati et al., 2010). The precise measurement of sustainability is impossible as it is a site-specific and dynamic concept (Ikerd, 1993). To some extent, what is defined as sustainable depends on the perspectives of the analysts (Webster, 1999, in Hayati et al., 2010). Although precise measurement of sustainable agriculture is not possible, when specific parameters or criteria are selected, it is possible to say whether certain trends are steady, increasing or decreasing (Pretty, 1995, in Hayati et al., 2010).

Focusing more specifically on water use, the water footprint has become an increasingly popular method of analysing environmental issues associated with the consumption of water resources in the global supply chain of consumer goods (Feng et al., 2011). The water footprint is an indicator used to measure the degree of sustainability with which freshwater is used to produce consumer goods, measured along the whole supply chain of the product.

1.2 AIM AND OBJECTIVES

Given the importance of the available water resources, their use in the production of table grapes and wine in South Africa and the importance of ensuring the sustainability of these industries and investigating indicators of sustainability, the WRC, together with Winetech, co-funded research into the water footprint of wine and table grapes produced in South Africa.

The project assessed the water footprint of table grapes and wine produced in South Africa. This project had the following specific objectives:

- Review how water footprint methodologies can be applied to table and wine grape production.
- Apply the water footprint for selected and representative grape commodities and products, and make recommendations for improvement.
- Develop and demonstrate a procedure whereby WFA can be carried out through the utilisation of spatial datasets.
- Propose a set of guidelines that industries or organisations can follow for implementing WFA within their organisations or industries.
- Promote the benefits of a WFA to industries.
- Build capacity and competence in WFA in the wine and table grape industries.

Initially, this project was designed to be executed over a four-year period (2017 to 2021). However, in agreement with the WRC and Winetech, the project scope (and contract) was altered in March 2019 to enable the completion of the project at an earlier date (at the end of 2019).

This resulted in two main changes:

- A revised project scope, where the detailed economic valuation and sustainability assessment components of this project, which typically form part of a complete WFA, were removed
- A shortened project time frame to allow for the completion of the project by the end of 2019, while still meeting the set objective outlined above

1.3 STRUCTURE OF THE REPORT

A brief introduction to this study and its aim and objectives were given Chapter 1. The importance of water and the table grape and wine industries and their sustainability were described.

Chapter 2 reviews knowledge related to table grape and wine production in South Africa in detail, including the range in production regions and conditions, cultivars cultivated and economic value. The different methodologies for WFA are also reviewed, the benefits of WFA are explored and examples of WFA studies related to table grape and wine production are listed. Spatial technologies and data in support of WFA are also described.

The WFA approach and framework employed in this research are described in Chapter 3. The case studies, study area and data considered are all defined.

Chapter 4 describes some research aspects explored in this project, illustrating the use of large data sets and spatial technologies to support a WFA framework, while Chapter 5 outlines the water footprint results for table grapes and wine.

Chapter 6 concludes the report with remarks relating to the research and recommendations for future research activities.

CHAPTER 2: KNOWLEDGE REVIEW

2.1 GRAPE AND WINE PRODUCTION IN SOUTH AFRICA

2.1.1 Table grape industry

An overview is provided of the table grape industry of South Africa, outlining the wide range of cultivation conditions. Much of what is included below has been summarised from Avenant (2017) and SATI (2019a).

2.1.1.1 Production regions

Table grapes are produced in five production regions situated across South Africa. The South African Table Grape Industry (SATI, 2019a) gives a summary of the area under cultivation for table grapes in South Africa, which comprised 21 798 ha in total for 2018 (SATI, 2019a). Table grapes are commercially produced in the winter rainfall region of the Western Cape (the Hex River Valley, Berg River Valley and Olifants River Valley regions) and the Little Karoo, as well as in the summer rainfall region of South Africa (the Lower Orange River and Northern Provinces regions) (see Figure 2.1).

On the basis of the number of hectares cultivated and the volume exported, the two most important table grape production regions are the Hex River Valley in the Western Cape and the Lower Orange River Region (Van der Merwe et al., 1997; OABS, 2006; Anon, 2007; SATI, 2019a). Groblersdal/Marble Hall is the most important region for table grape production in the northern summer rainfall region (SATI, 2019a) (see Figure 2.1).

The table grape-growing regions of the Western Cape are subdivided into several sub-regions according to harvest dates, ranging from early to late harvesting dates. These sub-regions are described below.

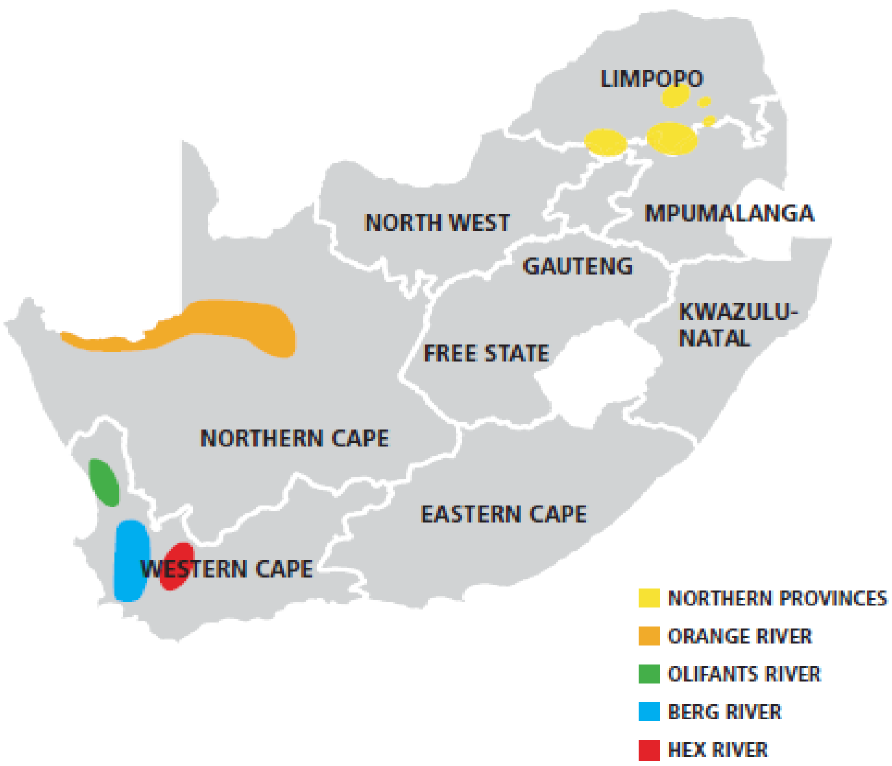


Figure 2.1: Table grape production regions of South Africa (SATI, 2018)

2.1.1.1.1 Olifants River Valley

The Olifants River Valley region stretches from Citrusdal to Lutzville. It is classified as semi-arid to arid. In terms of climate and ripening time, the Olifants River Valley is intermediate between the Orange River and Berg River Valley regions. In this region, the harvest season starts in the middle of December and continues until around the end of January.

In 1997, 467 ha of table grapes had already been cultivated in this region, of which Thompson Seedless comprised 52.5% (Van der Merwe et al., 1997). In 2009, 530 ha was under table grape cultivation in this region, with the major cultivars being Thompson Seedless and Crimson Seedless. Table grape production in this region has increased rapidly in the last decade, and in 2018, 1 200 ha was under table grape cultivation. Despite the drought, 2.4 million 4.5 kg equivalent cartons of table grapes were exported from this region in the 2018/19 season (SATI, 2019a).

The region is dependent on water from the Olifants River irrigation scheme since rainfall is very low, which is a limiting factor for any additional expansion of table grape production. The long-term annual rainfall is only 213 mm, with an average maximum temperature of 28 °C and an average minimum temperature of 11 °C. Large temperature fluctuations occur, with heat waves that can damage grapes. The fluctuations between day and night temperatures are beneficial to the colour development of red and black cultivars.

2.1.1.1.2 Berg River Valley

The Berg River Valley includes Piketberg, Porterville, Saron, Riebeeck Kasteel, Paarl and Wellington. The proximity of the Cape Town harbour has always been an advantage for this region. In Piketberg, the climatic conditions are hot and dry (26 °C average maximum temperature, 11.7 °C average minimum temperature and 278 mm rain annually) and harvesting occurs early. Paarl has a wetter climate (25 °C average maximum temperature, 12.6 °C average minimum temperature and 772 mm rain annually) and a later harvesting season.

The total area under table grape production remained constant from 2005 to 2009 (3 600 ha), with an increasing focus on seedless cultivars over time. In 2018, the total area under table grapes was 5 210 ha, and in the 2018/19 season, 13.8 million 4.5 kg equivalent cartons of table grapes were exported from this area (SATI, 2019a).

2.1.1.1.3 Hex River Valley and Worcester

The Hex River Valley produces the most table grapes in South Africa. Table grapes have been cultivated in this valley for over 100 years. The region has a dry summer climate and ample irrigation water. The average maximum temperature of the region is 24 °C, with an average minimum temperature of 9 °C and a long-term average annual rainfall of 175 mm. It has the longest harvesting period in the country, with the season starting in January and continuing until May. Although the Hex River Valley is the centre of this growing region, other smaller growing areas, such as Brandwag, De Wet, Nonna and Nuy, also form part of this production region.

In 1997, 4 577 ha of table grapes, including Barlinka (27%), Dauphine (22%), Alphonse Lavallée (10%), La Rochelle (7%), Waltham Cross (6%) and Sunred Seedless (6%), was cultivated in the region. In 2018, approximately 6 600 ha of table grapes was under cultivation, with the major cultivar being Crimson Seedless. In the 2018/19 season, 18.6 million 4.5 kg equivalent cartons of table grapes were exported (SATI, 2019a).

2.1.1.2 Cultivars

The South African Table Grape Industry (SATI, 2019a) gives a summary of the most planted table grape cultivars cultivated in South Africa. Exports per cultivar group in the 2018/19 season were 30% white seedless, 48% red seedless, 5% red seeded, 13% black seedless, 2% black seeded and 1% white seeded (more than 80% seedless in total). According to SATI's 2019 statistics, Crimson Seedless is the most planted cultivar, followed by Prime, Thompson Seedless, Tawny Seedless, Sugranineteen (Scarlotta Seedless®), Sugrathirteen (Midnight Beauty®), Flame Seedless, Grapaes (Early Sweet®), Sugraone and Redglobe.

Several research projects assessed the water use or actual evapotranspiration (ET_{act}) of table grapes. The studies involved different cultivars grown under different conditions. The results listed below show the wide range in actual water use. For example, ET_{act} was estimated to be as follows:

- 256 (low-frequency drip irrigation) to 492 mm (daily pulse drip irrigation) for Dan-ben Hannah produced in the Berg River Valley (Myburgh and Howell, 2012)
- 411 (drip irrigation) to 569 mm (micro-irrigation) for Barlinka produced in the Hex River Valley (Saayman and Lambrechts, 1995)
- 663 (Myburgh, 1996) to 741 mm (Fourie, 1989) for Barlinka under micro-irrigation in the Hex River Valley
- 879 mm for Sunred Seedless and Muscat Supreme under micro-irrigation in the Hex River Valley (Myburgh and Howell, 2007b)
- 655 to 1 348 mm for micro-irrigated Sultanina in the Orange River Valley (Myburgh, 2003b)
- 854 to 1 343 mm for flood-irrigated Sultanina in the Orange River Valley (Myburgh, 2003a)

This range in ET_{act} is reflected in the range in the irrigation applied to grow table grapes. According to a survey conducted, Avenant (2017) found that irrigation applied to table grape vineyards vary greatly across the production regions. These values are summarised in Table 2.1 and represent the average of various cultivars.

Table 2.1: Irrigation applied per production region (Avenant, 2017) where a full water allocation is available

Production region	Rainfall region	m^3 per ha per season
Berg River Valley	Winter	7,358 to 7,414
Olifants River Valley	Winter	11,100 to 13,200
Hex River Valley	Winter	4,598 to 10,560
Lower Orange River	Summer	12,301 to 18,634
Northern Provinces	Summer	4,710 to 8,402

2.1.1.3 Grape production

In the 2018/19 season, 274,950 t of table grapes (61.1 million 4.5 kg equivalent cartons) was produced in South Africa for export alone (SATI, 2019a). In 2016, there were 382 registered table grape production units (farms) in South Africa (SATI, 2016). At present, the South African table grape industry is employing 12,600 permanent and 61,200 seasonal workers (SATI, 2019a). This industry is export-driven, with more than 90% of the crop produced being exported. The three major export markets for South African table grapes are the European Union (51%), the United Kingdom (24%) and the Far East (6%). South Africa is the sixth-largest exporter of table grapes in the world (representing 6.6% of the value of total global exports in 2018/19) and the third-largest exporter in the southern hemisphere. Chile, Peru and South Africa contributed 49%, 29% and 20%, respectively, to the total volume of table grape exports from the southern hemisphere in the 2018/19 season.

2.1.2 Wine industry

An overview of the wine industry of South Africa, outlining the wide range of cultivation conditions, is provided. Much of this information was taken from Wines of South Africa (WOSA) (2020) and SAWIS (2018).

2.1.2.1 Wine of origin regions

Wine grapes are produced in different provinces across South Africa, with most wine grapes produced in the Western Cape. The production regions can be defined according to the Wine of Origin (WO) system. The WO programme legislates how the wine regions of South Africa are defined and can appear on wine labels. The WO system makes provision for different layers, with the geographical unit (province) overlaying the overarching region, region, district and ward (Wine and Spirit Board of South Africa, 2019). According to the WO system, there are five production regions in the Western Cape: the Cape South Coast, the Coastal Region, the Breede River Valley, the Klein Karoo and the Olifants River (Figure 2.2).

According to SAWIS (2018), a total area of 117,808 ha is currently under grape cultivation. The Stellenbosch and Paarl regions have the largest areas under vines at 16.19 and 15.87%, respectively, followed by Swartland (13.81%), Robertson (13.75%), Breedekloof (13.55%), Olifants River (10.42%), Worcester (6.99%), Northern Cape (4.14%), Cape South Coast (2.83%) and Klein Karoo (2.44%).

Each WO production region has different characteristics. Only the WO regions considered in this study are described briefly below.

2.1.2.1.1 Breede River Valley

The Breede River Valley WO region includes the districts of Breedekloof (~13.75%), Robertson (~13.55%) and Worcester (6.99%), and is the largest in terms of wine-growing hectares (~34.29%). The Breedekloof district is characterised by vineyards that flourish on alluvial valley soils with adequate drainage as they rest on a bed of river stones. It covers a large proportion of the Breede River Valley and its tributaries. There are marked variations between the soils and meso-climates in the different river valleys. This district incorporates the Goudini and Slanghoek wards (WOSA, 2020).

Robertson lies in the Breede River Valley. Although the summer temperatures can be high in this region, cooling south-easterly winds channel moisture-laden air into the valley. Robertson is renowned for the quality of its wines (WOSA, 2020). Traditionally known for its white wines (Chardonnay and Sauvignon Blanc), it is also the source of some of the Cape's finest red wines (Shiraz and Cabernet Sauvignon). Fortified dessert wines continue to be produced in this region. The district of Robertson incorporates 14 wards, including Ashton and Bonnievale.

Worcester is the most important brandy-producing area and home to the largest distillery of its kind in the southern hemisphere (WOSA, 2020). Several cellars in this district bottle quality wines under their own labels. This district comprises four wards.

2.1.2.1.2 Olifants River Valley

This region stretches in a belt from north to south along the broad valley of the Olifants River. The summers in this valley range from relatively warm to cool and rainfall is low. Soils vary from sandy to red clay loams. With careful canopy management, which ensures that grapes are shaded by the vines' leaves, combined with modern winemaking techniques, the Olifants River Valley is proving to be a source of quality, affordable wines. The soils are mainly sandy alluvial soils from the surrounding Table Mountain Sandstone in the southern part of the valley up to Clanwilliam. The Clanwilliam Dam provides high-quality irrigation water.

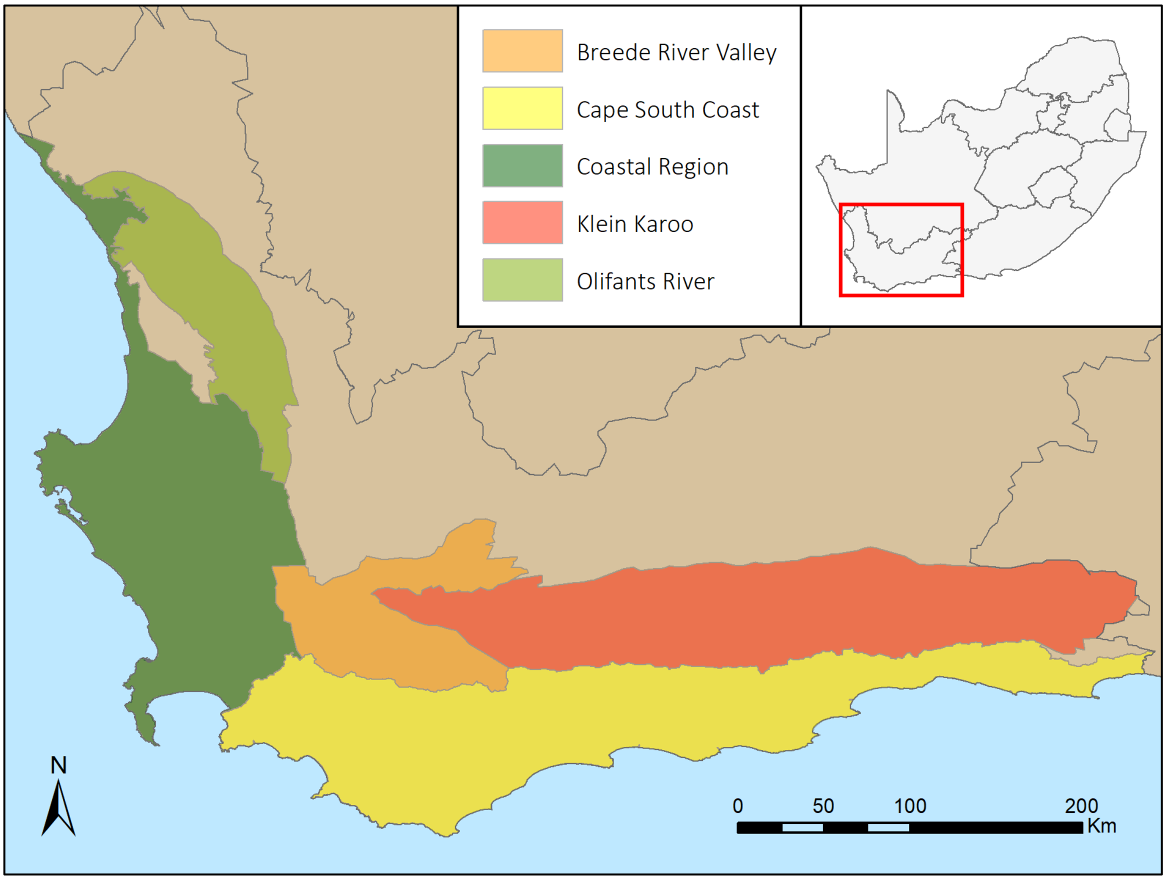


Figure 2.2: Wine of Origin map (Version April 2019) outlining the wine-producing regions of the Western Cape

2.1.2.1.3 Coastal Region

The Coastal WO region includes the districts of Cape Town, Darling, Franschhoek and Franschhoek Valley, Paarl, Stellenbosch, Swartland, Tulbagh, Wellington and the Lutzville Valley. The largest districts in terms of hectares are Stellenbosch (16.19%), Paarl (15.87%) and Swartland (13.81%) (SAWIS, 2018).

The mountainous terrain of Stellenbosch, good rainfall, deep, well-drained soils and the diversity of terroirs make this a sought-after viticulture area. This district hosts a rapidly increasing number of wine estates, and producers (~170) produce almost all the noble grape varieties. The area is known for the quality of its blended reds (SAWIS, 2018; WOSA, 2020).

The Paarl wine district lies to the north of Stellenbosch. The Berg River runs through Paarl and is the life-giving artery of this wine-producing area. The valley land requires supplementary irrigation in the hot growing season before the harvest, but vineyards on the eastern slopes, having better water retention, often do not require irrigation. A large variety of grapes is grown in Paarl, of which Cabernet Sauvignon, Pinotage, Shiraz, Chardonnay and Chenin Blanc are important cultivars (WOSA, 2020).

The Swartland wine district includes the wards of Malmesbury, Paardeberg, Paardeberg-South, Riebeekberg, Riebeeksrivier and St Helena Bay. Parts of this district are situated along the banks of the Berg River and others are situated at the foothills of the mountains. Some award-winning red and white wines have emerged from this district in recent years, in addition to port-style wines. Pinotage, Shiraz and Cabernet Sauvignon are grown here, as well as Chardonnay, Chenin Blanc and Sauvignon Blanc (WOSA, 2020).

2.1.2.2 Climate

Viticulture mainly takes place at a latitude range of 27 to 34° south in an area with a Mediterranean climate (WOSA, 2020). The Western Cape is cooler than its position might suggest, with conditions that are ideal for growing a wide range of noble wine cultivars. The traditional wine-growing areas along the coastal zone are seldom more than 50 km from the ocean and experience beneficial coastal conditions, especially cool sea breezes. The temperate climate features warm summers and cool winters. Frost is rarely a problem (WOSA, 2020).

Rain falls mainly between May and August, and diminishes in a northerly and northwesterly direction, caused by the cold Benguela current along the west coast and the prominent mountain ranges that follow the coastline, making irrigation essential in many areas. Temperature is probably one of the most influential factors in grape production as it influences almost every aspect of the vines' functioning. Temperatures follow an inverse pattern to rainfall, increasing in a northerly direction and with distance from the sea (WOSA, 2020).

2.1.2.3 Cultivars and wine styles

A wide range of white and red varieties is cultivated in South Africa. White wine varieties constitute 55.6% of the plantings for wine, while red wine varieties comprise 44.4% (SAWIS, 2018). In 2018, the most important white wine cultivars in terms of area were Chenin Blanc (18.2%), Colombar(d) (11.8%), Sauvignon Blanc (9.6%), Chardonnay (8%) and Muscat d'Alexandrie (2.1%). The most important red wine cultivars in terms of area were Cabernet Sauvignon (12%), Shiraz (10.3%), Pinotage (6.5%), Merlot (6.4%) and Ruby Cabernet (2.2%). A full list of white and red wine cultivars is available on WOSA's website (WOSA, 2020).

The wide range of varieties cultivated in South Africa is used to produce a range of wine styles (WOSA, 2020). These wine styles include the following:

- Alternative white/red wines
- Blanc de Blancs
- Blends, consisting of the following:
  - Cuvée
  - Red blends: the Bordeaux style, the Shiraz-led Rhône style and the "Cape-blend" style (the latter requires 30 to 70% of Pinotage as a component)
  - White blends: Bordeaux-style blends (Sauvignon Blanc and Semillon) and Chenin Blanc-led Mediterranean-style blends
  - Extended barrel-aged white/gris
  - Fumé blanc
- Fortified/dessert wines, e.g. Hanepoort, Jerepiko/Jerepigo, Muscadel and sun wines
- Méthode Cap Classique (MCC) and sparkling wines
- Natural wines
- Rosé wines
- Port- and sherry-style wines

2.1.2.4 Grape and wine production

In 2018, South Africa had 2,873 primary grape producers, 542 wine cellars that crush grapes and 121 bulk wine buyers (SAWIS, 2018). About 41% of the primary grape producers produced up to 100 tons of grapes, 31% produced between 100 and 500 tons, 21% produced between 500 and 10,000 tons, and 7% produced more than 10,000 tons. Some 86% of the wine cellars are classified as private wine cellars, with the remaining percentage split between producer cellars (9%) and producing wholesalers (5%) (SAWIS, 2018).

In 2018, 1,243,597 tons of grapes were crushed in South Africa: 64% was from white varieties and 32% from red varieties. The remaining fraction (4%) came from table grapes. From this, 960.2 million litres of wine or juice was produced: 86% for wine, 3.8% for brandy, 9% for distilling wine, and the remainder for grape juice concentrate and grape juice. The litres of wine produced was divided into 63% white wine and 37% red wine (SAWIS, 2018).

2.2 METHODOLOGIES FOR WATER FOOTPRINT ASSESSMENT

2.2.1 Origin of approaches

The concept of virtual water and the water footprint indicator has been developed over many years, with the concept defined in the 1990s. The concept of virtual water was first introduced by Allan (1997; 1998; 2002). It was defined as the water volume required to produce products or services during the production processes and not only the volume directly present in products (i.e. the "virtual" content). The concept was further developed by Hoekstra and Hung (2002), Chapagain and Hoekstra (2003), Hoekstra (2003), Oki et al. (2003), Zimmer and Renault (2003) and De Fraiture et al. (2004), who quantified the global virtual water flows. In particular, the virtual water concept was closely related to the water footprint, where the latter was introduced to account for the appropriation of natural capital in terms of the water volumes required for human consumption (Hoekstra, 2015). The water footprint concept therefore analyses all links between human consumption and water use (both directly and indirectly embedded in products and services).

The water footprint concept has grown since its first introduction by Hoekstra (2003). Ultimately, the aim of the water footprint is to investigate the sustainability of freshwater use by comparing the water footprint with freshwater availability (Hoekstra and Mekonnen, 2011; Hoekstra et al., 2012).

2.2.2 Water footprint assessment frameworks

There are two schools of thought regarding the water footprint as a sustainability indicator. They differ in terms of the way in which a water footprint is defined and the way in which it is calculated and the values interpreted. The first is generally known as the Global Water Footprint Standard or GWFS (Hoekstra et al., 2011), while the second approach is known as the water footprint assessment or WFA through life cycle assessment (LCA) (Ridoutt and Pfister, 2010).

2.2.2.1 Water footprint as per the GWFS

The concept of the water footprint provides a suitable framework of analysis with which to find the link between the consumption of agricultural goods on the one hand and the use of water resources on the other. The water footprint is an indicator of the indirect and direct appropriation of freshwater resources, thus referring to the total volume of freshwater that is used to produce a product, measured along the full supply chain, with the aim of investigating the sustainability of freshwater use. Importantly, while a large part of a WFA focuses on calculating the volume of water used to produce a product (volumetric water footprint indicator), the aim of a comprehensive WFA is rather to assess the degree of sustainability with which freshwater is used to produce the particular product (Mekonnen and Hoekstra, 2010). As such, the volumetric water footprint indicator is to be interpreted in the context of water availability to determine whether the freshwater resource is used sustainably. Hoekstra et al. (2011) emphasised that the water footprint is regarded as a comprehensive indicator of freshwater use and should be used along with traditional and restricted measures of water withdrawal.

A WFA, as per the GWFS approach, is divided into four distinct phases, which add more transparency to the methodology and help stakeholders understand the process:

- The first phase involves setting the scope and goal(s) of the assessment. This step is important because it will determine how the assessment will be approached.
- The second phase is where data is collected and actual calculations are made.
- The third phase involves a sustainability assessment where the WFA is evaluated from an environmental, economic and social perspective.
- The fourth phase is a conclusion of the first three phases, as well as the formulation of response options and strategies (Hoekstra et al., 2011).

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

- A blue water footprint (WF_{blue}) refers to the surface and groundwater that is "consumed" along the value chain of a product and therefore reflects the loss of surface or groundwater from a catchment. Losses can occur through incorporation into a product, evaporation or when the water returns to a different catchment or the sea.
- A green water footprint (WF_{green}) refers to rainwater that is evaporated or incorporated into a product and does not become runoff.
- Polluted water needs quantities of freshwater to assimilate the load of pollutants to acceptable standards. A grey water footprint (WF_{grey}) refers to the volume of freshwater that is required to dilute polluted freshwater along a product supply chain for this water to meet the specified quality standards once again.

Hoekstra et al. (2011) described different types of water footprints that can be assessed to determine the impact of human behaviour on sustainable water use. Hence, a water footprint analysis can be performed for several different entities. Depending on the scope of analysis, these entities can include a processing step, a product, a consumer or group of consumers, business or business sectors, or a specified geographical area (Hoekstra et al., 2011).

The water footprint of a product is the total volume of freshwater used, directly or indirectly, to produce a product. It is determined by considering the water consumption and pollution in all the steps or processes of the production chain. It can include freshwater that is consumed, evaporated or transpired, or incorporated into the product. A product water footprint shows the pressure that a product puts on freshwater resources. It can be measured in cubic metres (m^3) of water per tonne (t) of production. The water footprint of a product is a multidimensional indicator as it does not only refer to the virtual water of a product, but also to the type of water that was used (green, blue or grey) and where and when the water was used. Virtual water includes all the water evaporated during the production process and incorporated into products, and includes both blue and green water.

A consumer's water footprint is defined as the total volume of freshwater used and polluted to produce goods and services used by consumers. The water footprint of a group of consumers is equal to the sum of the water footprints of individual consumers. The water footprint of a consumer is calculated by adding the direct water footprint of the individual and their indirect water footprint.

The water footprint of a geographical area is defined as the total volume of freshwater used and polluted within the boundaries of the area. The area can include catchments and river basins, a province, a state or nation, or any other hydrological or administrative spatial unit. The water footprint within a geographically delineated area is calculated as the sum of the process water footprint of all water-using processes in that area.

The water footprint of a business, also known as an organisational or corporate water footprint, is defined as the total volume of freshwater that is used directly or indirectly to run and support a business. It consists of an operational (direct) and supply chain (indirect) component. The water footprint of a business, therefore, considers the volume of freshwater consumed or polluted due to the operations of the business and the volume of freshwater consumed or polluted to produce all the goods and services that form part of the inputs of production of the business. When dealing with the water footprint of a company or corporation, it is important to distinguish between the operational and supply chain water footprint. Often, due to policy issues, a company has either direct or indirect control over its operations and supply chain footprints.

The specific type of water footprint to calculate and the categories of water footprints to consider in the assessment depend on the aim and scope of the WFA.

2.2.2.2 Water footprint as per the life cycle assessment

Life cycle assessment is an applied environmental tool that provides a measure of various environmental indicators pertaining to agricultural produce (Berger and Finkbeiner, 2010; Berger and Finkbeiner, 2011). The water footprint, in accordance with the LCA approach, focuses on the impact of certain processes on the scarce freshwater resource. A water stress index is calculated to determine whether freshwater withdrawal exceeds the water body's replenishment (Roux et al., 2016). Importantly, the focus is only on the environmental impact, with no consideration of the social and economic aspects associated with the activity (Boulay et al., 2013). Pfister et al. (2009) suggest that a stress-weighted water LCA approach should be used to calculate the water footprint.

There are a few major differences between the water footprint conceptualised as the GWFS (Hoekstra et al., 2011) and the water footprint in the context of LCA. The LCA does not directly account for the green water footprint (Ridoutt and Pfister, 2010). It is assumed that green water is directly related to the occupation of land, and is hence accounted for elsewhere in the LCA. The LCA approach to water footprint assessment does not include a grey water footprint either, calculated through the dilution factor method, as done by Hoekstra et al. (2011). The deterioration of water quality is dealt with by means of other impact categories, such as eutrophication or freshwater eco-toxicity (Ridoutt and Pfister, 2010; Jefferies et al., 2012). Thus, the focus of WFA, as per the LCA approach, is solely on the blue water resource. Lastly, the focus of WFA according to LCA is on the environmental impact of a change in water and land use behaviour, with the water footprint being reported as water equivalents.

Based on the above, it is evident that there are significant differences between the two groups of scientists' conceptualisations of the water footprint. In order to address the differences, the International Standards Organisation (ISO) has endeavoured to establish a more standardised understanding of the water footprint concept. As a result, ISO 14046 (ISO, 2014) was published.

2.2.2.3 ISO 14046

The aim of the International Organisation for Standardisation is to ensure a form of consistency between different methodologies. This is achieved by standardising the terminology used in the various methods' calculations and reporting (ISO, 2014). More specifically, ISO 14046 (ISO, 2014) provides principles, requirements and guidelines for the quantification, reporting and critical review of water footprint assessments.

Jordaan et al. (2019) described the application of a water footprint assessment according to the GWFS and LCA approaches in the context of ISO 14046 (ISO, 2014). Some of the most important guidelines specified in ISO 14046 (ISO, 2014), as summarised by Jordaan et al. (2019), include the following:

- The term "water footprint" can only be used to describe the result of a comprehensive impact assessment. A water footprint is, in other words, the quantification of potential environmental impacts related to water (some prescriptions are included on how the term "water footprint" is to be used in situations where a full environmental impact assessment was not done).
- ISO 14046 (ISO, 2014) is applicable to products, services, processes and organisations, hence it accommodates an assessment of the impact of the production and consumption of a product or service, and processes and organisations on the freshwater resource.
- Several different water uses have been defined (i.e. consumption and degradation of freshwater).
- The water footprint can be reported as one value or as a profile of indicator results.

While ISO 14046 (ISO, 2014) aims to standardise the understanding and use of the term "water footprint", it is important to realise that ISO 14046 has the following characteristics:

- It does not prescribe the method to be used for calculating a water footprint, but rather serves as a guideline of what to include in a comprehensive WFA.
- It focuses solely on assessing the environmental aspects of sustainability.
- It does not police the use of the term "water footprint".

Given the difference between a WFA as per the LCA and GWFS, and the fact that ISO 14046 (ISO, 2014) only provides guidelines, Jordaan et al. (2019) made the following recommendations regarding the water footprint assessment:

- It is very important to clearly specify the aims and scope of the assessment to emphasise the purpose of the assessment.
- The method applied to conduct the WFA should be specified in order to guide the reader in the correct interpretation and use of the results.
- The specific data that was used must be clearly outlined.

Regardless of the approach that is followed, it is important to inform the user of the findings to allow the correct interpretation of the assessment. The following sections focus on the different methods available to determine or measure the water footprint of products.

2.2.3 Water footprint assessment estimation methods

2.2.3.1 Introduction

Several methodologies are available to calculate a water footprint. These include the following:

- A consumptive water use-based volumetric water footprint method proposed by the Water Footprint Network (WFN) (Hoekstra et al., 2011).
- The LCA, which only accounts for the blue water footprint, is based on the theory that green water use cannot be separated from the occupation of land and is accounted for elsewhere in the LCA.
- An approach by Milà i Canals et al. (2008), who consider green and blue water resources, further classifies blue water as groundwater (fund), fossil groundwater (stock) and rivers (flow).
- An approach by Deurer et al. (2011), who suggest the use of the hydrological water balance method (this approach determines blue, green and grey water footprints annually on a local scale and characterises the hydrological system by indicating all inflows and outflows, as well as storage changes).

2.2.3.2 Water footprint assessment for a product

Hoekstra et al. (2011) described the use of different types of water footprint to determine the impact of human behaviour on sustainable water use. Hence, there are different entities for which a water footprint analysis can be performed.

Depending on the scope of analysis, these entities can include a processing step, a product, a consumer or group of consumers, a business or business sectors, or a specified geographical area (Hoekstra et al., 2011).

For this project, the water footprint of a product has relevance. The water footprint of a product is the total volume of freshwater used, directly or indirectly, to produce a product (table grapes or wine in this project). The water footprint is determined by considering the water consumption and pollution in all the steps or processes of the "production" chain. It can include freshwater that is consumed, evaporated or transpired, or incorporated into the product. A product water footprint shows the pressure that a product puts on freshwater resources.

The GWFS approach distinguishes between the direct and indirect water use, as well as the different types of water footprints. It shows that the return flow, which is the non-consumptive part of water withdrawals, is included in the footprint. It further illustrates that the water footprint concept includes consumptive blue and green water footprints that do not become runoff or return to the original catchment, as well as the grey water footprint that accounts for polluted water. This is for both direct and indirect water use. Determining the water footprint of a product starts with determining the water footprint of each process along the value chain (process water footprint), after which the total water footprint is calculated from all the respective process water footprints. Figure 2.3 provides a schematic representation of a water footprint in accordance with the GWFS approach (Hoekstra et al*.,* 2011).

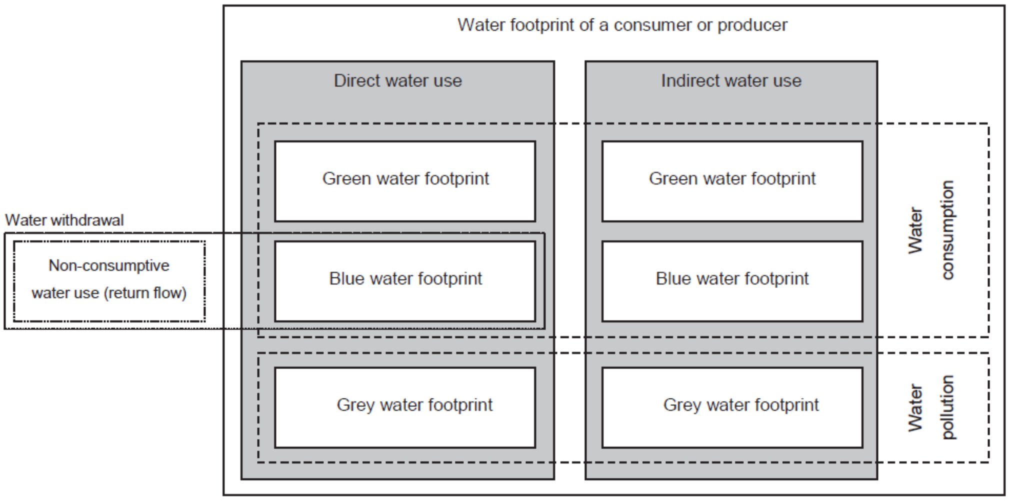


Figure 2.3: Schematic representation of a water footprint in accordance with the GWFS (Hoekstra et al., 2011)

The calculations of the water footprint are therefore done for the distinct sources of the water: blue, green and grey water.

Blue water footprint

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

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

Evaporation is often found to be the most significant component of blue water consumption. Consumptive use is therefore often equated to evaporation. Other components should, however, be included in consumptive use whenever relevant and possible. Consumptive use does not imply that the water "vanishes" from the hydrological cycle. Instead, it means that it is not immediately available for alternative use. The equation used to calculate the blue water footprint, as suggested by Hoekstra et al. (2011), is as follows (Eq. 2.1):

$WF_{proc,blue}$ = Blue water evaporation + blue water incorporation + lost return flow	*(2.1)*

Green water footprint

The green water footprint accounts for rainwater that does not become runoff, but is lost through evapotranspiration or incorporated into a product. Green water is further described as rainwater stored in the soil, which is only available for vegetation growth and transpiration. Hoekstra et al. (2011) noted that WF_{green} is the total volume of rainwater consumed during the production process. The authors further emphasised the importance of the green water footprint for agricultural and forestry production, where the WF_{green} refers to the total rainwater evapotranspiration from the fields, together with the water incorporated into the harvested crop. The equation to calculate the WF_{green}, as suggested by Hoekstra et al. (2011), is as follows (Eq. 2.2):

$WF_{proc,green}$ = Green water evaporation + green water incorporation	*(2.2)*

In agriculture, green water consumption can be physically measured, or it can be estimated with a model suitable for estimating the evapotranspiration of a specific crop based on input data on soil, crop and climate characteristics. Several such methods exist and are referred to in Section 2.5.1.3.

Grey water footprint

Polluted water requires quantities of freshwater to dilute the load of pollutants to acceptable standards. The volume of freshwater needed to reduce the pollutants to ambient levels is the WF_{grey}. The volumetric-based WF_{grey} does not include an indicator of the severity of the environmental damage of the pollution, but is simply a method to include the volume of water required to reduce the pollution to acceptable norms. Hoekstra et al. (2011) formulated the calculation of WF_{grey} as follows (Eq. 2.3):

$$WF_{proc,grey} = \frac{PL}{c_{max} - c_{nat}}$$	*(2.3)*

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

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

After calculating the WF_{blue}, WF_{green} and WF_{grey} of each process along the value chain, the total water footprint is calculated to get the total volume of water consumed to produce the product and deliver it to the end consumer. In this study, two processes were considered, with the water footprint at both the field level and production unit (packhouse and cellar) level calculated.

Two alternative approaches could be applied to calculate the WF_{total} of the final product. These are the chain summation approach and the stepwise accumulative approach (Hoekstra et al., 2011) and are discussed in more detail below. Normally, the chain summation approach is used when a single output product is produced, while the stepwise accumulative approach is used when more than one output product is produced.

The chain summation approach

Figure 2.4 is a schematic representation of this approach. Such cases, where one can simply divide the total water usage by the production quantity, rarely exist in practice.

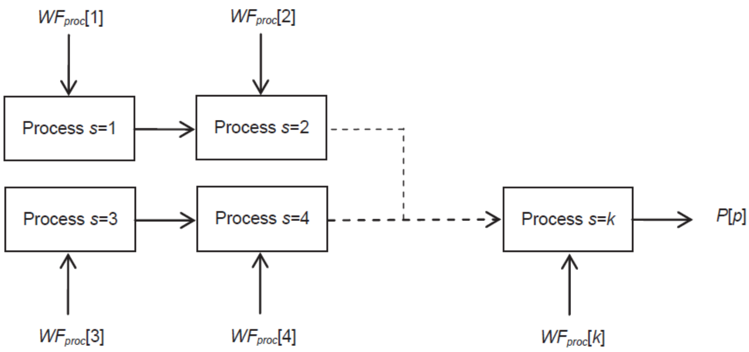


Figure 2.4: The chain summation approach (Hoekstra et al., 2011)

The calculation of the water footprint of a production system with a single output can be explained in terms of the water footprint of the product *p* ($WF_{prod}[p]$) (volume/mass). The calculated water footprint is equal to the sum of the relevant process water footprints divided by the production quantity of product *p* ($P[p]$) (Eq. 2.4):

$$WF_{prod}[p] = \frac{\sum_{s=1}^{k} WF_{proc}[s]}{P[p]} \qquad [volume/mass] \qquad (2.4)$$

The $WF_{proc}[s]$ is the process water footprint of process step *s*, as indicated in Figure 2.4, and is therefore calculated for each process step along the complete value chain of the product.

The stepwise accumulative approach

A more generic approach to calculate the water footprint of a product is the stepwise accumulative approach, indicated in Figure 2.5. In production systems with complex input and output combinations, the water footprint can only be calculated by using the proportional water footprints of the varying inputs. If the production system depicted is considered, the water footprint of product *p* can be calculated as follows (Eq. 2.5):

$$WF_{prod}[p] = \left(WF_{proc}[p] + \sum_{i=1}^{y} \frac{WF_{prod}[i]}{f_p[p,i]}\right) \times f_v[p] \qquad (2.5)$$

$WF_{prod}[p]$ is the water footprint (volume/mass) of output product *p* and the water footprint of input *i* is represented by $WF_{prod}[i]$. The process water footprint of the processing step is denoted by $WF_{proc}[p]$, and it transforms the *y* input products into the *z* output products. The $f_p[p,i]$ parameter is known as the “product function”, while $f_v[p]$ is a “value function”. The value function of input *p*, $f_v[p]$, is defined as the ratio of the market value of the input products in relation to the aggregated market value of all the output products (from $p = 1$ to $p = z$) (Eq. 2.6):

$$f_v[p] = \frac{price[p] \times w[p]}{\sum_{p=1}^{z}(price[p] \times w[p])} \quad (2.6)$$

In the above equation, price [*p*] represents the price of the output product *p* (monetary unit/mass). The summation in the denominator is done over all z (the output products) that are produced in the considered production process. Output product *p*'s product function is defined as the quantity of the output product (*w*[*p*], mass), produced per quantity of input product (*w*[*i*], mass) (Eq. 2.7):

$$f_p[p,i] = \frac{w[p]}{w[i]} \qquad [mass/mass] \quad (2.7)$$

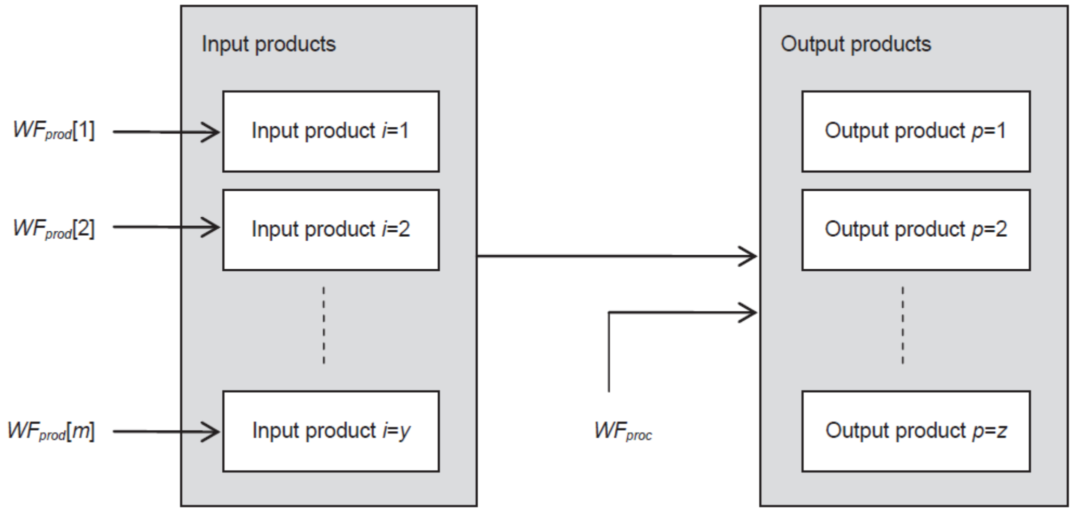


Figure 2.5: The stepwise accumulative approach (Hoekstra et al., 2011)

2.3 EXAMPLES OF THE WATER FOOTPRINT ASSESSMENT OF TABLE GRAPES AND WINE

The wine industry is one of the most innovative and competitive industries on a global scale; even so, the environmental issues of this industry remain poorly perceived (Costa et al., 2016). The exploitation of natural resources is a matter of global concern, which requires improved policies and technology to attain sustainable production processes and services (Bonamente et al., 2015). In this section, examples of water footprint estimates for table grapes and the winemaking process are discussed with evidence from relevant literature.

Herath et al. (2013) evaluated the water footprint of a bottle of wine produced in New Zealand. Two regions with different climatic conditions (Marlborough and Gisborne) were selected and a water footprint analysis was done using different water footprint methods. These methods were evaluated in terms of impacts on local water resources, the usefulness of the metrics to key stakeholders in terms of ease of understanding, the ability to set targets to reduce the footprint, and the applicability in regulatory policy formulation.

The authors suggested that the water-balance method provided a better expression of the water footprint since the hydrological water-balance method to determine the water footprint considers all relevant liquid and vapour flows when assessing the net use of the resource (Deurer et al., 2011; Herath et al., 2013). At the farm level, this study used the soil-plant-water-atmosphere system model (SPASM). Irrigation volumes were collected from the growers and producers through the Sustainable Winegrowing New Zealand (SWNZ) initiative. The authors indicated that the WFN method and the two LCA-based methods were based on consumptive water use, and, because local evaporation is linked to local rainfall in the short run, assessing water use impacts based on water consumption alone can lead to unintended consequences (Herath et al., 2013; Deurer et al., 2011).

Herath et al. (2013) found that the water footprint of a bottle of wine was 742.5 ℓ/750 mℓ (constituting 82% WF_{green}, 10% WF_{blue} and 8% WF_{grey}) and 667 ℓ/750 mℓ (constituting 90% WF_{green} and 10% WF_{grey}) for the irrigated Marlborough and rainfed Gisborne regions, respectively. Herath et al. (2013) stated that the water footprint analysis, based on the WFN approach, provided a sensible measure of the impact of grape production because it represents useful information for setting measurable targets to reduce the impacts through the water footprint itself. In the context of resource regulators, such as the catchment water management area (CWMA), matching the demand to availability with the use of geohydrological modelling was useful for managing resources and tracking improvements.

In Sicily, Italy, the supply chain of six different wines from the same winery was evaluated using the newly developed water footprint methodology Valutazione Impatto Viticoltura sull'Ambiente (VIVA) and the WFN approach (Lamastra et al., 2014). For estimating the WF_{green}, the reference crop evaporation (ET_o), the crop coefficient (K_c), as well as the soil water stress coefficient (K_s) for the respective growth periods were used. To determine the WF_{blue} at field level, a farm survey was conducted to capture real consumption-use data, which was used instead of less accurate estimates. At the processing level, due to a lack of detailed data, the blue water footprint only considered the total amount of water used in the wine-making process (Lamastra et al., 2014). In the case of grey WFA using the WFN approach, the procedure as described in Hoekstra et al. (2011) was followed with a fixed percentage to predict nitrogen water body contamination. For the WFN assessment, the chain summation approach was employed to calculate the total water footprint of a bottle of wine. The results obtained from this assessment indicated that WF_{green} ranged between 74 and 99.6% when using the WFN and between 63.7 and 94.5% when using VIVA, while blue water ranged between 0.3 and 5.5% when using the WFN and between 0.2 and 5.4% when using VIVA. The WF_{grey} ranged between 0 and 22% when using the WFN and between 0 and 26% when using VIVA. Interestingly, the authors also explored the factors that contributed to a larger water footprint. The factors that had the greatest impact on the results included distance from the water supply body, fertilizer application rate and the amount and ecotoxicological behaviour of the active ingredients used. The authors concluded that, to reduce the impact of grapes on freshwater, the focus should be on vineyard management (Mekonnen and Hoekstra, 2010). According to the results by Lamastra et al. (2014), the WF_{green} accounted for more than 81.5% of the total water footprint in both methods. The authors also explored the factors that contributed to a larger water footprint. Like the above, the factors that had the greatest impact on the results included distance from the water supply body, fertilizer application rate and the amount and ecotoxicological behaviour of the active ingredients used. The authors concluded that, to reduce the impact of grapes on freshwater, the focus should be on vineyard management (Mekonnen and Hoekstra, 2010).

The new VIVA methodology detected differences between vines of the same winery, as well as water body contamination by pesticides application, whereas the WFN methodology only considered fertilizer application (Lamastra et al., 2014; Bonamente et al., 2015). Lamastra et al. (2014) concluded that the VIVA approach is an improvement on previous approaches and that it more adequately accounts for impacts related to wine production. The inclusion of local climatic information and specific scenario features and management options makes the method more sensitive to local conditions than previous methods (Lamastra et al., 2014; Bonamente et al., 2015).

The grey WFA also reflects both a precise water body contamination and the required virtual volume strictly related to the local situation (Lamastra et al., 2014; Bonamente et al., 2015). The results demonstrate that the water footprint estimates from VIVA are closely related to the farm condition. In the VIVA approach, nitrogen leaching (6%) was based on annual precipitation. In the WFN approach, an estimate of 10% was used and groundwater volumes exhibited in the farm scenario were not accounted for.

Similarly, Bonamente et al. (2015) evaluated the WF_{grey} of a typical red wine produced by a medium-sized Umbrian winery using the LCA. Water volumes of each stage were defined according to the ISO 14046 international standard. VIVA was implemented at the water footprint accounting phase. An effort was made to improve the methodological definition of the WF_{grey} assessment in order to overcome the limitations of the reference approach. However, limitations were noted. Firstly, grey water could only be accounted for when the pollutant concentration is greater than the limit concentration, which does not allow for a true reflection of different processes on the same reservoir (Bonamente et al., 2015; Lamastra et al., 2014). Secondly, only maximum runoff, leaching and drift dilution volumes imply that the water is capable of diluting pollutants present at different locations, such as underground and surface water. This may cause an underestimation of the volume effectively required (Bonamente et al., 2015; Lamastra et al., 2014).

Results indicated that the water footprint was found to be 3% higher when using the VIVA approach compared to when the WFN approach was used. When using the VIVA approach, the distribution of the different categories of water footprints was on average 98.3% green, 1.2% grey and 0.5% blue. Interestingly, the WF_{grey}, as calculated with the VIVA approach, was substantially larger when compared to the WF_{grey} calculated with the WFN approach (Bonamente et al., 2015; Lamastra et al., 2014). VIVA was considered to be more accurate than the WFN approach in assessing the WF_{grey} due to an upper and lower limit when considering runoff and leaching. The accuracy may be attributed to the more specific data included in the VIVA approach (Bonamente et al., 2015; Lamastra et al., 2014).

VIVA thus provides an alternative accounting method for WFA that uses more input data at the farm level and therefore a better appropriation of the water footprint of a product. However, if one stipulates the scope for WFA carefully, it is clear that any factor outside that scope would either increase or decrease the water footprint. Since VIVA uses data from a single production year, not necessarily monthly or daily, applying this method could be useful for raising awareness of WFA, highlighting the largest and lesser contributors to the overall water footprint and indicating site-specific water footprint reduction strategies.

Mekonnen and Hoekstra (2010), with the use of global data averages, determined the WF_{green}, WF_{blue} and WF_{grey} for crops and derived products for the period 1996–2005. This was done to raise awareness and to identify the most significant contributor to the overall water footprint of a product. The global WF_{total} of table grapes was found to be 607 m^3/t. Of this, 70% could be attributed to the WF_{green}, 15% to the WF_{blue} and 14% to the WF_{grey}. For wine grapes, the water footprint was 707 m^3/t, which consisted of 69.8% WF_{green}, 15% WF_{blue} and 14% WF_{grey}. Raisins had the highest global WF_{total} at 2,433 m^3/t (assuming a product function of 0.25). This WF_{total} consisted of 70%, 15.8% and 14% for WF_{green}, WF_{blue} and WF_{grey}, respectively.

