# A FRAMEWORK TO APPLY WATER FOOTPRINTING FOR SUSTAINABLE AGRICULTURAL WATER MANAGEMENT: A CASE STUDY ON THE STEENKOPPIES AQUIFER

By

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# SUMMARY

## A FRAMEWORK TO APPLY WATER FOOTPRINTING FOR SUSTAINABLE AGRICULTURAL WATER MANAGEMENT: A CASE STUDY ON THE STEENKOPPIES AQUIFER

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Key words: Blue and green water footprint sustainability assessments, Catchment management, Catchment water balance, Crop water requirements, Sustainability targets, Water productivity, Carrots (*Daucus carota*), Beetroot (*Beta vulgaris*), Cabbage and Broccoli (*Brassica oleracea*), Lettuce (*Lactuca sativa*), Maize (*Zea mays*), Wheat (*Triticum aestivum*)

This study was conducted to better understand the usefulness of water footprint (WF) information for vegetable crops produced on a water-stressed aquifer in South Africa. Different methodologies were investigated in a literature review and the methodologies proposed by the Water Footprint Network (WFN), the Life Cycle Assessment (LCA) communities, and the hydrological-based WF community were selected for a case study on the cultivation of carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*), lettuce (*Lactuca sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*) on the Steenkoppies Aquifer, Gauteng, South Africa. A key aim was to identify one or more simple yet effective WF method(s) that can be applied in South Africa to improve water resource management and for raising consumer awareness.

The case study on the Steenkoppies Aquifer indicated that WF metrics from the three methodologies differed notably. For example, an annual two-crop rotation sequence (carrots in summer and cabbage in winter) had an average blue WF of 57 $m^3$ $tonne^{-1}$ according to the WFN methodology, compared to 32 and 44 $m^3$ $tonne^{-1}$ according to the hydrological-based method and the LCA methodology, respectively. Estimated WFs differed notably between different crops and growing seasons, for example, according to the WFN methodology the blue plus green WFs of lettuce in summer was 56 $m^3$ $tonne^{-1}$, compared to 327 $m^3$ $tonne^{-1}$ for the blue plus green WF of broccoli in winter.

The WFN methodology consists of goals and scoping phase, an accounting phase, determining the volume of water required to produce a product, followed by a sustainability assessment, which interprets the impact of the WF in the local context of water availability. Finally, a suitable response is formulated. The WFs according to the WFN methodology is not considered to be suitable for awareness raising if it is communicated without the sustainability assessment or outside the local

environmental context of the water use. As an alternative, the LCA-based WF methodologies have been developed to incorporate the environmental sustainability in the WF assessments, and represent a stress weighted index of water use, which can be used together with other LCA metrics. Also, a hydrological-based methodology has been proposed and developed to incorporate all the water flows and other aspects of the hydrological system, so the WFs can be reported as a stand-alone value. While the latter two methodologies aimed to develop single WF values that indicate the sustainability of a water use, due to the vast number of variables, complexities and trade-offs involved in sustainable water use, obtaining such a number still does not seem possible at this stage. Following this comparison, the WFN method was selected as the key methodology for this research project for reasons that include the following:

- The methodology is simple and well-developed.
- The WFs are based on actual water volumes used for a product, a process or by an entity, which can potentially be used in different information systems, such as water use licensing, up-scaling to a catchment level, and quantifying water consumed by different users for allocation purposes.
- By using different functional units, such as nutritional value and economic gain, the volume of water can be directly linked to certain benefits derived from the product.
- The volumetric WFs can reveal impacts on water resources in different seasons of a hydrological or calendar year.
- It can indicate high WFs of certain crop species, such as broccoli, or certain growing regions, such as those which experience relatively high vapour pressure deficits or with poor soils.
- It allows for local geographic contextualisation if there is suitable information to conduct the sustainability assessment.

Despite the relative simplicity of the WFN methodology, some complexities were encountered in its application for quantification of WFs of selected vegetable crops on the Steenkoppies Aquifer. In this study, we assessed that WF outcomes are influenced by several factors, including natural variations in weather conditions between growing seasons and between different years. Therefore, WFs should be site specific and calculated for a particular season or year. Water footprints are also directly dependent on crop simulation model outputs, which are in turn affected by the quality of parameterisation and input data used. Whether solar radiation (Rs) data was measured or estimated were found to have a notable impact on estimates of crop reference evapotranspiration ($ET_o$) and crop yields in summer season. It was recommended that if estimated data for a specific weather variable is used for crop parameterisation, the same type of data be used when simulations are executed with those crop parameters (assuming that the variation in the error in Rs will be consistent for a crop calibrated in summer or winter and simulated in the same season). The error in Rs estimates was, however, not consistent over different seasons and parameters generated for crop in a particular season should be used cautiously for other seasons. Variations in water content between different crops can impact the WFs, which are most commonly expressed as a volume of water (e.g. in $m^3$) used per unit of yield (e.g. in tonnes) in fresh mass. This resulted in relatively higher WFs for grain crops with low moisture contents, when using yields in fresh mass. For example, alternative functional units, such as nutritional content (such as zinc or iron) or economic gain are proposed to be used to link the WFs to a more specific potential benefit, which makes comparisons possible.

Packhouse WFs were calculated to quantify the volume of water used in cleaning and/or packaging a unit yield of carrots, cabbage and lettuce in a packhouse on the Steenkoppies Aquifer according to the WFN methodology. As observed in previous studies, packhouse blue WFs were relatively low compared to the WFs linked to the cultivation phase (ET) (2.2% of the total field to farm gate WF for carrots, 0.5% for cabbage and 1.5% for lettuce). This highlights the importance of water use during cultivation, as compared to the rest of the supply chain, when considering measures to reduce water use impacts on the aquifer. Using phosphorus (P) as the critical pollutant, packhouse grey WFs were estimated to be considerably larger than the packhouse blue WFs. For carrots, cabbage and lettuce, packhouse grey WFs were 44, 12 and 16%, respectively, of the grey WF linked to the cultivation of these crops. The inclusion of recycling and filtration systems, final fate of the disposed water and associated pollutants, and assimilation capacity of the natural environment make the estimation and interpretation of grey WFs challenging! Grey WF assessments, which were not validated by the Steenkoppies Aquifer water quality measurements, require further research and refinement.

Water footprints according to the WFN were used to develop the catchment WF framework, in which total ET of agriculture was estimated by linking WFs of crops with total yields produced on the aquifer. The catchment WF framework is a new concepts and is considered the main contribution to current research that was produced in this study. Total ET of agriculture, together with other water flows, was used to calculate the catchment water balance. According to the catchment water balance, total water flowing into the aquifer exceeds total water losses on an annual basis. This can either be explained by errors in the assumptions made for this study, or by the possibility that other losses may occur from the aquifer boundaries that we are currently not aware of. There was, however, a good correlation between estimated and measured outflows, and water outflows (ET plus discharges from the aquifer outlet) are very similar to precipitation inflows during years with low rainfall and/or high agricultural water use.

Applying this framework, total ET estimates of a catchment can potentially be used to improve hydrological models. Using WFs to determine a water balance of the catchment is, however, also considered to be part of a process towards developing a simplified and more cost-effective approach to understanding water dynamics of an aquifer, in contrast to complex and expensive hydrological assessments. A better understanding of the reasons why WFs vary, such as the influence of seasonal weather conditions, may assist in the standardisation of WFs under different conditions, thus alleviating the need to estimate WFs each year. The framework requires relatively little information for an agriculture-dominated catchment, including rainfall data, the total yield of different crops cultivated and their respective WFs, and the WF of natural vegetation present within the catchment. By linking WFs to crop yields, the catchment WF framework can also potentially be used to specify limits to agricultural production based on the availability of water. Crop modelling required for WF calculations may increase the difficulty of applying the framework, depending on which model is used, the variation in soil properties (particularly where crops have deeper root systems) or rainfall throughout a catchment, and what data is available for the catchment. Whether this framework can be directly applied to other catchments depends on the specific characteristics of the catchment. The WFN approach assumes that the difference between over-irrigation and ET recharges the blue water source. This framework, therefore, only applies to situations where the difference between over-irrigation and ET can be considered unimportant or as recharge to the same water resource, which supplied the irrigation. Green water is assumed equally important, and its use must be maximised to enable optimal use of blue water. This will also reduce other ecological impacts associated with over-irrigation and the impact of lags (due to temporary unavailability in the vadose zone) on blue water availability in systems like the Steenkoppies Aquifer.

The blue WF sustainability assessment indicated that the irrigated agriculture on the Steenkoppies Aquifer became unsustainable after 1986, which aligns with the measured reductions in outflows from the Maloney's Eye, as well as measured reductions in groundwater levels in the aquifer during this time. The green WF sustainability assessment indicates that there is still further opportunity to horizontally expand rainfed crops based on a natural vegetation conservation target of 24% specified for the study area.

Water footprints of food wastage between harvesting and the consumer present potential opportunities to reduce water use impacts. However, classifying waste is complex, because wasted food all along the supply chain is often used for other beneficial purposes such as composting and animal feed. Further reductions in food wastage may come at a cost, for example, ecological impacts due to pesticide application, or carbon emissions associated with energy use for refrigeration. This needs further investigation. However, reductions or even elimination in wastage of crops produced on the Steenkoppies Aquifer alone will not be sufficient to achieve blue water sustainability targets. The percentage of crop wastage calculated here is already much lower than what has been recorded in other studies for other parts of the world and for sub-Saharan Africa. Given current technologies, further reductions in crop wastage may be unlikely. For example, lettuce has relatively high wastage rates along the supply chain, partly because the crop has a short shelf-life and because it cannot be preserved or frozen. However, in the face of food insecurities food wastage is still important and should therefore be considered as one of several measures to be implemented to reduce the WFs on the Steenkoppies Aquifer and improve overall sustainability of agricultural production on the aquifer.

New crop parameters were developed for the fancy lettuce cultivars, cos and butterhead for application in the Soil Water Balance (SWB) model. Water footprint results for these cultivars were lower than all the other crops that were investigated in this study. This is partly because they are very efficient in producing biomass and lettuce cultivars have a high harvest index. The duration of the growing period had a notable impact on the WFs of crops, because the crops accumulate more dry matter per volume of water during the later stages of the growing season. It was found that alternative cultivars, cos and butterhead lettuce and increasing growing periods of these alternative crops may play an important role in achieving sustainable water use of the aquifer. Currently the growing period is often cut short, because crops are harvested when market prices for the produce are high.

The International Standards Organization (ISO) published a global WF standard (ISO 14046) in August 2014, which closely resembles the LCA approach, but it remains to be seen if it gains any momentum. From this study, it is concluded that WFs according to the WFN method can potentially provide important information to improve water resource management at farm and catchment level. On a local level, it informs farmers on which crops during which seasons will be most productive with a certain volume of water, or can be used as a benchmark for a specific growing region. On a catchment scale, WFs are considered to provide valuable information if used within a catchment WF framework to determine limits to agricultural production that will ensure sustainable water use. Water footprints can also provide important information needed to prioritise actions, by indicating, for example, that reducing water used in the packhouse and by reducing crop wastage is less important than measures to reduce WFs during cultivation, such as finding alternative crops with low WF and increasing the growing period of these alternative crops. Water footprints will have an important role to play in improving water resource management, and if combined with a sustainability assessment it can create awareness among consumers to make wise decisions about their water use.

The following opportunities have been identified that can be addressed in future research on the Steenkoppies Aquifer:

- To record data on the water used for cleaning and packing beetroot and broccoli at the packhouse level
- To improve current understanding of the nitrogen balance of intensive cropping systems and the whole aquifer.
- To record actual production within the catchment for the estimation of WFs. This will require a willingness of farmers to share their production records.
- Future geohydrological assessments are required to confirm the hypothesis of an unknown outlet.

The following opportunities have been identified that can be addressed in future research on catchments in general:

- Standardisation of crop WFs according to the WFN under different conditions (variation in climate, soil and management).
- To further develop WF methodologies using alternative functional units, such as crop nutritional content, and economic gain and job creation per unit water used.
- To improve the understanding of how initial soil water content at planting and where this water originated from impacts the blue and green WF. This concern was not considered important for this study, because long term monitoring was done and the initial water content only affected the first year. In other models where long term modelling is not possible this may, however, have a notable impact on the results.
- To further refine the catchment WF framework to estimate outflows from the aquifer more accurately (assuming these can be accurately measured) and to improve and verify estimations of ET of the natural vegetation.
- Using catchment scale WFs to determine maximum allowable production on an aquifer to achieve multi-generational sustainability targets as proposed by Gleeson et al. (2012).
- To improve the blue and green WF sustainability assessments. With regards to determination of natural runoff, additional components that can be included in the calculation of blue water availability (such as water allocated to downstream users), and accounting for recharge of the aquifer under natural vegetation, which may be defined as available blue water.
- To improve classification of wastage to account for other beneficial uses of produce that is not suitable for selling.
- Compare the increased ecological and carbon footprints with the gains of reducing WFs when implementing different strategies to reduce food wastage.
- Quantifying the causes for vegetable wastage at the packhouse level, which is generally where most wastage occurs.
- To assess alternative cultivars or species, for example, indigenous species that are drought resistant, to find crops with lower WFs, which may become an important measure in which sustainability can be achieved.
- To determine how the length of the growing season affects the WFs of crops in general.
- To determine the impact of increasing the growing season on crop yield and quality for different cultivars
- To compare the efficiency of WFs to change consumer behaviour with other potential ways such as marketing and incentives.

# LIST OF ABBREVIATIONS

| | |
|---|---|
| $C_{max}$ | Maximum concentration of pollutant |
| $C_{nat}$ | Natural concentration of pollutant |
| COD | Chemical oxygen demand |
| CPI | Consumer Price Index |
| CWP | Crop water productivity |
| CWR | Crop water requirement |
| DAP | Days after planting |
| DWR | dry-matter-water ratio |
| $E_c$ | Radiation conversion efficiency |
| EFR | Environmental flow requirement |
| EFR | Ecological footprint |
| ET | Evapotranspiration |
| $ET_a$ | Actual evapotranspiration |
| $ET_{blue}$ | Blue water evapotranspiration |
| $ET_{env}$ | Evapotranspiration of the environment |
| $ET_{green}$ | Green water evapotranspiration |
| $ET_o$ | Reference crop evapotranspiration |
| $ET_{unprod}$ | Evapotranspiration of unproductive land |
| FAO | United Nation’s Food and Agriculture Organization |
| FC | Field capacity |
| FD | Freshwater depletion |
| FEI | Freshwater ecosystem impacts |
| FI | Fractional interception |
| GDD | Growing day degrees |
| HPA | High Plains Aquifer |
| ISO | International Standards Organisation |
| K | Canopy Extinction Coefficient |
| $K_c$ | Crop coefficient |
| $K_s$ | Stress coefficient |
| L | Pollutant load |
| LAI | Leave area index |
| LCA | Life Cycle Assessment |
| N | Nitrogen |

| | |
|---|---|
| P | Phosphorus |
| $P_{eff}$ | Effective rainfall |
| PWP | Permanent wilting point |
| $R_{nat}$ | Natural runoff |
| Rs | Solar radiation |
| SLA | Specific leaf area |
| SWB | Soil Water Balance crop model |
| VF | Variation factor |
| WA | Water availability |
| $WA_{blue}$ | Blue water availability |
| $WA_{green}$ | Green water availability |
| WF | Water footprint |
| WFN | Water Footprint Network |
| WRC | Water Research Commission |
| WS Index | Water stress index according to the Pfister et al (2009) LCA methodology |
| $WS_{blue}$ | Blue water scarcity |
| $WS_{green}$ | Green water scarcity |
| WSI | Water stress indicator according to i Canals et al (2009) LCA methodology |
| WTA | Withdrawal to availability ratio |
| WU | Water use |
| WUE | Water use efficiency |

# DECLARATION

I, Carolina Elizabeth le Roux, hereby declare that this thesis, which I submit for the degree PhD Agronomy, at the University of Pretoria, is my own work and has not been submitted at any other university. The work contained in this thesis is a result of my own research, except where acknowledged otherwise.

leRoux

Carolina Elizabeth le Roux

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# 1 CHAPTER 1: INTRODUCTION AND BACKGROUND

## 1.1 INTRODUCTION

The Global Risk Report for 2015 and 2016 identified the reduction in good quality fresh water as the most important risk to society for the next ten years (World Economic Forum, 2016). This is motivated by the significant impacts on human health and the economy that can be expected if fresh water becomes scarce. Climate change, population growth and improved standards of living will exacerbate this even further in the future. Future water scarcities will present many challenges, of which global food production is of specific concern. The decline in good quality water will make it difficult to maintain current food production, while population growth places an increasing demand on water to produce more food (Postel, 1999). Current food production often relies on the unsustainable use of groundwater. A study done by Wada et al. (2012) indicated that the global use of non-renewable groundwater abstractions increased by more than three times between the years 1960 and 2000. In the year 2000 unsustainable use of groundwater supplied approximately 234 $km^3$ $yr^{-1}$, which is 20% of the gross irrigation water demand. Climate change is expected to increase the risks in food production as water becomes more scarce. According to Rosenzweig and Parry (1994), food production in developing countries will suffer most from the effects of climate change. Schulze (2000) illustrated the complexity of southern African hydrology and the difficulty in predicting the local effects of climate change on freshwater availability.

Water management in South Africa is particularly challenging, because of severe waters shortages in most parts of the country and a highly variable climate (Smakhtin et al., 2001). In many catchments throughout South Africa, water supply no longer meets demand (Department of Water Affairs, 2013). Irrigated agriculture uses approximately 40% of South Africa's exploitable runoff on around 1.7 million hectares of land (Backeberg and Reinders, 2009). Agricultural products account for approximately 6.5% of the total South African national exports, approximating 3% of Gross Domestic Product (South Africa Yearbook, 2015). Nieuwoudt et al. (2004) estimated that 90% of vegetable and fruit products are grown under irrigation in South Africa, because of low and erratic rainfall and the high value of these crops. These industries are therefore highly dependent on the continued availability of irrigation water to remain sustainable. However, surface water resources in South Africa are already almost fully developed, and although alternative sources can still be exploited, it will be done at significantly higher costs than previously (Department of Water Affairs, 2013). The vulnerability of food production in South Africa was emphasized by the drought of 2015 which was, according to the South African Weather Bureau, the driest calendar year since nationwide recordings started in 1904 (de Jager, 2016). As a result, preliminary estimates on crop production for the 2016 calendar year indicate that production of most crops is expected to decrease (Crop Estimates Committee, 2016). One of the key findings of the Water Resource Reconciliation Strategies for major cities and towns in South Africa, was that little additional surface water can be made available to agriculture in the future, and that many areas are already considering the re-allocation of irrigation water to other users (Department of Water Affairs, 2013). The Reconciliation Strategy for the Crocodile West Water Supply System, for example, suggested that leakages in the distribution network of irrigation water from the Crocodile Catchment be addressed and that this water be reallocated to augment water requirements of the rapid developments in the Lephalale area or for urban and rural use (Nditwani et al., 2009). Improved water resource management practices that will inform water conservation at all levels to sustainably produce more food with the same or less water are essential. Ideally, these water resource management practices must be simple to use and easily adaptable in a changing environment.

The water footprint (WF) concept is an emerging approach, which first started when Allan (1998) introduced the term virtual water. He indicated that economically and logistically it is more reasonable to import, for example, one tonne of grain instead of the 1000 tonnes of water required to produce one tonne of grain. Hoekstra (2003), who initiated the Water Footprint Network (WFN) in 2008, further developed this concept of virtual water by saying that a nation's WF, for example, does not only consist of locally sourced water used, but also includes the water used to produce the products they consume. A water scarce country can import water intensive products thereby reducing the pressure on its own water resources.

The WFN published the first manual on WFs (Hoekstra et al., 2009), which was followed up with a later edition (Hoekstra et al., 2011), aiming to better quantify the impacts of human activities on water quantity and quality and guide improved decision making and management. In this thesis, this methodology is referred to as the WFN methodology. The WFN quantifies water consumption along the entire production chain of products, processes, businesses and within nations or catchments (Hoekstra et al., 2011). In an agricultural context, a WF is the volume of water required to produce a certain mass of crop yield. A WF assessment consists of four phases, namely (i) goals and scope definition, (ii) accounting, where the volume of water used is quantified, (iii) sustainability assessment and (iv) response formulation. Water footprints can indicate water consumption, defined as the loss of water from a particular catchment, for example, through evaporation or transfers to other catchments, along the entire production chain per yield of product (Hoekstra et al., 2011). The sustainability of the WF is determined by comparing the volume of water consumed to the available water. Available water is defined as the total natural runoff minus the water requirements of the environment (Hoekstra et al., 2011). The availability of water is spatially and temporally variable and the sustainability of using a volume of water depends on the availability of water at a specific time and place. Thus, geographical and temporal components are included in the sustainability assessment step.

Whereas traditionally the focus has been on agricultural producers and the technical aspects of irrigation and drainage to reduce impacts on freshwater resources, WFs further potentially allow water issues to be addressed through regional trade policies and consumer attitudes (Deurer et al., 2011). Although the WF in terms of water consumption (total evapotranspiration (ET) divided by crop yield), is merely the inverse of crop water productivity (CWP) (Crop yield divided by ET) (Zwart and Bastiaanssen, 2004), the WF concept is a valuable tool that makes some unique contributions to water resource management. For example, WFs added the concepts of blue, green and grey water. Surface and underground water resources, which are available to multiple users, are defined as blue water. In a crop production context, the blue WF therefore consists predominantly of the irrigation water consumed. Green water is water originating from rainfall that is stored in the soil and available for vegetation growth only. In order to account for water quality impacts, Hoekstra et al. (2011) proposed the concept of a grey WF, which is the volume of water required to dilute emitted pollutants to ambient levels. Expressing water pollution impact in this way enables the reporting of a total (blue + green + grey) WF as a volume which includes water quality and quantity impacts. Furthermore, compared to CWP, WFs is more intuitively perceivable to those consumers that are more aware of and concerned over water scarcity and less aware of food shortage, despite the subtle difference between these two concepts. Water footprint accounting has the potential to provide crop water use metrics in an easily understandable way, which can assist farmers to improve the management of their water resource by informing production decisions. If WFs can be established for a number of well-managed farms, these could serve as benchmarks that can be used by farmers to improve their water use efficiency. Water footprinting also made it possible to add different water flows along the supply chain and to include indirect water uses, such as electricity, to obtain a more comprehensive assessment of water used by a product.

As a result of a number of short-comings that were identified for the approach developed by the WFN, new methodologies have been proposed by other scientists. For example, an approach that additionally accounts for regional water stress (i Canals et al., 2009, Pfister et al., 2009), and an approach that considers the hydrological system in which the water use occurs focusing on water flows and storage changes (Deurer et al., 2011). Depending on the method used, WF outcomes can vary significantly (Jeswani and Azapagic, 2011) and there was a need for standardisation. Therefore, the International Standards Organization (ISO) published a WF standard in August 2014 (ISO 14046, 2014).

## 1.2 HYPOTHESES, AIMS AND OBJECTIVES OF THIS STUDY

This research was conducted as part of a Water Research Commission (WRC) funded project (Water Research Commission, 2014) on WFs. The WFs of vegetable production on the Steenkoppies Aquifer were used as a case study to better understand the WF methodology and the potential usefulness of the information that it generates in integrated water resource management.

In a South African agricultural context, detailed WF information is hypothesized to be useful for:

- Identifying opportunities to reduce the water consumption/impact at a local level, for example on-farm.
- Providing a simplified tool to monitor and manage the sustainability of agricultural water use at a regional level, for example management of water resources at the catchment scale.
- Informing policy formulation and creating consumer awareness at the national level.

This study is concerned with assessing the above hypotheses and with addressing the following gaps in current scientific knowledge on WFs:

- **Uncertainty regarding the most suitable methodology for different applications by various users.** It has been indicated that WFs can be used for awareness raising (Ridoutt and Pfister, 2010), in policy making (Pahlow et al., 2015) in catchment water management (Deurer et al., 2011, Multsch et al., 2016) and in water use sensitivity assessments (Hoekstra et al., 2011) etc. Different methodologies have arised to address all these requirements from various water users and policy makers. It remains unclear which methodology is most useful for different purposes, both in terms of the information that is generated and the accuracy of the information.
- **Uncertainty regarding the usefulness of WFs in water resource management**. Some scientists (Perry, 2014, Wichelns, 2011) have criticised the usefulness of WFs, arguing that the method is too simple to address all complexities in water resource management. The usefulness of WFs are therefore unclear and a number of complexities in using the methodologies have not yet been reported.
- **Uncertainty about how WFs can be used in a simplified framework to inform management decisions on a catchment scale:** Mitchell (1990) and Biswas (2008) indicated that water resource management can be extremely complex with a vast number of variables that must be considered. However, water resource managers often do not have the time to take all these variables into account when making decisions and simplified methods are required.
- **A lack of research on various applications of WFs,** for example the relative importance of packhouse water consumption compared to cultivation in South Africa, water lost through vegetables wastage and the WFs of alternative crops.

In order to address the above the aims of the study were to:

- Compare different WF methodologies to better understand their ability to inform water users and decision makers at local, regional and national levels.

- Select the most appropriate methodology for an aquifer under stress to be applied in a case study on the Steenkoppies Aquifer to:
    - Determine blue, green and grey WFs of cultivating vegetables and determine complexities associated with the use of the methodology;
    - Compare the WFs at the packhouse level with the WFs of cultivation, to determine the relative importance of packhouse water use;
- Apply the selected methodology to estimate a catchment scale blue plus green WF for the Steenkoppies Aquifer to:
    - Assess the sustainability thereof, using data on Maloney's Eye outflows and groundwater levels for verification of the outcomes;
    - Determine whether the selected WF methodology can provide a more simplified way to manage water resources of a water-stressed aquifer, as opposed to complex hydrological assessments;
- Calculate the WFs of food wastage along the food supply chain.
- Develop crop parameters and calculate WFs for two cultivars of fancy lettuce, cos and butterhead, that are commonly cultivated on the Steenkoppies Aquifer and compare the outcomes with the WFs of other crops.
- Evaluate the ability of WFs to provide the information needed to prioritise actions and measures that are required to achieve sustainable water use on the Steenkoppies Aquifer, and aquifers in general.

## 1.3 THE STEENKOPPIES AQUIFER

The Steenkoppies Aquifer (Lat: 26.03° S to 26.19° S, Long: 27.65° E to 27.48° E; Altitude 1560 to 1650 m) located west of Tarlton, in Gauteng, South Africa (**Figure 1-1**), is a dolomitic karst aquifer and a source of irrigation water for one of the country's major vegetable producing regions.

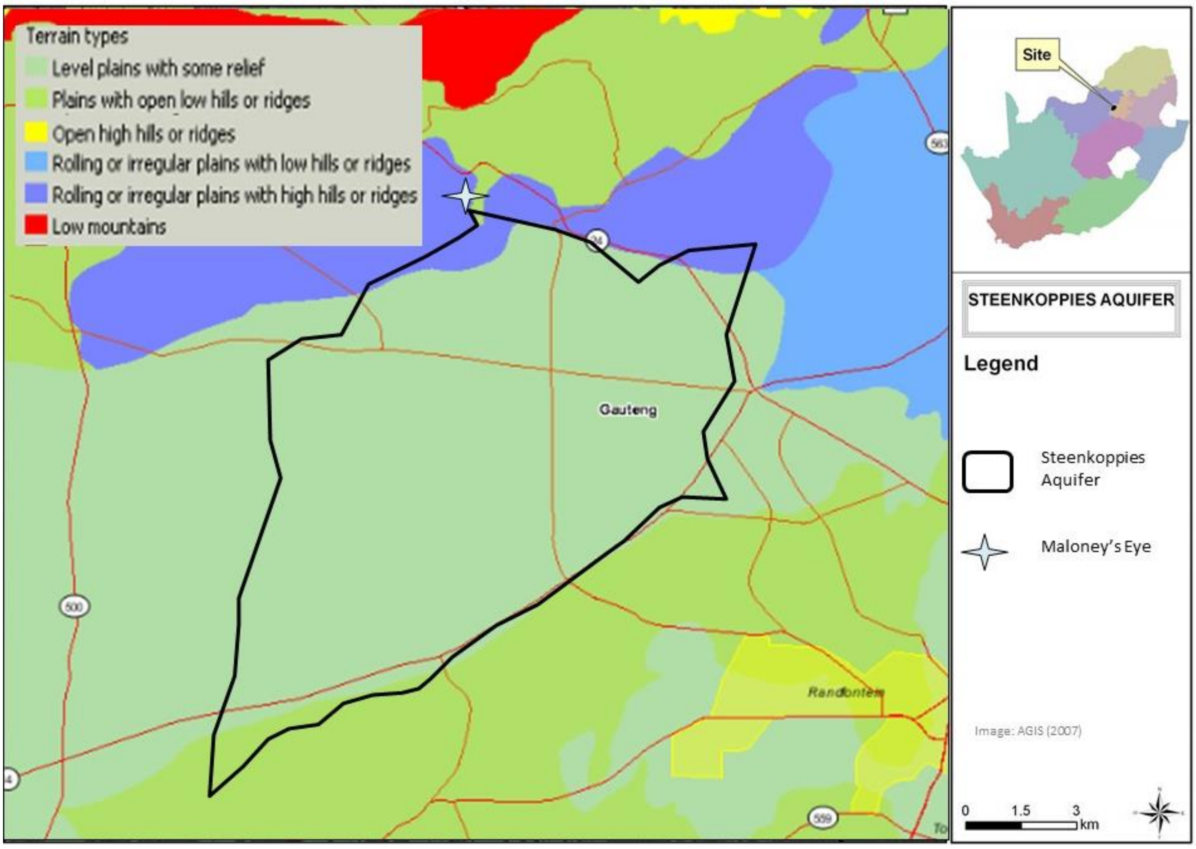

**Figure 1-1: The Steenkoppies Aquifer location and terrain types**

The aquifer is within the A21F quaternary catchment, which is in the upper reaches of the Crocodile West River Basin. The aquifer has a natural outlet, namely Maloney's Eye (**Figure 1-1**), from where it discharges into the Magalies River. The Magalies River supports important riparian ecosystems and provides irrigation water to a number of downstream farms (Vahrmeijer et al., 2013). Further downstream the Magalies River discharges into the Hartbeespoort Dam, which was constructed for irrigation purposes and is now well known for its hypertrophic water (Department of Water and Sanitation, 2016). The catchment area of the Maloney's Eye is referred to as the Maloney's Eye Catchment and includes the Steenkoppies Aquifer (14 400 ha) and an area of 5 300 ha above the Steenkoppies Aquifer. The Maloney's Eye is the only known outlet for the Steenkoppies Aquifer, and is therefore also the only known outlet for all the water draining from the Maloney's Eye catchment.

During the 1980's, agricultural activities on the Steenkoppies Aquifer increased significantly, sourcing irrigation water from the aquifer through boreholes. Flow of water from Maloney's Eye was drastically reduced as a result (**Figure 1-2**) (Department of Water and Sanitation, 2014). The initial decreasing trend coincided with unusually high flows from the Maloney's Eye in 1980. This decreasing trend continued and after 1986 the average flows were lower than previously. The reduction in flow resulted in conflict between farmers on the aquifer and downstream users, especially following two major droughts from 1990-1992 and 2002-2005 (Vahrmeijer et al., 2013). Downstream water users established the Magalies River Crisis Committee in an attempt to save their livelihoods and the ecological integrity of the river. They made a request to the South African Presidency to prohibit all abstractions from the Steenkoppies Aquifer, but the socio-economic impacts of such a measure were considered too high (Wiegmans et al., 2013). The largest carrot producer in Africa is situated on the Steenkoppies Aquifer, and according to Vahrmeijer (2013) more than 4000 people are employed by all agricultural activities on the aquifer. The farmers on the aquifer disputed the claims that they were responsible for the reduction in flow from the Maloney's Eye (Wiegmans et al., 2013). Very little is currently being reported regarding this conflict.

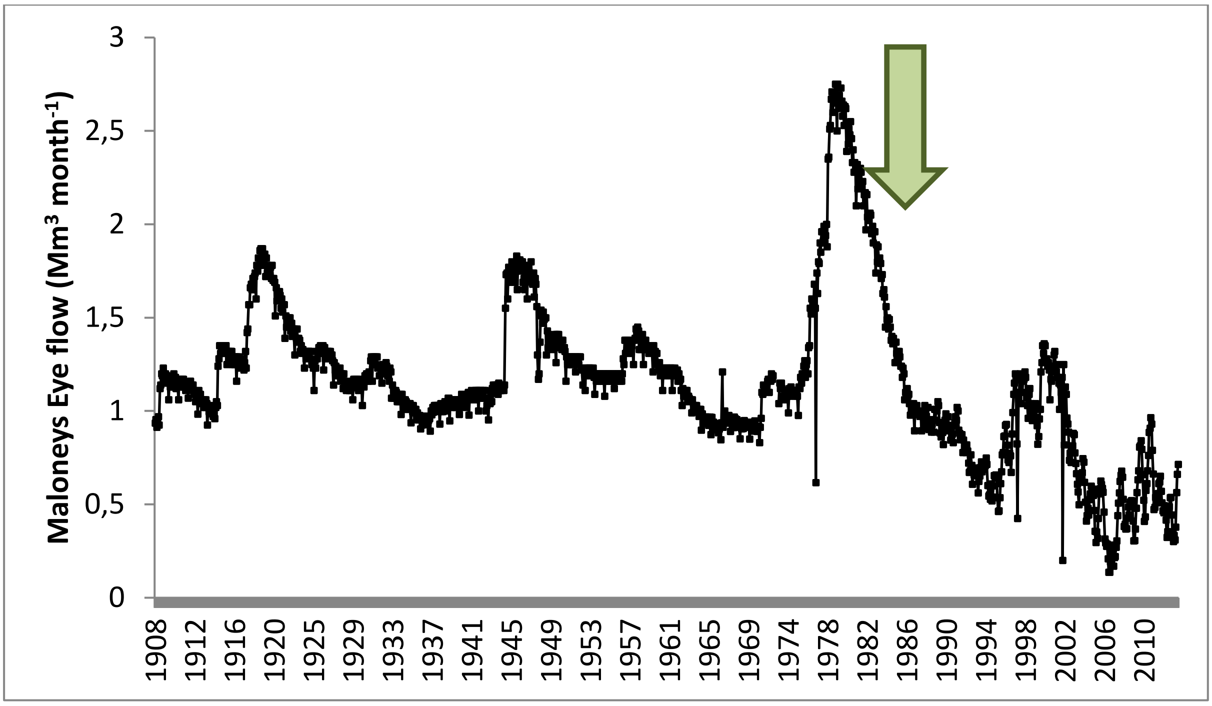

**Figure 1-2: Maloney's Eye outflows from 1908-2012. Reduction in flow has been observed since the commencement of intensive irrigated agriculture in 1986 (Department of Water and Sanitation, 2014).**

## 1.4 OVERVIEW OF THE CHAPTERS

This thesis reports on the research that was conducted from 2014 to 2016 to achieve the above-mentioned aims. This section provides an overview of all the chapters in the thesis.

- **Chapter 1: Introduction and background**

This chapter gives the background of the study, discusses the challenges in water resource management and introduces the WF as a tool that has been proposed to address some of these challenges. The chapter also provides the hypotheses, gaps in current scientific knowledge, aims and objectives and the research questions that are addressed in the study.

- **Chapter 2: Literature review**

A literature review was conducted to determine the WF methodologies used and to compare the strengths and weaknesses of the main WF methodologies as reported in literature.

- **Chapter 3: A worked example comparing different WF methodologies for crops grown on the Steenkoppies Aquifer**

On the Steenkoppies Aquifer, vegetable crops are exclusively cultivated under irrigation. Carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*), lettuce (*Lactuca sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*) are the most important crops cultivated under irrigation on the Steenkoppies Aquifer and were therefore selected for WF accounting. Blue, green and grey WFs for cultivating these crops on the Steenkoppies Aquifer were calculated according to the methodologies proposed by the WFN (Hoekstra et al., 2011), the 'LCA community' (Pfister et al., 2009) and the 'hydrological community' (Deurer et al., 2011). The methodologies were compared in terms of the usefulness of the information they provide. The comparison between the methods reported in **Chapters 2** and **3** was submitted as a manuscript to the journal *Irrigation and drainage.*

- **Chapter 4: The water footprints of selected vegetable crops in the packhouse**

The WFs of crops in the packhouse were calculated according to the WFN approach. These results were compared to the WFs during cultivation.

- **Chapter 5: Understanding complexities in estimating water footprints of vegetable crops**

This chapter reports on how WF outcomes can potentially be influenced by several factors, such as variations in weather conditions between growing seasons and between different years. Water footprints are also dependent on simulated model outputs, which are influenced by the quality of parameterisation and other input data used. Variation in water content of different crops can potentially impact the WFs which are expressed as a volume of water used per yield in fresh mass. Finally, complexities in using the grey WF method were assessed, and aquifer water quality measurements were used to challenge the grey WF results. A journal article based on this chapter has been published in the journal *Water* (Le Roux et al., 2016)

- **Chapter 6: The water footprint of agriculture on the Steenkoppies Aquifer**

The WFs of irrigated and rainfed crops were used, together with crop yield estimates, to determine a WF for the Steenkoppies Aquifer, which represented the agricultural water use in the Maloney's Eye Catchment. The total blue and green water used by agriculture on the Steenkoppies Aquifer was then assessed in terms of the blue and green water sustainability. The catchment scale agricultural water use was used, together with estimates of evapotranspiration (ET) of natural vegetation and urban areas, and measurements of other in- and outflows from the catchment to better understand the water balance of the catchment. The catchment water balance was used to develop a framework that requires relatively little data and that can potentially provide important information to a water resource manager if complex hydrological studies are not available. A journal article based on this chapter's work has been published in the journal *Science of the Total Environment* (Le Roux et al., 2017).

- **Chapter 7: Food wastage**

The WFs of wasted vegetables produced on the Steenkoppies Aquifer was evaluated for each step in the supply chain from the farm to the consumer. The work reported in this chapter was submitted as a manuscript to the journal *Water.*

- **Chapter 8: Fancy lettuce parameterisation**

New crop parameters were developed for two fancy lettuce cultivars, cos and butterhead using the Soil Water Balance (SWB) model. The feasibility of using alternative cultivars to achieve sustainable water use on the aquifer was evaluated.

- **Chapter 9: Discussion**

In this chapter, the information generated by WF methodologies is evaluated in terms of its usefulness and applications. Recommendations are made for other research groups, and for the way forward. Future research opportunities include the improvement of the grey WF methodology, continuous interactions between geohydrological and WF studies for the Steenkoppies Aquifer, development of sustainability targets (Gleeson et al., 2012) for the Steenkoppies Aquifer, application of the catchment WF framework to other study areas for further development and the calculation the WFs of alternative crops that use water more efficiently.

- **Chapter 10: Conclusion**

Final conclusions are drawn on the most appropriate WF methodologies and the way in which it should be used and interpreted and on the potential usefulness of the results on local, regional and national levels. Further conclusions are drawn on the ability of WFs to provide the information needed to prioritise actions and measures that are required to achieve sustainable water use on the Steenkoppies Aquifer, and aquifers in general.

# 2 CHAPTER 2: LITERATURE REVIEW

## 2.1 INTRODUCTION

This chapter reports on a comprehensive literature review on different, promising methodologies that have been proposed to estimate water footprints (WF). The methodologies proposed by the Water Footprint Network (WFN) (Hoekstra et al., 2011), the Life Cycle Assessment (LCA) community (i Canals et al., 2009, Pfister et al., 2009), and the hydrological-based WF community (Deurer et al., 2011) were evaluated in a literature review. Strengths and weaknesses for each are scrutinized in an attempt to inform the most appropriate methodologies based on specific scenarios as well as intended application of the information. This literature review served to inform the WF study that was conducted on vegetable production on the Steenkoppies Aquifer, but it is also envisaged to inform other WF studies conducted in South Africa.

## 2.2 ESTIMATION OF WATER FOOTPRINTS ACCORDING TO DIFFERENT METHODOLOGIES

### 2.2.1 WATER FOOTPRINT NETWORK

#### *2.2.1.1 Concept*

In 2011 the WFN published the first comprehensive WF assessment manual containing prescribed methodology to determine the impact on water resources by individuals, communities, businesses as well as during the production of products (Hoekstra et al., 2011). Hoekstra et al. (2011) was the first to distinguish between blue, green and grey WFs.

#### *2.2.1.2 Calculation*

The WFN proposes four phases, including a WF accounting phase and a sustainability assessment of the WF. During the accounting phase a volume of water consumed per product yield is determined. In an agricultural context the blue and green WFs are equal to blue and green water ET divided by product yield, respectively. Calculating the WF of growing a crop can be done using one of two models, namely the Crop Water Requirement (CWR) option and irrigation schedule option.

- **CWR option**

The CWR option assumes optimal growing conditions with no diseases or shortages of water and fertiliser that limits evapotranspiration (ET). Evapotranspiration requirement of a crop ($ET_c$) is calculated using **Equation 2-1**.

$$ET_c = ET_0 \times K_c$$

**Equation 2-1**

Where $ET_0$ is the ET rate of the reference crop, namely any well-watered actively growing grass with full cover and a uniform height of 8 cm to 15 cm (Allen et al., 1998). $ET_0$ is calculated using the FAO modified Penman-Monteith equation and is only influenced by climatic parameters (Chapagain and Orr, 2009). The crop coefficient, $K_c$, integrates the specific crop characteristics that differentiates its ET rates from that of the reference crop (Hoekstra et al., 2011).

The green WF is calculated as the minimum of $ET_c$ and effective rainfall ($P_{eff}$). The blue WF is equal to the difference between $ET_c$ and $P_{eff}$, if $ET_c > P_{eff}$. The blue WF is zero if $ET_c < P_{eff}$ (Hoekstra et al., 2011).

- **Irrigation schedule option**

The irrigation schedule option is more accurate than the CWR option, because it also accounts for environmental stresses that impact on water use. These stresses are incorporated into the $ET_c$ through a stress coefficient ($K_s$) to determine the actual evapotranspiration ($ET_a$) as follows:

$$ET_a = ET_c \times K_s = ET_0 \times K_c \times K_s$$

**Equation 2-2**

The model requires climate, crop, soil and irrigation data and can be used to estimate green and blue ET ($ET_{green}$ and $ET_{blue}$) under both rainfed and irrigated conditions. In the case of rainfed conditions, the $ET_{blue}$ is zero. $ET_{green}$ is calculated by specifying 'no-irrigation' when running the model. The model then calculates the $ET_a$, which in this case is equal to the $ET_{green}$ (Hoekstra et al., 2011).

According to the WFN manual blue water ET is equal to the minimum of the total net irrigation (irrigation applied) and actual irrigation requirement (crop ET minus effective rainfall) (**Equation 2-3a**). Green water ET is equal to total ET minus $ET_{blue}$ (**Equation 2-5**). Therefore, unless actual irrigation is less than irrigation requirement, $ET_{green}$ is equal to effective rainfall and blue water ET is equal to irrigation requirement. According to the WFN equations, blue plus green water ET is equal to total crop ET. This approach does not reflect over-irrigation, because excessive irrigation is considered to return to the blue water resource as recharge. In order to improve these WFs to also become an indicator of water use efficiency, the equations given by the WFN can be altered by using 'actual irrigation *applied*' instead of 'irrigation *requirement*' (**Equation 2-4 b**). Similar to the original equations from the WFN, this modification still results in a blue plus green water ET that equals total crop ET, but the ratio between blue and green WFs reduces with inefficient irrigation.

$$Blue\ WF\ (WFN) = \frac{min\ (Crop\ ET,\ Irrigation\ \boldsymbol{requirement})}{Yield} \quad \text{[volume/mass]}$$

**Equation 2-3 a:** Blue water footprint according to the Water Footprint Network

$$Blue\ WF\ (indicating\ over-irrigation) = \frac{min\ (Crop\ ET,\ Irrigation\ \boldsymbol{applied})}{Yield} \text{[volume/mass]}$$

**Equation 2-4 b:** Proposed calculation for the blue water footprint, indicating over-irrigation

and

$$Green\ WF = \frac{[Crop\ ET - min\ (Crop\ ET,\ Irrigation\ requirement)]}{Yield} \quad \text{[volume/mass]}$$

**Equation 2-5**

where, *crop ET* is the crop evapotranspiration (mm) and *irrigation* is the total irrigation (mm) from planting to harvesting. Grey water is equal to the volume of freshwater required to dilute emitted pollutants to ambient levels. **Equation 2-6** shows the formula that is used to calculate the grey WF (Hoekstra et al., 2011).

$$Grey\,WF = \frac{L}{C_{max} - C_{nat}} \qquad \text{[volume/mass]}$$

**Equation 2-6**

where $L$ is the load of pollutant released to the water source, $C_{max}$ is the maximum concentration of pollutant at ambient water quality standards and $C_{nat}$ is the natural concentration of the pollutant in the receiving water source. The natural concentration of the pollutant in the receiving water source and the ambient water quality standards differ across different catchments and regions. Therefore the same pollutant load will have different grey WFs depending on the natural background concentration and the chosen water quality standards (Hoekstra et al., 2011). The blue, green and grey volumetric WF is divided by crop yield to give units in volume of water per fresh mass of crop yield (Hoekstra et al., 2011).

- **Sustainability assessment**

According to Hoekstra et al. (2011), water use in a catchment is not sustainable when the Environmental Flow Requirement (*EFR*) or ambient water quality standards are compromised, or when water allocation is inefficient or unfair. Two criteria for judging sustainability are proposed: (1) when a process is situated in a certain catchment at a certain time of year where the overall WF is unsustainable, and (2) when either the blue, green or grey WF can be reduced or avoided altogether at acceptable societal cost. Accordingly, the overall sustainability of the WF of the catchment or basin as a whole needs to be known before a sustainability assessment for a product or process can be assessed. At this level, the authors argue that the available waste assimilation capacity and issues of fair and efficient water resources allocation are best understood.

Hoekstra et al. (2011) also propose that sustainability be assessed from three different perspectives as follows:

- Environmental – River and groundwater flows must be maintained at levels that adequately support the dependent ecosystems and human livelihoods. Pollutant levels must remain below water quality standards (although these standards are not always prescribed).
- Social – A minimum amount of safe and clean water is needed for basic human needs, namely drinking, cooking and washing (United Nations, 2010). The Universal Declaration of Human Rights (United Nations, 1948) established food as a human right, so the water required to produce this food can be linked and considered a right even if not formally established. As communities can import their food from other catchments, allocation of water to food security can be secured at a global level.
- Economic – The allocation and use of water needs to be done in an economically efficient way, and the benefits of use should outweigh the costs, including 'externalities, opportunity costs and a scarcity rent'.

Identifying and quantifying sustainability criteria, followed by the identification of 'hotspots' are the first two steps of a site-specific sustainability assessment. Hotspots are defined as periods of the year for which WFs are regarded as unsustainable for specific (sub) catchments (sustainability assessment is described in the next section). The WFN's WF is placed in a geographic context by comparing the calculated WF with available water resources ($m^3$ $yr^{-1}$) in the same sub-catchment, catchment or basin (termed the hydrological unit). Specific time periods are also considered to account for seasonal variations and to place the WF in a temporal context. Deciding at which scale to look for hotspots appears to be a challenge, hotspots may disappear at coarser resolutions, but much more data is needed to identify hotspots at finer resolutions. For the case of pollution, pollutants may accumulate downstream, in which case problems might only emerge at larger scales.

According to Hoekstra et al. (2011) green water availability ($WA_{green}$) in a catchment $x$ is calculated as the total ET of rainwater from land ($ET_{green}$) minus ET from land reserved for natural vegetation ($ET_{env}$) and minus ET from land that cannot be made productive ($ET_{unprod}$) (e.g. mountainous areas with steep slopes or periods not suitable from crop production) for month $t$ (**Equation 2-7**). The level of green water scarcity ($WS_{green}$), or fraction of green water appropriation, is the ratio of the total green WFs ($\Sigma WF_{green}$) to green water availability ($WA_{green}$) (**Equation 2-8**).

$$WA_{green}[x,t] = ET_{green}[x,t] - ET_{env}[x,t] - ET_{unprod}[x,t] \qquad \text{[volume/time]}$$

**Equation 2-7**

$$WS_{green}[x,t] = \frac{\Sigma WF_{green}[x,t]}{WA_{green}[x,t]} \qquad \text{[volume/time]}$$

**Equation 2-8**

Hoekstra et al. (2011) acknowledge that the issue of quantifying green water scarcity is 'largely unexplored', for example, data on the water use of natural vegetation is often lacking, and therefore recommend that this approach only be used in pilot studies to explore the usefulness of such an approach. Hoekstra et al. (2011) also note that the difference in green water use between crops and natural vegetation may affect blue water availability, but indicated that will generally be small on the basin scale and can therefore be neglected.

The total blue water availability ($WA_{blue}$) for a catchment is defined as the natural runoff in the catchment ($R_{nat}$) minus the *EFR* (quantities and timing of flows required to sustain freshwater and estuarine ecosystems) (Hoekstra et al., 2011):

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

**Equation 2-9**

If the blue WF exceeds $WA_{blue}$, then the EFR has been violated. It is possible that this may only be the case for certain months of the year. Note that natural and not actual runoff is used, because in most cases actual runoff has already been affected by upstream water consumption. As with $WS_{green}$, blue water scarcity ($WS_{\text{blue}}$) is defined as ratio of the total blue WFs ($\Sigma WF_{blue}$) to blue water availability:

$$WS_{blue}[x,t] = \frac{\Sigma WF_{blue}[x,t]}{WA_{blue}[x,t]} \qquad \text{[volume/time]}$$

**Equation 2-10**

It is recommended that $WS_{blue}$ be calculated on a monthly rather than an annual basis to capture seasonal water scarcities. In addition, the impact of the blue WF on 'blue water stocks' (water stored in dams and aquifers), should also be considered. Richter (2010) proposes that 'sustainable boundaries' should be established below which water levels should not drop and above which water levels should not be augmented. These boundaries should be flexible based on changing circumstances and should not just focus on low flows, but must ensure sufficient flood levels in the correct season to mimic the natural variation in flow (Richter, 2010).

From this it is clear that in an irrigated agriculture context, not only crop models, but also larger scale hydrological models (which range from simple to highly complex) are required to estimate blue and green water availability and scarcity. Both crop and large scale hydrological modelling skills, which are often scarce, are therefore required for comprehensive WF sustainability assessments.

Finally, in order to make their WF accounting compatible with LCA studies and to better enable visualization of local impact, Hoekstra et al. (2011) propose the calculation of WF indices. It is calculated using the blue/green WF of a product specified by catchment *x* and month *t*, and blue/green water scarcity by catchment and month. The two matrices are multiplied and the resulting matrix is summed. The grey WF index is based on the grey WF and the level of water pollution, both specified by catchment and month. Hoekstra et al. (2011) caution that these impact indices can add limited value as it is the underlying variables that contain information that can guide mitigation measures.

#### *2.2.1.3 Strengths and weaknesses*

The WFN approach is useful, because it provides guidelines to do a water use inventory assessment. The strong points of the method are the inclusion of:

- Blue, green and grey WFs.
- Environmental flow requirement in the sustainability assessment.
- Temporal and geographic components.

The WFN approach, however, has been criticized for having a number of shortcomings including (Pfister et al., 2011, Ridoutt and Pfister, 2010, Wichelns, 2010, Wichelns, 2011):

- The method does not provide information on opportunity costs of inputs or compare incremental costs and benefits of water uses. This information is required by policy makers.
- Representing water quality impacts in terms of a volume, i.e. grey water, has limitations as discussed in **Section 2.4.3**.
- The summation of blue, green and grey water is problematic, because of differences in their associated impacts and costs (refer to **Section 2.4.4**).
- It does not adequately characterise impacts on local water resources (refer to **Section 2.4.5**).
- The proposed sustainability assessment does not give a clear indication of how information can be obtained to give the volumetric WF a stress weighting.
- Meaningful comparisons with volumetric WFs are not possible, because of the lack of local impact characterisation. Consuming the same volume of water in two different places will have different environmental impacts due to differences in water availability and demand.
- While a monthly $WS_{blue}$ is envisaged to be valuable information from a water resources management perspective, it may not adequately account for the buffer capacity provided by water stored in aquifers or dams (which is replenished in wet periods) during dry periods. This will require WF accounting at a larger temporal scale, for example taking into account dry-wet year cycles of a particular region.

#### *2.2.1.4 Examples of application in agriculture*

Several WF studies have been conducted, which indicated that WFs can be a useful tool to quantify direct and indirect water use with its flexibility being particularly advantageous, as it can be applied to various entities, including products, consumers, businesses and catchments (Ranchod et al., 2015).

- **Water footprints of products**

A number of studies have been conducted on the WFs of various crops. The WFN calculated the WFs for several crops from global databases on a high resolution at a 5 x 5 arc minute grid (Mekonnen and Hoekstra, 2011). In South Africa, WFs were calculated for the cultivation of various crops, including cabbage (*Brassica oleracea*), tomatoes (*Solanum lycopersicum*), spinach (*Spinacia oleracea*), potatoes (*Solanum tuberosum*) and green beans (*Phaseolus vulgaris*) cultivated under different smallholder irrigation schemes (Nyambo and Wakindiki, 2015), for lucerne (*Medicago sativa*) that serves as livestock feed for milk production (Scheepers and Jordaan, 2016), for sugarcane (*Saccharum officinarum*) (van der Laan et al., 2015) and for the biodiesel crop *Jatropha curcas* (Jongschaap et al., 2009). A product WF was calculated for producing beer by SABMiller in South Africa (SABMiller and WWF, 2009). The importance of calculating WFs with local data and interpreting WFs within the local context were noted (Nyambo and Wakindiki, 2015, Scheepers and Jordaan, 2016).

Chapagain and Orr (2009) calculated the virtual WF of tomatoes consumed in Europe, but originating from Spain. Tomatoes in Spain are cultivated in open systems and in plastic covered houses. The virtual water content of tomatoes is defined as crop water use per yield. Crop water use is classified as evaporative water use, i.e. blue and green water use, and non-evaporative water use, i.e. grey water use. Green and blue water use is determined by the evaporation requirement of the specific crop and the availability of soil water, which are both calculated using the CROPWAT model as discussed in **Section 2.2.1.2**.

The study indicated that the evaporative virtual water content of tomatoes grown in open systems is 63.7 $m^3$ $tonne^{-1}$ and in covered systems it is 33.5 $m^3$ $tonne^{-1}$. Non-evaporative water use, i.e. grey WF, resulted in 8 $m^3$ $tonne^{-1}$ and 4 $m^3$ $tonne^{-1}$ for open and closed systems respectively. Tomatoes exported from Spain have a green, blue and grey WF of 13.6 $m^3$ $tonne^{-1}$, 60.5 $m^3$ $tonne^{-1}$ and 7.2 $m^3$ $tonne^{-1}$, respectively. The consumption of Spanish tomatoes in the European Union has a green, blue and grey WF of 13.6 $Mm^3$ $yr^{-1}$, 57.9 $Mm^3$ $yr^{-1}$ and 7.2 $Mm^3$ $yr^{-1}$, respectively (Chapagain and Orr 2009). The study determined volumetric WFs only, but emphasised the need to integrate findings with Ecological Footprint (EF) studies and Life Cycle Assessments (LCA) to characterise water use in the context of local water availability (Chapagain and Orr 2009).

In a study to estimate the impact of food wastage on natural resources, the United Nation's Food and Agriculture Organization (FAO) used the WFN approach, together with assessments of the EF, and land-use and climate change impacts. It was determined that globally 1.3 G tonnes of food are wasted. This is more than 20% of global agricultural production of food and other crops. The consumptive blue WF of food wastage is approximately 250 $km^3$. Combining these four methods was considered useful because together they gave an indication of the extent and significance of the impacts of food wastage, and they made it possible to prioritise management actions and to identify opportunities (FAO, 2013).

- **Water footprint of a nation**

Chapagain and Orr (2008) determined the WF of the United Kingdom through the consumption of agricultural and industrial products and the use of water in households. Both locally and globally sourced products were included in the analysis. In terms of agricultural products, the WF was calculated for 503 crops, including cotton, food and flowers and 141 livestock products sourced both from within the UK and from other parts of the world. Industrial products used in the analysis included chemicals, machinery etc. It was determined that the UK consumes 102 $Gm^3$ per annum, which amounts to an average of 4 645 ℓ per person per day. The WF of agricultural products consumed in the UK is 74.8 $Gm^3$ $yr^{-1}$, which is 73% of the total footprint. Industrial products consumed made up 24%, while household water use was only 3% of the total WF. The study identified sugar cane, tomatoes and cotton as crops of which high volumes are consumed in the UK that are grown in countries with high water scarcity. Water footprints were calculated for South Africa as a whole, where WFs were considered useful to inform policy making and to improve sustainable development (Pahlow et al., 2015).

- **Water footprint in a catchment**

Hoekstra et al. (2012) calculated the blue water scarcity (defined as the ration blue WF: blue water availability) for 405 river basins from 1996 to 2005. The study focused on water consumption instead of water withdrawal and also used monthly water use data instead of annual data, which gave a complete picture of seasonal water scarcity. Only 20% of runoff is considered to be available for use, in order to account for flow requirements of the aquatic systems. Blue WFs were included in this assessment, but green and grey WFs were excluded. Blue water consumption was determined as the difference between water used under rainfed conditions (green WF) and under irrigated conditions.

The study indicated that on average 92% of the global blue WF is caused by agriculture. This is, however, variable between seasons and from one year to the next. It was found that 12 river basins consume more than 40% of available runoff, i.e. causing severe water stress, throughout the year. The Groot-Kei River Basin in the Eastern Cape, South Africa, has severe water scarcity for eleven months of the year. Several river basins, including most of South Africa, suffered severe water scarcity for only a few months in the year, highlighting the importance of analysing WFs on a monthly level (Hoekstra et al 2012).

Other WF studies have also been conducted on a catchment level. Water footprints were calculated for agriculture in the Breede Water Management Area and was considered to assess water used in terms of economic gains and job creation (Pegasys, 2012). This study concluded that WFs provided important information for water allocation decisions, for example that apples produced in Overberg West created more jobs than those produced in the Central Breede per volume of water; apples and tables grapes created more jobs and income than wine grapes per volume of water; and cereals and fodder used water inefficiently.

Water footprints of crops were combined with crop yields on the High Plains Aquifer (HPA) to assess agricultural water use within the aquifer (Multsch et al., 2016). Areas within the HPA that were determined to have high agricultural water uses, when applying this method, correlated well with measured reductions in groundwater levels. This study is further discussed in **Chapter 6**.

- **Water footprint of businesses**

SABMiller, in partnership with the World Wildlife Fund (WWF) and the WFN, did WF assessments of their own operations in South Africa and Czech Republic. Water footprints provide information to a business such as SABMiller on how much water is used where, which enables them to identify operational, reputational and regulatory risks associated with water scarcity. A WF method must enable a business to reduce business risks and environmental impacts by improving management of operations and by informing collaboration with suppliers and government. The WF was calculated for the entire supply chain, starting with primary production and ending with disposal and recycling of bottles. SABMiller provided datasets for all stages of its supply chain and from its suppliers. Data gaps were filled through literature surveys. The WFs were calculated for direct and indirect water uses and excluded the virtual water used to produce machinery and vehicles. It was determined that the blue and green WF of beer produced in South Africa and the Czech Republic was 155 ℓ and 45 ℓ per liter of beer respectively. The difference is attributed to water use during the crop production stage, where South Africa has higher evaporation rates, relies more on irrigation and imported crops etc. Local impacts of crop water use were included by mapping all crops grown with the South African Water

Management Areas (WMAs) and considering the constraints in each WMA. The information from the WFs were used to develop a water risk matrix, which led to the formulation of local action plans to mitigate these risks (SABMiller and WWF, 2009).

The WFN approach assisted The Coca Cola Company to achieve a 20% reduction in its water use from 2004 to 2012 (The Coca Cola Company, 2010). In 2004 The Coca Cola Company used 2.7 ℓ of water to produce 1 liter of product, and in 2009 this was reduced to 2.36 ℓ. The work done by the Coca Cola Company emphasised the high proportion of water used in the primary production stage of their supply chain.

Using the WFN methods, Unilever identified the water use for tomatoes and sugar production as being a priority. Locations were also identified where water use impacts have to be addressed. This enabled Unilever to prioritise actions and develop plans with their suppliers to reduce water use impacts (Unilever, 2012).

### 2.2.2 LCA APPROACH BY PFISTER ET AL. (2009)

#### *2.2.2.1 Concept*

Pfister et al. (2009) suggested a WF method based on the Life Cycle Assessment (LCA) approach. A regional Water Stress Index (WS Index) is calculated to characterise local water use impacts. This method is therefore useful in showing the region-specific effects of water consumption (Ridoutt and Pfister, 2010). The index follows a logistic function from 0.01 to 1, with a withrawal-to availability ratio of 0.4 (often referred to as the threshold between moderate and severe water stress) resulting in a WS Index of 0.5. The results are a stress-weighted index reported as ‘water equivalents’ (H2O-e) which gives an indication of the product or activities’ impact on water resources (Ridoutt and Pfister, 2010).

In this methodology, green water is not considered to have any direct impacts on water availability. It is argued that green water, like soil and solar radiation, is only available through occupation to land, leading therefore to an inseperability between green water and land. While changes in green water use by crops versus natural vegetation may have impacts on blue water resources, most agricultural systems have been noted to intercept less precipitation than natural vegetation (Scanlon et al., 2007). For this reason, this method does not include green water in WF accounting (Ridoutt and Pfister, 2010). There is a recognised need to quantify water quality impacts as part of the WF, but the grey water concept is not considered to be ideal. An alternative method is proposed by Ridoutt and Pfister (2013), which makes use of advanced LCA modelling using eutrophication, freshwater eco-toxicity and human health impacts as impact indicators (Ridoutt and Pfister, 2013).

The International Standards Organization (ISO) published a global WF standard in August 2014 (ISO 14046, 2014). The Standard is closely related to the LCA method proposed by Pfister et al. (2009), it gives broad and flexible guidelines and includes a few important principles. Water footprints, according to the Standard, must consider the full life cycle of a product, must include an environmental impact assessment and must preferably be based on scientific evidences. The Standard also has specifications on how WF are reported, in order to ensure transparency. However, the scope of the ISO standard does not include a way to report the results as product labels. Similar to the LCA methodology of Pfister et al. (2009) it is suggested that results be reported as ‘water equivalents’ (H2O-e) and the Standard also proposes the use of other mid-point indicators firmly established in Life Cycle Assessment methodology, such as estimating eutrophication potential in ‘phosphate-equivalents’ in the case of nitrogen and phosphorus pollution from agriculture.

#### 2.2.2.2 Calculation

A life cycle inventory is generated to determine all products consumed. The volume of water consumed to produce the relevant products is taken from the virtual water database published by Chapagain and Hoekstra (2004). This consumptive water use is further analysed using the WS Index (Pfister et al., 2009).

The WS Index is determined using the WATERGAP 2 global hydrological and global water use models (Alcamo et al., 2003). The WS Index is based on the water withdrawal (*WU*) to water availability (*WA*) ratio (*WTA*). Annual data is used to determine the WTA, but a variation factor (*VF*) is included to reflect the monthly and annual variation of precipitation. Dams reduce the variation in water availability; as a result the variation factor is reduced for regulated catchments (Pfister et al., 2009). **Equation 2-11** to **2-11** shows the calculation of the WS Index.

$$WTA\ in\ regulated\ catchments = \sqrt{VF} \times \frac{WU}{WA}$$

**Equation 2-11**

$$WTA\ in\ non-regulated\ catchments = VF\ \times \frac{WU}{WA}$$

**Equation 2-12**

$$VF = e^{\sqrt{\ln(S_{month})^2 + \ln(S_{year})^2}}$$

**Equation 2-13**

where $S_{month}$ and $S_{year}$ is the standard deviation of monthly and annual precipitation respectively. The VF is weighted by the mean annual precipitation. The WTA is used to calculate the *WS Index* as follows (Pfister et al., 2009):

$$WS\ Index\ = \frac{1}{1 + e^{-6.4\,WTA}(\frac{1}{0.01} - 1)}$$

**Equation 2-14**

The WS Index follows a logistic function. The minimum WS Index value is 0.01, which represents no stress and the maximum WS Index is 1, which represents extreme water stress. Minimal, moderate and severe water stress is linked to the WS Index values based on expert opinions. It describes water stress at the local watershed level at a spatial resolution of 0.5 degrees (Pfister et al., 2009).

#### 2.2.2.3 Strengths and weaknesses

The WS Index approach of Pfister et al. (2009) has the following strengths:

- It compares impacts of activities on a local scale.
- The WS Index reflects the volume of available water in the area where the activity occurs; and
- The method simultaneously determines the potential impacts of water pollution on human health, ecosystem quality and resource depletion. If these endpoint impact categories can be determined correctly it can assist in management decisions.

Weaknesses of this method include:

- Although a VF is included to account for seasonal variation in precipitation, this factor is calculated using the average variation in rainfall and does not reflect times of particular high water scarcity or abundance.
- The WTA ratio requires that water inflows exceed outflows, because stored water cannot be sustainably utilised in the long term. However, this ratio does not take into account the important role of water storage in water attenuation on the short term (Berger and Finkbeiner, 2013).
- Determining endpoint impact categories such as human health, ecosystem quality and resource depletion involves many assumptions and uncertainties (Goedkoop et al., 2013).
- This method does not focus on quantification of water volumes, particularly for green water; hence does not offer information and insights into opportunities for allocation and management of water resources at catchment-scale, particularly in terms of green water.

#### *2.2.2.4 Examples of application in agriculture*

This method was evaluated in case studies on the production of Dolmio ® pasta sauce and M&M® peanuts (Ridoutt and Pfister, 2010) and cotton (Pfister et al., 2009). Ridoutt and Pfister (2010) demonstrated that the WS Index-based approach successfully reflected regional impacts. The assessment resulted in a higher WF in areas with local water scarcity, despite low volumes of water consumption. The case study on cotton concluded that WF assessments should be done on a watershed level, because country level analyses do not reflect local variations (Pfister et al., 2009).

Allocation methods are required to identify the footprint of a product that is produced in a process where several other products are also produced. Each product should be allocated a portion of the impact that comes from the entire process. This allocation can, for instance, be done based on mass or economic value of each product. Luo et al. (2009) compared different allocation methods with each other in a case study on maize stover-based fuel ethanol. Impacts on ozone layer depletion, climate change and eutrophication potential were considered among others. The study indicated that there were significant differences between the allocation methods used, and this type of method in LCA should still be refined. This issue will likely be relevant to WF studies and should receive attention in further research (Luo et al., 2009).

### 2.2.3 LCA ADAPTED APPROACH PROPOSED BY I CANALS ET AL. (2009)

#### *2.2.3.1 Concept*

A WF methodology adapted for use in LCA that differentiates between two main impact pathways, namely, Freshwater Ecosystem Impacts (FEI) and Freshwater Depletion (FD) was proposed by i Canals et al. (2009).

This method also distinguishes between blue and green water resources. The use of green water by crops is considered to have the same impact as green water used by natural vegetation. Green water is therefore only important, because it is used to determine the portion of blue water used. Blue water resources are further classified as flow (such as rivers and rain), fund (such as groundwater) and stock (such as fossil water). Water uses are classified as evaporative and non-evaporative. Evaporative uses cause water to be temporarily unavailable to other users. Non-evaporative water use occurs when water is returned to the basin where it originates from and becomes available to other users (i Canals et al., 2009).

An important feature of this method is the inclusion of land-use impacts on the availability of water. Transformed landscapes can result in a reduction in infiltration and an increase in runoff. For transformed land-uses where infiltration rates are reduced, the volume and velocity of runoff is increased. Such fast moving volumes of runoff is unlikely to replenish aquifers, may cause flooding and impact on aquatic ecosystems. Land-use impacts that result in increased runoff will therefore have an increased WF. The contribution of land-use to the WF is calculated by the difference between the water loss of the specific land-use and the water loss of a typical forest, which is the reference land-use (i Canals et al., 2009).

#### 2.2.3.2 Calculation

A Water Stress Indicator (WSI) for FEI is calculated using the following formula:

$$WSI = \frac{WU}{(WR - EFR)}$$

**Equation 2-15**

Where *WU* is water use, *WR* is available water resources and *EFR* is environmental flow requirement. Estimates of water loss for different land-uses were presented by i Canals et al. (2009). This volume is added to the volume of blue water consumption before multiplying the total with the WSI as the characterisation factor.

Freshwater depletion is calculated using an Abiotic Depletion Potential (ADP) formula (i Canals et al. 2009):

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

**Equation 2-16**

where: $i$ is relevant water resource, $sb$ is antimony (serves as the reference resource), $ER_i$ is the extraction rate of resource i, $RR_i$ is the regeneration rate of resource i, $R_i$ is the ultimate reserve of resource $i$, $R_{sb}$ is the ultimate reserve of antimony and $DR_{sb}$ is the deaccumulation rate of antimony.

#### 2.2.3.3 Strengths and weaknesses

This method makes a contribution to WF assessments by:

- Accounting for changes in ET and runoff due to land-use changes, which makes it useful in transformed landscapes and.
- Including ecosystem water requirements.

However, the method excludes water required by the social and economic system and it has been criticised for:

- Providing complex results that are difficult to understand. Normalisation with the rate of depletion of antimony, for instance, doesn't give an indication of the sustainable use of water (Clothier et al., 2012).
- The regional average data that is used does not reflect water use efficiency on a specific farm (Clothier et al., 2012, Jeswani and Azapagic, 2011).
- Annual data conceals seasonal water scarcity (Jeswani and Azapagic, 2011).

- The WSI implies that water impacts will increase linearly with water use, which is improbable (Jeswani and Azapagic, 2011).

#### *2.2.3.4 Examples of application in agriculture*

This method was tested on broccoli production in Spain and the UK (i Canals et al., 2010). The results indicated the following:

- The WF reflected local impacts on water resources. The calculated WF was higher for Spain, which is a water scarce country where irrigation is required. The footprint in the UK was low, because the country has abundant water and produces broccoli under rainfed conditions.
- The method proved to be useful in incorporating ecological sensitivities in the WF. This provided management priorities to save water in areas and production steps that will have most benefit to aquatic ecosystems.
- Like most other WF methods the WF is based on ET, which has the potential to underestimate the WF of a farm where water is wasted and lost through leakages (i Canals et al., 2010). These leakages are, however, often considered to be recharge if it returns to the blue water source.

### 2.2.4 HYDROLOGICAL BASED WATER FOOTPRINT APPROACH

#### *2.2.4.1 Concept*

Deurer et al. (2011) introduced a WF method based on hydrology, considering all components of the water balance and not just water consumption. According to this method a negative WF is possible if the recharge of the blue water resource through return flows and precipitation exceeds the volumes abstracted. A negative WF is therefore required to sustain ecosystems that are dependent on groundwater. A positive WF indicates water abstraction exceeds recharge through return flows and precipitation (Deurer et al., 2011). A zero WF is possible if return flows and precipitation is equal to abstraction volumes. Data used to calculate WFs is obtained on a local scale and over an annual water cycle (Herath et al., 2013). Formulae are provided to calculate blue and green WFs. Grey WFs are calculated in the same way as proposed by Hoekstra et al. (2011).

#### *2.2.4.2 Calculation*

This approach uses a hydrological water-balance method, considering inflows, outflows and storage changes (Deurer et al., 2011, Herath et al., 2013). The calculation of the blue WF is based on the following equation:

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

**Equation 2-17**

where $D^r$ is drainage under rainfed conditions, $D^{ir}$ is the difference between drainage under rainfed and irrigated conditions, $R^r$ is runoff under rainfed conditions and $R^{ir}$ is the difference between runoff under rainfed and irrigated conditions. Drainage and runoff collectively forms the inflow into the blue water resource. *IR* is the amount of water abstracted from the blue water resource for irrigation and represents the outflow from the blue water resource.

The calculation of the green WF is based on the **Equation 2-18**.

$$\Delta \, Green \, water = \; D^r + ET^r + R^r - RF$$

**Equation 2-18**

where $ET^r$ is the ET under rainfed conditions and $RF$ is the effective rainfall, i.e. excluding any water that is intercepted by the plant canopies. Collectively $D^r$, $ET^r$ and $R^r$ form the outflows from the green water resource and RF is the inflow into the green water resource.

#### *2.2.4.3 Strengths and weaknesses*

This method has advantages because:

- It is the only method that considers all aspects of the hydrological system, including climatic conditions, topography and soil characteristics, which is useful to regulators that allocate water for irrigation (Herath et al., 2013).
- Important local scale information is generated.

However, the method has some shortcomings including:

- Over-irrigation does not increase the WF, because it is considered to contribute to water inflows through drainage and runoff, therefore the results will underestimate the WF of a farm that loses water through leakages etc.
- The sustainability indicator does not consider water requirements in the ecological, social and economic systems.
- This method conceals seasonal water scarcity, because it calculates water use and availability over an annual hydrological cycle, although this could be a strength in areas where groundwater storage buffers the seasonal (monthly) water scarcity
- It assesses hydrologic impacts of water use based on inflows and outflows, but does not provide quantitative information to help with water allocation decisions.
- It does not consider the environmental flow requirements in assessing the hydrological impacts.

#### *2.2.4.4 Examples of application in agriculture*

This approach was used to calculate the WF of the production of kiwifruit (Deurer et al., 2011), export apples (Clothier et al., 2012), potatoes (Herath et al., 2013) and wine (Herath et al., 2013) in New Zealand. In all these studies a green WF was determined to be zero, because soil water is replenished during the rainy season. This approach gave negative blue WFs for the primary production of kiwifruit, export apples, potatoes and grapes because groundwater inputs from return flows and precipitation is higher than the volumes abstracted.

The study on potato production done by Herath et al. (2013) provided useful information that contributed to the reduction of the grey WF. During the first 60 days after planting, the seedlings required very little fertiliser. The results indicated that fertiliser application during the first 60 days after planting results in increased $NO_3$-N leaching. The grey WF could therefore be reduced significantly if fertiliser is applied at 55 days after planting without compromising yield. The study claims that these findings are a result of the WF method they propose, but it is more likely a result of developing good agronomic practices.

The hydrological WF assessment on wine production done by Herath et al. (2013) indicated that primary production of grapes had a significantly higher WF than all other activities associated with the winery. Grey WFs were higher for Gisborne than for Marlborough, which, according to Herath et al. (2013), could be explained by the possibility that higher rainfall in Gisborne increases $NO_3$ leaching.

Gleeson et al. (2012) used a method based on the hydrological concept and defined the groundwater footprint as the surface area required to sustain water users and the environment. This tool provides a way to evaluate water use and renewal rates as well as ecosystem requirements at the aquifer scale. It also provides information to assess potential increases in agricultural yields, by comparing the spatial distribution of areas with low groundwater stress with areas that present opportunities for agricultural expansion. Global groundwater footprints were determined by comparing water flows into and out of aquifers. The assessment indicated that global water users require 3.5 times the surface area of current aquifers. It also indicated that only 20% of aquifers are overexploited, therefore the global WF is concentrated in a few countries.

Wu et al. (2012) improved the calculation of the grey WF of Hoekstra et al. (2011) by using the hydrological SWAT model to determine the fate of nitrates after application. This case study also identified the need for field verification of data used in WF assessments.

## 2.3 A REVIEW OF PUBLISHED COMPARISONS BETWEEN DIFFERENT METHODS

### 2.3.1 LCA APPROACH VERSUS WFN APPROACH

For the estimation of WFs of Dolmio ® pasta sauce and M&M® peanuts, Ridoutt and Pfister (2010) utilised the WS Index approach proposed by Pfister et al. (2009), accounting for blue water with the primary objective being 'the avoidance of water scarcity'. Grey WF were calculated according to the WFN approach, because the LCA methodology for the WF of pollution (Ridoutt and Pfister, 2013) had not been developed at the time. For the agricultural ingredients used in the products, a WS Index of 0.011 was used for the Clarence River Catchment of New South Wales, Australia, while a WS Index of 0.996 was used for the San Joaquin Valley of California, USA. The authors observed that the grey WF contributed 30 and 62% of the total WF for the pasta sauce and peanuts, respectively. From the figures presented in **Table 2-1**, the authors concluded that simply judging a product's water impact from a volumetric WF can fail to direct attention to the ingredient of greatest concern. Ridoutt and Pfister (2010) observed that the agricultural stage of production contributed up to 97% of the total footprint for the two products.

**Table 2-1: Major agricultural ingredients contributing to the volumetric and stress-weighted water footprints (including grey water) of Dolmio ® pasta sauce and M&M® peanuts (Ridoutt and Pfister, 2010)**

| Ingredient | Volumetic water footprint (ℓ) | Stress-weighted water footprint (ℓ) |
|---|---|---|
| **Dolmio ® pasta sauce** | | |
| **Tomato products** | 149.9 | 133.9 |
| **Sugar** | 22.9 | <0.1 |
| **Onion** | 12 | 1.8 |
| **Garlic** | 5.9 | 0.1 |
| **Minor ingredients** | 3.3 | 1.9 |
| **M&M® peanuts** | | |

| | | |
|---|---|---|
| **Cocoa derivatives** | 690.1 | 4.1 |
| **Peanuts** | 140.2 | 1.1 |
| **Sugar** | 135.1 | 0.9 |
| **Milk derivatives** | 133.6 | 5.3 |
| **Palm oil derivatives** | 27.3 | <0.1 |
| **Minor ingredients** | 17.8 | 0.2 |
| **Tapioca starch** | 7.9 | 0.5 |

The WFN has since proposed including a sustainablility assessment step which can include weighting of the WF according to water availability/scarcity in the catchment being considered, although no specific method is prescribed. This weighting will allow similar conclusions to be drawn using the WFN method as was established in the Ridoutt and Pfister (2010) study. What remains to be debated is the inclusion of the green WF, and this is addressed further in the Discussion (**Section 2.5**).

Jeswani and Azapagic (2011) compared WF methods in a case study of maize-derived ethanol. Water footprint methods compared in the study included the WFN approach, the LCA approach by i Canals et al. (2009) and the LCA approach by Pfister et al. (2009). The study revealed significant differences between the results of the various WF methods that were compared, and revealed the importance for standardized methodology (Jeswani and Azapagic, 2011).

Several problems with these methods were identified, namely:

- Data on a national and river basin level (i.e. catchments of large rivers), as used by i Canals et al. (2009), does not always reflect the observed spatial variation within a county or smaller catchments. Data on this level is therefore inappropriate to fully describe the impacts of water users.
- Water footprints are highly dependent on climatic conditions and seasonal variations, especially with regard to rainfall. Annual average data, as used by i Canals et al. (2009), also does not capture temporal variation of water availability and stress within a year and is not considered suitable to reflect the impacts of water use. Average seasonal variations, as used by Pfister et al. (2009), still does not reflect specific seasonal variations.
- For each of the methods, availability of data to conduct site-specific assessments was simply lacking. Lack of measurement of groundwater usage and discharge volumes was a major issue.

### 2.3.2 HYDROLOGICAL APPROACH VERSUS THE WFN METHODOLOGY

Studies have been conducted in New Zealand to compare the outcomes of the hydrological WF approach with the WFN approach in terms of blue and green WFs. These studies did not compare grey WFs, as the hydrological based approach employs the same method to calculate the grey WF as the WFN. Estimating the WF for kiwifruit production, Deurer et al. (2011) observed a negligible net change in soil water, concluding that it is replensihed by rain each year, and concluded that the green WF can be discarded in similar studies. The authors further found that a net depletion of groundwater only occurred in two kiwifruit growing regions, with the rest resulting in a negative blue WF. On a regional average, the blue WF of a tray of kiwifruit was -500 ℓ when calculated according to the hydroloically based approach, compared to 100 ℓ based on the WFN approach. The authors claim that their approach is more ‘hydrologically rational’ than the WFN approach, as it does not just focus on only water consumption. Similar conclusions were reached following WF studies for apples and for wine production (Clothier et al., 2012, Herath et al., 2013). It is unclear whether this approach can be applied to all hydrologic systems, such as catchments with surface water flows where excessive water applied forms runoff that will not be avaialable to the same catchment, or where exessive water applied causes erosion or become polluted. It is also unclear how virtual water flows can be calculated from WFs estimated according to the hydrologically based method.

## 2.4 WATER FOOTPRINTS: POTENTIAL SHORTCOMINGS AND KEY CHALLENGES

### 2.4.1 DEFINING THE AIM OF WATER FOOTPRINT ASSESSMENTS

According to Launiainen et al. (2014) the different WF methods address different questions related to water use. Water footprint assessments can measure the volumes of water utilised by humans, indicate the sustainability of water uses or it can provide a tool to manage and increase efficiency of water uses. The specific aim would determine which approaches and datasets are required (Launiainen et al., 2014).

### 2.4.2 CRITIQUE ON THE INCLUSION OF GREEN WATER IN WATER FOOTPRINT ANALYSES

According to Hoekstra et al. (2011), green water must be included in the calculation of WFs because green water is a scarce resource and its availability can reduce the volumes of blue water required. In opposition to this view, several authors suggest that green water impacts are often zero, because green water stores are replenished during the following rainy season (Clothier et al., 2012, Deurer et al., 2011, Herath et al., 2013). However, considering impacts on green water sources over an annual cycle must be challenged, because it does not reflect seasonal variation, which could be very significant.

Ridoutt and Pfister (2010) argue that green water use is not considered an impact, because of the inseparability of green water and land occupation. However, if less green water is used by a specific land use it may lead to increased blue water in rivers and aquifers as a result of higher levels of runoff or drainage.

According to Wichelns (2011), the distinction between blue and green water does not capture the hydrological complexity of water moving from soil to groundwater or surface water bodies and vice versa, i.e. continuous changes between green and blue water. Rainfall can either infiltrate to become soil water or it can become runoff. However, only green water is considered to originate from rainfall. Wichelns (2011) argues that established terms such as rainfall, soil water, groundwater and surface water is a better classification of water than blue and green water. However, although established water management practices are already better developed, the WF concept can add value by conveying information to the general public in a way that is easy to understand.

### 2.4.3 CRITIQUE ON THE GREY WATER CONCEPT IN WATER FOOTPRINT ANALYSES

Ridoutt and Pfister (2013) criticize the concept of grey water proposed by Hoekstra et al. (2011) concepts for the following reasons:

- The LCA provides other innovative methods to measure such impacts.
- There are compounds in polluted water that does not have specified standards.
- It does not reflect resident times of pollutants.
- The term ‘grey water’ creates confusion, because it is also used to describe waste water from households, and.

- It creates the impression that polluted water must actually be diluted to manage its impact.

Wichelns (2011) pointed out that the impacts of substances that bio-accumulate (e.g. selenium) cannot be prevented by dilution and the grey WF would theoretically be infinite. He also argues that the grey WF does not address the complexity of water quality management. Water quality management normally deals with the effects of different pollutants, interactions between the pollutants or the effect of the physical characteristics of the farms and the application methods on the fate of pollutants (Wichelns, 2011).

Nitrogen (N) and phosphorus (P) pollution from agriculture has received much attention because of the well-known role these nutrients play in eutrophication of surface water resources (Conley et al., 2009, Nagar et al., 1974, Schindler and Fee, 1974, Schindler, 2006). While eutrophication might not become a problem if either N or P are limiting, it is important to minimise the amount of both N and P entering our surface and groundwater resources. In an aquatic ecosystem where only P levels are controlled, excess N can still result in eutrophication of water resources further downstream including estuaries and coastal marine ecosystems (Conley et al., 2009). Both N and P should therefore be taken into account when calculating grey WFs. Nitrogen is of additional concern, because of the health risks it poses to infants younger than six months (blue baby syndrome) (Walton, 1951). Inorganic N is usually more mobile than P in soil, because P is adsorbed to clay particles (Conley et al., 2009, Sims et al., 1998, Smolders et al., 2010). Nitrogen pollution can also indirectly mobilise P by oxidising geological pyrite deposits and increasing sulphate levels, which react with iron compounds, causing adsorbed P to be released and mobilised, potentially causing eutrophication (Smolders et al., 2010) Gleeson et al. (2012) also highlighted the need to set groundwater sustainability targets that meet drinking water standards, and this highlights the importance of including N in grey WFs for groundwater.

The differences in water quality standards from one country to the next as well as different natural background concentrations of pollutants causes the grey WF of a certain mass of pollutant released into the environment to be different from one location to the next. This adds further complexity to the grey water concept. Nonetheless, the grey WF concept is giving the impact of human activities on water quality the necessary attention. While the method may not be suitable for pollutants where load is more important than concentration, or for pollutants where there is no prescribed standard, in agriculture, which makes up over 90% of the world’s footprint, eutrophication which results from nitrogen (N) and phosphorus (P) export from agricultural systems is extremely important. As eutrophication is related to the concentration of N and P in the water, the grey WF does add value.

### 2.4.4 REPORTING A WATER FOOTPRINT AS AN AGGREGATED NUMBER

Reporting WFs of blue, green and grey water as a single value is justified by previous studies on climate change (Weidema et al., 2008). A single score is easy to understand and therefore useful for raising public awareness and motivate behavioural changes. However, according to Ridoutt and Pfister (2010), blue, green and grey water differ with regards to the implications of impacts on the water source and also with regards to the opportunity cost associated with the management of these impacts. Interpretation of WFs reported as one aggregated number is not possible.

### 2.4.5 LOCAL NATURE OF WATER

The WF of an activity differs from carbon footprints, where an activity that releases $CO_2$ will have an equal effect on the global atmosphere irrespective of where the activity takes place. The WF of an activity, on the other hand, will differ from one region to another (Ridoutt and Pfister, 2010). For example, using one liter of water in the Nama Karoo might have a much greater impact on the environment than using one liter of water in the Eastern Cape. This local nature of water resources complicates the assessment of WFs, because site-specific data is often not available (Alcamo et al., 2003, Hoekstra et al., 2011, Jeswani and Azapagic, 2011, Launiainen et al., 2014, Pfister et al., 2009).

Hoekstra et al. (2011) considers water to be a global resource based on the concept of virtual water trade. They argue that countries with abundant water can produce and export products to relieve the pressure on water scarce countries. Poor water resource management and inefficient use will therefore have a similar impact on global water resources, regardless of local conditions. Therefore, according to this approach, the WF is only determined by the volume of water consumed. This has been criticised by subsequent literature (Deurer et al., 2011, Ridoutt and Pfister, 2010, Wichelns, 2011), because water use in one area will have different impacts on water resources depending on local environmental and hydrological conditions. The concept of virtual water trade as a means to relieve the pressure of water scarcity in a country is criticized by Wichelns (2011), because international trade depends on many factors, such as comparative advantage and economic and strategic factors, and is not driven by the availability or scarcity of water.

### 2.4.6 SUSTAINABILITY ASSESSMENT

Water footprint assessments should ultimately indicate the sustainability of a water use. This sustainability is influenced by water availability and demand, which is complex to determine. A number of methods have been proposed to determine water use sustainability. Most methods determine sustainability indicators based on withdrawal-to-availability or consumption-to-availability ratios. These ratios understandably do not quantify water stocks in aquifers and dams, because the use of these resources will result in depletion over the long term. However, these ratios do not take into account the important buffering function of stored water in aquifers and reservoirs (Berger and Finkbeiner, 2013).

## 2.5 DISCUSSION AND RECOMMENDATIONS

### 2.5.1 SUMMARY OF KEY FEATURES OF THE WATER FOOTPRINT METHODS

**Table 2-2** summarises the four WF methods in terms of their respective classification of water, spatiotemporal scales, sustainability indicators, strengths, weaknesses and usefulness in agriculture.

**Table 2-2: Summary of the approaches and usefulness of the four Water Footprint Methods**

| Water Footprint Method | Water Classification | Spatio-temporal Scale | Sustainability indicator | Strengths | Weaknesses | Application Potential (Usefulness) |
|---|---|---|---|---|---|---|
| **WFN** | Blue, green, grey | Geographical and temporal components are included and used to identify ‘hotspots’, which are defined as periods of the year for which WFs are regarded as unsustainable for specific catchments. | Unsustainable blue and green WFs = water used > availability.<br>Available green water = Total ET minus ET of natural ecosystems and unproductive land.<br>Blue water availability = runoff minus ecological flow requirements.<br>The grey WF is unsustainable if ambient water quality standards are exceeded. | Accounts for impacts on water quantity and quality.<br>Temporal and geographic components are included.<br>Ecological flow requirements are included in the sustainability assessment. | Results do not provide information on opportunity costs or compare incremental costs and benefits of water uses, which is required to inform policy.<br>Issues with the concepts of grey water and reporting water quality and quantity impacts as an aggregated number.<br>Water uses considered to have a global impact, which underestimate local impacts.<br>The sustainability assessment does not give a clear indication of where information can be obtained.<br>Volumetric WFs cannot be compared, because of the local nature of water use impacts.<br>Blue water scarcity determined on a monthly scale does not give an indication of the buffering | It provides a simple guideline to determine WFs.<br>Also useful to monitor virtual water flows. |

| Water Footprint Method | Water Classification | Spatio-temporal Scale | Sustainability indicator | Strengths | Weaknesses | Application Potential (Usefulness) |
|---|---|---|---|---|---|---|
| | | | | | capacity of storage structure over the long term. | |
| **LCA approach (Pfister et al., 2009)** | Blue | Spatial: Watershed, i.e. catchment of a smaller stream.<br>Temporal: Annual rainfall with consideration of average monthly variation. | Midpoint indicator: Water Stress Index based on withdrawal to availability ratio.<br>Endpoint indicators: Impact of blue water use on human health, ecosystem quality and resource availability. | Watershed scale provides information on local variation.<br>Water Stress Index reflects water availability / scarcity.<br>Includes estimations of endpoint indicators.<br>Easier to understand as only blue water is considered. | Average variation in monthly rainfall conceals specific variations (Jeswani and Azapagic, 2011).<br>Withdrawal to availability ratios do not consider the important role of stored water.<br>Calculation of endpoint indicators involves uncertainties. | Useful tool to determine local impacts of water use.<br>Useful management tool, because it considers impacts on human health (**social impact**), ecosystem quality (**ecosystem impact**) and resource availability (**economic impact**). |
| **LCA approach: (i Canals et al., 2009)** | Blue and Green<br>Blue: Fund, stock and flow<br>Water use classification: Evaporative and non-evaporative | Spatial: River basin level, i.e. catchment of large rivers.<br>Temporal: Annual | Indicator of freshwater depletion: abiotic depletion potential formula.<br>Indicator of freshwater ecosystem impact: Water Stress Indicator based on | Considers loss of water due to land-use changes.<br>Incorporates ecological water requirements. | Results are difficult to interpret (Clothier et al., 2012).<br>River basin scale conceals local impacts (Jeswani and Azapagic, 2011).<br>Annual data conceals seasonal water scarcity (Jeswani and Azapagic, 2011).<br>WS Indicator implies linear increase in water impact with | Useful in transformed landscapes.<br>Useful to determine regional impacts of water use. |

| Water Footprint Method | Water Classification | Spatio-temporal Scale | Sustainability indicator | Strengths | Weaknesses | Application Potential (Usefulness) |
|---|---|---|---|---|---|---|
| | | | withdrawal to availability.<br>Available water excludes volumes required by ecosystems. | | water use (Jeswani and Azapagic, 2011). | |
| **Hydrological-based method** | Blue, green (generally considered to be zero), grey | Spatial: Local<br>Temporal: Annual averages | Extraction exceeds recharge. | Considers all aspects of the hydrological cycle.<br>Valuable local scale information generated. | Results will underestimate the WF of a farm that irrigates inefficiently, if excessive water is considered to be return flow, which is seen as an input in the blue water resource.<br>Ecological, social and economic water demands are not included.<br>Seasonal water scarcities are concealed. | Useful to determine water availability vs. demand on a local scale. |

### 2.5.2 FUNDAMENTAL VIEWPOINT

A fundamental viewpoint must be defined to give an indication of what is expected from a WF calculation method. Each WF method can be evaluated according to this viewpoint. This study is based on the fundamental viewpoint that WF assessments must primarily promote sustainable water use (**Figure 2-1: A**). Sustainable water use is determined by several variables (**Figure 2-1: B**), including:

- Variables in the hydrological system, i.e. the system that determines water availability:
    - Climatic conditions such as rainfall and evaporation rates
    - Soil types
    - Topography
    - Landscape characteristics and land-use
- Variables that define the environment, i.e. the system that determine water demands:
    - Ecological system
    - Social system
    - Economic system (including agriculture)
- Variables related to water use:
    - Water use management and allocations
    - Efficient and productive use of water by consumers

The hydrological cycle and the environment are complex systems, which are difficult to manipulate, but variables related to water use, such as sustainable water use management and allocation and water use efficiency and productivity, can be enforced through policies or achieved through increasing public and commercial enterprises awareness (**Figure 2-1: C**). In order to manage water use and increase the efficiency of water use, the volumes of water consumed and degraded must be measured and characterised according to local water resource availability and sensitivity (**Figure 2-1 E & F**). Impact characterisation should be informed by both the hydrological system that influences water availability, as well as the environmental setting where water is required. Current and future water demands and management practices should also be considered as part of the environmental assessment, which has been neglected by the WF methodologies assessed (**Figure 2-1: B**).