Mekonnen and Hoekstra (2010) also documented the water footprint of products produced in different parts of the world. Without differentiating between table and wine grapes, the total water footprint of grapes at national levels was found to be 6,490.30 m^3/t for Spain, 3,693.72 m^3/t for France, 2,136.88 m^3/t for China, 639.93 m^3/t for South Africa, 547.77 m^3/t for Chile, 412.91 m^3/t for Germany, 410.0 m^3/t for Algeria, 356.30 m^3/t for Brazil and 247.85 m^3/t for Egypt, to mention a few. From these results, it is evident that the WF_{total} for grapes produced in Spain, France and China was three to seven times that of the global WF_{total} average, while the WF_{total} for Egypt and Brazil was half of the world average, and Algeria, Germany, Chile and South Africa were 57 to 90% of the total global average.

In semi-arid regions, water resource management has become a controversial issue, and most water resource experts admit that water conflicts are not caused by physical water scarcity, but rather by inadequate water management practices (Aldaya et al., 2010). In Spain, Aldaya et al. (2010) assessed the relationship between the virtual water trade and the water footprint of agricultural products. These authors looked at the crop area percentage of irrigated and rainfed agriculture within the Mancha region (crops occupying over 1% of land) and found that vineyards had the largest crop area percentage for both irrigated (51%) and rainfed agriculture (31%).

Only consumptive water footprints were considered in this study and the water footprint was assessed for a dry, average and humid year. Under dry conditions, the composition of the water footprint of grapes was a 15% green and a 85% blue water footprint. In an average year, this proportion changed to 29.5% green and 70.5% blue. Under humid conditions, the water footprint proportions were 87% green and 13% blue.

Ene et al. (2013) assessed the total water footprint of grape production within Iasi County, Romania, for a medium-sized winemaking industry. This study followed the WFN approach and focused on the actual economic and environmental perspective of WFA. Total crop water requirement, irrigation and effective rainfall requirements were estimated using the CROPWAT model. The WFA was conducted using climatic data from the National Institute of Meteorology and Hydrology. Crop coefficients for grapes were taken from the Food and Agricultural Organisation (FAO) (Ene et al., 2013). For this case study, it was assumed that 1 ℓ of wine is made from 1.3 kg of grapes and 2 ℓ of water, used mainly for washing and cleaning equipment. Wastewater flows in the production process were significantly treated before being disposed of, therefore there was no WF_{grey} or grey operational footprint (Ene et al., 2013; Hoekstra et al., 2011). Results indicated that the total water footprint of grapes (the viticulture part) in the Iasi Country for the period 2005 to 2008 was 1,401 m^3/t (double the global average). Of this, 82% was accounted to the WF_{green}, 15.1% to the WF_{grey} and 2.8% to the WF_{blue}. For the vinification part, it was estimated that 2 ℓ of water was used per litre of wine produced, which added 2% to the total water footprint of a litre of wine.

The literature clearly indicates that climatic conditions are critical in estimating the total water footprint of table and wine grapes. Spatio-temporal data per production region per season better explains the derived water footprints per region and time.

2.4 IMPORTANCE AND BENEFITS OF A WATER FOOTPRINT ASSESSMENT

Literature indicates that performing a WFA throughout the winemaking process highlights the importance of the objective quantification of this industry's environmental impact, particularly on water. Different water metrics that involve the precise quantification of water inputs and outputs make it easier to assess the economic and environmental performance of vineyards and the winery (Costa et al., 2016). It also makes it possible to predict future water needs and expenses under favourable and unfavourable scenarios that would most likely be caused by stricter environmental rules.

In California, a water sustainability matrix helped to increase water productivity, reduce cost and increase sustainability (Costa et al., 2016). In New Zealand, water use benchmarks were established by local vineyards and wineries through individuals' submissions of water use information to the SWNZ and subsequent availability to its members (Costa et al., 2016; Herath et al., 2013). Similarly, in Australia and Portugal, vineyards provide water use benchmarks where parameters such as yield, crop water use efficiency, returns per water applied, cost of water per ton of fruit, irrigation efficiency, yield per volume of drainage and cost of drainage are taken into account to establish benchmarks (Costa et al., 2016). This helped improve efficiency because of a set standard and a reference point, which a WFA provides. The process of articulating and assessing the water footprint of a product, process and ultimately an organisation is driven by the requirement to provide a widely applicable and acceptable tool that is able to guarantee transparency and credibility (Bonamente et al., 2015; Lamastra et al., 2014).

An increased number of governments and companies are realising that performing a WFA and reducing water footprints are good corporate governance policies that should feature in a corporate environmental strategy (Aldaya et al., 2010; Hoekstra et al., 2011). With this said, it is essential that site-specific information on the water footprint of agricultural products is available since the water footprint is heavily influenced by climatic variability, different agronomic strategies (irrigated and non-irrigated) and the genotype of the crop being produced. Popularised values for a WFA for a commodity can conceal deviations between regions and may mislead consumers and authorities (Costa et al., 2016). This emphasises the importance of using the highest level of spatio-temporal detail for a WFA (Hoekstra et al., 2011).

The WFN aims to aid decision makers to improve water stewardship and make efforts towards longer-term sustainable water consumption (Lamastra et al., 2014). When the link between consumption and water use is determined, a system with new strategies for water governance can be developed. Integrating all critical drivers is crucial to defining policies for wise water governance and helping policy makers understand the long-term consequences of their decisions across political and administrative boundaries (Ercin and Hoekstra, 2013).

Business transparency in the 21st century is a crucial aspect for consumers who increasingly make well-informed decisions on purchases (Costa et al., 2016). For consumer perspective and marketing, it is important that wine industries develop appropriate frameworks to help consumers differentiate between sustainable and non-sustainable products in order to avoid classification under terms such as green and organic, which have been largely misunderstood and incorrectly used (Costa et al., 2016).

2.5 TECHNOLOGIES IN SUPPORT OF WATER FOOTPRINT ASSESSMENT

2.5.1 Geospatial technologies and machine learning for WFAs

A WFA requires information on crop water use or evapotranspiration and crop production (yield) at a range of spatial and temporal scales, which is not always readily available. The following sub-sections briefly summarise advances made in evapotranspiration and yield estimations using remotely sensed data relevant to this study. The section concludes with an overview of recent applications of remote sensing for WFAs.

2.5.1.1 Geospatial technologies

Geospatial technologies, such as GIS and RS, are often employed to support WFA. GIS is used to manage and analyse spatially referenced or geographical data (Heywood et al., 2006) and provides quick and easy access to large volumes of data for analysis purposes. Over the last 20 years, GIS has developed into a mature technology and has been shown to have value in answering questions about location, patterns, trends, conditions and their implications.

Datasets of different formats at varying scales can be incorporated into a single GIS database. These datasets may be stored as vector and/or raster data and enable spatial modelling, which involves constructing models to predict spatial outcomes that simulate the dynamics of natural processes (O'Sullivan and Unwin, 2010). Spatial modelling in GIS embraces techniques and models that apply quantitative structures to systems in which the variables of interest vary across space. Spatio-temporal models simulate change over time with the use of equations that represent real-world processes, while taking spatial patterns and spatial interaction of the system into account (Karssenberg et al., 2008). Such spatial and temporal process models can be used for decision making regarding spatial phenomena (spatial decision support systems), but are also used to evaluate our understanding of complex spatial systems (Heywood et al., 2006). Models can be used to establish (*a priori*) theory or explore (*a posteriori*) theory (Hardisty et al., 1993). When modelling in GIS, the questions of validation and the roles of scale and accuracy need to be carefully considered (Goodchild, 2005).

Remote sensing or earth observation is the practice of deriving information about the earth's land and water surfaces using images acquired from an overhead perspective by employing electromagnetic radiation in one or more regions of the electromagnetic spectrum reflected or emitted from the earth's surface (Campbell, 2007). Earth observation methods are complementary to GIS and allow for large-scale phenomena to be recorded at a certain time and over large areas of the earth's features. Over time, the imagery becomes a historical record of changes, which is useful for multitemporal studies. Earth observation data also allows near real-time monitoring and therefore forms the foundation for many spatial datasets, including land cover and evapotranspiration.

Remotely sensed earth observation data is acquired by sensors mounted on aeroplanes or satellites. These sensors can be either passive or active. Passive sensors mainly operate in the visible and the infrared regions of the electromagnetic spectrum. The visible spectrum contains those wavelengths of radiation that can be perceived by human vision, i.e. from violet to red light. Wavelengths longer than those of the visible spectrum (but shorter than those of microwave radiation) are termed infrared. This spectrum can be subdivided into near, mid- and far infrared. The primary source of near and mid-infrared radiation is the sun, and electromagnetism in these wavelengths is reflected by the earth’s surface in the same manner as electromagnetic radiation in the visible wavelengths. Hence, the near and mid-infrared wavebands, together with the visible bands, are sometimes collectively known as the optical bands. Far infrared radiation, however, is absorbed and then emitted by the earth’s surface in the form of heat or thermal energy and is sometimes known as thermal infrared radiation. Thermal infrared bands are generally less common in sensors than visible, and near and mid-infrared bands (Campbell, 2002; Mather, 2004).

The longest wavelengths commonly used in remote sensing fall in the microwave spectrum. In this spectrum, even though the earth itself emits some microwave energy, solar irradiance is negligible. However, this emitted energy is rarely measured in remote sensing, as most microwave sensors are active sensors. Active sensors use their own energy to irradiate the ground and then measure the portion of energy reflected to them, whereas passive sensors measure the energy generated by an external source (usually the sun) (Campbell, 2002; Mather, 2004). Radar (radio detection and ranging) is an example of an active sensor. An imaging radar system consists of the following basic components: a transmitter, a receiver, an antenna array and a recorder. The transmitter transmits repetitive microwave pulses at a specific frequency through the antenna array, which controls the propagation of the electromagnetic wave through devices known as waveguides. Usually, the same antenna then receives the echo of the signal. This is then accepted by the receiver, which filters and amplifies it as required and passes it on to the recorder (Campbell, 2002).

2.5.1.2 Machine learning

Remotely sensed data is, in most cases, of little use in its raw format and requires analysis to extract meaningful data. The objective of such analysis is often to convert the data into informational classes (i.e. nominal data) that can be used in a GIS along with other geospatial data. The conversion of remotely sensed reflectance (continuous) measurements into regional crop-type maps is a good example of how earth observation data can be employed to provide up-to-date information over large areas. However, remotely sensed data is complex as it often consists of many variables (e.g. bands, indices and transformations) that are skewed (not normally distributed). The imagery can also be cumbersome to analyse, especially if it covers large areas at high resolutions and when it is acquired at short temporal intervals. Traditional statistical techniques are consequently not always appropriate or suitable for extracting useful information from such data. In contrast to many statistical techniques, machine learning algorithms do not require data to be normally distributed and it can be applied to nominal (e.g. existing crop maps), ordinal (e.g. high, medium or low), interval (e.g. biomass) and ratio data (e.g. temperature), separately or in combination.

Machine learning is a supervised classification approach in which the application of *a priori* information of real-world classes (e.g. known yield for a sample of vineyard blocks) is used to determine the identity of unknown elements (e.g. vineyard blocks for which no yield data is available). Data for the real-world classes is acquired from an external source and is used as input to the classifier in the form of designated and labelled polygons termed “training areas” or “training data”. These training areas contain statistical information regarding the spectral properties of each class, which is used by a machine learning algorithm to identify the labels of unknown pixels (Mather, 2004; Campbell, 2007).

Supervised classification algorithms vary widely, but are all designed to compare predictor attributes (e.g. evapotranspiration, biomass and cultivar) of target classes (e.g. yield classes) with those of unknown cases and assign a class based on the results of that comparison. A range of non-parametric machine learning (also called artificial intelligence) classifiers has become popular in recent years, including the decision tree and random forest.

The decision tree classifier allows many predictor variables as input and results in a decision tree where each branch of the tree consists of a predictor threshold rule leading to the most probable class (Lawrence and Wright, 2001). The model is cross validated by iteratively dividing and comparing subsets of the target variable data to each other and can be pruned to avoid model over-fitting (i.e. generating a model that only works on the training dataset) (Campbell, 2007; Lawrence and Wright, 2002).

The random forest is an enhancement of the decision tree (Immitzer et al., 2012), which uses multiple different decision trees generated using a random vector sampled independently from the input vector. The decision trees are then compared, with each individual decision tree casting a vote to assign the most popular class of the input variable (Breiman, 2001; Bosch et al., 2007). Random forests are further enhanced using bagging, a technique that generates a training set for feature selection, which allows random forest classifiers to have a low sensitivity to small training set sizes (Breiman, 1996; Rodriquez-Galiano et al., 2012). A random forest is generally considered to be a more rigorous classifier compared to the decision tree and is not as susceptible to over-fitting. However, it has the disadvantage that the classification process cannot be easily visualised (i.e. it is a “black box” classifier).

2.5.1.3 Remote sensing-derived evapotranspiration

Evapotranspiration refers to the water losses from a surface and includes the evaporation of soil water and intercepted water and transpiration by vegetation. Crop water use is often equated to evapotranspiration where a crop is present since all water loss from a surface during the production of a crop should be considered. Many methods have been developed to estimate actual evapotranspiration and transpiration at field and catchment scales.

Many field-based methods exist to estimate evapotranspiration from the land surface (e.g. lysimeters, eddy co-variance, Bowen ratio, soil-water balance and scintillometry) and have been applied and reviewed widely in South Africa (Jarmain et al., 2009; Savage et al., 2010). Most of these methods do not capture spatial variation within an area and provide point-specific information. In addition, numerous field-based and catchment-scale models have been developed in South Africa and are available to estimate crop water use and irrigation requirements. Many of these are reliant on crop coefficients.

Advances in the interpretation of remotely sensed information make it possible to determine crop water use spatially for each pixel of a satellite image, without having to rely on generalised crop coefficients. Numerous methods have been developed to provide information at a range of temporal and spatial scales and for various applications. Examples of these include the surface energy balance algorithm for land model, the surface energy balance system model, the mapping evapotranspiration with high resolution and internalised calibration (METRIC^{TM}) model, the vegetation index/temperature trapezoid (VITT) model, the two-source energy-balance model, the atmosphere-land exchange inverse model and the normalised difference vegetation index diurnal surface temperature variation (NDVI-DSTV) triangle model.

A selection of these methods was reviewed in terms of their accuracy in estimating evapotranspiration and their potential for operational application in South Africa (e.g. by Jarmain et al. (2009, 2014)). Many other review papers describe these various methods, including Choudhury (1997), Courault et al. (2005), Kustas and Norman (1996), Verstraeten et al. (2005, 2008). O’Connell et al. (2010) investigated the possibility of using satellite remote sensing of crop water use in perennial horticultural crops in Australia. Evapotranspiration from the vineyard and not the cover crop was determined from vegetation cover (NDVI), land use (provided by SunRISE21 Inc.) and evaporative demand information at the time of image acquisition.

The results from this study suggested that a satellite remote sensing approach offers an affordable, robust method for acquiring field-scale crop water requirement information.

In semi-arid regions of southern Europe, table grapes represent a key economic activity, where productivity, defined as the ratio between crop produced and water consumed, is directly associated with the vineyard water consumption and evapotranspiration (Vanino et al., 2015). Vanino et al. (2015) found that using the FAO-56 K_c values result in an underestimation of crop water requirements for the local "tendone" vineyards at all phenological stages. They found that the acquisition of crop parameters and evapotranspiration derived from remotely sensed data could be helpful for downscaling to field level, local weather conditions and agronomic practices, and thus may be the basis for supporting grape growers and irrigation managers. In this case, the interpretation of remotely sensed data is based on the known relationships between spectral reflectance and biophysical crop parameters. One important advantage of deriving canopy parameters or crop coefficients from spectral measurements is that their values do not depend on other variables such as planting date and density, but on the effective cover (Vanino et al., 2015). Vavino et al. (2015) demonstrated the importance of local climate conditions for the water management and irrigation scheduling of table grapes and confirm the requirement of site-specific K_c values, considering the seasonality in precipitation during the growing seasons in the study area. The methodology and results of this research confirm the usefulness of earth observation data in supporting irrigation scheduling and agricultural water management. Furthermore, the approach described in this paper also constitutes the basis for a potential irrigation advisory service using earth observation data as an operational service.

D'Urso et al. (2008) evaluated the use of remote sensing techniques to improve on-farm irrigation efficiency. They also found that an important advantage of deriving crop coefficients from spectral measurements is that K_c values do not depend on variables such as planting date and density, but on the effective cover. Therefore, as such, the spectral K_c value includes variability within the same crop type due to actual farming practices.

2.5.1.4 Grape yield estimation

The estimates from the grape yield prediction models in South Africa are far from accurate. For wine grapes, the expected error could be up to 20% for forecasts based on bunch counts in spring, 10-15% for forecasts based on berry counts at fruit set and 5% on harvesting segments close to the harvest. Every year, producers under- or overestimate the yield of the vines. This leads to under- or overestimated volumes and could lead to monitory losses. It is therefore of great importance for the industry to correctly establish the yield per year in order to limit the economic impact.

Variation occurs naturally in vineyards. This includes variation within a row of vines (Hunter et al., 2010), variation between two vineyard blocks situated close to each other and variation within an area (Blanco-Ward et al., 2007). Terroir, a set of natural environmental factors, can be described as the interaction within an ecosystem, which includes human factors (Seguin, 1986; Seguin, 1988). These factors can be the soil, aspect, altitude, geology, effective soil depth, water supply and others.

The environmental factors cannot be manipulated or changed easily (Carey et al., 2002). Traditionally, yield prediction is performed using historical yield and weather indices, combined with manual measurements in the vineyard. The latter refers to harvesting whole segments of vines or randomly sampling inside the vineyard, weighing bunches and combining average bunch weight with the number of bunches per vine in order to infer the yield of the entire vineyard.

Le Roux (1974) suggested that the use of degree-days is advantageous in the attempt to establish yield through a growth curve. This includes marking bearers that have been pruned with either long or short bearers. Ten bearers were selected and used in the trail (Booysen, 1977). These bearers were then used to calculate the mass and number of berries per bunch, using the growth curve in modelling the block. This entails the harvesting of one bunch per vine.

May (1972) proposed that the final berry volume can be established through two measurements (a week apart) between four and five weeks after full bloom. The date at which full bloom occurs is of great importance. The number of bunches is to be recorded at various stages, including after bud break or before bloom. This can be done through the Merbein Bunch Count method (Antcliff et al., 1972). This method entails the counting of bunches, after which the selected bunches receive a code for future reference. After fruit set, the marked bunches are harvested and the number of berries per bunch counted. This is then translated into the number of bunches per vine.

The determination of the number of berries per bunch can occur any time between set and harvest, although 28 days after full bloom is proposed to be a good time to do so since pea-sized berries are easier to handle in the laboratory than flowers or recently formed berries. The predicted yield should be compared to the actual yield of each vine.

Yield can be determined by several equations. This can be done through the gathering of dependable values for the various measuring methods (Booysen, 1977). The equation (Eq. 2.8), suggested by Booysen (1977) is as follows:

$$Predicted\ yield\ mass\ A = \frac{Interim\ mass\ A\ \times Yield\ mass\ B}{Interim\ mass\ B} \tag{2.8}$$

where A = Prediction year

Interim mass A = Average mass of 100 berries in the year of prediction

Interim mass B = Average mass of 100 berries of the previous year

Yield mass B = Mass of yield for the previous year

Field visits and reports are the grounds for conventional yield estimation (Sawasawa, 2003), but are time consuming, expensive and subjective. These methods usually contain large errors due to the lack in the efficiency of the observations, which might be due to the limited knowledge or interpretation of the variation that occurs in the field (Reynolds et al., 2000). When looking at sensor-based bunch yield parameters, results demonstrated yield estimates that capture up to 75% of spatial yield variance with an average error of between 3 and 11% of total yield. Weather stations and patterns are also used in the forecasting of yield, but are limited by the distribution of the weather stations and hindered by unattainable timely weather data (De Wit and Boogaard, 2001).

Traditional yield forecasting methods are expensive, time consuming, not accurate and require a lot of field and laboratory work. Models that only make use of empirical (field-based) data also demand large sets of input data and are often impractical due to their complexity and methods of analysis (Sawasawa, 2003). Innovative yield forecasting methods based on remote sensing data have been proposed to improve prediction efficiencies and accuracies. Remote sensing offers an automatic and non-destructive way of yield estimation (Nuske et al., 2014) as it provides an up-to-date overview of actual crop-growing conditions over large areas at multiple stages of the growing period and can therefore increase the efficiency of field data collection (Schuler, 2002; Sun et al., 2017).

Computerised remote sensing approaches hold much potential due to their non-contact and non-destructive nature (Cherawala et al., 2006). Multispectral images have been particularly useful for improving yield estimations (Nuske et al., 2014). Cunha et al. (2010) proposed a remote sensing-based forecast model to estimate the annual variation in regional wine yield (hℓ ha^{-1}) for the main wine regions of Portugal. The model, developed between 1998 and 2008, was based on the NDVI obtained by the vegetation sensor mounted on the *Satellite Pour l'Observation de la Terre* (SPOT). The authors noticed that, in the second decade of their study, there was a strong correlation between NDVI values for April to harvest (about 17 months prior to harvest) and wine yield in all the regions tested.

Using appropriate statistical tests, the model explained 77 to 88% of the inter-annual variability in wine yield (with an average spread deviation between 2.9 and 7.1% in the different regions). They concluded that the improvements in forecasting accuracy, particularly in the early stages of the season, outweigh the marginal costs of the imagery and that the use of such data makes economic and technical sense for the winery and viticulture industry.

Jarmain et al. (2018) investigated the use of remote sensing, machine learning and statistical multivariate analysis to model wine grape yield in South Africa as part of Winetech-funded research. Large datasets consisting of thousands of data points were used. The results illustrated the complexities of wine grape yield modelling and the big impact of production regions on yield modelling. Few cultivars and region-specific yield models showed potential, but more research is required before implementation can be considered.

2.5.2 Applications in water footprint assessment

Remote sensing-derived data has the potential to improve water footprint estimates. Spatially and temporally explicit information can contribute greatly. For instance, Romaguera et al. (2010) discussed the potential of using remote sensing-based techniques for the global assessment of the water footprint of crops utilising remote sensing-derived estimates of precipitation, evapotranspiration, runoff, water storage and land use. They concluded that using remote sensing-based data and techniques in the field of water management, particularly for water footprint studies, provides new tools for global WFA and represents an innovative approach to global irrigation mapping.

Romaguera et al. (2012) proposed an innovative method for identifying irrigated areas and quantifying the blue ET (ET_b) by using the global land data assimilation system and remote sensing-based ET_{act} estimates obtained from Meteosat second-generation satellites. They concluded that remote sensing techniques based on the energy balance are more suitable for observing the ET_{act}. Mekonnen and Hoekstra (2010) showed the validity of remote sensing estimates, with less than 20% difference between the derived and measured ET_b values (Romaguera et al., 2012). Romaguera et al. (2014) assessed the improvement in ET_b estimates by combining remote sensing data in model simulations. They found that estimating green and blue water use was improved when crops are monitored in the appropriate space and time scale, and that determining ET_b from irrigated farm fields is crucial to improve water management. Toulios et al. (2013) also investigated the potential of remote sensing techniques for improving agriculture WFAs and virtual water trade accounting. They emphasised that the combination of remotely sensed data (to assess the volume of irrigation applied) and the green and blue water footprint have several limitations with respect to discrepancies in spatial and temporal resolution and data availability.

Surprisingly, little attention has been given to the use of modern remote sensing image classification and machine learning algorithms for agricultural and water-related applications. Combining remote sensing data with a machine learning approach could lead to improved partitioning between consumptive water use from green (rainfall) or blue (ground or surface) water sources. A machine learning approach may also allow for extrapolating (transferring) WFA models to areas with limited datasets.

CHAPTER 3: FRAMEWORK FOR WATER FOOTPRINT ASSESSMENT

3.1 STUDY APPROACH

3.1.1 Introduction

As discussed in Chapter 2.2.2.1, the WFA concept is multidimensional and considers all the water used to produce a product (e.g. a bottle of wine) according to the sources from which water is extracted and the volumes of freshwater required to assimilate polluted water to ambient levels. For this project, the water footprint of a product has relevance (see Chapter 2.2.3.2), since the agricultural products (table grapes and wine) are the focus. The water footprint of these products will reflect the total volume of freshwater used, directly or indirectly, to produce table grapes and wine, respectively, and will consider the water consumption and pollution in all the steps or processes of the production chain. The GWFS approach will be used as the basis for the water footprint estimation, and spatial data and lookup values will be used in the calculations.

A water footprint assessment, according to the GWFS approach, typically involves four distinct steps (see Chapter 2.2.2.1). Initially, this project was designed to address all of these, as illustrated in Figure 3.1. However, as mentioned in Chapter 1.2, the project objectives changed, and – in the end – the project only focused on setting the scope and goal(s) of the assessment, data collection and the actual water footprint calculations. It is envisaged that the sustainability assessment of and response formulation to these results will take place at a later stage, since it could add much value to the calculated water footprint values.

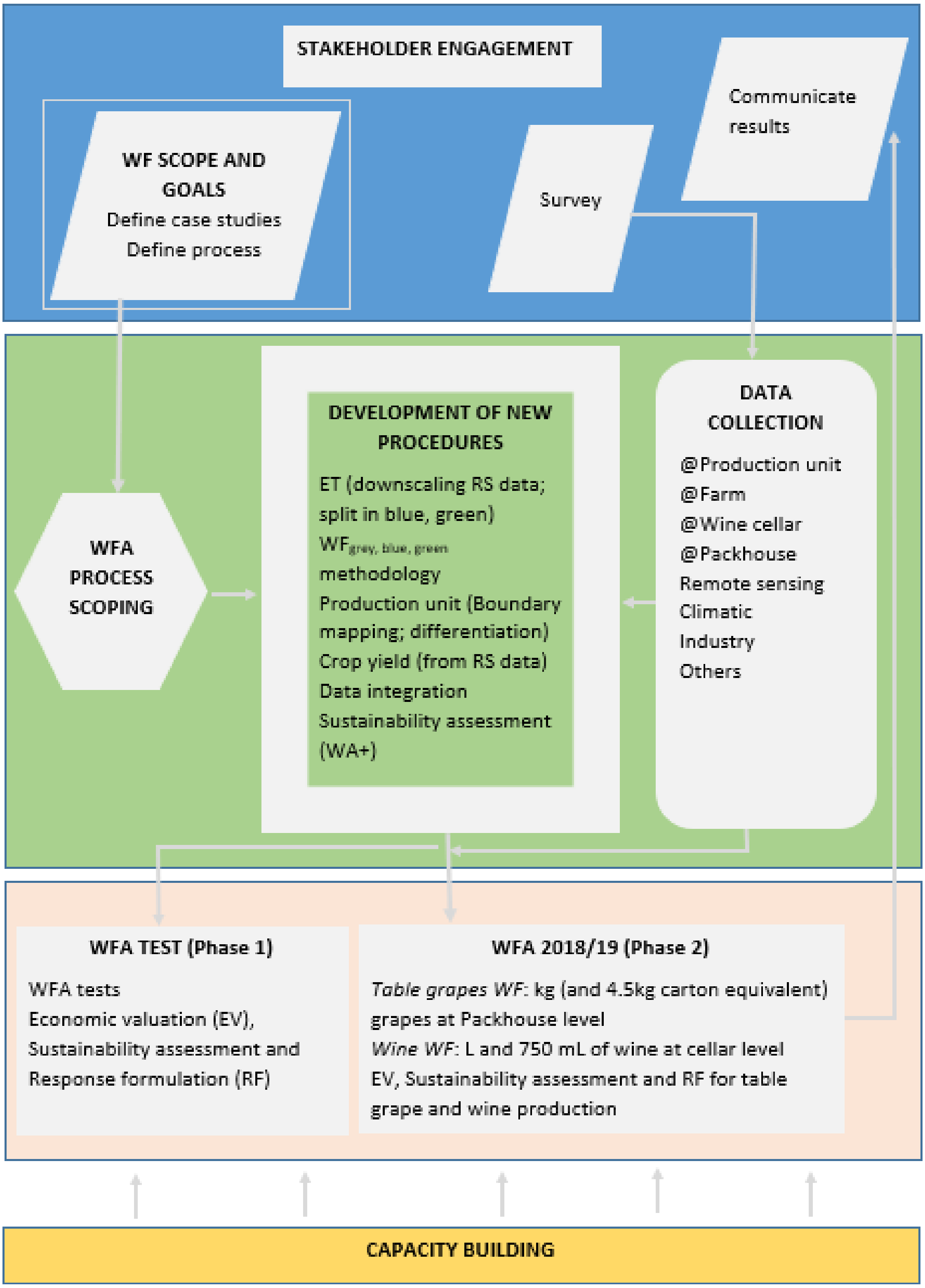


Figure 3.1: Schematic representation of the key aspects considered in the original project scope, in applying the GWFS approach, and linked to the project's aim and objectives

The research was designed to be executed in two phases (Figure 3.2) in order to set the scope and goals of this water footprint assessment, and to calculate the actual water footprint of table grapes and wine produced in South Africa.

- Phase 1: WFA method development using historical data
- Phase 2: WFA method application using data from 2018/19

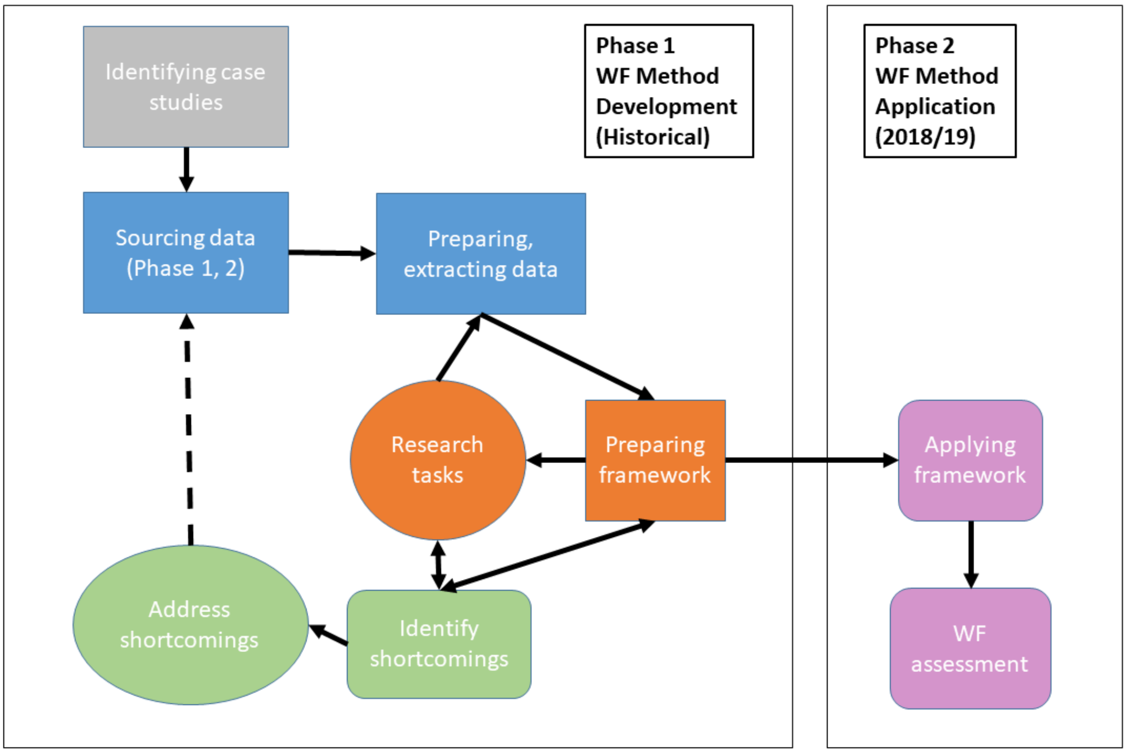


Figure 3.2: Illustration of the main phases and processes of the WFA employed in this project: Phase 1: Water footprint method development and Phase 2: Water footprint method application, with associated activities and their interlinkages

Each of the phases involved several steps:

- Identifying case studies (section 3.1.2)
- Data sourcing, collection, extraction and preparation (section 3.2)
  - For the first phase, relying on historical data (2014/15 season where data was available)
  - For the second phase, focusing on the 2018/19 production season
- Addressing data shortcomings (Chapter 4), including extrapolating and upscaling actual evapotranspiration data, splitting evapotranspiration data into a blue and green water use component, modelling crop yield and preparing lookup tables for information not readily available.
- Collating all the data into a database and spreadsheets to perform the water footprint calculations (Chapter 5)
- Continued engagement with industry and participating members

Phase 1 of the project was very valuable in determining which actual datasets were available and in what formats. This guided the research activities and the efficient sourcing and integration of datasets during Phase 2 of the project. Data collection activities were reported on in detail in the progress reports related to this project. This final report only reports on the data collection activities for Phase 2, which mirrored, but expanded on the activities for Phase 1.

3.1.2 Case studies and conditions considered

Due to the extent of grape cultivation in South Africa, which spans multiple provinces, and the data requirements needed to perform a water footprint assessment, it was proposed that the WFA should be done for selected case studies for the table and grape industries. Since this study aimed at illustrating the use of spatial crop water use (evapotranspiration) data for calculating blue and green water use at field level, and since such data is only freely available for the Western Cape, the study was limited to case studies in this province. Since about 60% of table grapes (SATI, 2019a) and about 95% of wine grapes (SAWIS, 2018) are produced in the Western Cape, these case studies should provide good examples for both industries.

The case studies were designed in consultation with the table grape and wine industries. The final selection of cases is listed in Table 3.1, with the extent of the study areas for table grapes and wine shown in Figure 3.1. Data from the 2018/19 production season was used in the actual water footprint calculations for these case studies (Phase 2), which represent the implementation of the WFA approach (Figure 3.2). The period under consideration spanned 1 August 2018 to 31 July 2019.

Table 3.1: Summary of the water footprint case studies performed in this study

		WFA regions			
Product	Unit considered	Olifants River Valley	Breede River Valley (table grapes: Hex River Valley)	Coastal (table grapes: Berg River Valley)	Processes considered
Wine	Producer cellar	ℓ of water per ℓ of wine [ℓ of water per 750 mℓ bottle of wine]			Vineyard to wine, before bottling
Table grapes (conventionally produced)	Packhouse	ℓ of water per kg of grapes [ℓ of water per 4.5 kg carton equivalent of grapes]			Vineyard to packaged grapes, before final cooling

Some important details or conditions relating to the WFA cases studies (Table 3.1) are listed below:

- Case studies were only undertaken in three production regions (Figure 3.3) and the results are reported for each region separately, and for all three regions in combination:
  - Wine grape production regions considered include the Coastal, Breede River Valley and Olifants River Valley regions
  - Table grape production regions considered include the Berg River Valley, Hex River Valley and Olifants River Valley regions
- The water footprints of table grapes and wine were calculated at packhouse level and cellar level respectively.
- For table grapes, the water footprints are expressed as water use per kilogram of table grapes produced. The estimates are also shown in water use per 4.5 kg of carton equivalent table grapes produced, for industry reference.
- For wine, the water footprints are expressed as water use per litre of wine produced. For knowledge dissemination to the public, the water footprint values were also converted and are shown as water use per 750 mℓ bottle of wine produced.
- The conditional boundaries of the processes considered in the water footprints are clearly stated:
  - The water footprint of table grape calculations includes all direct water uses from grape production in the vineyard up to the packing of grapes in the packhouse, but prior to final cool

storage (Figure 3.4). This includes WU_{green}, WU_{blue} and WU_{grey} at field level and WU_{blue} at packhouse level. WU_{grey} at packhouse level was not considered.
- The water footprint of wine considered all direct water uses from grape production in the vineyard up to the winemaking process, but prior to bottling (Figure 3.5). This includes WU_{green}, WF_{blue} and WF_{grey} at field level and WU_{blue} and WU_{grey} at cellar level.
- The water footprint of wine was only determined for producer cellars. The water footprint of table grapes focused on grapes produced conventionally, i.e. not under nets.
- The GWFS approach was used as the basis for developing an improved methodology for the WFA.

- The use of remote sensing-derived information and large datasets formed a major focus of this study.

3.1.3 Participation and confidentiality

In identifying the case studies and following inputs from producers, production managers and viticulturists representing farms, packhouses and cellars, the need for participant anonymity emerged. This was done to the best of the research team's ability. In some instances, the team was requested to sign non-disclosure agreements (to prevent the project team from sharing results between participants and outside of this project). The team complied to this request and did so under the supervision of the project's reference group. Note, therefore, that participation in this project is only summarised per production region and in terms of fields involved in this study rather than providing specific details of packhouses or producer cellars.

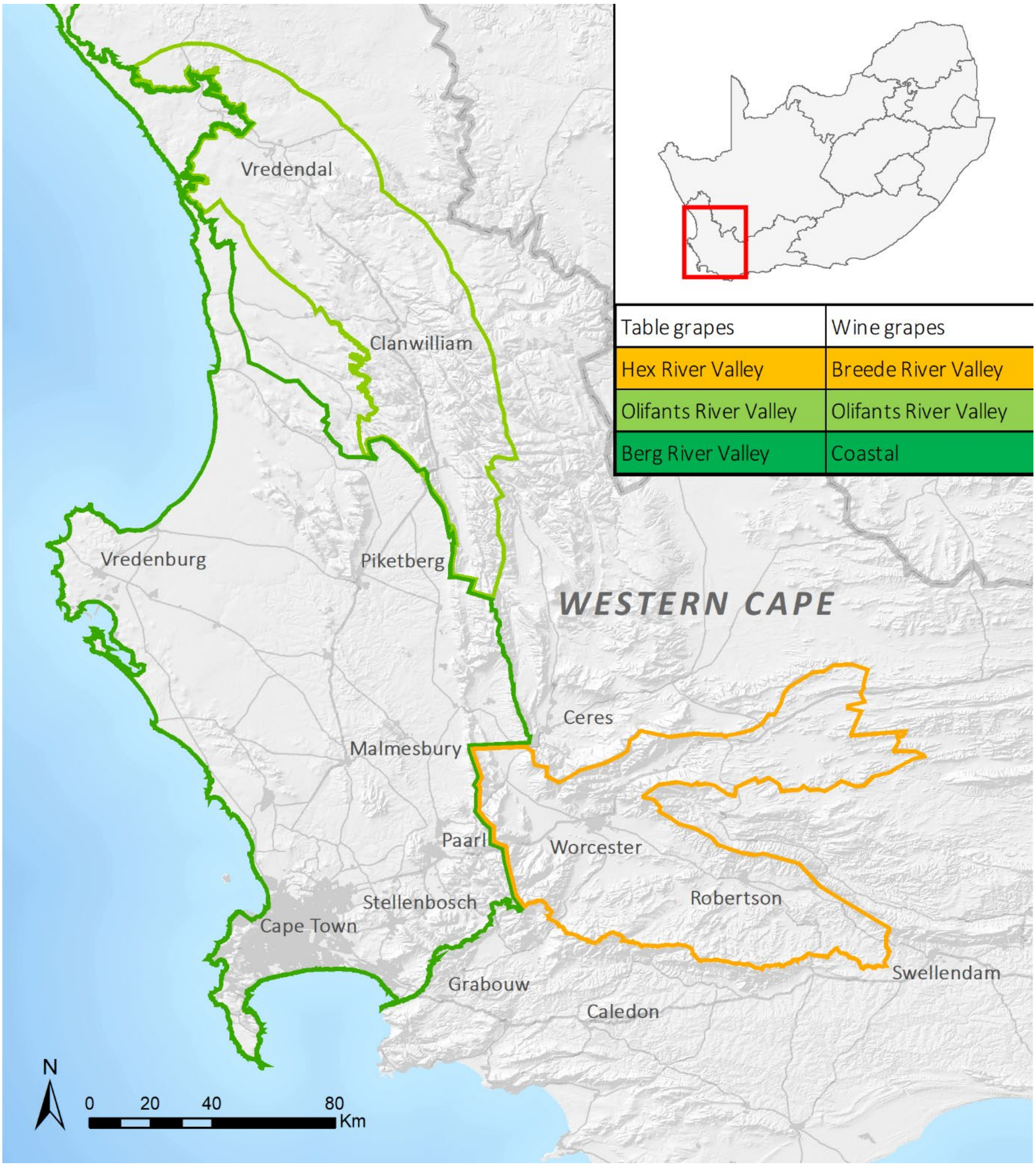


Figure 3.3: Location and extent of the three table grape production regions and WO wine grape regions considered in this study

		
Cultivation	**Delivery and pre-cooling**	**Packing**
Direct WU: Irrigation, dust prevention, fertiliser, pesticides, herbicides, containers washing, sanitation, Indirect WU: Water for chemical dilution	Direct WU: Cleaning of the delivery container, cooling, cleaning surfaces, sanitation	Direct WU: Cooling, cleaning surfaces, sanitation

Figure 3.4: Processes considered when determining the water footprint of table grapes packed in a packhouse (processes relating to storage and cooling, distribution and consumer steps are excluded from this assessment). Photographs: Caren Jarmain and Chris Potgieter.

Cultivation and transport	Winemaking process
Direct WU: Irrigation, fertiliser, pesticides, herbicides, Indirect WU: Water for chemical dilution	Direct WU: Before and after washing (processes of tipping, crush, juice, fermentation, winemaking, filter and cold stabilisation, waste) Water for cooling Water for mixing chemicals, yeast Sanitation Indirect WU: Water for chemical dilution Water for waste (skins, stems, pips)

Figure 3.5 Processes considered when determining the water footprint of wine produced and bottled at cellar level (the bottling, distribution and consumer steps are excluded from this assessment). Photographs: Caren Jarmain and Shutterstock.

3.2 DATA CONSIDERED IN THIS STUDY

3.2.1 Introduction

The data collected in Phase 1 was similar in form to that collected in Phase 2. It will not be described in the sections below since it was only used as a test dataset for the development of the WFA framework.

The focus of this report is on the data used in the research activities (as described in Chapter 4) and the final WFA application and water footprint calculations (as reported on in Chapter 5). All the data sources used in these components are described below. Multiple datasets, both captured in spatial and non-spatial formats, were considered and include information on the following:

- Production: table and wine grape production, as well as wine production
- The position of fields considered in the study: field boundaries
- Field or block-specific information, e.g. block size, cultivar, rootstock, trellis system, planting date and planting density
- Crop water use: spatial evapotranspiration from various sources
- Weather data: mainly rainfall data
- Field level chemical spray and fertilizer records
- Packhouse and cellar water use
- Water quality records for cellars and the environment

3.2.2 Spatial datasets

3.2.2.1 FruitLook

Field level crop water use or evapotranspiration used in the WU_{blue} and WU_{green} calculations were obtained from the FruitLook (FL) databases. FruitLook is an online remote sensing analysis service funded by the Western Cape Department of Agriculture and assists farmers in making agricultural decisions at field level, specifically relating to improved water use efficiency (WUE). A core component of this service is the ET_{act} data provided. All data provided through FruitLook is generated by eLEAF, using the ETLook and METEOLOOK models (Bastiaanssen et al., 2012) and satellite imagery from a combination of platforms (Landsat 5, 7 and 8, MODIS, VIRRS, Deimos, UK-DMC-2 and Sentinel 2). The satellite data used and the data processing are described in more detail by Goudriaan (2013), Jarmain et al. (2011), Klaasse and Jarmain (2012) and Jarmain (2019). The ET_{act} quantifies the consumptive water use from the land surface through transpiration by plants, the evaporation of water from the soil and open water bodies, as well as the evaporation of water intercepted by plant canopies. In addition to ET_{act}, seven other biophysical variables commonly used in agriculture are also available (Table 3.2).

For this study, the spatial ET_{act} data was of great use, since it represents the consumptive crop water use of table and wine grapes at field level. The ET_{act} contributes to both the WU_{blue} and WU_{green} components considered in the water footprint calculations.

Table 3.2: Fruitlook variables considered in various aspects of this study

Biophysical variable	Unit
Biomass production (Bio)	kg/ha/week
Biomass WUE (BioWUE)	kg/m^3
Actual evapotranspiration (ET_{act})	mm/week
Evapotranspiration deficit (ET_{def})	mm/week
LAI (Leaf Area Index)	m^2/m^2
Normalised Difference Vegetation Index (NDVI)	Unitless ratio
Nitrogen in a plant (N_{plant})	kg/ha
Nitrogen at the top of the plant (N_{top})	kg/ha

The FL data is available as a series of 20 m spatial resolution images for each biophysical variable provided at weekly intervals. Over time, the temporal coverage increased, with coverage from October to April for the 2010/11 to 2015/16 seasons, August to April for the 2016/17 season, and August to July for the 2018/19 season. The spatial coverage of the images also increased over time. Initially, it was limited to the fruit- and wine-producing areas of the Western Cape (2010/11 to 2015/16 seasons), but the coverage was expanded to cover most of the Western Cape from the 2016/17 season onwards.

Five FL seasonal datasets were used during the scope of this project (Phase 1 and Phase 2) (Table 3.3). Data from the 2014/15 to 2017/18 seasons was mainly used during the development of the water footprint method (Phase 1), including the splitting of evapotranspiration into ET_{green} and ET_{blue}, as well as various research tasks overviewed in interim reports to the WRC. All the FL raster images used in this study were supplied by eLEAF, including data for the 2018/19 season, with the latter used in the application of the water footprint method (Phase 2).

Table 3.3: Fruitlook seasonal datasets used in Phase 1 and Phase 2 of the project

Season	Coverage	Number of weeks	Use in project
2014/15	Selected agricultural areas	30	Water footprint method development (Phase 1)
2015/16	Selected agricultural areas	30	Water footprint method development (Phase 1)
2016/17	Seamless for Southwestern Cape	38	Water footprint method development (Phase 1)
2017/18	Seamless for Western Cape	40	Water footprint method development (Phase 1)
2018/19	Seamless for Western Cape	51	Water footprint method application (Phase 2)

FruitLook data is generally made available at weekly time steps, although the LAI, NDVI and nitrogen datasets represent estimates for specific dates within each week. Since much of the analysis undertaken in this study as part of the water footprint development, application and research tasks, required FL data to be consolidated at monthly timesteps, all weekly FL biophysical variables for all seasons were converted to monthly products. This was done using the simple formula shown below (Eq. 3.1). The weekly input and monthly output dates per season are listed in Table A1 of Appendix 1.

$$Monthly\ pixel\ value = \left(\frac{\left(\frac{FL\,1}{7}\right)+\left(\frac{FL\,2}{7}\right)+\cdots+\frac{FL\,n}{7}}{Number\ of\ weeks}\right) \times Number\ of\ days \qquad (3.1)$$

where *monthly pixel value*	calculated monthly FL pixel value
FL	calculated weekly FL dataset
Number of weeks	calculated number of weeks in the month
Number of days	calculated number of days in the month
n	calculated number of weekly datasets used

Since this study considered data at field or block level and not pixel level, all the FL data was analysed and aggregated per field or vineyard block using a process known as zonal statistics. When applying zonal statistics, the values of all raster pixels that fall within a specified zone (e.g. block) are averaged, and the average value is attributed to that block. Figure 3.6 provides a conceptual illustration of this process, e.g. for ET_{act}.

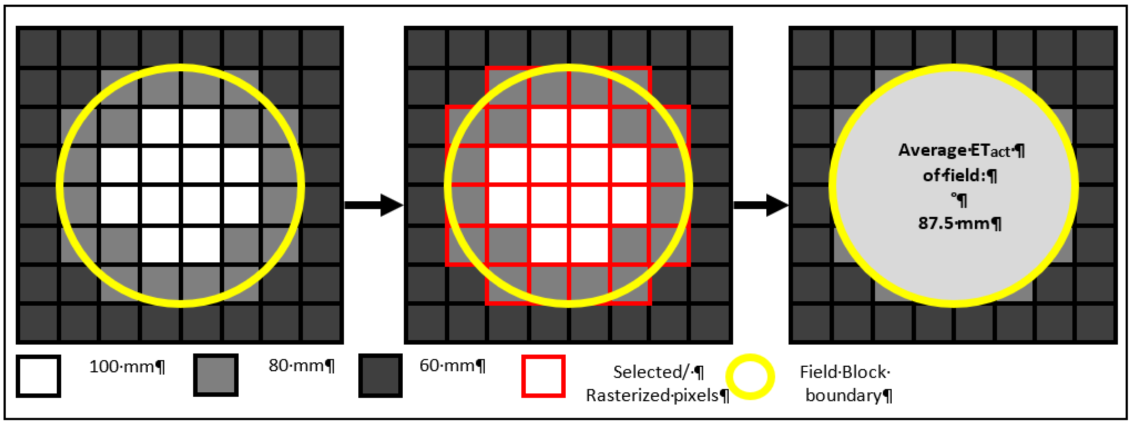


Figure 3.6: Conceptual overview of using zonal statistics to calculate the average monthly ET_{act} for a hypothetical vineyard block

3.2.2.2 Field boundaries

Since the water footprint calculations of both table grapes and wine involved the actual estimation of the water footprint at field level, the boundaries defining these fields were required. Producers and viticulturalists made these available in shapefile (.shp), Google Earth (.kml), Google maps or in hard copy format. All the digital data was standardised in shapefile format, the block boundaries were improved according to the most recently available aerial photographs and block numbers were encoded as attributes to these datasets. The hard copy maps were manually digitised and attributed in a similar manner. The spatial evapotranspiration, production and block information were linked to these field boundaries in digital format.

3.2.2.3 Production region boundaries

The official WO regions, as defined by the Wine and Spirit Board of South Africa, were used to define the production regions (Figure 2.2). The WO map delineates the recognised grape production wards, districts and regions. An electronic copy of this map (shapefile) was obtained through Vinpro (Wine and Spirit Board of South Africa, 2019). The data used in the water footprint estimates was extracted and collated or integrated according to these boundaries, specifically for the Coastal (Berg River Valley for table grapes), Breede River Valley (Hex River Valley for wine grapes) and Olifants River Valley regions.

3.2.2.4 Other spatial datasets

In addition to the data sources listed above, several other spatial datasets were also used in the research components of this project. The first five datasets listed below were prepared for use as described in Figure 3.6.

3.2.2.4.1 WRC 2014/15 ET dataset

The WRC 2014/15 ET dataset is a 250 m national evapotranspiration product (Van Niekerk et al., 2018). The evapotranspiration data product was developed by eLEAF using the ETLook model, which was calibrated to account for the highly diverse climatic regions of South Africa. The dataset provides monthly consumptive water use or evapotranspiration data (mm/month) for a 12-month period: August 2014 to July 2015. This dataset was used to develop the water footprint methodology (Phase 1), specifically investigating methods of extrapolating high-resolution evapotranspiration data.

3.2.2.4.2 Water Productivity Open-Access Portal dataset

The Water Productivity Open-Access Portal (WaPOR) dataset is a spatial evapotranspiration dataset for the whole of Africa, funded by the Food and Agricultural Organisation of the United Nations. The dataset (also developed by eLEAF) is freely accessible via the FAO's WaPOR (FAO, 2018). The dataset encompasses a 10-year period from 2009 to 2019, with the data being generated and uploaded in near-real-time. Evapotranspiration data is derived using the ETLook model, but due to the extremely large extent, it is not specifically calibrated for South African conditions. This dataset is represented at a 250 m spatial resolution, with decadal mean evapotranspiration values (10 day mean, mm/day). The WaPOR dataset was used to develop the water footprint methodology (Phase 1) and was converted to monthly datasets (mm/month) for the months of August 2014 to July 2015.

3.2.2.4.3 MOD16 dataset

The MOD16 product was developed by the National Aeronautics and Space Administration (NASA) and the United States Geological Survey, and has been used to estimate global evapotranspiration since 2000. This dataset is created using inputs of daily meteorological reanalysis data along with MODIS remotely sensed data products such as vegetation property dynamics, albedo and land cover (Running et al., 2017).

The evapotranspiration values were derived using an algorithm based on the Penman-Monteith formulation (Running et al., 2017). This dataset is represented at 1,000 m spatial resolution with eight-day cumulative evapotranspiration values (mm/eight days) and is freely available from the Atmosphere Archive and Distribution System (LAADS) Distributed Active Archive Centre (DAAC)'s web portal (NASA, 2020).

3.2.2.4.4 High-resolution vegetation indices

In support of the FL temporal modelling, high-resolution vegetation indices (HRVIs) were processed and extracted from the Google Earth Engine cloud interface (Gorelick et al., 2017) to produce high-resolution (30 m) NDVI layers for each month from 2014 to 2018. This was done using a combination of Landsat-8 (30 m) and Sentinel-2 (down-sampled to 30 m) satellite imagery to calculate the maximum NDVI pixel value for each month. By using the maximum NDVI per pixel, the monthly NDVI composite layer would minimise the presence of clouds, while giving a good representation of vegetation vigour for that month (Lück and Van Niekerk, 2016).

3.2.2.4.5 Low-resolution vegetation indices

The MODIS satellite system produces several low-resolution vegetation index (LRVI) products. The MOD/MYD13Q1 data product (Didan, 2015) consists of two vegetation indices as 16-day composites at 250 m spatial resolution, namely the NDVI (also referred to as MxD13 NDVI) and the enhanced vegetation index (EVI) (also referred to as MxD13 EVI). The EVI was developed specifically for the MODIS mission to be more sensitive to high vegetation densities, while reducing atmospheric influences (Hui Qing Liu and Huete, 1995). These layers were acquired for each month from 2014 to 2018 in support of the FL temporal modelling.