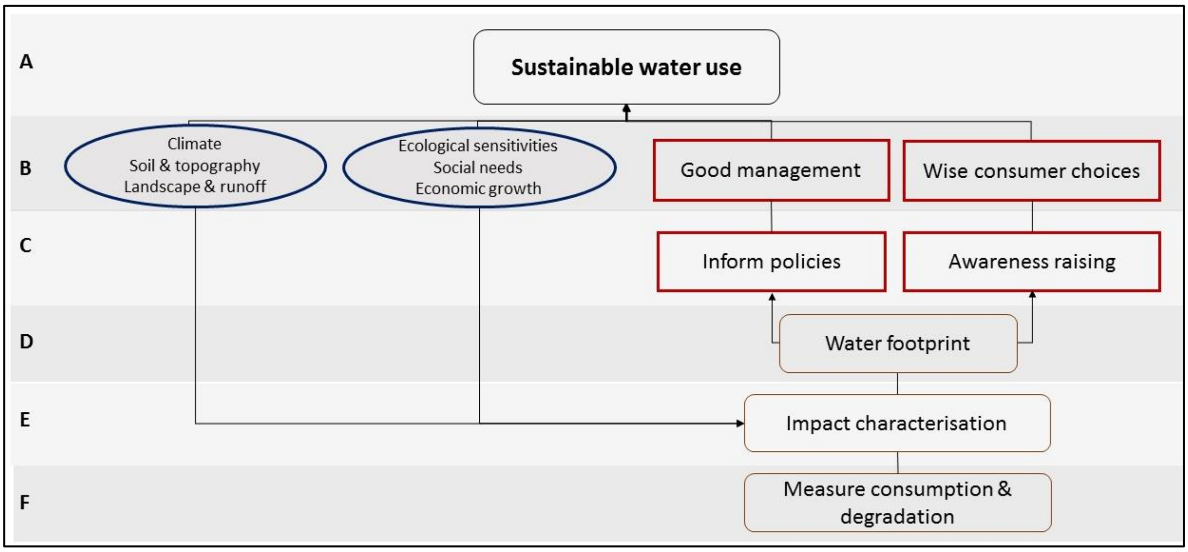

**Figure 2-1: Schematic representation of the role of water footprint assessments towards the goal of sustainable water use. Brown circular boxes are variables that impact on sustainable water use, but these are complex systems that are more difficult to manage and to change. Red square boxes indicate variables that impact sustainable water use and how these impacts can be managed through water footprint assessments.**

### 2.5.3 ASSESSMENT OF WATER FOOTPRINT METHODS

The fundamental viewpoints of the four WF methods were compared with the fundamental viewpoint defined for this review. It must be noted that the similarities identified here are only a reflection of the aspects that are considered by the various methods and not an indication of how successfully these aspects are measured.

The WFN proposed a useful way to measure water consumption and pollution. The method differs from the fundamental viewpoint in that the WF is calculated before the sustainability assessment, and is therefore not a sustainability indicator in itself (note the inverse in Levels D and E for **Figure 2-2**). Ecological impacts are accounted for by considering water quality impacts through grey WFs and impacts due to consumption by including ecological flow requirements. The method mentions the need to reserve flow for basic human and economic needs, but has not yet been developed to quantify these needs. Soil type is captured by the green WF, i.e. more green water will be available for soils with a higher water holding capacity. If all relevant information, such as landscape and land use effects on runoff is included in the calculation of water availability, all aspects of the hydrological cycle will be included. The method proposes the concept of virtual water, which can inform policies by providing a simple universal way to estimate consumptive use per yield of product, and in later chapters it is illustrated how the method can assist catchment management practices. The WF according to the WFN quantifies the volume of water used and it is therefore relatively easy to inform water allocation. The WFN has managed to raise awareness of water use impacts as a result of water consumed to make and distribute products. Whether the WFs that are communicated to consumers will enable them to make wise decisions that will lead to sustainable water use is uncertain, especially if they are used outside the local context or without the sustainability assessment (**Figure 2-2**).

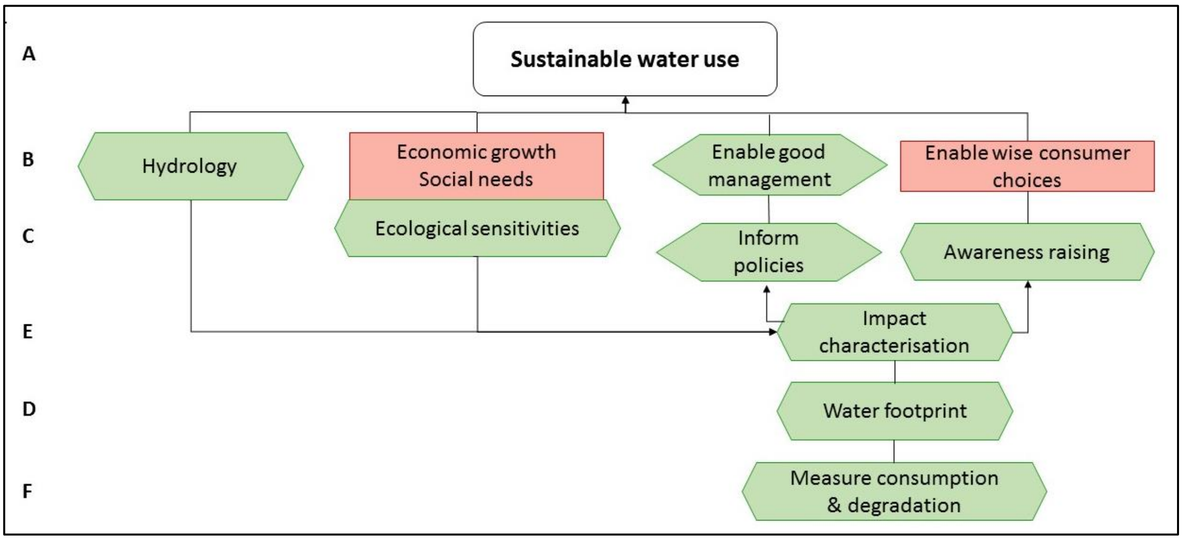

**Figure 2-2: Similarities between the fundamental viewpoint of the WFN and the fundamental viewpoint proposed in Figure 2-1. Hexagon shapes (green) indicate similarities in the viewpoints and square shapes (red) indicate aspects lacking in the WFN approach.**

The LCA approach presented by Pfister et al. (2009) provides a stress weighted method to characterise the impacts of volumetric blue water consumption. A sustainability indicator, namely the WS Index, is based on the withdrawal to availability ratio. Water availability is determined using monthly and annual rainfall data. Landscape characteristics are considered in terms of stream flow regulation in the particular catchment. Green water is excluded, because it can only be accessed through occupation of land. Therefore, the effects of soil types and topography are not addressed. This indicator is used to determine impacts on human health (social need), ecosystem quality (ecological sensitivity) and resource depletion (economic requirements). However, ecological, social and economic systems are extremely complex and measurements of these endpoint indicators are mostly calculated with many uncertainties (Goedkoop et al., 2013). The methods will require testing and continual improvement. The WS index generated by this method can theoretically be used on product labels for awareness raising or to inform policies, but it cannot really contain all the information needed by consumers and policy makers to make wise decisions that will lead to sustainable water use with all the complexities this involves (**Figure 2-3**).

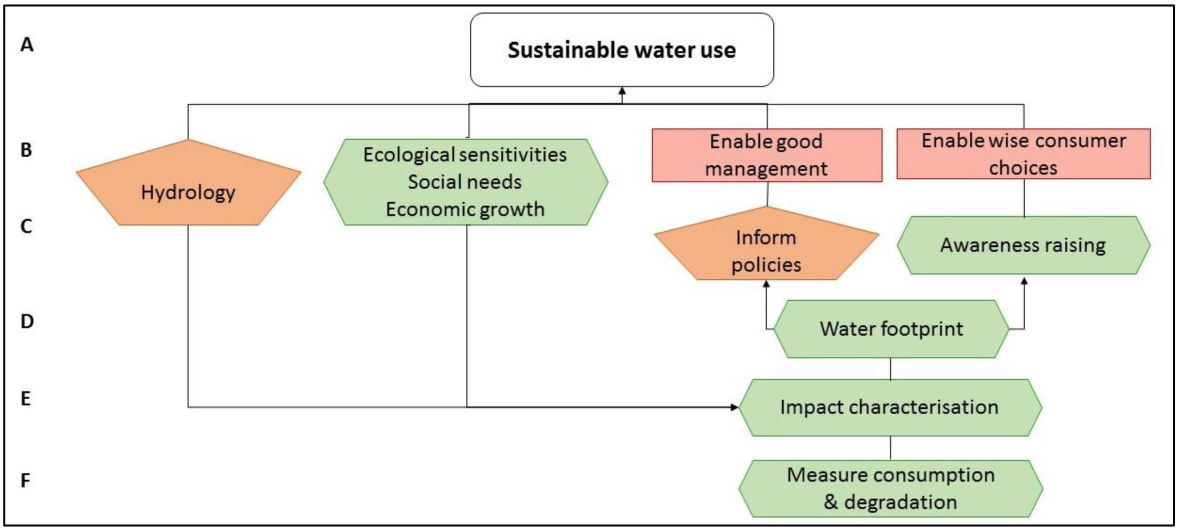

**Figure 2-3: Similarities between the fundamental viewpoint of the LCA approach by Pfister et al. (2009) and the fundamental viewpoint proposed in Figure 2-1. Hexagon shapes (green) indicate similarities in the viewpoints, square shapes (red) indicate aspects lacking, pentagon shapes (orange) indicate aspects partly included in the LCA approach by Pfister et al. (2009).**

The LCA based approach proposed by i Canals et al. (2009) determines blue and green WFs. Water availability due to soil types and topography are reflected by the green WF. Water availability and the ecological water requirements are used to characterise water use impacts. Landscape characteristics are considered by calculating water losses due to various land-uses. This approach excludes social and economic requirements from the sustainability indicator. Despite the potential of this method, it is complex to use and interpret, which may limit its impact and potential use for awareness raising (**Figure 2-4**).

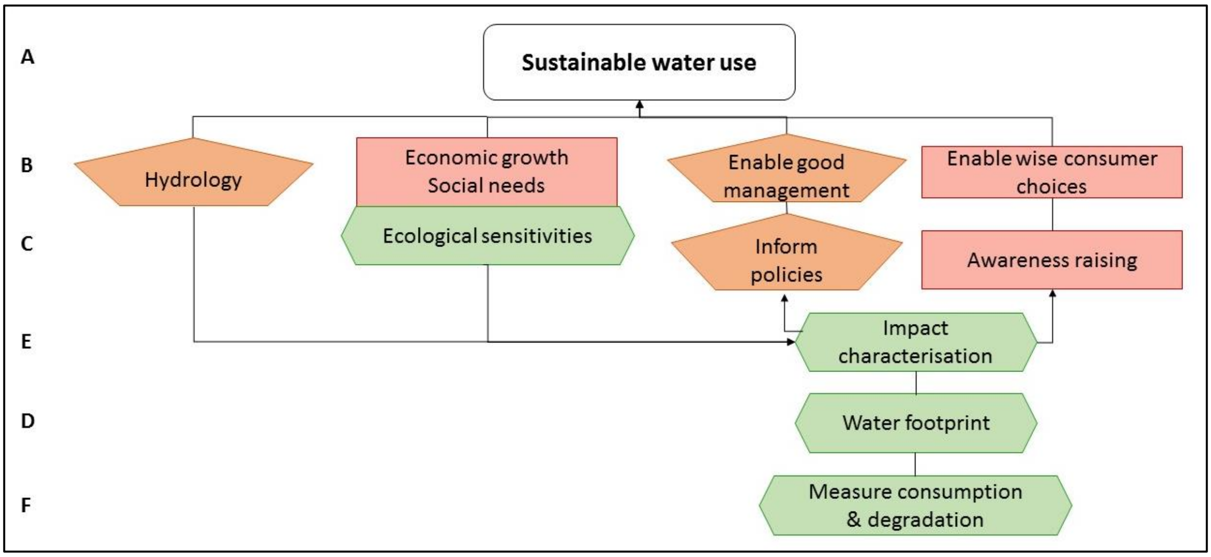

**Figure 2-4: Similarities between the fundamental viewpoint of the LCA approach of i Canals et al. and the fundamental viewpoint proposed in Figure 2-1. Hexagon shapes (green) indicate similarities in the viewpoints, square shapes (red) indicate aspects lacking, pentagon shapes (orange) indicate aspects partly included in the LCA approach of i Canals et al. (2009)**

The hydrological approach provides information on the local climate and geographical features that determine water inputs, outputs and changes in water storage to produce a sustainability indicator that includes all components of the hydrological cycle. The sustainability indicator of this approach does not address social needs and economic requirements. Ecological impacts due to pollution are taken into account through the grey WF, but the impacts on ecosystems due to a reduction in water availability and changes in river flows are not yet considered. The WF according to this approach may provide valuable information to a water resources manager, but care is needed as the result may be counterintuitive (for example a zero or negative WF could be obtained for a product even if the catchment as a whole is overexploiting its water resource), which would not help improve consumer awareness and decision making (**Figure 2-5**).

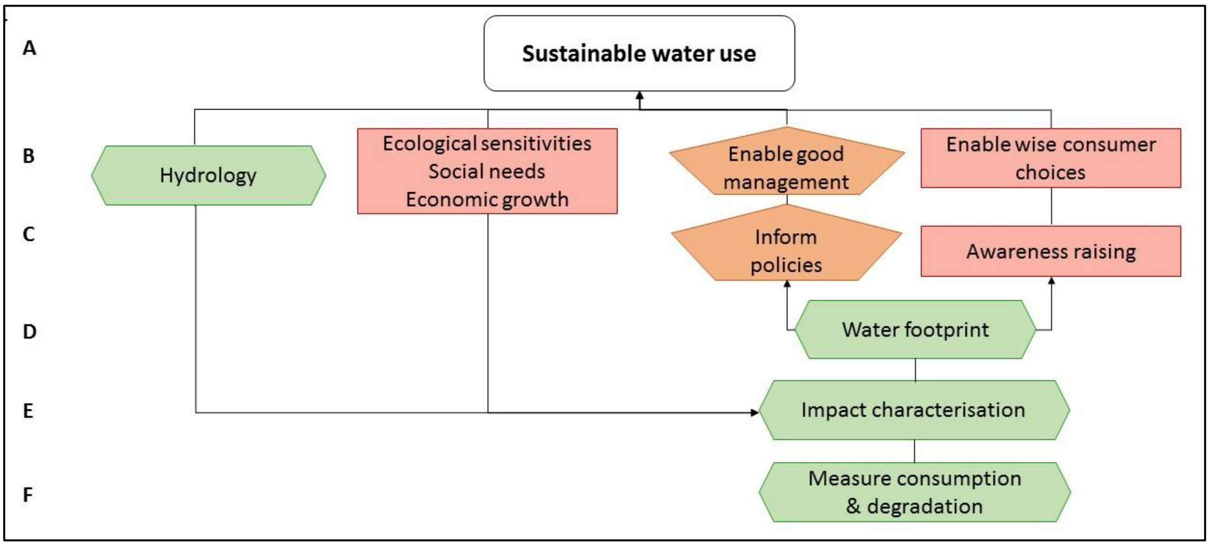

**Figure 2-5: Similarities between the fundamental viewpoint of the hydrological based approach and the fundamental viewpoint proposed in Figure 2-1. Hexagon shapes (green) indicate similarities in the viewpoints, square shapes (red) indicate aspects lacking, pentagon shapes (orange) indicate aspects partly included in the hydrological approach.**

### 2.5.4 CAN WATER FOOTPRINT INFORMATION BE USEFUL IN A SOUTH AFRICAN CONTEXT?

South Africa is a water scarce country, and as a developing nation with many social issues, provision of freshwater to all users has proven to be extremely challenging. As a result, information to guide improved Integrated Water Resources Management can potentially be extremely valuable. Following this review, we envisage that WFs certainly has the potential to provide information for water management on a national scale (through policy making), on a regional scale (understanding water related risks and guide water allocation and management) and on a local or farm scale (identify opportunities to reduce consumption and degradation). Exploring ways that WF information can guide improved water management at these different levels (especially the latter two) is a key aim of this project. Universally, WFs has certainly raised awareness amongst various water users to better conserve this resource.

The WFN method has been heavily criticized by multiple groups, and has since been refined, most notably between 2009 and 2011 with the inclusion of a sustainability assessment step (Hoekstra et al., 2009; Hoekstra et al., 2011). What is still lacking is a more descriptive methodology on how to determine water availability/scarcity in a (sub)catchment. Conclusions on WF applicability following the review of the literature are summarized below.

#### *2.5.4.1 Use of water footprints on a national scale*

Hoekstra et al. (2011) point out that driven by growing international trade in water intensive commodities, freshwater is increasingly becoming a global resource. Users of water resources have 'become spatially disconnected from consumers', and as a result it is now possible for water scarce regions to attain food security through the import of agri-food products produced in regions where water is more abundant. Estimating the virtual water linked to food products that South Africa imports/exports according to the WFNs consumptive WF approach is envisaged to provide valuable information to policy makers with the job of ensuring that South Africa is food secure, more especially as water becomes an increasingly scarce resource. Crude estimations have already been done, but these should be improved on by local scientists using appropriate data. The Water Research Commission (WRC) is already providing funding to address this issue.

#### *2.5.4.2 Use of water footprints on a regional scale*

Some of the concepts used in WFs are already covered in South African legislation, for example, accounting for changes in ET and runoff due to land-use changes (i Canals et al., 2009) which is considered in the Water Act of 1998 as a Streamflow Reduction Activity, and accounting for ecological flow requirements (Hoekstra et al., 2011 and i Canals et al., 2009), which is similar to our 'Ecological Reserve' concept. However, the WF concept can add much value and can potentially provide useful information to a catchment or aquifer manager. By linking WFs with total agricultural yields within a catchment or on an aquifer can provide information on the volume of ET used to obtain crop yields. Such information is seldom available and can also assist a manager to allocate water and monitor the water use according to crop yields.

#### *2.5.4.3 Use of water footprints on a local scale*

Water footprints can provide valuable information to farmers. A farmer can use WFs to determine which crops during the different seasons will provide the best yields when water limitations and allocations are enforced. Alternatively, a farmer can use WFs to determine which crops will provide the highest income or nutritional value with a certain volume of water. Currently, however, farmers are making decisions about which crops to plant based on market demands.

There is growing interest in farm-level assessments for the purposes of on-farm water management or planning and for emerging concepts such as Water Stewardship accounting (Alliance for Water Stewardship, 2012) and Global Gap certification (GlobalG.A.P., 2013). WFs can potentially become a metric used to indicate good irrigation management practices. Where over-irrigation occurs, irrigation volumes applied exceed crop water requirements, resulting in an entirely blue WF (consumption) despite significant rainfall during the growing season. Raising awareness of this issue amongst farmers to increase their ratio of green: blue water use has numerous advantages: it may lead to a greater volume of water remaining in the river as environmental flow or available to other users, reduced greenhouse gas emissions as a result of less irrigation water pumping and potentially less leached nutrients and pesticides from the system.

#### *2.5.4.4 Merit of classifying water as blue, green and grey*

It remains to be debated whether green water is important for inclusion in the overall WF. There is some merit to LCA groups' argument that green water consumption and land use are inseparable and should therefore be excluded from the quantification of water scarcity impact. Whether green water use of natural vegetation should be considered to establish a baseline also needs to be further assessed. The hydrological based method, which quantifies green water uses by considering changes in soil water content over an annual hydrological cycle has weaknesses which need to be better understood.

Flaws in the grey WF have been discussed, but the major strength of this concept is that impact on water quality, often neglected in the past, is now getting the attention it deserves. This is particularly important in a South African context as we have some of these most polluted water bodies in the world. Quantifying non-point source pollution from agricultural systems is extremely complex and carries large uncertainties. Some advocate the use of LCA methodology to quantify water quality impacts (e.g. potential eutrophication, potential exotoxicity), but for South Africa, locally relevant database information for LCA is largely lacking, making this option unavailable in many cases.

## 2.6 CONCLUSION

In order to conduct a WF assessment, active data collection for the product or process we are interested in is required. This acquired data already has the potential to improve understanding of the system and, therefore, its management. How much value placing this information in a WF framework adds is a concept requiring further exploration. Following this review, it is believed that WF certainly has the potential to assist in improving the management of a water-stressed landscape. While the idea of accounting for blue water consumption is logical and universally accepted, the value of green water accounting is less clear, and established weaknesses with the grey WF concept has constrained widespread application.

This review highlighted the strengths and weaknesses of four different WF methodologies, based on existing literature. Preliminary indications from this review have shown that choice of method may be driven by site-specific characteristics, and that the different methods can complement each other. Further comparisons between three of these methods, namely the WFN (Hoekstra et al., 2011), LCA of Pfister et al. (2009) and the hydrological (Deurer et al., 2011) methods, were made by applying them to vegetable crops on the Steenkoppies Aquifer in **Chapter 3**.

# 3 CHAPTER 3: EVALUATION OF METHODOLOGIES TO ESTIMATE WATER FOOTPRINT OF PRODUCING SELECTED VEGETABLES IN THE STEENKOPPIES AQUIFER

## 3.1 INTRODUCTION

In **Chapter 2** a literature review was conducted to compare different water footprint (WF) methodologies according to published information. In this chapter, WFs of vegetables produced on the Steenkoppies Aquifer are calculated according to three methodologies, namely the Water Footprint Network (WFN) methodology (Hoekstra et al. 2011), the hydrological methodology (Deurer et al. 2011) and the Life Cycle Assessment (LCA) methodology (Pfister et al. 2009). The WF results according to each methodology are compared to better understand the usefulness of the information generated and to select a methodology that is most suitable for the Steenkoppies Aquifer case study.

## 3.2 MATERIALS AND METHODS

The Steenkoppies Aquifer is located in a summer rainfall region. Average maximum temperatures range from 19°C in winter to 25°C in summer, and average minimum temperatures range from 4°C in winter to 12°C in summer (AgroClimatology Staff, 2014). Mean annual rainfall for the past 60 years is 670 mm (AgroClimatology Staff, 2014). The topography of the Steenkoppies Aquifer is characterised by almost flat undulating plains with no outcrops and no significant surface water, except for the Rietspruit. The area is underlain by dolomites from the Malmani subgroup of the Chuniespoort Group (Wiegmans et al., 2013). The Steenkoppies Aquifer is also known as a dolomitic compartment, because the flow of groundwater is constricted to the west by the Eigendom Dyke and to the east by the Tarlton West Dyke (Vahrmeijer et al., 2013). The northern boundary is formed by the Pretoria Group, which comprises of shale and quartzites (Barnard, 1996) and this is where water is discharged through the Maloney's Eye. The southern boundary consists of various rock types, including igneous basement and sedimentary rocks of the Witwatersrand Supergroup (Barnard, 1996, Wiegmans et al., 2013).

Farmers on the Steenkoppies Aquifer produces mostly vegetables, maize and wheat under irrigation. Maize is also produced under rainfed conditions. Water footprints were determined for carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*), lettuce (*Lactuca sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*), which are the most important crops cultivated on the Steenkoppies Aquifer. The two grain crops are included here for comparative purposes. On the Steenkoppies Aquifer, these crops are mainly cultivated under centre pivot or sprinkler irrigation (**Figure 3-1**).

**Figure 3-1: Carrots (A), and lettuce (B) cultivated and cabbage in a packhouse (C) on a farm on the Steenkoppies Aquifer, and (D) a pivot irrigation system on the Steenkoppies Aquifer.**

Vegetable crops generally have relatively short growing seasons, and are often planted at different times throughout the year, as is the case for the main vegetable crops on the Steenkoppies Aquifer. The planting schedule given in **Table 3-1** shows crop sequences on one representative farm on the Steenkoppies Aquifer (220 ha) from 2011 to 2013, and illustrates the intensive nature of irrigated agriculture on the aquifer. Preliminary simulations indicated that the planting date and growing season have a significant impact on the magnitude of the WF. As a result, four seasonal WFs were calculated for each of the selected vegetable crops. The seasons are defined as follow:

- Summer: November – February, using 7 November as planting date.
- Autumn: March and April, using 1 March as planting date.
- Winter: May – August, using 7 May as planting date.
- Spring: September and October, using 1 September as planting date.

In South Africa, maize is only planted in summer and wheat is only planted in winter. WFs were therefore only calculated for maize planted on 7 November and wheat planted on 7 May each year.

**Table 3-1: Planting schedule on a representative farm on the Steenkoppies Aquifer from October 2011 to January 2014 indicating the high intensity of irrigated agriculture**

| Field | Size (ha) | Oct-11 | Nov-11 | Dec-11 | Jan-12 | Feb-12 | Mar-12 | Apr-12 | May-12 | Jun-12 | Jul-12 | Aug-12 | Sep-12 | Oct-12 | Nov-12 | Dec-12 | Jan-13 | Feb-13 | Mar-13 | Apr-13 | May-13 | Jun-13 | Jul-13 | Aug-13 | Sep-13 | Oct-13 | Nov-13 | Dec-13 | Jan-14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **A3** | 3.5 | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | | | | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Cabbage | Cabbage | Cabbage | Cabbage | Cabbage | | | | Lettuce | Lettuce | |
| **A4** | 3.7 | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | | | | | | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | Carrots | | | | | | | |
| **B1** | 3.4 | | | | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | | Beetroot | Beetroot | Beetroot | Beetroot | | | | | | | | | | |
| **B2** | 3.7 | | | | | Cabbage | Cabbage | Cabbage | Cabbage | Cabbage | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | | |
| **B3** | 3.6 | | | | | Carrots | Carrots | Carrots | Carrots | Carrots | | | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | | | | | | | | | | |
| **B4** | 3.4 | | | | | | | | | | | | | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | Carrots | | | | | | | | |
| **C1** | 3.3 | | | | | | | | | | | | | | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | | | | Carrots | Carrots | Carrots | Carrots | Carrots |
| **C2** | 3.8 | | | | | | | | | | | | | | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | | | | Carrots | Carrots | Carrots | Carrots | Carrots |
| **C3** | 3.7 | | | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | | Cabbage | Cabbage | Cabbage | Cabbage | Cabbage | Lettuce | Lettuce | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | |
| **C4** | 3.4 | | | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | Cabbage | Cabbage | Cabbage | Cabbage | Cabbage | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | |
| **D2** | 3.7 | | | | | | | | | | | | Carrots | Carrots | Carrots | Carrots | Carrots | Lettuce | Lettuce | | | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots |
| **D3** | 3.6 | | | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | Lettuce | Lettuce | Lettuce | | | | | | | | Cabbage | Cabbage | Cabbage | Cabbage |
| **D4** | 3.7 | | | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | | Lettuce | Lettuce | Lettuce | | | | | | | | Cabbage | Cabbage | Cabbage | Cabbage |
| **E4** | 2.5 | | | | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | | | | | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | | | | | | |
| **F1** | 2.4 | | | | | | | | | | | Cabbage | Cabbage | Cabbage | Cabbage | Cabbage | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | Carrots | | | | | |
| **F2** | 2.6 | | | | | | | | | | | Cabbage | Cabbage | Cabbage | Cabbage | Cabbage | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | | |
| **F3** | 2.5 | | | | | | Cabbage | Cabbage | Cabbage | Cabbage | Cabbage | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | Carrots | | | | | | | | | | |
| **F4** | 2.5 | | | | | | | | | | | | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | | | | | | | | | | |
| **F5** | 2.5 | | | | | Cabbage | Cabbage | Cabbage | Cabbage | Cabbage | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Beetroot | Beetroot | Beetroot | Beetroot | | | | | | | | |
| **F8** | 2.5 | | | | | | | Cabbage | Cabbage | Cabbage | Cabbage | Cabbage | Cabbage | | Carrots | Carrots | Carrots | Carrots | Carrots | | | | | | | | | | |
| **G1** | 2.3 | | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | Cabbage | Cabbage | Cabbage | Cabbage | | Beetroot | Beetroot | Beetroot | | | | | | | | | |
| **G4** | 2.5 | | | | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Lettuce | Lettuce | Cabbage | Cabbage | Cabbage | Cabbage | | | | | | | | | | |
| **G6** | 2.6 | | | | Lettuce | Lettuce | Lettuce | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | Cabbage | Cabbage | Cabbage | Cabbage | Cabbage | | | | | | | | |
| **G8** | 2.7 | | | | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | Carrots | | | Cabbage | Cabbage | Cabbage | Cabbage | | | | | | | | | | |
| **H1** | 3.4 | | | Cabbage | Cabbage | Cabbage | Cabbage | | | | | | | Carrots | Carrots | Carrots | Carrots | Cabbage | Cabbage | Cabbage | Cabbage | Cabbage | | Lettuce | Lettuce | Lettuce | Lettuce | | |

<table>
<tr><th>Field</th><th>Size (ha)</th><th>Oct-11</th><th>Nov-11</th><th>Dec-11</th><th>Jan-12</th><th>Feb-12</th><th>Mar-12</th><th>Apr-12</th><th>May-12</th><th>Jun-12</th><th>Jul-12</th><th>Aug-12</th><th>Sep-12</th><th>Oct-12</th><th>Nov-12</th><th>Dec-12</th><th>Jan-13</th><th>Feb-13</th><th>Mar-13</th><th>Apr-13</th><th>May-13</th><th>Jun-13</th><th>Jul-13</th><th>Aug-13</th><th>Sep-13</th><th>Oct-13</th><th>Nov-13</th><th>Dec-13</th><th>Jan-14</th></tr>
<tr><td><b>H2</b></td><td>3.8</td><td colspan="9"></td><td colspan="7">Carrots</td><td colspan="4">Cabbage</td><td colspan="2"></td><td colspan="4">Lettuce</td><td colspan="2"></td></tr>
<tr><td><b>H3</b></td><td>3.6</td><td colspan="5"></td><td colspan="4">Cabbage</td><td colspan="6">Carrots</td><td colspan="5">Cabbage</td><td colspan="3"></td><td colspan="3">Lettuce</td><td colspan="2"></td></tr>
<tr><td><b>I3</b></td><td>3.8</td><td colspan="4"></td><td colspan="9">Carrots</td><td colspan="3">Cabbage</td><td></td><td colspan="8">Beetroot</td><td colspan="3"></td></tr>
<tr><td><b>I4</b></td><td>4.1</td><td colspan="5"></td><td colspan="6">Cabbage</td><td colspan="3">Lettuce</td><td colspan="6">Carrots</td><td colspan="2"></td><td colspan="4">Cabbage</td><td colspan="2"></td></tr>
<tr><td><b>I5</b></td><td>3.7</td><td colspan="11"></td><td colspan="5">Carrots</td><td colspan="4">Cabbage</td><td></td><td colspan="7">Carrots</td></tr>
<tr><td><b>I6</b></td><td>3.6</td><td colspan="5"></td><td colspan="7">Cabbage</td><td colspan="3">Lettuce</td><td colspan="5">Carrots</td><td colspan="8"></td></tr>
<tr><td><b>I7</b></td><td>3.9</td><td colspan="2"></td><td colspan="6">Carrots</td><td colspan="5"></td><td colspan="6">Carrots</td><td colspan="4"></td><td colspan="3">Cabbage</td><td colspan="2"></td></tr>
<tr><td><b>I8</b></td><td>4.0</td><td colspan="12"></td><td colspan="5">Carrots</td><td></td><td colspan="4">Cabbage</td><td colspan="2"></td><td colspan="3">Lettuce</td><td></td></tr>
<tr><td><b>J2</b></td><td>3.9</td><td colspan="5"></td><td colspan="8">Carrots</td><td colspan="2"></td><td colspan="2">Lettuce</td><td colspan="8">Carrots</td><td colspan="3"></td></tr>
<tr><td><b>J4</b></td><td>3.7</td><td colspan="4"></td><td colspan="5">Cabbage</td><td colspan="2"></td><td colspan="5">Carrots</td><td colspan="4">Cabbage</td><td></td><td colspan="4">Lettuce</td><td colspan="3"></td></tr>
<tr><td><b>J5</b></td><td>4.1</td><td colspan="3"></td><td colspan="4">Cabbage</td><td colspan="4">Cabbage</td><td colspan="5">Carrots</td><td></td><td colspan="4">Cabbage</td><td colspan="7"></td></tr>
<tr><td><b>J6</b></td><td>3.8</td><td></td><td colspan="7">Carrots</td><td colspan="3"></td><td colspan="5">Cabbage</td><td colspan="5">Carrots</td><td colspan="7"></td></tr>
<tr><td><b>J7</b></td><td>3.8</td><td></td><td colspan="7">Carrots</td><td colspan="3"></td><td colspan="5">Cabbage</td><td colspan="5">Carrots</td><td colspan="7"></td></tr>
<tr><td><b>J8</b></td><td>3.7</td><td colspan="6">Carrots</td><td colspan="7"></td><td colspan="5">Carrots</td><td colspan="6">Cabbage</td><td colspan="4"></td></tr>
<tr><td><b>K1</b></td><td>3.9*</td><td colspan="9"></td><td colspan="6">Carrots</td><td colspan="4">Beetroot</td><td colspan="2"></td><td colspan="5">Carrots</td><td colspan="2"></td></tr>
<tr><td><b>K2</b></td><td>3.9*</td><td colspan="4"></td><td colspan="2">Lettuce</td><td colspan="6"></td><td colspan="5">Carrots</td><td colspan="8">Beetroot</td><td colspan="3"></td></tr>
<tr><td><b>K3</b></td><td>3.9*</td><td colspan="4"></td><td colspan="7">Carrots</td><td></td><td colspan="3">Lettuce</td><td colspan="4">Carrots</td><td colspan="2"></td><td colspan="5">Cabbage</td><td colspan="2"></td></tr>
<tr><td><b>K4</b></td><td>3.9*</td><td colspan="4"></td><td colspan="7">Carrots</td><td></td><td colspan="3">Lettuce</td><td colspan="4">Carrots</td><td colspan="2"></td><td colspan="5">Cabbage</td><td colspan="2"></td></tr>
<tr><td><b>K5</b></td><td>3.9*</td><td colspan="9"></td><td colspan="4">Lettuce</td><td colspan="5">Carrots</td><td colspan="10"></td></tr>
<tr><td><b>K6</b></td><td>3.9*</td><td colspan="8"></td><td colspan="4">Lettuce</td><td></td><td colspan="5">Carrots</td><td colspan="10"></td></tr>
<tr><td><b>K7</b></td><td>3.9*</td><td colspan="12"></td><td colspan="5">Carrots</td><td colspan="3">Cabbage</td><td colspan="4">Lettuce</td><td colspan="4"></td></tr>
</table>

Note: White spaces indicate fallow land; * Estimated averages

Evapotranspiration (ET) during the cultivation phase has been reported to have the highest WF along the supply chain (Hoekstra et al., 2011, Hoekstra and Chapagain, 2011, Ridoutt and Pfister, 2010). Any water consumed in the packhouse and along the supply chain to the consumer was considered out of scope for this Chapter. The WFs of vegetables in the packhouse are presented in **Chapter 4**. Further, water used to raise crop seedlings was excluded, because this water is often sourced from other catchments and in **Chapter 8** it was determined that the quantities used to raise lettuce seedlings are relatively small compared to total ET during cultivation. Water embedded in the crop was also excluded, because this only represents about 1% of total crop water use (Hoekstra et al., 2011). In **Chapter 4** it was determined that the indirect WF of packhouse electricity use was negligible, even though the packhouse used a lot of energy for hydrocooling, refrigeration, pumps, lights etc. Thus, for this reason, the indirect water use through pumping water during cultivation was considered negligible and was therefore excluded from these calculations.

### 3.2.1 CROP WATER USE MODELLING

The data required for blue and green WF calculations were generated using the Soil Water Balance (SWB) crop model (Annandale et al., 1999). SWB is a mechanistic, daily time-step, generic crop model. Crop growth is simulated to be either water- or radiation-limited. SWB requires weather, soil and crop data as inputs. The SWB model was considered the most appropriate model for this application, because it can simulate growth of a range of different crops, it is able to simulate daily crop water use, has been extensively tested in South Africa, and is relatively simple to use (Annandale et al., 1999). For each crop, SWB provided daily and seasonal ET, irrigation applied and yield data for ten years from 2004 to 2013. Standard deviations were calculated for irrigation and yield over the ten years. A new functionality was programmed into SWB that automatically calculates the WF according to the WFN methodology (Hoekstra et al., 2011), using yield dry matter as the functional unit.

#### *3.2.1.1 Weather data*

Daily weather data inputs include rainfall (mm), minimum and maximum temperature (°C), relative humidity (%), solar radiation (MJ $m^{-2}$ $day^{-1}$) and wind speed (m $s^{-1}$). This data is used to calculate the reference ET ($ET_o$) using the modified Penman-Monteith equation (Allen et al., 1998). If wind speed, solar radiation and relative humidity are unavailable, SWB estimates these values according to FAO 56 recommendations (Allen et al., 1998). Wind speed is assumed to be 2 m $s^{-1}$, solar radiation is estimated based on latitude and temperature, and humidity is estimated based on minimum temperatures (Allen et al., 1998, Annandale et al., 1999).

Weather data for the Steenkoppies Aquifer was sourced from the Deodar Weather Station (Lat: S26.1426; Long: E27.57438; Altitude: 1591m). This station is a standard automatic weather station, which is centrally located on the Steenkoppies Aquifer and provided updated weather data from January 1983 to May 2014. The Deodar weather dataset had several data gaps, which were filled as follow:

- Rainfall, minimum and maximum temperature data gaps for the following dates were completed using the following data sources:
  - 1 December 1985 to 31 Jan 1990 (Source: SWB's weather generator; (Jovanovic et al., 2003))
  - 26 May to 2 June 1997 (Source: SWB's weather generator; (Jovanovic et al., 2003))
  - 7 April to 21 May 1997 (Source: SWB's weather generator; (Jovanovic et al., 2003))

  - 29 to 31 August 2003 (Source: Agricultural Research Council Institute for Soil, Climate and Water (ARC ISCW data) for Deodar weather station)
  - 1 to 13 January 2010 (Source: ARC ISCW data for Deodar weather station)

- SWB generated data (Jovanovic et al., 2003) was used to fill maximum temperature data gaps for 12 to 13 October 1990 and minimum temperature data gaps for 13 to 14 October 1990.

- Deodar data sourced from the Agricultural Research Council – Institute for Soil Climate and Water (ARC ISCW) was used to complete minimum and maximum temperature data gaps for 1 to 4 January 2004 and to complete minimum temperature for 5 January 2004.

- Monthly averages from the entire dataset were used to complete maximum temperature for 12 January 2004 and minimum and maximum temperature data gaps for 13 to 26 January 2004.

- Monthly averages were assumed for minimum and maximum temperature data gaps for 9 June 2006 to 27 August 2006. Outstanding rainfall data during this period were assumed to be zero because it was in the winter season.

- Single day data gaps in minimum temperatures existed in some places in the database and these were completed using the average between the day before and after.

As a result, a weather dataset representative for the region was compiled from 1 January 1950 to 15 May 2014, without any gaps in the daily rainfall, minimum and maximum temperature data (**Figure 3-2**). Total annual precipitation data from 1950 that was used in SWB modelling is shown in **Figure 3-3.**

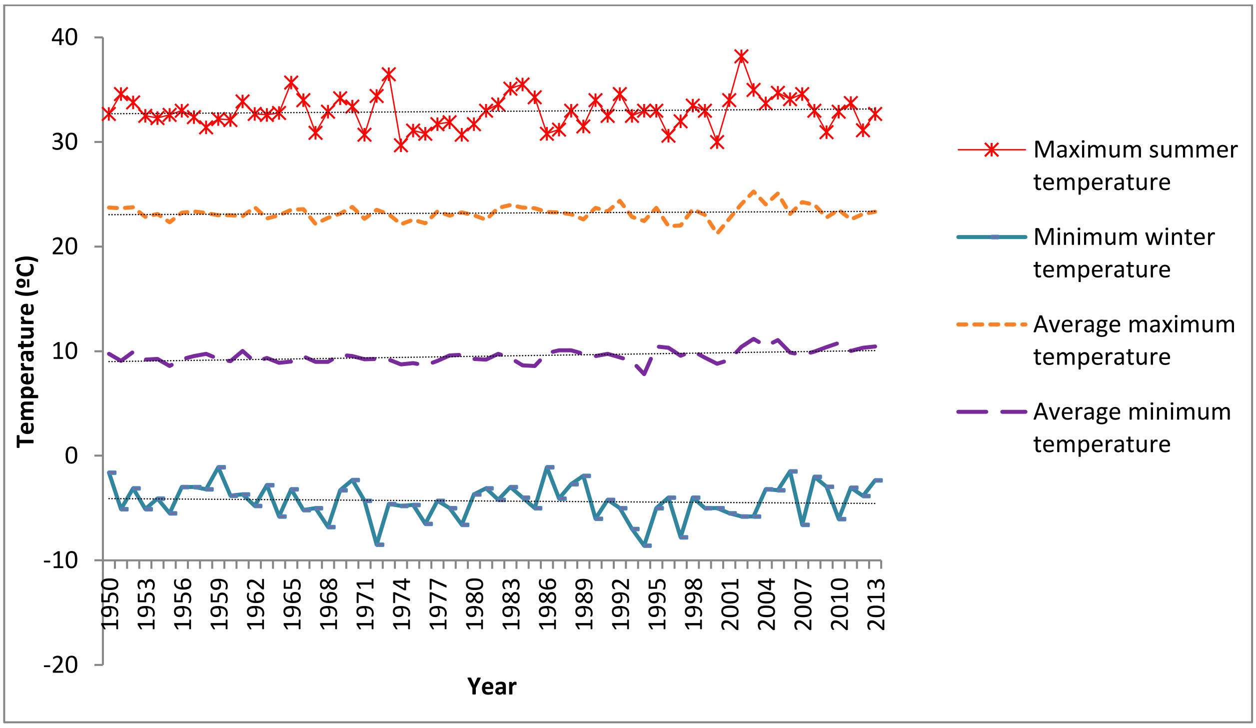

**Figure 3-2 Temperature data used for crop modelling summarised as the maximum summer temperatures, minimum winter temperatures, and average annual maximum and minimum temperatures for each year. The gradients of the linear trendlines indicate insignificant change in annual temperature trends.**

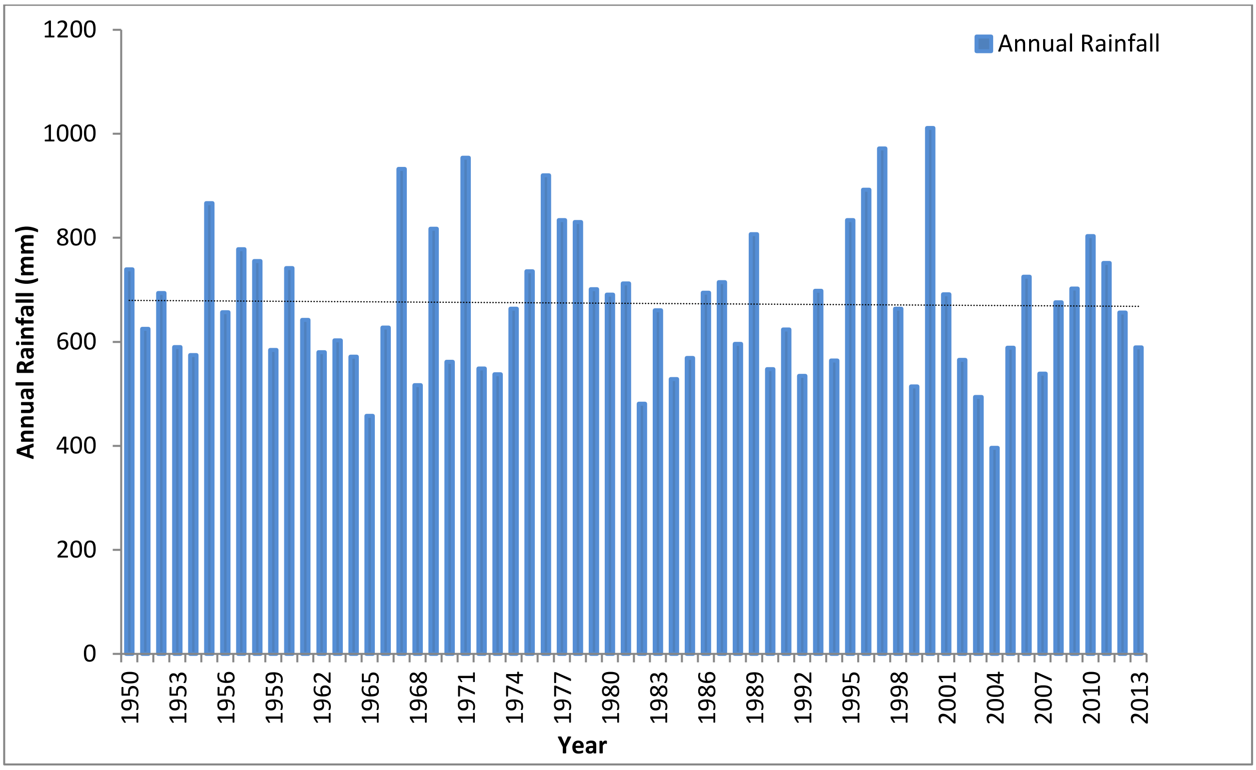

**Figure 3-3 Total annual precipitation data used for crop modelling**

### *3.2.1.2 Soil data*

Soil data sampled from the study area, as described by Vahrmeijer (2016), has been used to parameterise the SWB model (**Table 3-2, Table 3-3**). This data is considered to be representative of the whole aquifer, because the aquifer is relatively small, the geology is uniform and the topography is relatively flat. Differences in soil depth across the aquifer is also not considered to be important, because the vegetables crops that are grown have shallow root depths. Soil input data used to parameterise and calibrate the SWB model for the whole profile included a drainage factor (0 to 1), drainage rate (mm day$^{-1}$) and maximum rooting depth (m) (Annandale et al., 1999). For each of the 11 soil layers the following data was parameterised: depth of layer (m), volumetric water content (m$^3$ m$^{-3}$) at field capacity and permanent wilting point, initial water content at the beginning of model simulations (mm) and bulk density (Mg m$^{-3}$).

**Table 3-2 General soil profile data parameterised in SWB based on sampling in the Steenkoppies Aquifer**

| **Soil profile data** | |
|---|---|
| **Texture** | Sandy Loam |
| **Runoff no** | 250 |
| **Field capacity (kPa)** | -10 |
| **Permanent Wilting Point (kPa)** | -1000 |
| **Drainage factor** | 0.8 |
| **Drain rate (mm day$^{-1}$)** | 70 |
| **Root depth limit (m)** | 1 |
| **Profile water content at full capacity (mm)** | 190* |
| **Profile water content at saturation (mm)** | 440* |
| **Profile water content at Permanent Wilting Point (mm)** | 72* |

* Estimated by the model from individual layer parameters

Table 3-3 Detailed data for each soil layer of a sampling point on the Steenkoppies Aquifer

| Soil Layer | Depth (m) | Field capacity ($m^3\ m^{-3}$) | Initial water content ($m^3\ m^{-3}$) | Permanent wilting point ($m^3\ m^{-3}$) | Bulk density ($Mg\ m^{-3}$) |
|---|---|---|---|---|---|
| **1** | 0.05 | 0.140 | 0.147 | 0.067 | 1.42 |
| **2** | 0.15 | 0.147 | 0.140 | 0.067 | 1.42 |
| **3** | 0.2 | 0.151 | 0.151 | 0.082 | 1.54 |
| **4** | 0.3 | 0.151 | 0.151 | 0.082 | 1.54 |
| **5** | 0.4 | 0.187 | 0.187 | 0.088 | 1.54 |
| **6** | 0.5 | 0.187 | 0.187 | 0.088 | 1.54 |
| **7** | 0.6 | 0.215 | 0.215 | 0.086 | 1.46 |
| **8** | 0.7 | 0.215 | 0.215 | 0.086 | 1.46 |
| **9** | 0.8 | 0.215 | 0.215 | 0.086 | 1.46 |
| **10** | 0.9 | 0.215 | 0.215 | 0.086 | 1.46 |
| **11** | 1 | 0.215 | 0.215 | 0.086 | 1.46 |

#### *3.2.1.3 Crop parameters*

Crop parameters that are required by the SWB model include:

- A *Canopy Extinction Coefficient (K)*, which is a constant value in the model representing the exponential relationship between fractional interception (FI) (the fraction of solar radiation that is intercepted by the leaves of the plant) and the leaf area index (LAI) (total one-sided area of green leaves per surface area of the ground below the leaves). A higher K value will result in a higher FI value if LAI is constant (Annandale et al., 1999).
- A *dry-matter-water ratio (DWR)* (Pa), which represents the relationship between transpiration and dry matter accumulation of a crop. It represents the water use efficiency (WUE) of a crop, where a higher DWR indicates that more biomass is accumulated with an increase volume of water transpired (Annandale et al., 1999). The DWR must be corrected for differences in vapour pressure deficit (Tanner and Sinclair, 1983).
- *Radiation conversion efficiency ($E_c$)* (kg $MJ^{-1}$), which is a crop specific parameter that indicates how much dry matter is accumulated for each MJ of Rs intercepted by the crop. This parameter is used to calculate dry matter production for radiation limited growth and is relatively linear if water supply is not limited (Monteith and Moss, 1977).
- *Base temperature* (°C) which is a crop specific parameter that indicates the minimum temperature below which crops do not grow (Annandale et al., 1999).
- *Temperature optimal light* (°C) which is the optimal temperature at which radiation is intercepted and crop growth takes place.
- *Cut off temperature* (°C) which is the temperature at which crop growth ceases (Annandale et al., 1999).
- *Growing day degrees* (GDD) which is the difference between average daily temperatures and basal temperatures (Annandale et al., 1999). Plant growth is slower during cooler days with fewer GDD. Each crop requires a certain number of GDD before it reaches the next phenological stage. GDD are determined for different phenological stages including:

  - Emergence day degrees, which is the number of GDD required before the crop emerges from the ground
  - Flowering day degrees, which is the number of GDD required before the crop flowers
  - Maturity day degrees, which is the number of GDD required before the crop reaches maturity
  - Transition day degrees, which is the number of GDD required for transition from vegetative to reproductive growth
  - Maximum leaf age, which is the number of GDD required before leaf senescence begins
- Maximum height of the plant (m).
- Maximum rooting depth (m).
- *Stem to grain translation* factor, which determines the fraction of translocation of dry matter from the stem (or vegetative parts) to the grains (or reproductive parts)(Annandale et al., 1999).
- *Canopy storage* (mm), which is a crop specific parameter that, if multiplied by FI, equals the volume of rainfall or irrigation that is intercepted by the canopy and does not reach the soil (Annandale et al., 1999).
- *Minimum leaf water potential* (kPa) which is the minimum leaf water potential at which root water uptake occurs.
- *Maximum transpiration rate* (mm day$^{-1}$).
- *Specific leaf area* (m$^2$ kg$^{-1}$) is the surface area of all leaves divided by the mass of the leaves.
- *Leaf-stem partition* (m$^2$ kg$^{-1}$) determines the fraction of dry matter partitioned into leaves (Annandale et al., 1999).
- *Top (aboveground) dry matter* at emergence or transplanting (kg m$^{-2}$).
- *Root fraction* is the proportion of newly produced dry matter allocated to the roots.
- *Root growth rate (mm day$^{-1}$).*
- *Stress day index*, which is used to determine partitioning between different plant organs under water stress conditions.

New crop parameters for carrots, cabbage, beetroot, broccoli and lettuce (**Table 3-4**) were recently calibrated for the region based on intensive growth analyses data by Vahrmeijer (2016). Trials were done on commercial farms on the Steenkoppies Aquifer under commercial management practices. Cultivars used most commonly by farmers on the Steenkoppies Aquifer for each season were selected for parameterisation. Cabbage cultivars 'Tenacity' and 'Grandslam', carrots cultivars 'Star 3006' and 'Dordogne', and broccoli cultivars 'Star 2204' and 'Parthenon' were used for summer and winter, respectively. The beetroot cultivar 'Red Ace' and lettuce cultivar 'Robbenson' was used for all seasons. Parameters that were developed for summer were also applied for spring, except for beetroot which required slightly different parameters in spring, and the parameters developed for winter were also applied for autumn. Crop parameters for maize and wheat were sourced from Annandale et al. (1999). Further detail is provided in **Chapter 5**.

#### *3.2.1.4 Verification of SWB results*

SWB results were verified by comparing simulated yield and irrigation data (with standard deviations), to independent actual measurements made on ten farms on the Steenkoppies Aquifer (Vahrmeijer, 2016). Four replications of 1 $m^2$ plots were demarcated on cropped areas of each farm. Rain gauges were installed within the cropped area to measure irrigation and rainfall and outside the fields to measure rainfall only. The crops were harvested at the commercial harvesting date and the harvestable portion was weighed to determine yield in terms of both fresh mass and dry matter. The grain crops data were validated by Jovanovic et al. (2004), and were included for comparative purposes. **Table 3-5** summarises irrigation and yield data that was available for verification of the simulation results of the vegetables.

**Table 3-4. Locally produced crop parameters used in the Soil Water Balance model to simulate the data required for WF calculations (Vahrmeijer, 2016)**

| Parameters | Carrots | | Cabbage | | Beetroot | | | Broccoli | | Lettuce | Maize | Wheat |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Summer & spring | Autumn & winter | Summer & spring | Autumn & winter | Summer | Spring | Autumn & winter | Summer & spring | Autumn & winter | All seasons | Summer | Winter |
| **Extinction coefficient (-)** | 0.76 | 0.76 | 0.78 | 0.62 | 0.64 | 0.64 | 0.64 | 0.77 | 0.81 | 0.92 | 0.56 | 0.55 |
| **Dry-matter-water ratio (Pa)** | 8 | 8 | 9 | 6 | 7 | 7 | 7 | 6 | 7 | 9 | 4 | 4 |
| **Conversion Efficiency (kg MJ$^{-1}$)** | 0.00087 | 0.00087 | 0.00094 | 0.00094 | 0.0012 | 0.0012 | 0.0012 | 0.001 | 0.001 | 0.0009 | 0.0012 | 0.0017 |
| **Base temperature (°C)** | 7.2 | 7.2 | 4.4 | 2 | 4.4 | 4.4 | 4.4 | 0 | 0 | 7.2 | 10 | 4 |
| **Temperature optimal light (°C)** | 15 | 15 | 15 | 10 | 15 | 15 | 15 | 15 | 10 | 15 | 25 | 15 |
| **Cut off temperature (°C)** | 23.9 | 23.9 | 23.9 | 23.9 | 23.9 | 23.9 | 23.9 | 23.9 | 23.9 | 23.9 | 30 | 25 |
| **Emergence day degrees (°C)** | 103 | 103 | 130 | 50 | 64 | 64 | 64 | 123 | 95 | 71 | 50 | 50 |
| **Flowering day degrees (°C)** | 200 | 200 | 800 | 750 | 200 | 200 | 500 | 1100 | 650 | 175 | 900 | 750 |
| **Maturity day degrees (°C)** | 1450 | 1300 | 1300 | 1445 | 1300 | 1000 | 1356 | 1700 | 1200 | 529 | 1700 | 1500 |
| **Transition day degrees (°C)** | 1238 | 1238 | 400 | 500 | 700 | 700 | 700 | 500 | 1200 | 475 | 10 | 400 |
| **Maximum leaf age** | 1450 | 1300 | 1300 | 1445 | 1300 | 1000 | 1356 | 1700 | 1200 | 529 | 900 | 900 |
| **Max height (m)** | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.4 | 0.3 | 2.2 | 1 |
| **Maximum root depth (m)** | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.4 |
| **Stem to grain translation** | 0.5 | 0.5 | 0.05 | 0.05 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.01 | 0.05 | 0.01 |
| **Canopy storage (mm)** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Minimum leaf water potential (kPa)** | -1500 | -1500 | -1500 | -1500 | -1500 | -1500 | -1500 | -1500 | -1500 | -1500 | -2000 | -1500 |
| **Maximum transpiration (mm day$^{-1}$)** | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| **Specific leaf area (m² kg$^{-1}$)** | 17.9 | 17.9 | 11 | 9.5 | 13 | 13 | 13 | 10.5 | 9.5 | 20 | 15 | 12 |
| **Leaf stem partition (m² kg$^{-1}$)** | 3.08 | 3.08 | 1.55 | 0.56 | 3.02 | 3.02 | 3.02 | 1.54 | 1.54 | 6.33 | 0.8 | 1.2 |
| **Total Dry Mass at emergence or transplanting (kg m$^{-2}$)** | 0.0005 | 0.0005 | 0.005 | 0.01 | 0.003 | 0.003 | 0.003 | 0.001 | 0.007 | 0.0008 | 0.0019 | 0.0019 |
| **Root fraction** | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.2 | 0.01 | 0.02 |
| **Root growth rate ()** | 2 | 2 | 2 | 2 | 4 | 4 | 4 | 2 | 2 | 2 | 4 | 7 |
| **Stress index** | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 |

**Table 3-5 Metadata describing irrigation and yield data obtained for carrots, cabbage, broccoli, beetroot and lettuce from selected farms on the Steenkoppies Aquifer (Vahrmeijer, 2016)**

| Farm | Carrots | Cabbage | Broccoli | Beetroot | Lettuce |
|---|---|---|---|---|---|
| **A** | **Irrigation and yield** (summer and spring, 2008) | - | - | - | |
| **B** | **Irrigation and yield** (autumn and winter 2008 and 2009) | **Irrigation and yield** (spring 2008 and autumn 2009) | **Irrigation and yield** (spring 2008 and autumn 2009) | **Irrigation and yield** (summer 2009 and autumn 2009) | **Irrigation and yield** (summer 2008 and winter 2008 and 2009 ) |
| **C** | **Irrigation** (all seasons 2011-2013) | **Irrigation** (all seasons 2011-2013) | - | **Irrigation** (summer and autumn 2012-2013) | **Irrigation** (summer, winter and spring 2012 – 2013) |
| **D** | - | **Irrigation and yield** (autumn 2009) | - | **Irrigation and yield** (autumn 2009) | **Irrigation and yield** (summer and spring 2008 and winter 2009) |
| **E** | | **Irrigation and yield** (winter 2008 summer 2008 autumn 2009) | | **Irrigation and yield** (autumn 2009) | **Irrigation and yield** (spring 2008 and winter 2009) |
| **F** | | | **Irrigation and yield** (autumn 2009) | | **Irrigation and yield** (winter 2009) |
| **G** | **Irrigation and yield** (autumn 2009) | | **Irrigation and yield** (autumn 2009) | | **Irrigation and yield** (winter 2009) |
| **H** | | **Irrigation and yield** (winter and spring 2008 and autumn 2009) | | | **Irrigation and yield** (winter 2009) |
| **I** | | **Irrigation and yield** (spring 2008, summer 2009 and autumn 2009) | | | **Irrigation and yield** (spring 2008 and winter 2009) |
| **J** | | **Irrigation and yield** (spring 2008, summer 2009 and autumn 2009) | | | **Irrigation and yield** (spring 2008) |

### 3.2.2 WATER FOOTPRINT NETWORK METHODOLOGY CALCULATIONS

For this chapter the goal was set to account blue, green and grey WFs of the main crops grown on the Steenkoppies Aquifer according to the WFN method. A sustainability assessment of these WFs has been done in **Chapter 6.** The scope defined in **Section 3.2** applies to these WFs. Using the verified modelled data and long term simulations from 2004 to 2013, blue and green WFs were calculated according to the WFN methodology (Hoekstra et al., 2011) as given in **Equation 2-3** and **Equation 2-5**, respectively (**Chapter 2**). Water footprints were affected by a lack of solar radiation data, and could therefore not be calculated for the years before 2004. This issue is further discussed in **Chapter 5**. In SWB the result under irrigation applied has taken effective rainfall into account and therefore represents the irrigation requirement. As per Hoekstra et al. (2011), yield in fresh mass was used. Water footprints were also calculated using yield in dry matter as an alternative (kg $m^{-2}$).

In **Section 2.4.3** it was argued that the combined effect of nitrogen (N) and phosphorus (P) are important for eutrophication in agricultural areas, but that N are also of specific concern, because of health impacts and certain cases where N can cause eutrophication even when P discharges are limited. Nitrogen is also the most common agricultural pollutant that has been used for calculating grey WFs (Chapagain and Hoekstra, 2011, Mekonnen and Hoekstra, 2010, Mekonnen and Hoekstra, 2011, Mekonnen and Hoekstra, 2012), which enables comparisons with a wide range of other WF studies reported in the literature. Therefore, N was used as the critical pollutant during the cultivation phase to determine grey WFs of the vegetables selected for this study, while recognising that other pollutants, including P and pesticides, might be more appropriate in other studies. Grey WFs were determined according to **Equation 2-6**.

The general standards for N in wastewater of 15 mg $\ell^{-1}$ (Department of Water Affairs and Forestry, 1999) was taken as $C_{max}$. This value was taken, because it is a standard given for wastewater from industries, as it is assumed that the water would be diluted further downstream. This value would result in a lower grey WF, compared to the WF that would result if environmental standards are used for $C_{max}$, and therefore it would represent the lowest grey WF that could be obtained. If this lowest grey WF would suggest some impacts on water quality, one would expect to see this impact on the water quality in the Steenkoppies Aquifer. The natural concentration ($C_{nat}$) is the N concentration of the water if no human influences are present. Despite intensive agricultural activities on the Steenkoppies Aquifer, the water in the aquifer has very low N concentrations, with an average of 0.3 mg $\ell^{-1}$ (Department of Water Affairs, 2014). Thus, the low average natural N concentration of the aquifer was considered to represent natural concentrations and was taken as $C_{nat}$. **Chapter 5.3.4** further discusses the observation that the aquifer does not yet reflect the expected impacts of intensive agricultural activities.

The N load that leaches into the aquifer was determined by estimating the surplus N applied to the crops together with a leaching-runoff factor, according to the method provided by Franke et al. (2013). To determine the surplus N, the N content of the harvested product (which represents the portion of N that is taken up by the plant and removed from the field) was subtracted from the N application per crop. Typical N fertiliser application rates for carrots, cabbage, beetroot and lettuce were provided by farmers on the Steenkoppies Aquifer, and N application to broccoli was assumed to be the same as for cabbage. Nitrogen application given by the Fertiliser Society of South Africa (Misstofvereniging van Suid Afrika, 2007) was used for beetroot, maize and wheat. For maize and wheat, the application rates were also linked to expected irrigated yields for the aquifer. The N contents of the crops were taken from the literature (Alexandrova and Donov, 2003, ANZECC and ARMCANZ, 2000, Mossé et al., 1985, Petek et al., 2012, Sorensen, 1998). Nitrogen fertiliser application rates and crop N content used in the calculations are summarised in **Table 3-6**.

**Table 3-6. Nitrogen (N) application rates and crop N contents of selected crops used to determine surplus N applied**

| | Application (kg N $ha^{-1}$) | N content of fresh mass (%) |
|---|---|---|
| **Beetroot** | 140 | 0.2% [1] |
| **Carrots** | 190 | 0.1% [2] |
| **Cabbage** | 190 | 0.2% [2] |
| **Broccoli** | 190 | 0.4% [2] |
| **Lettuce** | 130 | 0.2% [3] |
| **Maize** | 220 | 0.9% [4] |
| **Wheat** | 240 | 1.5% [5] |

References: [1]Petek et al. (2012), [2]Sorensen (1998), [3]ANZECC and ARMCANZ (2000), [4]Alexandrova and Donov (2003), [5]Mossé et al. (1985).

The surplus N applied was multiplied by a leaching-runoff fraction to estimate the amount of N that leaches into the aquifer, with the assumption that all runoff that does occur ends up recharging the aquifer due to the flat terrain of the area. The first step in determining the leaching-runoff fraction was to complete the score card given in **Table 3-7**. The weighted scores were then used to calculate the leaching-runoff fraction in terms of surplus N applied (β) using **Equation 3-1** (Franke et al., 2013).

$$\beta = \beta_{min} + \left(\frac{\sum_i S_i \times W_i}{\sum_i W_i}\right) \times (\beta_{max} - \beta_{min})$$

**Equation 3-1**

Where *S* is the score(s) in Row *x* and W is the weight(s) in Column *y* of **Table 3-7**, $\beta_{min}$ and $\beta_{max}$ are the minimum and maximum leaching-runoff fractions. For N a $\beta_{min}$ value of 0.08 was used and a $\beta_{max}$ value of 0.8 was used as given by Franke et al. (2013). Management practices in **Table 3-7** was considered average, because some farmers use old methods to determine when irrigation is required, and farmers mostly irrigate with pivots, which are not considered as efficient as drip irrigation. A leaching-runoff fraction of 0.46 was obtained.

**Table 3-7: Determination of the leaching runoff potential of nitrogen (N) for the Steenkoppies Aquifer (Franke et al., 2013)**

| **Category** | **Factor** | | **Leaching-runoff potential** | **Very low** | **Low** | **High** | **Very high** | **Weighted Score *** |
|---|---|---|---|---|---|---|---|---|
| | | | **Row *x*** Score (s) | 0 | 0.33 | 0.67 | 1 | |
| | | | **Column *y*** Weight | | | | | |
| **Environmental factors** | Atmospheric input | N-deposition (g N $m^{-2}$ $yr^{-1}$) | 10 | <0.5 | >0.5 | <1.5 | >1.5 | **0** |
| | Soil | Texture (relevant for leaching) | 15 | Clay | Silt | Loam | Sand | **10.05** |
| | | Texture (relevant for runoff) | 10 | Sand | Loam | Silt | Clay | **3.3** |
| | | Natural drainage (relevant for leaching) | 15 | Poorly to very poorly drained | Moderately to imperfectly drained | Well drained | Excessively to extremely drained | **15** |
| | | Natural drainage (relevant for runoff) | 10 | Excessively to extremely drained | Well drained | Moderately to imperfectly drained | Poorly to very poorly drained | **0** |
| | Climate | Precipitation (mm) | 15 | 0-600 | 600-1200 | 1200-1800 | >1800 | **5** |
| **Agricultural practice** | N-fixation (kg $h^{-1}$) | | 10 | 0 | >0 | <60 | >60 | **3.3** |
| | Management practice | | 15 | Best | Good | Average | Worst | **10.05** |

*The weighted score is calculated by multiplying the score in Row *x* with the weight in Column *y*

### 3.2.3 HYDROLOGICAL WATER FOOTPRINT METHODOLOGY CALCULATION

The verified SWB model estimates also provided the data used to calculate WFs according to the hydrological methodology. The hydrological methodology has not proposed a water quality impact metric, and uses the grey WF methodology proposed by the WFN. Blue WFs are based on the change in groundwater storage and is calculated as per **Equation 2-17** (**Chapter 2**) (Deurer et al., 2011**).** In the original study Deurer et al. (2011) assumed that all runoff became drainage, because of the flat topography of their study area. This is why runoff in this formula reduces the blue WF on the aquifer. For this study runoff was also assumed to be zero, due to the absence of surface runoff on the Steenkoppies Aquifer. Rainfed conditions cannot be modelled for the vegetables on the Steenkoppies Aquifer, because some crops fail due to low rainfall conditions in winter. In SWB this is reflected by extremely low ET values and underdevelopment of the harvestable crop. Thus, for blue WF calculations total drainage under irrigated conditions was used instead of $D^r$ plus $D^{ir}$. This however presented a problem with calculating green WFs, which is based on the change in soil moisture originating from rainfall **Equation 2-18** (**Chapter 2**), where ET under rainfed conditions are required (Deurer et al., 2011). For this reason, the green WF was assumed to be zero, because over the long-term green water will be replenished by rainfall and the changes in soil water storage would be negligible.

The hydrological methodology, which considers the water balance over an entire calendar year, is not compatible with estimating the WFs of a single short season vegetable crop such as those cultivated on the Steenkoppies Aquifer. Therefore, the annual WF was calculated for typical cropping sequences within a twelve-month period. Fresh weight then equals the combined weight of all crops produced in the sequence. The WF will thus represent a combination of crops, instead of one single crop. A crop rotation of carrots and cabbage is typical on the Steenkoppies Aquifer (**Table 3-1**). A two-crop sequence of winter cabbage planted on 1 May each year and summer carrots planted on 7 November each year was therefore selected. Due to the intensive farming activities on the aquifer, a three-crop sequence was also selected, with winter broccoli planted on 1 May each year, spring cabbage planted on 25 August each year, and summer beetroot planted on 13 December each year. The crops selected for the three-crop sequence was based on the length of the growing seasons, so that the sequence can be completed in one calendar year for comparison with WFN results. Broccoli, which had a high WF according to the WFN results, was specifically included for comparison with WFN results.

In order to compare the hydrological WF results of the two-crop sequence with the WFN results the average between WFN WFs of carrots planted in summer and cabbage planted in winter was taken. Likewise, the average WFs according to the WFN for winter broccoli, spring cabbage and summer beetroot was taken to compare the hydrological WFs results of the three-crop sequence.

### 3.2.4 LCA WATER FOOTPRINT METHODOLOGY CALCULATIONS

A WS Index of 0.78, calculated by Pfister et al. (2009) for the area in which the Steenkoppies Aquifer is located, was used to convert the WFs of the crops on the Steenkoppies Aquifer. The blue WFs according to the WFN methodology were used to calculate LCA WFs, because these WFs quantify the volume of blue water used to produce a product. Site specific WS Indices for the Steenkoppies Aquifer were also calculated for five distinct periods classified in terms of the intensity of irrigated agriculture (**Chapter 6)** according to the methodology proposed by Pfister et al. (2009). The withdrawal to availability ratio (WTA) for regulated catchments were calculated according to **Equation 2-11** (**Chapter 2**) given by Pfister et al. (2009) The catchment scale agricultural blue WFs estimated in **Chapter 6** for the five periods were taken as the WU and average outflows from the Maloney's Eye from 1909 to 1950 were taken as WA, because abstractions for irrigated agriculture only commenced after this period, and this average was assumed to represent natural outflows. Long term monthly and annual precipitation data from 1950 to 2012 was used to calculate the VF according to the formula given by

Pfister et al. (2009) (**Equation 2-13** of **Chapter 2**). The WS Indices for each of the five periods were compared to determine if it produces a relatively constant result that can be applied to a catchment over the long term. The WS Indices that were calculated for the five periods were also compared to the WS Index of 0.78 calculated for the region by Pfister et al. (2009) (**Figure 3-4**).

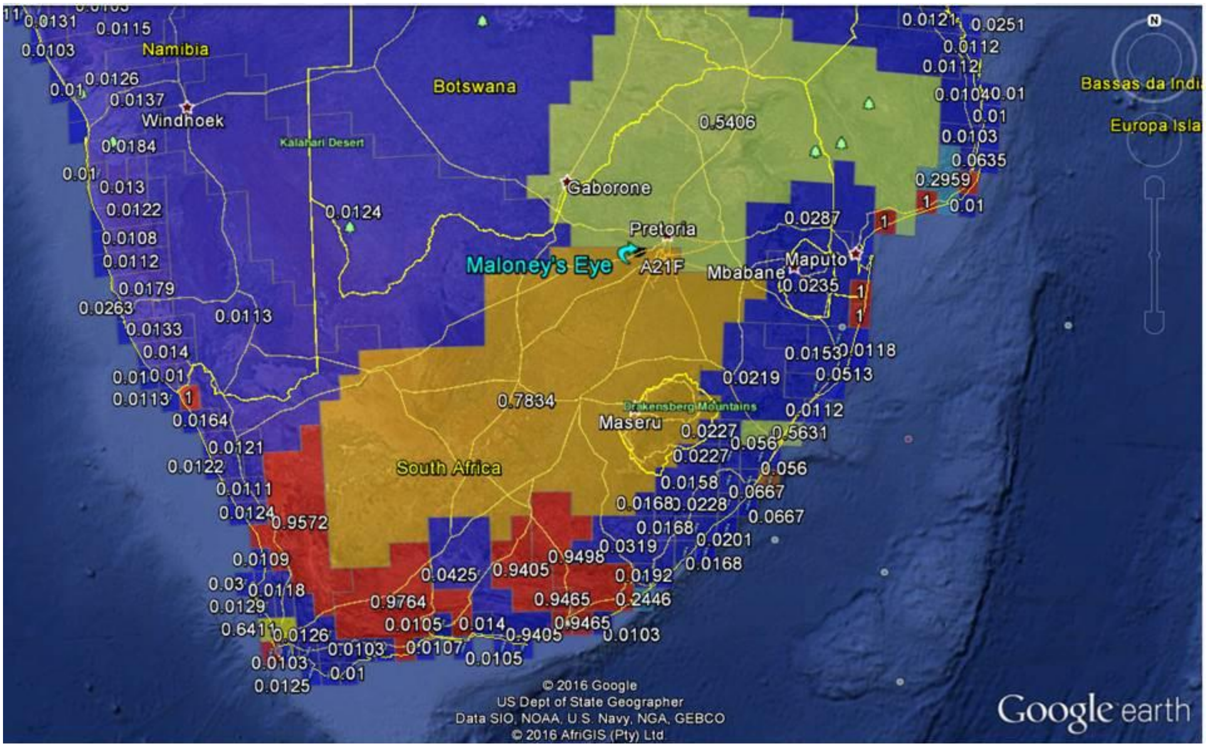

**Figure 3-4: The WS Index for South Africa as calculated according to the Life Cycle Assessment methodology by Pfister et al. (2009)**

## 3.3 RESULTS

### 3.3.1 SWB RESULTS

The verification of SWB irrigation and yield results are given in **Figure 3-5** and **Figure 3-6**, respectively. Irrigation is higher during winter even though atmospheric evaporative demand is lower, because the area receives little or no rainfall in winter and cooler temperatures lead to longer growing seasons. Irrigation and yield for lettuce is low because lettuce has a short growing season, while yields for broccoli are low, because of a low harvest index.

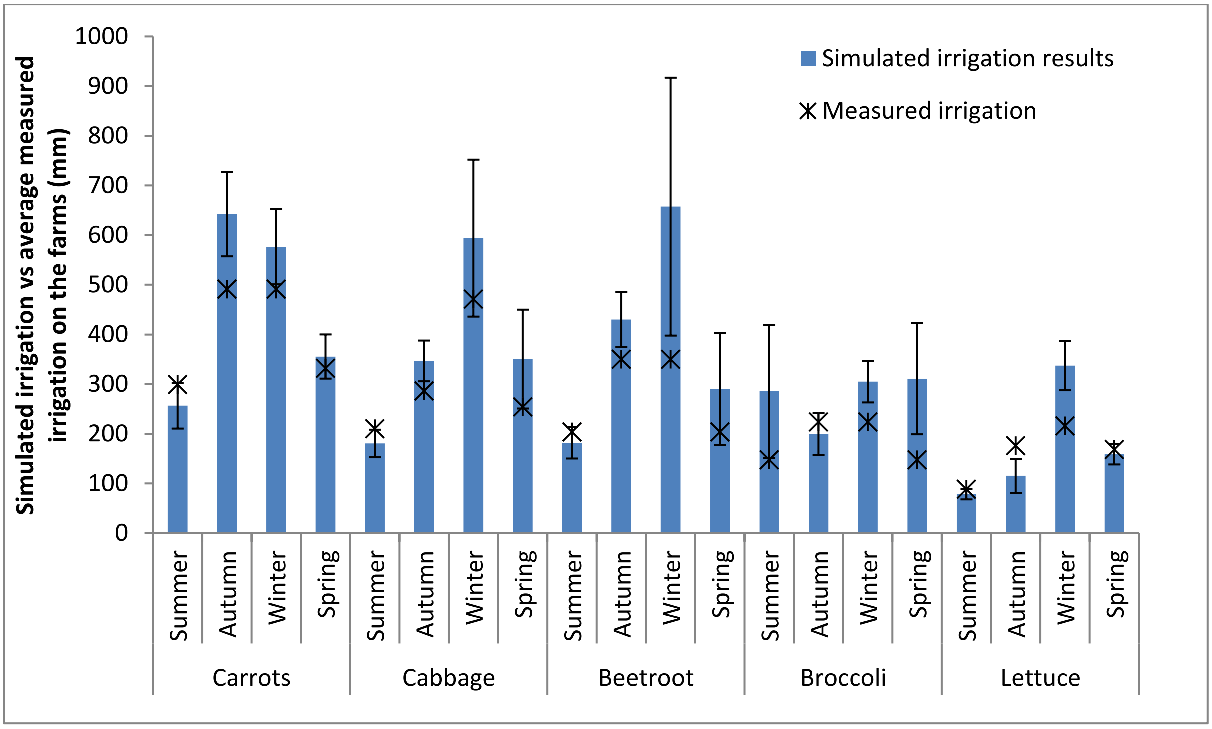

**Figure 3-5: Average of 10 year's (2004–2013) simulated seasonal irrigation with standard deviations (shown as error bars) of vegetable crops in the different growing seasons compared to measured irrigation verification data from farms on the Steenkoppies Aquifer.**

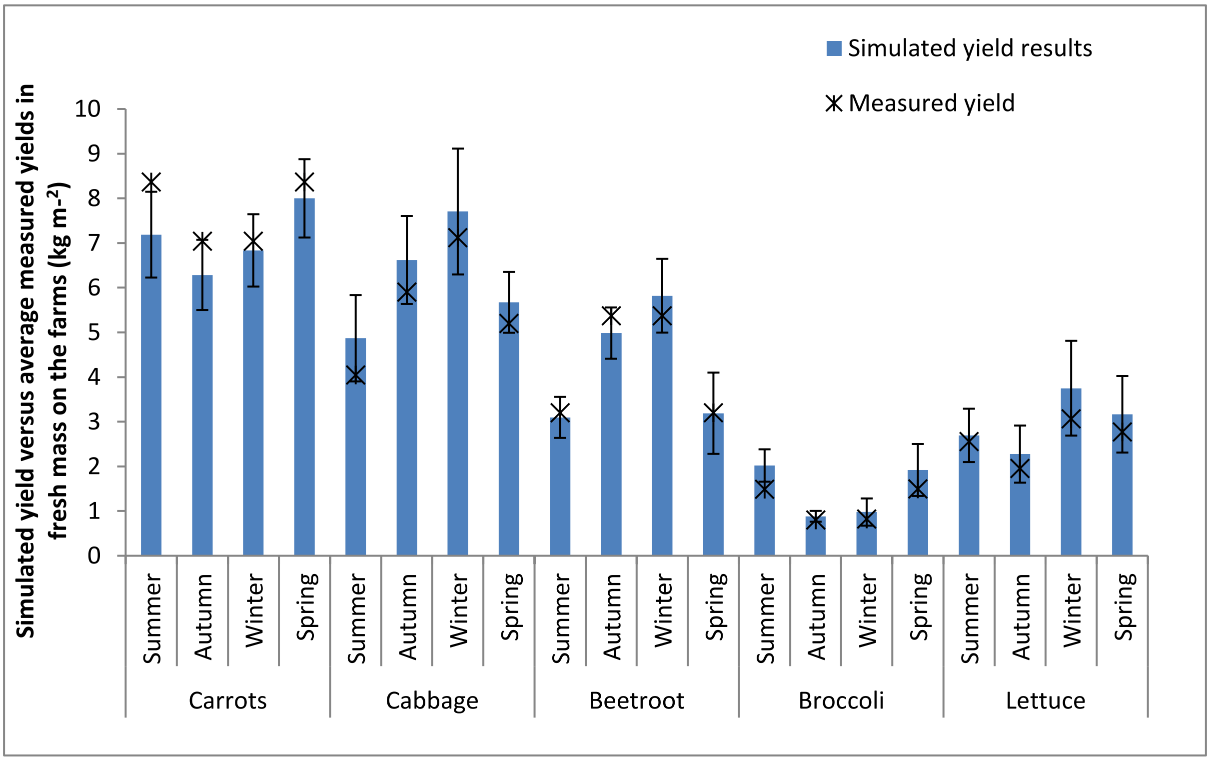

**Figure 3-6: Average of 10 year's (2004–2013) simulated seasonal yields with standard deviations (shown as error bars) of vegetable crops for the different growing seasons compared to measured fresh mass yield data from the farms on the Steenkoppies Aquifer.**

### 3.3.2 WATER FOOTPRINTS ACCORDING TO THE WFN

The WFN blue, green and grey WFs with fresh mass as the functional unit for the cultivation phase of each of the crops in each of the four growing seasons, and a single season in the case of maize and wheat, are given in **Table 3-8**. Compared to the other vegetables, broccoli has a high blue, green and grey WF, because the crop has a small harvestable portion, resulting in relatively low yields. The WFs of maize and wheat is notably higher than the vegetables. Key complexities in the calculations and interpretations of these WFs are discussed in **Chapter 5**, for example the use of fresh mass versus dry matter as a functional unit.

**Table 3-8: Average of 10 year's blue, green and grey water footprints (WFs) using fresh mass as a functional unit for cultivating the main vegetable and grain crops grown on the Steenkoppies Aquifer**

| **Crop** | **Month** | **Average crop ET (mm)** | **Average seasonal WFs of crops ($m^3$ $tonne^{-1}$)** | | | |
|---|---|---|---|---|---|---|
| | | | Blue | Green | Blue + Green | Grey |
| **Carrots** | Summer | 435 | 36 | 25 | 61 | 48 |
| | Autumn | 715 | 104 | 12 | 116 | 60 |
| | Winter | 628 | 88 | 7 | 95 | 52 |
| | Spring | 491 | 45 | 17 | 62 | 39 |
| **Cabbage** | Summer | 317 | 38 | 29 | 66 | 66 |
| | Autumn | 412 | 53 | 11 | 64 | 31 |
| | Winter | 599 | 77 | 1 | 79 | 18 |
| | Spring | 441 | 63 | 16 | 79 | 46 |
| **Beetroot** | Summer | 308 | 60 | 40 | 100 | 92 |
| | Autumn | 499 | 87 | 14 | 101 | 33 |
| | Winter | 670 | 121 | 3 | 124 | 20 |
| | Spring | 339 | 104 | 15 | 118 | 96 |
| **Broccoli** | Summer | 522 | 142 | 120 | 262 | 183 |
| | Autumn | 262 | 225 | 76 | 301 | 575 |
| | Winter | 304 | 322 | 5 | 327 | 540 |
| | Spring | 398 | 170 | 44 | 214 | 214 |
| **Lettuce** | Summer | 142 | 31 | 24 | 56 | 100 |
| | Autumn | 156 | 51 | 20 | 71 | 131 |
| | Winter | 334 | 93 | 1 | 93 | 56 |
| | Spring | 177 | 56 | 6 | 62 | 80 |
| **Maize** | Summer | 745 | 452 | 253 | 707 | 377 |
| **Wheat** | Winter | 619 | 732 | 30 | 762 | 443 |

### 3.3.3 BLUE AND GREEN WATER FOOTPRINTS ACCORDING TO THE HYDROLOGICAL METHODOLOGY

The blue and green WF results of the two and three crop rotations according to the hydrological methodology compared to the WFN methodology are displayed in **Figure 3-7**. The hydrological blue WFs of the three-crop rotation are higher than the two-crop rotation per tonne of crops produced. Average blue WFs according to the hydrological method are lower than average blue WFs according to the WFN method. This is because the WFN accounts for total ET, while the hydrological methodology considers rainfall to reduce the WF. The methodology for green WF calculations could not be applied here, because that requires simulations under rainfed conditions, which resulted in crop failures, especially during winter months. Green WF was assumed to be zero over the long term, because soil moisture is replenished in the rainy season.

Hydrological studies typically work in hydrological years, which include wet and dry seasons. For this reason it was proposed by Deurer et al. (2011) that WFs must also work according to the hydrological year. However, total annual water budgets over a hydrological year concealed seasonal green water scarcities and high WFs of certain crops, such as broccoli, which were clearly revealed by the WFN results.

Positive blue WFs according to the hydrological methodology indicate a net reduction in water in the aquifer under the two- and three- crop rotation fields. There are, however, areas on the aquifer with natural vegetation and other land uses where water is not abstracted from the aquifer, where a net recharge is expected. For example, as shown in **Figure 3-8**, 122 mm average drainage was estimated to occur under natural vegetation. Up-scaling to aquifer level is therefore required to fully understand the long-term sustainability of all land uses combined, and specifically the agricultural activities, on the aquifer. Doing the WF of the entire hydrological year required that crop sequences be used for the short season vegetable crops in this study and this complicated up-scaling to a catchment level. Up-scaling would require that typical crops sequences be used, instead of simply using total yields. Although there are only a few crops on the aquifer, there are numerous combinations of crops planted in different sequences over a year, which requires more assumptions and generalisations to be made to up-scale hydrological WFs to a catchment level.

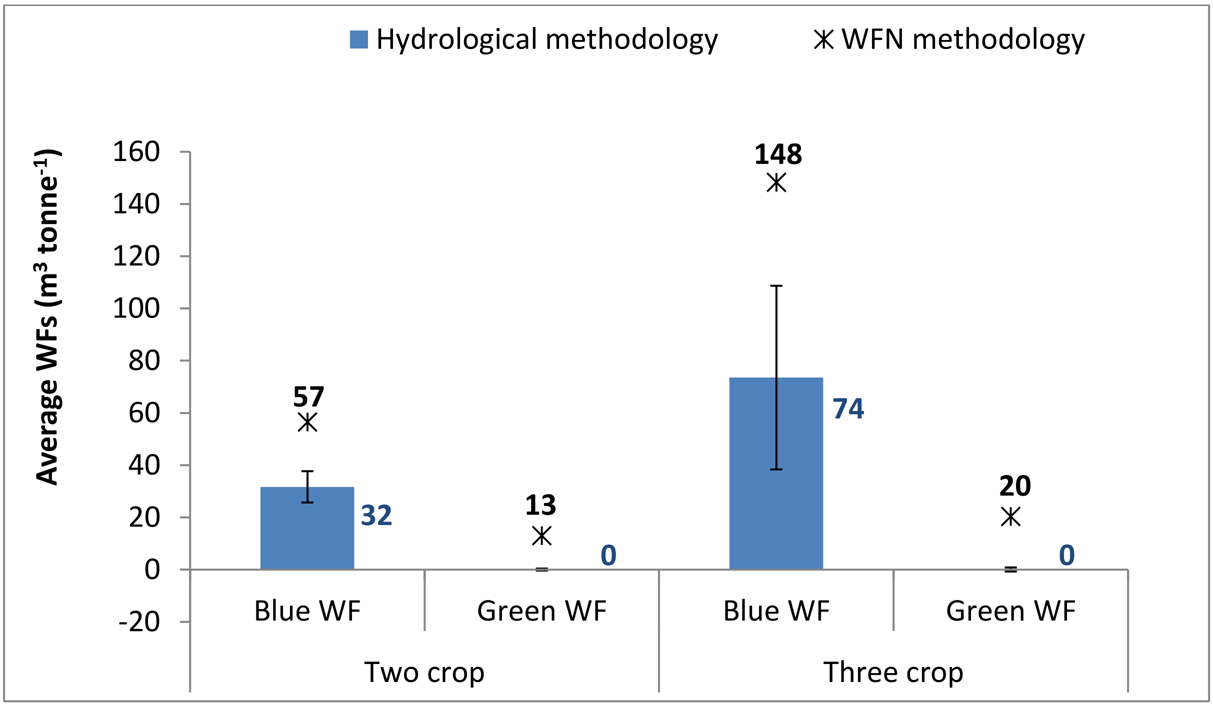

**Figure 3-7: Average of 10 year's hydrological blue and green water footprints (WFs) of an annual two crop rotation sequence (carrots summer and cabbage winter) and an annual three crop rotation sequence (broccoli winter, cabbage spring and beetroot summer) compared to average WFs according to the Water Footprint Network (WFN) methodology**

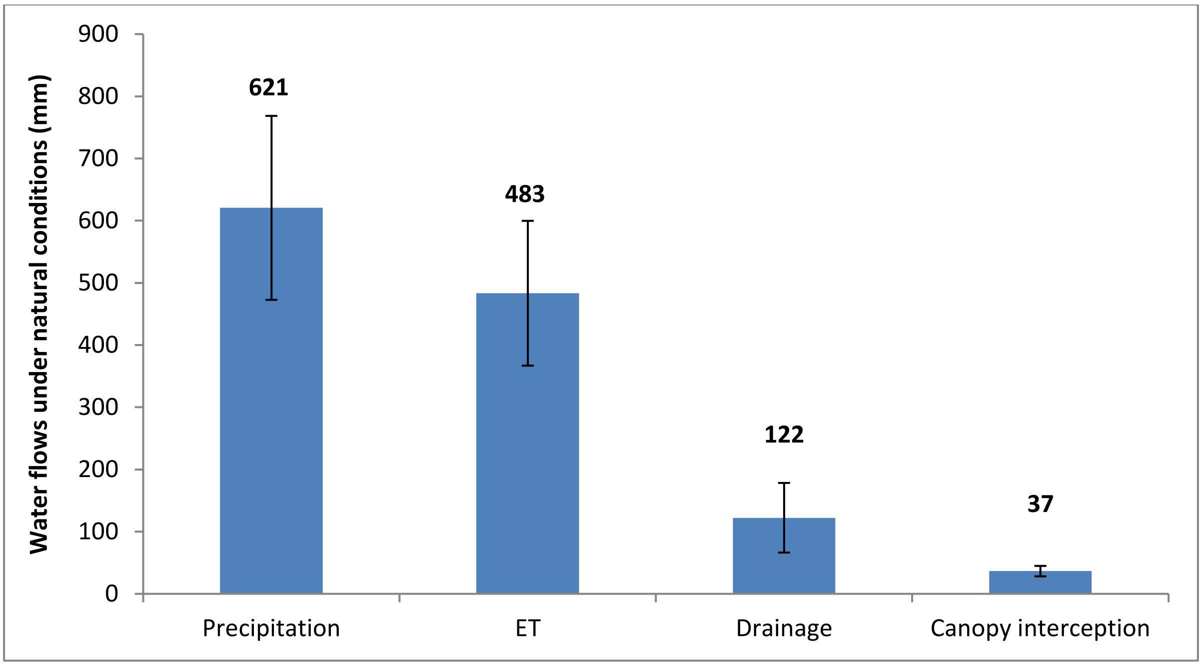

**Figure 3-8: Average of 10 year's precipitation, evapotranspiration (ET), drainage and canopy interception estimated for natural vegetation on the Steenkoppies Aquifer.**

### 3.3.4 BLUE WATER FOOTPRINTS ACCORDING TO THE LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

Water stress (WS) Indices for South Africa, as calculated by Pfister et al. (2009) are shown in **Figure 3-4**. The Maloney's Eye Catchment is at the northern border of an extremely large inland area of 452 765 km$^2$ with a WS Index of 0.78 (orange area in **Figure 3-4**). WS Indices calculated with more local data for five periods from 1950 to 2012 is given in **Table 3-9**. The relatively high VF of 30 was calculated for the Maloney's Eye Catchment, compared to the median VF of 1.8 that was used by Pfister et al. (2009) in a global case study. This high VF resulted in high WS Indices, even though it is reduced to 5.5 after taking the square root as formulated for regulated catchments such as the Maloney's Eye Catchment. For example, the WS Index for 1950 to 1980 where the WU is only 2 Mm$^3$ still exceeds the threshold (0.5) between moderate and severe water stress as specified by Pfister et al. (2009). There is, however, a notable difference between the WS Index of the first period and that of the later periods, due to differences in blue water use for agriculture on the Steenkoppies Aquifer. The WS Index given by Pfister et al. (2009) is also different from WS Indices calculated with local data.