3.2.2.4.6 Western Cape crop census

The 2017 Western Cape Crop Census (WCCC) is a vector database of field boundaries with associated crop types. It was used for several research components in this project. Also known as "flyover data", the dataset is an update of a similar census undertaken in 2013 (Western Cape Department of Agriculture, 2014), also commissioned by the WCDoA (Western Cape Department of Agriculture, 2018). In the case of the 2017 flyover data, field boundaries were manually delineated from high-resolution aerial imagery dated late 2016 and, in isolated cases, Sentinel-2 imagery dated January 2018. Crop information per field was obtained through aerial and vehicle surveys between May 2017 and March 2018, with the final database collated in May 2018. The database also contains information on the use of nets in crop production. For some research tasks in this project, the older version of the flyover dataset was also consulted.

3.2.3 Non-spatial datasets

Several non-spatial datasets were also used in this study and are described below.

3.2.3.1 Packhouse production and field data

The table grape industry does not have a standard data management system for capturing production and descriptive information, whether at field level or cultivar group level. Each producer and export group uses its own system. Hence, the data obtained from the table grape participants were in different formats – mainly electronic file format (.docx and .xlsx), with some hard copies or pdf files that required digitisation.

Details obtained directly from farmers, export production managers or viticulturists included the following:

- Table grape production data split into export, local distribution and grapes used for wine or drying
- Block-related data, including block size, age, cultivar, rootstock, trellis system, irrigation system and whether nets were used

Since the water footprint is calculated as water use divided by grape production, the accuracy of the production data was critical since it affected the accuracy of the estimated water footprints directly. Hence, a substantial effort went into checking the production data against the age of the fields (newly bearing fields or not), production quality (export vs. dry/wine fractions) and density of vines.

3.2.3.2 Cellar production and field data

Wine grape production and associated field level data (cultivar, rootstock, trellis system, planting density and wine grape quality indicators like pH, acidity and sugar), as well as wine production data at cellar level, was extracted from the WineMS software solution. All producer cellars participating in this project made use of this software; hence, the data was obtained and extracted with permission and in a standardised format. This large wine grape and wine production database, which consists of thousands of block records, was used in the water footprint case studies for wine, as well as the related research tasks. The water footprint of wine grapes at field level was estimated for each of the more than 3,000 fields considered in this study.

WineMS, a product of Farm Management Systems (Pty) Ltd, is a widely used data management software for the wine industry. The software is used to manage the winemaking process – from the planting of the vines to the sale of bulk or bottled wine. Data on crop yield is captured through the WineMS Grape Receipt module, a core module within WineMS that allows wineries to manage the block records, estimates, receipt and payment of grapes (grape receipt process). The WineMS software contains a vast record of block-related data, including crop production quality and quantity that is stored in a single centralised database and updated at regular intervals from the wineries using the software. Wine grape production and field data was extracted per field and made available per producer cellar. The wine production data was summarised per producer cellar and details provided per cultivar (total grape production, wine production and recovery rate). For Phase 2 of the project, the wine grape data for the 2019 season and the wine production data as on 30 April 2019 were used.

3.2.3.3 Rainfall data

For Phase 2 of this project, rainfall data was obtained for the period 1 August 2018 to 31 July 2019. The daily rainfall records were obtained from three sources to ensure fair coverage of the study area:

- South African Table Grape Industry
- Agricultural Research Council
- Hortec

South African Table Grape Industry provided weather data at no cost for use within the project and for the following stations: De Doorns De Vlei, De Doorns Normandi, Paarl Mỏrewag, Piketberg Môrester, Porterville Die Tuin and Trawal Doringrivier. In addition, weather data was purchased from the Agricultural Research Council (ARC) and Hortec for the stations Vredendal Vlieg, Klawer, Wellington Bassano, Rawsonville Blaarfontein, Worcester Hexberries, Goudini Hugoskraal, Morgenster, Paarl Perdeberg, Riebeek and Paarl Vinpro. The daily rainfall records were checked and converted into monthly and annual rainfall totals. The rainfall data was specifically used to determine the effective rainfall fraction, which was used in a later step to split the consumptive water use (evapotranspiration) into a WU_{green} and a WU_{blue} component.

3.2.3.4 Other data sources

3.2.3.4.1 Chemical spray programmes

To estimate WU_{blue} at the field level, standard spray programmes from two different agrochemical companies (Viking and Nexus, supplied by BASF (2019)) were sourced to calculate the volume of blue water generally used for spray applications in table and wine grape vineyards.

This was in addition to the actual spray records obtained from commercial production units included in this and a previous study (Kangueehi, 2018; Avenant, 2019). For table grapes, spray records were sourced from 125 blocks. Where the same cultivar occurred in more than one block per farm, only one record of that cultivar was considered for that farm. A single such record was considered representative of all the blocks of the cultivar on that farm. A total of 41 spray records for table grapes cultivated in the three production regions was finally captured. For wine grapes, only five spray programmes or records were supplied by the farms or cellars participating in this study, and these were used together with the industry recommendations.

3.2.3.4.2 Blue water use at packhouse level

To estimate WU_{blue} in packhouses, water use records were requested from the units participating in the study. During Phase 1, the lack of blue water use measurements at packhouses was identified as a data need. Therefore, at the beginning of the 2018/19 season, six water meters were purchased and provided to selected participants to monitor packhouse water use during the 2018/19 season. Unfortunately, not all users made use of these meters, but those who could install them into their systems provided the research team with actual packhouse water use estimates. Four table grape packhouses supplied water use data, of which two were from measurements (water meters at packhouses) and two were estimated values. In addition, packhouse water use records (obtained from commercial production units in a previous study (Kangueehi, 2018; Avenant, 2019) were also included and compared to the current study's results.

3.2.3.4.3 Blue water use at cellar level

To estimate WU_{blue} at wine cellars, water use records were requested from the participants in the study. All producer cellars participating in this project monitored the water use at cellar level. Although datasets could not be obtained from all the participants, samples were obtained for each region. Unfortunately, the water use measurements at the cellars did not always include only the actual cellar water use. Sometimes other water uses, e.g. from a garden or restaurant, were included in the measurements. The water use data was also not always available for the same period.

3.2.3.4.4 Fertilizer application and other records

Soil-applied fertilizer treatments that contribute to pollutant accumulation in the soil and have an impact on the WF_{grey} needed to be identified and quantified. The typical nutrients and levels of these nutrients that would be applied in a standard programme, based on specific production categories, were established, based on standard South African fertilizer norms and recommendations for both table grape (Van Schoor et al., 2000; Raath and Avenant, 2018) and wine grape production (Conradie, 1994; Van Schoor et al., 2000).

Nitrogen and phosphate are the most documented pollutants, with clear maximum and natural concentrations within the Breede, Olifants, Hex, Berg River Valley and Coastal regions. Nitrogen is the most common agricultural pollutant used for calculating the grey water footprint and enables comparisons with a wide range of water footprint studies reported on in the literature. Therefore, these two pollutants were selected for WF_{grey} assessment at field level.

3.2.3.4.5 Environmental records

The maximum and natural concentration of each pollutant considered was required to calculate WU_{grey}. For natural concentrations, the oligotrophic condition concentration of the pollutants according to the Department of Water Affairs and Forestry (DWAF) (1996) were used. For the maximum allowable concentrations, the mesotrophic condition concentration for each pollutant for the specific river was taken according to the proposed classes of the Water Resource and Resource Quality Objectives for the Breede-Gouritz Water Management Area, as well as for the Berg River catchment, published in the Government Gazette in 2018 and 2019 (DWS, 2018; DWS, 2019).

CHAPTER 4: PHASE 1: RESEARCH TO SUPPORT THE WATER FOOTPRINT FRAMEWORK

4.1 INTRODUCTION

This project aimed to quantify the water footprint of table grapes and wine produced in South Africa, where the water footprint is defined as the volume of water (ℓ) used to produce the product – in this study 1 kg of grapes or 1 ℓ of wine. In the simplest terms, this requires information on water use (considering water use in all processes involved) and production (product). This then would imply knowledge of three aspects summarised in Table 4.1:

- *What:* The crop or product type, water use and production for which information is required
- *Where*: The different levels, like field or production unit, for which information is required
- *How*: The “conditions” of water use, the crop or product to consider

The second and third objectives of this research involve applying the WFA method for selected and representative grape commodities or products, and developing and demonstrating a procedure whereby water footprint assessment can be carried out utilising a spatial dataset. Research in the use of geospatial technologies and machine learning to model some of the aspects listed in Table 4.1 , directly or indirectly related to water footprint estimation, has been ongoing for several years in South Africa. In the subsequent sections, research into the use of these datasets and machine learning in support of a water footprint assessment is described. More work is required before some of these spatially explicit methods can be implemented.

Some of the required data (what-where-how combinations) will likely never be derived from spatial datasets. In these cases, lookup tables based on field records and industry knowledge hold great potential. The development of these lookup tables and implementation in the WFA processes are also described in the sections below. These relate specifically to the WU_{blue} (chemical spray) and WU_{grey} estimation at field and production unit level.

Table 4.1: Knowledge elements required for water footprint estimation

What	Where	How	Research/ WFA aspect	Section
Crop type (table or wine grapes)	Field boundaries	Conventional production or under nets	Crop type mapping	4.2.2
			Field boundary delineation	4.2.1
			Net mapping	4.2.3
Water use	Field level	From rainfall (green water)	Determining ET Splitting ET	4.3 4.5
		From irrigation (blue water)	Splitting ET	4.5
		Chemical spray (blue water)	Lookup table	4.6
		Chemical dilution (grey water)	Lookup table	4.8
	Unit-level (packhouse or cellar)	Actual water use (blue water)	Lookup table	4.7
		Chemical dilution (grey water)	Lookup table	4.9
Production	Field level		Crop yield modelling	4.4
	Unit level (cellar)			

4.2 IDENTIFYING TABLE AND WINE GRAPE FIELDS

4.2.1 Automated field boundary delineation

Many spatial analysis operations that form part of water footprint assessments, such as zonal statistics (Figure 3.6), require an accurate delineation of boundaries of blocks (fields). Currently, the only national field boundary dataset is one collated and distributed by the Department of Agriculture, Forestry and Fisheries (DAFF) as part of the Crop Estimates Consortium (CEC) (Crop Estimates Consortium, 2017). This dataset is updated on a regular basis and the latest version (2017) of the agricultural field boundaries comprises most of the agricultural field boundaries of South Africa, digitised from a 1.5 m SPOT 6/7 true colour mosaic. The CEC data is ideal for its intended use (crop estimations at regional scales), but for the purposes of a water footprint assessment, it has several drawbacks. First, the digitisation was carried out on a relatively small (1:10 000) mapping scale, and, as such, the boundaries are, in some instances, too generalised to be used for the WFA method. Second, the boundaries were digitised from a mixture of 2013, 2014 and 2015 imagery, resulting in some of the boundaries being outdated.

The 2017 WCCC (see Chapter 3.2.2.4.6) is more recent and detailed than the CEC field boundary data, but only covers the Western Cape, which limits its application for a water footprint assessment. Apart from the great expense at which the dataset was produced, it is updated every three to four years and takes almost two years to complete. For frequent water footprint assessments, faster and more cost-effective methods are needed to delineate field boundaries.

Although research on automated field boundary delineation was not directly part of this project, it contributed indirectly to field boundary delineation by providing an additional application for this technology. This builds on the work that was done at Stellenbosch University and funded by the WRC (Van Niekerk et al., 2018). In short, an automated field boundary delineation methodology that makes use of multitemporal Sentinel-2 satellite imagery was developed by Watkins and Van Niekerk (2019a) and validated in Watkins and Van Niekerk (2019b). Figure 4.1 shows an example of the field boundaries that were extracted using this technology. The developed methodology holds much potential for future water footprint assessments as it enables automated aggregation of remotely sensed ET_{act} data.

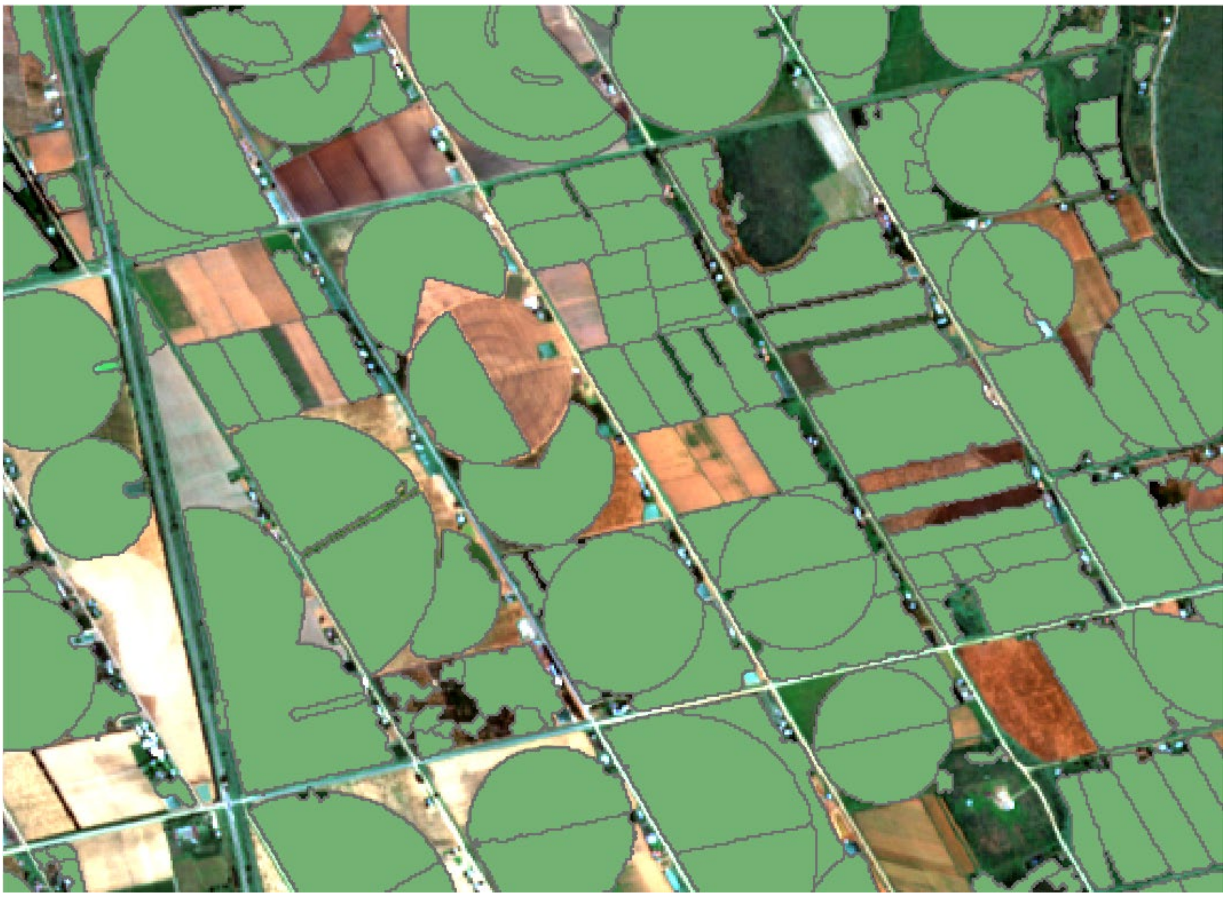


Figure 4.1: An example of an area where field boundaries were automatically delineated using multitemporal Sentinel-2 imagery

4.2.2 Automated crop type mapping

Water footprint assessments are normally carried out per crop type (e.g. table grapes). As such, maps showing where target crops are planted are needed as input to the water footprint assessment. The traditional approach to producing crop type maps (as was done in this project) is to carry out crop surveys involving farm visits, questionnaires and telephonic interviews (Peña-Barragán et al., 2008). Due to the cost and time involved, such surveys are usually only carried out at representative (sampled) locations within a region. Another approach is to manually digitise agricultural fields from aerial or satellite imagery (see the previous section) and then to assign crop type labels to each field from information collected from aerial and ground surveys. Larger areas (e.g. entire provinces) can be covered using this approach. Despite being more effective than traditional crop surveys, a comprehensive agricultural census remains a very time-consuming, labour-intensive and costly exercise (Yalcin and Günay, 2016). It is also prone to human error and bias (Peña-Barragán et al., 2014).

Agricultural censuses are not routinely carried out in developing countries. Although the South African CEC routinely carries out estimates of crop plantings through the Producer Independent Crop Estimates System programme,[1] these estimates only relate to grain crops and do not provide an indication of perennial plantings. The WCDoA consequently embarked on an initiative to routinely map all agricultural areas in the Western Cape (for more information, refer to Chapter 3.2.2.4.6). Although invaluable, the latest census took several years to complete, which means that the information was outdated by the time it was released.

[1] https://www.siq.co.za/pices.php

An alternative approach is to make use of remotely sensed imagery to generate crop type maps in an automated or semi-automated manner at regional scales (Gilbertson and Van Niekerk, 2017). Such approaches often employ supervised machine learning in which the operator provides training data (agricultural fields with known crop types) from which the algorithm develops a statistical characterisation of each crop type. Once created, the characterisation can be employed to label fields from which the crop type is not known (Al-Doski et al., 2013; Eastman, 2006). Popular machine learning algorithms include the decision tree, neural network, random forest, k-nearest neighbour and support vector machine (Al-Doski et al., 2013; Gilbertson et al., 2017). The biggest obstacle to employing machine learning for crop type mapping is to obtain adequate training data (i.e. examples of fields for which crop type data are known so that statistical profiles of their spectral properties can be generated). Crop plantings are by nature highly dynamic, particularly annual crops that are planted on a rotational basis. However, the WCDoA's agricultural censuses for 2012-13 and 2017-2019 provide an excellent source of training data that has not yet been fully exploited. Several projects relating to the use of this information for automated crop type mapping are currently being carried out at Stellenbosch University. For instance, Figure 4.2 shows the result of an automated (machine learning) mapping procedure performed on light detection and ranging (LiDAR) data to map vineyards in Constantia, Cape Town. Accuracies of more than 80% were achieved. Maponya (2019) achieved an overall accuracy of 72.2% for differentiating perennial crops (citrus, pome fruit, stone fruit, exotic fruit, planted pastures and grapes) in the Swartland region using machine learning on freely available Sentinel-2 imagery.

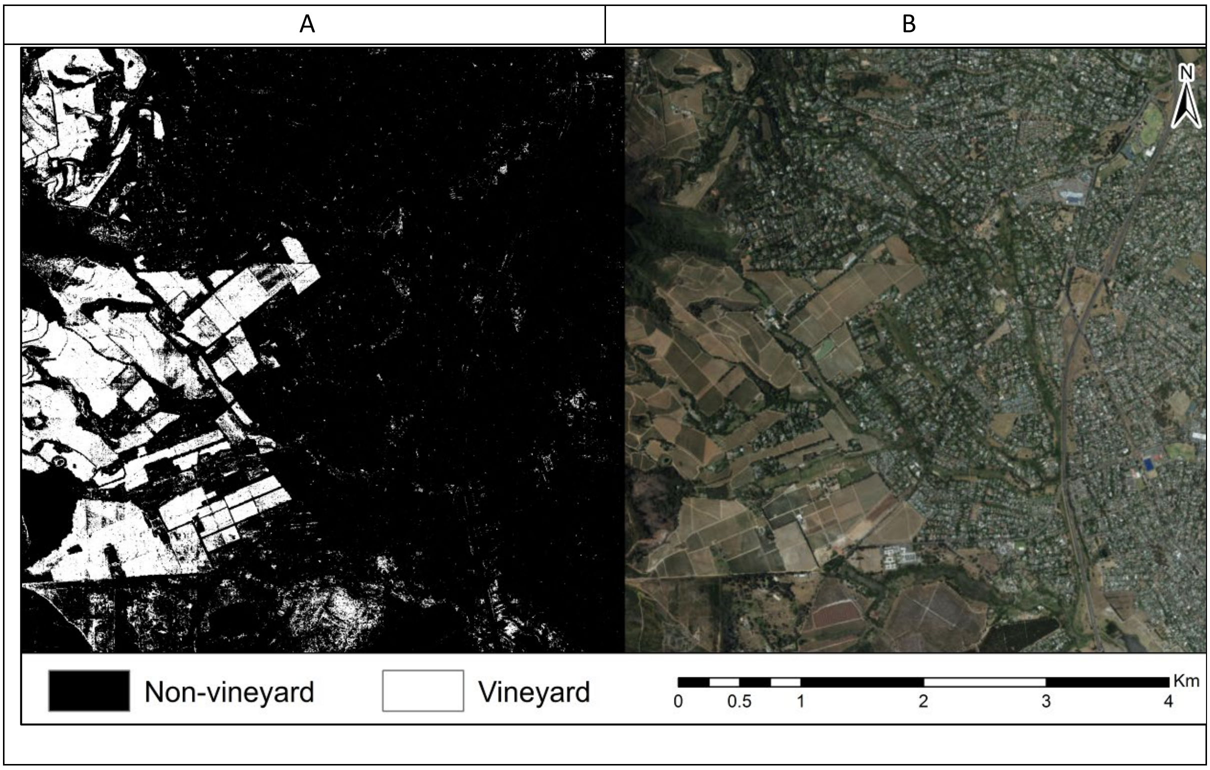


Figure 4.2: The mapping result of a vineyard (A,) compared to an aerial photograph of the same area in Constantia, Cape Town (B) (Prins, 2019)

Despite recent progress related to crop type mapping using remotely sensed data, more research is needed to establish a methodology that can generate crop type maps on an operational, accurate and frequent (seasonal) basis. Many challenges remain. Obtaining good-quality training data (actual crop plantings) is the main obstacle for developing machine learning approaches. It is likely that a combination of machine learning and an expert system approach is the most viable solution for an operational system.

4.2.3 Earth observation for monitoring crops under nets

As illustrated in the preceding sections, remote sensing can provide timely and accurate images covering large areas, which has made this technology an indispensable tool for mapping, monitoring and managing agricultural activities (Atzberger, 2013). Some of the applications of remote sensing within agriculture include the estimation of water stress in plants, the assessment of plant health or the determination of crop yield, which provide essential information that is needed to maintain a successful agricultural sector (Mulla, 2013). However, the introduction of agricultural nets has limited the applications of remote sensing within the agricultural sector.

Netted agriculture is an aerial modification technique for optimising the conditions for plant growth. Agricultural nets are used to protect crops from adverse weather conditions such as wind, hail, snow or excessive rainfall. Furthermore, the nets protect against pests such as insects or birds and provide shade for the crop (Scarascia Mugnozza et al., 2012). Aerial modifications have undergone rapid expansion in recent years, covering an estimated 500,000 ha worldwide (Agüera et al., 2008). In South Africa, the use of agricultural nets has increased rapidly (by up to 290% since 2013 for certain crops) due to increased weather variability, unreliable rainfall and the increased frequency of extreme weather conditions (Pienaar, 2018). It is estimated that more than 1,300 ha of table grapes are currently planted under shade netting (Pienaar, 2018).

When electromagnetic radiation from the sun reaches surfaces like clouds, much of the radiation in the visible and infrared regions is reflected. However, when the radiation reaches a surface like a net that covers a specific crop, some of the radiation in these regions is reflected, while the remainder is transmitted through the net. Physical differences in net characteristics dictate the interaction between the net and electromagnetic radiation, ultimately controlling the amount of radiation that is reflected and transmitted. Different applications for nets result in different physical net characteristics, e.g. different threading patterns, material, weight, colour, porosity and permeability (Castellano et al., 2008).

For example, Figure 4.3 shows the differences in reflectance, as measured by the Sentinel-2 satellite, for table grapes grown under nets and conventionally (in open vineyards). The reflectance values of netted grapes are consistently higher than those of conventional vineyards. However, the percentage difference in reflectance is not consistent at all wavelengths. Much larger differences are observed in the red (Band 4) and red edge (bands 5-7) regions of the electromagnetic spectrum, while the reflectance values are very similar in the infrared (Band 8) and shortwave infrared (bands 10-12) regions.

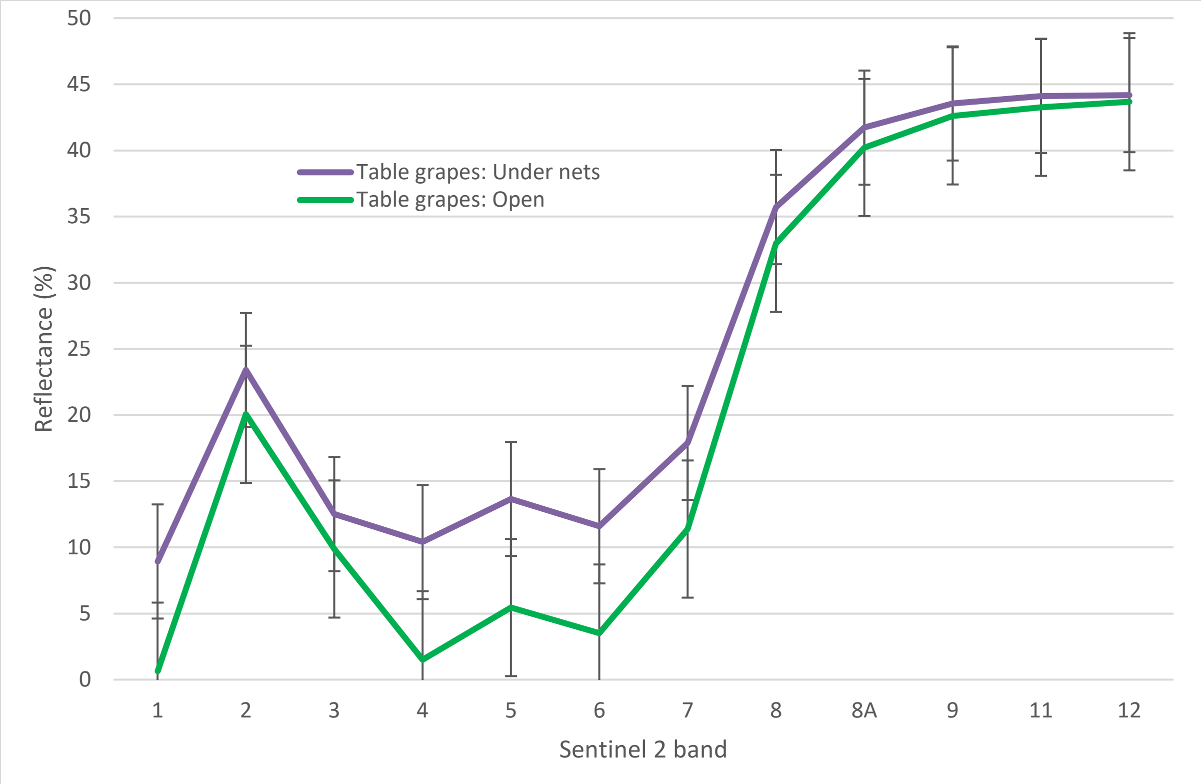


Figure 4.3: Comparison of Sentinel-2 reflectance values for table grapes planted under nets and in open vineyards

Table 4.2: Description of Sentinel-2 bands

Bands	Central wavelength (µm)	Resolution (m)	Bandwidth (nm)
Band 1 – Coastal aerosol	0.443	60	20
Band 2 – Blue	0.490	10	65
Band 3 – Green	0.560	10	35
Band 4 – Red	0.665	10	30
Band 5 – Vegetation red edge	0.705	20	15
Band 6 – Vegetation red edge	0.740	20	15
Band 7 – Vegetation red edge	0.783	20	20
Band 8 – Near-infrared	0.842	10	115
Band 8A – Narrow near-infrared	0.865	20	20
Band 11 – Short-wave infrared	1.610	20	90
Band 12 – Short-wave infrared	2.190	20	180

The standard error vertical bars in Figure 4.3 suggest that the variance in the means of the reflectance values overlap in all regions of the spectrum measured by Sentinel-2. Assessing the interaction of nets and electromagnetic radiation requires a thorough understanding of the net, e.g. its material, porosity and colour, and the physical properties of incoming radiation, e.g. the angle of incident radiation (determined by seasonality) (Al-Helal and Abdel-Ghany, 2011; Hemming et al., 2008; Scarascia-Mugnozzo et al., 2011; Shahak et al., 2004). Given the diverse nature of agricultural practices and the variety of applications for which agriculture nets are used, the physical and spectral properties of these nets vary greatly (Briassoulis et al., 2007). Consequently, agricultural nets are difficult to identify, classify and map using remote sensing.

Several studies have attempted to gain a better understanding of the diverse spectral properties of agricultural nets (Agüera et al., 2008; Hemming et al., 2008; Levin et al., 2010). Using spectrometry, Sica and Picuno (2008) successfully identified a common absorption feature of nets at around 1,800 nm, while Shahak et al. (2004) found that different nets had similar responses in the near-infrared portion of the electromagnetic spectrum. However, these findings have had limited success when applied to satellite remote sensing and mapping applications (Agüera et al., 2008). Furthermore, authors have investigated methods for mapping agricultural nets using several different classification approaches (Aguilar et al., 2016; Carvajal et al., 2006; Hörig et al., 2001). These studies found that very high-resolution imagery, as acquired by WorldView or Quickbird satellites, was effective for this purpose. However, the use of medium-resolution sensors was unsuccessful and required further investigation (Levin et al., 2010; Novelli et al., 2016).

Van Niekerk et al. (2018) used remote sensing to quantify the water usage of irrigated crops, but had to exclude areas that used agricultural nets due to their effect on the spectral reflection of crops and the uncertainties they cause in modelling evapotranspiration using remotely sensed data. Figure 4.4 illustrates the impact of nets on remotely sensed ET_{act} estimates from FruitLook (Jarmain, 2019). It is not clear whether the lower evapotranspiration estimates of netted table grapes are the result of improved water use efficiency (which is to be expected) or whether it is caused by differences in the spectral responses of crops under nets. For instance, Figure 4.5 shows that there is a dramatic difference in the NDVI values for table grapes grown under nets compared to those grown conventionally (Jarmain, 2019). Given that NDVI (or at least some variant of it) is often used in evapotranspiration models, these differences likely affect the evapotranspiration estimates.

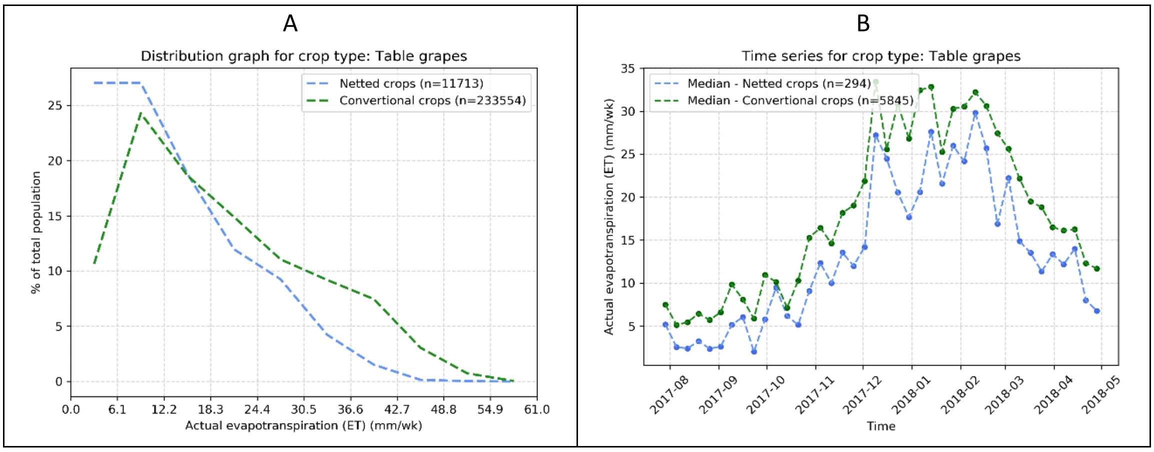


Figure 4.4: The impact of nets on evapotranspiration estimates for table grapes using remotely sensed data, with (A) histogram of evapotranspiration and (B) evapotranspiration time series (Jarmain, 2019)

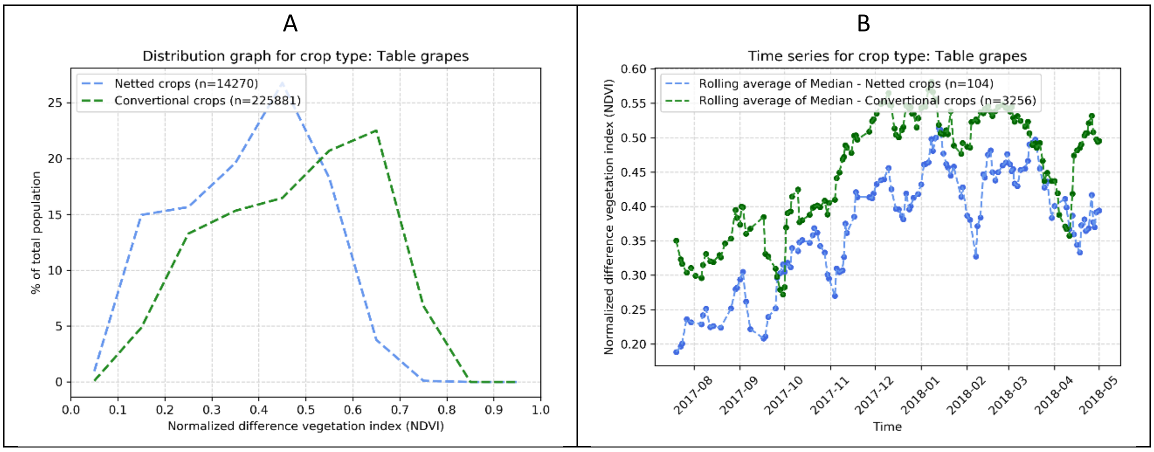


Figure 4.5: Comparison of FL NDVI for table grapes grown under nets and those grown in conventional vineyards, with (A) a histogram of NDVI and (B) an NDVI time series (Jarmain, 2019)

In order to effectively utilise remote sensing in the agriculture sector, new methods are required for mapping crops, estimating water use by crops, assessing plant health and determining crop yield for crops under nets. The development of such methods would require a better understanding of the spectral properties of agricultural nets from a satellite remote sensing perspective. More research is required regarding both the use of high-resolution, cost-effective satellite imagery, such as Sentinel-2 imagery, and different classification approaches for mapping agricultural nets and developing methods that are effective in analysing the status of crops under nets.

4.2.4 Summary and conclusion

For an entirely independent water footprint assessment to be performed without inputs from industry, various data sources related to agricultural fields are required, for example, the physical field boundaries, the type of crop (e.g. table or wine grapes), as well as additional information on the cultivation practices (i.e. whether nets are used). In the preceding sections, progress with automated field boundary delineation and crop type mapping was described. In addition, research into the automated identification of fields with agricultural nets and of the impact of these nets on parameters like evapotranspiration were briefly described. Although progress has been made, more work is required before these approaches can be implemented in an independent WFA process.

4.3 MODELLING AND EXTRAPOLATING SPATIAL EVAPOTRANSPIRATION DATASETS

4.3.1 Spatial extrapolation of evapotranspiration

The crop water use or evapotranspiration often constitutes the largest water use considered in the water footprint calculations and the WFA process. Evapotranspiration data generated with the ETLook model and available through FruitLook was the primary data source for the analyses described below. Various other evapotranspiration datasets are available for the Western Cape, but at different (lower) spatial and temporal resolutions. A comparison between the FL evapotranspiration data and three other data sources was undertaken to better understand how these datasets complement each other and to determine their viability in future water footprint assessments. This section summarises the methods and results reported on in detail in the project progress reports.

4.3.1.1 Evapotranspiration data considered

Three evapotranspiration datasets were compared to the FL data: the 250 m WRC 2014/15 ET dataset, the 250 m WaPOR ET dataset and the 1 000 m MOD16 dataset, detailed in Chapter 3.2.2.4.

The comparison was undertaken for the period August 2014 to July 2015 (due to the limitation of the WRC 2014/15 dataset) at field level. All vineyards in the Western Cape 2013 Flyover dataset that fall within the extent of the 2014/15 FL ET dataset were considered. The field boundaries used in the analysis were extracted from the Western Cape 2013 Flyover data, resulting in 85,254 fields covering 302,868 ha. The crop type information of the extracted fields is summarised in Table 4.3.

Table 4.3: Summary of crop types considered in the evapotranspiration comparison

Generalised crop type	Number of fields	Minimum area (ha)	Maximum area (ha)	Mean Area (ha)	Total area (ha)	Percentage area (ha)
Grapes	37,716	0.02	77.3	2.4	91,519.3	30.2
Grains	4,866	0.06	155.9	12.3	59,923.2	19.8
Planted pastures	9,052	0.03	175.8	6.3	56,946.7	18.8
Pome fruit	13,365	0.03	59.5	2.0	26,633.8	8.8
Non-crop (fallow, weeds, natural grazing)	5,511	0.01	210.3	4.4	24,140.2	8.0
Stone fruit	6,835	0.02	31.4	1.9	12,848.4	4.2
Citrus fruits	4,002	0.01	51.8	2.3	9,077.2	3.0
Vegetables	1,196	0.03	132.3	4.4	5,235.0	1.7
Teas	458	0.31	79.2	10.5	4,830.8	1.6
Oil seeds	233	0.33	92.6	19.0	4,437.2	1.5
Lupines	282	0.24	151.8	14.2	3,991.3	1.3
Tree fruit – other	747	0.08	24.1	2.0	1,470.2	0.5
Flowers	499	0.10	13.0	1.6	794.6	0.3
Berries	268	0.03	12.3	1.7	451.1	0.1
Other crops	224	0.07	36.3	2.7	568.5	0.2
Total	**85,254**	**-**	**-**	**-**	**302,868**	

Table 4.3 indicates that the highest proportion (30.2%) of the fields considered were planted with grapes, with other major crop types including grain (19.8%), planted pastures (18.8%) and pome fruit (8.8%). Although the crop type data is dated 2012/13, it was assumed that the perennial crops (especially grapes) would remain relatively unchanged up to the period for which the different sources of evapotranspiration data was available (August 2014 to July 2015).

4.3.1.2 Mixed pixel effect on vineyards

In remote sensing, mixed pixels occur when a pixel is not representative of a single homogenous land cover category (Campbell, 2007). The lower the spatial resolution of an evapotranspiration dataset, the more susceptible it is to the mixed pixel effect. For example, a single pixel of the 250 m evapotranspiration dataset (6.25 ha) is often representative of multiple land cover classes. This will have a significant effect on the smaller blocks planted with grapes, which have a mean field size of 2.4 ha (roughly a third of a 250 m pixel). This means that the mean evapotranspiration value for a small field will be influenced by the surrounding land cover, resulting in either an over- or an underestimation of its true evapotranspiration value. This effect is illustrated in Figure 4.6, which shows a significant underestimation (compared to the FL data) of ET_{act} for both the WRC 2014/15 and MOD16 databases for all three vineyards.

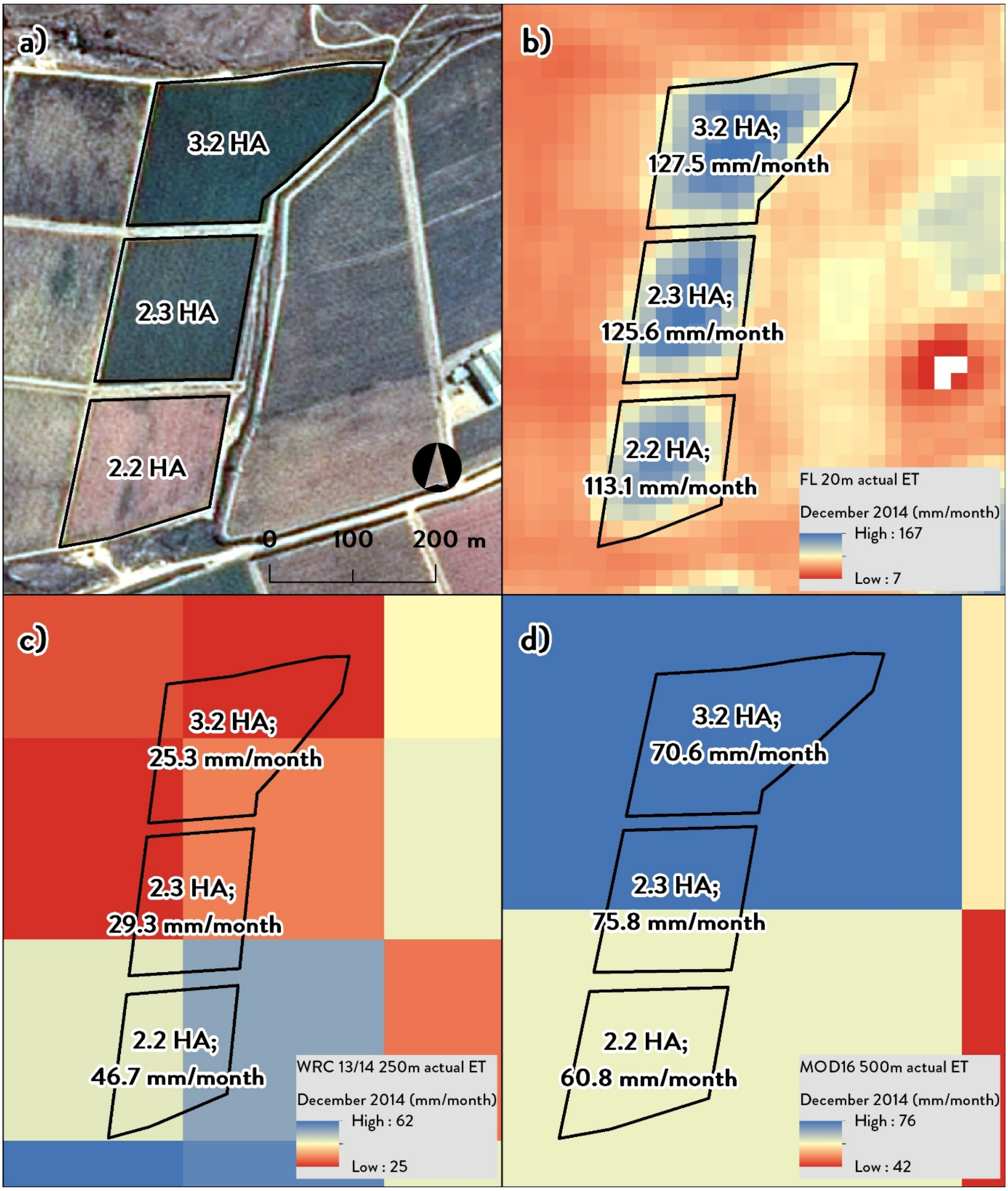


Figure 4.6: The effect of spatial resolution on vineyards, with (a) representing SPOT 6/7 2015 true colour mosaic, (b) 20 m FL ET data, (c) 250 m WRC 2014/15 ET data, and (d) 500 m MOD16 ET data

4.3.1.3 Vineyard size analysis

The effect of mixed pixels is particularly significant when accounting for the size of vineyards in the Western Cape. This is illustrated in Figure 4.7, which shows the frequency distribution of vineyards by size. More than 80% of vineyards in the study area had areas of less than 4 ha, i.e. smaller than one pixel of the WRC 2014/15, WaPOR or MOD16 ET datasets. Figure 4.7 shows the distribution of the vineyard sizes between 0 and 4 ha.

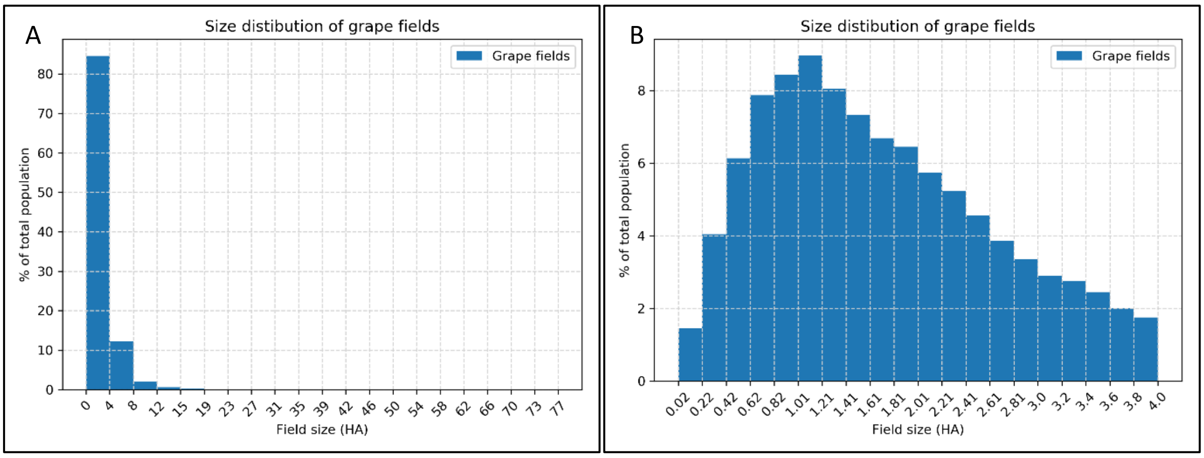


Figure 4.7: Frequency distribution of vineyard size for (A) all vineyards and (B) small (0-4 ha) vineyards

4.3.1.4 Statistical analysis of evapotranspiration data

The monthly mean of the FL evapotranspiration values of vineyards smaller than 4 ha was compared to that of the WRC 2014/15, WaPOR and MOD16 evapotranspiration values. The results are shown in Figure 4.8. Compared to FruitLook, both the WRC 2014/15 and WaPOR datasets appear to underestimate evapotranspiration from November to January, while overestimating evapotranspiration from March to April. This over- and underestimation is less accentuated in the WRC 2014/15 dataset, likely because more detailed climate and land cover data were used in its modelling. The MOD16 dataset appears to grossly underestimate evapotranspiration for most of the year compared to the other data. This is likely due to its larger spatial resolution (500 m), which results from the surrounding land cover types (with low evapotranspiration) being included in the analysis and low overall evapotranspiration values per field calculated.

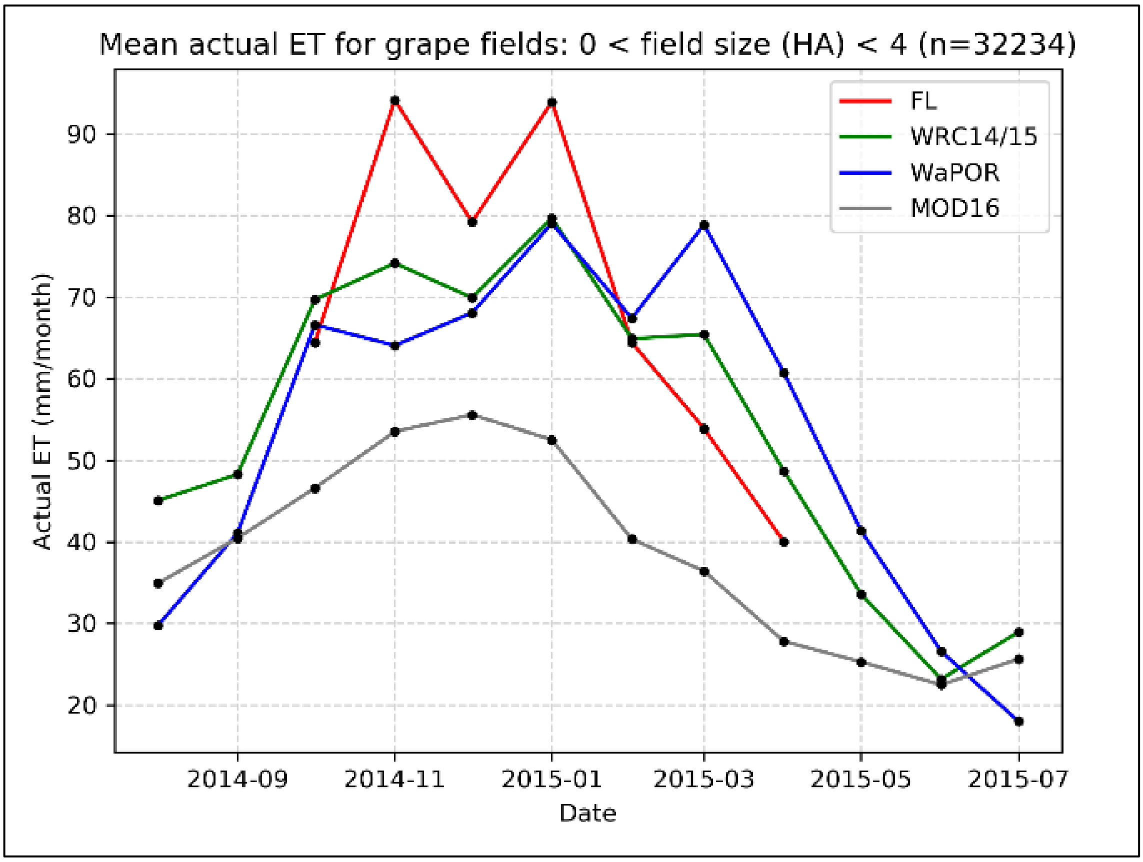


Figure 4.8: Monthly evapotranspiration from FruitLook, WRC 2014/15, WaPOR and MOD16 for vineyards smaller than 4 ha

Frequency distributions and quantitative analysis measures in the form of linear, quadratic and cubic regression, Pearson correlations and root mean square error (RMSE) were calculated for the months showing the highest deviation from the FL data: November 2014 and March 2015. The results of these analyses can be seen in Figure 4.9 and Figure 4.10.

For November 2014, the MOD16 dataset shows poor correlation with the FL data (R = 0.306), although this marginally improves in March (R = 0.543). A similarly weak correlation can be seen with the WaPOR, showing correlation values with the FL data of R = 0.375 and 0.477 for November and March, respectively. Conversely, the correlations between the WRC 2014/15 and FL datasets are consistently higher. November 2014 shows a correlation of R = 0.504, improving to R = 0.659 in March (towards the end of the growing season). Given that the correlations between WaPOR and FruitLook are consistently weaker than those of WRC 2014/15, it is clear that the use of local land cover and climate data in the evapotranspiration modelling makes a significant difference.