**Table 3-9: Summary of Water Stress (WS) Indices for the Maloney's Eye Catchment and data used in the calculation for five periods from 1950 to 2012**

| Period | Average water use (Mm$^3$ yr$^{1-}$) | Average water availability (Mm$^3$ yr$^{1-}$) | Withdrawal to availability ratio | WS Index |
|---|---|---|---|---|
| **1950 to 1979** | 2 | 15 | 0.1 | 0.5 |
| **1980 to 1986** | 4 | 15 | 0.3 | 1.0 |
| **1987 to 1995** | 13 | 15 | 0.9 | 1.0 |
| **1996 to 2004** | 20 | 15 | 1.3 | 1.0 |
| **2005 to 2012** | 25 | 15 | 1.7 | 1.0 |
| **Average 1950 to 2012** | 10 | 15 | 0.7 | 1.0 |

WFs according to the LCA methodology were lower than the WFs according to the WFN methodology (**Table 3-10**). Looking at the comparison between WF results according to the WFN methodology and the LCA methodology, it appears as if the LCA methodology does not add much value since LCA WFs reduce the WFN WFs of all crops by the same proportions. However, the results are potentially useful to compare water use in one part of the country with similar water uses in other areas around the world. This method will therefore not be very useful to water resource managers working in one hydrologically linked catchment or aquifer where the water stress in one area will impact the entire system. Catchment managers may also require more quantitative data which gives them the option of interpreting data within their own information systems.

**Table 3-10: Average of 10 year's water footprints according to the Life Cycle Assessment (LCA) methodology**

| Crop | Season | Blue WF according to the Water Footprint Network (m$^3$ tonne $^{-1}$) | LCA Water footprint of the functional unit (m$^3$ $H_2O$ e) | | |
|---|---|---|---|---|---|
| | | | WS Index: 0.78[1] | WS Index: 0.5[2] | WS Index: 1[3] |
| **Carrots** | Summer | 36 | 28 | 18 | 36 |
| | Autumn | 104 | 82 | 52 | 104 |
| | Winter | 88 | 69 | 44 | 88 |
| | Spring | 45 | 35 | 22,5 | 45 |
| **Cabbage** | Summer | 38 | 30 | 19 | 38 |
| | Autumn | 53 | 42 | 26,5 | 53 |
| | Winter | 77 | 61 | 38,5 | 77 |
| | Spring | 63 | 50 | 31,5 | 63 |
| **Beetroot** | Summer | 60 | 47 | 30 | 60 |
| | Autumn | 87 | 68 | 43,5 | 87 |
| | Winter | 121 | 95 | 60,5 | 121 |
| | Spring | 104 | 81 | 52 | 104 |
| **Broccoli** | Summer | 142 | 112 | 71 | 142 |
| | Autumn | 225 | 176 | 112,5 | 225 |
| | Winter | 322 | 252 | 161 | 322 |
| | Spring | 170 | 133 | 85 | 170 |
| **Lettuce** | Summer | 31.3 | 24 | 15,65 | 31.3 |
| | Autumn | 51.2 | 40 | 25,6 | 51.2 |
| | Winter | 92.6 | 73 | 46,3 | 92.6 |
| | Spring | 56.2 | 44 | 28,1 | 56.2 |
| **Maize** | Summer | 453 | 355 | 226,5 | 453 |
| **Wheat** | Winter | 732 | 573 | 366 | 732 |

**[1.] Water Stress Index according to (Pfister et al., 2009); [2.] Water Stress Index calculated for 1950-1979 (Table 3-9); [2.] Water Stress Index calculated for 1980-2012 (Table 3-9)**

## 3.4 DISCUSSION

Water footprints according to the WFN can be useful in various ways, for example, because they can indicate high water uses per yield in certain seasons and by certain crops. However, the crop WFs according to the WFN, which is a volume of water used per yield of crop, can be misleading if communicated outside the context of the local circumstances and without the sustainability assessment step for the WF in a particular area. This raised concern from the LCA and hydrology communities, who indicated that a volume of water used must be interpreted within the local context. Although this is true, there are a number of challenges involved in producing a standard method that can cover all the complexities involved in understanding the impact of a water use on local resources.

The hydrological method takes all water flows into account, as opposed to the WFN that considers crop ET only. Although the hydrological method seems more comprehensive than the WFN method, the following issues were encountered in the assessment of the methodology:

- According to the hydrological methodology (Deurer et al., 2011), blue WFs are the difference between volumes abstracted through irrigation and volumes recharged due to deep drainage and runoff. In the original method by Deurer et al. (2011), runoff is considered to recharge the blue water source, which was groundwater in their case, because of the flat topography of their study area. However, in different circumstances runoff will more likely flow out from a catchment and will not replenish the aquifer. In this case, therefore, the method will overestimate aquifer replenishing rates and underestimate blue WFs.
- Green WF calculations are based on the change in soil moisture originating from rainfall. It was, however, not possible to calculate green WFs in the same way as the methodology suggests, because modelling under rainfed conditions are required and some of the crops will fail due to low rainfall, particularly in the dry winter season. The methodology for green WFs is therefore not considered suitable for an irrigation system, like the Steenkoppies Aquifer, and is more applicable to rainfed systems. For this study zero green WFs were assumed.
- Deurer et al. (2011) prescribes that WFs according to the hydrological approach are calculated over a year. To determine the WFs for the short season vegetable crops in this study, crop sequences were used for a year. This, however, concealed the high WFs of certain crops, like broccoli, and the impact on water resources in dry seasons.
- The methodology does not include guidelines on the water requirements of downstream users or specify the volumes of water that is required to flow from a particular catchment.
- Finally, the method was not also considered useful for the Steenkoppies Aquifer case study, because the WFs for the crop sequences presented more complexities to upscale the crop WF results to a catchment level.

The LCA methodology have some important strengths, most notably the more advanced calculation of water quality impacts in terms of eutrophication, freshwater ecotoxicity and human health (Pfister et al., 2009). The method takes multiple environmental impacts into account, like water consumption and carbon footprints. Considering the unique geohydrological characteristics and water issues of the Steenkoppies Aquifer, more local WS Indices are required. However, although spatial variations may impact the WS Index, the WS Index should also be sensitive to temporal variations. The LCA method addresses temporal variation by including a variation factor (VF) as a measure of variation in climatic conditions. The VF increases the WS Index of the catchment and will result in increased WFs. The VF is lower for catchments with dams or aquifers that regulate flows and reduce variations in water availability (Pfister et al., 2009). The aquifer will reduce variations in water availability, which will reduce the WS Index. The intensive use of the Steenkoppies Aquifer has caused severe reductions in groundwater levels and outflows from Maloney's Eye, and the aquifer has become more water-stressed as a result. Therefore, despite the inclusion of the VF, the increased WTA ratio created the need to have different WS Indices over time, as calculated and displayed in **Table 3-9**. Global average WS Indices may therefore not be incorrect only because of a lack in local data, but also because of temporal variations in WTA.

The aim of a WF assessment is to address sustainable water use. This must be done on national, regional and local levels and ultimately it must aim to change the behaviour of water consumers. The so-called knowledge hierarchy (Ackoff, 1989) provides a useful way to better understand the difference between WF methodologies and the complexities involved in developing and using them. As indicated in **Figure 3-9** (taken from Rowley (2007)), data is at the bottom of the knowledge hierarchy. Data that is interpreted becomes information, knowledge is the know-how or experience of what to do with information and wisdom is the judgement of whether our actions are right or wrong. In a WF context, the volume of water that is used to produce a product is data. This data only becomes informative when interpreted in a local context of water availability and environmental demand. Somehow the information should be communicated to consumers, producers and water resources managers in order for them to make wise decisions that will ensure the sustainability of the water used to produce a product. Awad and Ghaziri (2004) as cited by Rowley (2007) also indicates that data can be programmed, while wisdom cannot be programmed or generated by a computer (**Figure 3-9**). This is why it is really difficult to develop a WF method of which the outcome is an undisputed number that can be used on labels and will indicate 'right' or 'wrong' to a consumer.

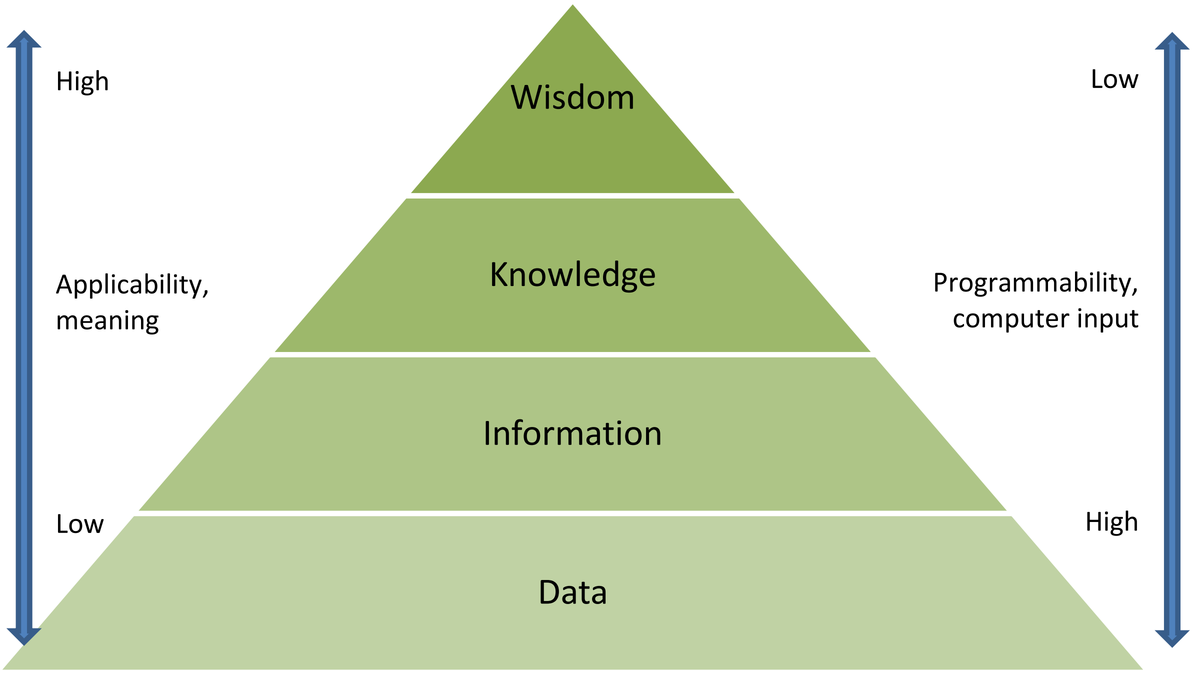

**Figure 3-9: The knowledge hierarchy (Rowley, 2007)**

Volumetric WFs according to the WFN methodology are at the level of data, defining the WF as a volume of water used to produce a product or provide a service. Data is often most valuable, because a water resource manager can interpret it within his specific location to get the necessary information for decision making. However, care must be taken not to communicate a WF defined as a volume of water used, which is mere data, as information or wisdom implying that a volume used is 'good' or 'bad'. For this reason, the LCA and hydrological communities developed modified methodologies seeking to interpret the data to obtain information (a better understanding of the water use in terms of water availability and the hydrology) and wisdom (the LCA methodology potentially providing consumers with a label that will indicate the degree of impact).

Although it is very important to get from data to wisdom, there are many complexities involved in standardising a method on these higher levels of the knowledge hierarchy. **Figure 3-9** taken from (Rowley, 2007) also indicates this, by showing that the higher levels of the knowledge hierarchy cannot be programmed and calculated by computers. For example, the WS Index calculated for the LCA methodology considers the availability of water within a certain area. Although it is important to consider water availability in relation to water use, it is not the only consideration in terms of sustainability. Water demands by the ecosystem, people or for economic use must all be considered. This can become very complex, taking ecological water requirements as an example. It is commonly recognised that flow reductions in rivers are not desirable (Lake, 2003) and that floods are important ecological events that flush the river from alien vegetation and sediments (Rountree, 2014). However, changes in the seasonality of flows such as increasing dry season flows and decreasing wet season flows, which is common in irrigation schemes, also have an impact on river ecosystems (Lake, 2003, Pattie et al., 1985, Rountree, 2014). Aquatic species are adapted to certain flow regimes, which support connectivity in the aquatic ecosystem and habitats (Bunn and Arthington, 2002). Changes to geohydrological characteristics, such as groundwater converted to surface water are undesirable (Rountree, 2014). Managing water uses to ensure the sustainability of a river ecosystem is further complicated by differences in river sensitivities. Maintaining natural flows of rivers are more important if the aquatic and riparian biodiversity is sensitive with, for example, red data species (Rountree, 2014). Often a water resource manager has to decide whether to allocate water to people or ecosystems, which involves trade-offs of various impacts. These are only some of the complexities associated with the water demand of an ecosystem, and the WFs according to the LCA methodology do not address these.

One of the drawbacks of water becoming a global resource is that the water users become disconnected from and unaware of the impacts of their water uses. It is therefore very important to consider ways of influencing consumer behaviour. How this should be done has been debated by scientists that are involved in WF assessments. The volumetric WF of the WFN is not a suitable metric for communication to consumers and for product labelling, because it cannot be used outside the environmental context of the water use. The ISO standards (ISO 14046 2014) did not specify ways of reporting WFs to consumers for awareness raising, indicating that they too struggled with the complexity of standardising such a method. The other methods have attempted to interpret and modify the WFN data, most notably the LCA method that aimed to produce product labels. This study on WFs has indicated that calculating WF labels still requires much refinement and debate and will most likely result in a symbol indicating responsible water use or stewardship, as opposed to a quantitative or even stress-weighted volumetric WF label. Consumers need all levels of the knowledge hierarchy (data, information, knowledge and wisdom) to make educated decisions about the products they buy. However, influencing consumers through education may have unpredictable outcomes. Some consumers may choose products based on potential impacts on people, others could make decisions based on ecological sustainability. Advertisement and marketing is another way of influencing market demands and the interpretation of information. Crops with a sustainable WF according to local assessments could be promoted above crops with unsustainable WFs. Governments can subsidise crops with sustainable WFs to reduce their retail prices. Future studies must pay attention to the various ways in which consumer behaviour can be influenced to change market demands.

## 3.5 CONCLUSIONS

Through a case study on the Steenkoppies Aquifer, three WF methodologies were assessed and compared in terms of their usefulness to water resource managers and consumers. It is concluded that blue and green water footprints calculated according to the WFN methodology are most useful for a catchment or aquifer manager, because it is quantitative and can therefore do the following:

- They potentially indicate high WFs of certain vegetables, like broccoli.
- They reveal WFs in the dry winter season.
- They are relatively simple to calculate and understand.

- They can be used within different information systems, such as water use licencing or water allocation decisions.

The concern over the way in which WFs of the WFN is communicated outside the context of the environment in which the water is used, is however, legitimate and these results should not be used for awareness raising. The other two methodologies attempt to develop a single value that will indicate the sustainability of a water use, but due to the vast number of variables, complexities and trade-offs involved in sustainable water use, such a number seems to be an unrealistic goal. Product labels will more likely be in the form of a symbol that indicates good water stewardship.

The WFN methodology was therefore selected to apply in further assessments on the Steenkoppies Aquifer. For the remainder of this thesis, the term WFs therefore refers to the WFN results given in **Table 3-8**, unless specified otherwise. In the next chapter the WFN methodology is used to determine the WF of cleaning and packaging crops in the packhouse.

# 4 CHAPTER 4: WATER FOOTPRINTS OF CROPS IN THE PACKHOUSE

## 4.1 INTRODUCTION

It has often been proven that the evapotranspiration (ET) of a crop during the cultivation phase constitutes the largest portion of the total water used to produce agricultural products (Dominguez-Faus et al., 2009, Hoekstra et al., 2011, Hoekstra and Chapagain, 2011, Ridoutt and Pfister, 2010). For this reason, most water footprint (WF) studies place a lot of emphasis on water used during the cultivation phase. The ET of crops during cultivation defined the scope of **Chapter 3**. The aim of this chapter is to quantify the blue and grey WFs of different vegetable crops at the packhouse level. The water used in a packhouse on the Steenkoppies Aquifer was compared to the crop WFs during cultivation from **Chapter 3**, to determine the relative impact the water use in the packhouse will have on the sustainability of the water use on the catchment.

## 4.2 MATERIALS AND METHODS

### 4.2.1 SCREENING ASSESSMENT OF THE PACKHOUSE

Initially three packhouses were visited and selected for monitoring, but due to a lack of willingness to cooperate, two of these packhouses were excluded from further monitoring. The packhouses differed in terms of the produce that was processed, the equipment they used and what they did with the produce (for example washing, packaging etc). It may therefore be necessary to investigate other packhouses in future research. However, the packhouse that was assessed cleaned carrots, used equipment that required relatively high volumes of water and included all relevant processes from cleaning to packaging. The water use in this packhouse was therefore considered to represent the maximum volume of water required for processing of crops. The selected packhouse on the Steenkoppies Aquifer was visited to do initial screening (**Figure 4-1**). A qualitative assessment was done on the packhouse to determine what equipment was used for the different crops that were cleaned and packed and to better understand the flow of water through the packhouse. During this screening exercise, a suitable place was identified where a flow meter could be installed, which included all packhouse activities, but excluded washrooms and toilets and other facilities used by staff, but not appropriate for inclusion in the WFs of vegetable crops. The water used by the staff is excluded, because, as indicated by Hoekstra et al. (2011), this water use is not a direct consequence of the crop packaging, and would have occurred even if there were no production or packhouse activities. The selected packhouse currently processes on average 53 tonnes carrots (*Daucus carota*), 38 tonnes cabbage (*Brassica oleracea*) and 13 tonnes lettuce (*Lactuca sativa*) per day. The other crops investigated in **Chapter 3** are not currently packed or cleaned on the Steenkoppies Aquifer. The packhouse operated every weekday, and closes for weekends and holidays.

During the screening assessment, it was observed that cabbage and lettuce heads do not require extensive cleaning and therefore use very little water, apart from a bucket or two that is used to clean the work station at the end of each day. Carrots, however, require an extensive process of getting rid of sand, cleaning, polishing and hydrocooling, which uses both water and electricity. Electricity, which is an indirect water use, is also used for lights, conveyor belts, water pumps and computers. For this chapter the indirect WF of electricity use were also calculated.

**Figure 4-1: Cabbage and carrots packed and cleaned in a packhouse on the Steenkoppies Aquifer**

A schematic representation of the process of cleaning carrots is illustrated in **Figure 4-2**. A more recent development in the packhouse is a series of ponds for water treatment, after which water is recycled back into the packhouse. Sludge from the pond system is discharged into an artificial wetland. This is, however, not a common practice in the packhouses in the study area. Water inputs through boreholes are still required by the polisher on a daily basis and by the hydrocooler every second week. The flow meter was installed to measure these water inputs over a three-month period during the winter and spring seasons (June to September). There are, therefore, three different water flows, including water recycled within the system, borehole water inputs and sludge outputs. A flow meter was installed at the main inlet where groundwater enters the packhouse.

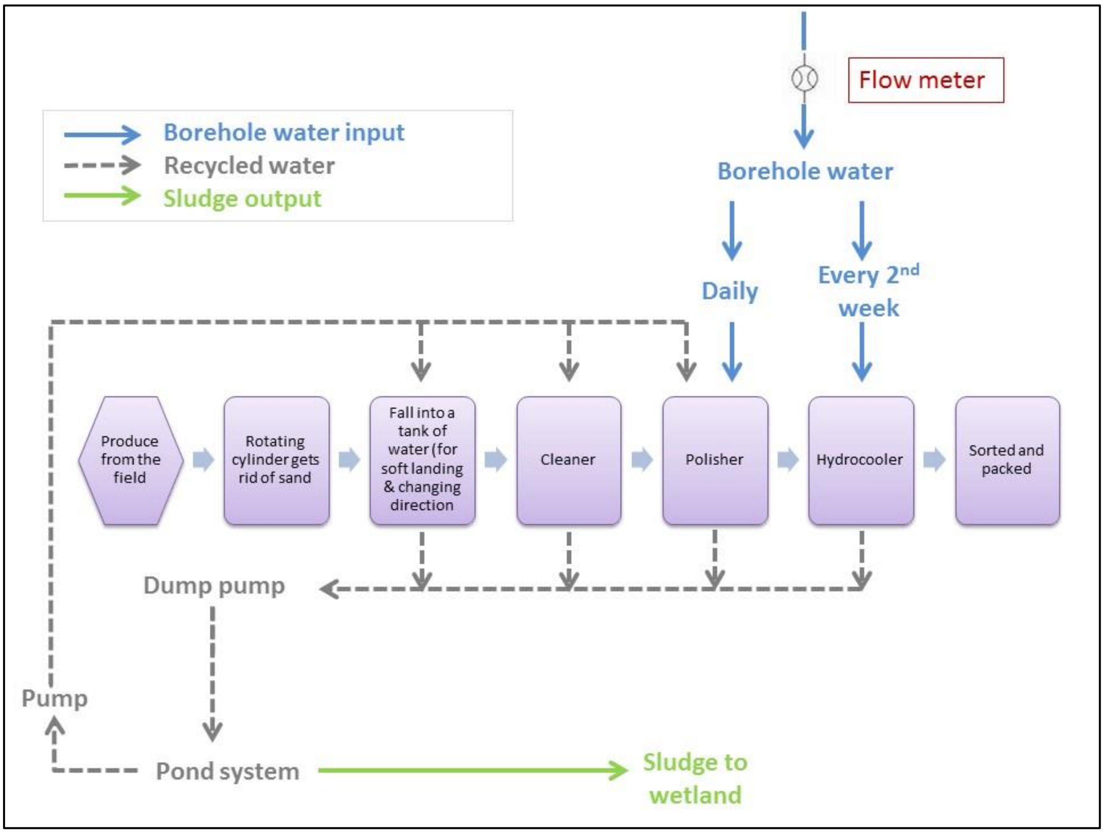

**Figure 4-2: Schematic representation of the process of cleaning and cooling carrots in a packhouse on the Steenkoppies Aquifer.**

### 4.2.2 BLUE WATER FOOTPRINT OF PROCESSING CROPS IN THE PACKHOUSE

Packhouse blue WFs for carrots, cabbage and lettuce were calculated according to the WFN methodology. The blue WF in the packhouse includes direct water used for cleaning and cooling as well as water used indirectly through electricity use. A ‘40 MS’ multi-jet magnetic water meter (Arad, Israel) was installed at the main inflow to the packhouse in June 2016. Flow measurements were taken daily before operations start. The total water flowing into the packhouse had to be apportioned to each vegetable that was cleaned and packed as well as to general cleaning of the packhouse. Data is not available to do this and it was thus based on estimates given by the packhouse managers. According to the packhouse manager, 70% of water used in the packhouse was used for carrots, because of the polisher and hydrocooler used for cleaning carrots, 5% was used for cabbage and 5% for lettuce. The remaining 20% was used for general packhouse maintenance and cleaning. General cleaning and maintenance of the packhouse cannot be ascribed directly to any specific crop, and therefore the percentage water used for cleaning the packhouse was apportioned to carrots, cabbage and lettuce based on the average quantities of each crop that are packed. Thus, 76.6 %, 11.6% and 11.6% of the total inflows into the packhouse were apportioned to carrots, cabbage and lettuce, respectively.

Daily production reports for the full period while the flow meter was monitored, June to September, were obtained which indicated quantities of different vegetables that have been packed in the packhouse (Production Report, 2016). These reports indicated both quantities of crops received by the packhouse and quantities packed by the packhouse, the difference was assumed to be wastage. To determine water used per crop, the quantities received by the packhouse were used as opposed to the quantities packed. The difference in packhouse level water use between vegetables that were received and vegetables that were packed is considered wasted water.

### 4.2.3 GREY WATER FOOTPRINT OF PROCESSING CROPS IN THE PACKHOUSE

Grey WFs of cleaning and packing vegetables in the packhouse were determined using **Equation 2-6** given in **Chapter 2**. Grab samples of effluent were taken from two packhouses on the Steenkoppies Aquifer for water quality analyses (**Table 4-1**). Chemical Oxygen Demand (COD) exceeded wastewater discharge limits, indicating high concentrations of organic material in the effluent. The exceptionally high concentrations of COD in the effluent water, indicates that COD is actually the most critical pollutant. However, methodology has not been developed to understand the fate of COD concentrations and how it impacts the water quality of the aquifer, which should be addressed in future research. The results indicated that both inorganic nitrogen (N) and phosphorus (P) concentrations were within wastewater discharge limits. When considering the limits for N and P to maintain ecosystems and prevent eutrophication (Department of Water Affairs and Forestry, 1996), P concentrations were of greater concern.

**Table 4-1: Water quality analyses for effluent grab samples taken at two packhouses on the Steenkoppies Aquifer**

| **Analyses** | **Sample Identification** | | **Aquatic Ecosystems Limits (Department of Water Affairs and Forestry, 1996)** |
|---|---|---|---|
| | **Farm A** | **Farm B** | **Eutrophic conditions** |
| **pH – Value at 25°C** | 6.9 | 6.3 | |
| **Nitrate as N (mg ℓ$^{-1}$)** | <0.2 | <0.2 | **2.5-10** |
| **Nitrite as N (mg ℓ$^{-1}$)** | <0.1 | <0.1 | |
| **Total Phosphate as P (mg ℓ$^{-1}$)** | 5.1 | 6.9 | **0.025-0.25** |
| **Ortho Phosphate as P (mg ℓ$^{-1}$)** | 0.6 | 1.5 | |
| **Biochemical Oxygen Demand as $O_2$ (mg ℓ$^{-1}$)** | 72 | 72 | |
| **Chemical Oxygen Demand as $O_2$ (Total) (mg ℓ$^{-1}$)** | 480 | 1 040 | |
| **Free & Saline Ammonia as N (mg ℓ$^{-1}$)** | <0.2 | <0.2 | |

The lower limit of total phosphate in eutrophic conditions according to the Department of Water Affairs and Forestry (1996) is 0.025 mg ℓ $^{-1}$, which was taken as $C_{max}$. The natural concentration ($C_{nat}$) is the P concentration of the water if no human influences are present. In general the aquifer has very low P concentrations, with a median value of 0.007 mg ℓ $^{-1}$, based on 327 observations between 1978 and 2014 (Department of Water Affairs, 2014). There were, however, some outliers in the dataset with extremely high P concentrations, resulting in an average of 0.014 mg ℓ $^{-1}$, which is much higher than the median. These outliers were most likely caused by agricultural activities and must be excluded from the value used as $C_{nat}$. Thus, median natural P concentrations of the aquifer were considered to represent the natural conditions and were taken as $C_{nat}$. Total P concentrations in the effluent were used in the load, and not the surplus, because the surplus only applies to the cultivation phase.

It was assumed that the average volume of effluent discharged equals the average volume of water flowing into the packhouse. The P concentration was multiplied by the average volume of water used per crop (determined according to methodology described in **Section 4.2.2**) to determine the load of P released in effluent outflows. It was assumed that carrots, cabbage and lettuce contribute equally to the total P concentration in the effluent. The effluent is discharged in ponds outside the packhouse and can therefore return to the aquifer. The fate of phosphate and the fraction that leaches to the aquifer is therefore important to determine the actual load for grey WF calculations. The first step in determining the leaching-runoff potential was to complete the score card given in **Table 4-2**. The weighted scores were used to calculate the leaching-runoff potential in terms of P applied (β) using **Equation 4-1** (Franke et al., 2013).

$$\beta = \beta_{min} + \left(\frac{\sum_i S_i \; x \; W_i}{\sum_i W_i}\right) x \; (\beta_{max} - \beta_{min})$$

**Equation 4-1**

where *β* is the leaching-runoff potential of P discharged, *S* is the scores in Row *x* of **Table 4-2**, *W* is the weights in Column *y* of **Table 4-2**. $\beta_{min}$ and $\beta_{max}$ are the minimum and maximum leaching-runoff potential. For P a $\beta_{min}$ value of 0.0001 was used and $\beta_{max}$ was taken to be 0.1 as given by Franke et al. (2013). The fraction of P leaching to the aquifer was divided by total production, taken from the daily production reports of July 2016 to obtain total P load per tonne of crop.

Table 4-2: Determination of the leaching-runoff potential of phosphates (Franke et al., 2013)

| Category | Factor | | Leaching-runoff potential | Very low | Low | High | Very high | Weighted score* |
|---|---|---|---|---|---|---|---|---|
| | | | **Score (s)** | **0** | **0.33** | **0.67** | **1** | |
| | | | **Weight** | | | | | |
| **Environmental factors** | Soil | Texture (relevant for runoff) ** | 25 | Sand | Loam | Silt | Clay | 8.25 |
| | | Soil erosion ** | 25 | Low | Moderate | High | Very high | 8.25 |
| | | P content (g P $m^{-2}$) ** | 20 | <200 | 200-400 | 400-700 | >700 | 13.4 |
| | Climate | Rain intensity | 15 | Light | Moderate | Strong | Heavy | 4.95 |
| **Agricultural factors** | Management practice | | 15 | Best | Good | Average | Worst | 10.05 |
| **Total score to be used for leaching-runoff fraction (no units applicable)** | | | | | | | | **0.45** |

*The weighted score is calculated by multiplying the score in the second row with the weight in the fourth Column. **Data taken from Franke et al. (2013)

### 4.2.4 ASSESSMENT OF INDIRECT WATER USE IN THE PACKHOUSE

Generating electricity is a water intensive process and this indirectly contributes to the WF of processing vegetables in the packhouse. This water use is part of the WF of crops, although the water that is used does not originate from the aquifer, so it is an indirect WF. Data on electricity use in the packhouse was obtained from electricity bills over 13 months from November 2014 to October 2015. The electricity measurements, however, also includes two borehole pumps and the farm house together with the packhouse electricity use. The accountant indicated that the packhouse use of electricity represents 85% of the total electricity use. Electricity in South Africa is mostly generated by the parastatal, Eskom, through coal-fired power stations. Eskom uses an average of 1.32 liters of water to generate 1 kilowatt hour of electricity that is generated (Eskom, 2016). This relatively low volume of water used for electricity generation has been achieved through the implementation of dry-cooling technology in certain power stations, which typically results in the total water usage in a power station to be 15 times lower than conventional wet-cooled power stations (Eskom, 2016). This average value was used to convert the electricity use to an indirect water use. The total electricity use in the packhouse was apportioned to individual vegetables packed according to the percentages 76.6%, 11.6% and 11.6% for carrots, cabbage and lettuce, respectively, as detailed in **Section 4.2.2**. Carrots are also expected to use the higher proportion of electricity, because of the extensive process required for cleaning and packing carrots which includes the polisher and hydrocooler. Input volumes from daily production reports for the same period (November 2014 to October 2015) were obtained and used for the WF calculations.

## 4.3 RESULTS

### 4.3.1 BLUE WATER FOOTPRINT IN THE PACKHOUSE

The blue WFs of packing and cleaning carrots, cabbage and lettuce in a packhouse on the Steenkoppies Aquifer are 1.3 m$^3$ tonne$^{-1}$, 0.3 m$^3$ tonne$^{-1}$ and 0.9 m$^3$ tonne$^{-1}$, respectively (**Table 4-3** and **Figure 4-3**). The measured blue water entering the packhouse were considered as the blue water consumed, and not as return flow recharging the groundwater, because it was assumed that very little of this relatively small quantity of water will recharge the aquifer. These packhouse WFs are notably much lower compared to average blue WFs of cultivation in all growing seasons, which were 68 m$^3$ tonne$^{-1}$, 58 m$^3$ tonne$^{-1}$ and 58 m$^3$ tonne$^{-1}$ for carrots, cabbage and lettuce, respectively (**Chapter 3**). Thus, the packhouse blue WFs for carrots, cabbage and lettuce were, respectively, 2.2%, 0.5% and 1.6% of the average cultivation blue WFs taken over all seasons. **Figure 4-4** to **4-6** shows the proportions of packhouse WFs in relation to the blue plus green and grey WFs during cultivation of carrots, cabbage and lettuce, respectively.

More than 76% of the water used in the packhouse was attributed to carrot processing, because of the extensive requirements for cleaning and cooling, which explains the relatively high WF of carrots during this stage. The WF of lettuce in the packhouse is higher than cabbage, even though it was assumed that both use 11.6% of the total water supplied to the packhouse (**Section 4.2.2**). This is because the weight of lettuce heads (average of 0.6 kg) is much lower than that of cabbage (average of 3.5 kg), which resulted in a lower yield in terms of mass. If water used per crop heads was determined, the WF of lettuce would have been lower than that of cabbage during this stage, because the input volumes of lettuce are higher than cabbage in terms of crop head counts.

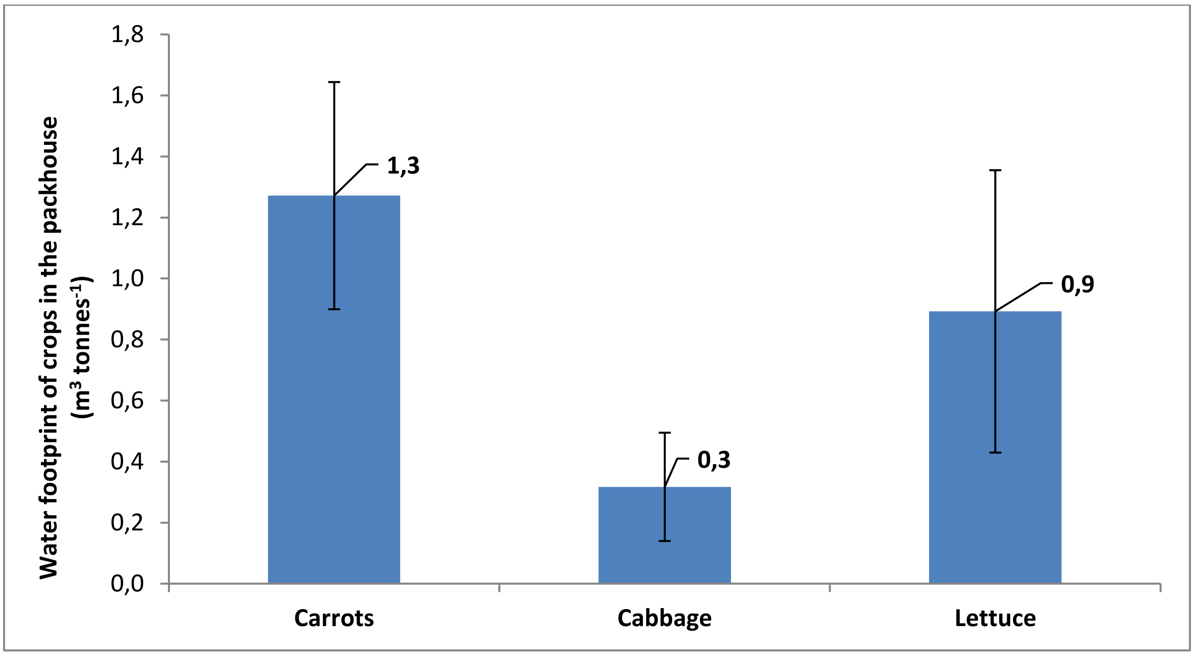

**Figure 4-3: Blue water footprints of carrots, cabbage and lettuce for cleaning and packing in a packhouse on the Steenkoppies Aquifer**

**Table 4-3: Blue water footprints (WFs) for cleaning and packing carrots, cabbage and lettuce in the packhouse**

| Date | Flow meter ($m^3$ $day^{-1}$) | Water use attributed to crop ($m^3$ $day^{-1}$) | | | Production (tonnes) | | | Blue water footprint ($m^3$ $tonne^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Carrots | Cabbage | Lettuce | Carrots | Cabbage | Lettuce | Carrots | Cabbage | Lettuce |
| **24-Jun-16** | 93 | 72 | 11 | 11 | 79 | 24 | 11 | 0,9 | 0,4 | 1,0 |
| **25-Jun-16** | 114 | 87 | 13 | 13 | 76 | 58 | 18 | 1,2 | 0,2 | 0,7 |
| **27-Jun-16** | 108 | 83 | 13 | 13 | 87 | 85 | 13 | 1,0 | 0,1 | 1,0 |
| **29-Jun-16** | 105 | 81 | 12 | 12 | 63 | 68 | 19 | 1,3 | 0,2 | 0,7 |
| **30-Jun-16** | 100 | 77 | 12 | 12 | 63 | 60 | 16 | 1,2 | 0,2 | 0,7 |
| **01-Jul-16** | 187 | 143 | 22 | 22 | 50 | 36 | 16 | 2,8 | 0,6 | 1,3 |
| **06-Jul-16** | 92 | 71 | 11 | 11 | 69 | 75 | 12 | 1,0 | 0,1 | 0,9 |
| **07-Jul-16** | 93 | 72 | 11 | 11 | 63 | 55 | 13 | 1,1 | 0,2 | 0,8 |
| **08-Jul-16** | 99 | 76 | 12 | 12 | 60 | 39 | 5 | 1,3 | 0,3 | 2,4 |
| **09-Jul-16** | 111 | 85 | 13 | 13 | 38 | 45 | 10 | 2,2 | 0.3 | 1.3 |
| **11-Jul-16** | 92 | 71 | 11 | 11 | 63 | 93 | 6 | 1,1 | 0,1 | 1,8 |
| **12-Jul-16** | 93 | 72 | 11 | 11 | 54 | 61 | 13 | 1,3 | 0,2 | 0,8 |
| **13-Jul-16** | 92 | 71 | 11 | 11 | 63 | 63 | 12 | 1,1 | 0,2 | 0,9 |
| **14-Jul-16** | 93 | 72 | 11 | 11 | 63 | 50 | 8 | 1,1 | 0,2 | 1,4 |
| **15-Jul-16** | 126 | 97 | 15 | 15 | 50 | 74 | 28 | 1,9 | 0,2 | 0,5 |
| **18-Jul-16** | 93 | 72 | 11 | 11 | 57 | 53 | 16 | 1,3 | 0,2 | 0,7 |
| **19-Jul-16** | 96 | 74 | 11 | 11 | 50 | 48 | 14 | 1,5 | 0,2 | 0,8 |
| **20-Jul-16** | 93 | 72 | 11 | 11 | 54 | 48 | 12 | 1,3 | 0,2 | 0,9 |
| **15-Aug-16** | 105 | 81 | 12 | 12 | 48 | 49 | 17 | 1,7 | 0,2 | 0,7 |
| **16-Aug-16** | 106 | 82 | 12 | 12 | 59 | 22 | 16 | 1,4 | 0,6 | 0,8 |
| **17-Aug-16** | 104 | 80 | 12 | 12 | 63 | 30 | 18 | 1,3 | 0,4 | 0,7 |
| **18-Aug-16** | 105 | 81 | 12 | 12 | 62 | 25 | 24 | 1,3 | 0,5 | 0,5 |
| **19-Aug-16** | 180 | 138 | 21 | 21 | 126 | 73 | 53 | 1,1 | 0,3 | 0,4 |
| **22-Aug-16** | 104 | 80 | 12 | 12 | 68 | 39 | 12 | 1,2 | 0,3 | 1,0 |
| **23-Aug-16** | 104 | 104 | 0 | 0 | 52 | 0 | 0 | 2,0 | - | - |
| **24-Aug-16** | 106 | 106 | 0 | 0 | 63 | 0 | 0 | 1,7 | - | - |
| **25-Aug-16** | 102 | 78 | 12 | 12 | 58 | 22 | 16 | 1,4 | 0,5 | 0,7 |
| **26-Aug-16** | 273 | 209 | 32 | 32 | 46 | 55 | 50 | 4,5 | 0,6 | 0,6 |
| **29-Aug-16** | 103 | 79 | 12 | 12 | 62 | 39 | 16 | 1,3 | 0,3 | 0,8 |
| **30-Aug-16** | 103 | 79 | 12 | 12 | 49 | 34 | 28 | 1,6 | 0,4 | 0,4 |
| **31-Aug-16** | 102 | 78 | 12 | 12 | 53 | 40 | 22 | 1,5 | 0,3 | 0,5 |
| **01-Sep-16** | 106 | 82 | 12 | 12 | 56 | 43 | 18 | 1,5 | 0,3 | 0,7 |
| **02-Sep-16** | 61 | 47 | 7 | 7 | 73 | 15 | 16 | 0,6 | 0,5 | 0,4 |
| **03-Sep-16** | 61 | 47 | 7 | 7 | 62 | 17 | 9 | 0,8 | 0,4 | 0,7 |
| **04-Sep-16** | 61 | 47 | 7 | 7 | 27 | 21 | 10 | 1,8 | 0,3 | 0,7 |
| **05-Sep-16** | 107 | 82 | 12 | 12 | 66 | 48 | 5 | 1,3 | 0,3 | 2,7 |
| **06-Sep-16** | 106 | 82 | 12 | 12 | 68 | 45 | 10 | 1,2 | 0,3 | 1,3 |
| **07-Sep-16** | 104 | 80 | 12 | 12 | 57 | 51 | 10 | 1,4 | 0,2 | 1,3 |
| **08-Sep-16** | 105 | 81 | 12 | 12 | 60 | 53 | 11 | 1,3 | 0,2 | 1,1 |
| **12-Sep-16** | 104 | 80 | 12 | 12 | 59 | 38 | 9 | 1,4 | 0,3 | 1,3 |
| **13-Sep-16** | 103 | 79 | 12 | 12 | 54 | 44 | 8 | 1,5 | 0,3 | 1,5 |
| **14-Sep-16** | 102 | 78 | 12 | 12 | 50 | 57 | 14 | 1,6 | 0,2 | 0,9 |
| **16-Sep-16** | 108 | 83 | 13 | 13 | 62 | 40 | 18 | 1,3 | 0,3 | 0,7 |
| **17-Sep-16** | 109,4 | 84 | 13 | 13 | 24 | 57 | 23 | 3,4 | 0,2 | 0,5 |
| **19-Sep-16** | 104 | 80 | 12 | 12 | 52 | 68 | 20 | 1,5 | 0,2 | 0,6 |
| **20-Sep-16** | 104 | 80 | 12 | 12 | 61 | 75 | 22 | 1,3 | 0,2 | 0,6 |
| **21-Sep-16** | 106 | 82 | 12 | 12 | 76 | 59 | 24 | 1,1 | 0,2 | 0,5 |
| **22-Sep-16** | 104 | 140 | 0 | 0 | 79 | 0 | 0 | 1,3 | - | - |
| **23-Sep-16** | 56 | 43 | 7 | 7 | 68 | 45 | 14 | 0,6 | 0,1 | 0,5 |

| Date | Flow meter ($m^3$ $day^{-1}$) | Water use attributed to crop ($m^3$ $day^{-1}$) | | | Production (tonnes) | | | Blue water footprint ($m^3$ $tonne^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Carrots | Cabbage | Lettuce | Carrots | Cabbage | Lettuce | Carrots | Cabbage | Lettuce |
| **24-Sep-16** | 58 | 44 | 7 | 7 | 16 | 51 | 24 | 2,8 | 0,1 | 0,3 |
| **26-Sep-16** | 108 | 83 | 13 | 13 | 64 | 65 | 29 | 1,3 | 0,2 | 0,4 |
| **Average** | **95** | **69** | **10** | **10** | **46** | **28** | **9** | **1.3** | **0.3** | **0.9** |

### 4.3.2 GREY WATER FOOTPRINT AT THE PACKHOUSE LEVEL

The data used to calculate P loads discharged per tonne of crop produced are summarized in **Table 4-4**. The leaching-runoff potential fraction was determined to be 0.045. At the packhouse level, grey WFs are higher than the blue WFs. However, grey WFs at the packhouse level are small compared to grey WFs during the cultivation phase. Grey WF of cabbage at the packhouse level was notably lower than that of carrots and lettuce, because cabbage required relatively low volumes of water compared to carrots, and in terms of fresh mass, more cabbage was packed on an average day compared to lettuce.