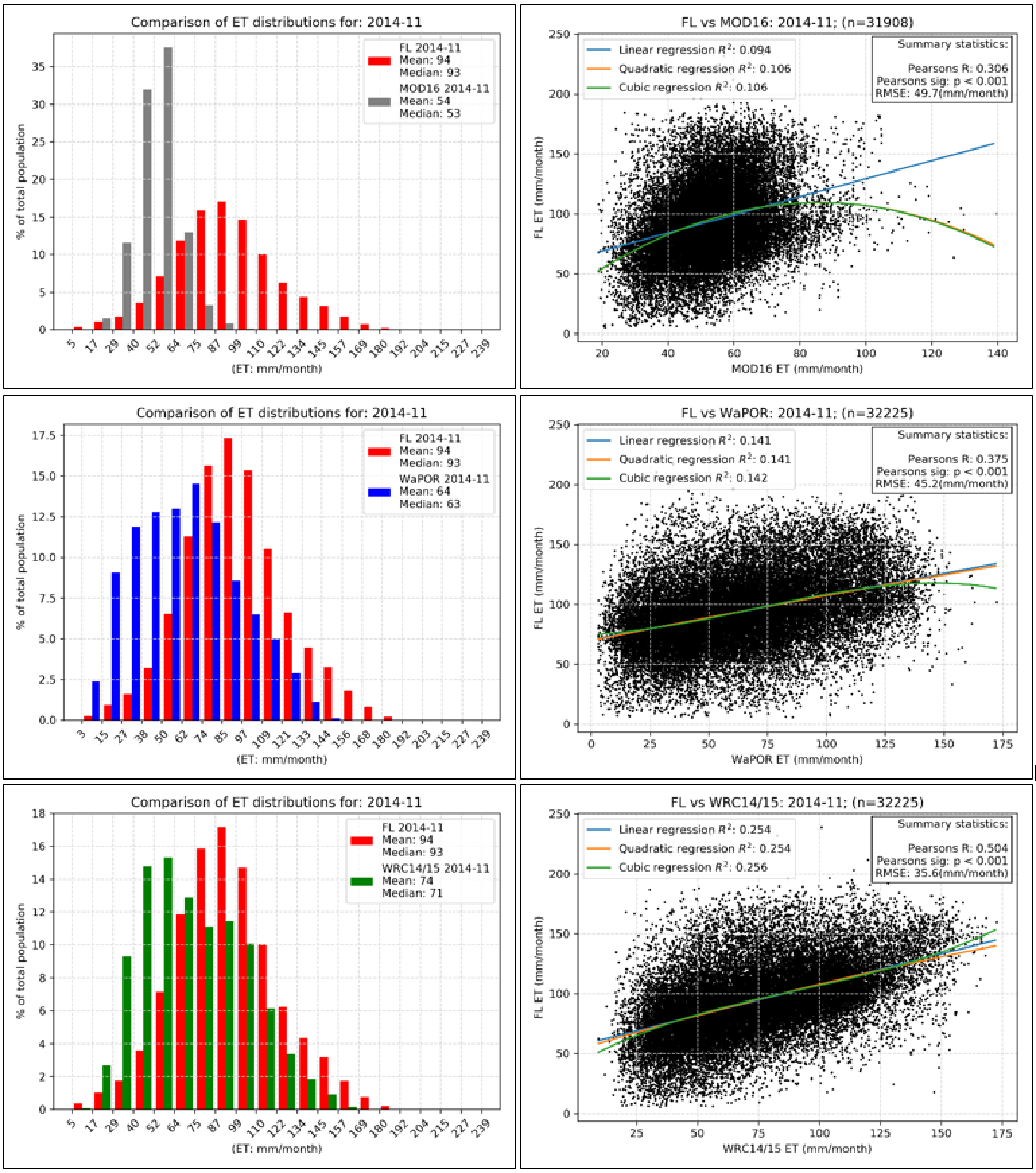


Figure 4.9: Descriptive and correlation and regression statistics for evapotranspiration comparisons: November 2014

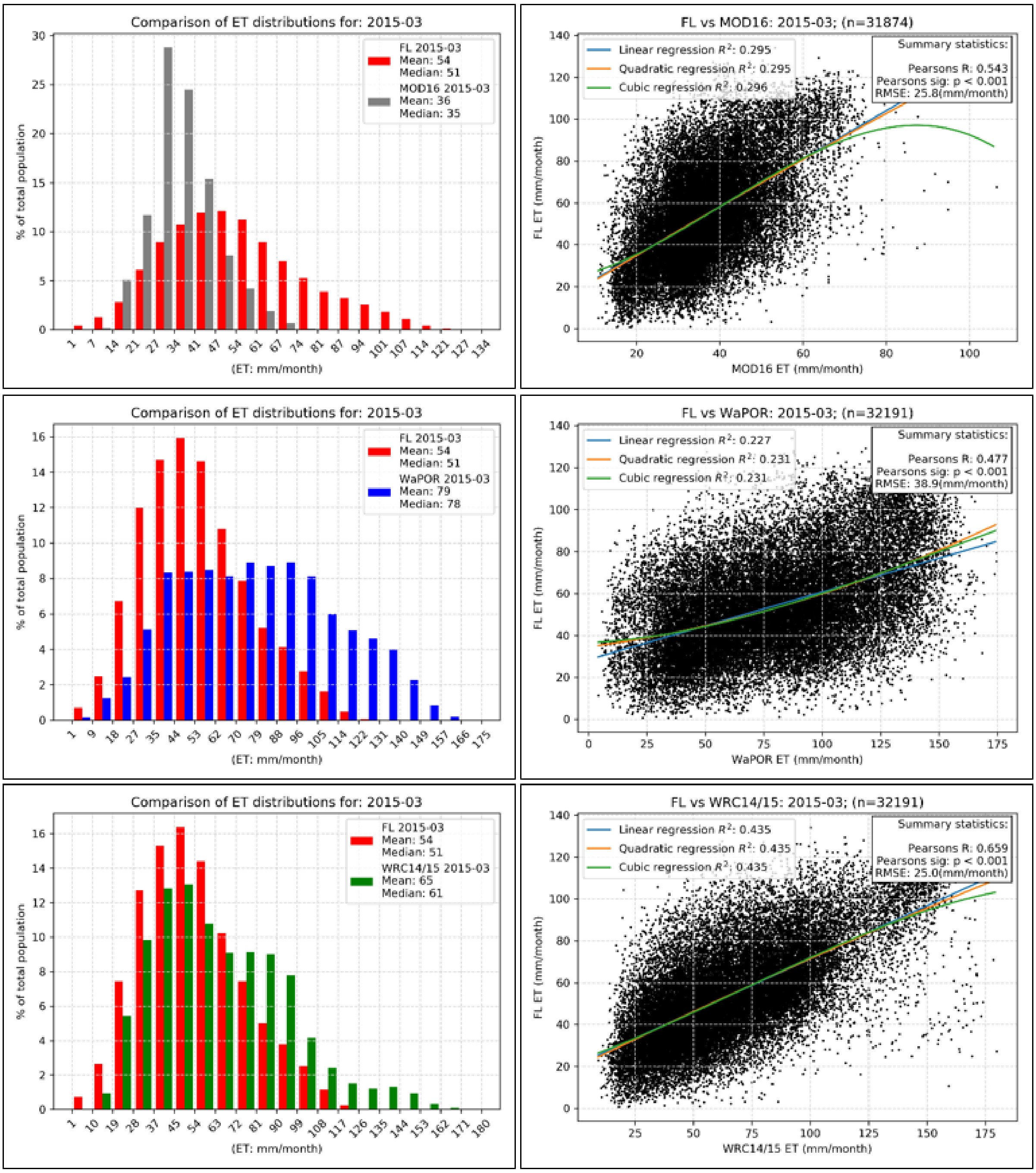


Figure 4.10: Descriptive and correlation and regression statistics for evapotranspiration comparisons: March 2015

The results of the evapotranspiration dataset comparisons are encouraging, as the lower-resolution WRC 2014/15 and WaPOR datasets are generally reasonably correlated with those of FruitLook, especially when the accumulative evapotranspiration over the growing season is considered. For instance, the median accumulative evapotranspiration of vineyards smaller than 4 ha from October 2014 to April 2015, based on the FL data, was 470 mm, compared to the median values for WRC 2014/15 and WaPOR of 444 mm and 467 mm, respectively. Another notable finding is that the correlation among datasets is higher at the beginning and end of the growing season, which suggests that the lower-resolution WRC 2014/15 and WaPOR datasets can potentially be used as surrogate evapotranspiration sources during the months for which FL data was not available. However, the results also show that caution should be applied when using the 250 m and 500 m data sources for water footprint assessments.

4.3.2 Temporal evapotranspiration modelling

The evapotranspiration datasets from FruitLook were used in this study to estimate specifically WU_{green}, and WU_{blue} at field level. When the proposal for this research was submitted, it was unclear whether the FL data would be available for a full 12-month period for the 2018/19 season. Hence, a substantial amount of work went into developing a methodology for extending the eight- to nine-month FI datasets to a 12-month period. Although this approach was ultimately not applied or required in this study, the methodology and findings are still of value and described briefly here. A more detailed breakdown of the analysis is given in the progress report detailing the preparation of datasets for the WFA process.

4.3.2.1 Modelling methodology

The period for the model building was four FL growing seasons: 2014/15, 2015/16, 2016/17 and 2017 /18. Conventional statistics (regression), machine learning and imputation methods using ancillary datasets were examined for modelling the missing months of FL biophysical values. Two biophysical variables, ET_{act} and biomass production, were considered as the target (dependent) variables for modelling (Table 4.4). The explanatory (independent) variables consisted of additional evapotranspiration and Vegetation Index (VI) data (Table 4.4). All the biophysical datasets (Table 4.4) were standardised to a monthly period for comparison purposes. For more details on the datasets used, see Chapter 3.2.2.

Table 4.4: Summary of the spatial data used in the FL temporal modelling.

Dataset	Spatial resolution	Time frame (year – months)
a) FruitLook ET dataset (mm/week) to (mm/month) (FL ET)	20 m	2014 – 10, 11, 12 2015 – 1, 2, 3, 4, 10, 11, 12 2016 – 1, 2, 3, 4, 8, 9, 10, 11, 12 2017 – 1, 2, 3, 8, 9, 10, 11, 12 2018 – 1, 2, 3, 4
b) FruitLook biomass (kg/ha/week) to (kg/ha/month) (FL Bio)	20 m	2014 – 10, 11, 12 2015 – 1, 2, 3, 4, 10, 11, 12 2016 – 1, 2, 3, 4, 8, 9, 10, 11, 12 2017 – 1, 2, 3, 8, 9, 10, 11, 12 2018 – 1, 2, 3, 4
c) WaPOR ET (mm/10-days) to (mm/month) (WaPOR)	250 m	2014 – 1 to 12 2015 – 1 to 12 2016 – 1 to 12 2017 – 1 to 12 2018 – 1 to 12
d) MOD/MYD 16 ET (mm/8-days) to (mm/month) (MxD16)	500 m	2014 – 1 to 12 2015 – 1 to 12 2016 – 1 to 12 2017 – 1 to 12 2018 – 1 to 12
e) HRVIs; Sentinel-2/Landsat-8: NDVI (maximum monthly VI – unitless) (HRVI)	30 m	2014 – 1 to 12 2015 – 1 to 12 2016 – 1 to 12 2017 – 1 to 12 2018 – 1 to 12
f) Low-resolution vegetation indices; MODIS: NDVI and EVI (average 16-day composite – unitless) (MxD13 EVI, MxD13 NDVI) (LRVI)	250 m	2014 – 1 to 12 2015 – 1 to 12 2016 – 1 to 12 2017 – 1 to 12 2018 – 1 to 12

All vineyards extracted from the 2017 WCCC were used as the unit of analysis. The primary advantage of using a field-based over a pixel-based approach is the higher degree of scale-independence, as the resulting product is not restricted to a specific spatial resolution (e.g. 20 m or 250 m).

4.3.2.2 Evapotranspiration model building

Three different methods were tested to establish a relationship between the FL datasets and the ancillary datasets in order to model (interpolate and extrapolate) the FL biophysical variables for the missing months.

This first method was a conventional statistical approach in the form of multiple linear regression (MLR) analysis. The MLR is an extension of ordinary least-squares (OLS) regression that involves more than one explanatory variable to predict the outcome of one dependant (target) variable. The result from the MLR is an equation (model) and an R^2 value illustrating the model's "goodness-of-fit". The R^2 value, however, only explains the variation within the model itself and is as such not an indication of how the model would perform on unseen data.

The second method was a machine learning algorithm: the random forest regressor. Random forest algorithms consist of an ensemble of decision trees and make use of bootstrapping and unit voting for each tree classifier (Breiman, 2001; Gislason et al., 2006). In contrast to the original implementations of the random forest (Breiman, 2001), which combines classifiers by giving each classifier a vote for a single class, a modified version of random forest that combines classifiers by averaging their probabilistic prediction was used in this study (Pedregosa et al., 2011). The random forest regressor was trained with 200 trees per forest with an unlimited tree depth. The random forest regressor similarly produces an R^2 value to illustrate the model's "goodness-of-fit".

A third method, matrix-completion imputation, was tested for filling the gaps in the FL time series. Multivariate imputation by chained equations is one of the principal methods for dealing with missing data (Azur et al., 2011; García-Laencina et al., 2010; Van-Buuren and Groothuis-Oudshoorn, 2010). Various imputation algorithms were automated in this study within a Python environment using the open-source library fancyimpute (Rubinsteyn, 2018). The imputation algorithms tested are listed in Table 4.5 (Little and Rubin, 1989; Van-Buuren and Groothuis-Oudshoorn, 2010).

Table 4.5: Imputation algorithms tested in evapotranspiration modelling

Imputation algorithm	Description
K-nearest neighbour impute	A nearest neighbour imputation technique that weights samples using the mean squared difference on features for which two rows both have observed data.
Soft impute	A matrix completions technique by iterative soft thresholding of singular value decomposition decompositions (Mazumder et al., 2010).
Iterative imputer	A strategy for imputing missing values by modelling each feature with missing values as a function of other features in a round-robin fashion.
Matrix factorisation	A method that directly factorises the incomplete matrices that are solved by gradient descent.

During preliminary experimentations, the iterative imputer outperformed the other imputation algorithms outlined in Table 4.5 and was thus chosen for model building. The iterative imputer does not provide any measure of model performance (e.g. R^2).

The RMSE was calculated within the experimental design to directly compare the three modelling techniques. The RMSE is the standard deviation of the predicted errors and presents an error value within the unit of measurement. This can be used to calculate a percentage error. It should be noted that, since each error is proportional to the size of the squared error, larger errors will have a disproportionately large effect on the RMSE, making it sensitive to outliers.

4.3.2.3 Experimental design

Experimentation was done on table grapes and wine grapes, respectively, to limit in-class variation and improve model accuracy. The experimentation design is summarised in Figure 4.11. Each experiment was iterated 50 times. A 70% random sample was selected for model training, and 30% of samples were used for model testing in each iteration.

The blue boxes in Figure 4.11 illustrate the quantitative outputs from the model-building process. The random forest regressor and the iterative imputer techniques have "black box" characteristics, which means that it is difficult to gain insights into how the model interpolates the dependent variable. The MLR, on the other hand, produced full model parameters, allowing for easy model recreation and a better understanding of what happens during the interpolation process. The (50-fold) average RMSE values from each model were used for model comparison.

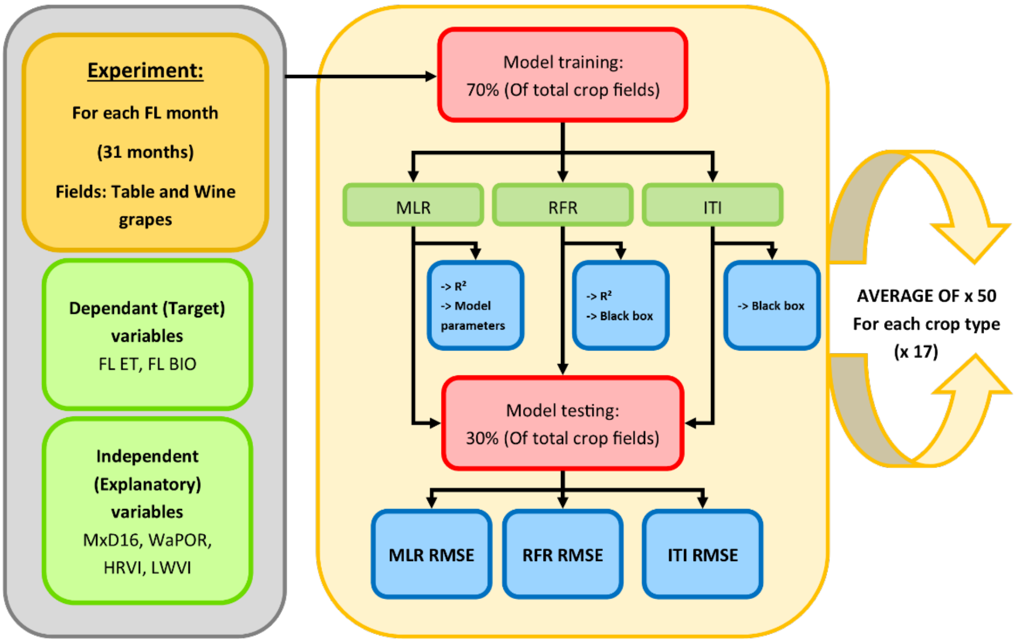


Figure 4.11: Experimental design for model building

4.3.2.4 Results and discussion

Results of the modelling of evapotranspiration and biomass production are summarised in Table 4.6 and Table 4.7, respectively. The mean percentage error of all the analyses are ~15% for both evapotranspiration and biomass production. The random forest regressor method slightly outperformed the MLR and iterative imputer methods. Table grapes achieved slightly better results over wine grapes, even though they were modelled on a smaller sample size.

Table 4.6: Results from Experiment 2 of the FL ET dataset. The RMSE values, together with the mean column are presented in mm/month units

			OLS		Random forest		Iterative imputer	
Number of fields	**Crop type**	**Mean**	**RMSE**	**Percentage error**	**RMSE**	**Percentage error**	**RMSE**	**Percentage error**
5,859	Table grapes	96.6	13.1	13.6	12.7	13.1	13.1	13.6
40,246	Wine grapes	66.6	11.8	17.7	10.3	15.5	11.8	17.7
	Average	**81.6**	**12.45**	**15.3**	**11.5**	**14.1**	**12.45**	**15.3**

Table 4.7: Results from Experiment 2 of the FL Bio dataset. The RMSE values, together with the mean column are presented in kg/ha/month units

			OLS		Random forest		Iterative imputer	
Number of fields	**Crop type**	**Mean**	**RMSE**	**Percentage error**	**RMSE**	**Percentage error**	**RMSE**	**Percentage error**
5,859	Table grapes	3,535	475	13	453	13	475	13
40,246	Wine grapes	2,096	409	20	360	17	429	20
	Average	**2,815.5**	**442**	**15.7**	**406.5**	**14.4**	**452**	**16.1**

Model simplicity was preferred in the process of interpolating the biophysical variables for table and wine grapes. Therefore, although the random forest model slightly outperformed the MLR model, the latter was preferred due to its transparency and potential for reimplementation.

The MLR models used in interpolating the evapotranspiration and biomass production for table and wine grapes are presented in Eq. 4.1 and Eq. 4.2 (table grapes) and Eq. 4.3 and Eq. 4.4 (wine grapes), respectively.

$$\begin{aligned}\boldsymbol{ET_{tablegrapes}} = {} & -0.085577103(WaPOR) + 0.056324373(MxD16) \\ & - 0.00171841(MxD13\ EVI) + 0.005285735(MxD13\ NDVI) \\ & + 1.634478083(HRNDVI) - 18.63726607\end{aligned} \quad (4.1)$$

with mean R^2: 0.74 and mean RMSE: 13.15 mm/month.

$$\begin{aligned}\boldsymbol{BIO_{tablegrapes}} = {} & 3.657101145(WaPOR) + 7.657060478(MxD16) \\ & - 0.17401765(MxD13\ EVI) - 0.061835557(MxD13\ NDVI) \\ & + 84.92362158(HRNDVI) - 2324.436651\end{aligned} \quad (4.2)$$

with mean R^2 0.85 and mean RMSE: 4.81 kg/ha/month.

$$\begin{aligned}\boldsymbol{ET_{winegrapes}} = {} & 0.004362612(WaPOR) + 0.086771201(MxD16) \\ & - 0.003758548(MxD13\ EVI) + 0.004639149(MxD13\ NDVI) \\ & + 1.509862281(HRNDVI) - 12.33985791\end{aligned} \quad (4.3)$$

with mean R^2: 0.7 and mean RMSE: 12 mm/month.

$$\begin{aligned}\boldsymbol{BIO_{winegrapes}} = {} & 2.11577495(WaPOR) + 12.65348401(MxD16) \\ & - 0.17499954(MxD13\ EVI) + 0.196048754(MxD13\ NDVI) \\ & + 71.43879501(HRNDVI) - 1958.506817\end{aligned} \quad (4.4)$$

with mean R^2 0.8 and mean RMSE: 409 kg/ha/month.

4.3.3 Crop water use under nets

The use of hail netting for the cultivation of table grapes is an accepted practice in the northern summer rainfall region of South Africa. Recently, there has been a growing interest in the cultivation of table grapes under netting in the Western Cape and the Lower Orange River area, raising questions about water management and water use and evapotranspiration of crops cultivated under nets (also see Chapter 4.2.3).

Accurate estimation of vineyard evapotranspiration is important for irrigation scheduling in order to optimise yield, growth and quality (Myburgh, 2016). Published results of studies on water relations and the evapotranspiration of table grapes in South Africa include the work of Saayman and Lambrechts (1995), Myburgh (1996, 2012, 2016), Myburgh and Howell (2006a, 2006b, 2007a, 2007b, 2012), Klaasse et al*.* (2007) and Eustice (2008). None of these studies included vineyards under netting.

Research results (Avenant, 1994; Avenant and Avenant, 2002), from a study conducted at Roodeplaat experimental farm in the northern summer rainfall region of South Africa, indicated a 15% decrease in water use where hail netting with a 20% shade effect was used. Several South African table grape producers report observations of decreased water use under nets, but other than the study of Avenant (1994), no scientific data exists to support these observations. There are a few international publications regarding the effect of netting on the water use of table grapes, all conducted in Mediterranean climates (Rana et al., 2004; Moratiel and Martínez-Cob, 2012; Suvacarev et al., 2013). None of these was conducted over a full seasonal cycle or included uncovered plots with no netting for comparison. Developing a methodology for estimating evapotranspiration for table grapes under nets could benefit the industry by providing parameters to be used for the irrigation scheduling of table grape vineyards under netting in South Africa.

A project to investigate the water use of table grapes under netting in the Lower Orange River Region, co-funded by the Department of Agriculture in the Northern Cape and SATI, commenced in the 2018/19 season. The research aimed to determine whether netting decreases water use and increases the water use efficiency of table grape vineyards. A field trial is being conducted on a mature, commercial block with Sultanina H5 as scion cultivar and Ramsey as the rootstock in Kanoneiland. The experimental block is divided into two experimental subplots: one part is covered with hail netting and the other part is uncovered (no netting). In each of the experimental subplots, various parameters are measured: climate data, evapotranspiration, temperature, soil water content and irrigation volumes. Phenology, vegetative growth, fertility, yield and grape quality of the subplots under nets are compared to the subplots without nets. Physiological measurements (photosynthesis, stomatal conductance and stem water potential) are being done to link the water use of table grapevines under netting with the effect of netting on the physiological activity of the grapevine. The water use efficiency and WF_{blue} will be determined for both subplots. Data collected for the period 1 September 2018 to 31 August 2019 is currently being analysed and will hopefully enhance our understanding of the impact of nets on table grape water use.

4.3.4 Summary and conclusion

Since evapotranspiration often constitutes the largest water use considered in the water footprint calculations of a crop, accurate estimates of evapotranspiration are required. Since various evapotranspiration datasets are available for the Western Cape, but at different spatial and temporal resolutions, a comparison of different evapotranspiration sources was undertaken to better understand how these datasets complement each other, and to determine their viability in future water footprint assessments. The results of the evapotranspiration dataset comparisons are encouraging, as the lower-resolution WRC 2014/15 and WaPOR datasets are generally reasonably correlated with those of FruitLook, and the correlation among datasets is higher at the beginning and end of the growing season. However, the results show that caution should be applied when using the 250 m and 500 m data sources for water footprint assessments, since it shows large deviations from the higher-resolution FL evapotranspiration data. Therefore, for field-level water footprint assessments in the Western Cape, the available high-resolution FL evaptranspiration data provides the best option at present.

4.4 ESTIMATING CROP YIELD OF TABLE GRAPES

Water footprint calculations at field level require knowledge of crop yield. Jarmain et al. (2018) investigated the use of remote sensing, machine learning and statistical multivariate analysis to model wine grape yield as part of Winetech-funded research. Large datasets that consist of thousands of data points across three production regions in the Western Cape were used in the research. The results illustrated the complexities of wine grape yield modelling and the strong impact of production regions on yield modelling. Few cultivars and region-specific yield models showed potential. However, the results indicated that more research is required.

In the section that follows, the focus falls on table grape yield modelling, utilising the production data collated as part of this project.

4.4.1 Data preparation

The location and extent (boundaries) of hundreds of table grape vineyard blocks were obtained for several packhouses and in various formats (see Chapter 3.2.3). Information on the names, farm names and individual block numbers of packhouses was obtained for each block and added as attributes to the spatial data. These datasets were standardised and combined into one spatial geodatabase, and all the biophysical FL variables were extracted for each block at a monthly interval for the 2013/14 to 2018/19 seasons (see Chapter 3.2.2).

Production data (in t/ha and t/block) was obtained for each of the farms or packhouses and represented total production from export, local distribution, and winemaking and drying. In addition, data for the following other variables related to the vineyard was obtained: production region, farm name, packhouse name, block number, block size, cultivar, rootstock, trellis system and vineyard row width.

Additional variables were calculated from the supplied data, e.g. plant age (the year being considered minus the vineyard plant year) and plant density = 10 000 / (row width x vineyard spacing).

The spatial geodatabase was joined to the production dataset using a unique code that was generated by combining the packhouse name, farm name and block number. Numerous blocks with missing or zero production data were excluded from the database.

4.4.2 Modelling methods

Regression modelling and machine learning approaches were used to investigate the relationships between table grape yield and the remotely sensed FL data. Regression analysis is used to describe a functional relationship between variables, where the value of one variable (the dependent variable) can be determined by the value of a second variable (the independent or predictor variable), but where the reverse is not necessarily true (McKillup, 2006). More simply put, the values of the dependent variable can be determined from a predictor variable.

Machine learning undertakes the classification of a categorised target variable using a series of predictor variables. The target variable in this instance was yield in tons per hectare, categorised into four nominal yield classes from low to very high (see Table 4.8).

Table 4.8: Nominal classes for the target variable table grape yield

Class	Class ranges (t/ha)	
	Minimum	Maximum
Low	0	11.25
Medium	11.25	22.5
High	22.5	33.7
Very high	33.7	80

The FruitLook variables that were used as predictors are listed in Table 4.9. The vineyard variables also considered as predictors are shown in Table 4.10.

Table 4.9: FruitLook variables used as machine learning model predictors

FruitLook predictors	Time frame
Biomass production	Monthly from 2013/14 to 2018/19
Biomass water use efficiency	Monthly from 2013/14 to 2018/19
Actual evapotranspiration	Monthly from 2013/14 to 2018/19
Evapotranspiration deficit	Monthly from 2013/14 to 2018/19
Leaf Area Index	Monthly from 2013/14 to 2018/19
Normalised Difference Vegetation Index	Monthly from 2013/14 to 2018/19
Nitrogen in a plant	Monthly from 2013/14 to 2018/19
Nitrogen at the top of the plant	Monthly from 2013/14 to 2018/19

Table 4.10: Vineyard variables used as machine learning model predictors

Vineyard predictors	Description
Production region	Olifants River, Hex River or Berg River
Field size	Vineyard field size in hectares
Cultivar	Cultivar type
Rootstock	Rootstock type
Trellis	Trellis type
Vine spacing	Vine spacing in metres
Row spacing	Row spacing in metres
Plant density	Vineyard planting density
Monthly rainfall data	Rainfall for the 2018/2019 season per month (mm)
Plant year	Planting year
Plant age	Current age of the vineyard
Block size	Area in hectare

4.4.3 Model design

Linear, quadratic and cubic regression models were applied, with tons per hectare as the dependent variable. The predictor variables (see Table 4.9 and Table 4.10) were individually regressed against the yield values. Nominal variables (i.e. production region, cultivar, rootstock and trellis types) were excluded, as regression modelling requires numerical values as input.

Twenty-two yield modelling experiments were carried out by applying decision tree and random forest machine learning models on the following 11 sets of predictor variables:

1. All vineyard and FL variables from all seasons
2. Vineyard and 2016/17 FL variables
3. Vineyard and 2017/18 FL variables
4. Vineyard and 2018/19 FL variables
5. Vineyard, 2016/17, 2017/18 and 2018/19 FL variables
6. Vineyard variables only
7. Vineyard variables and rainfall
8. FruitLook 2016/17 variables only
9. FruitLook 2017/18 variables only
10. FruitLook 2018/19 variables only
11. FruitLook 2016/17, 2017/18 and 2018/19 variables

Each experiment was labelled according to the variable set (1-11) and machine learning algorithm used, e.g. Experiment RF01 used the random forest algorithm with dataset 1 (vineyard variables and FL variables from all seasons) as input.

4.4.4 Results

The ten strongest regression models are listed in Table 4.11. The strongest model was attained when N_{top} (Month 1, 2018) was fitted to a cubic model (R^2 = 0.085), followed by a cubic model (R^2 = 0.078) fitted to BioWUE (Month 2, 2018). None of the predictors achieved an R^2 greater than 0.1, which suggests that yield cannot be described with any of the individual variables considered in this research.

Table 4.11: Top 10 results of the regression modelling

Regression model	Predictor	R^2
Cubic regression	N_{top} (Month 1, 2018)	0.085
Cubic regression	BioWUE (Month 2, 2018)	0.078
Cubic regression	ET_{def} (Month 2, 2017)	0.077
Cubic regression	BioWUE (Month 7, 2017)	0.069
Cubic regression	ET_{def} (Month 0, 2017)	0.069
Quadratic regression	BioWUE (Month 7, 2017)	0.067
Cubic regression	N_{plant} (Month 1, 2018)	0.065
Cubic regression	Block size	0.063
Cubic regression	BioWUE (Month 6, 2017)	0.062
Cubic regression	ET_{def} (Month 6, 2018)	0.06

The multivariate decision tree and random forest modelling results for all the experiments are listed in Table 4.12. Poor results were achieved by both machine learning models (< 50%), although random forest produced slightly better models in general. The best model was produced when vineyard and FL 2017/18 predictors were used as input to random forest, resulting in a model accuracy of 45.1%. The best-performing decision tree model (vineyard variables and rainfall) produced an accuracy of 40.5%.

Table 4.12: Decision tree and random forest machine learning results

Model	Experiment	Set of predictors	Number of predictors	Accuracy (%)
Decision tree	DT01	All predictors	358	34.1
	DT02	Vineyard variables and FL 2016/17	106	38.5
	DT03	Vineyard variables and FL 2017/18	138	33.8
	DT04	Vineyard variables and FL 2018/19	106	36.7
	DT05	Vineyard variables and FL 2016/17, 2017/18 and 2018/19	190	34.7
	DT06	Vineyard variables only	9	40.2
	DT07	Vineyard variables and rainfall	22	40.5
	DT08	FL 2016/17	84	36
	DT09	FL 2017/18	116	34.2
	DT10	FL 2018/19	84	30.6
	DT11	FL 2016/17, 2017/18 and 2018/19	168	40
Random forest	RF01	All predictors	358	35.8
	RF02	Vineyard variables and FL 2016/17	106	35.8
	RF03	Vineyard variables and FL 2017/18	138	45.1
	RF04	Vineyard variables and FL 2018/19	106	40.4
	RF05	Vineyard variables and FL 2016/17, 2017/18 and 2018/19	190	37
	RF06	Vineyard variables only	9	41.4
	RF07	Vineyard variables and rainfall	22	41.4
	RF08	FL 2016/17	84	39
	RF09	FL 2017/18	116	40.2
	RF10	FL 2018/19	84	37.4
	RF11	FL 2016/17, 2017/18 and 2018/19	168	33.9

The ten variables that contributed the most to the best-performing random forest and decision tree models are listed in Table 4.13. Area (ha) was found to be the predictor variable with the highest importance for the decision tree, whereas cultivar was the predictor with the best score for the random forest model.

Table 4.13: Top 10 variables for decision tree and random forest machine learning models

DT07		RF03	
Predictor	**Score**	**Predictor**	**Score**
Block size	31.38	Cultivar	3.05
Cultivar	19.15	LAI (Month 6, 2018)	2.91
Age	17.99	Bio (Month 1, 2017)	2.8
Irrigation type	5.28	BioWUE (Month 3, 2017)	2.5
Vine spacing	4.32	ET_{def} (Month 10, 2018)	2.37
Row spacing	4.11	BioWUE (Month 7, 2018)	1.93
Rainfall (Month 5)	3.84	ET_{def} (Month 7, 2018)	1.93
Trellis	3.67	Bio (Month 7, 2018)	1.85
Rootstock	3.45	ET_{act} (Month 6, 2017)	1.82
Production region	2.59	ET_{def} (Month 1, 2017)	1.76

4.4.5 Conclusions

The weak models obtained with the regression modelling were not unexpected, as it is known that yields are influenced by multiple factors. However, the regression modelling provided an indication of the variables that may play a role in yield estimations. The findings show that, apart from the block size and cultivar, the remote sensing variables were more informative than the characteristics of vineyards (collected from the producers), with N_{top} and BioWUE being the best-performing FL variables, which suggests that nitrogen content in the canopy and water use have some impact on table grape yields.

This result contrasts with Jarmain et al. (2018), who found that monthly NDVI (R^2 = 0.79) and LAI (R^2 = 0.79) were the most informative FL variables for predicting yields of wine grapes (Pinotage in the Coastal winegrowing region).

The poor machine learning results (45.1% for best-performing experiment, RF03) were disappointing and are likely attributed to the following factors:

- Too few samples
- Inaccurate target variable data (yield data)
- Inappropriate class breaks
- Too much variation (noise) in predictor variables
- Inappropriate predictor variables

Machine learning models generally require *n* samples (*s*) per class, where *n* is the number of predictor variables. Given that 358 predictor variables were considered in experiments RF01 and DT01, and given that four classes were targeted, a total of 358 x 4 = 1,432 samples are theoretically needed to produce a good model (only 229 were available).

However, the fact that the accuracies did not improve with a smaller set of predictor variables (e.g. experiments RF02 and DT02) suggests that sparseness (s << n) was not the main cause of the poor performance of the machine learning modelling.

Although all possible efforts were made to obtain accurate yield data from the producers, some errors may still be present in the data received. This could have increased accuracies. In addition, the class breaks used to produce the target yield classes (Table 4.8) may have introduced a differentiation between samples that could not be modelled by the algorithms. For instance, there is almost no difference between 33.6 and 33.8 t/ha, yet samples with such values would have been classified as "high" and "very high", respectively. Such subtle, but discrete boundaries between target classes can substantially reduce classification accuracies. This is accentuated if the class breaks are inappropriately chosen.

The quality of the predictor variables could also have influenced the machine learning results. Although random forest is known to be insensitive to noisy data, large discrepancies in the predictor variables (e.g. missing data) could have negatively influenced the models. It is likely that better results may be obtained with additional data cleaning.

The most likely explanation for the poor machine learning (and regression) results is that the chosen predictor variables do not adequately explain (or play a role in) yields. For instance, vineyard management (in the current season, as well as in previous seasons) is likely a key factor in production outputs, but this factor is not directly represented in the predictor variables considered.

4.5 SPLITTING EVAPOTRANSPIRATION INTO BLUE AND GREEN WATER USE

A water footprint consists of three components: a green, blue and grey component. Consumptive crop water use or evapotranspiration often constitutes most of the green and blue water use at field level. Often, the evapotranspiration, together with effective rainfall, is used to determine the green and blue water footprint fractions. In Phase 1 of this project, an approach was proposed to determine the WU_{green} and WU_{blue} components at field level, using estimates of ET_c. The approach was applied to a 10-day time step (initial approach). The effective rainfall was calculated using an equation proposed by the United States Department of Agriculture (USDA) Soil Conservation Service (USDA SCS method) (Smith, 1992).

4.5.1 Initial approach

Green water evapotranspiration was calculated with a time step of 10 days. The ET_c was obtained from FruitLook, and effective rainfall (decade) was calculated by the adjusted equation proposed by the USDA SCS:

$$P_{eff(dec)} = P_{tot(dec)} \frac{125 - 0.6P_{tot(dec)}}{125} \quad \text{for } P_{tot(dec)} \leq (250/3) \text{ mm} \tag{4.5}$$

and

$$P_{eff(dec)} = \frac{125}{3} + 0.1P_{tot(dec)} \quad \text{for } P_{tot(dec)} > (250/3) \text{ mm} \tag{4.6}$$

where $P_{eff(dec)}$ is the effective rainfall (mm) and $P_{tot(dec)}$ is the total rainfall (mm).

ET_{green} (mm/season) was calculated by the following equation:

$$ET_{green} = \sum_{Sep2}^{May1} \min\{P_{eff}, ET_c\} \tag{4.7}$$

Blue water evapotranspiration was calculated with a time step of ten days using the values of irrigation requirements and actual irrigation. Where available, irrigation requirements were calculated as $ET_c - P_{eff(dec)}$ and actual irrigation, expressed in mm/event, was calculated using the irrigation time (hours).

ET$_{blue}$ (mm/season) was calculated by the following equation:

$$ET_{blue} = \sum_{Sep2}^{May1} \min\{Irrigation\ requirement, Actual\ irrigation\} \quad (4.8)$$

It was proposed here that evapotranspiration (mm/season) could again be estimated as follows:

$$ET = ET_{blue} + ET_{blue} \quad (4.9)$$

and *CWU* is the total crop water use (m^3/ha) calculated as follows:

$$CWU = (ET_{blue} + ET_{blue}) * 10 \quad (4.10)$$

However, since reliable estimates of actual irrigation and irrigation requirements are not always available, ET_{blue} can also be estimated as follows:

$$ET_{blue} = ET_{actual} - ET_{green} \quad (4.11)$$

4.5.2 Second approach

Since the available spatial evapotranspiration data used in this study was prepared as monthly and seasonal totals, a different approach was sought and proposed. The approach, considering monthly estimates of rainfall and evapotranspiration (Brouwer and Heibloem, 1986), is described below.

$$P_{eff} = 0 \quad \text{for} \quad P_{tot} \leq 12.5\ mm \quad (4.12)$$

and

$$P_{eff} = 0.6P_{tot} - 10 \quad \text{for} \quad 12.5 < P_{tot} \leq 70\ mm \quad (4.13)$$

and

$$P_{eff} = 0.8P_{tot} - 25 \quad \text{for} \quad P_{tot} > 70\ mm \quad (4.14)$$

where P_{eff} is the effective rainfall (mm/month) and P_{tot} is the total rainfall (mm/month).

Subsequently, ET$_{green}$ (mm/month) can be calculated as follows:

$$ET_{green} = \min\{P_{eff}, ET_{actual}\} \quad (4.15)$$

and ET_{blue} (mm/month) estimated as follows:

$$ET_{blue} = ET_{actual} - ET_{green} \quad (4.16)$$

In this study and its various case studies, ET$_{green}$ and ET$_{blue}$ represented the consumptive crop water use, and were used in the field-level water footprint calculations.

4.5.3 Summary and conclusion

In order to express the water footprint in its different colour components – blue, green and grey – a means of calculating the individual components is required. Evapotranspiration often constitutes most of the green and blue water use at field level. The second approach outlined above, where monthly evapotranspiration and rainfall estimates are used, provided a means of calculating an ET_{green} and ET_{blue} component, which contributed to the WU_{green} and WU_{blue} estimates and were used in the field-level water footprint calculations.

4.6 FIELD-LEVEL BLUE WATER USE

4.6.1 Introduction

The water footprint describes the total volume of water, direct and indirect, used to produce a product. In table grape production, a substantial part of the WU_{blue} is at field level. Part of the WU_{blue} at field level is the result of irrigation and is often derived as a fraction of consumptive crop water use. The other WU_{blue} at field level comes from water use due to chemical spray applications, as described below.

There are very few published estimates of seasonal total water use and the water footprint for grape vineyards in South Africa. In order to optimise yield, growth and quality, accurate estimation of vineyard water use is needed for irrigation scheduling (Myburgh, 2016). Transpiration is primarily determined by the size of the leaf area per grapevine (Myburgh, 1998). Grapevines with similar leaf area trained onto horizontally orientated trellis systems transpired more than those on vertical trellises under the same atmospheric conditions (Myburgh, 2016). Most research on the water use and irrigation strategies of grapevines in South Africa was on wine grapes, where vertical trellis systems are used. Published results of studies on the water use of table grapes (where horizontal trellis systems are used) in South Africa include the work of Saayman and Lambrechts (1995), Myburgh (1996, 2012, 2016), Myburgh and Howell (2006a, 2006b, 2007a, 2007b, 2012), Klaasse et al. (2007) and Eustice (2008).

Vineyards' water use varies between regions, irrigation practices, canopy characteristics and vine vigour. Results from studies regarding annual irrigation requirements or applications of table and raisin grape vineyards trained onto horizontal trellis systems under South African conditions are inconsistent. They vary between 256 mm with low-frequency drip irrigation to 492 mm with the daily pulse drip irrigation of Dan-ben Hannah in the Berg River Valley (Myburgh and Howell, 2012), to 854 to 1,343 mm for flood-irrigated Sultanina in the Lower Orange River Valley (Myburgh, 2003a).

In Chapter 3.1.2, the estimation of one part of the WU_{blue} – associated with irrigation and ET_{blue} – was described. Below, the WU_{blue} fraction calculations associated with field-level chemical spray applications are described. Available chemical spray application records were assessed, and data summarised into lookup tables, which can be applied to a range of field-specific production conditions, taking cognisance of the region and cultivars.

4.6.2 Table grapes

The volume of water use for chemical and fertilizer spray applications (nutrition in Table 4.14) at the field level contributes to WU_{blue} and WF_{blue}.

In Chapter 3.1.2, the case studies conducted as part of this research, as well as field-level data records obtained (Section 3.2) are described. Representative commercial table grape production units and packhouses from the various production regions (and sub-regions) were selected after consultation and meetings with industry role players, for inclusion in this study. The regions are characterised by different climatic conditions, which impact on the vineyards' seasonal growth pattern, water use and need for chemical interventions.

The application of irrigation (which also forms part of the WF_{blue}) on these farms is aimed at the optimal supply of water during each phenological stage. Fertilization and pest/disease management practices contribute to WF_{grey} and WF_{blue} and are implemented on the farms according to standard practices for a cultivar and region. Other viticultural practices are applied as recommended to produce export-quality table grapes (SATI, 2017).

Since details pertaining to the volume of blue water used for fertilizer spray application (nutrition in Table 4.14), as well as pest and disease management practices, are not readily available, a lookup table was compiled to capture blue water use from these practices (Table 4.14). This lookup table makes provision for capturing data from the selected production units, grouped according to region and cultivar. The template includes an example of a "medium to high" input cultivar regarding plant bioregulator (PBR) use, as well as a "low" input cultivar. For a "medium to high" PBR input cultivar, PBRs are generally used for bunch thinning, berry size improvement and colour improvement. For a "low" PBR input cultivar, no PBRs are used, or PBRs are used for only one purpose (thinning, berry size improvement or colour improvement) and physical bunch manipulations are mainly applied.

To generate this table (Table 4.14), standard spray programmes, obtained from two different agrochemical companies (Viking and Nexus, supplied by BASF, 2019), were used. The table was compiled for the three regions included in the study and situated in the Western Cape: the Hex River Valley, Berg River Valley and Olifants River Valley regions. In addition, actual spray records obtained from commercial production units included in a previous study (Kangueehi, 2018; Avenant, 2019), as well as actual spray records from the blocks included in this study for the 2018/19 season, were used to compile the lookup table (also see Chapter 3.2.3.4).

Table 4.14: Blue water use based on spray application for table grapes: plant protection spray applications (pest and disease control), nutrition, plant bioregulators and herbicides. Data is shown for three production regions and two cultivar examples. The WU_{blue} includes all water use for chemical spray applications in m^3/ha.

Region	Programme	Cultivar	Category	Plant protection	Nutrition	Plant bio-regulators	Herbicides	WU_{blue}
				m^3/ha	m^3/ha	m^3/ha	m^3/ha	m^3/ha
Berg River Valley	Standard	CSS	Medium-high	16.30	2.8	6.5	1.0	26.6
	Standard	RGB	Low	16.30	2.8	2.5	1.0	22.6
Hex River Valley	Standard + actual	CSS	Medium-high	12.35	4.5	6.5	1.0	24.4
	Standard + actual	RGB	Low	12.35	4.5	0.5	1.0	18.4
Olifants River Valley	Standard + actual	CSS	Medium-high	10.35	1.0	6.0	1.0	18.4
	Standard + actual	RGB	Low	12.35	0.0	1.0	1.0	14.4

In drafting the lookup table, the following assumptions were made:

- Standard fungicide, insecticide and herbicide sprays for plant protection, standard PBR rest-breaking sprays, as well as other PBR sprays according to cultivar category were included, with the spray volume per spray application ranging from 500 to 1,000 ℓ/ha, depending on the vineyard phenological stage and spray purpose.

- The fruit fly is a major phytosanitary pest of table grapes. Therefore, fruit fly bait sprays are recommended and applied for all cultivars and regions throughout the year. The seasonal total spray volumes indicated in the lookup table include fruit fly bait spray applications throughout the year for all cultivars and regions.
- Canopy (foliage) size is the major factor determining spray volume. As the vineyard progresses through the different phenological stages (from the dormant leafless stage to bud break, flowering, veraison, harvest and post-harvest) and the canopy size increases, the spray volumes applied increase. In standard spray programmes for table grapes, the spray volume used per spray application will range from 500 ℓ/ha during the dormant period and at the beginning of the season, to a maximum of 1,000 ℓ/ha from about two weeks before full bloom until the post-harvest period. Table grape vineyards are trained onto larger trellis systems using wider plant spacings than for wine grape vineyards, resulting in a larger vine and canopy size per vine, hence the higher spray application volumes recommended and used for table grape vineyards, compared to wine grape vineyards (per phenological stage, as well as the total spray application volume over the whole season).
- High application volumes that are used for specific insecticides in the dormant stage until bud break are where the applications are done either as targeted high-volume sprays with handheld spray guns, or soil-drench applications that are applied around the base of each individual infected vine.

For the Hex River Valley and the Olifants River regions, some adaptions were made based on actual records (for example, leaving out high-volume insecticide sprays for mealybug, which are included in the standard programme, but that will only be sprayed in problem blocks with high infestations and usually as “spot treatments” of individual infected vines). The approach followed and the ranges of the values obtained were verified with Mr Petrie de Kock, BASF’s Regional Sales Manager: Grapevines, Western Cape and Northern Cape (De Kock, 2019).

The WU_{blue} values in m^3/ha/season and shown in Table 4.14 were used in the field-level WF_{blue} calculations. After consideration of the size of each field, the production region and whether a cultivar fell within the medium-high or low category, an estimate was calculated for each field. Notice that the highest WU_{blue} values were calculated for the Berg River Valley (22.6 to 26.6 m^3/ha) and the lowest for the Olifants River Valley (14.4 and 18.4 m^3/ha). The main contributor to these values (~60%) was from the plant protector spray applications.

4.6.3 Wine grapes

Similar to table grapes, representative commercial wine grape production units and wine cellars from different production regions were selected for inclusion in this study. Since the climatic conditions of these regions vary, the vineyards’ seasonal growth patterns, water use and need for chemical interventions also vary. The application of irrigation on these farms is aimed at the optimal supply of water during each phenological stage. Fertilization and pest and disease management practices are applied to the farms according to standard practices for a cultivar and region. Other viticulture practices are applied as recommended to produce wine with the required style and characteristics, as determined by cultivar, region and market requirements.

Similar to the lookup table described in Chapter 4.6.2, a lookup table was compiled to capture WU_{blue} from chemical spray applications for wine grapes (Table 4.15). This table made provision for capturing data from the selected production units, grouped according to region and cultivar. The lookup table includes an example of a “medium to high” input cultivar regarding PBR use, as well as a “low” input cultivar. In the wine grape industry, rest-breaking agents for improved bud break are the only PBR group used on a commercial scale (De Kock, 2019), and they are only used on specific cultivars (mainly Sauvignon Blanc, Chardonnay and Shiraz), which, in this table, are classified as “medium to high” PBR input cultivars.

Standard spray programmes obtained from two different agrochemical companies (Viking and Nexus, supplied by BASF, 2019), as compiled for the three regions included in this study, were used to develop the lookup table.

For the medium-high category, the following assumptions were made:

- Standard fungicide, insecticide and herbicide sprays for plant protection, as well as standard PBR rest-breaking sprays, were included, with the spray volume per spray application ranging from 250 to 750 ℓ/ha, depending on the vineyard's phenological stage and the spray's purpose.

For the low category, the following assumptions were made:

- Only standard fungicide, insecticide and herbicide sprays for plant protection were included, with the spray volume per spray application ranging from 250 to 750 ℓ/ha, depending on the vineyard's phenological stage and the spray's purpose.

Fruit fly bait sprays are applied on wine grape farms where other fruit crops are also produced on the same farm or close to that farm. Therefore, for each region, provision was made to include or exclude fruit fly bait sprays over the whole year. The seasonal total spray volumes indicated in the lookup table include fruit fly bait spray applications throughout the year for all the cultivars in the medium-high category for all regions. The approach and the ranges of the values obtained were verified with Mr Petrie de Kock, BASF's Regional Sales Manager: Grapevines, Western Cape and Northern Cape (De Kock, 2019).

Table 4.15: Blue water use based on spray application for wine grapes: plant protection spray applications (pest and disease control), nutrition, plant bioregulators and herbicides. Data is shown for three production regions and two cultivar examples. The WU_{blue} includes all water use for chemical spray applications in m^3/ha.

Region	Programme	Cultivar	Category	Plant protection	Plant bio-regulators	Herbicides	WU_{blue}
				m^3/ha	m^3/ha	m^3/ha	m^3/ha
Breede River Valley	Standard	Chardonnay, Sauvignon Blanc	Medium-high	10.8	0.5	1.0	12.3
	Standard	All other	Low	9.4	0.0	1.0	10.4
Coastal	Standard	Chardonnay, Sauvignon Blanc	Medium-high	12.0	0.5	1.0	13.5
	Standard	All other	Low	10.7	0.0	1.0	11.7
Olifants River Valley	Standard	Chardonnay, Sauvignon Blanc	Medium-high	10.8	0.5	1.0	12.3
	Standard	All other	Low	9.4	0.0	1.0	10.4

As for table grapes, the WU_{blue} values in m^3/ha/season shown in Table 4.15 were used in the field-level WF_{blue} calculations. Considering the size of each field, the production region and whether a cultivar fell within the medium-high or low category, a value was calculated for each field considered. The highest WU_{blue} from chemical spray applications was calculated for the Coastal Region (11.7 to 13.5 m^3/ha), while the estimates for the Breede and Olifants River Valley regions were the same. Again, the largest contributor to this WU_{blue} was plant protection spray applications.

4.6.4 Summary and conclusion

In grape production, a substantial part of the WU_{blue} is at field level, in part from irrigation (often derived as a fraction of consumptive crop water use) and in part from water used in chemical spray applications, as described above. Since estimates of WU_{blue} at field level are not readily available, in this study, it was calculated indirectly from P_{eff} and evapotranspiration and using the lookup tables described above. These lookup tables summarised the WU_{blue} from chemical spray applications, taking typical spray programmes per region and cultivar groups into account, and provided a means of accounting for all WU_{blue} at field level.

4.7 BLUE WATER USE AT PRODUCTION LEVEL

4.7.1 Introduction

At field level, WU_{blue} for the production of table or wine grapes is from chemical spray applications (see Chapter 4.6) and irrigation derived from ET_{blue} (see Chapter 4.5). However, to complete the picture of the water use and water footprint of table grapes or wine, the water use at the production unit – in this case the table grape packhouse and wine cellar – should also be considered. There are very few published estimates on table grape packhouse or wine cellar water use – whether from South Africa or internationally. Therefore, to account for all components of the blue water footprint assessment included in this study, water use data from table grape packhouses and wine cellars was sourced from participants to this study and collated into lookup tables.

4.7.2 Table grape packhouse

Packhouse level WU_{blue} (Table 4.16) refers to all water used for cleaning crates and work surfaces, as well as in pre-cooling systems and cooling systems used in the packhouse. Packhouse water use is linked to the packhouse processes, pre-cooling and/or cooling techniques applied, the size of the production unit serviced by the packhouse, as well as the length of the harvesting and packing season.

For example, in the Hex River Valley, the harvesting season extends from late December/early January to mid/end April (± 16 weeks); in the Berg River Valley, it extends from late December/early January to mid-March (± 14 weeks); and in the Olifants River Valley, it extends from December to the end of February (± 12 weeks). In general, packhouses in the Hex River Valley would be smaller and have a lower capacity (cartons per day) compared to the Berg River Valley and Olifants River Valley regions.

To illustrate how a table can be used to calculate packhouse water use, data obtained in a previous study for the Breede River Valley, the Orange River Region, as well as Limpopo (Avenant, 2019), is also presented in Table 4.16. The duration of the harvest period, as well as the packhouse capacity of the Orange River Region and Limpopo, is comparable to that of the Olifants River Valley. The Berg River Valley's harvest period and packhouse capacity are intermediate (they fall between these two regions).

In the study reported by Avenant (2019), only one farm (two production units and packhouses) supplied measured values obtained via a water meter in the packhouse and only a total water use volume was given (no breakdown of the water used for different activities or purposes). All other values were calculations or estimates provided by the producers. There is a vast variation that occurs due to, among others, an absence of pre-cooling at the Hex River Valley farms included in the study, while pre-cooling was applied in the Orange River Region and Limpopo. The main reason for the difference in packhouse water use between the Orange River and Limpopo was that closed system pre-cooling (and therefore less water) was used at Limpopo.

In this study, packhouse water use data was obtained from four of the packhouses included in the study and varied from 0.06 to 0.76 ℓ/kg grapes packed (Table 4.16). Only one packhouse provided a breakdown of water used for different processes in the packhouse. In all packhouses, pre-cooling was applied. From the data and information supplied, there is no clear explanation for the differences between the packhouses' water use. The water use at the packhouse level (< 0.76 ℓ/kg) only contributes slightly to the total water footprint in the production and packing process of table grapes. Due to the limited amount of data available, the maximum contribution calculated (0.76 ℓ/kg) was applied to all regions and used in the water footprint calculations, providing a worst-case scenario contribution based on available data (Table 4.16).

In the study reported by Avenant (2019), blue water use at packhouse level, based on water use by farmworkers, was also obtained for production units and packhouses for the Breede River Valley, the Orange River Region, as well as Limpopo. This data is presented in Table 4.17. All the values were calculations or estimates made by the producers. Regarding estimated water use by farm workers (Table 4.17), producers suggested that 11 ℓ per worker per day is a realistic value (1 ℓ drinking water and 10 ℓ use for personal hygiene and toilet). This seems like quite a low value. The calculation of the total m^3/ha per year (worker water use for the production process and the packhouse process combined) was based on one permanent worker per hectare and two seasonal workers per hectare for the Breede River Valley, with 245 permanent working days and 110 seasonal working days per year, respectively. The calculations for both the Orange River Region and Limpopo were based on one permanent worker per hectare and three seasonal workers per hectare, with 245 permanent working days and 110 seasonal working days per year, respectively. The labour requirements per hectare of the Orange River Region and Limpopo are comparable to those of the Olifants River. The Berg River Valley's labour requirement is intermediate (it lies between these two regions).

The approach used in the study of Avenant (2019) was used as a departure point for the current study, although, in the current study, details on the exact contributors to the WU_{blue} were not available. Where packhouse water use is measured, it will represent the total volume. For future water use and water footprint assessments, it is recommended that a more detailed breakdown of packhouse water use, as well as farmworker water use in the production process and in the packhouse, is obtained and that, where possible, measured values are obtained.

Table 4.16: Packhouse-level WU_{blue} and WF_{blue} based on table grape packhouse water use. Data is shown for different production regions collected as part of this study and previous research

Subregion	Farm/ field no.	Season	Total production	Packhouse water use	Packhouse water use/ha		Packhouse water use per 4.5 kg carton equivalent				WF_{blue}
					Unit size	Water use	Packhouse capacity			Water use	
			t	m³/season	ha	m³/ha	Cartons/day	Days/season	Cartons/season	ℓ/carton	ℓ/kg
Hex River Valley	1	2014/15	900	21	40	0.5	2,500	80	200,000	0.11	0.02
	3	2014/15	900	21	40	0.5	2,500	80	200,000	0.11	0.02
	4	2014/15	788	21	35	0.6	2,188	80	175,000	0.12	0.03
Orange River	16	2014/15	1,800	900	80	11.3	6,667	60	400,000	2.25	0.50
	16	2015/16	1,800	944	80	11.8	6,667	60	400,000	2.36	0.52
	17	2014/15	1,800	900	80	11.3	6,667	60	400,000	2.25	0.50
	18	2014/15	1,800	900	80	11.3	6,667	60	400,000	2.25	0.50
	19	2014/15	1,800	900	80	11.3	6,667	60	400,000	2.25	0.50
	20	2014/15	1,800	900	80	11.3	6,667	60	400,000	2.25	0.50
	20	2015/16	1,800	944	80	11.8	6,667	60	400,000	2.36	0.52
Limpopo	21	2014/15	1,035	195	46	4.2	3,833	60	230,000	0.85	0.19
	23	2014/15	788	34	35	1.0	2,917	60	175,000	0.19	0.04
Hex River Valley	B1-28	2018/19	506	321	32	10.0	1,874	60	112,444	2.85	0.63
	G1-29	2018/19	934	242	40	6.1	5,189	40	207,556	1.17	0.26
Berg River	1-73	2018/19	2,431	144	113	1.3	10,804	50	540,222	0.27	0.06
Olifants River	1-26	2018/19	1,012	771	46	16.8	7,496	30	224,889	3.43	0.76

Table 4.17: Blue water use at packhouse level based on farmworker water use (Avenant, 2019)

Region	Subregion	Farm/ field no.	Season	Number of farm workers		Work days		Worker WU		Worker WU_{total}
				Permanent	Seasonal	Permanent	Seasonal	Drinking water	Toilet and hygiene	
				No/ha	No/ha	No/year	No/year	ℓ/pp/day	ℓ/pp/day	m^3/ha
Western Cape	Hex River	1	2014/15	1	2	245	110	1	10	5.1
		2	2014/15	1	2	245	110	1	10	5.1
		3	2014/15	1	2	245	110	1	10	5.1
		4	2014/15	1	2	245	110	1	10	5.1
Orange River	Kanoneiland	16	2014/15	1	3	245	110	1	10	6.3
	Kakamas	17	2014/15	1	3	245	110	1	10	6.3
	Kakamas	18	2014/15	1	3	245	110	1	10	6.3
	Raap en Skraap	19	2014/15	1	3	245	110	1	10	6.3
	Kanoneiland	20	2014/15	1	3	245	110	1	10	6.3
Limpopo	Groblersdal	21	2014/15	1	2	245	110	1	10	5.1
		22	2014/15	1	2	245	110	1	10	5.1
		23	2014/15	1	2	245	110	1	10	5.1

4.7.3 Wine grapes cellar

A flow chart for a wine production system, studied by Herath et al. (2013) as part of a water footprint assessment conducted in New Zealand, is presented In Figure 4.12. The various steps included in the production process of wine grapes, as well as the production of wine in the cellar, are similar to the processes applied in the South Africa wine industry. The field level WU_{blue} for wine grape production is discussed in Chapter 4.6.3. In South African wine cellars, blue water is also used for the following: washing and cleaning work areas, equipment and tanks, the winemaking process, bottling, and staff (worker) water use. Where cooling systems are used in a cellar (not included in Figure 4.2), blue water will also be used for this purpose. Table 4.18 was compiled to derive blue water use at cellar level, making provision for capturing the volume of water used for each of these processes. Data from individual cellars was captured using the format and categories provided in these tables.

Cellar water use data obtained from several participating producer cellars situated in the different production regions was captured in Table 4.18. Unfortunately, the datasets did not span the same period, hence daily water use estimates in m^3/ℓ/d were first made, after which a seasonal volume was calculated. Where data from more than one cellar per region was available, the maximum estimated cellar blue water use value was used in the WF_{total} calculations, representing the worst-case scenario.

As was the case for the water footprint at table grape packhouse level, Table 4.18 shows that the cellar-level water footprint was low and in a close range across the regions: 1.7 to 2.4 ℓ/ℓ. The highest value was calculated for the Olifants River Valley (2.4 ℓ/ℓ), and the lowest cellar water footprint value was that of the Breede River Valley at 1.7 ℓ/ℓ. The region-specific cellar level WF_{blue} estimates, as shown in Table 4.18, were subsequently used in the WF_{total} calculations for wine.

Table 4.18: Deriving WU_{blue} at cellar level (total per season) for the different regions considered.

Region	Cellar water use		
	m^3/day	m^3/year	ℓ/ℓ
Coastal	53	19 232	2.1
Olifants River Valley	159	58 033	2.4
Breede River Valley	244	89 180	1.7

4.7.4 Summary and conclusion

The water footprint of table grapes and wine does not merely comprise water use at field level, but also comprises water use at packhouse and cellar level. Since WU_{blue} data at the packhouse and cellar is not always readily available and does not always consider the same water uses, the available data was summarised per region in a lookup table and used in this study as an indication of the WF_{blue} at packhouse and cellar level.

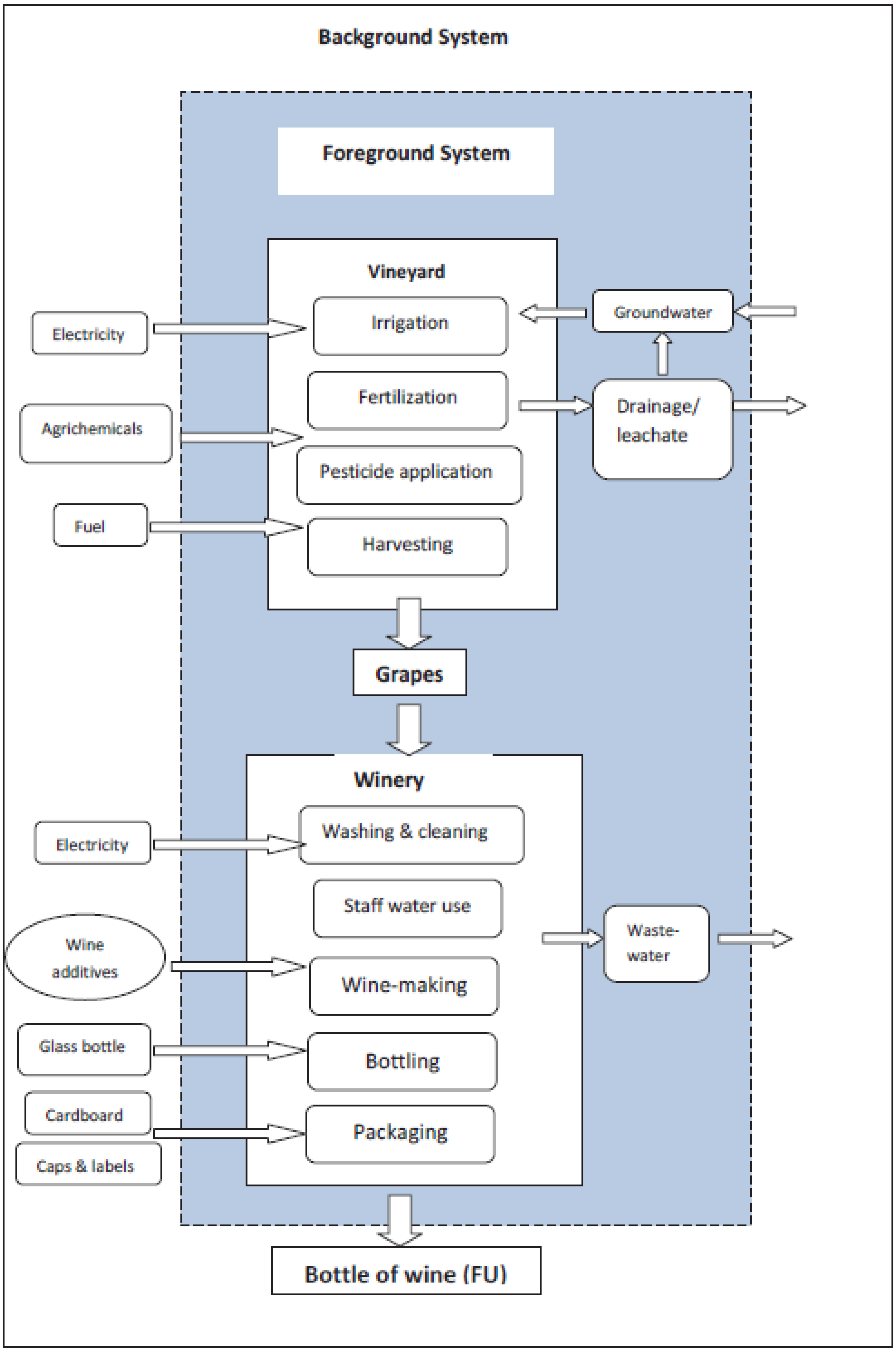


Figure 4.12: Flow chart for a wine production system (Herath et al., 2013). The shaded area marked with dashed lines indicates the foreground system included in the water footprint assessment. The square boxes with rounded corners represent activities that are included in the blue water footprint assessment, and round shapes indicate excluded activities.

4.8 FIELD-LEVEL GREY WATER USE

4.8.1 Introduction

The WF_{grey} is an indicator of the water volume needed to assimilate a pollutant load that reaches a water body. As an indicator of water resources appropriation through pollution, it provides a tool to help assess the sustainable, efficient and equitable use of water resources. The application of WF_{grey} by different stakeholders (from companies to environmental non-governmental organisations (NGOs) and governmental institutions) has shown its diverse usability as an indicator for water resource management. For the purpose of this study, a Tier 1 level assessment was used. This implies that a leaching-runoff fraction, which translates the amount of a chemical substance applied to the soil, was used as an estimate of the amount of the substance entering the groundwater or surface water system.

4.8.2 Table grapes

In water footprint studies, the estimation of WF_{grey} is often omitted or neglected. This study proposes the use of lookup tables to determine WF_{grey} at field level. The lookup table that captures fertilizer applications for table grape vineyards is included in Table 4.19. This data was used in combination with environmental standards to estimate WU_{grey} (Table 4.20). Table 4.19 also outlines data from the participating grape production units, grouped according to the region and yield category.

The kilogram of nutrient element applied per hectare is determined by the production (t/ha). Therefore, yield categories rather than cultivar categories were used in the lookup tables for WU_{grey}, because the same cultivar could be low/medium or high yielding, depending on the specific block and situation. Based on the range of production levels of the blocks included in the case study, four categories were defined, based on realistic industry targets, as indicated in Table 4.19. For the WU_{grey} calculations of the specific blocks included as case studies, the blocks were categorised according to the four categories, and the relevant kilogram element per hectare values were used in the calculations. Standard fertilizer norms and recommendations for table grape production in South Africa (Van Schoor et al., 2000; Raath and Avenant, 2018) were used to compile the lookup table and calculate values for the examples included. Data from individual production units was captured using the format and categories provided in Table 4.19. The approach and the ranges of the values were discussed and verified with Mr Danie Kritzinger, soil scientist/horticulturist and Business Development Manager, Agrimotion (Kritzinger, 2019).

Table 4.19: Fertilizer applications for table grapes linked to WU_{grey}

Region	Yield category (t/ha)	Grey water category based on	Nutrient	Product	Product composition	Macro element fertilizer applications (kg of element per ha)						
						kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	Total
						Bud break to flowering	Flowering	End of flowering to pea size	Pea size to veraison	Veraison to harvest	Post-harvest	kg/ha
All (Hex River Valley, Berg River Valley, Olifants River Valley)	0-11.25	Low	N	LAN	28% N, 5% Ca	6	6	6	11	2	19	49
			P	Super phosphate	10.5% P	1	2	2	2	0	2	9
			K	Potassium chloride	50% K	6	4	9	10	4	6	38
			Ca	Calcium sulphate	29.4% Ca, 23.5% S	3	4	6	6	2	6	25
			Mg	Magnesium sulphate	20% Mg, 26.7% S	1	1	1	2	1	2	8
All (Hex River Valley, Berg River Valley, Olifants River Valley)	11.25-22.5	Medium	N	LAN	28% N, 5% Ca	11	11	12	22	4	37	97
			P	Super phosphate	10.5% P	3	3	3.2	4.4	0.4	4.1	18
			K	Potassium chloride	50% K	12	8	17	20	7	12	76
			Ca	Calcium sulphate	29.4% Ca, 23.5% S	5	7	11	12	4	11	50
			Mg	Magnesium sulphate	20% Mg, 26.7% S	2	1.6	2.5	4	1.9	3.4	15
All (Hex River Valley, Berg River Valley, Olifants River Valley)	22.5-33.7	Medium-high	N	LAN	28% N, 5% Ca	16	16	18	33	6	55	145
			P	Super phosphate	10.5% P	4	4	5	7	1	6	27
			K	Potassium chloride	50% K	18	12	25	30	10	18	114
			Ca	Calcium sulphate	29.4% Ca, 23.5% S	7	10	16	18	6	16	75
			Mg	Magnesium sulphate	20% Mg, 26.7% S	2	2	4	6	3	5	22

Region	Yield category (t/ha)	Grey water category based on	Nutrient	Product	Product composition	Macro element fertilizer applications (kg of element per ha)	Region	Yield category (t/ha)	Grey water category based on	Nutrient	Product	Product composition
						kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
						Bud break to flowering	Flowering	End of flowering to pea size	Pea size to veraison	Veraison to harvest	Post-harvest	kg/ha
All (Hex River Valley, Berg River Valley, Olifants River Valley)	33.7-45	High	N	LAN	28% N, 5% Ca	22	22	24	44	8	74	194
			P	Super phosphate	10.5% P	6	6	6	9	1	8	36
			K	Potassium chloride	50% K	24	16	34	40	14	24	152
			Ca	Calcium sulphate	29.4% Ca, 23.5% S	10	14	22	24	8	22	100
			Mg	Magnesium sulphate	20% Mg, 26.7% S	3	3	5	8	4	7	30

With the fertilizer table compiled (Table 4.19) and potential pollutants identified, data on the maximum and natural concentration of these pollutants within the specified production regions was captured. Because of the roles nitrogen (N) and phosphate (P) play in the eutrophication of surface water, these nutrients are the most documented pollutants with clear maximum and natural concentrations for the Breede, Olifants and Hex River Valley regions. Nitrogen is the most common agricultural pollutant used for calculating WF_{grey} at field level. Considering this pollutant in the calculations will therefore allow direct comparison with other water footprint studies reported on in the literature. It is for these reasons that nitrogen and phosphate were selected for consideration in the WF_{grey} at field level.

Resource quality objectives according to the South African water quality guides were used to estimate the natural and maximum concentration of nitrogen and phosphate. These objectives specify that river nutrient levels must be maintained in an oligotrophic condition, which is accepted as the natural concentration, while the pollutant requirement for mesotrophic condition was accepted as the maximum allowable concentration of each pollutant.

For both table (and wine) grapes, an average leach-runoff fraction of 10% was assumed for nitrogen and 3% for phosphate as per the WFN guidelines (Franke et al., 2013). For the Hex and Olifants River Valley regions, the natural concentration for nitrogen and phosphate (0.5 mg/ℓ for nitrogen and 0.005 mg/ℓ for phosphate) were sourced from the South African Water Quality Guidelines of 1996. The maximum concentrations (1.75 mg/ℓ for nitrogen and 0.075 mg/ℓ for phosphate) were sourced from the proposed classes of the water resource and resource quality objectives for the Breede-Gouritz Water Management Area (DWS, 2018). For the Berg River Valley, both the natural and maximum concentration of nitrogen (0.7 mg/ℓ; 1.75 mg/ℓ) and phosphate (0.025 mg/ℓ; 0.075 mg/ℓ) were obtained from the proposed classes of water resource and resource quality objectives for the Berg River Catchment (DWS, 2019).

Table 4.20 captures the main data components used in the calculation of WU_{grey} for table grapes at field level. The WU_{grey} is shown in m^3/ha for the different regions and production classes. It is based on the fertilizer data summarised in Table 4.19. The C_{nat} values used for the Berg River Valley for nitrogen and phosphate were higher than those for the other two regions. Hence, for the same production class, this resulted in different WU_{grey} estimates – with the values calculated for the Berg River Valley being higher than those for the other two regions. The pollutant nitrogen contributed greatly to the WU_{grey} estimate, exceeding the WU_{grey} from phosphate by more than 2.5 times (Table 4.20). In this study, the approach by Franke et al. (2013) was applied where the value of the biggest pollutant was used, resulting in a domination of nitrogen applications and the nitrogen pollutant in the WU_{grey} estimation at field level.

For each individual table grape field considered in this study, the maximum contributing water use value – whether from nitrogen or phosphate as shown in Table 4.20 – was applied in the water footprint calculations for each case according to the production region and class.

Table 4.20: Grey water use estimated for table grapes, where nitrogen and phosphate are considered. Data is shown per production region and yield class and the field level WU_{grey} as the maximum of the nitrogen and phosphate values. Data is shown in m³/ha.

Region	Yield category	Nutrient	Total nutrient quality applied	Application rate (AR)	Leach: runoff fraction	Pollutant	C_{max}	C_{nat}	WU_{grey}	WU_{grey}	Maximum (N,P) WU_{grey}
	t/ha					kg	kg/ℓ	kg/ℓ	ℓ	m³/ha	m³/ha
Hex River Valley	0-11.25	N	49	13.8	0.1	1.38	0.00000175	0.0000005	1,104,000	1,104	
	0-11.25	P	9	0.9	0.03	0.027	0.00000008	0.00000001	385,714	386	1,104
Berg River Valley	0-11.25	N	49	13.8	0.1	1.38	0.0000018	0.0000007	1,314,286	1,314	
	0-11.25	P	9	0.9	0.03	0.027	0.00000008	0.00000003	540,000	540	1,314
Olifants River Valley	0-11.25	N	49	13.8	0.1	1.38	0.00000175	0.0000005	1,104,000	1,104	
	0-11.25	P	9	0.9	0.03	0.027	0.00000008	0.00000001	385,714	386	1,104
Hex River Valley	11.26-22.5	N	97	27.2	0.1	2.72	0.00000175	0.0000005	2,176,000	2,176	
	11.26-22.5	P	18	1.9	0.03	0.057	0.00000008	0.00000001	814,286	814	2,176
Berg River Valley	11.26-22.5	N	97	27.2	0.1	2.72	0.00000175	0.0000007	2,590,476	2,590	
	11.26-22.5	P	18	1.9	0.03	0.057	0.00000008	0.00000003	1,140,000	1,140	1,140
Olifants River Valley	11.26-22.5	N	97	27.2	0.1	2.72	0.00000175	0.0000005	2,176,000	2,176	
	11.26-22.5	P	18	1.9	0.03	0.057	0.00000008	0.00000001	814,286	814	2,176
Hex River Valley	22.6-33.7	N	145	40.6	0.1	4.06	0.00000175	0.0000005	3,248,000	3,248	
	22.6-33.7	P	26	2.8	0.03	0.084	0.00000008	0.00000001	1,200,000	1,200	3,248
Berg River Valley	22.6-33.7	N	145	40.6	0.1	4.06	0.00000175	0.0000007	3,866,667	3,867	
	22.6-33.7	P	26	2.8	0.03	0.084	0.00000008	0.00000003	1,680,000	1,680	3,867
	22.6-33.7	N	145	40.6	0.1	4.06	0.00000175	0.0000005	3 248 000	3 248	

Region	Yield category	Nutrient	Total nutrient quality applied	Application rate (AR)	Leach: runoff fraction	Pollutant	C_{max}	C_{nat}	WU_{grey}	WU_{grey}	Maximum (N,P) WU_{grey}
	t/ha					kg	kg/ℓ	kg/ℓ	ℓ	m³/ha	m³/ha
Olifants River Valley	22.6-33.7	P	26	2.8	0.03	0.084	0.00000008	0.00000001	1,200,000	1,200	3,248
Hex River Valley	33.8-45	N	194	54.3	0.1	5.43	0.00000175	0.0000005	4,344,000	4,344	
	33.8-45	P	36	3.8	0.03	0.114	0.00000008	0.00000001	1,628,571	1,629	4,344
Berg River Valley	33.8-45	N	194	54.3	0.1	5.43	0.00000175	0.0000007	5,171,429	5,171	
	33.8-45	P	36	3.8	0.03	0.114	0.00000008	0.00000003	2,280,000	2,280	5,171
Olifants River Valley	33.8-45	N	194	54.3	0.1	5.43	0.00000175	0.0000005	4,344,000	4,344	
	33.8-45	P	36	3.8	0.03	0.114	0.00000008	0.00000001	1,628,571	1,629	4,344

4.8.3 Wine grapes

As for table grapes, a lookup table was generated to capture fertilizer applications for wine grape vineyards (Table 4.21), which was linked to WU_{grey} estimations according to region, cultivar, yield category and soil characteristics. In examples included in the lookup table (Table 4.21), three yield categories, based on industry targets and records (Van Zyl and Van Niekerk, 2017), were used: 10-15 t/ha, 15-20 t/ha and 20-25 t/ha. In practice, the first class was applied to all fields with grape production less than 10 t/ha and the latter to all fields with a grape production more than 20 t/ha. The template includes an example of a soil with "low maintenance fertilizer requirements" (where mainly nitrogen maintenance fertilizer will be needed, based on production), as well as an example of a soil with "high-medium maintenance fertilizer requirements" (e.g. sandy soil with low cation exchange capacity, where it can be assumed that N, P, K, Ca, Mg and S maintenance fertilizer will be needed, based on production). Standard fertilizer norms and recommendations for wine grape production in South Africa (Conradie, 1994; Van Schoor et al., 2000) were used to compile the lookup table and calculate values for the examples included.

Similar to the Hex River Valley, the natural concentrations for nitrogen and phosphate in the Breede River Valley (0.5 mg/ℓ for nitrogen and 0.005 mg/ℓ for phosphate) were sourced from the South African Water Quality Guidelines (DWAF, 1996). The maximum concentrations (1.75 mg/ℓ for nitrogen and 0.075 mg/ℓ for phosphate) were sourced from the proposed classes of the water resource and resource quality objectives for the Breede-Gouritz Water Management Area (DWS, 2018).

For the Coastal Region, both the natural and maximum concentrations of nitrogen (0.7 mg/ℓ; 1.75 mg/ℓ) and phosphate (0.025 mg/ℓ; 0.075 mg/ℓ) were sourced from the proposed classes of water resource and resource quality objectives for the Breede-Gouritz catchment (DWS, 2019).

Table 4.22 captures the main data components used in the calculation of WU_{grey} for wine grapes at the field level, in m^3/ha and for different regions and production classes. It is based on the fertilizer data summarised in Table 4.21. The C_{nat} values for nitrogen and phosphate were higher for the Coastal Region than for the other two regions. For the same production class, this resulted in a higher WU_{grey} estimate for a field in the Coastal Region compared to the other two regions. As for table grapes, the WU_{grey} fraction from nitrogen greatly exceeded the WU_{grey} contribution from phosphate.

As mentioned previously, the approach by Franke et al. (2013) was applied in this study, where the water use value of the biggest pollutant was used. This approach meant that the WU_{grey} estimation at field level was always dominated by nitrogen pollution and applications.

For each individual wine grape field considered in this study, the maximum contributing water use value – whether from nitrogen or phosphate as shown in Table 4.22 – was implemented in the water footprint calculations according to the production region and class.

Table 4.21: Fertilizer application for wine grapes linked to WU_{grey}.

Region	Yield category (t/ha)	Grey water category based on production and fertilizer	Nutrient	Product	Product composition	Macro element fertilizer applications (kg of element per ha)						
						kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	Total
						Bud break to flowering	Flowering	End of flowering to pea size	Pea size to veraison	Veraison to harvest	Post-harvest	
All (Breede River Valley, Coastal, Olifants River Valley)	10-15	Low	N	LAN	28% N, 5% Ca	5.5	5.5	6.5	11.0	2.5	19.0	50
			P	Super phosphate	10.5% P	1.7	1.8	1.9	2.5	0.2	2.4	11
			K	Potassium chloride	50% K	7.2	5.0	10.4	11.7	4.1	6.8	45
			Ca	Calcium sulphate	29.4% Ca, 23.5% S	3.3	4.5	6.6	6.9	2.1	6.6	30
			Mg	Magnesium sulphate	20% Mg, 26.7% S	1.2	1.2	1.9	2.9	1.5	2.5	11
All (Breede River Valley, Coastal, Olifants River Valley)	15-20	Medium	N	LAN	28% N, 5% Ca	6.6	6.6	7.8	13.2	3.0	22.8	60
			P	Super phosphate	10.5% P	2.2	2.4	2.5	3.4	0.3	3.2	14
			K	Potassium chloride	50% K	9.6	6.6	13.8	15.6	5.4	9.0	60
			Ca	Calcium sulphate	29.4% Ca, 23.5% S	4.4	6.0	8.8	9.2	2.8	8.8	40
			Mg	Magnesium sulphate	20% Mg, 26.7% S	1.7	1.7	2.6	3.9	2.0	3.3	15
All (Breede River Valley, Coastal, Olifants River Valley)	20-30	High	N	LAN	28% N, 5% Ca	8.8	8.8	10.4	17.6	4.0	30.4	80
			P	Super phosphate	10.5% P	3.4	3.6	3.8	5.0	0.4	4.8	21
			K	Potassium chloride	50% K	14.4	9.9	20.7	23.4	8.1	13.5	90
			Ca	Calcium sulphate	29.4% Ca, 23.5% S	6.6	9.0	13.2	13.8	4.2	13.2	60
			Mg	Magnesium sulphate	20% Mg, 26.7% S	2.5	2.5	3.8	5.9	2.9	5.0	23

Table 4.22: Grey water use estimated for wine grapes, where nitrogen and phosphate are considered. Data is shown per production region and yield class and the field level WU_{grey} as the maximum of the nitrogen and phosphate values. Data is shown in m^3/ha.

Region	Yield category	Nutrient	Total	Application rate (AR)	Leach: runoff fraction	Pollutant	C_{max}	C_{nat}	WU_{grey}	Maximum (N,P) WU_{grey}
	t/ha		kg/ha			kg	kg/ℓ	kg/ℓ	m^3/ha	m^3/ha
Breede River Valley	≤ 15	N	50	14	0.1	1.4	0.00000175	0.0000005	1,120	
	≤ 15	P	11	1.16	0.03	0.0348	7.50E-08	5.00E-09	497	1,120
Coastal	≤ 15	N	50	14	0.1	1.4	0.00000175	0.0000007	1,333	
	≤ 15	P	11	1.16	0.03	0.0348	7.50E-08	2.50E-08	696	1,333
Olifants River Valley	≤ 15	N	50	14	0.1	1.4	0.00000175	0.0000005	1,120	
	≤ 15	P	11	1.16	0.003	0.00348	7.50E-08	5.00E-09	50	1,120
Breede River Valley	> 15 to 20	N	60	16.8	0.1	1.68	0.00000175	0.0000005	1,344	
	> 15 to 20	P	14	1.47	0.03	0.0441	7.50E-08	5.00E-09	630	1,344
Coastal	> 15 to 20	N	60	16.8	0.1	1.68	0.00000175	0.0000007	1,600	
	> 15 to 20	P	14	1.47	0.03	0.0441	7.50E-08	2.50E-08	882	1,600
Olifants River Valley	> 15 to 20	N	60	16.8	0.1	1.68	0.00000175	0.0000005	1,344	
	> 15 to 20	P	14	1.47	0.03	0.0441	7.50E-08	5.00E-09	630	1,344
Breede River Valley	> 20	N	80	22.4	0.1	2.24	0.00000175	0.0000005	1,792	
	> 20	P	21	2.2	0.03	0.066	7.50E-08	5.00E-09	943	1,792
Coastal	> 20	N	80	22.4	0.1	2.24	0.00000175	0.0000007	2,133	
	> 20	P	21	2.2	0.03	0.066	7.50E-08	2.50E-08	1,320	2,133
Olifants River Valley	> 20	N	80	22.4	0.1	2.24	0.00000175	0.0000005	1,792	
	> 20	P	21	2.2	0.03	0.066	7.50E-08	5.00E-09	943	1,792

4.8.4 Summary and conclusion

Estimates of WF_{grey} at field level are often omitted from water footprint studies due to the complexity of accounting for this water use estimate. Lookup tables summarising water use from fertilizer applications were generated to aid in estimating WF_{grey} at field level. These tables considered production region, yield classes and important nutrients, and provided a means of accounting for this grey water use.

4.9 PRODUCTION-LEVEL GREY WATER USE

4.9.1 Wine cellar

To calculate the WF_{grey} at the cellars, the South African Water Quality Guidelines' specifications for industrial use were consulted (DWAF, 1996). Pollutant limits were selected according to Category 4 of this guide, where no additional treatment is required prior to use. The pollutant load was estimated by multiplying the abstraction and effluent volume by the concentration of the pollutant in the abstraction (inflow) and in the effluent (outflow). The natural (C_{nat}) and maximum (C_{max}) concentration of these pollutants for each region were sourced from the Department of Water and Sanitation (DWS, 2018).

Table 4.23 shows some of the pollutants' data captured and used, together with environmental conditions for three production regions. The data is based on actual water quality analysis data at participating cellars. Although data was captured for numerous pollutants (chemical oxygen demand (COD), total dissolved solids (TDS), chloride (Cl), sulphate, phosphate and nitrogen), C_{nat} and C_{max} values were not readily available for all, hence the selection (COD, TDS and Cl) shown in Table 4.23.

The WF_{grey} at cellar level showed marked differences in the estimates for these chemicals: from 0 to 173 ℓ/ℓ. For example, the contribution of COD to the WF_{grey} was substantially larger than the contribution from other pollutants and is therefore seen as the dominating pollutant in the Coastal and Breede River Valley regions. Unfortunately, no COD data was available for the Olifants River Valley.

Note that where more than one laboratory report was available per region, the maximum concentration of each pollutant was used. Abstraction was given per day and used per season for each region, while production data was available per season. Abstraction was not tested before it was used in the cellar; therefore, $C_{act} = C_{nat}$.

Table 4.23: WF_{grey} calculated for wine cellars. Data is shown in ℓ/ℓ and is based on actual data obtained from cellars participating in this research

Region	Pollutant	Pollutant description	Effluent	C_{effl}	C_{max}	C_{nat}	WF_{grey}	Maximum WF_{grey}
			m³/year	mg/ℓ	mg/ℓ	mg/ℓ	ℓ/ℓ	ℓ/ℓ
Breede River Valley	COD	Chemical oxygen demand	27,877	2,860	75	6	72	72
	TDS	Total dissolved solids	27,877	3,348	1,600	358	4	
	COD	Chemical oxygen demand	14,964	2,780	75	6	70	
	TDS	Total dissolved solids	14,964	2,509	1,600	358	3	
Olifants River Valley	TDS	Total dissolved solids	58,033	1,468	1,600	553	2	2
	Cl	Chloride	58,033	74	500	0	0	
Coastal	COD	Chemical oxygen demand	19,232	6,070	75	6	183	183
	TDS	Total dissolved solids	19,232	879	1,600	358	1	
	Cl	Chloride	19,232	36	500	0	0	

Considering the maximum WF_{grey} per region, the values for the Coastal and Breede River Valley regions were 183 and 72 ℓ/ℓ, respectively. In both instances, COD dominated (Table 4.23). In the absence of a COD estimate for the Olifants River Valley, the WF_{grey} estimated for this region, considering only TDS and Cl, was significantly lower (2 ℓ/ℓ) than for the other regions. Therefore, for implementation in the study, the actual WF_{grey} estimates for the Coastal and Breede River Valley regions – 183 ℓ/ℓ and 72 ℓ/ℓ, respectively – were used (Table 4.23). For the Olifants River Valley, the maximum regional load, based on the available data for all regions (183 ℓ/ℓ), was assumed and used. This value may provide an overestimation of the actual conditions, but can only be tested in the presence of available COD data and will present a likely worst-case scenario.

4.9.2 Table grapes

Since no water quality information was available at the packhouse level, the WF_{grey} for the packhouse could not be calculated and was omitted. It is, however, recognised that the WF_{grey} for the packhouse will increase the packhouse-level WF_{total} estimates for table grapes, but this is a currently unknown fraction.

4.9.3 Summary and conclusion

As for WF_{grey} at field level, estimates of WU_{grey} at packhouse and cellar level have been omitted in other studies due to water quality data not being readily available. A lookup table summarising the water quality from different cellars was generated to aid in estimating the WF_{grey} at cellar level. This table considered production region and wine production and provided a means of accounting for this grey water use.

CHAPTER 5: PHASE 2: WATER FOOTPRINT ASSESSMENT EXAMPLES

5.1 INTRODUCTION

In Chapter 3 and Chapter 4, details are provided on the case studies, as well as the data sourced and prepared for use in the water footprint calculations in this study. This chapter describes the water footprint results from using this data and implements it in two case studies related to table grapes and wine produced in South Africa. For both the table grape and wine industries, the water footprint results are expressed and calculated in two steps representing two levels of estimates (Figure 5.1):

- First, at field level:
  - for the actual table and wine grapes produced in the field: in ℓ/kg (considering all water use in the field).
- Secondly, at "production" level:
  - for table grapes at the packhouse level, where the WU_{blue} of the packhouse is added to the field level water use and the water footprint results are expressed in litres of water per kilogram of grapes (ℓ/kg)
  - for wine at the wine cellar level, where the water use (blue and grey) in the cellar, as part of the winemaking process, is added to the water use at field level, and the water footprint results are expressed in litres of water per litres of wine (ℓ/ℓ).

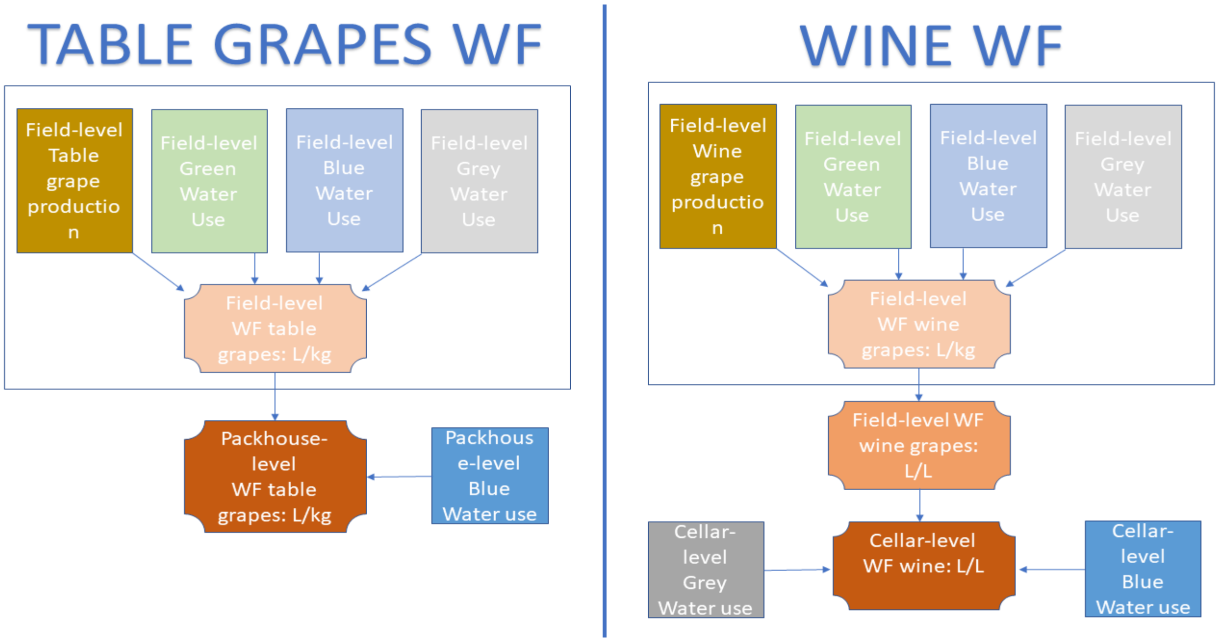


Figure 5.1: Illustration of the two levels considered in the water footprint assessment for table grapes and wine: field level and production (packhouse and cellar) level

For table grapes, the field-level water footprint (green, blue, grey, total) is first calculated and described, after which the packhouse level WF_{blue} is added (Figure 5.1). The resultant WF_{total} for table grapes up to packhouse level (packhouse level WF_{total}) for a litre of water per kilogram of grapes is shown for the three different production regions and all the regions combined. Note that since no water quality information was available at packhouse level, the WF_{grey} for the packhouse could not be calculated and was omitted. It is recognised that a WF_{grey} for the packhouse will increase the total estimate of the packhouse level WF_{total} for table grapes.

For the wine water footprint case studies, the field-level water footprint (green, blue, grey, total) of wine grapes is first described in ℓ/kg. Subsequently, the kilograms of wine grapes is converted to litres of wine, and WF_{blue} and WF_{grey} at cellar level are added together to express the WF_{total} of wine at cellar level (cellar water footprint for wine) (Figure 5.1).

5.2 WATER FOOTPRINT OF TABLE GRAPES

5.2.1 Background information

For the table grape water footprint case studies, various table grape fields associated with the different packhouses were considered. Some details pertaining to these fields and the production regions for the 2018 to 2019 seasons are summarised in Table 5.1. Across the three production regions considered, a total area of 642 ha was under table grapes, with 45% of the area situated in the Hex River Valley Region and 27% each in the Berg and Olifants River Valley regions. A total of 214 data records was considered, comprising mainly individual fields, but in some cases where production data was only available per cultivar group, this data was used as such. Data from 32 cultivars was considered, the most dominant cultivar being Crimson Seedless.

The median grape production calculated considering these fields was 22 t/ha, with the production ranging between 5 and 64 t/ha (Figure 5.2). Some 71% of the production is in the range of 10 to 30 t/ha, with 5.6% less than 10 t/ha and the remainder more than 30 t/ha. Note that the production represented all grapes produced per hectare, whether produced for export, local distribution, drying of grapes or winemaking. Based on the dataset, the Hex River Valley had the highest median grape production (26 t/ha) and the Berg River Valley the lowest (18 t/ha) (Table 5.1). Considering data from all regions, the median export fraction of the total production was 67%, while the remainder of production went to local distribution, drying of grapes or winemaking (Figure 5.2, Table 5.2). Note that the statistical median rather than the average was mainly reported on in this chapter (unless specifically indicated otherwise). The statistical median shows the more representative statistical value for large datasets with big ranges and is not skewed, as in the case of an average, by extreme (minimum or maximum) values.

The median vineyard age, considering all fields, was eight years, with the oldest fields of 28 years situated in the Olifants River Valley Region (Table 5.2). The fields considered in the Olifants River Valley Region also had the oldest median age (11 years), and those in the Hex River Valley had the youngest median age (six years), suggesting a bigger turnover or change in vineyards or cultivars in the Hex River Valley compared to the Olifants River Valley. After discussions with farmers and industry members, the decision was taken to exclude all young, unproductive fields from this analysis, since it skewed the results towards increased water footprint estimates, and since such vineyards will not yet make a significant contribution to grape production.

As noted in the description of the respective table grape production regions (Chapter 2.1.1.1), table grapes are typically produced in low rainfall regions in the Western Cape. Consequently, the production of table grapes is highly reliant on irrigation to supplement rainfall in order to meet the water requirements of table grapes. Rainfall records obtained from stations in the different regions showed that the total rainfall for the 2018/19 season (1 August 2018 to 31 July 2019) ranged between 142 mm/year in the Olifants River Valley and 345 mm/year in the Hex River Valley (Figure 5.3, Table 5.1). Note that, for the Olifants and Berg River Valley regions, the maximum, minimum, median and mean annual rainfall were the same since data from a single station was considered. However, in the Hex River Valley, the rainfall data from more than one rainfall station was considered, hence a range in annual rainfall is shown (229 to 345 mm/year) (Figure 5.3).

Table 5.1: Basic description of data considered in the case studies for the water footprint assessment of table grapes. Data is for the 2018/19 production season, considering three production regions.

Region	Statistics	Area	Cultivars	Record	Average age	Plant density	Production: export	Production: other	Production: total	Rainfall	P_{eff}	ET
		Ha	No	No	Years	Plants per ha	Ton per ha	Ton per ha	Ton per ha	mm/year	mm/year	mm/year
All areas	Total	642	32	214								
	Maximum				28	2,491	63	29	64	345	125	1,329
	Minimum				2	1,111	0	0	5	142	19	488
	Median				8	1,852	15	7	22	229	53	1,093
	Average				9	1,831	16	8	24	221	54	1,075
Hex River Valley	Total	286	22	93								
	Maximum				19	2,491	40	29	53	345	125	1,251
	Minimum				2	1,253	0	0	5	229	53	608
	Median				6	1,852	18	7	26	229	53	1,078
	Average				7	1,913	19	8	27	242	62	1,068
Berg River Valley	Total	175	12	44								
	Maximum				23	1,905	40	18	47	313	101	1,234
	Minimum				3	1,111	3	0	9	313	101	488
	Median				9	1,650	13	4	18	313	101	1,049
	Average				10	1,604	15	6	20	313	101	1,026
Olifants River Valley	Total	181	19	77								
	Maximum				28	2,222	63	21	64	142	19	1,329
	Minimum				3	1,111	0	0	7	142	19	519
	Median				11	1,667	12	8	20	142	19	1,121
	Average				12	1,861	13	9	21	142	19	1,110

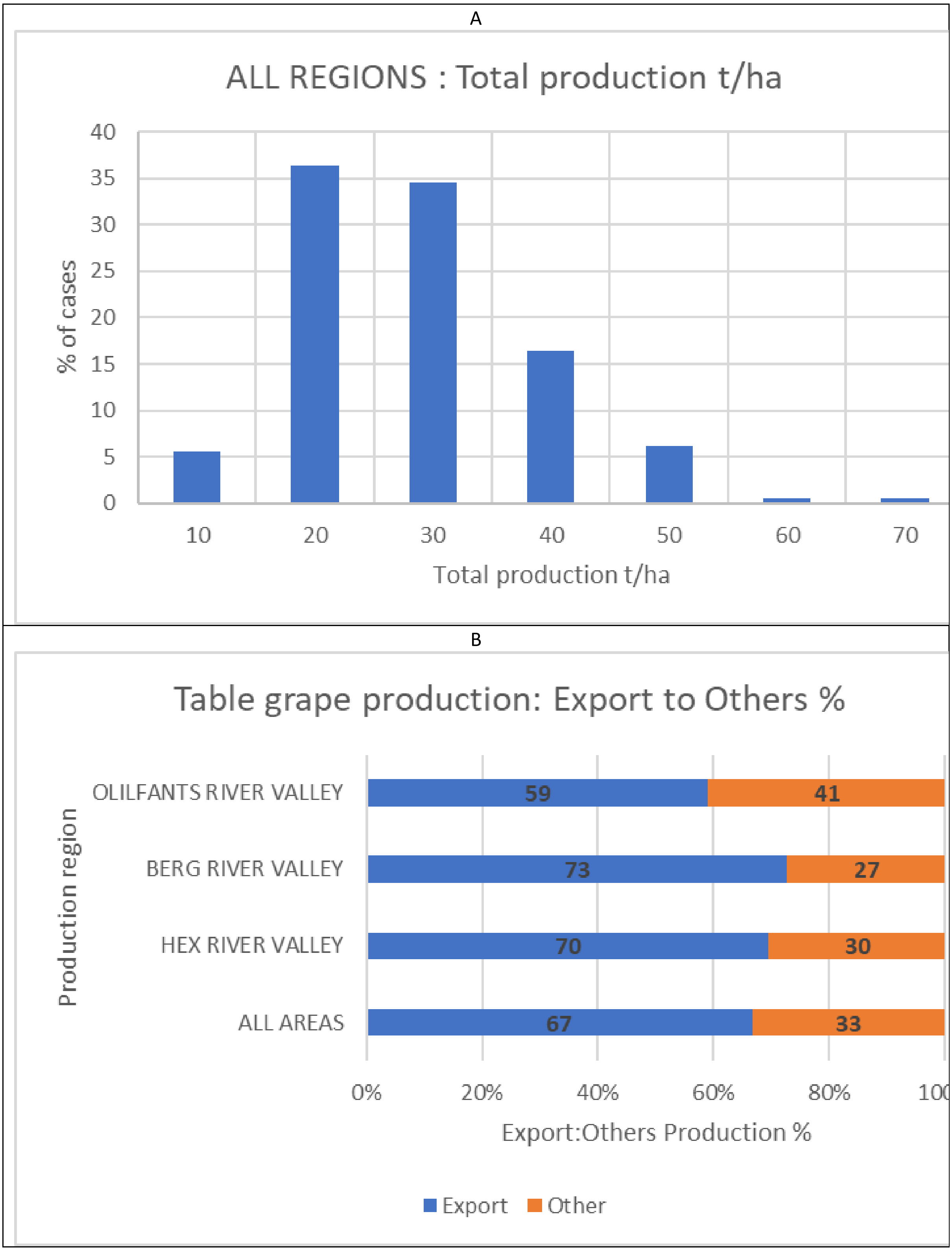


Figure 5.2: (A) Histogram showing the range in total table grape production, based on data for each field considered in the study in t/ha; and (B) export to other production fractions for table grape fields considered in this study. Data is for the 2018/19 production season, shown for all regions together and separately.

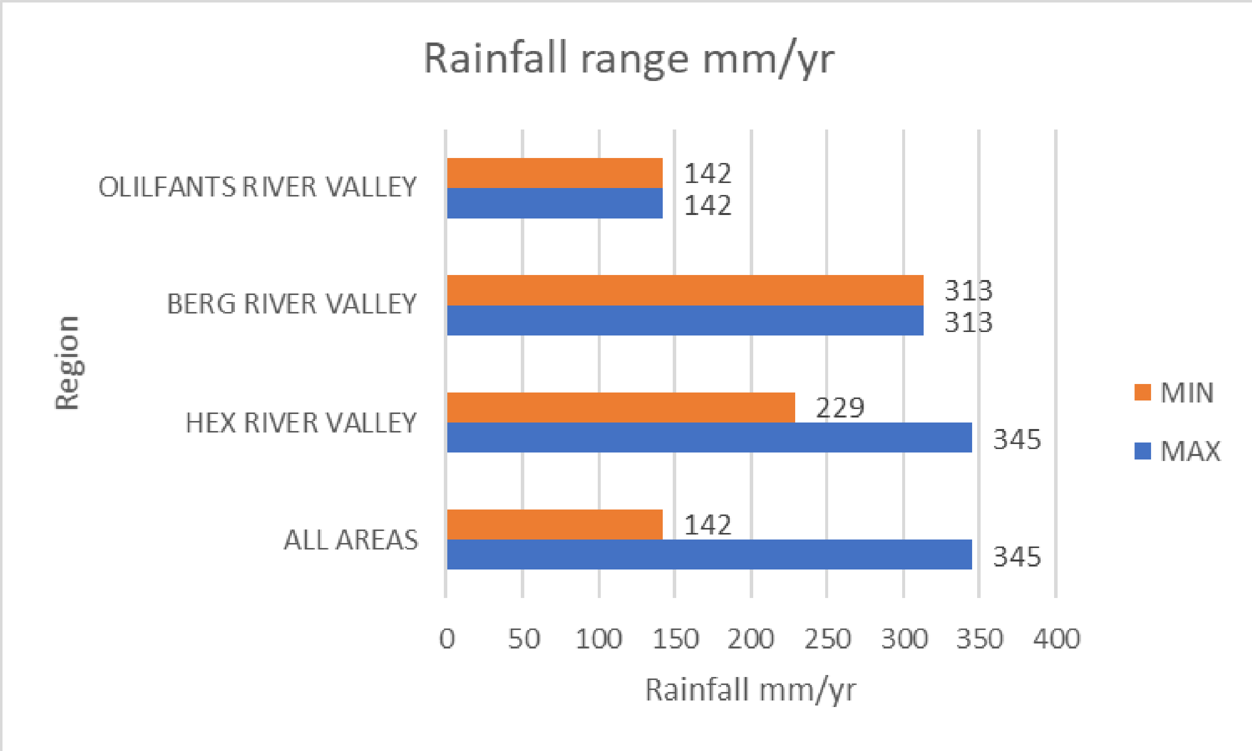


Figure 5.3: *Annual rainfall observed in the respective production regions considered in this study for the period 1 August 2018 to 31 July 2019. In the Hex River Valley, data from more than one rainfall station was used, hence showing a rainfall range (different maximum and minimum values).*

5.2.2 Field-level water footprint of table grapes

5.2.2.1 Field-level water footprint (green, blue, grey and total)

The field level water footprint results for table grapes, as calculated for each field or record considered, are described below. As shown in Figure 5.1, the field-level WF_{total} consists of three components: green, blue and grey water.

$Field\ level\ WF_{total} = Field\ level\ WF_{green} + Field\ level\ WF_{blue} + Field\ level\ WF_{grey}$	*(5.1)*

The green, blue and grey water uses (WU_{green}, WU_{blue}, WU_{grey}) at field level were first calculated, after which the respective water use values were divided by the production data (yield in t/ha) to give field-level water footprint values.

In very simple terms, the field-level WU_{green} or ET_{green} was calculated from (monthly) evapotranspiration and effective rainfall (P_{eff}) (see Chapter 4.5), summed to annual totals. The field-level WU_{blue} (annual total) consisted of two components, which were calculated in two steps: as the difference between the annual evapotranspiration and annual total WU_{green} or ET_{green} (see Chapter 4.5); and from typical chemical spray applications at farm level, determined by the production region in which the field is situated, the cultivar considered, as well as the size of the field in hectares. The latter component is described in Chapter 4.6.2 and is referred to below as the $WU_{bluelookupvalue}$. Lastly, the WU_{grey} was calculated by considering fertilizer chemical components or pollutants, production classes and region, and size of the field, as described in Chapter 4.8.2 and referred to below as the $WU_{greylookupvalue}$.

$WU_{green} = [\min(ET, P_{eff})] * area$	*(5.2)*

$WU_{blue} = [(ET - WU_{green}) + WU_{bluelookupvalue}] * area$	*(5.3)*

$WU_{grey} = WU_{greylookupvalue} * area$	*(5.4)*

The water use estimates were converted to field level WF_{green}, WF_{blue} and WF_{grey} estimates, using the field-specific grape production or crop yield data. The field level WF_{total}, in turn, was calculated as the sum of these respective water footprint components (see equation above).

The field level WF_{total} estimates for the respective fields presented in Figure 5.4 show a large variation for the 214 records considered, ranging from 267 to 2,519 ℓ/kg. The large variation could be expected, given the large variation in grape production in t/ha as presented in Figure 5.2. In order to gain more insight into the distribution of field-level WF_{total} estimates, these results were simplified in histograms, showing the percentage of cases in a particular water footprint class (Figure 5.5).

Considering the data from all regions, 86% of the cases had field-level WF_{total} estimates of less than 1,000 ℓ/kg, only 12% of the fields had values of even less than 400 ℓ/kg, but 47% (or nearly half) of the fields had values of less than 600 ℓ/kg (Figure 5.5). Interestingly, the Hex River Valley had the most cases (63%) where the field-level WF_{total} was less than 600 ℓ/kg, with both the Berg River Valley and the Olifants River Valley only having 34% of the cases below 600 ℓ/kg (Figure 5.5).

When considering the cases where the field-level WF_{total} exceeded 1,000 ℓ/kg, the Hex River Valley had the lowest number of cases (5%), while the ranges of the other two regions were nearly the same: 19% (Olifants River Valley) and 20% (Berg River Valley) (Figure 5.5). It is interesting to note that the field-level WF_{total} values in excess of 1,200 ℓ/kg (6% of the values) were associated with fields planted with Crimson Seedless, Autumn Royal, Sugrasixteen (Sable Seedless®), Moonballs, Prime, Desert Dawn and Starlight. These high field-level WF_{total} values resulted from very low production attributed to specific problems experienced in the field during the 2018/19 season, including rainfall leading to the rotting of the grape crop, and rainfall and wind damage during flowering, leading to the shattering of flowers and the presence of pests like thrips. Producers indicated that these problems caused the grape production of certain fields to be lower than the norm.

The frequency distributions graphs (Figure 5.5) provide more insight into the descriptive statistics presented in Table 5.2, where it is shown that the median field-level WF_{total} is the lowest in the Hex River Valley at 499 ℓ/kg and highest in the Berg River Valley at 713 ℓ/kg (Figure 5.5), with the median field-level WF_{total} considering all data from all regions calculated at 618 ℓ/kg. The ranges in the field level WF_{total} values (Figure 5.5 and Table 5.2) illustrate the variation in table grape production as a result of conditions experienced at regional and farm level and whether related to the production season (climate, water availability, pests and diseases) or the production potential and systems (cultivars, irrigation, trellis systems, planting density, etc.).