**Table 4-4: Grey water footprints and data used to calculate grey water footprints (WF) of processing and packing each crop in the packhouse.**

| Crops | Carrots | Cabbage | Lettuce |
|---|---|---|---|
| **Average Ortho Phosphate (as P) in effluent (kg $m^{-3}$)** | 0.00105 | 0.00105 | 0.00105 |
| **Average water use per crop in packhouse ($m^3$ $day^{-1}$)** | 68.6 | 10.5 | 10.5 |
| **Average crop throughput in packhouse (tonnes $day^{-1}$)** | 46.6 | 30.5 | 10.3 |
| **Phosphate load leaching to aquifer per tonne crop packed (kg P $tonne^{-1}$)** | 7 $e^{-5}$ | 0.00002 | 5 $e^{-5}$ |
| **Packhouse grey WFs ($m^3$ $tonne^{-1}$)** | **21.9** | **4.9** | **14.6** |
| **Grey WFs of cultivation average over all seasons ($m^3$ $tonne^{-1}$) (Chapter 3)** | 49.6 | 39.7 | 90.9 |
| **Percentage of grey water footprints in the packhouse in terms of grey WFs during cultivation (%)** | 44% | 12% | 16% |

### 4.3.3 INDIRECT WATER USED IN PACKHOUSE

The WF of electricity used in the packhouse to clean and pack carrots, cabbage and lettuce is indicated in **Table 4-5**. Indirect WFs of carrots, cabbage and lettuce were estimated to be 0.067 $m^3$ $tonne^{-1}$, 0.003 $m^3$ $tonne^{-1}$ and 0.005 $m^3$ $tonne^{-1}$, representing less than 1% of the blue plus green plus grey WFs of these crops during cultivation and 4.5%, 1.0% and 0.6% of the blue WF for cleaning and packing the crops. The indirect WF of crops at the packhouse level is not added to the blue WF of the packhouse, because it is sourced from other catchments and does not impact the Steenkoppies Aquifer.

Table 4-5: Water footprints (WFs) of electricity used in the packhouse for cleaning and packing carrots, cabbage and lettuce

| Date | Packhouse electricity use (kWh) | Water consumed to produce total electricity used ($m^3$ $day^{-1}$) | Water use attributed to crops packed ($m^3$ $day^{-1}$) | | | Production (tonnes) | | | WF ($m^3$ $tonne^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Carrots | Cabbage | Lettuce | Carrots | Cabbage | Lettuce | Carrots | Cabbage | Lettuce |
| **November 2014** | 114110 | 151 | 115 | 17 | 17 | 1929 | 6751 | 4051 | 0.060 | 0.003 | 0.004 |
| **December 2014** | 95635 | 126 | 97 | 15 | 15 | 1882 | 6586 | 3951 | 0.051 | 0.002 | 0.004 |
| **January 2015** | 127070 | 168 | 128 | 19 | 19 | 2245 | 7858 | 4715 | 0.057 | 0.002 | 0.004 |
| **February 2015** | 123268 | 163 | 125 | 19 | 19 | 1750 | 6126 | 3675 | 0.071 | 0.003 | 0.005 |
| **March 2015** | 129156 | 170 | 131 | 20 | 20 | 1669 | 5840 | 3504 | 0.078 | 0.003 | 0.006 |
| **April 2015** | 110389 | 146 | 112 | 17 | 17 | 1141 | 3994 | 2396 | 0.098 | 0.004 | 0.007 |
| **May 2015** | 91023 | 120 | 92 | 14 | 14 | 1310 | 4584 | 2750 | 0.070 | 0.003 | 0.005 |
| **June 2015** | 88602 | 117 | 90 | 14 | 14 | 1494 | 5228 | 3137 | 0.060 | 0.003 | 0.004 |
| **July 2015** | 93285 | 123 | 94 | 14 | 14 | 1802 | 6307 | 3784 | 0.052 | 0.002 | 0.004 |
| **August 2015** | 89681 | 118 | 91 | 14 | 14 | 1923 | 6730 | 4038 | 0.047 | 0.002 | 0.003 |
| **September 2015** | 106270 | 140 | 107 | 16 | 16 | 1474 | 5161 | 3096 | 0.073 | 0.003 | 0.005 |
| **October 2015** | 131504 | 174 | 133 | 20 | 20 | 1646 | 5763 | 3458 | 0.081 | 0.003 | 0.006 |
| **Average** | **108333** | **143** | **110** | **17** | **17** | **1689** | **5911** | **3546** | **0.067** | **0.003** | **0.005** |

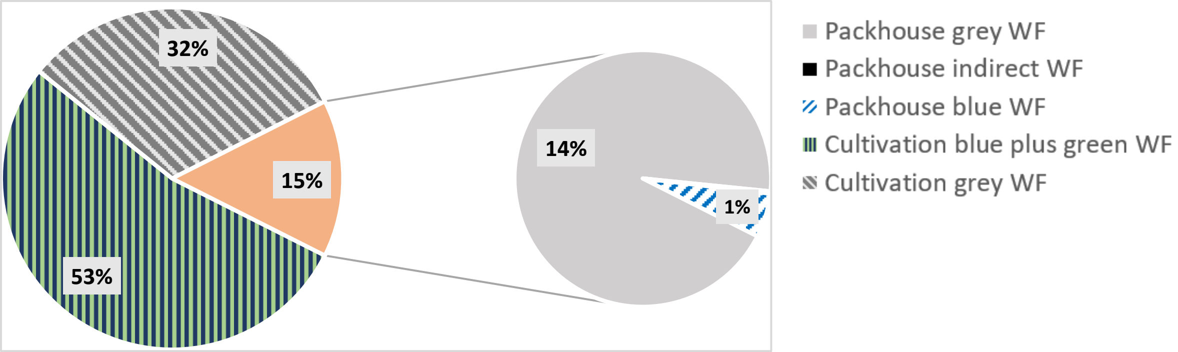

**Figure 4-4: Comparing the blue plus green and grey water footprints (WF) of carrots during cultivation with the blue, grey and indirect WFs at the packhouse level.**

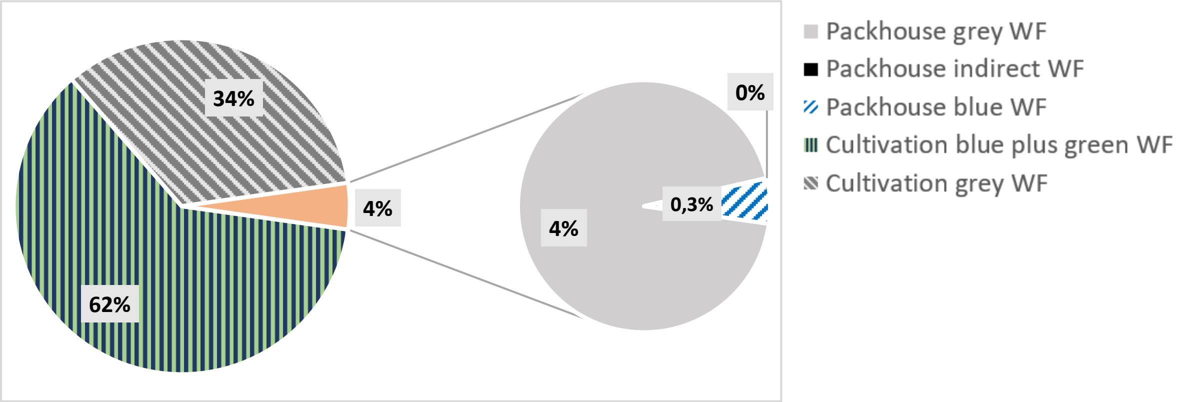

**Figure 4-5: Comparing the blue plus green and grey water footprints (WF) of cabbage during cultivation with the blue, grey and indirect WFs at the packhouse level.**

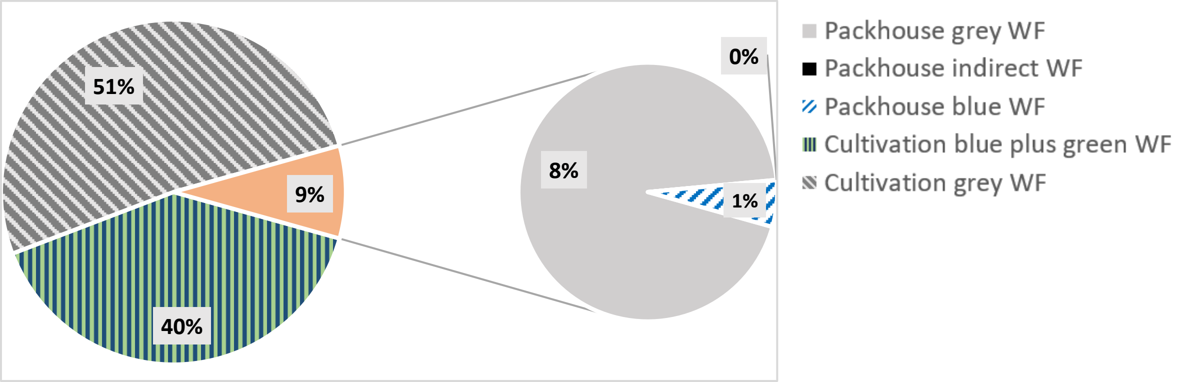

**Figure 4-6: Comparing the blue plus green and grey water footprints (WF) of lettuce during cultivation with the blue, grey and indirect WFs at the packhouse level.**

## 4.4 DISCUSSION

The results confirmed published literature indicating that WFs of cleaning and packing vegetables are relatively low compared to the WFs resulting from cultivation (Dominguez-Faus et al., 2009, Hoekstra et al., 2011, Hoekstra and Chapagain, 2011, Ridoutt and Pfister, 2010). Grey WFs of carrots, cabbage and lettuce in the packhouse were 44%, 12% and 16% of that of the cultivation phase, respectively. The indirect WF of electricity use in the packhouse are also relatively small compared to the packhouse level blue WF for carrots, cabbage and lettuce. The results, therefore, indicate that grey WFs are more important than blue WFs at the packhouse level. Water treatment before discharge will therefore provide an opportunity to reduce water use impacts from agriculture.

Defining water consumption can be complex. According to the WFN (Hoekstra et al, 2011), water is consumed if it is removed from a particular catchment within a certain timeframe. Therefore, return flows that recharges the blue water resource within a certain timeframe is not considered 'consumption'. According to this definition, the fraction of effluent discharged (*x liters*) that recharges the aquifer should be subtracted from the water flowing into the packhouse. However, if this *x liters* are in a continuous cycle where it gets withdrawn and discharged every day, it will not be available to any other users. Following this argument, even the water that is recycled within the packhouse is unavailable to other users, raising the question whether the recycled water should not also be included in the blue WF. For the purposes of this study the definition of the WFN was used and the assumption was made that none of the effluent discharge would recharge the aquifer.

The functional unit used for these WF calculations for the packhouse also had an impact on the outcomes. If lettuce and cabbage fresh mass are used, the WFs of lettuce in the packhouse is higher than that of cabbage, but if yield in heads were used the WFs of cabbage would be higher than lettuce. The blue WFs in the packhouse vary notably between crops, with carrots having a higher blue WF than cabbage and lettuce. The partitioning of water used to process the various crops in the packhouse were based on estimations, and improved monitoring of water flows within the packhouse could improve on these estimations. However, considering the relatively low volumes of water used in the packhouse compared to the cultivation phase, such investments may not be justified.

## 4.5 CONCLUSION

Water footprints, according to the WFN methodology, were calculated for carrots, cabbage and lettuce in the packhouse. The WFs of beetroot and broccoli at the packhouse level could not be calculated, because these crops were not being packed when the study was undertaken. Grey WFs are more relevant than blue WFs at the packhouse level. The grey WF could be lower when the more recent waste water treatment facilities are in operation, given that nutrient rich sludge is disposed of in such a way that nutrients cannot leach into the aquifer, thereby reducing the pollutant load.

From the calculations in this chapter it is seen that blue water used at the packhouse level is relatively small, between 0.5% and 2% of the blue WF resulting from the cultivation phase. In the packhouse that was investigated, there are also limited possibilities to further reduce the blue WF at the packhouse level, as water recycling has already been implemented as far as possible. In terms of management priorities, further reductions in packhouse water uses are less important, compared to the major reductions in blue WFs resulting from cultivation that are necessary to achieve sustainable blue water use.

Although the WFN methodology was considered to be the simplest method to apply and to interpret, some complexities were encountered in the calculations of WFs of vegetable crops. **Chapter 5** discusses these complexities and possible ways in which they can be dealt with.

# 5 CHAPTER 5: UNDERSTANDING COMPLEXITIES IN ESTIMATING WATER FOOTPRINTS OF VEGETABLE CROPS

## 5.1 INTRODUCTION

**Chapter 3** compared different methodologies that have been proposed to calculate the water footprint (WF) of a product. It was concluded that the Water Footprint Network (WFN) methodology is most useful to a water resource manager, because of its quantitative nature. Apart from the fact that WFs, according to the WFN, is not suitable for awareness raising and labelling, there are other complexities when applying this methodology in a crop production context.

This chapter explores the potential intricacies involved in calculating WFs of vegetable crops according to the WFN methodology using a case study on the water stressed Steenkoppies Aquifer. Factors influencing WF outcomes, including natural variations in weather conditions between growing seasons and between different years are discussed. Water footprints are also directly dependent on crop simulation model outputs, which are in turn affected by the quality of parameterisation and input data used, including weather data. Variations in the plant water content between different crops can impact the WFs, which are most commonly expressed as a volume of water used per yield in fresh mass, and we explore the impact of functional units on the results. Finally, some complexities in using the grey WF method are discussed, and aquifer water quality measurements used to challenge the calculation of grey WFs.

## 5.2 MATERIALS AND METHODS

### 5.2.1 INTER-SEASONAL AND INTER-ANNUAL VARIATION IN WFS

In **Chapter 3** WFs were determined for carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*), lettuce (*Lactuca sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*) in different seasons. Variations between WFs based on the seasonality of the vegetable crops were estimated and compared to more generic results published in the literature. Long term simulations were also considered necessary to better understand inter-annual variation in WFs of all crops, including the vegetables, maize and wheat, due to changes in prevailing weather patterns. Thus, WFs of each crop in all the relevant seasons were calculated from 2004 to 2013.

### 5.2.2 THE IMPORTANCE OF STANDARDISED WEATHER DATASETS

A weather dataset from 1983 to 2013, which included rainfall, minimum and maximum temperature, wind speed and humidity, was obtained from the Deodar Weather station (AgroClimatology Staff, 2014). Solar radiation data was available from 2004 onwards, when a pyranometer was added to the weather station. If solar radiation data is unavailable, SWB estimated these values according to the FAO 56 recommendations (Allen et al., 1998). Simulation results, and the effect it had on WFs, when using estimated datasets were compared to results when measured datasets are used.

### 5.2.3 USING DIFFERENT FUNCTIONAL UNITS FOR WF ASSESSMENTS

Rebitzer et al. (2004) defined a functional unit as 'a quantitative description of the service performance (the needs fulfilled) of the investigated product system'. The functional unit of crops, for example, can therefore be the crop yield, or a function of the crop, such as nutritional value. Despite the common use of fresh mass yield as a functional unit, it has been criticised for not being the most appropriate, because crops have different moisture contents and can provide a consumer with a certain nutritional benefit, which is not necessarily correlated with fresh mass (Ingwersen, 2012, Schau and Fet, 2008). Due to differences in water content some crops have a disproportionately high WF if yield in fresh mass is used, but if yield in dry matter is used these crops' WFs become relatively low. Yield results in SWB were estimated in dry matter (0% moisture), which was converted to fresh mass. The water contents of beetroot, lettuce, maize and wheat were taken from the United States Department of Agriculture (USDA) (United States Department of Agriculture, 2015). A constant percentage dry matter was assumed for the other crops. The harvestable dry matter results from SWB were converted to fresh mass by dividing it by the dry matter percentages, as summarised in **Table 5-1.**

**Table 5-1: Percentage crop dry matter used to convert Soil Water Balance model dry matter results to fresh mass**

| Crops | Percentage dry matter |
|---|---|
| **Carrots** | 10%[1] |
| **Cabbage** | 7%[1] |
| **Beetroot** | 13%[2] |
| **Broccoli** | 13%[1] |
| **Lettuce** | 4%[2] |
| **Maize** | 90%[2] |
| **Wheat** | 87%[2] |

[1]Assumed constant percentage; [2] obtained from United States Department of Agriculture (2015)

Using the nutritional value of the crops as a functional unit can be useful because water use is directly connected to a certain benefit derived from the crop. Water footprints were therefore also reported in terms of selected nutrients required by a person per day according to Mahan and Escott-Stump (2004). Required nutrients as a functional unit is complex, because there are a large number of variables involved, such as:

- The different WFs for each growing season.
- The differences in Recommended Dietary Allowances (RDA) depending on gender and age (Mahan and Escott-Stump, 2004).
- The different nutrients that a crop provides (United States Department of Agriculture, 2015).

The WFs of summer carrots, cabbage, beetroot, broccoli, lettuce and maize were selected to determine the volume of total blue plus green water required to fulfil the RDA of men between age 31 to 50 in terms of proteins, carbohydrates, iron, zinc and manganese. Winter WFs were used for wheat. The nutrient content of each crop were obtained from the National Nutrient Database for Standard Reference (United States Department of Agriculture, 2015). Recommended Dietary Allowance values obtained from Mahan and Escott-Stump (2004) are given in **Table 5-2**.

**Table 5-2: Recommended Dietary Allowance (RDA) of selected nutrients required daily by a man aged 31 to 50 years (Mahan and Escott-Stump, 2004).**

| Nutrient | RDA of a man aged 31 to 50 |
|---|---|
| **Proteins** | 56 g |
| **Carbohydrates** | 130 g |
| **Iron** | 8 mg |
| **Magnesium** | 420 mg |
| **Zinc** | 11 mg |

Finally, prices used to calculate the Consumer Price Index (CPI) were obtained for each crop and was used as a functional unit (Statistics South Africa, 2016). Monthly prices for CPI calculations from 2008 to 2015 were categorised into the four seasons and divided into WFs of each season to obtain a volume of water used per prices used for CPI calculation. Maize and wheat was excluded from this assessment, because there is not a single value for these grains in CPI, but different values for the various products derived from them.

## 5.3 RESULTS

### 5.3.1 INTER-SEASONAL AND INTER-ANNUAL VARIATION IN WATER FOOTPRINTS

The blue, green and grey WFs with fresh mass as the functional unit for the cultivation phase of each of the crops in each of the four growing seasons, and one season in the case of maize and wheat (shown in **Figure 5-6**), are compared to values published by the WFN (Mekonnen and Hoekstra, 2011) in **Table 5-3**.

**Table 5-3: Average of 10 year's blue, green and grey water footprints using fresh mass as a functional unit for cultivating vegetable crops, maize and wheat on the Steenkoppies Aquifer compared to outcomes from the literature**

| **Crop** | **Month** | **Average seasonal WF of crop ($m^3$ $tonne^{-1}$)** | | | | **WFs ($m^3$ $tonne^{-1}$) reported in the literature (Mekonnen and Hoekstra, 2011)** | | | | **Percentage difference between local and published blue + green WFs** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Blue | Green | Blue + Green | Grey | Blue | Green | Blue + Green | Grey | |
| **Carrots** | Summer | 36 | 25 | 61 | 48 | 28 | 106 | 134 | 61 | 120% |
| | Autumn | 104 | 12 | 116 | 60 | | | | | 15% |
| | Winter | 88 | 7 | 95 | 52 | | | | | 41% |
| | Spring | 45 | 17 | 62 | 39 | | | | | 116% |
| **Cabbage** | Summer | 38 | 29 | 66 | 66 | 26 | 181 | 207 | 73 | 212% |
| | Autumn | 53 | 11 | 64 | 31 | | | | | 224% |
| | Winter | 77 | 1 | 79 | 18 | | | | | 163% |
| | Spring | 63 | 16 | 79 | 46 | | | | | 162% |
| **Beetroot** | Summer | 60 | 40 | 100 | 92 | 26 | 82 | 108 | 25 | 8% |
| | Autumn | 87 | 14 | 101 | 33 | | | | | 7% |
| | Winter | 121 | 3 | 124 | 20 | | | | | -13% |
| | Spring | 104 | 15 | 118 | 96 | | | | | -9% |
| **Broccoli** | Summer | 142 | 120 | 262 | 183 | 21 | 189 | 210 | 75 | -20% |
| | Autumn | 225 | 76 | 301 | 575 | | | | | -30% |
| | Winter | 322 | 5 | 327 | 540 | | | | | -36% |
| | Spring | 170 | 44 | 214 | 214 | | | | | -2% |
| **Lettuce** | Summer | 31 | 24 | 56 | 100 | 28 | 133 | 161 | 77 | 256% |
| | Autumn | 51 | 20 | 71 | 131 | | | | | 169% |
| | Winter | 93 | 1 | 93 | 56 | | | | | 108% |
| | Spring | 56 | 6 | 62 | 80 | | | | | 212% |
| **Maize** | Summer | 452 | 253 | 707 | 377 | 81 | 947 | 1028 | 194 | 45% |
| **Wheat** | Winter | 732 | 30 | 762 | 443 | 342 | 1277 | 1619 | 207 | 120% |

The WFs of the five vegetable crops included in this study vary significantly depending on the growing season of the crops. Not only does the total blue plus green WF vary between growing seasons, but the blue WFs calculated for the vegetable crops on the Steenkoppies Aquifer are also much higher in winter. The high blue WF of broccoli in winter is due to a very low relative yield of the harvestable portion that is produced by the crop during this season. Some WFs are similar for different seasons, for example the small variation in blue plus green WFs for cabbage over all four seasons. Some WFs have high standard deviations, like wheat in winter and broccoli in summer and spring (**Figure 5-6** and **Figure 5-7**). These high standard deviations highlight the need to do long term simulations to capture the inter-annual variation in WFs due to the variation in weather conditions.

The WFs of the vegetable crops corresponded to the WFs reported by Mekonnen and Hoekstra (2011) in some seasons. There was a 15% difference between total blue plus green WFs of carrots given by Mekonnen and Hoekstra (2011) and local blue plus green WFs of carrots in autumn. Total blue plus green WFs of beetroot given by Mekonnen and Hoekstra (2011) corresponded to local blue plus green WFs of beetroot in summer, autumn and spring with a percentage difference of 8%, 7%, and -9%, respectively. The local WF of broccoli was higher than previously reported, but corresponded well to blue plus green WFs of Mekonnen and Hoekstra (2011) in spring with a -2% difference. Other seasons did not correspond well with WF results given by Mekonnen and Hoekstra (2011), for example the 120% difference in WF of summer carrots, 224% difference in WF for autumn cabbage and the 256% difference in WF of summer lettuce. Percentage differences between local WFs of cabbage and lettuce and those reported in the literature is very high for all seasons. Blue plus green WFs of wheat are much lower than the WFs given by Mekonnen and Hoekstra (2011), with a 112% difference. The reason for these differences could not be determined, because Mekonnen and Hoekstra (2011) did not report the data that was used for their calculations.

### 5.3.2 THE IMPORTANCE OF STANDARDISED WEATHER DATASETS

Compared to the measured solar radiation from 2004 to 2013, the solar radiation values from 1983 to 2003, which were estimated according to FAO 56 (Allen et al., 1998), were observed to result in noticeably different daily summer and spring $ET_o$ and yield estimates, in turn impacting the WF estimates (which use cumulative crop ET values and yield in their calculation). **Figure 5-1** and **Figure 5-3** show the effect of using estimated solar radiation on simulated yields of carrots, cabbage, beetroot, broccoli and lettuce planted during summer, as compared to yield results that were obtained with the measured solar radiation data post 2004. The coefficient of determination ($R^2$) between measured yields and yields simulated with measured solar radiation of the five vegetables was 0.94, indicating strong correlation (**Figure 5-4**). The $R^2$ for measured yields and yields simulated with estimated solar radiation for the five vegetables was 0.6, indicating poorer correlation. This effect was much more insignificant for crops planted in autumn and winter, and in some cases yields were slightly over-estimated in these colder seasons (**Figure 5-2**). The reason why this effect is more prominent in summer and spring is possibly because the study area is a summer rainfall region and solar radiation may be more accurately estimated in the absence of cloud cover, because fewer assumptions are required. This possibility could receive attention in future research studies.

Sensitivity to the quality of weather data and which variables are measured versus estimated should be carefully considered during parameterisation and application of crop parameters in models such as SWB. If crop parameterisation is based on weather datasets which include estimates and afterwards used with completely measured datasets, the results may be inaccurate. Instead it is recommended that the weather data that is used for parameterisation, whether specific variables are estimated or measured, must be used consistently over the simulation period. Estimated data can be used in this consistent way based on the assumption that the variation in the error in Rs will be consistent for a crop calibrated in summer or winter and simulated in the same season. The error in Rs estimates was, however, not consistent over different seasons, because the error was only observed during summer. Parameters generated for a crop in one season using estimated data should therefore be used cautiously for other seasons. In this study, volumetric green and blue WFs were calculated using only 2004 to 2013 weather data, because these data included measured values (including solar radiation, wind speed and humidity) for which crop parameterization was done, and provided the most accurate results compared to the verification data.

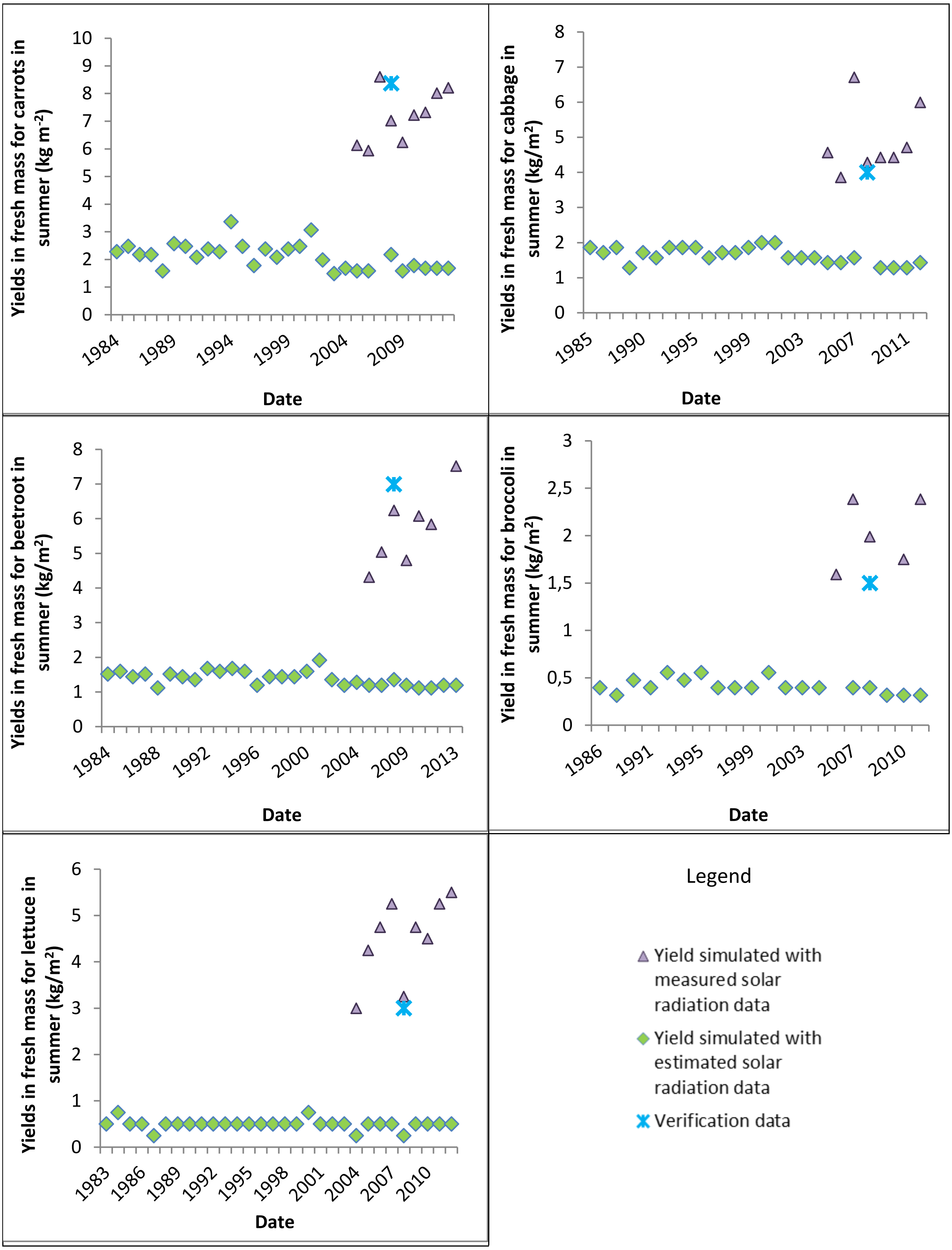

**Figure 5-1: Soil Water Balance model simulated yields versus actual yields of vegetable crop grown in summer indicating the influence of using estimated solar radiation data on simulated yield outcomes.**

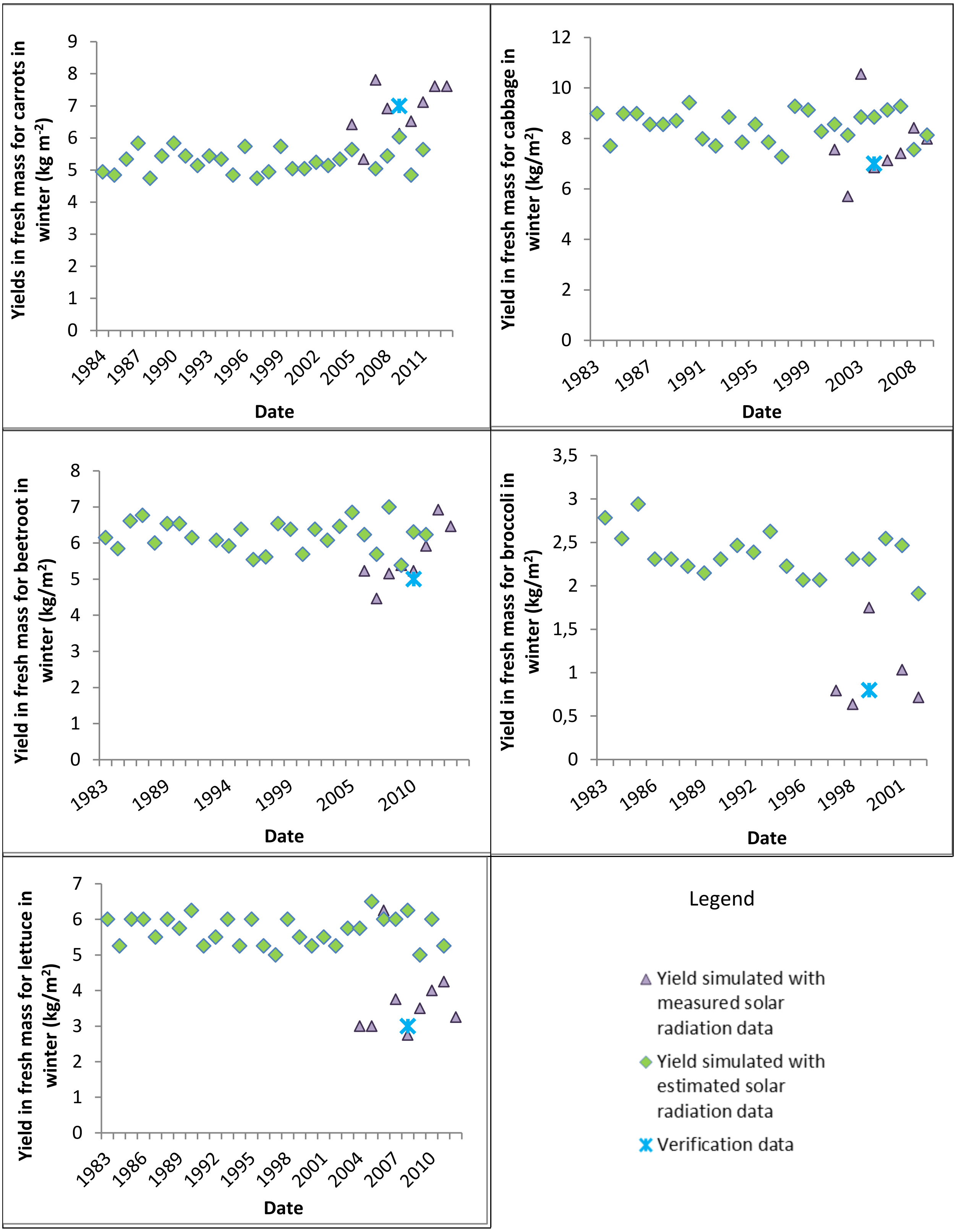

**Figure 5-2: Soil Water Balance model simulated yields versus actual yields of vegetable crop grown in winter indicating the influence of using estimated solar radiation data on simulated yield outcomes.**

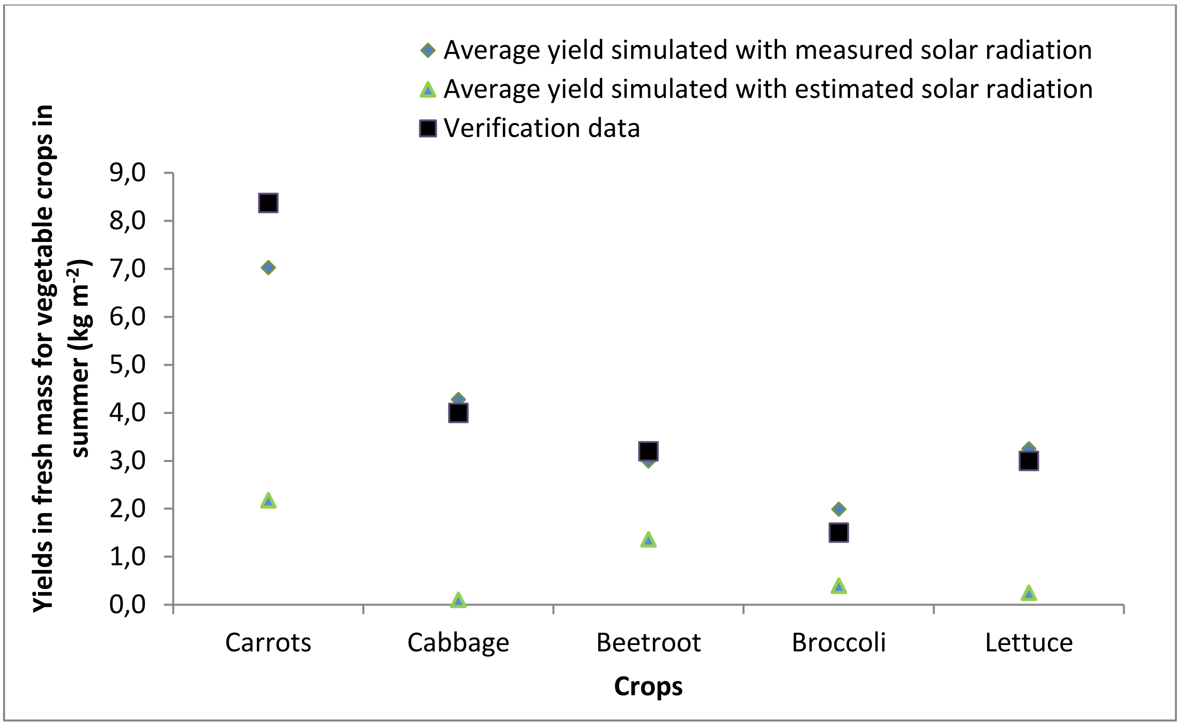

**Figure 5-3: Soil Water Balance model results for simulated and measured yield of carrots, cabbage, beetroot, broccoli and lettuce with measured and estimated solar radiation data compared to verification data.**

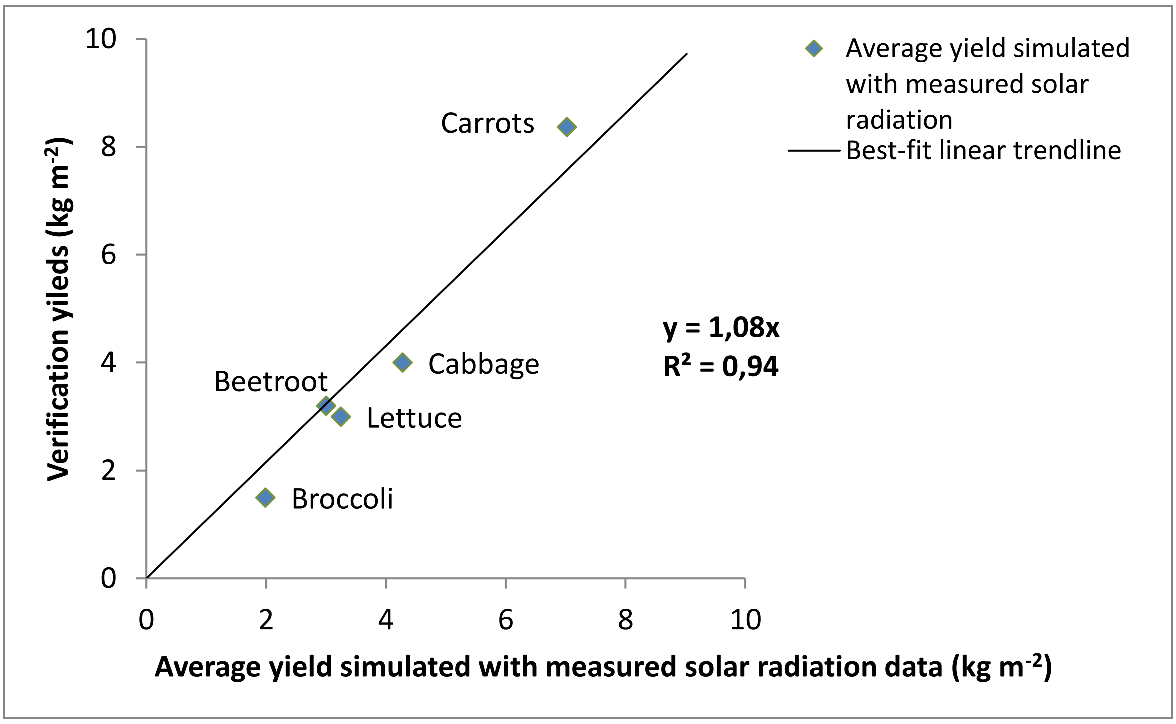

**Figure 5-4: Correlation between verification yield data and yields simulated with the Soil Water Balance model using measured solar radiation data for carrots, cabbage, beetroot, broccoli and lettuce.**

A method was developed to correct $ET_o$ values from simulations done with solar radiation data that was estimated according to FAO 56 (Allen et al., 1998). The $ET_o$ results simulated with estimated solar radiation data (from 1983) was compared to $ET_o$ values estimated with measured solar radiation data (from 2004) in a regression analysis to obtain $ET_o$ correction factors for each month separately. Two sets of statistics, which included minimum, maximum, median, 25th and 75th percentiles of $ET_o$ values, for simulations with estimated and measured solar radiation were calculated for each month. The statistics of $ET_o$ with estimated solar radiation were plotted against the statistics of $ET_o$ with measured solar radiation on a regression line, which had a linear distribution for all months. Regression equations were obtained for each month (**Table 5-4**) and applied as correction factors to monthly $ET_o$ values simulated with estimated solar radiation data. The corrected monthly $ET_o$ values simulated with estimated solar radiation data had a long-term average similar to average $ET_o$ values simulated with measured solar radiation data (**Figure 5-5**). This approach was not used here, because the complete set of weather data from the Deodar weather station from 2004 onwards was sufficient for the purposes of this study. However, this way of correcting the effect of estimated solar radiation data on simulations is recommended for situations where complete weather data is not available.

**Table 5-4: Regression equations to obtain corrected monthly $ET_o$ values (mm) for datasets without solar radiation data**

| Month | Equation to obtain corrected monthly $ET_o$ values (y) from $ET_o$ values (x) calculated without solar radiation data |
|---|---|
| **January** | y = 0.8x + 40.1 |
| **February** | y = 1.1x + 19.9 |
| **March** | y = 0.8x + 35.0 |
| **April** | y = 0.5x + 55.9 |
| **May** | y = 0.6x + 29.6 |
| **June** | y = 1.0x – 28.0 |
| **July** | y = 1.1x - 35.2 |
| **August** | y = 1.8x - 133.0 |
| **September** | y = 0.6x + 62.2 |
| **October** | y = 0.6x + 67.9 |
| **November** | y = 0.7x + 62.7 |
| **December** | y = 0.3x + 102.8 |

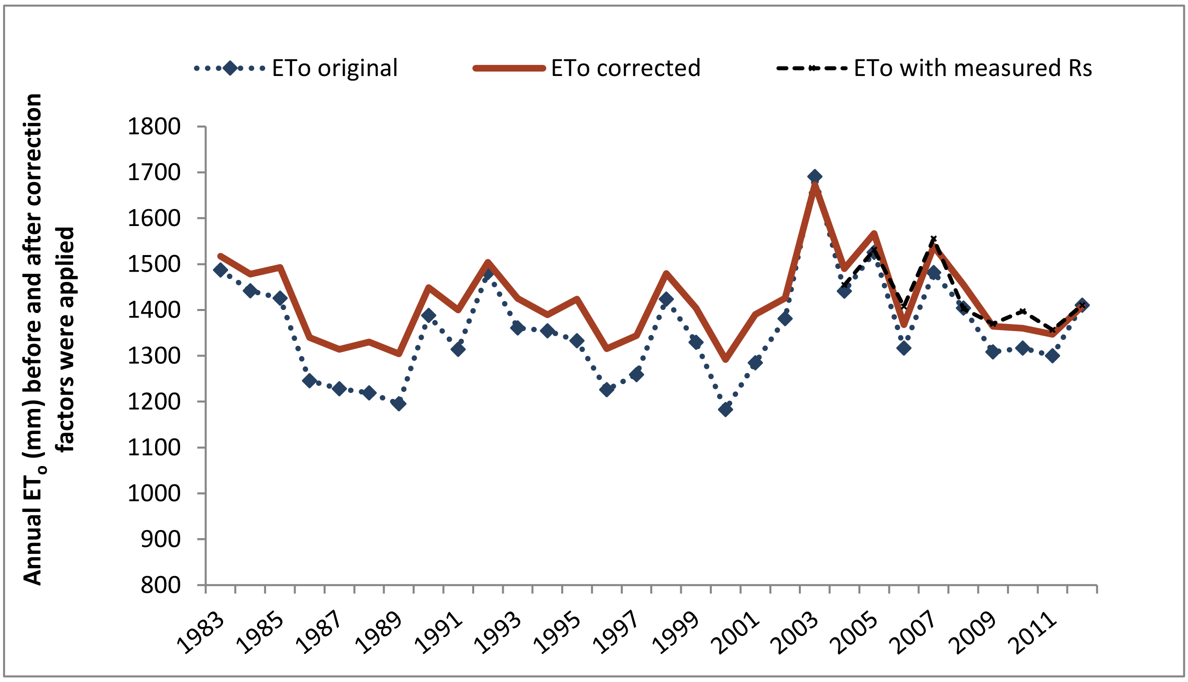

**Figure 5-5: Original $ET_o$ results from SWB versus corrected $ET_o$ results**

### 5.3.3 USING DIFFERENT FUNCTIONAL UNITS FOR WATER FOOTPRINT ASSESSMENTS

The WF results expressed in terms of fresh mass or dry matter are illustrated in **Figure 5-7**, respectively. Water footprints of maize and wheat are much higher than the vegetable crops if expressed in terms of fresh mass. However, if WFs are expressed in terms of dry matter, the WFs of maize and wheat are similar to those of vegetable crops. This is because the water content of maize and wheat is much lower (10% and 13%, respectively) compared to the vegetable crops (between 87% and 96%). The WF of lettuce expressed in terms of dry matter yield is relatively much higher than when expressed in terms of fresh mass. This is because of the high physical water content of lettuce (95%).