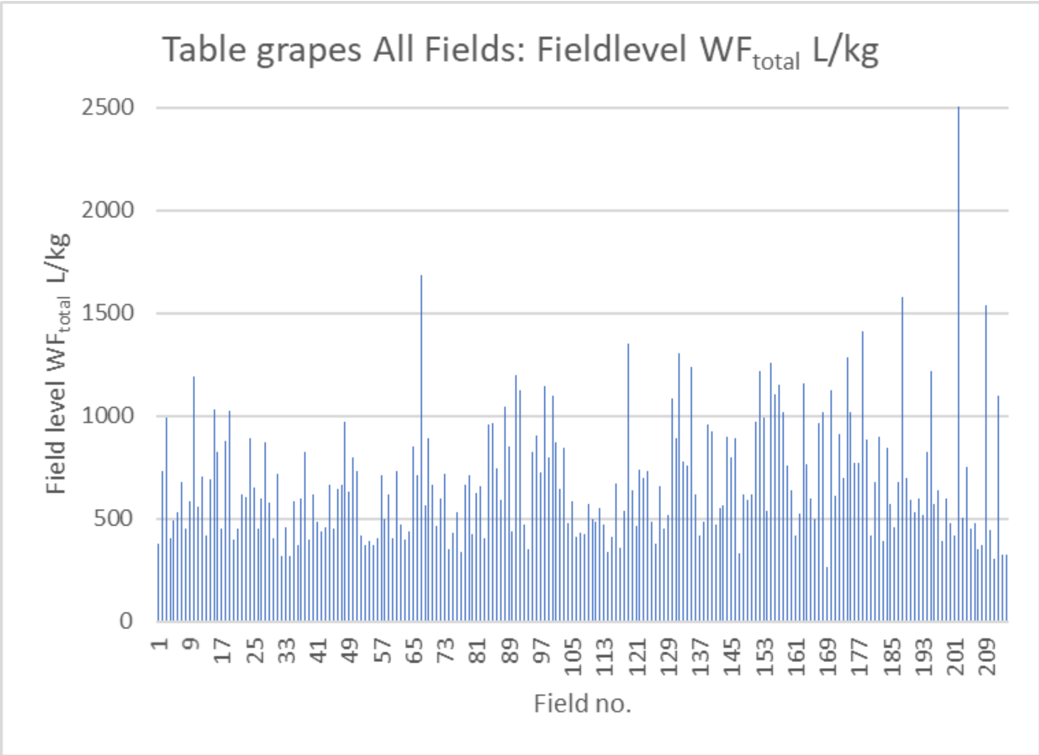


Figure 5.4: *Field-level WF_{total} in ℓ/kg for table grapes produced in the 2018/19 season. Data is from three production regions situated in the Western Cape. Data from all fields is considered.*

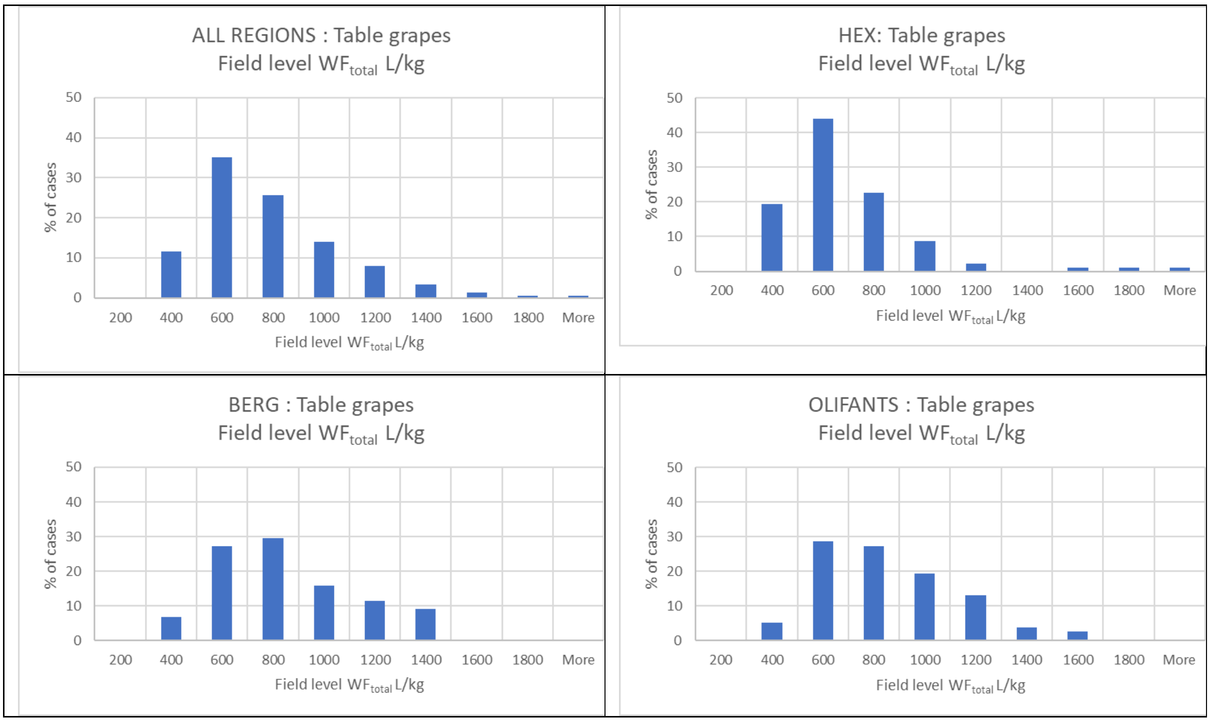


Figure 5.5: *Histograms summarising the field-level WF_{total} results for table grapes. The water footprint values are expressed in ℓ/kg and the percentage of cases per production class is shown. Data is for the 2018/19 season and for different production regions within the Western Cape and the combined (all) area.*

Lower production and quality in the 2018/19 season, which impacted on field-level water footprint values, was the main topic of discussion during the SATI Joint Marketing Forum meeting's post-season analysis of 2018/19 on 14 May 2019 (SATI, 2019b), where the 2018/19 season was described as "the most difficult season ever". Lower production and quality of certain cultivars were mainly attributed to abnormal weather conditions, including an unnaturally cool period in the Western Cape production regions from bud break until just before flowering (causing slower growth), followed by extremely high temperatures in the last nine days of October 2018 (causing very strong shoot growth, resulting in competition between bunches and shoots), followed by a sudden drop in temperature over two days from 41 ºC on 27 October to a minimum of 4 ºC on 29 October. Weekly rainfall occurring in the Berg River Valley Region from September contributed to a very high incidence of downy mildew. Some blocks on farms in Trawal and Vredendal (Olifants River Valley) were also still affected by the drought.

Table 5.2: Descriptive statistics related to table grape production, field-level water footprint and packhouse-level water footprint. Data is shown for all regions and separate regions. Data is calculated for the 2018/19 season. The water footprint and production data are also expressed as percentage fractions of the total estimates.

Region	Descriptive statistics	Production	Field WF_{green}	Field WF_{blue}	Field WF_{grey}	Field WF_{total}	Packhouse WF_{blue}	Field WF_{green}	Field WF_{blue}	Field WF_{grey}	Production export	Production other
		t/ha	ℓ/kg	ℓ/kg	ℓ/kg	ℓ/kg	L/kg	%	%	%	%	%
All areas	Mean	24	28	527	129	684	1	4	75	21	66	34
	Standard error	1	2	19	2	21	0	0	1	0	1	1
	Median	22	19	468	124	618	1	4	74	21	68	32
	Standard deviation	10	23	276	27	301	0	3	7	6	21	21
	Range	59	115	1,984	175	2,253	0	12	38	29	100	100
	Minimum	5	3	174	68	267	1	1	52	9	0	0
	Maximum	64	118	2,158	244	2,519	1	14	90	38	100	100
Hex River Valley	Mean	27	27	454	118	599	1	5	73	22	70	30
	Standard error	1	2	29	2	32	0	0	1	1	2	2
	Median	26	23	359	113	499	1	4	73	23	68	32
	Standard deviation	10	16	284	21	312	0	2	7	6	20	20
	Range	49	108	1,984	162	2,216	0	8	35	29	100	100
	Minimum	5	10	174	81	304	1	3	52	9	0	0
	Maximum	53	118	2,158	244	2,519	1	11	87	37	100	100
Berg River Valley	Mean	20	58	540	152	750	1	8	70	22	72	28
	Standard error	1	3	37	4	41	0	0	1	1	3	3
	Median	18	57	517	150	713	1	8	71	21	75	25
	Standard deviation	8	23	243	28	275	0	1	7	7	18	18
	Range	38	88	903	114	1,004	0	8	31	28	76	76
	Minimum	9	21	198	110	350	1	6	52	10	24	0
	Maximum	47	110	1,102	224	1,354	1	14	83	38	100	76
Olifants River Valley	Mean	21	11	609	129	748	1	1	80	19	58	42
	Standard error	1	1	30	3	32	0	0	1	1	3	3
	Median	20	9	569	125	681	1	1	81	17	62	38
	Standard deviation	9	5	263	24	278	0	0	6	6	22	22
	Range	56	23	1,206	121	1,311	0	1	27	27	100	100
	Minimum	7	3	195	68	267	1	1	63	9	0	0
	Maximum	64	26	1,401	189	1,578	1	3	90	36	100	100

In Figure 5.6, the field-level WF_{total} estimates, as well as the green, blue and grey components, are shown to illustrate the ranges in the absolute water footprint estimates. It is interesting to note that the field-level WF_{blue} that ranged between 174 and 2,158 ℓ/kg was only slightly lower than the field-level WF_{total} range (267 and 2,519 ℓ/kg) (Figure 5.6 and Table 5.2), showing the important contribution of the field-level WF_{blue} to the field-level WF_{total} estimates where table grapes are concerned. The field-level WF_{green} was low and ranged between 3 and 118 ℓ/kg with a median value of 19 ℓ/kg. Differences existed in the median field-level WF_{green}, with the highest median value estimated in the Berg River Valley (57 ℓ/kg) (Figure 5.6 and Table 5.2). The field-level WF_{grey} varied between 68 and 244 ℓ/kg (median value of 124 ℓ/kg) and with the highest median value again in the Berg River Valley (150 ℓ/kg). These values suggest that rainfall (impacting on WF_{green}) and pollutants (impacting on WF_{grey}) played a larger role in the Berg River Valley production region compared to the other production regions.

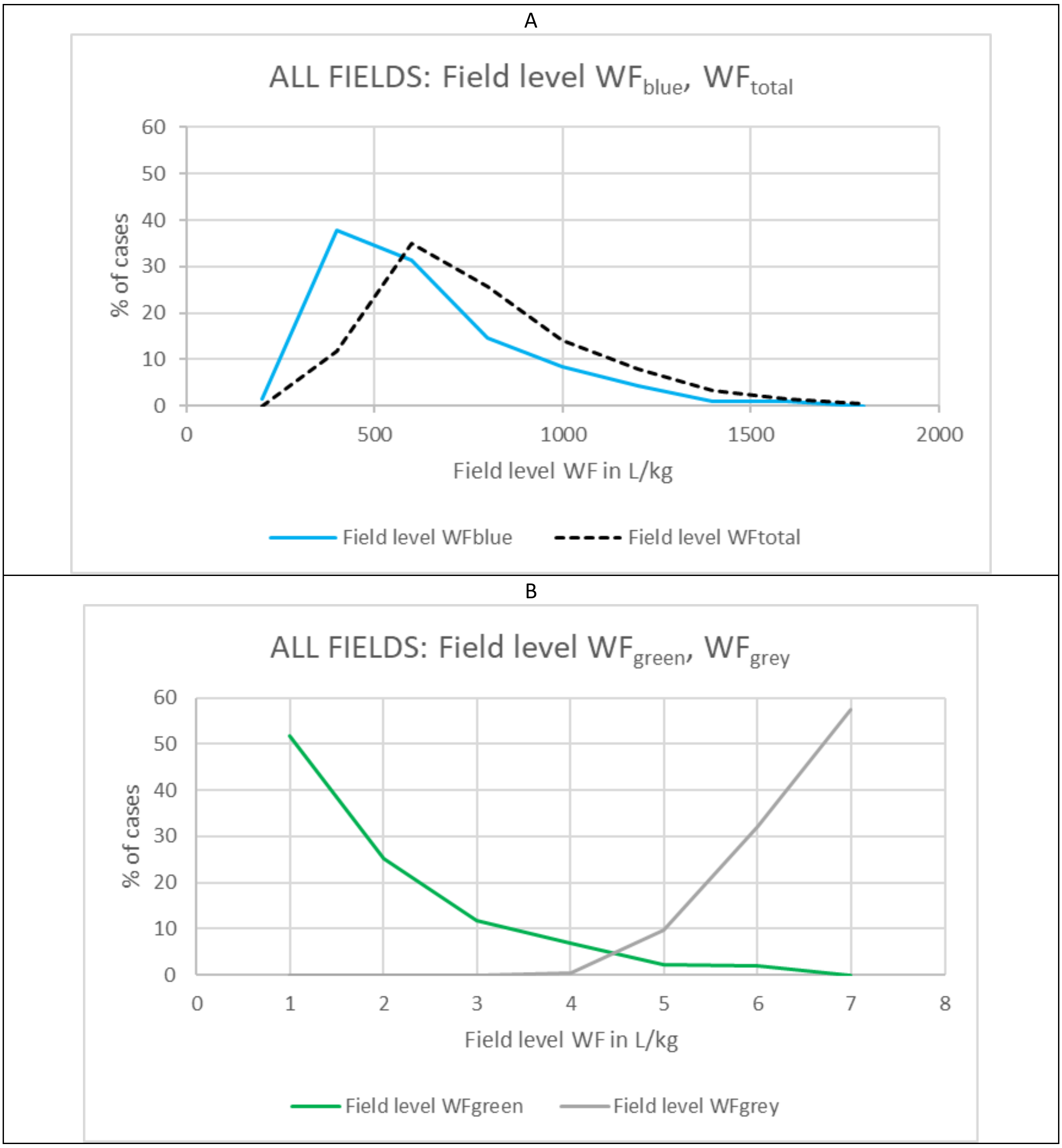


Figure 5.6: (A) Field level WF_{blue} and WF_{total} in ℓ/kg for all data and regions considered; and (B) field-level WF_{green} and WF_{grey} in ℓ/kg for all data and regions considered. Data is for the 2018/19 season. The percentage of cases for each water footprint class is shown.

5.2.3 Cultivar differences

Since the field-level water footprint of individual table grape fields was calculated and information was available on the respective cultivar of each field, it allowed for the exploration of differences in the field-level water footprint of the respective cultivars. The field-level WF_{total} of seven important table grape cultivars cultivated in South Africa (according to SATI, 2019a) was compared:

- Crimson Seedless
- Prime
- Thompson Seedless
- Tawny Seedless
- Sugranineteen (Scarlotta Seedless®)
- Sugrathirteen (Midnight Beauty®)
- Flame Seedless

Note again, as mentioned earlier, that a decision was taken to only include full-bearing and productive vineyards in this analysis. Therefore, records were omitted where a total crop loss was recorded due to adverse weather, pests and diseases, for example the scattering of grape flowers due to wind (such as for Tawny Seedless), the rotting of grapes due to rain (such as for fields with Crimson Seedless) and citrus thrips affecting some cultivars. Including water footprint estimates for such cases severely skewed the field-level WF_{total} results to unrealistic values.

Lower production and quality reported for specific cultivars at the SATI Joint Marketing Forum meeting's post-season analysis for 2018/19 on 14 May 2019 (SATI, 2019b; Van der Merwe, 2019) were ascribed to flower shatter before full bloom (Sugraone, Ralli Seedless, Thompson Seedless, Arrafifteen and Blagratwo (Melody™)), a high incidence of shot berries (Prime, Grapaes (Early Sweet®), Starlight, Ralli Seedless, Sugraone, Sugratwelve (Coachella Seedless®), Tawny Seedless, Sugrasixteen (Sable Seedless®), Sugrathirteen (Midnight Beauty®), Sheegene 3 (Magenta™), Sheegene 12 (Krissy™) and Autumn Royal), uneven berry size and physiological stage in one bunch, as well as "dead" pedicel and rachis due to downy mildew.

In Figure 5.7 the differences in field-level WF_{total} for seven cultivars are shown, illustrating that differences exist between cultivars, which is not clear from single median field-level water footprint values as displayed in Figure 5.4. Field-level WF_{total} data was again taken from all three production regions for the 2018/19 season. Table 5.3 shows the statistical descriptors of the field-level WF_{total} values estimated for each cultivar, including the maximum, minimum and median values.

Table 5.3 and Figure 5.7 show that, based on the data considered, the median field-level WF_{total} of Prime was the highest at 844 ℓ/kg and that of Sugranineteen (Scarlotta Seedless®) was the lowest at 429 ℓ/kg – the former value is, therefore, double the latter. The median field-level WF_{total} for the widely cultivated cultivar, Crimson Seedless, was 699 ℓ/kg (based on 76 samples), falling somewhere between the Prime and Sugranineteen (Scarlotta Seedless®) field-level WF_{total}. Figure 5.7 shows that, although the median field-level WF_{total} for Prime was the highest, field level WF_{total} estimates for Crimson Seedless, Thomson Seedless and Flame Seedless exceeded this value of 844 ℓ/kg (Table 5.3). The highest (maximum) field-level WF_{total} estimate was for Crimson Seedless at 1,688 ℓ/kg (Table 5.3). However, it is interesting to note that the lowest field-level WF_{total} was also calculated for a Crimson Seedless field (Table 5.3), emphasising the variation between fields even of the same cultivar. This is also clearly illustrated in Table 5.3, where the frequency distribution of the field-level WF_{total} for Crimson Seedless is given, showing the range in the field-level WF_{total} values calculated for this single cultivar and in one production season (2018/19).

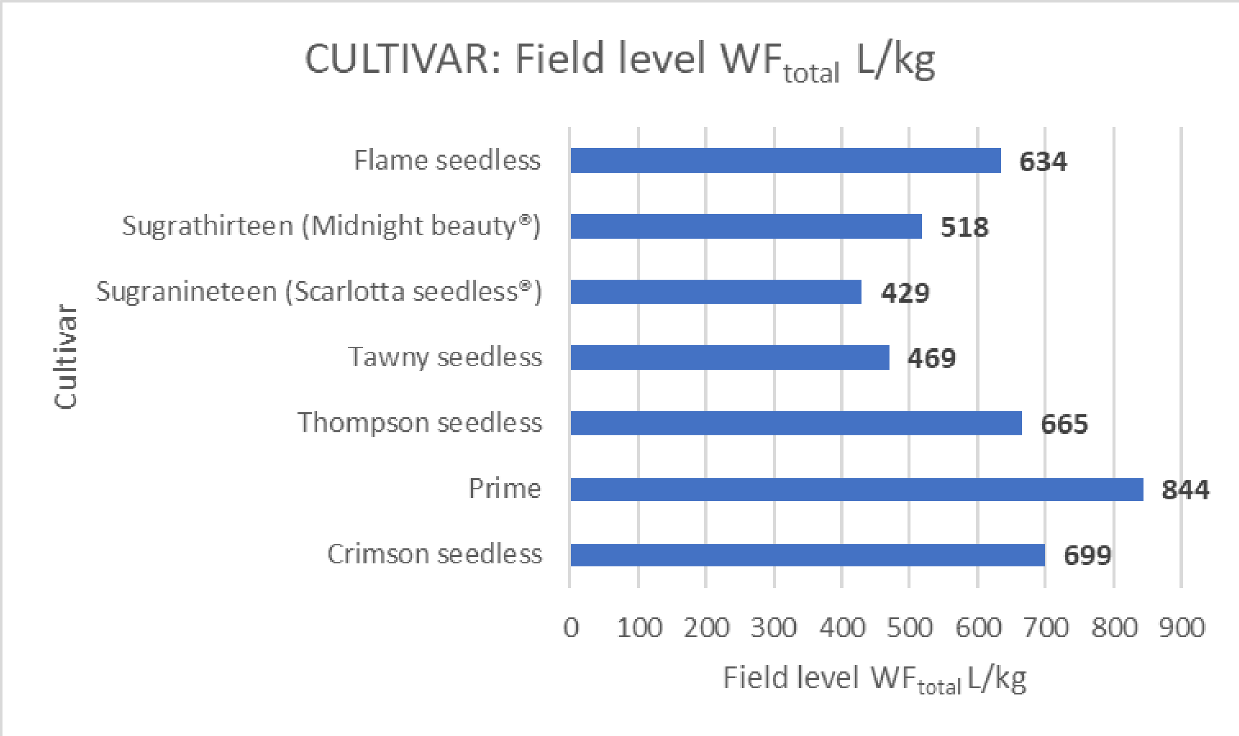


Figure 5.7: Median values of the field-level WF_{total} in ℓ/kg for seven important cultivars grown in South Africa. Median values are based on data from all regions considered in this study and for the 2018/19 season.

Table 5.3: Summary statistics of field-level WF_{total} in ℓ/kg for seven important table grape cultivars cultivated in South Africa. Data is from three production regions and the production season 2018/19. Median, maximum, minimum and range values, as well as the number of samples considered, are shown.

	Field level WF_{total} in ℓ/kg						
Statistics	**Crimson seedless**	**Prime**	**Thompson seedless**	**Tawny seedless**	**Sugranine teen (Scarlotta Seedless®)**	**Sugra-thirteen (Midnight Beauty®)**	**Flame Seedless**
Number of samples	76	6	4	12	10	9	6
Maximum	1 688	1 288	878	667	601	827	912
Minimum	315	598	419	317	350	341	577
Median	699	844	665	469	429	518	634
Range	1 372	690	460	350	251	486	335

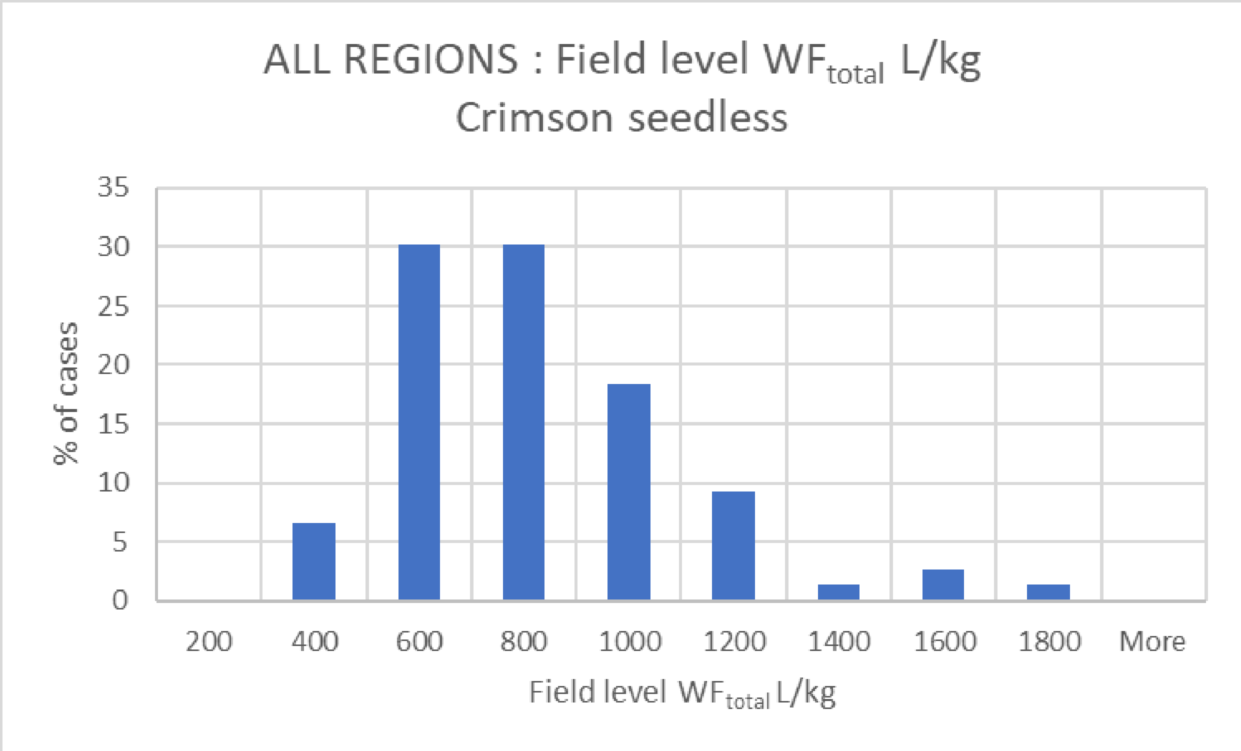


Figure 5.8: *Field-level WF_{total} in ℓ/kg for Crimson Seedless grapes produced in the three production regions considered in this study. The histogram shows the percentage cases of each field-level WF_{total} class. Data is for the 2018/19 season.*

5.2.3.1 Relationship between grape production and field level total water footprint

In earlier sections, it was mentioned that cases were omitted from this study, including young fields where the vines are not yet full-bearing and fields where there were severe crop losses due to adverse conditions. This relates to the fact that, due to the nature of the water footprint calculations, production has a very strong impact on the estimates. This is clearly illustrated in Figure 5.9, where the total grape production (export, local and other) is plotted against the field-level WF_{total}. Again, data is for all and individual regions and for the 2018/19 season. According to the graphs, it appears that a field-level WF_{total} of less than 500 ℓ/kg is unlikely for grape production of less than 25 t/ha. Similarly, a field-level WF_{total} of less than 1,000 ℓ/kg is unlikely for total grape production below 12 t/ha. Notice how sharply the field-level WF_{total} increases for table grape production below 10 t/ha (Figure 5.9). It is interesting to note that a power function ($y = 8\ 871.8x^{-0.862}$) fitted well ($R^2 = 0.9\ 303$) to this dataset (all data), where the y-axis represents the field-level WF_{total} in ℓ/kg and the x-axis represents the table grape production in t/ha.

The importance of high production on a low field-level WF_{total} was highlighted in preceding discussions. However, it is important to note that high quantities of high-quality grapes (export or local) should be the determinant and not just high quantities of low-quality grapes, since it will likely not realise a high economic value. For the difficult grape production season under consideration (2018/19) and the specific fields considered, the median export fraction of grapes was typically less than 73% (Figure 5.2 and Table 5.2). Therefore, the benefits of low field-level WF_{total} estimates in the presence of a fraction of poor-quality table grapes may not have been fully realised during this season, since a good export fraction is typically seen as 80% or higher (SATI, 2019b).

Values for water use and water footprint assessments must always be interpreted in context, specifically regarding the water used versus production, quality and income.

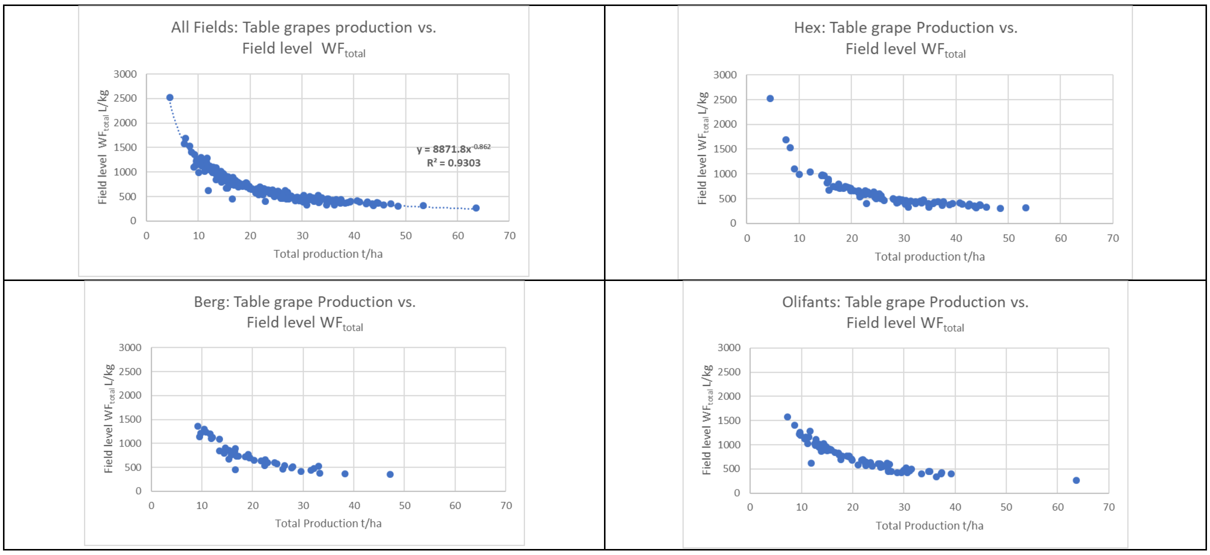


Figure 5.9: Total table grape production in t/ha plotted against field-level WF_{total} in ℓ/kg. Data is shown for all regions together and the three separate regions included in this study. Data is from the 2018/19 production season.

5.2.3.2 Summary of the contributions of the field-level green, blue and grey water footprint to the field-level total water footprint for table grapes

In order to further scrutinise the actual field-level water footprint values discussed in Chapter 5.2.2.1, information about the relative contribution of WF_{green}, WF_{blue} and WF_{grey} to the field-level WF_{total} can provide more insight. Figure 5.10 and Figure 5.11 show the proportional contribution of each component to the field-level water footprint estimates. Figure 5.10, representing the data for each field considered, shows that the WF_{blue} component dominates the estimates, ranging between 52 and 90% of the field-level WF_{total} estimates. The green water component of the field-level water footprint was the lowest, contributing 1 to 14% of the field-level WF_{total}. The smallest contribution of WF_{green} was found in the Olifants River Valley (< 3%), while the largest was found in the Berg River Valley (6 to 14%). Considering individual fields, the field-level WF_{grey} contribution to the field-level WF_{total} ranged between 9 and 38%, with not much difference between the respective regions. Also see Table 5.2 in which the statistics related to these estimates are summarised.

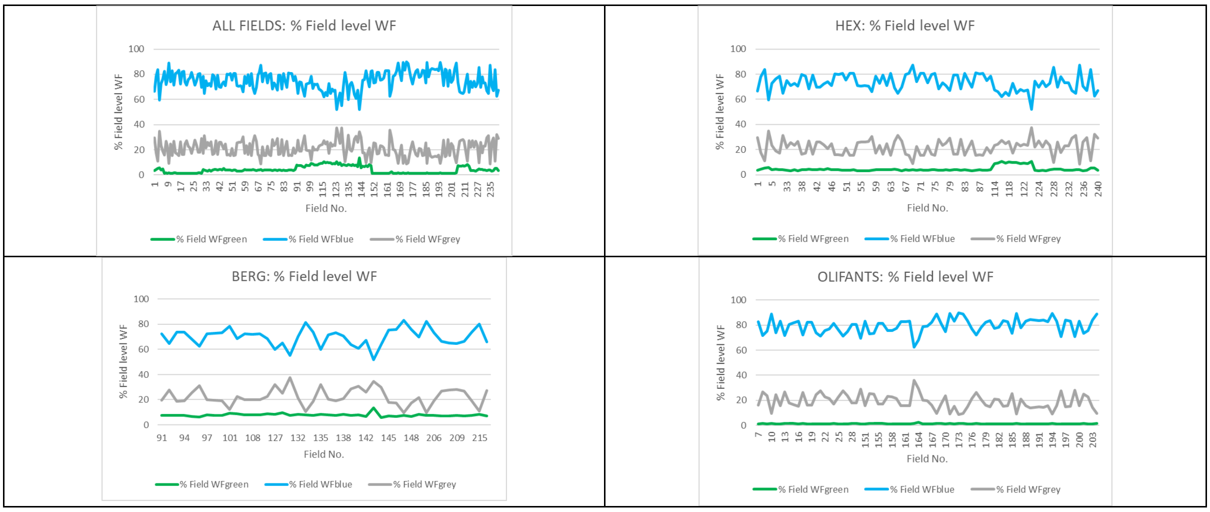


Figure 5.10: Percentage contribution of field-level WF_{green}, WF_{blue} and WF_{grey} to field-level WF_{total}. Data is shown for individual fields for all regions together and for the three regions considered separately. Data is for the 2018/19 season.

The contributions of the green, blue and grey components of the field-level WF_{total} estimates are summarised in Figure 5.11, which represents these as median values per region. Estimates are shown for all data considered together and per region. Figure 5.11 clearly illustrates that the field-level WF_{blue} component is dominating the field-level WF_{total} estimates (> 71%) and the field-level WF_{green} component is small (< 8%) for all regions, reflecting the low rainfall. The median field-level WF_{grey} is the lowest in the Olifants River Valley Region: 17% vs. 21 and 23% in the Berg and Hex River Valley regions, respectively. The significant contribution of the field-level WF_{blue} component in all areas, but even more so in the Olifants River Valley Region (median field-level water footprint of 81%) illustrates the importance of the efficient use of water for irrigation (Figure 5.11). Efficient management of the irrigation systems through the application of the correct amount of irrigation and at the appropriate time will impact on the field-level WF_{total} and could provide a means whereby the field-level WF_{total} values can be reduced. Also, with field-level WF_{grey} contributing nearly a quarter of the field-level WF_{total}, careful consideration of the application of fertilizer, especially in the Berg and Hex River Valley regions, could further reduce the field-level WF_{total}. Fertilizers with high concentrations of nitrogen will increase the field-level WF_{grey} and total components, and should be kept as low as possible, considering the production targets and region.

The results, indicating the blue component dominating the field-level WF_{total} and the green component making a very small contribution, provide context to the reason why all commercial table grape production in South Africa takes place under irrigation and not under dryland conditions.

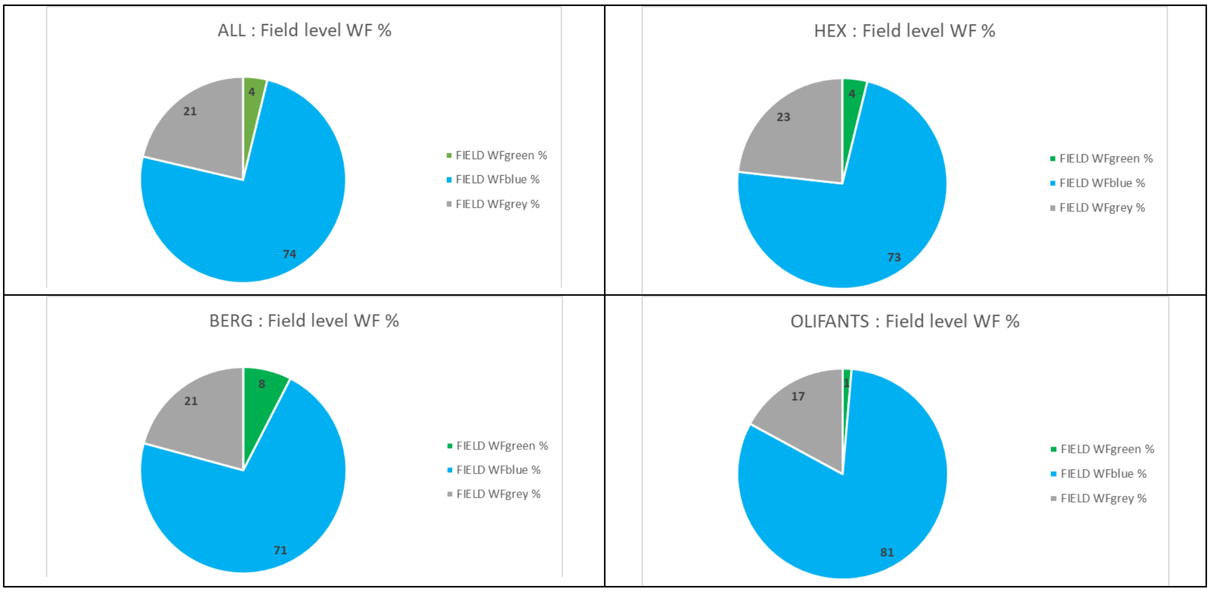


Figure 5.11: Percentage contribution of field-level WF_{green}, WF_{blue} and WF_{grey} to the field-level WF_{total} for all table grape regions and the three production regions considered separately. Data shown is the median values derived from all the individual fields considered and for the 2018/19 production season.

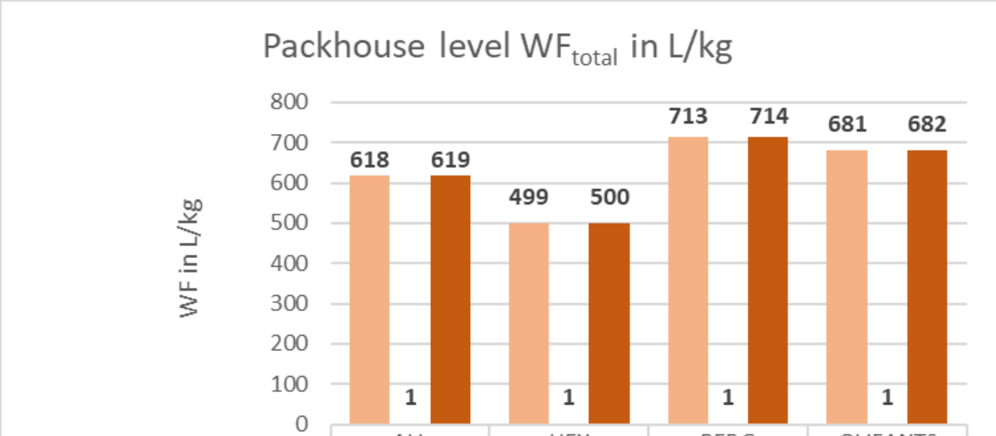
5.2.4 Packhouse level total water footprint of table grapes

The field-level WF_{green}, WF_{blue}, WF_{grey} and WF_{total} estimates for table grapes from this study were described in the preceding sections. In order to provide the complete picture of the packhouse-level water footprint estimate for table grapes, the data was finally integrated with WU_{blue} estimates at the packhouse itself. Only the blue water use contributions were considered in the case studies (see Chapter 4.7.2). The packhouse-level WF_{total} for table grapes was estimated as follows:

$$\begin{aligned} &Packhouse\ level\ WF_{total}\ (table\ grapes) = \\ &\quad = median\left(Field\ level\ WF_{green} + Field\ level\ WF_{blue} \right. \\ &\quad \left. + Field\ level\ WF_{grey}\right) + Packhouse\ level\ WF_{blue} \end{aligned} \qquad (5.5)$$

Figure 5.12 shows the field-level WF_{total} estimates, together with the packhouse-level WF_{blue} and packhouse-level WF_{total}. Data is expressed in ℓ/kg and is shown for all regions considered together and separately. The packhouse-level WF_{blue} was < 1 ℓ/kg (0.76 ℓ/kg) and had little impact on the packhouse-level WF_{total} of table grapes. The packhouse-level WF_{total} ranged between 500 ℓ/kg for the Hex River Valley production region and 714 ℓ/kg for the Berg River Valley production region, with the Olifants River Valley production region having a value of 682 ℓ/kg. The packhouse-level WF_{total} for the Berg River Valley was 1.5 times that of the Hex River Valley (Figure 5.12).

The median packhouse-level WF_{total} for table grapes produced in the 2018/19 season in the three production regions considered in this study was 619 ℓ/kg (Figure 5.12). These median packhouse-level WF_{total} values are direct consequences of the conditions of the 2018/19 production season and the fields considered in each production region. These values should, however, provide a good indication of the packhouse-level WF_{total} for table grapes.



	ALL	HEX	BERG	OLIFANTS
Field level WFtotal	618	499	713	681
Packhouse level WFblue	1	1	1	1
Packhouse level WFtotal	619	500	714	682

Figure 5.12: Packhouse-level WF_{total} in ℓ/kg estimated from data for the 2018/19 season as the sum of a (median) field-level WF_{total} and packhouse-level WF_{blue}. Data is shown for all regions together and for the separate regions.

The results summarised in Figure 5.12 clearly show that the water use during the production of table grapes at field and therefore farm level (field-level WF_{total}) is by far (99%) the largest contributor to the water footprint of table grapes (packhouse-level WF_{total}). Any activities aimed at reducing the water use or water footprint of table grapes at farm level should be encouraged to reduce the packhouse-level WF_{total} for table grapes. However, all role-players along the table grape production value chain (in the field, packhouse) will impact on the packhouse-level WF_{total}. At present, the contribution of the packhouse-level WF_{grey} could not be quantified, but any activities to reduce this fraction (the result of the impact of water quality in the region) are encouraged, since this will impact on the packhouse-level WF_{total}, irrespective of the actual value or relative contribution.

5.2.5 Packhouse-level total water footprint of table grapes in 4.5 kg carton equivalents

The table grape industry often uses a 4.5 kg carton of table grapes as a reference unit. Therefore, the packhouse-level WF_{total} for table grapes was also converted to ℓ/4.5 kg carton equivalent grapes produced (Figure 5.13). Accordingly, the median-value packhouse-level WF_{total} was 2,796 ℓ/4.5 kg, considering all regions. The values for the individual regions were 2,248, 3,213 and 3,067 ℓ/4.5 kg carton equivalent for the Hex, Berg and Olifants River Valley regions respectively.

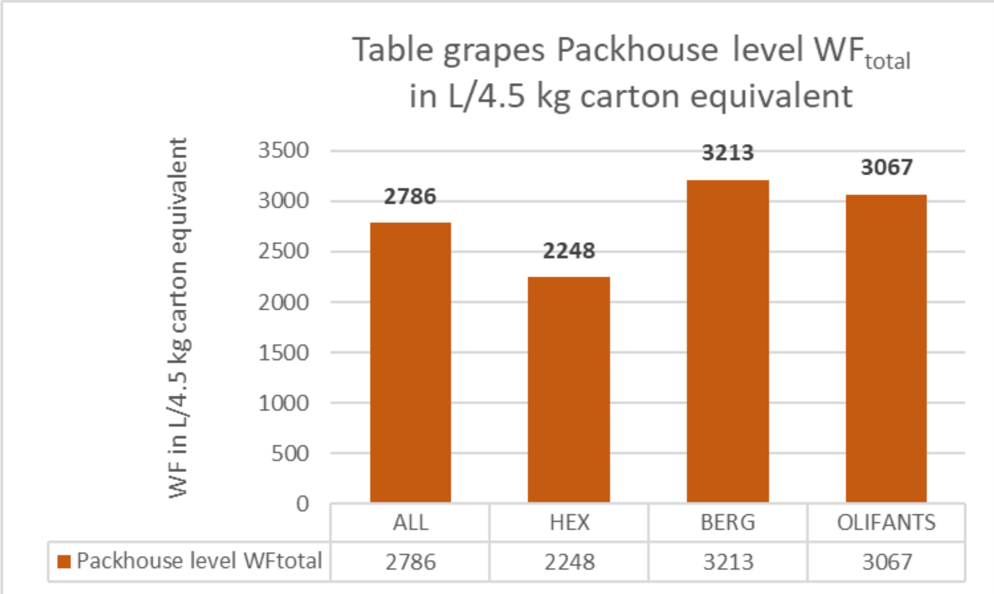


Figure 5.13: Packhouse-level WF_{total} in ℓ/4.5 kg carton equivalents estimated from data for the 2018/19 season as the sum of a (median) field-level WF_{total} and packhouse-level WF_{blue}. Data is shown for all regions together and for the separate regions.

5.3 WATER FOOTPRINT OF WINE GRAPES AND WINE

5.3.1 Background information

As mentioned in Chapter 5.1, the estimation of the water footprint of wine comprised two parts: firstly, it considered the field-level water footprint of wine grapes, and secondly, it added the cellar-level water footprint. The conditions pertaining to the field-level water footprint estimates of wine grapes are described below. Information related to the fields considered is summarised in Table 5.4.

For the water footprint of wine, producer cellars situated in three important WO regions of South Africa were considered (Figure 3.3): the Coastal, Breede River Valley and Olifants River Valley regions. In total, an area of 8.912 ha under wine grapes was considered: 64% of this area was in the Breede River Valley Region and 13 and 27% were in the Coastal and Olifants River Valley regions, respectively. Data from 3,605 vineyards was included in the analysis, with a median vineyard age of 17 years (Table 5.4). Young (more than 2 years) and old (up to 100 years) vineyards were considered in the analysis.

The wine grape production data considered in this study is summarised in the histogram shown in Figure 5.14 . The production values presented in Figure 5.14 and Table 5.4 show that there was a substantial variation in the yields attained during the season under consideration. Some 77% of the field had a production of 30 t/ha or less, 9% had a production above 40 t/ha and 4% had a production above 50 t/ha (Figure 5.14). The maximum wine grape production considered was 79 t/ha (Table 5.4). Note that fields with grape production in excess of 80 t/ha were excluded after consultation with the viticulturists from the producer cellars involved in this study since these were deemed unrealistic. The median production value across all regions was 19 t/ha. Based on the records for the respective regions considered, this median value was the lowest in the Coastal Region (8 t/ha) and the highest in the Breede River Valley Region (22 t/ha) (Table 5.4).

Data from 37 different cultivars was considered, with the Coastal Region representing the fewest cultivars (16) and the Breede River Valley Region the most (32) (Table 5.4). The planting densities in the vineyards considered ranged between 1,111 and 10,000 plants per hectare, with a median value of 3,086 plants per hectare (Table 5.4).

Table 5.4: Basic description of data considered in the case studies for the water footprint assessment of wine grapes and wine. Data is for the 2018/19 season and three wine grape production regions of South Africa.

Region	Statistics	Area	Cultivars	Record	Age	Plant density	Production	Rainfall	P_{eff}	ET
		Ha	No.	No.	Years	Plants per ha	t/ha	mm/year	mm/year	mm/year
All areas	Total	8,912	37	3,605						
	Maximum	22			119	10,000	79	608	291	1,257
	Minimum	0			2	1,111	0	61	7	273
	Median	2			17	3,086	19	345	125	781
	Average	2			17	3,078	21	321	124	773
Coastal	Total	1,135	16	393						
	Maximum	22			41	4,479	48	608	291	919
	Minimum	0			2	1,111	1	397	145	306
	Median	2			17	3,086	8	430	161	574
	Average	3			16	2,956	10	507	219	594
Breede River Valley	Total	5,684	32	2,096						
	Maximum	15			119	6,719	78	504	211	1,226
	Minimum	0			2	2,083	1	345	125	347
	Median	2			16	3,333	22	345	125	824
	Average	3			17	3,248	23	424	168	816
Olifants River Valley	Total	2,092	29	1,116						
	Maximum	11			48	10,000	79	61	7	1,257
	Minimum	0			2	1,366	0	61	7	273
	Median	2			19	2,667	17	61	7	747
	Average	2			19	2,803	21	61	7	753

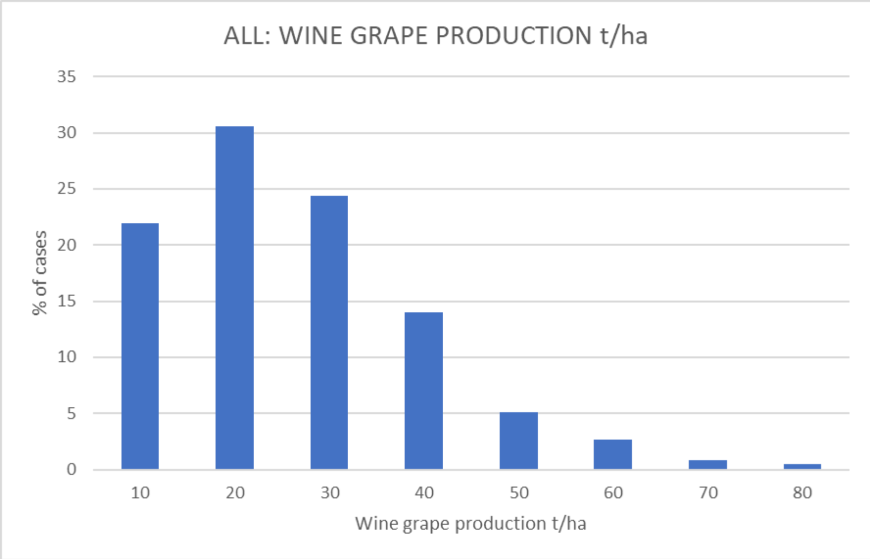


Figure 5.14: Histogram showing the wine grape production in t/ha – percentage of cases per production class. Data is based on all fields from all areas considered in this study. For the season 2018/19, any production estimates above 80 t/ha were omitted.

The annual rainfall for the period 1 August 2018 to 31 July 2019 is shown in Figure 5.15. The rainfall ranged between 61 and 608 mm/year across the three production regions (Table 5.4 and Figure 5.15). Note that, in the Coastal and Breede River Valley regions, data from more than one rainfall station was used and therefore a range (different maximum and minimum) in rainfall is shown. The rainfall in the Olifants River Valley was 61 mm (with a derived P_{eff} of 7 mm – see Chapter 4.5), while in the Breede River Valley, it ranged between 345 and 504 mm/year (P_{eff} 125 to 211 mm/year) and in the Coastal Region, it ranged between 397 and 608 mm/year (P_{eff} 145 to 291 mm/year) (Table 5.4).

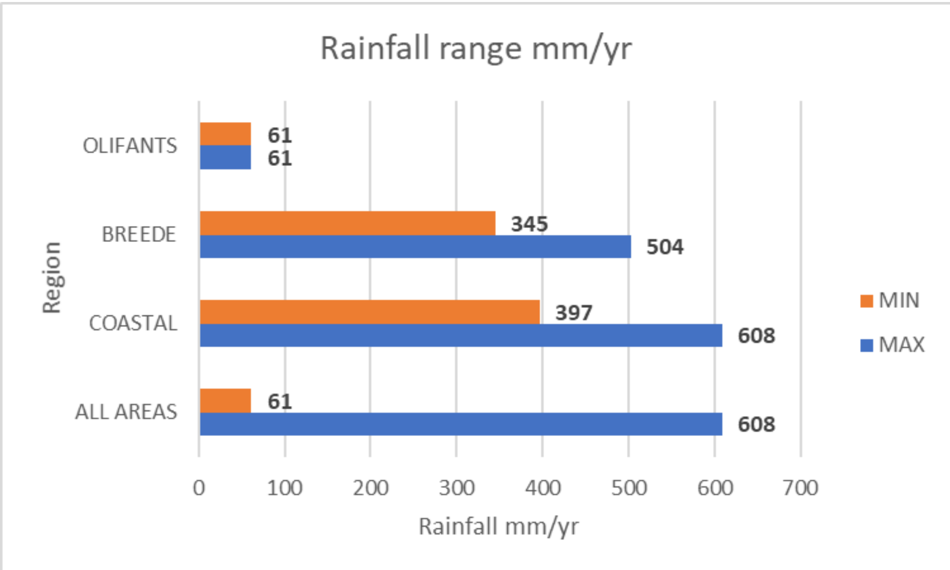


Figure 5.15: Annual rainfall for the study areas considered in the water footprint of wine case studies. The period considered was 1 August 2018 to 31 July 2019. Where data from only one rainfall station was used (Olifants River Valley), the maximum and minimum values were the same. For the other two regions, a range in rainfall (maximum and minimum) values is shown.

5.3.2 Field-level total water footprint of wine grapes

5.3.2.1 Field-level green, blue, grey and total water footprint for all production ranges

The steps involved in calculating the different field-level water footprint components were described in Chapter 5.1 and were followed for the wine grape estimates as well.

The field-level WF_{total} estimates for the 3,605 wine grape fields considered in this study are summarised in the histograms shown in Figure 5.16. The field-level WF_{total} for wine grapes of nearly three-quarters (76%) of all fields considered was below 800 ℓ/kg, with just over a third (36%) having values of below 400 ℓ/kg. However, larger values existed, with 6% of the cases (222) having field-level WF_{total} values in excess of 2,000 ℓ/kg. These higher values were calculated for vineyards located in all production regions and could be directly related to low production values. This fraction of field-level WF_{total} > 2 000 ℓ/kg was the highest in the Coastal Region with 15 and 10% in the Olifants River Valley. The Coastal Region also had the lowest fraction (10%) of field-level WF_{total} values below 400 ℓ/kg, compared to the 41 and 37% in the Breede and Olifants River Valley regions, respectively.

The median field-level WF_{total} of wine grapes (considering data from all regions) was 484 ℓ/kg, with the highest regional median field-level WF_{total} estimate for the Coastal Region nearly double that (1.7 times) or 842 ℓ/kg (Figure 5.16 and Table 5.5).

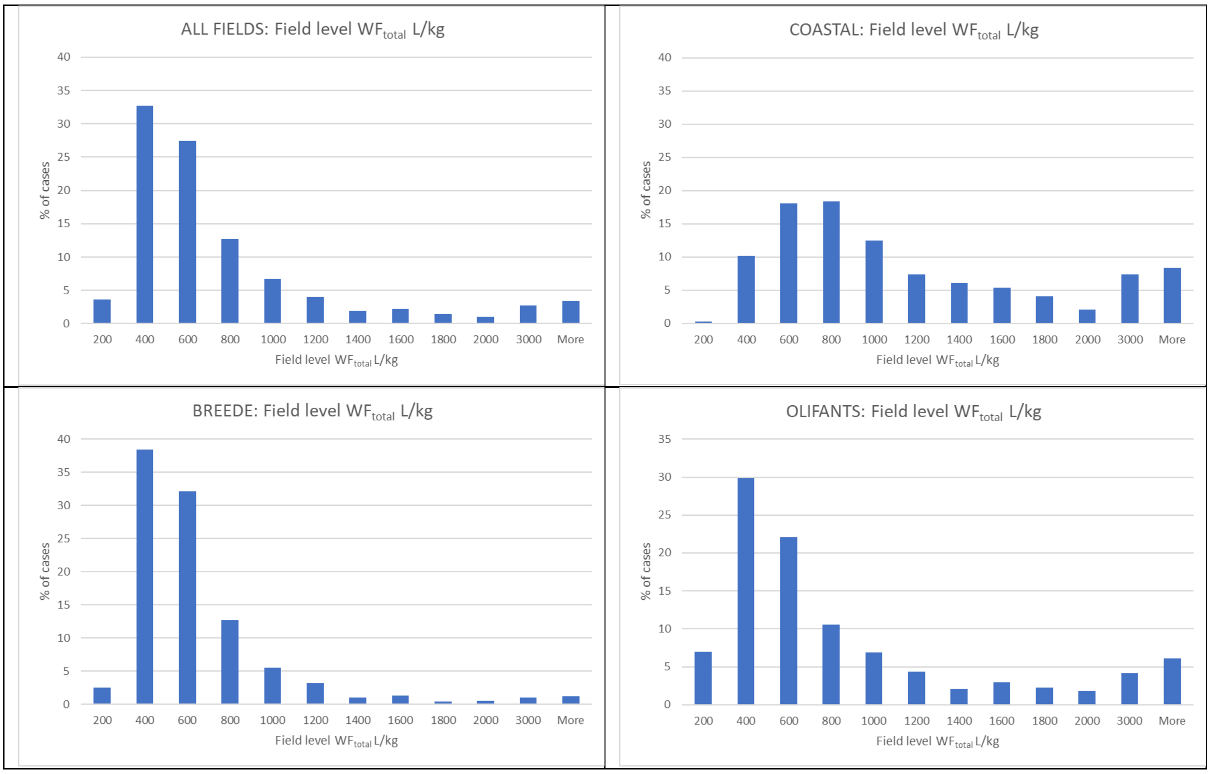


Figure 5.16: Histograms showing the field-level WF_{total} for wine grapes for each production region considered in this study. Data is for the 2018/19 season and presents the percentage of cases per WF_{total} range.

The ranges in the field-level WF_{total} values shown in Figure 5.16 reflect the variation in production (Figure 5.14) as a result of conditions experienced at regional and farm level, whether related to the production season (climate, pests and diseases) or the production system (irrigation and irrigation systems, soils, cultivars, trellis systems, planting density, etc.).

Figure 5.17 shows the histograms of field-level WF_{total}, WF_{green}, WF_{blue} and WF_{grey} components for wine grapes. The field-level WF_{blue} follows the frequency distribution of the field-level WF_{total} very closely. The field-level WF_{blue} ranged between 21 and 30,466 ℓ/kg and the field-level WF_{total} ranged between 91 and 34 841 ℓ/kg (Figure 5.17 and Table 5.5). The large variation in both WF_{blue} and WF_{total} reflects the large variation in grape production reported in Figure 5.14. The extremely high field-level WF_{blue} and field-level WF_{total} correspond to extremely low yields (less than 3 t/ha). Keep in mind that the water use is divided by crop yield in order to calculate the water footprint. The actual field-level WF_{green} and WF_{grey} values were much smaller in comparison. Some 73% of the field-level WF_{grey} was less than 100 ℓ/kg, but 4% of the values exceeded 400 ℓ/kg. Some 50% of the field-level WF_{green} values were below 60 ℓ/kg, and again 4% of the values exceeded 400 ℓ/kg.

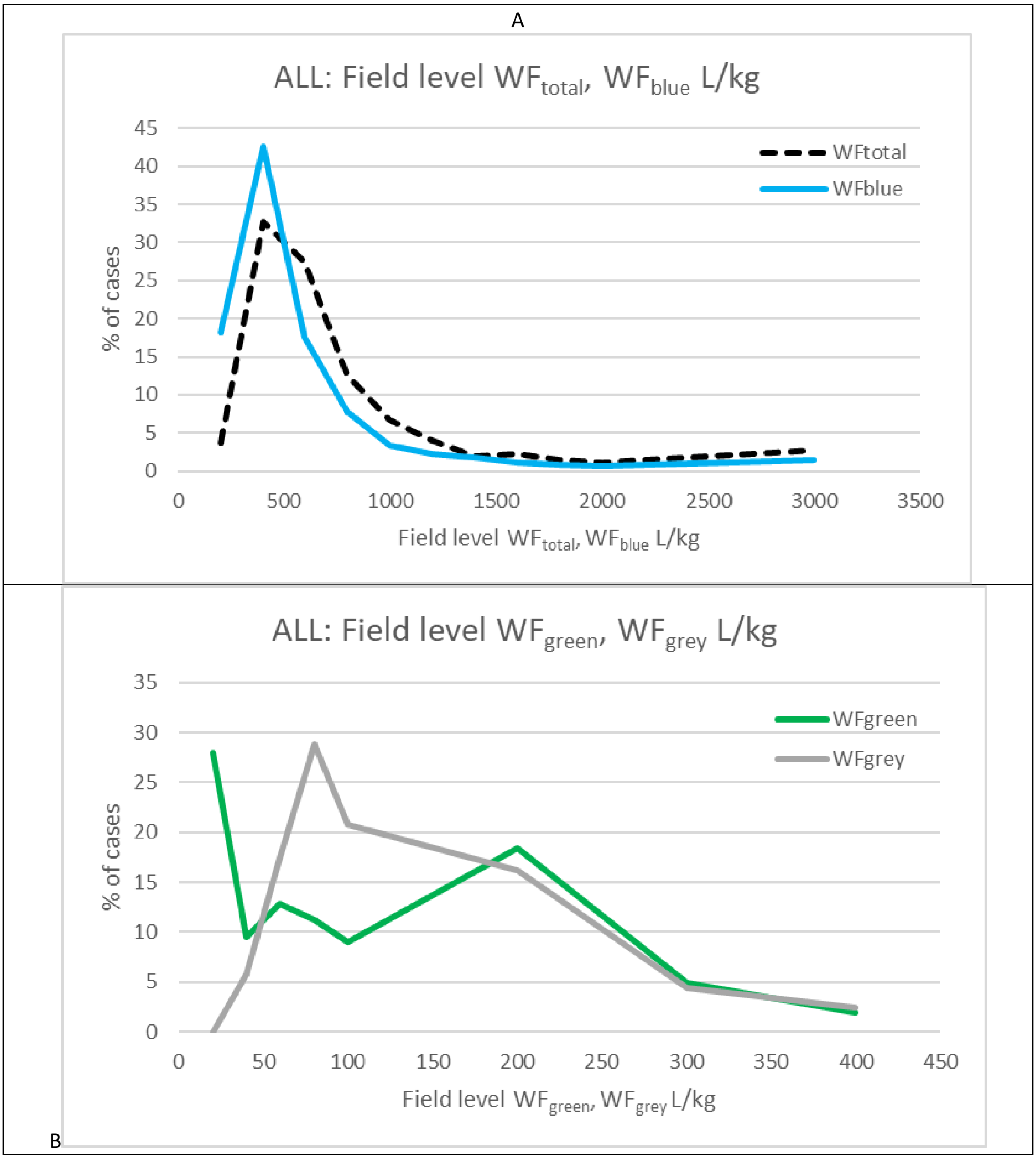


Figure 5.17: Histograms for (A) the field-level WF_{blue} and WF_{total}, and (B) field-level WF_{green} and WF_{grey} for wine grapes, considering all the data from all regions together. These histograms are based on data from the 2018/19 season.

Table 5.5: Descriptive statistics related to wine grape production, field-level and cellar-level WF_{blue}, WF_{grey} estimates, as well as cellar-level WF_{total} for wine. Statistics are based on the 2018/19 season and represent data from three production regions considered in the case studies.

Region	Descriptive statistics	Production	Field WF_{green}	Field WF_{blue}	Field WF_{grey}	Field WF_{total}	Field WF_{green}	Field WF_{blue}	Field WF_{grey}	Field WF_{total}	Cellar WF_{blue}	Cellar WF_{grey}	Cellar $WF_{blue,grey}$	Cellar WF (wine)	Field WF_{green}	Field WF_{blue}	Field WF_{grey}	Cellar $WF_{blue,grey}$/ Cellar WF (wine)	Field WF_{total}/ Cellar WF (wine)
		t/ha	ℓ/kg	ℓ/kg	ℓ/kg	ℓ/kg	ℓ/ℓ	ℓ/ℓ	ℓ/ℓ	ℓ/ℓ	ℓ/ℓ	ℓ/ℓ	ℓ/ℓ	ℓ/ℓ	%	%	%	%	%
All areas	Mean	21	109	589	127	825	142	771	167	1,080	2.2	128	185	1,477	14	70	17		
	Standard error	0	4	20	4	25	5	26	5	33	0.0				0	0	0		
	Median	19	60	330	79	485	76	427	102	626	2.4	128	185	863	13	72	16	21	73
	Standard deviation	14	218	1,195	220	1,479	292	1,591	294	1,970	0.3				11	12	4		
	Range	79	3 796	30,445	4,857	34,750	5,136	40,598	6,479	46,340	0.6				66	87	31		
	Minimum	0	1	21	23	91	1	29	29	121	1.7	72			1	4	9		
	Maximum	79	3,797	30,466	4,880	34,841	5,138	40,627	6,508	46,461	2.4	183			66	90	40		
Coastal	Mean	10	413	653	250	1 316	559	884	338	1 780	2.1	183	185	1,965	30	50	20		
	Standard error	0	24	37	14	72	33	50	19	98	0.0				0	1	0		
	Median	8	245	436	160	842	332	590	216	1,139	2.1	183	185	1,325	27	53	19	14	86
	Standard deviation	7	486	738	274	1 429	657	999	370	1,933	0.0				9	10	4		
	Range	48	3,764	5,500	2,225	10,389	5,092	7,441	3,011	14,056	0.0				51	66	23		
	Minimum	1	33	21	44	137	45	29	60	185	2.1	183			15	4	13		
	Maximum	48	3,797	5,521	2,270	10,526	5,138	7,470	3,071	14,241	2.1	183			66	70	36		
Breede River Valley	Mean	23	104	399	86	589	132	506	109	748	2.1	72	74	822	18	66	16		
	Standard error	0	3	10	2	14	3	13	2	18	0.0				0	0	0		
	Median	22	77	292	75	444	97	370	95	566	2.4	72	74	641	18	67	16	12	88
	Standard deviation	12	121	456	78	642	155	578	99	814	0.3				6	8	3		
	Range	77	2,202	7,865	1,484	10,979	2,826	9,936	1,875	13,868	0.6				35	53	24		
	Minimum	1	16	43	23	114	20	55	29	147	1.7	72			9	27	9		
	Maximum	78	2,218	7,909	1,507	11,093	2,846	9,991	1,904	14,015	2.4	72			44	80	33		

Region	Descriptive statistics	Production	Field WF_{green}	Field WF_{blue}	Field WF_{grey}	Field WF_{total}	Field WF_{green}	Field WF_{blue}	Field WF_{grey}	Field WF_{total}	Cellar WF_{blue}	Cellar WF_{grey}	Cellar $WF_{blue,grey}$	Cellar WF (wine)	Field WF_{green}	Field WF_{blue}	Field WF_{grey}	Cellar $WF_{blue,grey}$/ Cellar WF (wine)	Field WF_{total}/ Cellar WF (wine)
		t/ha	ℓ/kg	ℓ/kg	ℓ/kg	ℓ/kg	ℓ/ℓ	ℓ/ℓ	ℓ/ℓ	ℓ/ℓ	ℓ/ℓ	ℓ/ℓ	ℓ/ℓ	ℓ/ℓ	%	%	%	%	%
Olifants River Valley	Mean	21	10	923	161	1,094	13	1,230	215	1,459	2.4	183	185	1,644	1	83	16		
	Standard error	0	1	59	10	69	1	78	13	92	0.0				0	0	0		
	Median	17	4	423	81	508	6	564	108	677	2.4	183	185	863	1	83	16	21	79
	Standard deviation	16	22	1 963	330	2,306	29	2,618	439	3,075	0.0				0	4	4		
	Range	79	323	30,407	4,857	34,750	431	40,548	6,478	46,340	0.0				1	32	31		
	Minimum	0	1	59	23	91	1	79	30	121	2.4	183			1	59	9		
	Maximum	79	324	30,466	4,880	34,841	432	40,627	6,508	46,461	2.4	183			2	90	40		

5.3.2.2 Field level green, blue, grey and total water footprint for selected production datasets or ranges

The production range for the wine grape fields considered in this study is shown in Figure 5.14 and Table 5.5. This resulted in the wide range in field-level WF_{total} values summarised in Figure 5.16 for all the production data and all regions. The observed impact of wine grape production on the field-level WF_{total} and the statistics generated have already been highlighted. Therefore, in Table 5.6, the frequency of the field-level WF_{total} for different production ranges is shown for all data, and where fields with wine grape production of less than 3, 5 and 7 t/ha were excluded. Table 5.6 shows that the frequency (or percentage of cases) of the field-level WF_{total} of up to 600 ℓ/kg did not vary much where datasets considering production values of more than 7, 5 and 3 t/ha are compared: 74, 70 and 67% of the field-level WF_{total} of the values were within the 0 to 600 ℓ/kg range. Table 5.6 shows that all (100%) of the field-level WF_{total} values were less than 1,400 ℓ/kg where only production data higher than 7 t/ha was considered. Where production values of below 5 t/ha and 3 t/ha were included in the analysis, the field-level WF_{total} range for wine grapes was much larger – 100% of the data then fell below the 1,800 and 2,000 ℓ/kg estimate, respectively. This clearly illustrates that a larger fraction of higher-level WF_{total} values was observed where cases of lower wine grape production values were included in the analysis. This is also illustrated in Figure 5.18.

Table 5.6: Frequency distribution (percentage of cases) of field-level WF_{total} in ℓ/kg of wine grapes, shown for all production data considered in this study, and where production less than 3, 5 and 7 t/ha was omitted from the field-level WF_{total} calculations. Data shown is taken from all production areas for the 2018/19 season. Descriptive statistics for the different datasets is also shown.

	All production	Production > 7 t/ha	Production > 5 t/ha	Production > 3 t/ha
Field-level WF_{total} ℓ/kg	**Cumulative percentage of cases**	**Cumulative percentage of cases**	**Cumulative percentage of cases**	**Cumulative percentage of cases**
200	4	4	4	4
400	36	42	40	38
600	64	74	70	67
800	76	88	84	80
1,000	83	95	91	87
1,200	87	99	95	91
1,400	89	100	97	93
1 600	91	100	99	95
1,800	93	100	100	97
2,000	94	100	100	98
3,000	97	100	100	100
> 3,000	100	100	100	100
	Field-level WF_{total} ℓ/kg			
Statistics	**All production**	**Production > 7 t/ha**	**Production > 5 t/ha**	**Production > 3 t/ha**
Median	485	440	456	470
Average	825	496	541	609
Maximum	34,841	1,598	2,027	3,549
Minimum	91	91	91	91

The median field-level WF_{total} estimates were not greatly impacted on by omitting production values of less than 7 t/ha (compared to all data), showing a median range of 440 to 470 ℓ/kg (compared to the median value considering all production data of 485 ℓ/kg). However, the statistical parameter, the average field-level WF_{total} estimate, was 496 ℓ/kg when production data of more than 7 t/ha was considered, compared to 609 ℓ/kg where only production records of less than 3 t/ha were omitted. The maximum field-level WF_{total} estimates were the most affected by excluding some production data ranges (Table 5.6). Where fields of less than 7 t/ha were omitted, the maximum field-level WF_{total} estimate was 1,598 ℓ/kg, compared to 3,549 ℓ/kg when only production data of less than 3 t/ha was omitted. These maximum field-level WF_{total} estimates were still much lower than when all records were considered (34,841 ℓ/kg) (Table 5.6), showing the large impact of low production attained at field level on the field-level WF_{total} estimates.

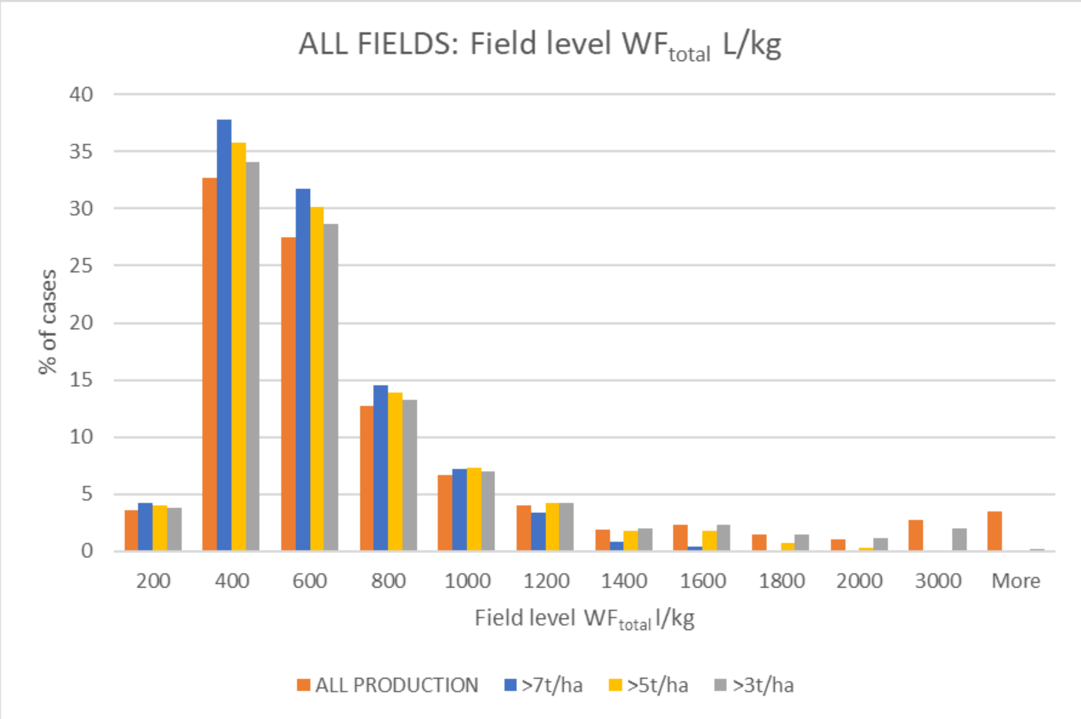


Figure 5.18: Histogram showing the frequency distribution (percentage of classes) of field-level WF_{total} ℓ/kg of wine grapes, where different production datasets were considered. Data is shown for all production values, and where production below 3, 5 and 7 t/ha was excluded.

5.3.2.3 Field-level water footprint cultivar differences

Data from 37 cultivars was considered in this study. According to the analysis, two cultivars – Chenin Blanc (24%) and Colombar (20%) – dominated, representing 44% of the area and number of fields combined. Other cultivars covering large areas were Shiraz (8%), Sauvignon Blanc (7%), Pinotage (7%), Chardonnay (6%), Cabernet Sauvignon (6%) and Merlot (5%).

In Figure 5.19, the field-level WF_{total} for wine grapes is shown for these eight cultivars. The field-level WF_{total} values are expressed in ℓ/kg and the ℓ/ℓ equivalent of wine. For the latter, cellar-specific conversion or recovery rates were applied to convert ℓ/kg to ℓ/ℓ. Figure 5.19 shows the range in the field-level WF_{total} estimates among the different cultivars, with the highest median field-level WF_{total} value calculated for Cabernet Sauvignon (1,131 ℓ/kg) and the lowest for Colombar (343 ℓ/kg) (data from all regions considered). Only Cabernet Sauvignon had a median field level WF_{total} exceeding 1,000 ℓ/kg. Interestingly, Chenin Blanc and Colombar, which represent 44% of the planted area in the study regions, had a field-level WF_{total} (median value) of less than 400 ℓ/kg.

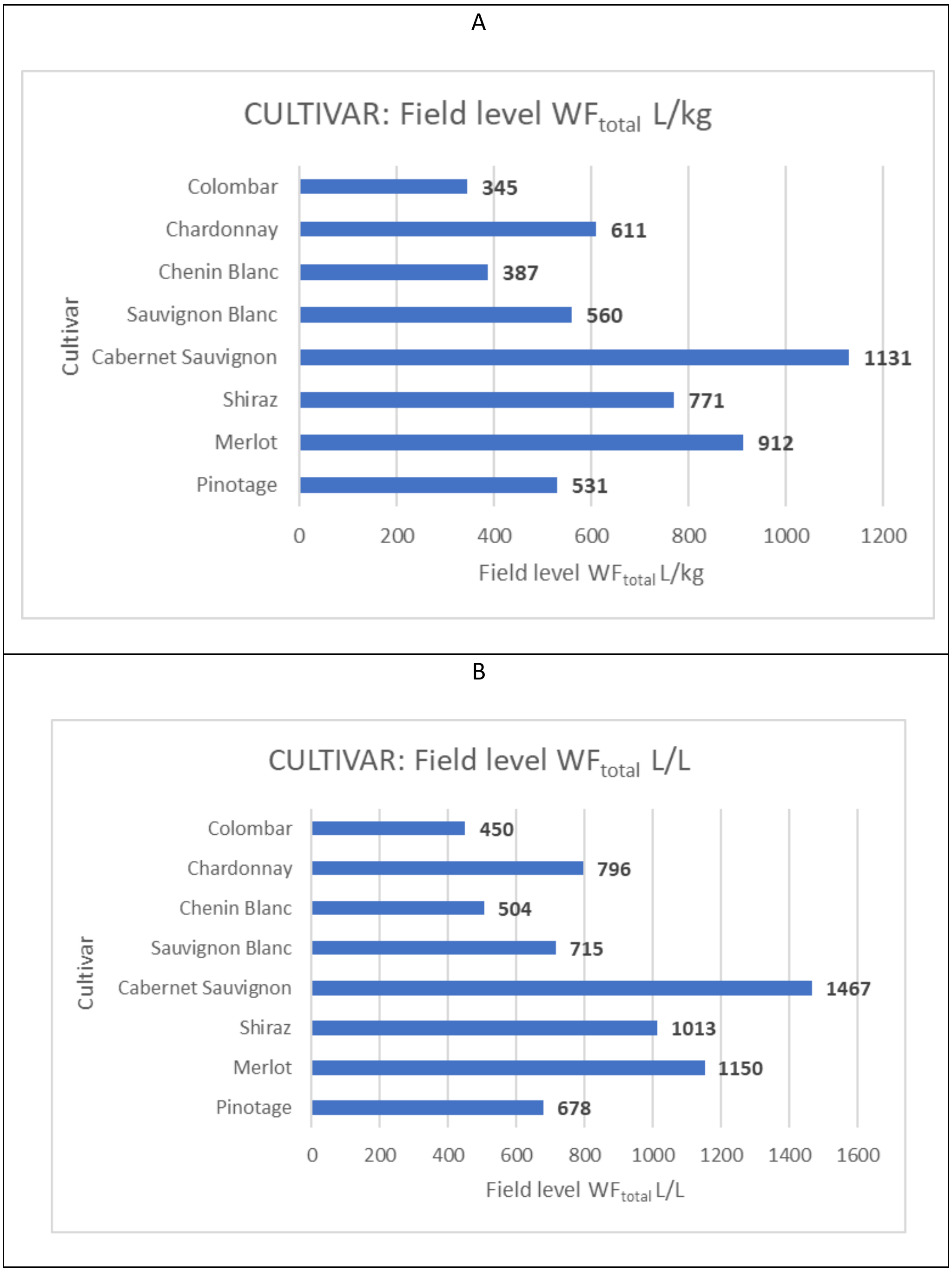


Figure 5.19: Field-level WF_{total} for eight wine grape cultivars cultivated in the areas considered. Data is expressed in (a) ℓ/kg of wine grapes, and (b) the ℓ/ℓ of equivalent wine. Cellar-specific conversion rates were applied to convert ℓ/kg to ℓ/ℓ. Data represents the median field-level values from fields from all regions.

To illustrate possible regional differences in the field-level WF_{total} of a specific cultivar, two cultivars were selected for illustration: Pinotage and Chenin Blanc, with the results shown in Figure 5.20. Here the field level WF_{total} is only expressed in ℓ/ℓ. For Pinotage, the highest field-level WF_{total} was calculated in the Olifants River Valley (1,392 ℓ/ℓ) and the lowest field-level WF_{total} median value was calculated in the Breede River Valley (537 ℓ/ℓ) – more than 50% lower. The Chenin Blanc values showed a smaller range, with the highest field-level WF_{total} median value calculated in the Coastal Region (674 ℓ/ℓ) and the lowest values calculated in the Breede River Valley (458 ℓ/ℓ).

It is important to note that the values quoted and shown in Figure 5.19 and Figure 5.20 represent the median field-level WF_{total}. Higher and lower values are to be expected for each cultivar, as illustrated in the histograms in Figure 5.16. In addition, although a low field-level WF_{total} is desirable, low field-level WF_{total} values do not necessarily reflect good grape or wine quality. Therefore, the water footprint estimates always need to be evaluated within the context of water used to attain a good quality and quantity of wine grapes.

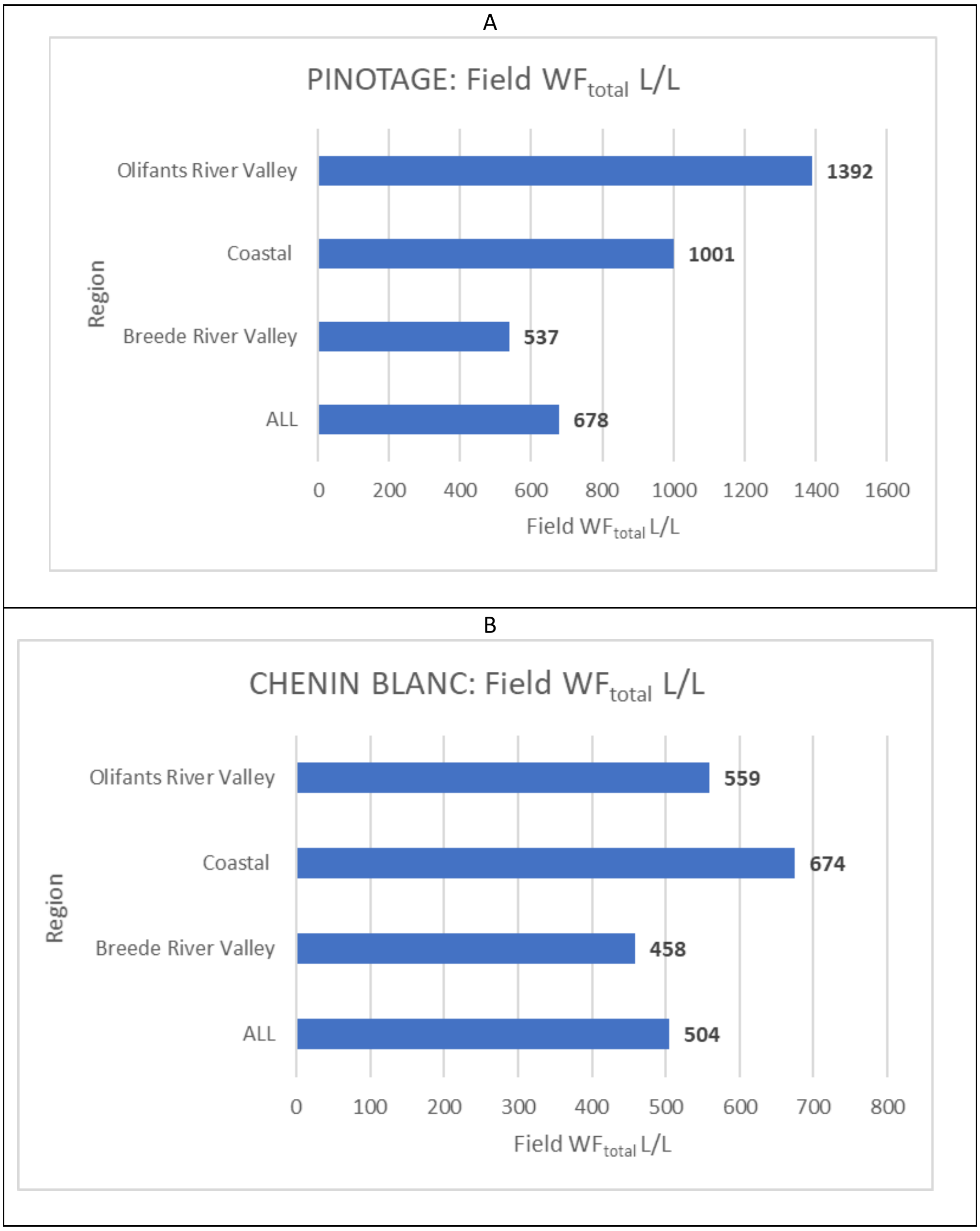


Figure 5.20: Field-level WF_{total} for (A) Pinotage and (B) Chenin Blanc in ℓ/ℓ. Median values per region are shown. Data is again for the 2018/19 season.

5.3.2.4 Relationship between wine grape production and field-level total water footprint

Given that the variation in grape production could have contributed directly to the large variation in water footprint (see Chapter 1.1.1.1), the relationship between grape production and the field-level water footprint required closer scrutiny. In earlier sections, it was explained that some data was excluded from this study.

Specifically, records presenting young fields where the vines are not full-bearing, and fields with production values exceeding 80 t/ha (seen as unrealistic values) were omitted. The field-level WF_{total} is strongly influenced by crop production due to the nature of the water footprint calculations, which is clearly illustrated in Figure 5.21. According to the graphs, it appears that a field-level WF_{total} of less than 500 ℓ/kg is unlikely for wine grape production at less than 15 to 20 t/ha. A wine grape production of 10 t/ha will result in a field-level WF_{total} estimate of approximately 850 ℓ/kg and lower. The water footprint estimates increase exponentially at a 5 t/ha grape production, resulting in a field level WF_{total} of around 1,600 ℓ/kg. As for table grapes, it is interesting to note that a power function ($y = 6\ 499x^{-0.881}$) fitted the data well ($R^2 = 0.9482$), where the y-axis is the field-level WF_{total} in ℓ/kg for wine grapes and the x-axis is the wine grape production in t/ha.

The relationship between wine grape production and the water footprint suggests that producers should strive to maximise production in order to decrease the field-level WF_{total}. However, although the importance of higher production values in reducing the field-level WF_{total} is clear, the quality of the grapes should also be considered. Product quality did not fall within the scope of this research. Like table grapes, the values of the water use and water footprint assessments of wine grapes must be interpreted in context, specifically regarding the water used versus production, quality and income.

Water availability has a strong effect on the total production of wine grapes, which is reflected in the relationship between wine grape production and the water footprint. For vineyards with a quality orientation, a certain level of water stress is often implemented to reduce vegetative growth and improve grape quality. This practice, referred to as “deficit irrigation”, promotes better-quality grape parameters, but implies a compromise in the final crop yield and hence increased water footprint.

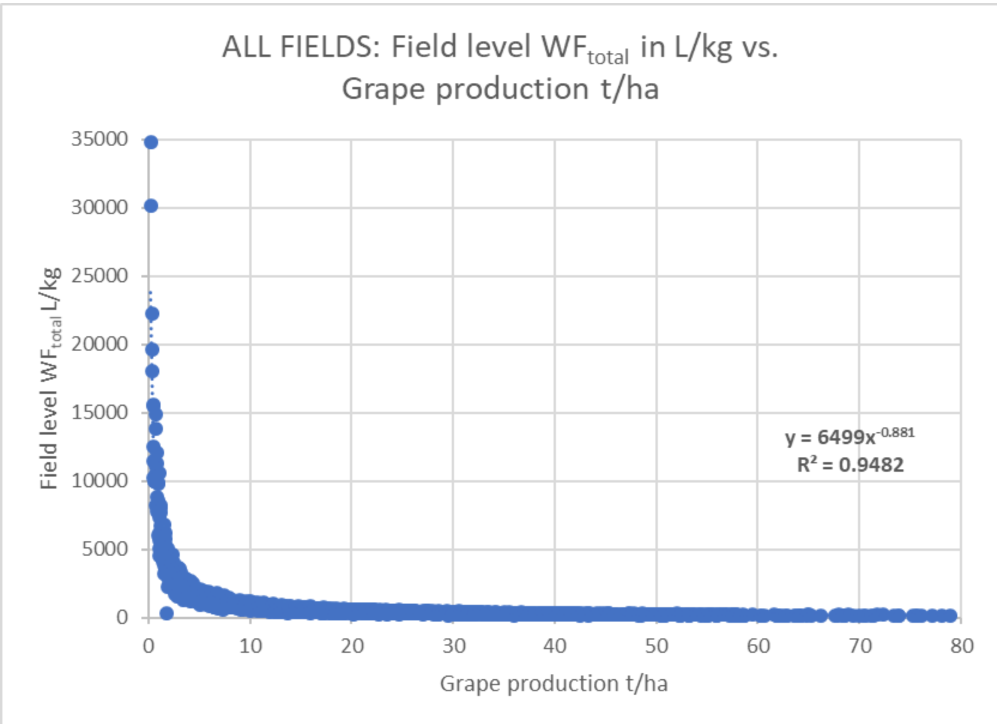


Figure 5.21: Total wine grape production in t/ha plotted against field-level WF_{total} in ℓ/kg for all regions together. Data is for the 2018/19 production season.

5.3.2.5 Summary of the contributions of field-level green, blue and grey water footprint to field-level total water footprint for wine grapes

In Chapter 5.3.2.1, the actual field-level water footprint values of wine grapes for the different components (green, blue and grey) were shown and discussed. In Figure 5.22 and Figure 5.23, the relative contribution of each component to the field-level WF_{total} estimates is shown. In Figure 5.22, the data is shown for each field considered in this study. According to Figure 5.22, the field-level WF_{blue} dominates the estimates in the Olifants River Valley (59 to 90%), but in the Breede River Valley and Coastal regions, the field-level WF_{green} plays a more important role (9 to 44% and 15 to 66% for these two regions, respectively). The field-level WF_{grey} contributed between 9 and 40% to the field-level WF_{total}, indicating a substantial contribution in certain fields. Also see Table 5.5.

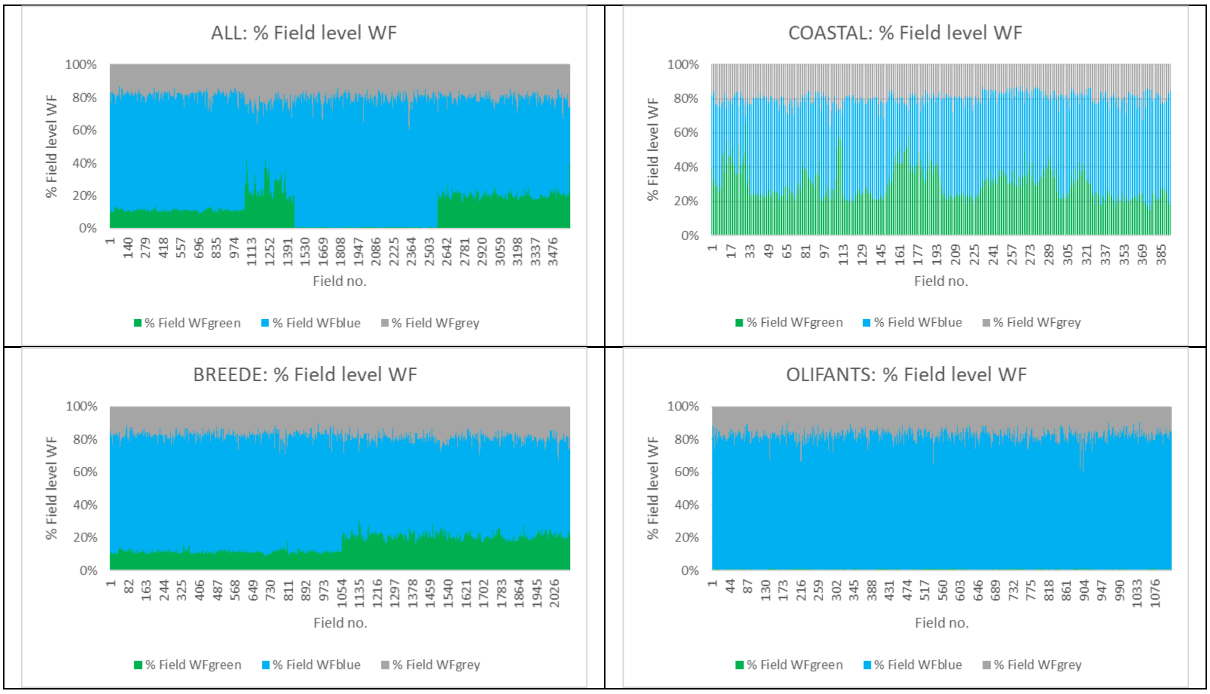


Figure 5.22: Percentage or relative contribution of field-level WF_{green}, WF_{blue} and WF_{grey} to the field-level WF_{total} of wine grapes. Data is shown for individual fields for all regions together and separately. Data is for the 2018/19 season.

The contributions of the field-level WF_{green}, WF_{blue} and WF_{grey} components to the field-level WF_{total} are summarised as median values in Figure 5.23. Median values that consider all data and regions for the 2018/19 season are shown. The field-level WF_{blue} constitutes the largest proportion of the field-level WF_{total} in all regions, with the Olifants River Valley region showing the highest estimate of 83%. The field-level WF_{green} contributes 27% of the field-level WF_{total} in the Coastal Region, but a mere 1% in the Olifants River Valley Region, which reflects the low rainfall measured in the latter region. The field-level WF_{grey} was slightly higher in the Coastal Region (19%) compared to 16% in the other two regions. The large contribution of field-level WF_{blue} shows the importance of irrigation water in the production of wine grapes in certain areas. Producers should take care to ensure the efficient use of water for irrigation to maximise the grape yield from the water used. With the field-level WF_{grey} contributing 20% of the field-level WF_{total}, consideration should also be given to fertilizer application (especially those rich in nitrogen) in order to minimise the leaching of excess nutrients and, in doing so, the need for freshwater to dilute polluted water to ambient water quality standards.

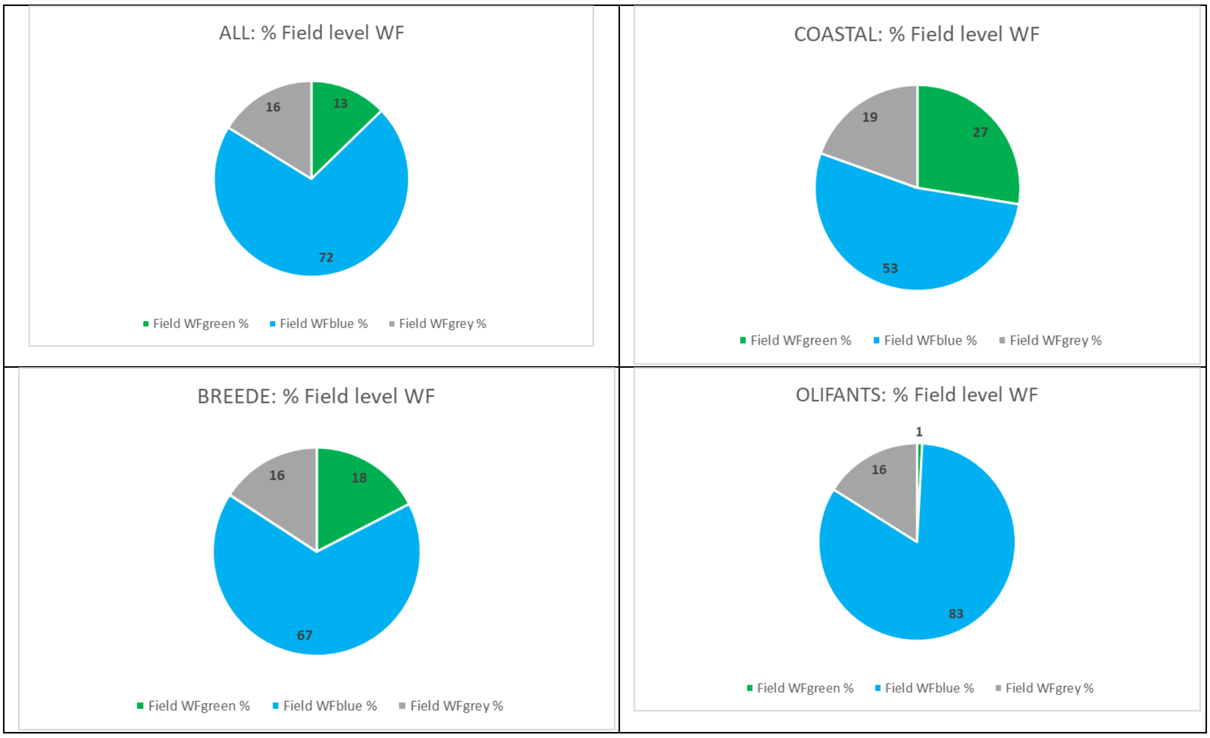


Figure 5.23: Percentage contribution of field-level WF_{green}, WF_{blue} and WF_{grey} to the field-level WF_{total} of wine grapes for all regions together and for the three production regions separately. Data shown is for the median values derived from all the individual fields considered for the 2018/19 season.

5.3.3 Cellar-level total water footprint of wine

The field-level WF_{green}, WF_{blue}, WF_{grey} and WF_{total} estimates for wine grapes considered in this study were reported in the preceding section. A cellar-level water footprint estimate for wine is required (per region or for all regions combined) for the case studies (Chapter 3.1.2). Therefore, field-level water footprint estimates for wine grapes were integrated with cellar-level WF_{blue} and WF_{grey} estimates (also see Chapter 5.1) and a cellar-level water footprint estimate for wine was calculated.

$$\begin{aligned} &Cellar\ level\ WF_{total}\ (wine) = \\ &\quad = median\big(Field\ level\ WF_{green} + Field\ level\ WF_{blue} \\ &\quad + Field\ level\ WF_{grey}\big) + (Cellar\ level\ WF_{blue} + Cellar\ level\ WF_{grey}) \end{aligned} \tag{5.6}$$

The cellar-level WF_{total} estimates for wine are shown together with the field-level WF_{total} and the cellar-level WF_{blue} and WF_{grey} estimates in Figure 5.24. Data is shown in ℓ/ℓ and for all regions considered together and separately. Results from the cellar-level WF_{blue} and WF_{grey} will be discussed first, followed by the cellar-level WF_{total} results for wine.

Note that the water footprint of the winemaking process at cellar level (cellar-level WF_{blue}, WF_{grey} – Chapter 4.7.3 and Chapter 4.9.1) was based on actual available data from cellars in the production regions considered in this study. The cellar-level WF_{blue} and WF_{grey} estimates consist of a blue and a grey component and the estimated values ranged between 74 ℓ/ℓ for the Breede River Valley and 185 ℓ/ℓ for the Coastal and Olifants River regions (Figure 5.24). These values represent the actual water used in the winemaking processes (cellar-level WF_{blue}) and the freshwater required to dilute the water polluted in the winemaking process to achieve ambient water quality standards (cellar-level WF_{grey}). It is interesting to note that cellar-level WF_{blue} and WF_{grey} is dominated by the grey fraction as shown in Table 5.5. The grey fraction was especially due to high COD values (see Chapter 4.9.1).

Of the cellar-level WF_{blue} and WF_{grey} estimates, the cellar-level WF_{blue} fraction only contributed 2.1 ℓ/ℓ (Coastal) to 2.4 ℓ/ℓ (other regions), with the remainder being contributed by the cellar-level WF_{grey} fraction. Considering this, and in order to minimise or reduce the impact of the winemaking processes on the overall cellar-level WF_{total} of wine, the focus should be on minimising the water pollution associated with effluent discharge at the wine cellar.

The cellar-level WF_{total} for wine grapes was calculated by summing the field-level WF_{total} related to the production of wine grapes and the cellar-level WF_{blue} and WF_{grey} as a result of the winemaking processes. The cellar-level WF_{total} for wine was 641, 863 and 1,325 ℓ/ℓ for the Breede River Valley, Olifants River Valley and Coastal regions, respectively. The median cellar-level WF_{total} value for wine, considering all areas, was 863 ℓ/ℓ. Some 79 to 88% of the cellar-level WF_{total} for wine was from the field-level WF_{total}, and 12 to 21% was from the cellar-level WF_{blue} and WF_{grey}. This once again illustrates the importance of managing the water use production balance at field level (Figure 5.25). The cellar-level WF_{total} for wine produced in three production regions of South Africa reflects the specific season and fields considered, and it is expected that the absolute values will be different for any other production season and region. However, the values calculated for 2018/19 should provide a good representation of the cellar-level WF_{total} of wine to be expected in these production regions of South Africa.

The substantial contribution of the field-level water footprint to the water footprint of wine again highlights the importance of focusing on water use at farm level in the production of grapes. Producers must take care to maximise the efficiency with which they use water to produce the grapes. The relatively higher WF_{grey} associated with the production of wine suggests that special care should be taken to minimise the pollution that would require freshwater to dilute pollutants to ambient water quality standards.

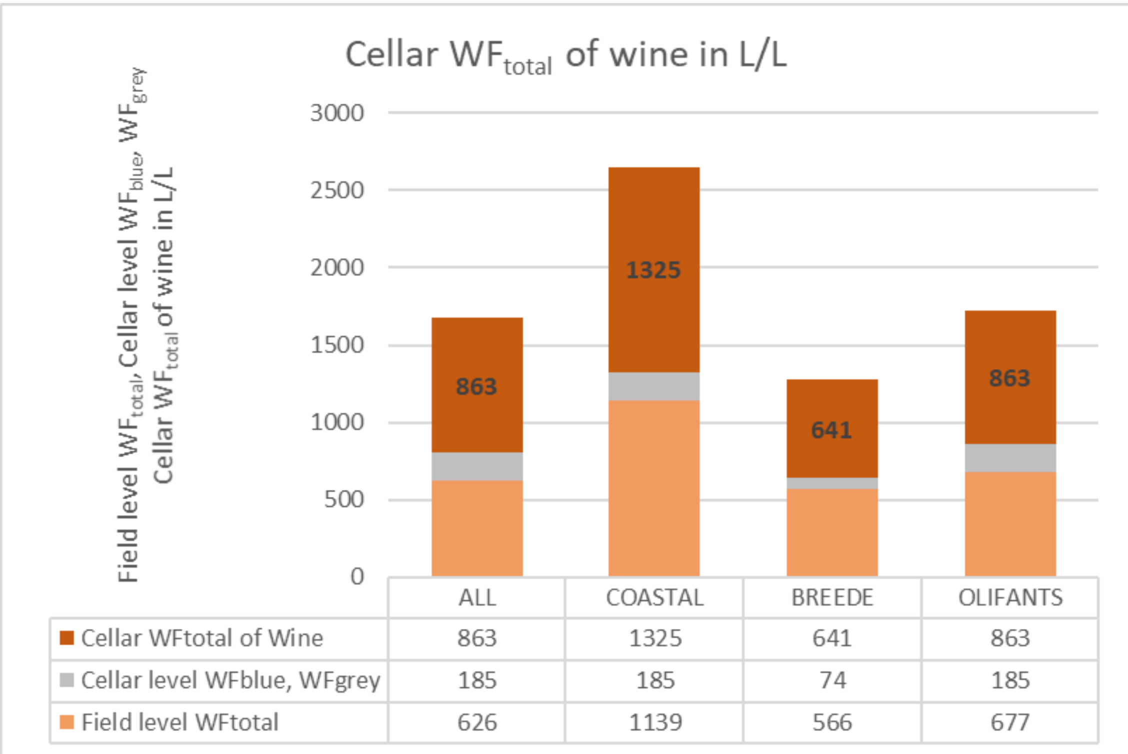


Figure 5.24: The cellar-level water footprint (wine) in ℓ/ℓ estimated from data for the 2018/19 season, as the sum of (median) field-level WF_{total} and cellar-level WF_{blue}, WF_{grey}. Data is shown for all regions together and for the separate regions.

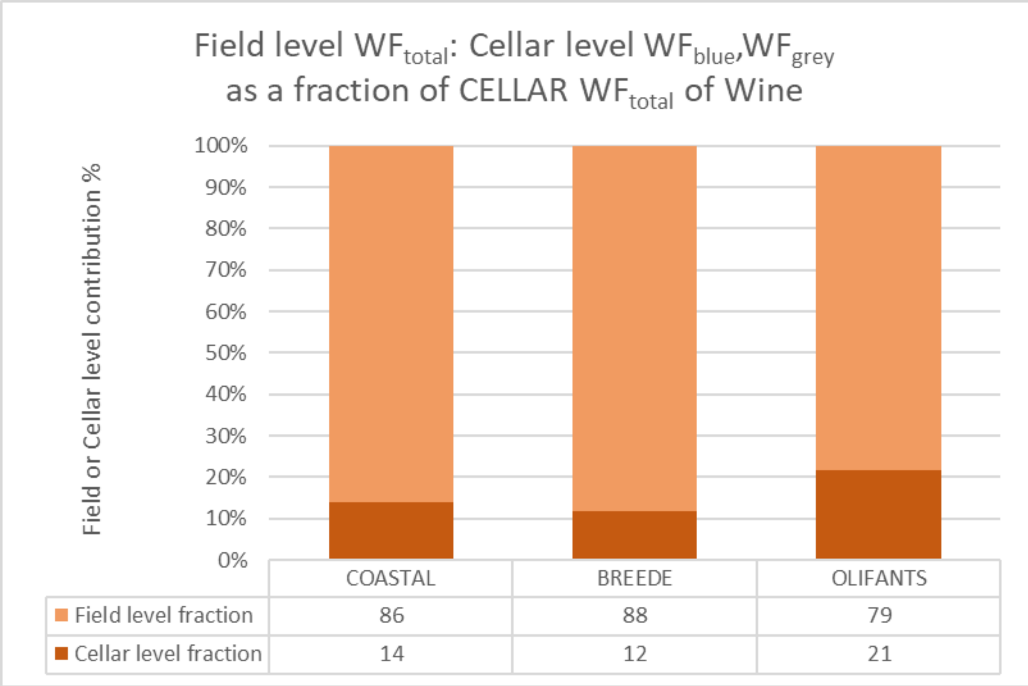


Figure 5.25: Field-level WF_{total} to cellar-level WF_{blue}, WF_{grey} as a fraction of the cellar-level water footprint for wine. Data considers three production regions and the 2018/19 season.

5.3.4 Cellar-level total water footprint of wine in 750 mℓ bottle of wine equivalent

Since wine is often sold in bottles of 750 mℓ, the cellar-level WF_{total} for wine was also expressed in litres of water used to produce a 750 mℓ bottle of wine, as shown in Figure 5.26. The median cellar-level WF_{total} for wine, considering data from all regions, was 647 ℓ/750 mℓ. As shown in Figure 5.26, the highest cellar-level WF_{total} for wine was calculated for the Coastal Region at 993 ℓ/750 mℓ of wine, and the lowest at 480 ℓ/750 mℓ of wine for the Breede River Valley and 647 ℓ/750 mℓ of wine for the Olifants River Valley.

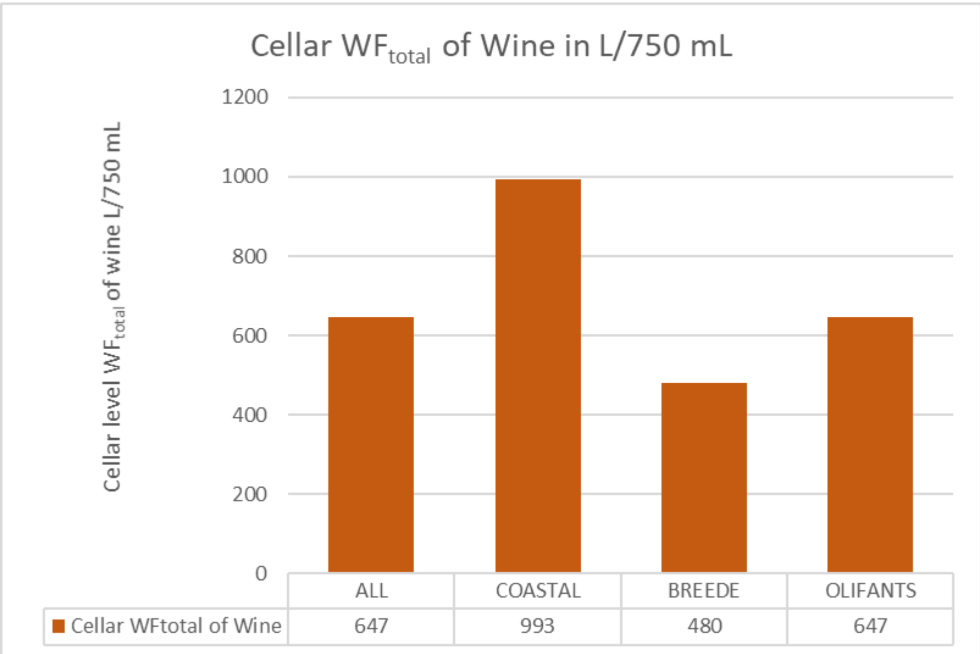


Figure 5.26: Cellar-level WF_{total} of wine in litres of water used to produce 750 mℓ of wine (ℓ/750 mℓ).