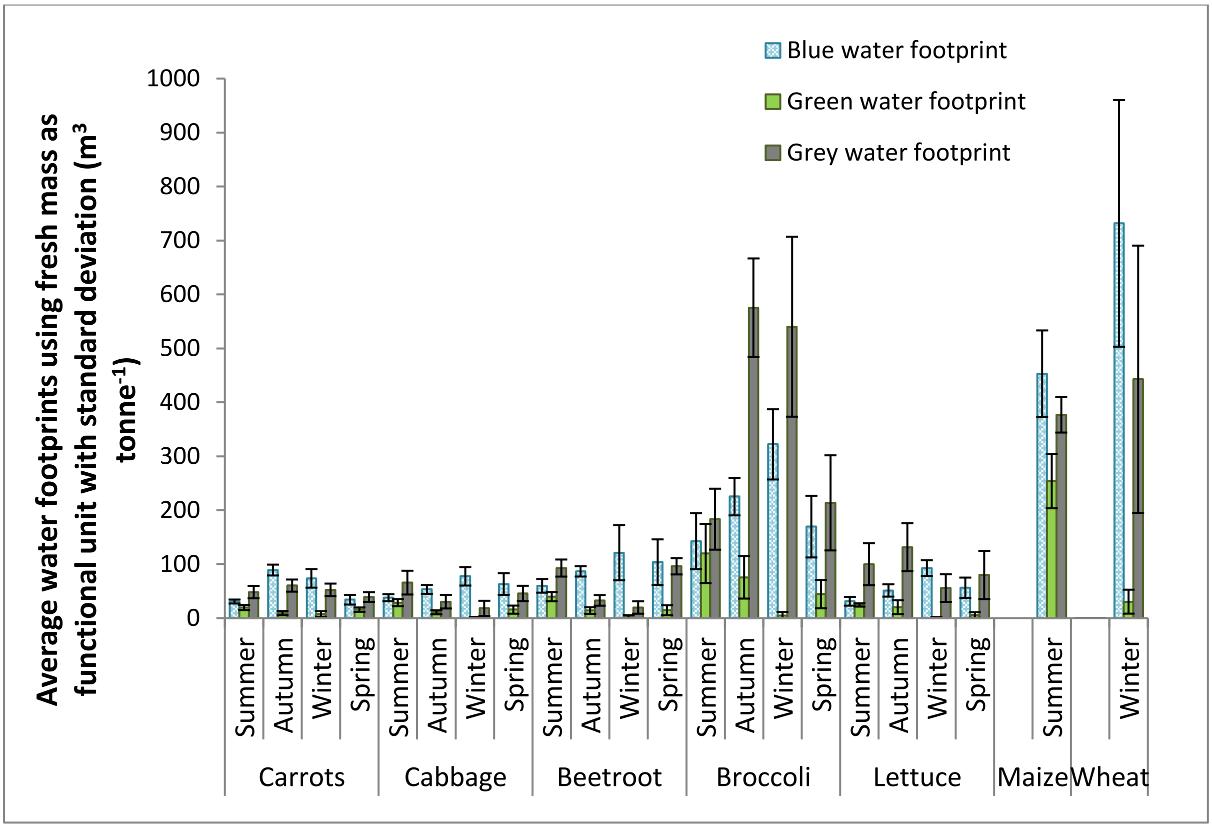

**Figure 5-6: Average of 10 year's blue and green water footprints (2004–2013) with standard deviations (shown as error bars) of vegetable and grain crops in the different growing seasons on the Steenkoppies Aquifer using fresh mass as a functional unit**

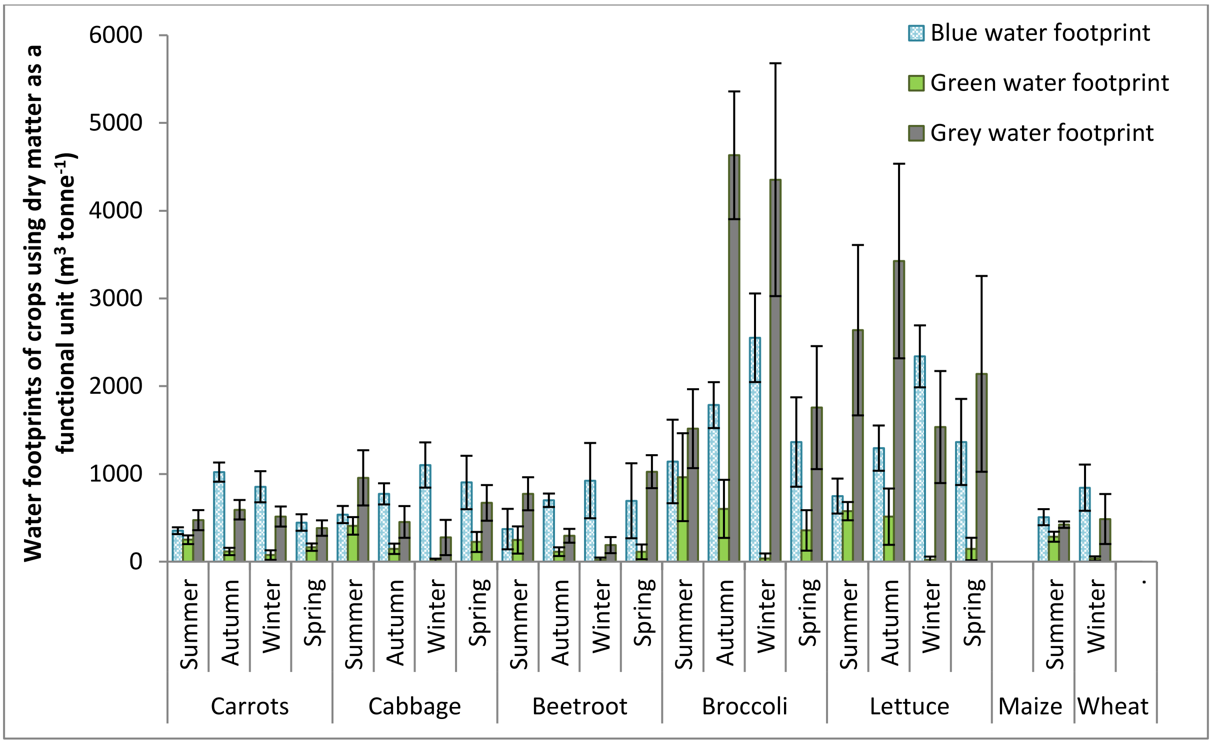

**Figure 5-7: Average of 10 year's blue and green water footprints (2004–2013) with standard deviations (shown as error bars) of vegetable and grain crops in the different growing seasons on the Steenkoppies Aquifer using dry matter as a functional unit**

The WF of summer crops using selected nutrients required to supply a man aged 31 - 50 with their RDA as a functional unit is illustrated in **Figure 5-8**. The high WF of broccoli, as expressed in terms of nutrient yield, now becomes comparable to the WFs of similar crops as a result of its high nutritional value. The WF of the nutrient with the highest WF can indicate the final WF of the crop, because the other nutrients are also produced. It is also important that local measurement of crop nutrient composition be used in future research, because the micro-nutrient uptake of crops is influenced by soil characteristics and fertilization. If WFs are expressed in terms of prices used to calculate the CPI (**Figure 5-9**), broccoli has a much more comparable WF, which is even lower than the WF of beetroot for all seasons.

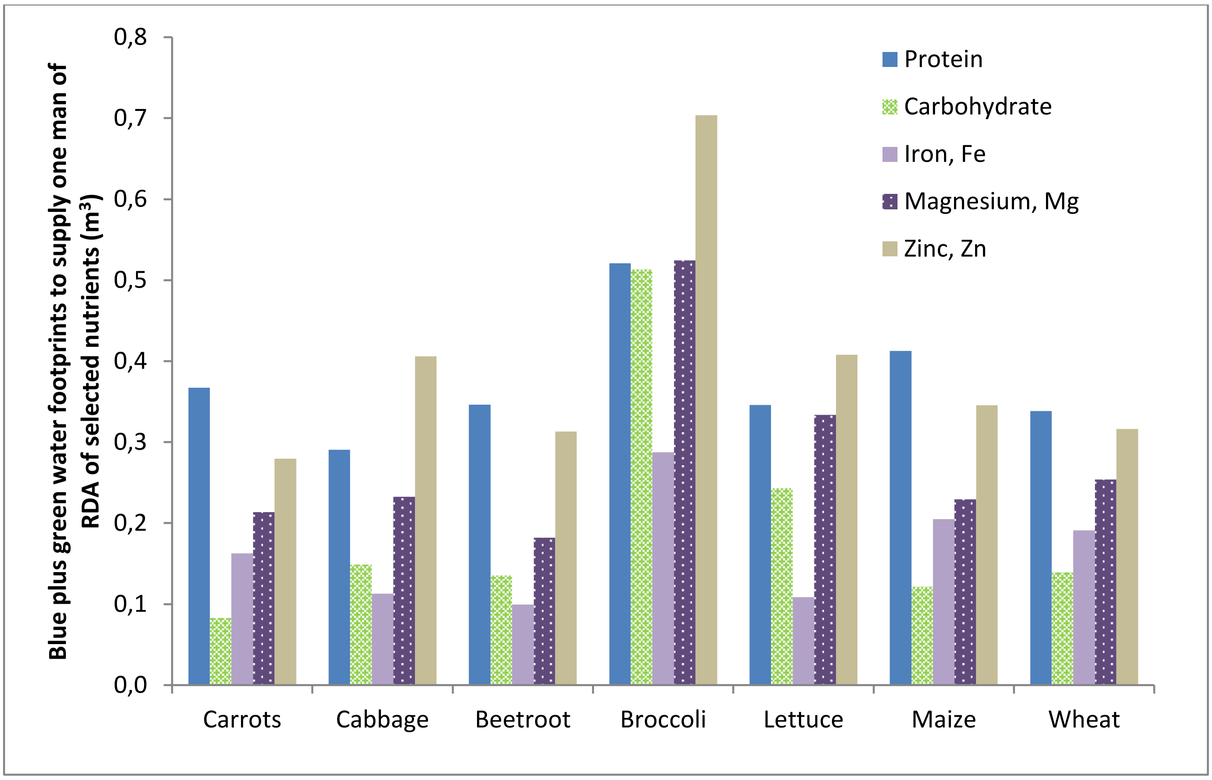

**Figure 5-8: Blue plus green water footprint to supply a man (aged 31 to 50) with their Recommended Dietary Allowance (RDA) (Mahan and Escott-Stump, 2004) in terms of selected nutrients.**

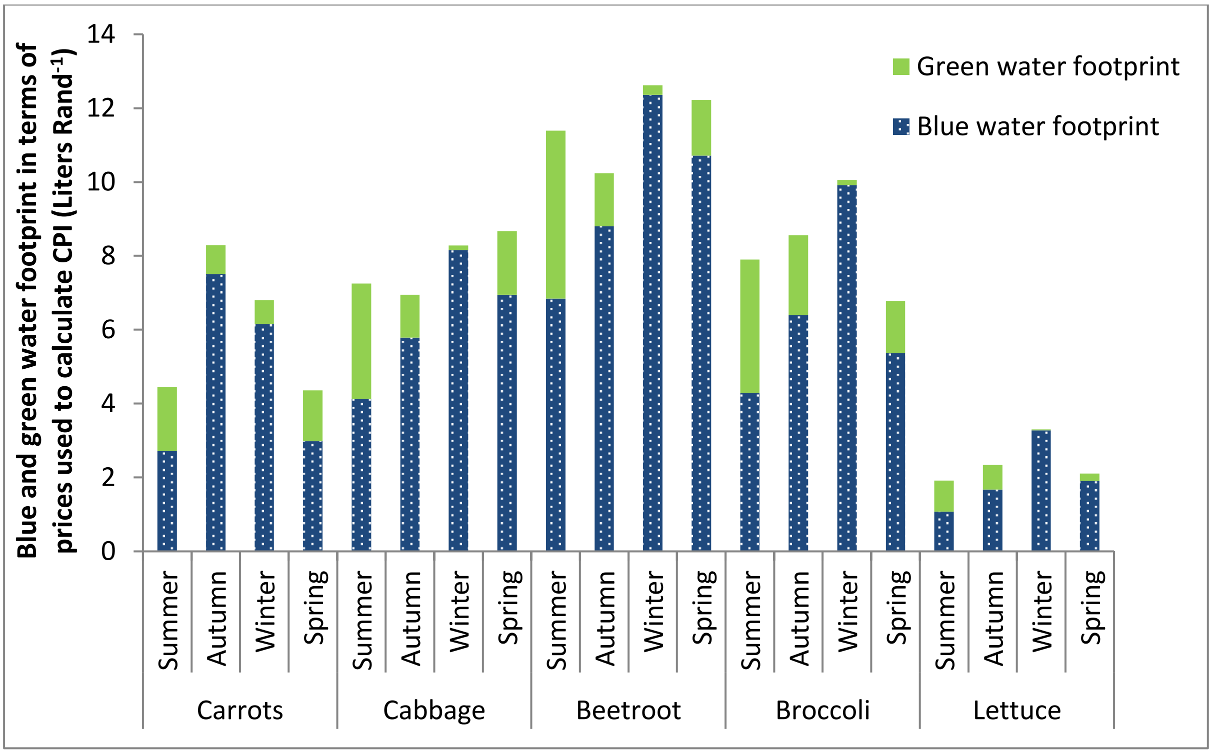

**Figure 5-9: Blue and green water footprint of crops in terms of prices used to calculate the Consumer Price Index (CPI)**

### 5.3.4 COMPLEXITIES IN GREY WATER FOOTPRINTS

Grey WFs of carrots, cabbage and beetroot given by Mekonnen and Hoekstra (2011) were similar to local grey WFs, especially for carrots in autumn, and cabbage and beetroot in winter (**Table 5-3**). Local grey WFs for lettuce in spring also compared well with the grey WFs given by Mekonnen and Hoekstra (2011). Grey WFs of broccoli in all seasons, maize and wheat were much higher than the grey WFs given by Mekonnen and Hoekstra (2011). As noted above, the reason for these differences could not be determined, because Mekonnen and Hoekstra (2011) did not report the data that was used for their calculations. High grey WFs of broccoli, as compared to the other crops in this study, were due to the low harvestable index of the plant.

The fate of N is very important in calculating grey WFs, yet it is very complex to determine. Analyses of the groundwater in the Steenkoppies Aquifer indicated that the 95th percentile of nitrate concentrations (0.45 mg $\ell^{-1}$) represented oligotrophic conditions (< 0.5 mg $\ell^{-1}$) (Department of Water Affairs and Forestry, 1996), with no sign of the impact of intensive crop production. This phenomenon could be explained to some extent by high rainfall water influx through the aquifer which can dilute the N reaching the aquifer. However, due to the intensive agriculture on the aquifer a significant water quality impact is expected at some stage. The annual cropped area on the Steenkoppies Aquifer is approximately 5300 ha. It is reasonable to expect that 50 kg $ha^{-1}$ of applied N (265 000 kg) leaches to the aquifer. The volume of rainfall that falls on the Steenkoppies Aquifer and the catchment above it is approximately 150 $Mm^3$ per year. If 10% of rainfall recharges the aquifer (Wiegmans et al., 2013), this will dilute the N that reaches the aquifer to 18 mg N $litre^{-1}$, a high concentration that should have altered the water quality of the aquifer by now. Possible dilution through irrigation was ignored, because irrigation water is not an additional source of water flowing into the Steenkoppies Aquifer, but is taken from the aquifer and does not cause any further dilution of nitrates. The fact that water quality impacts can be expected, but is not reflected by the actual water quality in the Steenkoppies Aquifer emphasizes the uncertainties regarding the fate of N after application to the field and requires further study.

## 5.4 DISCUSSION

Although WFs can provide very useful information in an agricultural context, there are still challenges involved in calculating WFs, interpreting the information and understanding the limitations of the information that need to be addressed. The aim of this study was to better understand the complexities involved in calculating WFs for vegetable crops.

A number of studies in the literature have reported different WFs due to spatial and annual variation in climatic conditions (Mekonnen and Hoekstra, 2011, Multsch et al., 2016, Sun et al., 2013). Inter-annual variation in blue, green and grey WFs of maize production in Beijing was found to be related to changing climate and agricultural management practices (Sun et al., 2013). Blue WFs increased and green WFs decreased as a result of both drier climates and intensifying agricultural inputs. Grey WFs were correlated to an increase in chemical inputs during more recent years (Sun et al., 2013). Multsch et al. (2016) reported increased green WFs in high rainfall parts of the High Plains Aquifer (HPA) and increased blue WFs in parts of the HPA with low rainfall and higher temperatures. By calculating average WFs for crops from 1996 to 2005, Mekonnen and Hoekstra (2011), recognised the inter-annual variation in WFs of crops. Our results show that it is also important to interpret WFs with specific reference to the growing season, especially for short season crops with a range of planting date options. High inter-annual variation for this case study was illustrated by the high standard deviations of some crops during certain growing seasons, for example broccoli in summer with an average blue plus green WF of 262 $m^3$ $tonne^{-1}$ and a standard deviation of 105 $m^3$ $tonne^{-1}$.

It should be widely recognised that WF estimates can be significantly influenced by the quality of data used to parameterise and run crop models. We observed that daily $ET_o$ estimates can differ significantly when either measured or estimated solar radiation data is used, so recommend that consistent weather data be used from parameterisation to model application, assuming an insignificant variation in the error in estimations within a particular season. The error in estimated data was observed particularly for solar radiation during summer and spring for our study region. Using estimated solar radiation data for crops planted in autumn and winter, however, resulted in smaller differences in $ET_o$ and yield estimates. Therefore the consistency in weather data that is used could potentially have a significant impact on WF results. Zhuo et al. (2014) obtained similar results with a sensitivity analysis of WFs of maize, soybeans, rice and wheat to errors in input variables. They found that WFs of these crops are particularly sensitive to variations in $ET_o$, which resulted in an increase in crop water use and a decrease in yield estimates. The comparison between WFs calculated using more generic data from Mekonnen and Hoekstra (2011) as given in **Table 5-3** not only highlights the importance of reporting WFs for a specific season, it also highlights the need to use local data, for example to parameterise a specific crop. All WFs reported by Mekonnen and Hoekstra (2011) had a high green and low blue WF, while locally produced WFs had a high blue and low green WF. This is due to the study area being located in the dry summer rainfall high central plateau of South Africa. The study area is considered to represent other areas in South Africa with similar climatic conditions.

The functional unit used to calculate WFs has a significant impact on WF metrics. Grains with low moisture content, such as maize and wheat, will have a disproportionately high WF compared to vegetables when using fresh mass yields. Depending on the objective of the study, different functional units for various crops can be used to reveal which crops will be more efficient, for example in producing important nutrients or generating most economic gain per volume of water. Assessing WFs in terms of other functional units such job creation is recommended for future research, because such alternative assessments can provide important information on how to allocate limited water supplies to achieve various objectives.

The high WF of broccoli due to the low relative yield of the harvestable portion that is produced by the crop presents a complexity and potential drawback in the application of the WF information, because the rest of the plant is often used for composting or animal feed. It can be argued that the beneficial use of the rest of the plant increases the total yield, and should be reflected in the WF. This could also be the case for many other crops. Compost will be incorporated into and increase the yield of the next crop and benefit soil health and the long-term sustainability of the system. Therefore, composting the non-edible part of the previous crop will potentially reduce the WF of the next crop. It can also be argued from a different point of view if one uses compost to reduce the need for fertilisers. Production of fertilisers will have a certain WF and the compost will reduce the WF of the crop by reducing the need for fertiliser and the water required to produce the fertiliser. The blue, green and grey WF of fertilisers has not yet been addressed. Composting can also reduce the grey water footprint, because the use of organic N will potentially reduce the need for inorganic N and create N use efficiency.

Initial soil water content at planting will theoretically impact the blue versus green WF outcomes, because it will determine the amount of irrigation required. This impact, however, was assumed to be relatively small, because it was assumed that most farmers irrigate the land to field capacity in order to prepare for planting and data modelling also assumed a relatively wet soil profile. It was also assumed that the soil water content was the same before planting and after harvesting.

The grey WF is a way of reporting impacts on water quality, which is a very important aspect of water resource management. The concept has, however, often been criticized for being too simplistic (Perry, 2014, Ridoutt and Pfister, 2013, Wichelns, 2011). In a crop production context, water pollution is an especially complex issue. Phosphates, salts, sediments and pesticides are also pollutants associated with agriculture, and need to be taken into account when addressing water quality. Therefore, it is not completely effective to assess the water quality impacts based on one pollutant. Similar to the WFs based on different nutrients, the grey water footprint can be calculated for various pollutants and the highest WF can be used as the total. There are uncertainties in the determination of the N load leaching into the aquifer, because the fate of N is not well understood. The intensive use of fertilisers and the vulnerability of the aquifer to pollutants, as indicated by Witthueser et al. (2009), suggested that some impact could be expected on the water quality due to cultivation of crops. However, water quality analyses of the underlying groundwater indicated very good quality water, despite the intensive farming that has occurred over the past few decades. It is clear that the process of water pollution and pollutants leaching into the groundwater in the Steenkoppies Aquifer is still difficult to quantify. Nitrates can be removed from the soil through denitrification, which is dependent on a number of factors. Being a strong oxidising agent, nitrates are often denitrified by dissolved organic carbon (DOC) or iron (Katz et al., 2014, Song et al., 2016, Xu et al., 2015). Redox conditions and depth of the groundwater, which in turns affects the availability of DOC, also play a role in denitrification (Katz et al., 2014, Starr and Gillham, 1993). The fate of N, which has a notable impact on the grey WF calculation, is therefore complex to determine. The use of grey WFs also becomes complex in a crop production context in cases where compost is used. Future research needs to address the potential benefits of composting crop residues in terms of the grey WF.

## 5.5 CONCLUSIONS

If water becomes scarce, farmers and water resource managers will have to ask the question of what they want to achieve with the available water. WF information can inform farmers to plant less water intensive crops or water resource managers to restrict certain crops during dry years or months. However, the method becomes complicated in a crop production context, because of inter-seasonal and inter-annual variations in WFs, the importance of local crop parameters and the requirement for comprehensive weather data. Crops, such as broccoli, with a low harvestable index will have a high WF, not representing how the residues of the plant are potentially used for other beneficial uses such as composting and animal feed. Water footprints that are calculated using fresh mass as a functional unit results in high WFs of crops with low water contents, such as maize and wheat, as compared to crops with high water contents, such as the vegetable crops. If WFs are calculated using dry matter, the high WFs of maize and wheat become more similar to the WFs of the vegetables. Using alternative functional units, such as nutritional content, potentially provides more meaningful information, which allows managers to make more informed decisions about water management and allocation. The current grey WF did not explain why the N concentration of the groundwater is within domestic standards, despite decades of agricultural activities on the Steenkoppies Aquifer. This could be due to an overestimation of the N load that reaches the aquifer or a big lag in the system. Grey WFs estimates does, however, indicated the relative potential of nitrate leaching per unit produced for different crops.

In this chapter the WFs of selected vegetable crops have been calculated for the different growing seasons. In the next chapter these calculated WFs will be used to determine catchment scale WFs for the Steenkoppies Aquifer, to determine the sustainability of the catchment WFs of agriculture and to better understand how WF information can improve water resource management

# 6 CHAPTER 6: CATCHMENT SCALE WATER FOOTPRINT OF THE STEENKOPPIES AQUIFER

## 6.1 INTRODUCTION

In **Chapter 3** blue, green and grey water footprints (WFs) were calculated for cultivating vegetable and grain crops on the Steenkoppies Aquifer. The WF outcomes of different methodologies were compared and it was concluded that the Water Footprint Network (WFN) approach is more useful in a catchment or aquifer resource management context because of its quantitative nature. A number of studies have determined WFs of various crops according to the method given by the WFN (Aldaya and Hoekstra, 2010, Bosire et al., 2015, Chapagain and Hoekstra, 2007, Gerbens-Leenes et al., 2009, Mekonnen and Hoekstra, 2011, Nyambo and Wakindiki, 2015). Although these WFs provide useful information on the water used to produce different products, there is often a need to upscale the WFs and findings to a catchment scale to compare total water used with total available water within a catchment. In this chapter the WFN blue and green WFs are up-scaled to a catchment level to better understand how WFs can inform a water resource manager to ensure the sustainable use of the aquifer and possibly to better understand the geohydrology of the aquifer. The Steenkoppies Aquifer presented a unique opportunity to verify WF sustainability outcomes, because of the following characteristics:

- The geohydrology of the aquifer is relatively simple with no surface water flowing into the aquifer or into the Maloney's Eye Catchment, except for the Upper Rietspruit River which carries water from the Randfontein waste water treatment works (WWTW). There is also no surface water flowing out of the aquifer or out of the Maloney's Eye Catchment, because flow in the Upper Rietspruit River reduces to almost zero within the boundaries of the aquifer. Therefore, according to current understanding, precipitation falling onto the Steenkoppies Aquifer either evaporates or recharges the aquifer. The Maloney's Eye is also currently the only natural outlet currently known.
- Numerous studies have been conducted on the Steenkoppies Aquifer, including geo-hydrological studies (Barnard, 1996, Barnard, 1997, Bredenkamp et al., 1986, Vahrmeijer et al., 2013, Wiegmans et al., 2013, Witthueser et al., 2009). These studies provided insights into water flows and could be used to validate results from the catchment scale WF assessment.
- Extensive datasets were available for different water flows and uses across the aquifer. The Maloney's Eye outflows have been monitored by the Department of Water and Sanitation on a daily basis since 1908. Some data exist for the outflows from the Randfontein WWTW. The Deodar weather station is also located within the Steenkoppies Aquifer (AgroClimatology Staff, 2014). Data has been collected on agricultural activities on the aquifer, including crop areas, average yield and irrigation for each of the major vegetable crops (Vahrmeijer, 2016).

Catchment scale water footprinting may represent a simplified yet effective approach to managing water resources at this scale, which can be very complex, particularly if the key data and information is not available. Mitchell (1990) observed that catchment managers at an operational level are often overwhelmed by the complexity of water resource management and the number of water related issues that should be incorporated into decision making. This is also true for the Steenkoppies Aquifer, where a vast number of variables can be monitored including precipitation, abstractions for irrigation, drainage, runoff or outflows to other catchments, groundwater levels, planted areas and total crop yields. Monitoring all these variables is not always possible. In this study, we ask whether measuring and/or estimating key variables (such as precipitation, yields, WFs of crops and natural vegetation and non-agricultural blue WFs) and using them in a WF accounting framework can provide useful, quantitative data to manage a catchment's water resources when detailed hydrological information is absent. The catchment WF framework is proposed that can potentially quantify the volumes of water consumed by irrigated and rainfed agriculture, which can assist in water allocation decisions and in setting sustainability targets. Outflows from many aquifers are not well recorded and the points of discharge are often unknown, thus the Maloney's Eye Catchment, with its simple geohydrology and available data, offers a unique opportunity to validate the catchment WF framework. Our study uses the original methodology proposed by the WFN, because it calculates a volume of water that is consumed per unit production, in this case evapotranspired through crop production, and the total volume of ET from agriculture on the aquifer can be used in a catchment water balance to better understand water flows through the catchment.

## 6.2 MATERIALS AND METHODS

### 6.2.1 CATCHMENT SCALE WATER FOOTPRINTS OF IRRIGATED CROPS

Seasonal blue and green WFs of carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*), lettuce (*Lactuca sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*), calculated according to the WFN in **Chapter 3** (**Table 3-8**), was linked to agricultural yields to obtain total agricultural water consumption on a catchment level from 1950 to 2012. This can be justified, despite potential spatial variation in soil types and irrigation practices. Firstly, because the vegetables have shallow roots and the effect of variation in soil types will have limited impact on the quantity of water use. Secondly, the majority of agricultural land on the Steenkoppies Aquifer is managed by a few large commercial farmers who uses similar irrigation (mostly pivots) and agronomic practices. The usefulness of this information was then assessed through comparisons with hydrological information. The catchment WF framework proposed here was used to calculate a water balance for the aquifer and the approach was validated by actual volumes of discharge from Maloney's Eye (**Section 6.2.2**). Thus, the grey WF, which does not provide a physical volume of water was not considered relevant to be used in the catchment water balance based on physical volumes.

Catchment scale water consumption of irrigated crops were determined for five distinct periods between 1950 and 2012. Crop areas or production data was not available for the years 1950 to 1995, but total abstractions were recorded in 1980 and 1986. Thus, to estimate agricultural water consumption for these years it was necessary to make several assumptions based on the available data for total abstractions, supported by expert judgement from local farmers. The first assumption was that abstractions exceeding crop ET were negligible, because available data indicated relatively low volumes abstracted in these periods, and it is unlikely that total crop ET were much lower in reality. Based on this assumption, blue plus green water consumption by agriculture is either more than or equal to total abstractions for these early year. Because of the crude methods used to determine irrigation requirements in earlier years, efficient irrigation and proper use of rainwater is unlikely. If **Equation 2-3 b** proposed in **Chapter 2,** is used to determine blue WFs, over-irrigation would result in zero green WF. Thus, the second assumption was made that the total water consumption by agriculture in 1950 to 1995 was only blue water with a zero green WF. The first and second assumptions, thus, would imply that total abstractions were equal to total crop ET of agriculture for these years. The potential impacts of possible incorrect assumptions are not considered important for these years, because the first assumption can possibly over-estimate agricultural water consumption, however, estimated agricultural water use was low, even if it was over-estimated. The second assumption only impacts on the blue:green water ratio, which is not important in the catchment water balance. The years 1950 to1979 are considered the first period and 1980 to 1985 the second period. In 1950, irrigated agriculture on the Steenkoppies Aquifer was practiced on a relatively small scale with maize being the main crop grown. About 4 Mm$^3$ water was reported to be abstracted for irrigation in 1980, representing blue WFs for the second period (Vahrmeijer et al., 2013) and based on expert judgement from local farmers it was assumed that the blue WF for the first period was 2 Mm$^3$ yr$^{-1}$. Thus, the first and second periods are considered to represent periods with very little impact on the aquifer, and therefore serves as control periods which are less complex and can be used to validate the results. According to Bredenkamp et al. (1986) 13.45 $Mm^3\ yr^{-1}$ of water was abstracted in 1986 and, based on the assumptions discussed for the first and second periods above this volume was assumed to represent the catchment scale blue water consumption for irrigated agriculture (with zero green water consumption) of the third period from 1986 to 1995. The year 1996 is when commercial irrigation drastically expanded on the Steenkoppies Aquifer (Vahrmeijer et al., 2013). **Figure 6-1** indicates irrigated field areas on the Steenkoppies Aquifer for the year 2015. There is a difference between field areas and cropped areas – the annual cropped area is higher than the physical field area as two or three crops may be planted on the same land each year. Refer to **Section 6.2.2** for a discussion on rainfed crops.

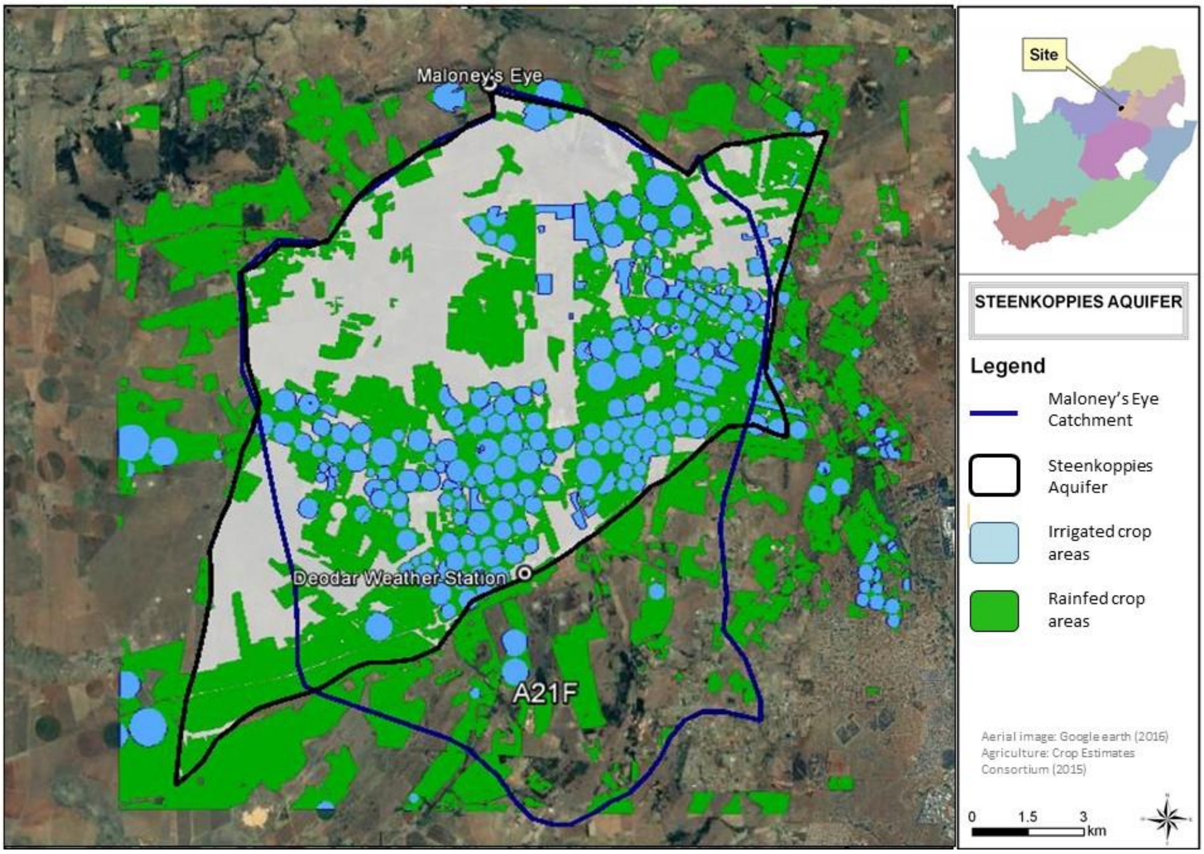

**Figure 6-1: Agricultural activities on the Steenkoppies Aquifer, west of Tarlton, Gauteng, South Africa (Crop Estimates Consortium, 2015). White areas on the aquifer represents mostly natural vegetation.**

According to a study by Vahrmeijer (2016), total irrigated areas in 1998 and 2005 were 4183 and 5349 hectares, respectively. These irrigated crop areas were verified, as described by Vahrmeijer (2016). Cropped areas of 1998 represented the fourth period (1996 to 2004) and cropped areas of 2005 represented the fifth period (2005 to 2012). For 2005 the crop species composition (for example x ha of broccoli, y ha of carrots and z ha of cabbage) was not determined, but for 1998 the crop species composition for 57% of the total irrigated cropped area was determined (**Figure 6-2**). The crop species composition determined for irrigated crops in 1998 was therefore assumed to be representative of the whole catchment and extrapolated to represent all years from 1996 onwards (**Table 6-3**). The selection of the different periods and the durations thereof, were therefore dictated by the available data.

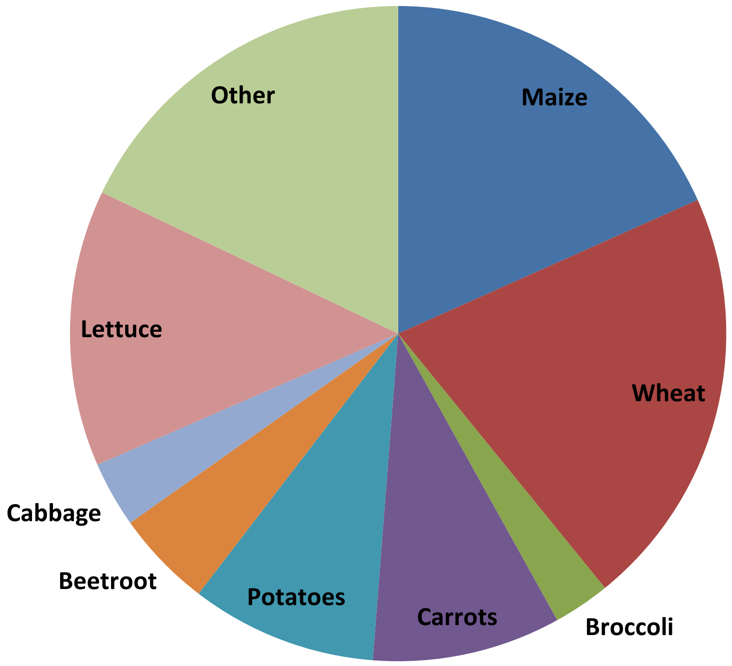

**Figure 6-2: Crop composition of the Steenkoppies Aquifer in 1998 (Vahrmeijer, 2016)**

**Table 6-1: Summary of verified crop areas on the Steenkoppies Aquifer in 1998 and extrapolations to total crop areas for 1998 and 2005**

| Crop | Crop area verified (hectares) | Percentage of verified crop area | Extrapolate total crop areas for 1998 (hectares) | Extrapolate total crop areas for 2005 (hectares) |
|---|---|---|---|---|
| **Maize** | 471 | 18.31% | 765.8 | 979.3 |
| **Wheat** | 536 | 20.83% | 871.5 | 1114.5 |
| **Broccoli** | 72 | 2.80% | 117.1 | 149.7 |
| **Carrots** | 239 | 9.29% | 388.6 | 496.9 |
| **Beetroot** | 123.4 | 4.80% | 200.6 | 256.6 |
| **Cabbage** | 83.5 | 3.25% | 135.8 | 173.6 |
| **Lettuce** | 351.07 | 13.65% | 570.8 | 729.9 |
| **Potatoes** | 236 | 9.17% | 383.7 | 490.7 |
| **Other** | 460.64 | 17.91% | 749.0 | 957.8 |

A typical planting schedule (**Table 6-2**) for vegetables on the Steenkoppies Aquifer by commercial growers was used to derive crop areas planted each month and enable WF calculations on a monthly basis. Total maize and wheat crop areas were equally divided between the four summer months (November - February) and the four winter months (May-August), respectively.

**Table 6-2: Planting schedule in 1998 for the selected vegetable crops taken from a farmer on the Steenkoppies Aquifer**

| Month | Beetroot (hectares) | Carrots (hectares) | Cabbage (hectares) | Lettuce (hectares) | Broccoli (hectares) |
|---|---|---|---|---|---|
| **January** | 0 | | | | |
| **February** | | | 2.9 | 1.2 | |
| **March** | 4.4 | 4 | 4.3 | 4.3 | |
| **April** | 8.8 | 12.7 | | | 0.4 |
| **May** | 5.8 | 6.7 | | | 0.3 |
| **June** | 4.2 | | 1.1 | 3.02 | 0.3 |
| **July** | | 5 | 2.4 | 3.1 | 1 |
| **August** | | 5 | 3.8 | 3.3 | 1.2 |
| **September** | 4.7 | 5 | 4.2 | 4.1 | 1 |
| **October** | | | 4.5 | 3.4 | 1.4 |
| **November** | 3.3 | 18.3 | 3 | 8.8 | 1.3 |
| **December** | 4.2 | 5 | 9.9 | 9.8 | 1.6 |

Irrigated crop areas were converted to yield using average yield per hectare in each of the corresponding growing seasons (summer, autumn, winter and spring). Average yield for each crop was generated using the calibrated Soil Water Balance (SWB) crop model for simulations over a nine year period (2004 to 2012) (Annandale et al., 1999, Le Roux et al., 2016). Simulated yield data was verified with locally measured independent data and not with data that was used to obtain model parameters. Estimated yields of the selected irrigated crops on the aquifer were then multiplied by the blue and green WFs for the relevant season and added to obtain the total water consumed per calendar year. The selected crops cover 73% of the individual cropped areas determined for 1998. The remaining 27% of crops were assumed to use on average the same volume of water per surface area, so the water use of the selected crops was extrapolated to obtain the total water use of all crops on the aquifer. **Table 6-3** includes a summary of the available verification data on cropped areas as used in this study.

**Table 6-3: Summary of Steenkoppies Aquifer cropped areas used to calculate the catchment scale water footprint**

| Surface areas | Period 1 1950 to 1979 | Period 2 1980 to 1985 | Period 3 1986 to 1995 | Period 4 1996 to 2004 | Period 5 2005 to 2012 |
|---|---|---|---|---|---|
| | | | **Irrigated cropped areas** | | |
| **Total irrigated cropped area planted** | 268 ha** | 536 ha** | 1 952 ha*(1) | 4 183 ha* | 5 349 ha* |
| **Percentage of total cropped area for which crop species composition was verified** | Maize only** | Maize only** | Maize only** | 57%* | 57%** |
| **Percentage of total crop area (as per 1998 verified data) represented by selected crops** | Maize only** | Maize only** | Maize only** | 73%* | 73%* |
| | | | **Rainfed cropped areas** | | |
| **Total rainfed(2) cropped area on the aquifer** | 3 108 ha** | 3 108 ha** | 6 215 ha** | 6 215 ha** | 6 215 ha* |

* Verified data; ** Assumed / expert opinion, (1) taken from Barnard (1997); (2) Refer to **Section 6.2.2** for a discussion on rainfed crops.

The assumption that cropped areas for 1998 and 2005 represent all the years in the fourth and fifth period could be challenged, because cropped areas and species planted vary from year to year, as driven primarily by market prices and because of the large number of assumptions that were made regarding the crop composition. A sensitivity analysis was therefore conducted to determine how sensitive the catchment scale WF is to a particular crop composition. Two hundred iterations were composed of random crop compositions, always adding up to the total irrigated cropped area of 2005 used in this analysis. For each of the randomly selected crop compositions, a catchment scale WF was calculated as described above. The resulting catchment scale WFs were plotted as a histogram (**Figure 6-3**) to illustrate the variation and spread in the data. The average catchment scale WF for the 200 iterations was 30 $Mm^3$ and the standard deviation was 3.8 $Mm^3$. The catchment scale WF for 2005 that was obtained for this study was 31.8 $Mm^3$ (**Table 6-4**), which is within the standard deviation of the sensitivity analysis. The sensitivity analysis indicated that the catchment scale WF for the Steenkoppies Aquifer is, therefore, relatively insensitive to variations in cropping patterns. This is likely because most crops that were used are short season vegetables with shallow root systems and relatively similar ET. The sensitivity analysis therefore reduces uncertainty in the catchment scale water use results for this particular study area.

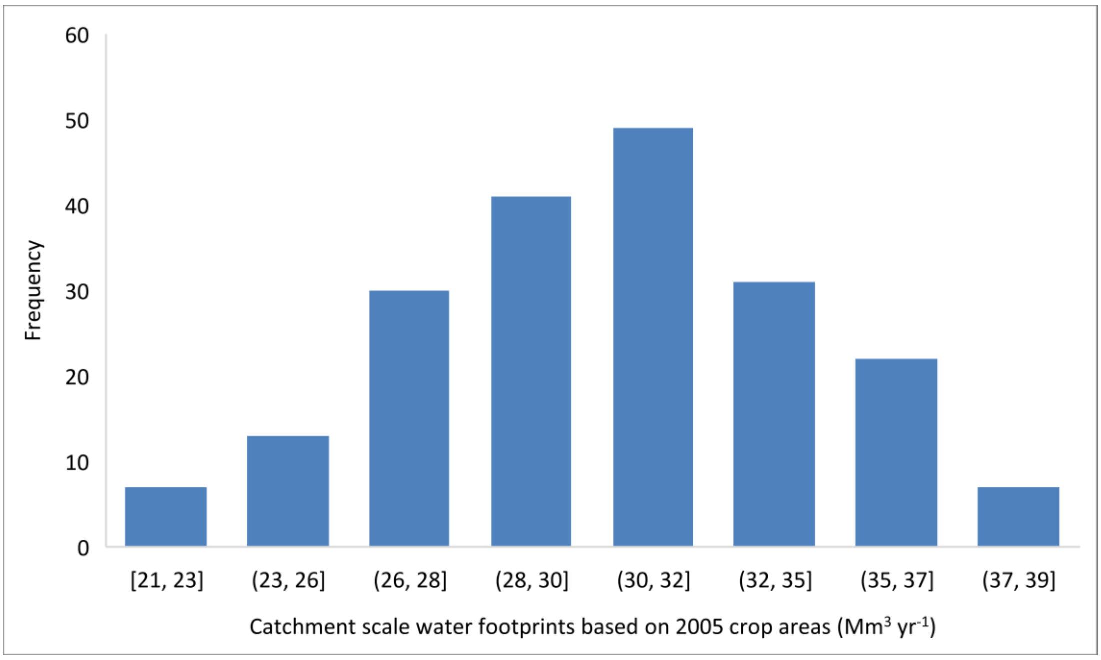

**Figure 6-3: Sensitivity of the catchment scale water footprint to randomly selected crop areas. All iterations in the analysis added up to the total cropped area of 2005.**

### 6.2.2 CATCHMENT WATER BALANCE

After the volume of water consumed by irrigated agriculture on the aquifer was calculated using WF accounting, a catchment water balance was calculated. The catchment water balance was calculated for the Maloney's Eye Catchment. Catchment boundaries were defined as the part of quaternary catchment A21F that is the area draining into the Maloney's Eye (Department of Water and Sanitation, 2016). Contour lines were used to delineate the northern boundary of the catchment, because the quaternary catchment includes a large area downstream of the Maloney's Eye, which is not relevant to this study. The northern boundary of the catchment is aligned with the northern boundary of the Steenkoppies Aquifer, because the aquifer boundary also coincides with ridges that define the northern boundary of the Maloney's Eye Catchment (**Figure 6-4**).

The other boundaries of the Maloney's Eye Catchment area are not exactly aligned with the boundaries of the Steenkoppies Aquifer. The aquifer overlaps the catchment to the east and west, and the catchment overlaps the aquifer to the south (**Figure 6-4**). Irrigated water used in the five periods between 1950 and 2012 were only related to irrigation activities above the aquifer, excluding the southern part of the catchment. Agricultural activities on this southern part of the catchment were considered insignificant, because the field areas under pivot irrigation are only 3% of total irrigation field areas within the Maloney's Eye Catchment (Crop Estimates Consortium, 2015). The other components of the catchment water balance, namely precipitation, ET of natural vegetation and rainfed maize, were for the Maloney's Eye Catchment area. It was also assumed that insignificant recharge of the aquifer occurs where the Steenkoppies Aquifer extends past the Maloney's Eye Catchment boundary to the east and west, because these areas are relatively small.

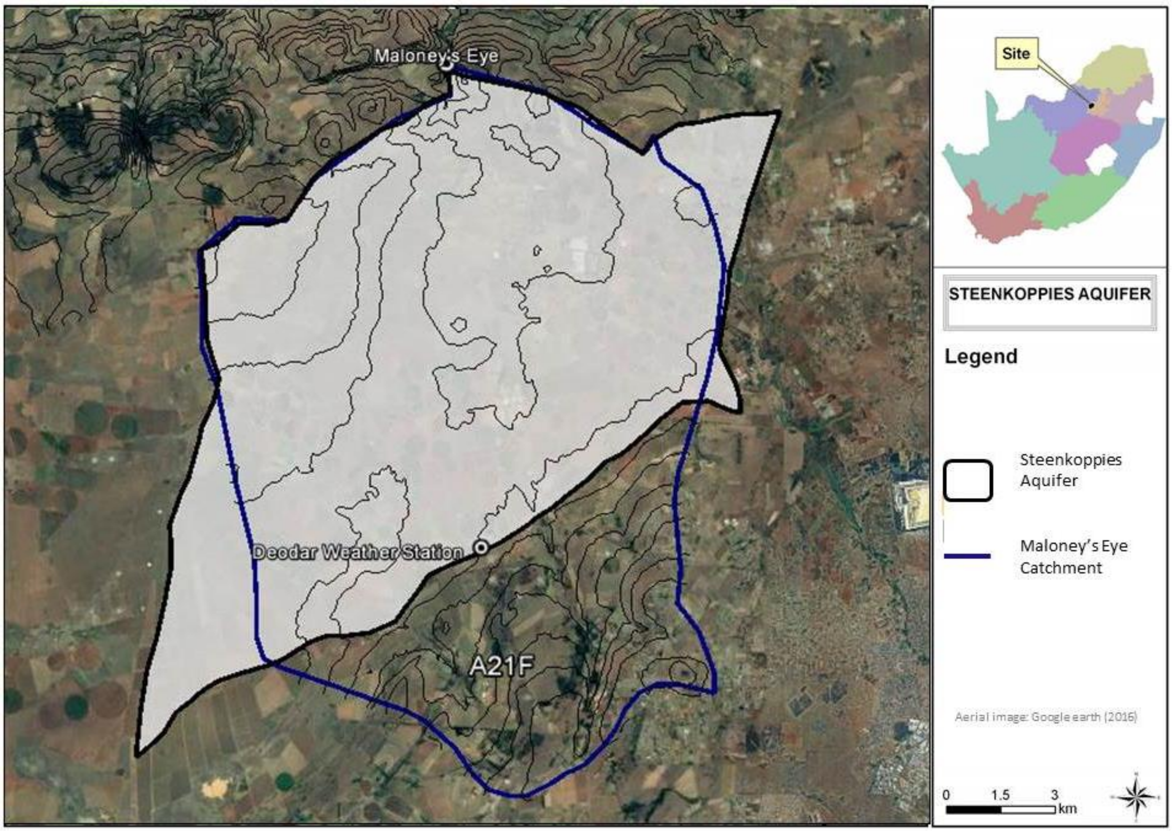

**Figure 6-4. The Steenkoppies Aquifer and Maloney's Eye Catchment boundary used for the catchment water balance/footprint calculations. Contours indicate high points in the landscape, according to which the Maloney's Eye Catchment boundaries were delineated.**

Based on the catchment water balance, annual outflows were then estimated using WF accounting. The first step was to estimate recharge of the aquifer ($Mm^3\ yr^{-1}$) according to **Equation 6-1.**

$$\begin{aligned} Aquifer\ recharge \\ &= Precipitation + Additional\ sources - ET\ of\ natural\ vegetation \\ &\quad - ET\ of\ agriculture - Additional\ uses \end{aligned}$$

**Equation 6-1**

Where, *precipitation* and *additional sources* are the volume of water inflows into the catchment. For aquifers in general, additional sources will include runoff from other catchments, inter-basin transfers of water into the area, or return flows from urban areas that were originally sourced from other catchments. *Additional uses* include water abstracted from the aquifer for purposes other than irrigation and transferred out of the catchment.