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 SUMMARY OF MAIN FINDINGS

This study determined the water footprint of table grapes and wine produced in three important production regions, each situated in the Western Cape. The potential of integrating large spatial datasets with large production databases and lookup tables for use in water footprint calculations was explored and illustrated.

Research aspects showed the progress made in using remotely sensed data to delineate field boundaries, in crop type mapping and to determine whether nets are present. It highlighted the challenges still faced in applying these activities operationally. It also highlighted research into the impact of nets on crop water use. It further collated participants' information and industry recommendations pertaining to field-level chemical spray and fertilizer application into lookup tables for use in the WF_{blue} and WF_{grey} calculations.

In collating the data required to determine the water footprint of table grapes and wine, the main challenge faced was the lack of data in an easily integratable format. Systems to manage wine grape and wine production are available to customers only, and currently do not contain a full spatial dimension, making integration with remotely sensed datasets tedious. As with all systems, the accuracy of the data captured in these systems is fully reliant on the customers and, to the researchers' knowledge, no in-built accuracy checks exist within these systems. In contrast, no single table grape data management system is used in South Africa, limiting easy access to production data and making data integration for multiple farms or packhouses complex. Here too, the data does not have a spatial dimension and linking the field data to remotely sensed data involves numerous steps and checks.

Despite increased pressure on available water in South Africa, the water use at field, farm and packhouse level is still not widely measured, and therefore alternative approaches had to be explored to come up with an estimate of water use in the production of grapes. Where water use data is available, it will often include all uses for multiple fields or the entire farm. Therefore, the use of spatial evapotranspiration data and regional specific lookup tables derived as part of this project was explored, with the latter providing a summary of valuable data.

Considering the above, this research highlighted the complexities of investigating the water footprint of extensive areas involving thousands of field records in the case studies for table grapes and wine production in South Africa. This explains the fact that many water footprint studies that involve an entire production process and all components that contribute to the water footprint process often only focus on one or a few fields.

Considering the WF_{total} for table grapes, the following important observations were made:

- The WF_{total} for table grapes considered all green, blue and grey water use at field level, as well as blue, but not grey water use at packhouse level, in its calculations.
- In this study, data from more than 200 cases was considered and represented the wide range of production conditions typical of the Western Cape, including large production ranges (up to 64 t/ha), a large number of cultivars, low annual rainfall (less than 345 mm/year) and a median export fraction of 67% for the 2018/19 season, representing a less than ideal production season.
- The WF_{blue} from the packhouse (less than 1% or 0.76 ℓ/kg) showed a small or negligible contribution to the WF_{total} for table grape at the packhouse. The field-level WF_{total} values, therefore, contributed 99% of the estimates. It is noted that this is in the absence of WF_{grey} at packhouse level, which the researchers accept will contribute to the WF_{total}.

- The WF_{total} for table grapes ranged between 500 and 714 ℓ/kg, with a median value of 619 ℓ/kg, considering the data from all areas. The results from the specific fields and seasons considered showed that the highest WF_{total} was calculated for grapes produced in the Berg River Valley.
- Variation in the WF_{total} was observed between cultivars. For the cultivars investigated in more detail, the highest median WF_{total} was calculated for Prime, an early-season cultivar, and the lowest for Sugranineteen (Scarlotta Seedless®), a mid-season cultivar. The results reflect the fields and seasons considered in this study.
- Nearly half (47%) of all the WF_{total} estimates for table grapes was less than 600 ℓ/kg and showed a strong relationship to and dependence on the crop yield. For production values of less than 10 t/year, a sharp increase in WF_{total} estimates was observed.
- For all areas studied, the WF_{blue} (field and packhouse) contributed most to the WF_{total}, at more than 70%, showing the importance of water use through irrigation on this water footprint component. The WF_{grey} contributed about 20% of the WF_{total}, showing that this water footprint component should not be omitted from studies.
- The resultant WF_{total} for table grapes directly reflects the fields considered in this study, the conditions experienced during the 2018/19 season and the quality of the table grapes produced.

Considering the WF_{total} for wine, the following were important observations and findings:

- This study allowed the researchers to estimate the WF_{total} for wine, where the green, blue and grey water footprints of wine grapes at field level were considered, as well as the blue and grey water footprints at wine cellar level.
- The WF_{total} of wine was calculated for three production regions of the Western Cape and considered data from more than 3,600 vineyards across these regions for the 2018/19 production season.
- The data considered represented a wide range of production conditions – with wine grape yields of up to 79 t/ha, 37 cultivars, a large range in age (two to 100 years) and rainfall in the production regions (61 to 608 mm/year).
- The median WF_{total} for wine (field level plus cellar level), considering the data from all areas, was 863 ℓ/ℓ. The largest WF_{total} for wine was calculated for the Coastal Region (1,325 ℓ/ℓ), with the field-level water use contributing 86% of the WF_{total} of wine. The lowest WF_{total} for wine was for the Breede River Valley (641 ℓ/ℓ), with an 88% contribution from field-level water use to this estimate. The Olifants River Valley saw the greatest contribution of cellar-level WF_{grey} to the WF_{total} of wine at 21%. It should be noted that, for the latter, the cellar-level WF_{grey} presents an estimated worst-case scenario or maximum value.
- Wine grape yield strongly impacted on the field-level WF_{total} for wine grapes and therefore the WF_{total} of wine. For wine grape production of less than 5 t/ha, the field-level WF_{total} increased exponentially to values higher than 1,600 ℓ/kg.
- The median field-level WF_{total} of wine grapes (considering all data from all regions) was 484 ℓ/kg, with the highest regional median field-level WF_{total} estimate for the Coastal Region nearly double that (1.7 times) or 842 ℓ/kg.
- Differences between cultivars were observed in the field-level WF_{total}. Of eight important cultivars considered, the field-level WF_{total} was the highest for Cabernet Sauvignon (1,131 ℓ/kg or 1,467 ℓ/ℓ) and the lowest for Colombar (345 ℓ/kg or 450 ℓ/ℓ).
- The field-level WF_{total} for a specific cultivar differed between regions. The results showed large differences for Pinotage (537 to 1,392 ℓ/ℓ), but small differences for Chenin Blanc (458 to 674 ℓ/ℓ).
- At field level, the WF_{blue} contributed greatly to the WF_{total} of wine (more than 83%), with a larger contribution of the WF_{green} in the Coastal Region (27%). The WF_{grey} was not insignificant and contributed most in the Coastal Region (19%).
- Converting the WF_{total} of wine to a 750 mℓ unit yielded a median value for all the fields considered of 647 ℓ of water for 750 mℓ of wine.

It can be concluded that this study successfully calculated the water footprint of table grapes and wine in different production regions of the Western Cape using spatial data, large production datasets and lookup tables. It illustrated how large numbers of field-level water footprint estimates can be integrated into final product water footprint estimates to show the range in production and water footprints related to a production unit like a packhouse or cellar. The water footprint results for the 2018/19 season provide a basis for future water footprint assessments for table grapes and wine production in South Africa.

To derive benchmarking values for both these industries and for the specific production regions, it is proposed that a similar approach be followed to that described in this study, that water footprint results be generated for more production seasons to account for the impact of climate and production conditions, and that these results be interpreted in the context of sustainability.

6.2 COMPARISON OF RESULTS WITH OTHER STUDIES ON THE WATER FOOTPRINT

6.2.1 Water footprint of grapes in general

Few studies have been conducted on grape water use efficiency and the water footprint. This study contributes to the limited information available. Most of the studies conducted on grape water use efficiency and the water footprint were desktop studies and did not include actual field records from production units (as included in this study). Many of the global water footprint and water use efficiency studies do not distinguish between different grape types (table grapes, raisins and wine grapes).

While some studies have determined the water use efficiency of table grapes (Araujo et al., 1995; Yunusa et al., 1997a; Yunusa et al., 1997b), limited research results are available regarding the total volume of water required throughout the production chain from field to packhouse. Apart from the water footprint analysis of the Breede Catchment (Pegasys, 2010), which focused on the economic impact of crop water use, as well as the study of Avenant et al. (2017) and Kangueehi (2018), whose research only focused on the WF_{blue} of table grapes, there are few publications on the water footprint of table grapes in South Africa.

Mekonnen and Hoekstra (2010) and Pahlow et al. (2015) reported a WF_{blue} for grapes of 97 m^3/t (global) and 157 m^3/t (South Africa). The WF_{blue} determined by Pahlow et al. (2015) was based on an average yield of 13.8 t/ha.

Mekonnen and Hoekstra (2010), with the use of global data averages, determined the WF_{green}, WF_{blue} and WF_{grey} for crops and derived products for the period 1996 to 2005. This was done to raise awareness and to identify the most significant contributor to the overall water footprint of a product. The global WF_{total} of table grapes was found to be 607 m^3/t, Of this, 70% was attributed to the WF_{green}, 15% to the WF_{blue} and 14% to the WF_{grey}. For wine grapes, the water footprint was 707 m^3/t. This consisted of 69.8% WF_{green}, 15% WF_{blue} and 14% WF_{grey}. Raisins had the highest global WF_{total} at 2,433 m^3/t (assuming a product function of 0.25). This WF_{total} consisted of 70, 15.8 and 14% for WF_{green}, WF_{blue} and WF_{grey}, respectively.

Mekonnen and Hoekstra (2010) also documented the water footprint of products produced in different parts of the world. Without differentiating between table grapes and wine grapes, the total water footprint of grapes at national levels was found to be 6,490.30 m^3/t in Spain, 3,693.72 m^3/t in France, 2,136.88 m^3/t in China, 639.93 m^3/t in South Africa, 547.77 m^3/t in Chile, 412.91 m^3/t in Germany, 410.0 m^3/t in Algeria, 356.30 m^3/t in Brazil and 247.85 m^3/t in Egypt, to mention a few. From these results, it is evident that the WF_{total} for grapes produced in Spain, France and China was 3 to 7 times that of the global WF_{total} average. The WF_{total} for Egypt and Brazil was half that of the world average, and that of Algeria, Germany, Chile and South Africa was 57 to 90% of the total global average.

6.2.2 Field level blue, green and grey water footprint of grapes

6.2.2.1 Study on table grapes in Cyprus (blue and green water footprint)

Zoumides et al. (2012) conducted a water footprint study in Cyprus and reported the following values for table grapes: a WF_{blue} ranging from 700 to 975 m^3/t (m^3/t is equivalent to ℓ/kg) and a WF_{green} ranging from 625 to 700 m^3/t. No field measurements or producer records were used in their study Water use values were obtained from an agricultural census for the period 1995 to 2009. Cyprus is described as a semi-arid island situated in the north-east of the Mediterranean Sea, with water scarcity due to high water demand compared to supply, limited and highly variable precipitation, high agricultural water use, overexploitation of groundwater resources and increasing domestic water use.

6.2.2.2 Study on dryland wine grapes in Spain (blue and green water footprint)

Aldaya et al. (2010) conducted a study in Spain and reported values for the dryland production of wine grapes (6 t/ha) in a "normal" (1,000 mm per year) rainfall year in the region included in the study. Water requirements of these vineyards (evapotranspiration of 128 mm) were entirely based on green water resources, resulting in a WF_{blue} of 0 m^3/t and a WF_{green} of 229 m^3/t.

6.2.2.3 Study on grapes in Saudi Arabia (blue, green and grey water footprint)

Multsch et al. (2013) conducted a study in Saudi Arabia, using a special decision-support system, SPARE:WATER, and reported calculated water requirements for perennial crops, e.g. dates, citrus and grapes, with 1,132, 15,1745 and 1,139 mm respectively, as well as "high irrigation requirement" grapes, which exceeded 2,000 mm. They calculated the following values for grapes (not specifying the type of grapes): WF_{blue} at 1,448 m^3/t, WF_{grey} at 341 m^3/t and WF_{green} at 72 m^3/t. Similar to South African production regions, the WF_{total} is dominated by the blue component (86%), with WF_{grey} and WF_{green} contributing 11 and 4%, respectively. The small contribution of WF_{green} reflects the very low annual rainfall.

6.2.2.4 Study on grapes in Romania (blue, green and grey water footprint)

Ene et al. (2012) conducted a study in Romania, estimating total crop water requirements, effective rainfall and irrigation requirements per region using the CROPWAT model. They reported values for grapes (average for the period 2005 to 2008): WF_{blue} at 7 m^3/t, WF_{grey} at 580 m^3/t, WF_{green} at 1,226 m^3/t and WF_{total} at 1,813 m^3/t. In the region in which the study was conducted, the irrigation infrastructure was underdeveloped, and all crop production was dependent on rainwater. Fluctuations occur between "normal" and "dry" years, and the evaluation of monthly green and blue water availability indicated that water availability and the contributions of the green and blue components differed between months within a year, as well as between years.

6.2.3 Bue and grey water footprint at cellar level

Ene et al. (2013) assessed the total water footprint of grape production within Iasi County, Romania, for a medium-sized winemaking industry. This study followed the WFN approach and focused on the actual economic and environmental perspectives of water footprint assessment. For this case study, it was assumed that 1 ℓ of wine is made from 1.3 kg of grapes, and 2 ℓ of water is mainly used for equipment washing and cleaning. Wastewater flows in the production process were significantly treated before being disposed of, therefore there was no WF_{grey} or grey operational footprint (Ene et al., 2013; Hoekstra et al., 2011). Results indicated that the WF_{total} of grapes (the viticulture part) in Iasi County for the period 2005 to 2008 was 1,401 m^3/t (double the global average). Of this, 82% was accounted to WF_{green}, 15.1% to WF_{grey} and 2.8% to WF_{blue}. For the vinification part, it was estimated that 2 ℓ of water was used per litre of wine produced, which added 2% to the WF_{total} of a litre of wine.

Herath et al. (2013) conducted a WFA of 36 wineries in two regions in New Zealand over a three-year period and reported a WF_{blue} of -81 ℓ/750 mℓ bottle of wine for irrigated wine grape vineyards and -415 ℓ/750 mℓ bottle of wine for rain-fed (dryland) vineyards. The negative values indicate that the water resources are recharged to field capacity during winter rainfall. Herath et al. (2013) reported a WF_{grey} of 40 ℓ/750 mℓ bottle of wine for irrigated vineyards and 188 ℓ/750 mℓ bottle of wine for rainfed vineyards. Like our study, Herath et al. (2013) also reported a large variation in the water footprint of wine grapes at field level due to the large variability in regional rainfall and vast differences in local soil properties. They also found that the impact of cellar water use on the WF_{total} is very small, compared to the contribution of the field vineyard water use.

6.3 PROPOSALS FOR FUTURE RESEARCH TASKS

6.3.1 Earth observation applications

This project demonstrated the value of remote sensing and earth observation for water footprint assessments. It highlighted the importance of remotely sensed ET_{act} data to quantify water use over large areas. It also emphasised the importance of accurate vineyard block (field) boundaries for estimating water use at field level. In this project, manually digitised block boundaries were utilised, but this process is time-consuming (expensive) and prone to human error. Although some progress has been made with automated field boundary delineation, more work is needed to operationalise such methods. This requires additional research to validate and verify automated methods for a range of different crop types, particularly for vineyards that are characterised by small field sizes.

The efficacy of combining multiple Sentinel-2 and one very high-resolution image per season (or longer period) (e.g. WorldView/SPOT) needs to be investigated, for instance. It is unlikely that any single method or data fusion or combination will be effective on all types of crops and in all regions. More work is needed to investigate whether a crop-specific approach (e.g. perennials and annuals) would be more suitable.

Automated crop type identification is another area of research that requires more work. The recent advances in machine learning hold much potential for detecting crop types and varieties, but building models with limited training data remains a big challenge. The availability of multitemporal satellite imagery at a five-day interval has opened many new possibilities for crop type differentiations, but the spectral and temporal variations within specific crop types (e.g. grapes) require large volumes of training data (blocks with known crop types). Such data is usually not available within a particular season and it is critical that databases such as the WCCC are used to start building spectral (and temporal) libraries of various crop types that can be used to automatically generate crop type maps on an annual, or even near real-time basis.

The dramatic increases in crops planted under agricultural nets and the use of remote sensing under such conditions is another aspect that requires further investigation. New crop type differentiation and water use modelling methods are needed for netted crops. Based on initial research, longer wavelengths (e.g. in the short-wave infrared region) are less affected by nets, and it is likely that new techniques using such data will have to be developed.

6.3.2 Splitting evapotranspiration into blue and green water use

With the methodology used in this research, once evapotranspiration and effective rainfall are calculated, it is possible to estimate the blue and green contribution to water use and the water footprint. In general, rainfall is insufficient for successful table and wine grape production in South Africa and hence irrigation applications supplement the crop water requirements.

The approach proposed in this study is simple and the implementation is relatively straightforward. The results of this approach can be compared to other studies and give a good indication of the main trends in terms of the contribution of green and blue water on a large scale.

However, this approach has some limitations regarding the accuracy of the estimates at farm level. The effective rainfall is determined with a general equation that considers standard conditions. Nevertheless, at farm level, it is necessary to calibrate this equation using the specific soil properties of the target area, together with field experiments to determine the water runoff and infiltration. Future research could possibly focus on this.

The determination of the blue and green water footprint with high accuracy at a large scale using remote sensing remains a research challenge since the parameterisation of the models requires large amounts of field data that are not readily available. Future research on this topic should be conducted to incorporate the latest remote sensing approaches for soil moisture estimations, such as those employing radar sensors (e.g. Sentinel-1, Synthetic Aperture Radar), as well in-depth field experiments to extrapolate field trends to wide scales (i.e. regional level).

6.3.3 Sustainability assessment

While calculating the water footprint is an important step towards evaluating the sustainability of freshwater use, a comprehensive sustainability assessment is required to direct water users, managers and policy makers in a holistic manner. Further research is required to assess the degree of sustainability with which resources are used in table grape and wine production in South Africa from an environmental, economic and social perspective. Research into environmental sustainability is required to assess whether enough water is available to meet environmental flow requirements after the water was used by the different water users (i.e. domestic, industrial and agricultural production) in the selected regions. If water use is such that the environmental flow requirement is not met, the water use in the region is considered unsustainable and must change. This relates directly to changes in crop production practices.

From an economic perspective, research is required to ensure the efficient use of the scarce resource. Economic water productivities must be explored to determine the economic returns from using freshwater to produce table grapes and wine in the selected regions. Lastly, from a social perspective, equitable access to the scarce resource is crucial. Research is required to determine whether access to the water resource in the selected regions is equitable.

6.3.4 Grey water footprint calculations

The grey water footprint calculated in this research is the first step towards gaining insight into the impact of pollution associated with the production of table grapes and wine on water resources in the selected study areas. Applying the dilution factor approach of Hoekstra et al. (2011) to calculate the WF_{grey} provided an estimate of the volume of freshwater needed to dilute polluted water to ambient water quality standards. It is noted, though, that the calculation of the WF_{grey} is dependent on the accuracy of data on pollution levels, but also on the water quality standards per region (maximum acceptable concentrations and natural concentrations of pollutants under consideration). The actual pollution level at farm level depends on the leaching of nutrients (i.e. nitrogen from fertilizer) into the water body. The leaching fraction is determined by the properties of the soil, among others. In this research, a standard leaching fraction of 10% was assumed. Further research is required to obtain more accurate leaching fractions of the soil in the fields in the study areas under consideration to get more accurate pollution levels for calculating the grey water footprint. Further research is also required on the impact of certain actions, such as water purification, as a response strategy to decrease the WF_{grey} at wine cellars.

6.3.5 Creating water footprint benchmarking standards

This study successfully calculated the water footprint of table grapes and wine in different production regions of the Western Cape using spatial data, large production datasets and lookup tables. It illustrated how large numbers of field-level water footprint estimates can be integrated into a final product water footprint estimate to show the range in production and water footprints related to a production unit like a packhouse or cellar.

Although the water footprint results provide a basis for future water footprint assessments for table grapes and wine production, they only provide insight into the water footprint for the 2018/19 season and the fields and conditions considered.

To derive water footprint benchmarking values for both these industries and specific production regions, it is proposed that water footprints be calculated for more production seasons to account for the impact of climate variation and the crop production responses to it. The results from multi-seasonal estimates should be used to set benchmarking standards considering industry and regional sustainability aspects.

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APPENDICES

APPENDIX 1: FRUITLOOK DATA TRANSFORMATION SUMMARY

Table A1: Fruitlook weekly variables and associated monthly output dates per season

No	2014/15		2015/16		2016/17		2017/18		2018/19	
	Dates	Month No	Dates	Month No	Dates	Month No	Dates	Month No	Dates	Month No
-9	N/A	N/A	N/A	N/A	N/A	N/A	26 Jul-1 Aug	-3,-2	7-13 Aug	-2
-8	N/A	N/A	N/A	N/A	6-12 Aug	-2	2-8 Aug	-2	14-20 Aug	-2
-7	N/A	N/A	N/A	N/A	13-19 Aug	-2	9-15 Aug	-2	21-27 Aug	-2
-6	N/A	N/A	N/A	N/A	20-26 Aug	-2	16-22 Aug	-2	28 Aug-3 Sept	-2, -1
-5	N/A	N/A	N/A	N/A	27 Aug-2 Sept	-2, -1	23-29 Aug	-2	4-10 Sept	-1
-4	N/A	N/A	N/A	N/A	3-9 Sept	-1	30 Aug-5 Sept	-2, -1	11-17 Sept	-1
-3	N/A	N/A	N/A	N/A	10-16 Sept	-1	6-12 Sept	-1	18-24 Sept	-1
-2	N/A	N/A	N/A	N/A	17-23 Sept	-1	13-19 Sept	-1	25 Sep-1 Oct	-1, 1
-1	N/A	N/A	N/A	N/A	24-30 Sept	-1	20-26 Sept	-1	2-8 Oct	1
1	1-7 Oct	1	30 Sept-6 Oct	1	1-7 Oct	1	27 Sept-3 Oct	-1, 1	9-15 Oct	1
2	8-14 Oct	1	10-16 Oct	1	8-14 Oct	1	4-10 Oct	1	16-22 Oct	1
3	15-21 Oct	1	17-23 Oct	1	15-21 Oct	1	11-17 Oct	1	23-29 Oct	1
4	22-28 Oct	1	24-30 Oct	1	22-28 Oct	1	18-24 Oct	1	30 Oct-5 Nov	1, 2
5	29 Oct-4 Nov	1,2	31 Oct-6 Nov	1, 2	29 Oct-4 Nov	1,2	25-31 Oct	1	6-12 Nov	2
6	5-11 Nov	2	7-13 Nov	2	5-11 Nov	2	1-7 Nov	2	13-19 Nov	2
7	12-18 Nov	2	14-20 Nov	2	12-15 Nov	2	8-14 Nov	2	20-26 Nov	2
8	19-25 Nov	2	21-27 Nov	2	16-22 Nov	2	15-21 Nov	2	27 Nov-3 Dec	2, 3
9	26 Nov-2 Dec	2,3	28 Nov–4 Dec	2, 3	23-29 Nov	2	22-28 Nov	2	4-10 Dec	3
10	3-9 Dec	3	5-11 Dec	3	30 Nov-6 Dec	2,3	29 Nov-5 Dec	2,3	11-17 Dec	3
11	10-16 Dec	3	12-18 Dec	3	7-13 Dec	3	6-12 Dec	3	18-24 Dec	3
12	17-23 Dec	3	19-25 Dec	3	14-20 Dec	3	13-19 Dec	3	25-31 Dec	3
13	24-30 Dec	3	26 Dec-1 Jan	3, 4	21-27 Dec	3	20-26 Dec	3	1-7 Jan	4
14	31 Dec-6 Jan	3,4	2-8 Jan	4	28 Dec-2 Jan	3,4	27 Dec-2 Jan	3,4	8-14 Jan	4
15	7-13 Jan	4	9-15 Jan	4	3-10 Jan	4	3-9 Jan	4	15-21 Jan	4
16	14-20 Jan	4	16-22 Jan	4	11-17 Jan	4	10-16 Jan	4	22-28 Jan	4
17	21-27 Jan	4	23-29 Jan	4	18-24 Jan	4	17-23 Jan	4	29 Jan-4 Feb	4, 5
18	28 Jan-3 Feb	4,5	30 Jan-5 Feb	4, 5	25-31 Jan	4	24-30 Jan	4	5 Feb-11 Feb	5
19	4-10 Feb	5	6-12 Feb	5	1-7 Feb	5	31 Jan-6 Feb	4,5	12-18 Feb	5
20	11-17 Feb	5	13-19 Feb	5	8-14 Feb	5	7-13 Feb	5	19-25 Feb	5

No	2014/15		2015/16		2016/17		2017/18		2018/19	
	Dates	Month No	Dates	Month No	Dates	Month No	Dates	Month No	Dates	Month No
21	18-24 Feb	5	20-26 Feb	5	15-21 Feb	5	14-20 Feb	5	26 Feb-4 Mar	5, 6
22	25 Feb-3 Mar	5, 6	27 Feb-4 Mar	5,6	22-28 Feb	5	21-27 Feb	5	5-11 Mar	6
23	4-10 Mar	6	5-11 Mar	6	1-7 Mar	6	28 Feb-6 Mar	5,6	12-18 Mar	6
24	11-17 Mar	6	12-18 Mar	6	8-14 Mar	6	7-13 Mar	6	19-25 Mar	6
25	18-24 Mar	6	19-25 Mar	6	15-21 Mar	6	14-20 Mar	6	26 Mar-1 Apr	6, 7
26	25-31 Mar	6	26 Mar-1 Apr	6, 7	22-28 Mar	6	21-27 Mar	6	2-8 Apr	7
27	1-7 Apr	7	2-8 Apr	7	29 Mar-4 Apr	6,7	28 Mar-3 Apr	6,7	9-15 Apr	7
28	8-14 Apr	7	9-15 Apr	7	5-11 Apr	7	4-10 Apr	7	16 Apr-22 Apr	7
29	15-21 Apr	7	16-22 Apr	7	12-18 Apr	7	11-17 Apr	7	23-29 Apr	7
30	22-28 Apr	7	23-29 Apr	7	19-25 Apr	7	18-24 Apr	7	30 Apr-6 May	7, 8
31	N/A	N/A	N/A	N/A	N/A	N/A	25 Apr-1 May	7, 8	7-13 May	8
32	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	14-20 May	8
33	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	21-27 May	8
34	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	28 May-3 Jun	8, 9
35	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	4 Jun-10 Jun	9
36	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	11-17 Jun	9
37	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	18-24 Jun	9
38	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	25 Jun-1 Jul	9, 10
39	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2-8 Jul	10
40	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	9-15 Jul	10
41	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	16-22 Jul	10
42	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	23-30 Jul	10

APPENDIX 2: CAPACITY BUILDING

The fifth aim of this project relates to capacity building, specifically to build capacity and competence in water footprint assessment in the wine and table grape industries. Water footprint assessment capacity in South Africa remains limited and strongly established in a few individuals and institutions, therefore this project aimed to expand this capacity to more individuals and industries.

The main aim of the capacity-building activities was on students. Initially, the project planned to involve five students in this research over the course of the four-year project, with one student registering for a PhD and the remaining four for MSc degrees (Table B1).

Table B1: Proposed student involvement as per the original proposal

Student	Degree	Institution	Department	Financial year with budget
1	PhD	University of the Free State	Department of Agricultural Economics	2018/19 2019/20 2020/21
2	MSc	University of the Free State	Department of Agricultural Economics	2017/18 2018/19
3	MSc	Stellenbosch University	Department of Viticulture and Oenology	2018/19 2020/21
4	MSc	Stellenbosch University	Department of Viticulture and Oenology	2019/20 2020/21
5	MSc	Stellenbosch University	Department of Geography and Environmental Studies	2019/20 2020/21

However, attracting students to participate in this research was not easy. The students that eventually participated in this project are listed in Table B2. Unfortunately, none of the students completed their studies under this project before it came to an end, but the supervisors are committed to supporting the students to complete their studies.

Table B2: List of students involved in this project

Student name	Current qualification	Qualification to be registered for, related to this project	Supervisors
Ms Anandi Theunissen	Grade 12	MSc Agric	Ms E Avenant Dr C Poblete-Echeverría
Ms Mashoto Mahlo	BSc Agric	MSc Agric	Ms E Avenant Dr C Poblete-Echeverría
Ms Rozanne Mouton	BSc (Hons) GeoInformatics	MSc GeoInformatics	Prof A van Niekerk
Ms Pascalina Matohlang Mohlotsane	MSc Agricultural Economics	PhD	Dr H Jordaan

MS ANANDI THEUNISSEN

Ms Theunissen is registered for the BSc Agric Viticulture and Soil Science degree (fourth and final year of study). She changed her degree programme from Viticulture and Oenology to Viticulture and Soil Science and therefore had to complete two modules during 2019 to complete her BSc Agric degree. She completed the first module during the first semester of 2019, completed the coursework for the second module during the second semester of 2019 and was to write the final examinations for this second module during the November 2019 examination period. She was well on track to completing her BSc Agric degree in December 2019, allowing her to register for the MSc Agric in the first semester of 2020. Her application for MSc Agriculture (Viticulture) was provisionally approved and she was expected to pass her remaining examination and complete her current programme at the end of the 2019 academic year and register for her MSc study in February 2020. She is based in Stellenbosch and has been working as a member of the research team since February 2019. Her main contribution to the completion of the deliverables of this project in 2019 was to assist working through water use data obtained from the production units included in the study, and extracting and summarising relevant data to be included in the lookup tables and water use tables. Her involvement in the project in 2019 was also to prepare her for her prospective MSc Agric degree study, which was planned to commence formally in 2020.

The proposed topic for her MSc Agric Viticulture study is "Evaluating/developing methodology for splitting the blue and green components of the water footprint of table and wine grapes". Her supervisor is Dr Carlos Poblete and her co-supervisor is Ms Eunice Avenant. It is proposed that she will incorporate data from the production units included in this project, as well as from other relevant units, in her study. It is proposed that she will be enrolled for her MSc Agric degree in 2020 and 2021. SATI and the South African Society for Enology and Viticulture (SASEV) have already been approached for the financial support of her study in 2020 and 2021.

MS MASHOTO MAHLO

Ms Mahlo is registered for her first year of study for the MSc degree in Wine Biotechnology. She is based in Stellenbosch and has been working as a member of the research team since February 2019. The topic of her study is "Water use efficiency of grapevines in South Africa: A case study of selected table and wine grape production units in the winter and summer rainfall regions". Her supervisor is Ms Eunice Avenant and her co-supervisor is Dr Carlos Poblete. She presented her project proposal to the Department of Viticulture and Oenology on 4 April 2019 and it was accepted. She is working with relevant data from this project for her MSc study, but is also collecting additional field data in three of the table grape blocks in the Berg River Region that were included in this study (two conventional and one covered with nets), as well as two table grape blocks in the Orange River Region (one conventional and one covered with nets), that form part of the water use under nets project that is co-funded by the Department of Agriculture of the Northern Cape and SATI. The rationale behind this is to obtain more field data for the validation of survey and remotely sensed data, as well as to obtain more field data where conventional blocks and net-covered blocks are compared in two production regions presenting a winter rainfall region with higher rainfall, a shorter growing season and a shorter irrigation season, as opposed to a summer rainfall region with low rainfall, a longer growing season and a longer irrigation season (with practically year-round irrigation).

ROZANNE MOUTON

Ms Mouton registered for an MSc in February 2019. Her study aims to increase our understanding of how agricultural nets affect various remotely sensed data and techniques. The first component focuses on mapping agricultural nets (i.e. differentiating crops planted under nets from other crops), while the second component analyses how nets influence the spectral characteristics of crops (including grapes). Each of these components is being prepared as a research article or chapter that will be submitted for publication to Computers and Electronics in Agriculture. Ms Mouton intended to complete her thesis by the end of 2020.

PASCALINA MATOHLANG MOHLOTSANE

Ms Mohlotsane has registered for her PhD at the University of the Free State. The working title of her thesis is "Water footprint assessment for better water governance and sustainable production of wine grapes" and her PhD presentation took place on 18 October 2019. The primary objective of her research is to develop a comprehensive water footprint assessment for better water governance and sustainable development by analysing the environmental, economic and socio-economic sustainability of wine grape production in the Western Cape. The study includes possible trade-offs for the reallocation of freshwater resources.

APPENDIX 3: PUBLICATIONS

Popular articles

No scientific publications were produced during this project. However, popular articles were published. For the wine industry, an article was published in Afrikaans in *Winetech Tegnies*[2] (Figure C1) and online in English in *WineLand*[3]. For the table grape industry, an article appeared in *South African Fruit Journal*[4] (Gifure C2).

IS-CREAS presentation

In December 2019, an abstract was submitted to and accepted by the International Symposium on Climate-resilient Agri-environmental Systems (IS-CRAES), with the title “Water footprint as a sustainability indicator for table and wine grape production”. The international symposium will take place from 19 to 22 May 2020 in Dublin, Republic of Ireland.

Abstract

In recent years, the available water resources in the Western Cape have been severely constrained due to below-average rainfall, resulting in an extensive and prolonged drought. This ongoing pressure on water initiated renewed discussions on the sustainable and efficient use of water for crop production, as well as the crop water footprint as an indicator of sustainable water use. The water footprint provides a measure of the amount of water used to produce crops, goods or services. It can be expressed in different ways, for example, litre of water used per kilogram of crop produced (ℓ/kg), or litre of water used to produce a litre of wine (ℓ/ℓ). The water footprint considers both the direct and indirect water needed to produce a crop or product and is often expressed in its colour components: green, blue and grey. Given the importance of the available water resources and their use in the production of table grapes and wine in South Africa, the water footprint of wine and table grapes produced in South Africa was studied as an indicator of sustainability. The water footprint assessment was done for selected case studies in three important production regions. Large spatial datasets on crop water use, large production databases and lookup tables were successfully used in the water footprint calculations. The study illustrated how large numbers of field-level water footprint estimates can be integrated into a final product water footprint estimate, capturing production and water footprint variation related to a production unit (like a packhouse or cellar). The research highlighted the complexities of investigating the water footprint of extensive areas involving thousands of field records and explains why many water footprint studies often focus on single fields. The water footprint results for the 2018/19 season provide a basis for the future water footprint assessments of South African table grape and wine production.

[2]Jarmain, C. (2019). Watervoetspoor van druiwe en wyn. *Winetech Tegnies* 353, pp. 66-67 (In: *Wineland* January 2019).
[3] Jarmain, C. (2019). Water footprint of grapes and wine. Available: https://www.wineland.co.za/water-footprint-of-grapes-and-wine/ (January 2019).
[4] Jarmain, C. (2019) Water footprint. *South African Fruit Journal* February/March 2019, pp. 13-14. Available: https://www.safj.co.za/wp-content/uploads/2019/02/safj-sa-fruit-journal-feb-march-2019.pdf. Accessed February 2020.

WATERVOETSPOOR VAN DRUIWE EN WYN

GEDURENDE DIE AFGELOPE SEISOEN, WAAR TALLE MENSE VAN DIE WES-KAAP MET 40 TOT 50 ℓ WATER PER PERSOON PER DAG MOES OORLEEF, IS BAIE SYFERS AANGEHAAL OM ONS TE HERINNER AAN DIE HOEVEELHEID WATER WAT ONS DAAGLIKS GEBRUIK. ONGEVEER 19 ℓ WATER WORD VIR 'N 90-SEKONDE STORT GEBRUIK EN EEN SPOEL VAN JOU TOILET GEBRUIK 9 ℓ. BAIE MENSE WAS VERDER VERRAS OM TE BESEF HOEVEEL WATER HULLE ONWETEND "DRINK" DEUR HUL DAAGLIKSE KOS TE EET. DIT VERG 132 ℓ WATER VIR 'N KOPPIE KOFFIE (125 mℓ), 196 ℓ VIR 'N GROOT EIER (60 G) EN 18 ℓ VIR 'N SNY BROOD (30 G). VIR AANDETE GAAN JOU 200 G BIEFSTUK JOU 3 083 ℓ WATER "KOS", MET 'N VERDERE 109 ℓ VIR JOU GLASIE WYN (125 mℓ). DIE VRAAG IS: WAT BETEKEN HIERDIE WAARDES WERKLIK EN MAAK DIT ENIGSINS SAAK?

DEUR CAREN JARMAIN

Hierdie waardes staan ook as 'n watervoetspoor (WF) bekend en is 'n maatstaf van die hoeveelheid water wat gebruik word om enige van die goedere en dienste wat ons gebruik, te produseer. Of dit nou jou gunsteling vrug, 'n glas wyn of jou gunsteling denimbroek is. As gevolg van die aard van goedere en dienste, kan 'n WF op verskillende maniere uitgedruk word, byvoorbeeld 'n liter water wat gebruik word per kg gewas geproduseer (ℓ/kg), maar ook die hoeveelheid water wat per eenheid afgeleide finansiële waarde (ℓ/R) gebruik word. Die WF beskou beide direkte en indirekte watergebruike en word soms in sy kleurkomponente uitgedruk: groen, blou en grys. Laat ek verduidelik. Die 109 ℓ water wat gebruik word om jou 125 mℓ wyn te produseer, sal alle water wat direk vanaf die produksie van druiwe op die plaas gebruik word (byvoorbeeld reënval en besproeiing) tot in die kelder in ag neem (byvoorbeeld wynmaakprosesse, verkoeling en skoonmaak), maar selfs verder langs die waardeketting, byvoorbeeld tot by die herwinning van jou wynbottel. Die indirekte gebruik van water sal die water wat gebruik word in die produksie van elektrisiteit, brandstof, die wynbottel, etikette en ander, insluit.

Die kleurklassifikasie verwys na die oorsprong of impak van die WF. Die groenwater komponent sal die reënval verteenwoordig wat in die grond beland en daarna gebruik word om die wingerdplante te laat groei en druiwe te produseer. Die blou water verteenwoordig weer alle "fisiese" water wat gebruik word (byvoorbeeld vir die besproeiing van die wingerde) en wat uit strome of grondwater onttrek word. Die gryswaterkomponent verteenwoordig iets heel anders as wat ons as gryswater by die huis beskou. Die gryswaterkomponent verteenwoordig die volume water wat benodig word om "besoedelde" water se kwaliteit tot 'n aanvaarbare vlak vir 'n spesifieke area te verbeter. Gryswater is gewoonlik die gevolg van chemiese toedienings op die plaas of afvalwater wat in die wynmaakproses gegenereer word.

'n Mens kan moontlik argumenteer dat die WF-"waardes" nie veel saak maak waar waterbeskikbaarheid voldoende, volhoubaar en van goeie gehalte is nie. Onder waterbeperkende toestande soos in die semi-droë gebiede van Suid-Afrika, insluitend die Wes-Kaap, behoort hierdie WF-getalle en hul betekenis baie saak te maak.

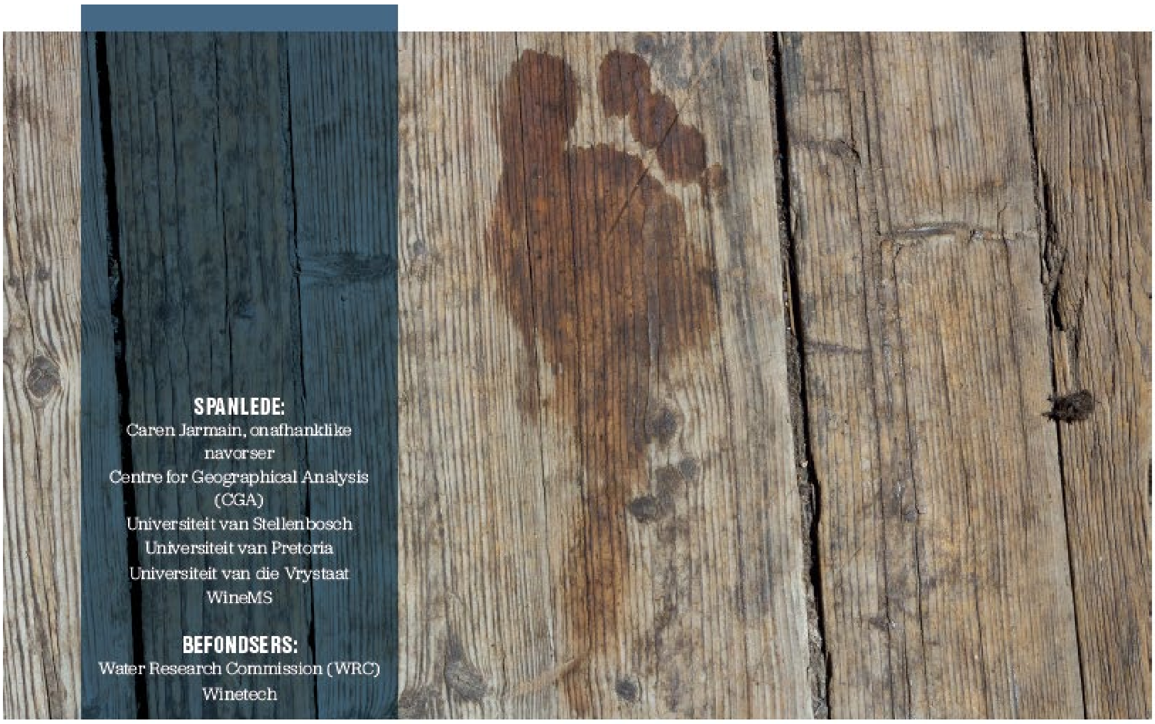
Maar hoeveel weet ons werklik van die WF van byvoorbeeld die wyn- of tafeldruiwe wat in die Wes-Kaap van Suid-Afrika geproduseer word? Waarskynlik minder as wat ons dink.

Die Watervoetspoornetwerk (WFN) is 'n goeie bron van WF-waardes vir 'n wye verskeidenheid gewasse en produkte wat in verskillende lande en streke geproduseer word en kan op waterfootprint.org besigtig word. Volgens die WFN, is die gemiddelde WF van wyndruiwe wat in Suid-Afrika geproduseer word 603 m³/ton, in vergelyking met die globale gemiddelde van 869 m³/ton. Interessant genoeg is die WF van vars druiwe 422 m³/ton, in vergelyking met die globale gemiddelde van 608 m³/ton. Deur net hierdie waardes te oorweeg, sal dit impliseer dat Suid-Afrika redelik goed in vergelyking met die globale gemiddeldes vaar. Ongelukkig, aangesien geen kontekstualisering van die waardes gegee word nie, kan ons nie werklik tot hierdie gevolgtrekking kom nie.

Om meer lig op WF te werp, is 'n nuwe studie geloods wat gesamentlik deur die Waternavorsingskommissie en Winetech befonds word. Die studie is daarop gemik om die watervoetspore vir tafel- en wyndruifproduksie as 'n volhoubaarheidsindikator te bepaal. Hierdie projek beoog om meer as net WF-getalle te genereer, maar dit in die konteks van die omgewings-, maatskaplike en ekonomiese toestande te plaas.

Die navorsing, onder leiding van dr Caren Jarmain, sal die WF van beide die wyn- en tafeldruifbedrywe oorweeg. Alhoewel beide die wyn- en tafeldruifbedrywe rondom die *Vitis vinifera*-plant draai, verskil die prosesse betrokke by die produksie van tafeldruiwe en wyn aansienlik. In hierdie studie sal die WF van wyn (in m³ water per ℓ wyn) die volume water wat gesamentlik in al die prosesse gebruik word, van die wingerdblok tot by die wynkelder, maar tot voor bottelering verteenwoordig. Net so vir tafeldruiwe, sal die WF (in m³ water/kg druiwe) die volume water tydens alle prosesse gebruik, van die wingerdblok tot in die pakstoor, maar tot voor die finale verkoeling van die druiwe oorweeg en verteenwoordig. Hierdie benadering sal die navorsers toelaat om die WF van die gedeelte tot by die plaashek van dit daarbuite te skei.

Hierdie navorsing word in die Wes-Kaap provinsie uitgevoer en 'n aantal



tafeldruifpakstore en koöperatiewe kelders uit die verskillende produksiestreke neem reeds deel. Dit beteken dat die wye verskeidenheid produksietoestande waarvoor die Wes-Kaap bekend is, verteenwoordig word. Om anonimiteit aan die deelnemers van hierdie studie te gee, beplan die navorsers om die finale WF-waardes per streek en nie per individuele pakstoor of koöperatiewe kelder uit te druk nie.

Wat hierdie studie besonders maak, is die gebruik van satelliet-afgeleide wingerdwater gebruiksdata en die integrasie daarvan met beskikbare druiwe- en wynproduksie, klimaat- en ander datastelle (byvoorbeeld kelderwatergebruik en grondwaterinhoud). Die feit dat blokspesifieke produksie- en wingerdwater gebruiksdata beskikbaar is, beteken dat die WF van wyn (van koöperatiewe kelders uit 'n spesifieke streek) of tafeldruiwe (vir pakstore uit 'n spesifieke streek) as 'n reeks WF-waardes, eerder as 'n enkele waarde, uitgedruk kan word. Hierdie WF-reeks waardes sal toelaat dat die variasie geïnterpreteer kan word, wat hopelik tot die identifisering van die bepalende faktore (produksie of ander toestande) van lae of hoë WF-waardes sal lei.

Ten slotte en aan die einde van hierdie projek (2020), behoort hierdie nuwe kennis die wyn- en tafeldruifbedrywe te bemagtig om die WF-waardes tot hul voordeel te gebruik. Of dit nou is om swak (hoë) WF's aan te spreek deur spesifieke veranderinge op plaas-, kelder- of pakstoorvlak aan te bring en dan die impak wat hierdie sektore op water het, te verbeter. Of deur die gebruik van hierdie kennis in die bevordering van Suid-Afrikaanse produkte en gewasse op grond van die relatief klein WF-waardes.

Let wel: Die span wat vir hierdie navorsing verantwoordelik is, is van die Universiteit van Stellenbosch (Sentrum vir Geografiese Analise, asook Wingerd- en Wynkunde), die Universiteit van die Vrystaat (Landbou-ekonomie), die Universiteit van Pretoria en WineMS, terwyl verteenwoordigers van Winetech en SATI toesig oor die projek hou en 'n ondersteunende rol speel. Die navorsingspan is baie dankbaar vir die ondersteuning wat tot dusver ontvang is van produsente, pakhuiseienaars, vrugte-uitvoerders, tegniese bestuurders en kelders, asook die deel van inligting om hierdie studie moontlik te maak. W

– Vir meer inligting, vrae of terugvoer oor hierdie navorsing, kontak dr Caren Jarmain by cjarmain@gmail.com.

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Figure C1: Popular article published in January 2019 in Winetech Tegnies: Watervoetspoor van druiwe en wyn*. The English version can be downloaded from: https://www.wineland.co.za/water-footprint-of-grapes-and-wine/. Accessed February 2020.*

Water Footprint = Wine from Water
Water Footprint = Grapes and Wine from Water
Water Footprint = Water for Wine

Dr Caren Jarmain, lead researcher explains what the Water Footprint of our favourite wine, table grape and other crops are all about.

During the past season, with many people living in the Western Cape trying to survive with a mere 40 to 50 ℓ of water per person per day, many figures were quoted reminding us just how much water is commonly used in our daily living. For example, that about 19 ℓ of water is used for a 90-second shower and that one flush of your toilet will use 9 ℓ . Many people were also surprised to realise just how much water they "consume" through eating their daily food. For example that it takes 132 ℓ of water to produce a single cup of coffee (125 mℓ), 196 ℓ for a large (60-gram) egg and 18 ℓ of water for a slice of bread of 30 grams. For supper, your 200 g steak will cost you 3083 ℓ of water and your small (125 mℓ) glass of wine 109 litres. But the question is: what do these values really mean and do they matter?

These values, also referred to as a "Water footprint (WF)", provide a measure of the amount of water used to produce each of the goods and services we use – whether your favourite fruit, a glass of wine or a pair of jeans. Because of the nature of goods and services a WF can be expressed in different ways, for example, a litre of water used per kg of crop produced (ℓ/kg), but also a litre of water used per unit of currency derived (ℓ/R). WFs consider both direct and indirect water uses and are sometimes expressed in its colour components: green, blue and grey. For example, the 109 ℓ of water used to produce your 125 mℓ of wine will take into account all water used right from the production of grapes on the farm (e.g. rainfall, irrigation), all the way to the cellar (e.g. harvest container washing, wine making processes, cooling, cleaning), but even beyond that, all the way up to the recycling of your wine bottle. Indirect water uses considered will include the water used in the production of electricity, fuel, the wine bottle, labels, and others.

The colour classification refers to the origin or impact of the WF, for example the green water component will represent the rainfall that ends up in the soil and is used to grow the grapes. Whereas the blue water represents all "physical" water used (for example for irrigating the crops) that is extracted from streams or groundwater. The greywater component represents something very different to that which we consider greywater at home, it's the volume of water required to dilute "polluted" water back to an acceptable standard for an area. Grey water is typically the result of on-farm chemical application or wastewater generated in a process such as making wine.

One could possibly argue that WF "numbers" do not matter much where water availability is sufficient, sustainable and of good quality. But, under water-constrained conditions like the semi-arid regions of SA, like the Western Cape, these WF numbers and their meaning should matter.

But just how much do we know about the WF of, for example the wine or table grapes

WF = the amount of water used to produce grapes and/or wine

HOW CAN YOU HELP?
- Take note and provide feedback
- Assist with data for research purposes

Contact Dr Caren Jarmain 073 579 1818

produced in the Western Cape of SA? Likely less than we think.

The Water Footprint Network (WFN) is a good source of numbers for a wide range of crops and products for different countries and regions and can be viewed on waterfootprint.org . According to the WFN, the average WF of wine grapes produced in SA is 603 m^3/ton of grapes, compared to the global average of 869 m^3/ton. Interestingly, the WF of fresh grapes is 422 m^3/ton of grapes, compared to the global average of 608 m^3/ton . According to these values SA is fairing quite well compared to the global averages. But the absence of contextualization of the numbers disallows for this conclusion to be drawn.

To shed more light on WFs a new study, jointly funded by the Water Research Commission and Winetech aims at determining the Water footprints for Table and Wine Grape Production, as a Sustainability Indicator. This project aims to generate more than just WF numbers - placing these into the context of the environmental, societal and economic conditions.

The research, under the leadership of Dr Caren Jarmain, will consider the WF of both the wine and table grape industries. Although both the wine and table grape industries revolve around the Vitis vinifera plant, the processes involved in producing table grapes and wine differ significantly.

In this study, the WF of wine (in m3 of water, per litre of wine) will represent the water used in all the processes, right from the vineyard block up to the wine cellar, but before bottling. Similarly, for table grapes, the WF (in m3 of water per kg of grapes) will consider all processes from the vineyard block up to packing the grapes in the packhouse, but before final cooling. This approach should allow the researchers to separate the WF into the part up to the farm gate, and beyond.

This research is conducted in the Western Cape Province and a number of table grape packhouses and cooperative cellars from the different production regions are already participating. Now, the wide range in production conditions for which the Western Cape is known will be accounted for. To provide anonymity to the participants of this study, the final WFs will be expressed per region and not per individual packhouse or cooperative cellar.

What makes this study unique is the use of satellite-derived vineyard water use data and the integration thereof with available grape and wine production, climatic and other datasets (e.g. cellar water use and soil water content). The fact that block-specific production and vineyard water use data are available, means that the WF of wine (of cooperative cellars from a specific region), or table grapes (for packhouses from a region) can be expressed as a range in WF values, rather than a single value. This WF range will allow for interpretation of the variation, which will lead us to understand the drivers (production or other conditions) behind low or high WFs.

Finally and at the end of this project (2020), this new knowledge should empower both the wine and table grape industries to make the most of these numbers! Whether by addressing poor (high) WFs by addressing specific practices on the farm, or in the cellar or packhouse to mitigate the impact these may have on water consumption. Or, by utilising this knowledge in promoting South African products and produce that have a relatively small WF.

For more information, questions or feedback on this research, please contact Dr Caren Jarmain at cjarmain@gmail.com.

Note: The team responsible for this research are from **Stellenbosch University** (Centre for Geographical Analysis, Viticulture and Oenology), **University of the Free State** (Agricultural Economics), **University of Pretoria** and **WineMS**; while representatives from **Winetech** and **SATI** are providing an overseeing and supporting role.

This team is very grateful for the support received thus far from numerous producers, packhouse owners, fruit exporters, technical managers and cellars who generously shared information to make this study possible.

The original publication appeared in the January 2019 issue of the Winelands magazine.

WRC WATER RESEARCH COMMISSION

CGA CENTRE FOR GEOGRAPHICAL ANALYSIS

Caren Jarmain (Ph.D. Agrometeorology) Independent Researcher

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Figure C2: Popular article published in South African Fruit Journal *in February/March 2019. Downloaded from https://www.safj.co.za/wp-content/uploads/2019/02/safj-sa-fruit-journal-feb-march-2019.pdf. Accessed February 2020.*

APPENDIX 4: ACCESS TO THE DATA GENERATED DURING THE PROJECT

A copy of the spatial data used in this project (maps and extracted evapotranspiration data), as well as a copy of the two water footprint calculation spreadsheets, will be stored at the Centre for Geographical Analysis at Stellenbosch University. Prof A van Niekerk is the contact person for future access to this data.