Volumes of precipitation for the catchment were estimated by multiplying measured daily precipitation data by the total surface area of the Maloney's Eye catchment. It was assumed that annual precipitation is relatively evenly distributed throughout the catchment, because the area is relatively small and has a flat topography. Actual precipitation data since 1984 was obtained for the Deodar weather station (Lat: S 26.1426 °; Long: E 27.57438 °, Altitude: 1591 mamsl), while simulated precipitation data was used for the period from 1951 to 1983 that was obtained from a database developed by a team from the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal using the South African Atlas of Climatology and Agro Hydrology (Van Heerden et al., 2009). The Maloney's Eye Catchment does not receive any runoff water from adjacent catchments that needed to be considered (Wiegmans et al., 2013). The Upper Rietspruit River is the only surface water resources within the Steenkoppies Aquifer and due to abstractions and losses from the river bed, the flow in this river is reduced to zero within the study area (Wiegmans et al., 2013).

The Randfontein Waste Water Treatment Works discharges 2.9 $Mm^3$ of effluent per year into the Maloney's Eye Catchment, of which 1.8 $Mm^3$ is used for irrigation. This 1.8 $Mm^3$ is an additional water source and was added to the water balance. The remaining 1.15 $Mm^3$ of the water is partly discharged into the Upper Rietspruit River and partly used for dust suppression. According to a geo-hydrological assessment by Wiegmans et al. (2013), this 2.9 $Mm^3$ $yr^{-1}$ effluent water evaporates and is not considered to recharge the aquifer, so this remaining 1.15 $Mm^3$ was excluded from the water balance. Apart from the 1.8 $Mm^3$ of irrigation water from the Upper Rietspruit River that is an additional source of water, there are no additional sources or uses of water in the catchment.

Evapotranspiration of irrigated agriculture for the first, second and third periods was taken to be 2, 4 and 13.45 $Mm^3$ $yr^{-1}$, respectively, as discussed in **Section 6.2.1**. The up-scaled irrigated crop WFs were used to estimate the total ET of irrigated agriculture for the fourth and fifth periods starting from 1996 and 2005, respectively. Rainfed agriculture shown in **Figure 6-1** (Crop Estimates Consortium, 2015) cover an area of 6 215 ha. This surface area was used to determine the ET of rainfed maize for the third to fifth periods. Based on local knowledge of the Steenkoppies Aquifer, it was estimated that rainfed agriculture totalled 3 107 ha during the first and second period (1950 to 1985) and this area was also used to estimate ET of rainfed maize for the first two periods.

The Acocks (1988) classification for the natural vegetation in the Maloney's Eye Catchment is Themeda veld to Bankenveld transition. Monthly ET of natural vegetation for the study area was simulated using SWB. A 'crop' factor for this vegetation type was obtained from Pike and Schulze (2004). The weather dataset that was used for crop modelling in SWB, as discussed in **Section 3.2.1.1**, did not include any data for 1950 to 1982. The weather database (Van Heerden et al., 2009) for Krugersdorp (Lat: S 26.1°; Long: E 27.8°, Altitude: 1730 mamsl), which is approximately 15 km from the Steenkoppies Aquifer, was used to expand rainfall, minimum and maximum temperature data from 1 January 1950 to 31 December 1982. Natural vegetation was assumed to include agricultural land left fallow, which is left unplanted at times during the year due to the relatively short growing season of vegetables crops and / or to 'rest' the soil. The area of natural vegetation was assumed to be the total catchment area minus irrigated and rainfed cropped areas minus 'built structures'. According to SANBI (2009) the surface area of urban areas in 2009 was 207 ha, which is insignificant compared to the total area of the Maloney's Eye Catchment and was therefore assumed as 'built structure' areas for all years considered in this study. To estimate cropped areas before 1996 it was assumed that only maize was irrigated. Average irrigation volume of maize per surface area was estimated from SWB outputs to determine total cropped areas that would require 2 $Mm^3$, 4 $Mm^3$ and 13.45 $Mm^3$ irrigated water (**Table 6-3**). Average SWB results for 2004 to 2012 provided lengths of crop growing seasons for each crop. The areas covered by crops each month for the fourth (1996 to 2004) and fifth (2005 to

2012) periods were determined by combining the crop lifetimes for a specific growing season with the crop areas planted. The total volume evapotranspired by natural vegetation in the catchment was calculated by multiplying daily ET of natural vegetation by the total surface area of natural vegetation for each of the five periods.

Actual outflows from Maloney's Eye, as measured by Department of Water and Sanitation (2014), was compared to estimated values to validate the WF accounting method used. In order to estimate outflows from Maloney's Eye, for comparative purposes, an eight-year moving average of estimated recharge was calculated, to mimic potential physical outflow regulations by the aquifer. An eight-year period was selected as it most closely aligned with the measured outflows from Maloney's Eye. The estimated outflows from 1950 to 1995 were plotted against measured outflows to determine the coefficient of determination ($R^2$) between them. Data from 1996 onwards were excluded, because high water uses by agriculture reduced the correlation between the variables.

Although the Steenkoppies Aquifer is considered relatively simple in terms of its geohydrology, lags in water flows through the aquifer complicate the understanding of the catchment water balance. Cumulative rainfall was compared to cumulative outflows from the aquifer to better understand possible lags in the Steenkoppies Aquifer.

### 6.2.3 SUSTAINABILITY ASSESSMENT

The sustainability of the catchment scale WF was assessed by comparing it with freshwater availability. In many cases average water availability over the year hides seasonal scarcities and it is therefore often important to consider monthly water availability or use (Hoekstra et al., 2011). However, water availability for the Steenkoppies Aquifer was calculated on an annual basis, because the aquifer has the ability to supply stored water during the dry seasons. Blue water availability ($WA_{blue}$) according to the WFN (Hoekstra et al., 2011) is calculated according to **Equation 2-9**. Average outflows from Maloney's Eye between 1909 and 1995, when impacts of irrigation were minimal, were 14.7 $Mm^3\ yr^{-1}$ and were used as the natural runoff ($R_{nat}$). Measured outflows after 1996 were excluded, because abstractions for irrigation impacted on the outflows during this time. The EFR for water flowing out of the Maloney's Eye and further downstream in the Magalies River was determined by the Department of Water Affairs (2011), as 46% of natural Mean Annual Runoff (MAR) in the Magalies River, downstream of the Maloney's Eye. The EFR for this study was therefore taken as 46% of the 14.7 $Mm^3\ yr^{-1}$ natural annual outflows from the Maloney's Eye.

In the past only $WA_{blue}$ was considered to be important, but according to the WFN green water is also scarce and can be used unsustainably. Green water availability ($WA_{green}$) was calculated according to **Equation 2-7**. Green water ET was calculated by multiplying annual ET of natural vegetation with the surface area of the whole catchment. The study area does not have any significant nature conservation areas so $ET_{env}$ was calculated according to a target conservation percentage for the veld type. According to Mucina and Rutherford (2006), the study area lies primarily within the Carletonville Dolomite Grassland (Gh15) for which a conservation target of 24% is set. The $ET_{env}$ is therefore calculated as ET of natural vegetation multiplied by 24% of the total catchment area. Total unproductive land includes all urban areas, which were multiplied by an estimated ET of 400 mm, as taken from the WFN handbook (Hoekstra et al., 2011). This volume represents an estimate, because actual ET in urban areas will be influenced by local weather conditions, soil properties and geology that determines drainage to the aquifer, plant cover and many other variables which have not been quantified. However, urban areas cover a relatively small area of the aquifer and variations to this estimate has a negligible impact on final results. Potential green water ET from irrigated areas was included in $ET_{green}$, because the green WF that is compared to this $WA_{green}$ includes green water used by both rainfed agriculture and irrigated crops.

## 6.3 RESULTS

### 6.3.1 CROP AND CATCHMENT LEVEL WATER FOOTPRINTS OF IRRIGATED CROPS

Average estimated blue and green water consumption by agriculture on the Steenkoppies Aquifer for the five periods investigated is given in **Table 6-4**. The catchment scale blue and green WFs for the fourth and fifth periods given in **Table 6-4** indicates that blue water is much higher than green water use, comprising 80% of the blue plus green WF. It highlights the large dependence of agriculture on irrigation water from the aquifer. The dramatic increase in blue plus green WFs of the catchment from the first to the fifth periods reflects the expansion of irrigation activities on the aquifer.

**Table 6-4: Total average blue and green water consumed by irrigated agriculture on the Steenkoppies Aquifer for five distinct periods between 1950 and 2012**

| Period | Cropped area planted per year (ha) | Water used by irrigated crops on the Steenkoppies Aquifer (Mm$^3$ yr$^{-1}$) | | |
|---|---|---|---|---|
| | | Blue | Green | Blue + Green |
| **1950 to 1979** | 268 | 2 | 0* | 2 |
| **1980 to 1985** | 537 | 4 | 0* | 4 |
| **1986 to 1995** | 2 335 | 13.5 | 0* | 13.5 |
| **1996 to 2004** | 4 183 | 19.9 | 4.8 | 24.6 |
| **2005 to 2012** | 5 349 | 25.4 | 6.2 | 31.5 |

*** Zero green water footprint assumed based on Equation 2-4 b**

### 6.3.2 CATCHMENT WATER BALANCE

The annual catchment water balance for the Steenkoppies Aquifer from 1950 to 2012, as estimated using WF accounting, is illustrated in **Figure 6-5**. During low rainfall years before 1996, annual water losses (measured outflows plus ET) are similar to the precipitation influxes. Average water influx from precipitation exceeds average water losses from the aquifer by 19 Mm$^3$ and the discrepancy is most pronounced during high rainfall years before 1996, when the water influx apparently exceeded the hydrologic conductivity of the system. During low rainfall years before and after 1996, water losses were similar to precipitation influxes. The first and second periods (before 1986) represent the natural condition, because abstraction from the aquifer for irrigation was still minimal (estimated at 2 to 4 Mm$^3$ yr$^{-1}$). Potential errors in the assumptions made for agricultural WF purposes can therefore not be responsible for the discrepancy between water in- and outflows, although errors in the ET of natural vegetation are one possible reason for the discrepancy between in- and outflows. Estimating ET of natural vegetation is, however, complex and further improvements are required in future research. It is also possible that excess water during high rainfall years recharges the aquifer, but this theory is contradicted by the fact that Maloney's Eye outflow drastically reduced when large-scale irrigation activities started despite the surplus water entering the aquifer during preceding high rainfall years. Annual water losses from the aquifer before 1996 almost never exceed the annual inflow. There is also a possibility that the aquifer boundaries are not completely impervious, as currently understood, and that excess water during high rainfall years can be lost through unknown outlets.

The third period, when commercial agriculture started to expand, is also the time first associated with significant reductions in Maloney's Eye outflows (**Figure 1-2**). During the fourth period considered (1996 to 2004), a few years with exceptionally high rainfall still caused a mismatch between water in- and outflows. However, during the fifth period (2005 to 2012) with relatively high water use for irrigation, coupled with some extremely low rainfall years, the total water losses resemble the inflows much more closely. Water losses were even higher than inflows for three years, 1999, 2004 and 2008.

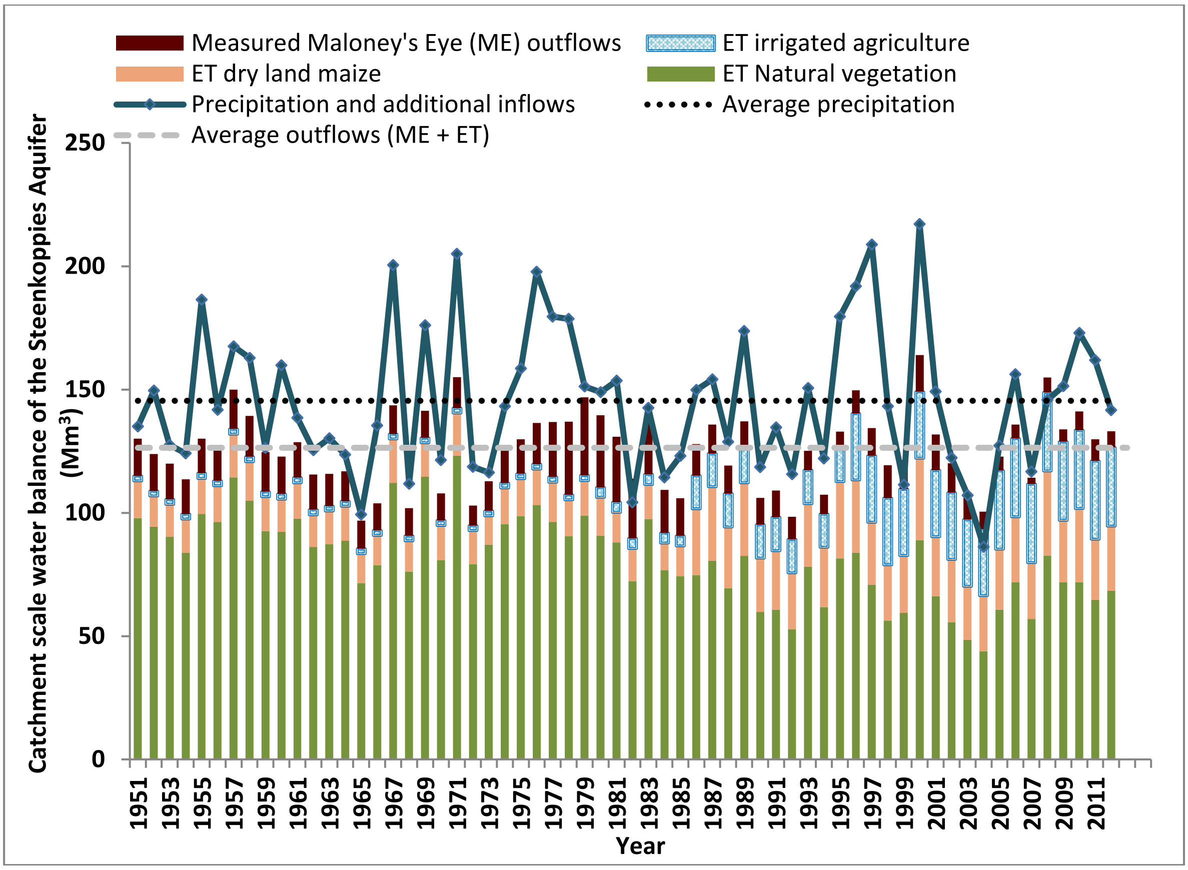

**Figure 6-5: Annual catchment water balance estimated using water footprint accounting and measured Malonye's Eye outflows for the Steenkoppies Aquifer. Outflows consist of evapotranspiration of natural vegetation rainfed and irrigated agriculture and aquifer discharge from Maloney's Eye (ME)**

Estimated annual recharge and estimated outflows (eight year moving average), were compared to measured outflows from Maloney's Eye (**Figure 6-6**). The eight-year moving average of the recharge represents estimated Maloney's Eye outflows. **Figure 6-7** indicates the correlation between measured and estimated outflows. Estimated outflows from Maloney's Eye has good correlation with measured Maloney's Eye outflows ($R^2$ = 0.75) from 1950 to 1995 (**Figure 6-7**). For the fourth period (1996 to 2004) there was also good correlation between estimated and measured outflows ($R^2$ = 0.86). A poor correlation between estimated and measured outflows ($R^2$ = 0.07) was found for the fifth period (2005 to 2012), which was probably due to the unpredictability in the system when large scale abstractions take place. However, although the average volume is more similar to actual outflows during the fifth period, it is overestimated for all years (**Figure 6-6**).

Cumulative precipitation versus cumulative outflows from the Steenkoppies Aquifer is given in **Figure 6-8** for each of the five periods from 1950 to 2012. Over time cumulative precipitation gradually exceeds cumulative outflows, due to the inflows in high rainfall years that cannot be accounted for in the catchment water balance. However, cumulative precipitation was closely related to cumulative outflows in Periods 2 and 5, because these were dry periods. The lag in the system is also seen in the Periods 2 and 5 graphs, where water inflows initially exceed outflows after which total estimated outflows catch up within about 1 year. The cumulative precipitation, however, does not explain the discrepancy between the in- and outflows of the catchment water balance during high rainfall years, indicating that this discrepancy is not due to lags in the system.

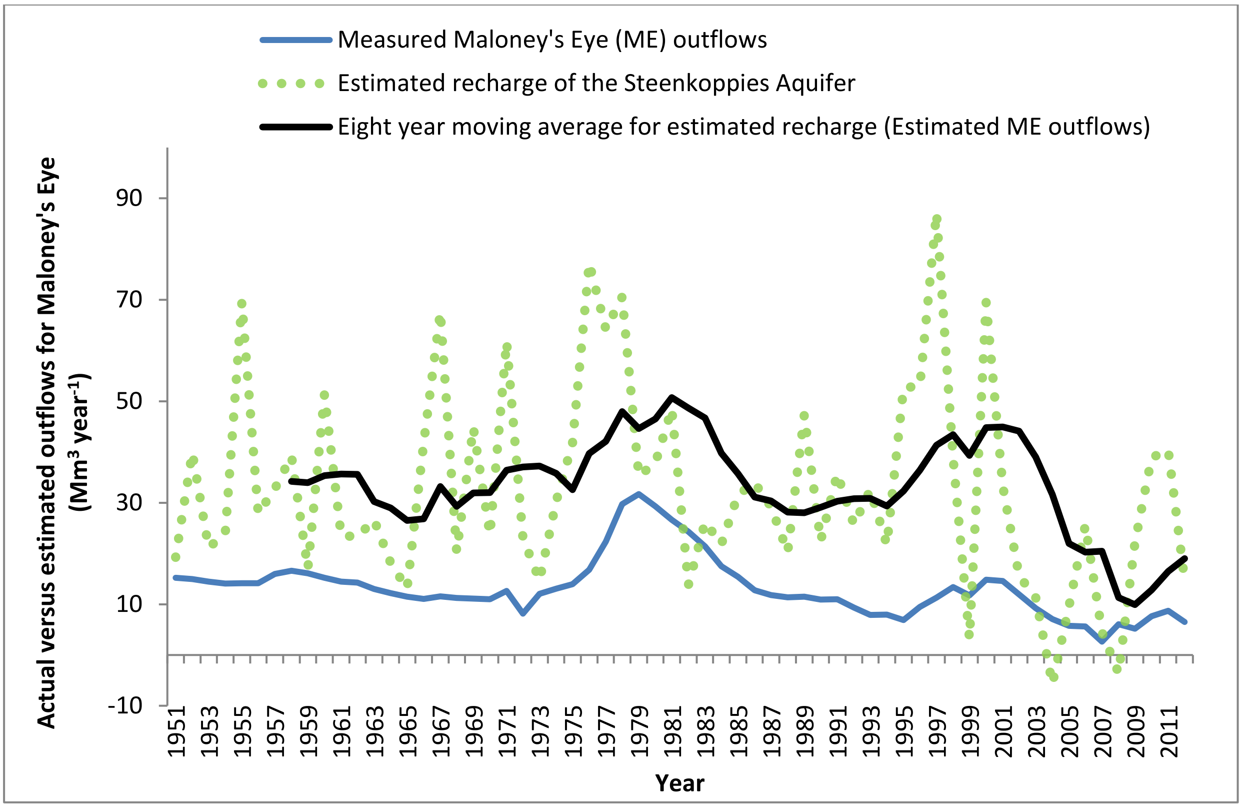

**Figure 6-6: Measured outflows from Maloney's Eye (ME) versus recharge of the aquifer estimated using water footprint accounting and estimated Maloney's Eye outflows represented by the eight-year moving average of estimated recharge**

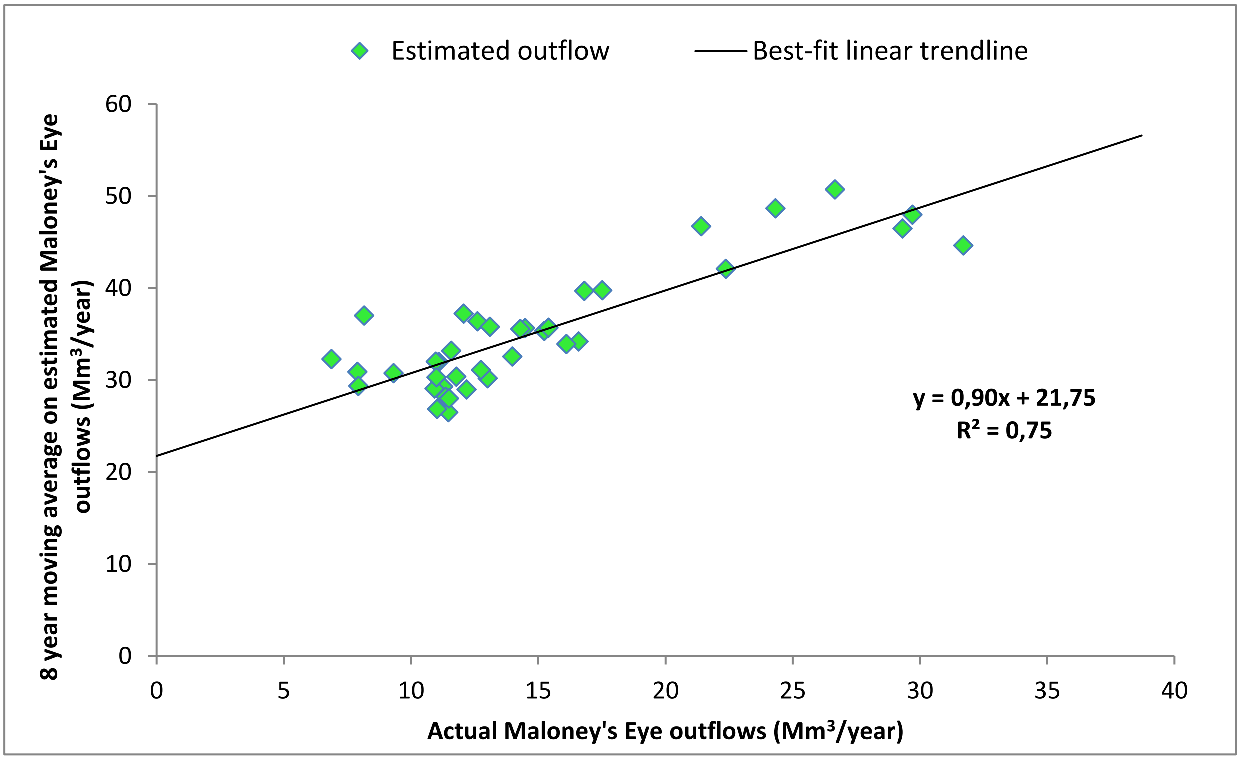

**Figure 6-7: Correlation between measured and estimated Maloney's Eye outflows from 1950 to 1995**

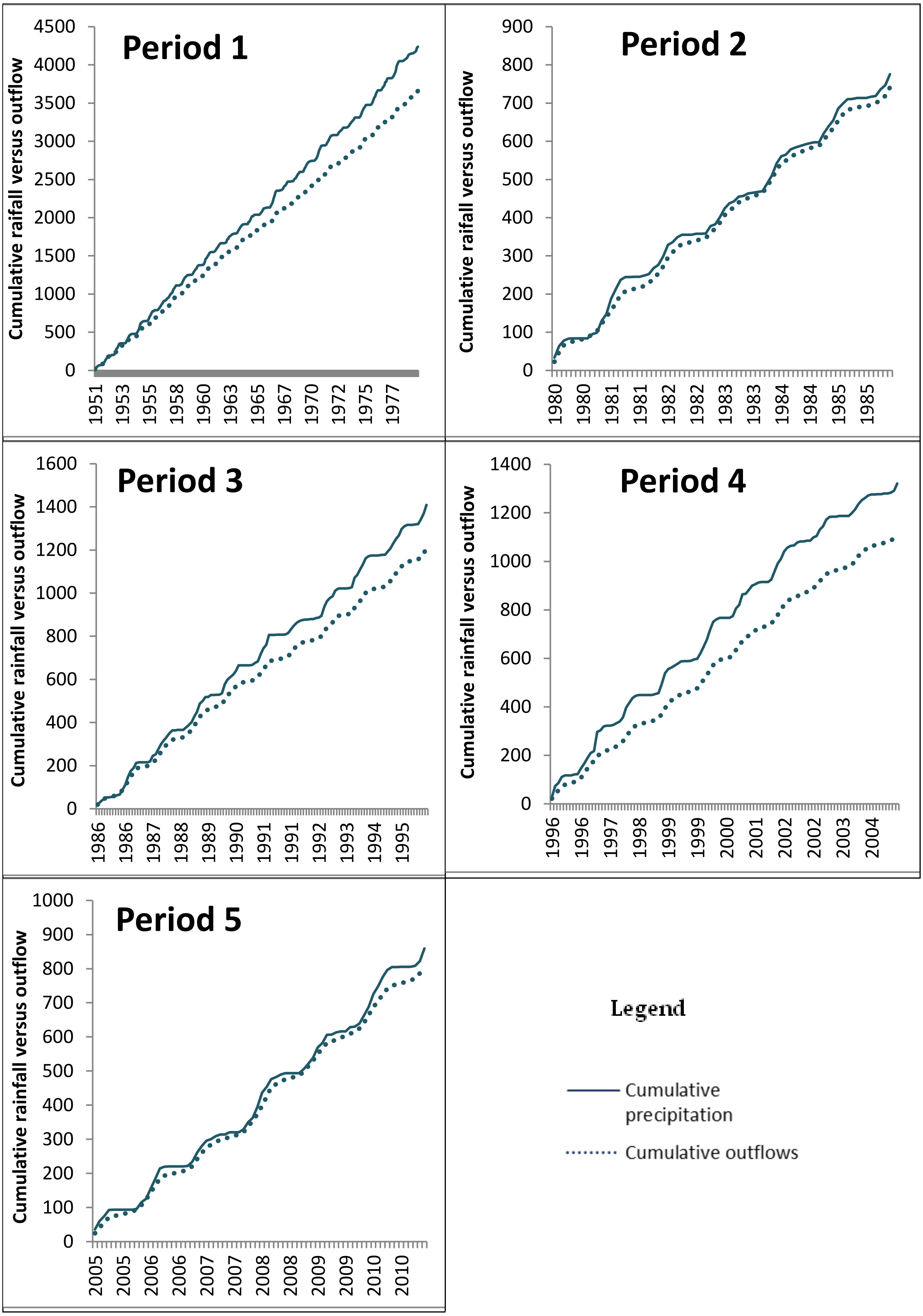

**Figure 6-8: Cumulative precipitation versus cumulative estimated outflows on the Steenkoppies Aquifer for the five periods from 1950 - 2012**

### 6.3.3 SUSTAINABILITY ASSESSMENT

The annual catchment scale blue WF of irrigated agriculture on the Steenkoppies Aquifer was compared to the annual $WA_{blue}$ in **Figure 6-9**. Although available blue water was not fully utilised during the first and second period (1950 to 1985), irrigated agriculture became unsustainable during the third period (1986 to 1995) (**Figure 6-9**). The discrepancy between $WA_{blue}$ and blue water consumption reached critical levels during the fifth period (2005 to 2012), due to further intensification of irrigated agriculture. Agricultural blue water use on the aquifer also exceeds Maloney's Eye outflows after 1986. This additional blue water is either sourced from groundwater stored in past years in the aquifer, or could also be explained by possible water movements across the boundary of the aquifer, where outflows from unknown outlets are reduced or possibly through water moving into the aquifer. Reductions in borehole levels taken at 26.04'37.6S; 27.34'35.1E, confirm the results of this sustainability assessment that water from the aquifer is being used faster than it is recharged (**Figure 6-10**). Borehole levels decline from the average after the year 2005, roughly coinciding with Periods 5 when abstractions for irrigation reached peak levels. The decline in borehole levels cannot be motivated by reduced rainfall, because despite dry years, the average annual rainfall during Period 5 (654 mm) was similar to the long term annual average since 1950 (671 mm). This confirms the results of this sustainability assessment that blue water from the aquifer is being over-utilised.

**Figure 6-11** shows the catchment scale green water used versus $WA_{green}$. Green water consumed by agriculture is less than available and there is still capacity left to increase rainfed agriculture within sustainable limits. Current agricultural green water use per hectare is relatively similar to the ET of natural vegetation, which defines $WA_{green}$. Therefore, the additional $WA_{green}$ results from areas under natural vegetation on the aquifer that can still be developed, if the conservation target of 24% is assumed (**Section 6.2.3**). For the blue and green WF calculations in **Chapter 3** optimal irrigation scheduling under pivot irrigation systems was assumed, as the crop was only irrigated when a specific soil water depletion threshold was reached. This assumption is supported by the data shown in **Figure 3-5**, where actual measured irrigation on the Steenkoppies Aquifer correlated well with simulated irrigation requirement modelled in SWB for all vegetables. Thus, irrigation scheduling cannot be improved to use green water more efficiently. However, green water use can potentially be further optimised through more efficient irrigation systems, such as drip irrigation or through water conservation techniques such as rainwater harvesting or mulching. As opposed to increasing rainfed agriculture, such measures to increase green WF use will also reduce the blue WF, which is highly encouraged considering the current unsustainable blue water use.

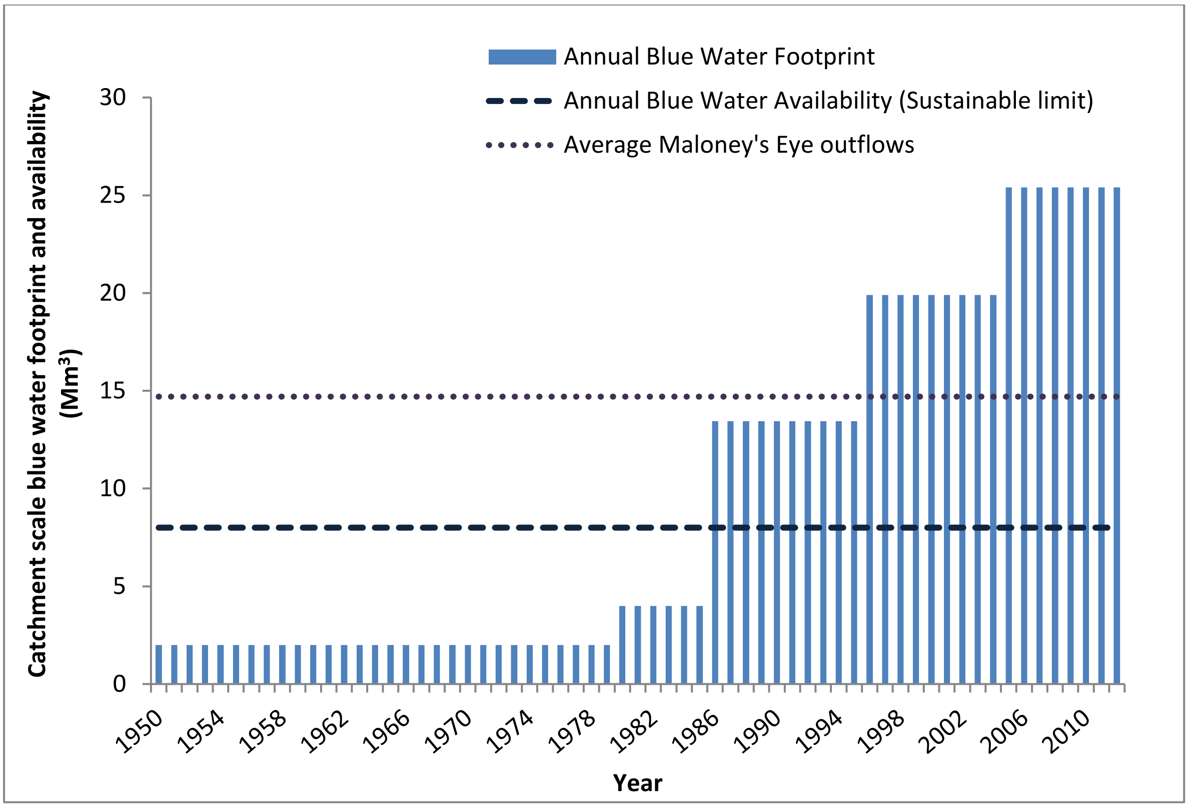

**Figure 6-9: Catchment scale blue water use of the Steenkoppies Aquifer versus the availability of blue water in the aquifer.**

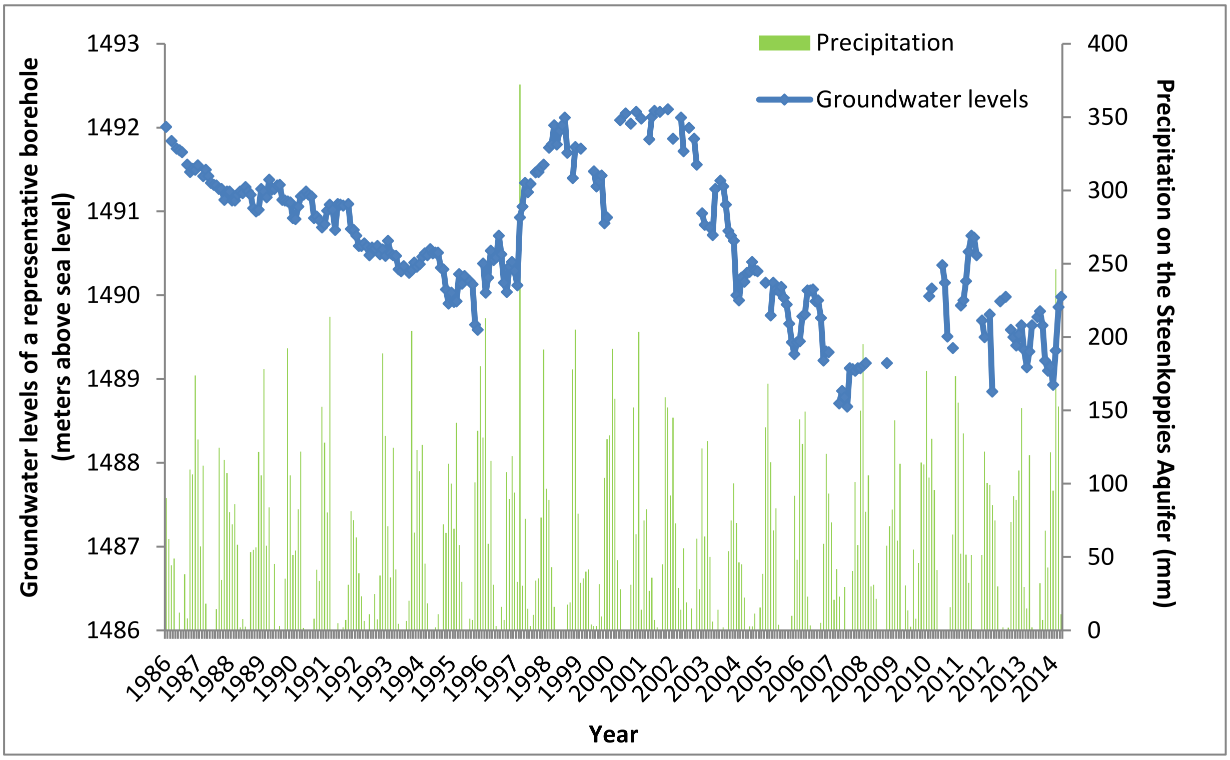

**Figure 6-10: Representative borehole levels which demonstrate reductions in groundwater level potentially due to abstractions for irrigation.**

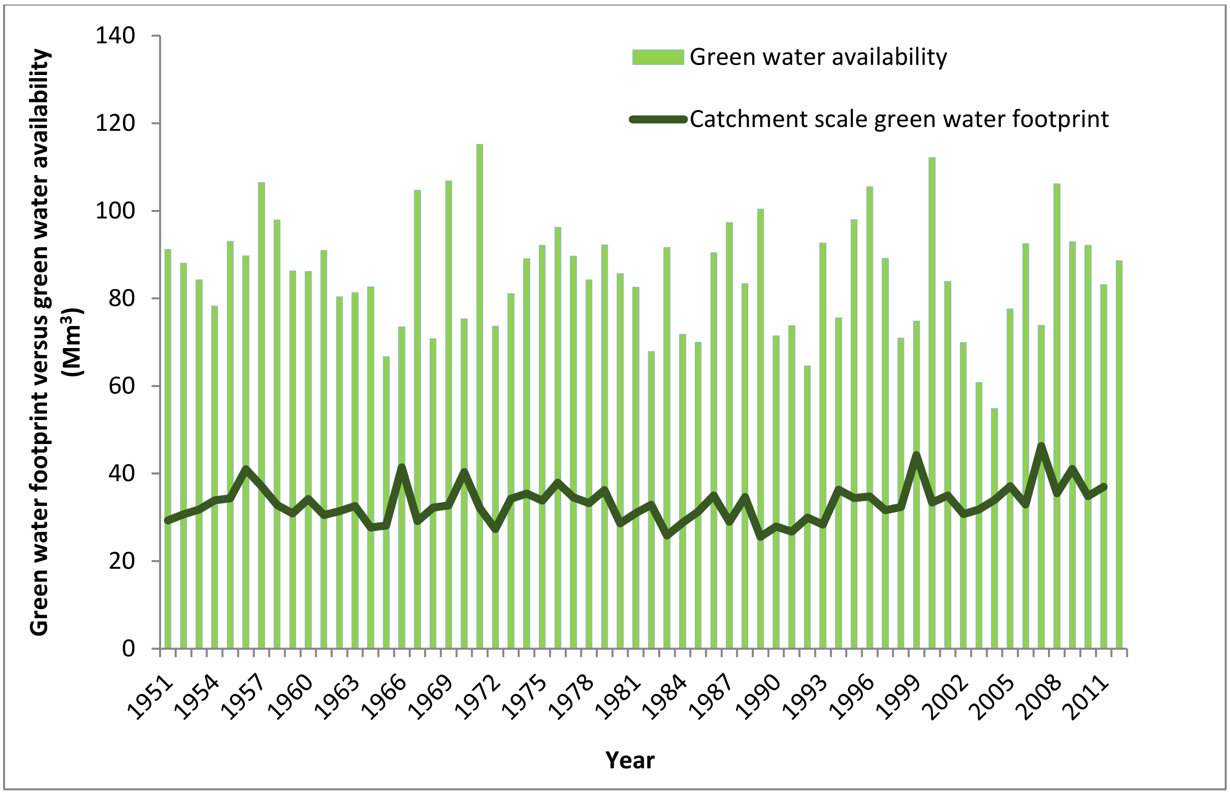

**Figure 6-11: Catchment scale green water use of agriculture of the Steenkoppies Aquifer versus green water availability for the catchment.**

## 6.4 DISCUSSION

In this study, agricultural water consumption was calculated for the catchment of the Steenkoppies Aquifer using water footprinting in a framework that we call the catchment WF framework. The catchment WF framework multiplied WFs calculated according to Hoekstra et al. (2011) with total yields to estimate agricultural water use on a catchment scale, which were then used with other water flows to determine a catchment water balance. A similar study was conducted for the High Plains Aquifer (HPA) (Multsch et al., 2016), where total yields were also linked to WFs to determine water used on the aquifer. The main difference between the catchment WF framework proposed here and the HPA study is scale. The HPA study was done on a smaller scale evaluating water use in different areas above the aquifer according to local impacts on groundwater levels. The strength of the HPA study was to highlight specific areas of concern within the aquifer, which is useful information for a water resources manager. The catchment WF framework proposed here evaluated the catchment and compared it to impacts on outflows and its strength is that it improved the understanding of the geohydrology and sustainability of current water use on the Steenkoppies Aquifer. In the past, total ET of the Maloney's Eye Catchment has not been quantified in hydrological studies on the Steenkoppies Aquifer, and this information can now be used to improve hydrological models. Other methods, such as remote sensing (Mo et al., 2005, Wu et al., 2015) can also be used to estimate ET over a catchment, but the catchment WF framework can also be used to predict ET based on planned crop areas. Using WFs to determine the water balance of the catchment can also be considered part of a process towards developing a simplified and more cost-effective approach to understanding water dynamics of aquifers in general, in contrast to complex and expensive hydrological assessments. With further research, it may be possible to standardise WFs for certain vegetables grown in certain areas within a particular season. For example, according to **Figure 5-6** inter-annual standard deviations of blue and green WFs for carrots, cabbage, beetroot and lettuce were relatively small in summer and autumn, and in such cases average values could be considered accurate for the particular area, potentially alleviating the need for recalculating WFs every year. The sustainability assessment, which requires an assessment of the EFR determined through complex hydrological assessments, is not required to calculate the catchment water balance, and the water balance alone can already give valuable information in terms of sustainable water use.

As illustrated by the catchment water balance (**Figure 6-5**), water flowing into the Steenkoppies Aquifer exceeds water losses, the reason for this being a key question that arises from this study. Since there is also no runoff from the catchment apart from Maloney's Eye, there are currently four plausible explanations for this:

- Errors in the assumptions made to calculate the catchment scale water use, particularly in estimating ET of natural vegetation. Estimating ET of natural vegetation is complex and further improvements are required in future research.
- Errors in estimating rainfall inflows due to spatial variability.
- Errors introduced via Steenkoppies Aquifer and Maloney's Eye Catchment spatial overlap assumptions.
- Poor understanding of soil and aquifer storage and conductivity dynamics.
- Other losses occurring from the aquifer boundaries that are currently not known. Although Maloney's Eye is currently considered to be the only natural outlet, a geo-hydrologist studying the Steenkoppies Aquifer recently had similar findings with hydrological models, and is investigating possible movement of water across the north-western boundary of the aquifer (Holland, 2016).

Although the WF approach currently overestimates Maloney's Eye outflows, there was a good correlation between estimated and measured outflows, and water outflows are very similar to precipitation inflows during years with low rainfall and / or high agricultural water use. These results affirm that the approach can potentially be developed into a useful and simplified tool to estimate outflows from an aquifer and better manage water resources, including through crop constitution decisions.

Agricultural blue and green WFs on a catchment scale can also be compared to water availability in a sustainability assessment, which is more informative than a volumetric crop WF in terms of crop yield. The blue water sustainability assessment for the Steenkoppies Aquifer indicated that irrigated agriculture became unsustainable after 1986, which is in line with measured reductions in the outflows from Maloney's Eye as well as reductions in groundwater levels during this time.

This catchment WF framework can potentially be applied to catchments in general to estimate volumes of water used by various water users in a catchment, some of which are difficult to measure, such as ET of crops and natural vegetation. Quantifying these water uses can provide useful near real time data to a catchment water resource manager to assess sustainability and improve decision-making. For example, the data can improve water allocation decisions, it can be used to set sustainable water use limits, and to assess the water productivity of different crops.

The catchment WF framework requires relatively little information for an agriculture-dominated catchment, including rainfall data, the total yield of different crops cultivated and their respective WFs, and the WF of natural vegetation. By using WFs calculated according to the WFN methodology automatically accounts for deep drainage of any excess irrigation water that is applied (because blue plus green water use equals total crop ET), alleviating the need to measure or estimate abstractions or percolation back into the aquifer. This should not create the impression that over-irrigation does not need to be addressed, because it can result in water logging, soil salinization, groundwater pollution, leaching of nutrients, and impacts on the soil such as acidification (Mostafa, 1977, Postel, 1999, Zilberman et al., 1997). The modification to the blue WF calculation according to the WFN methodology (**Equation 2-4 b**), however, does provide a way of reflecting over-irrigation as reduced or even zero green WF. It is therefore important to maximize green WFs together when using the catchment WF framework, in order to ensure that irrigation is conducted in a sustainable manner.

A key issue in the calculation of the $WA_{blue}$ for aquifers in general will be to determine the natural runoff. In most catchments natural runoff (which becomes blue water) is not known, either because of poor monitoring, complex systems with many outflows, or because of uncertainty regarding the impact of existing land use on natural flows. A number of additional components can be included in the calculation of $WA_{blue}$. Water allocated to downstream users should be subtracted from the natural runoff, for example, in this case from the Maloney's Eye outflows to calculate the volume of water that is available to irrigators on the Steenkoppies Aquifer. If ET of the natural vegetation is higher than ET of a rainfed crop, there will be more water recharging the aquifer under the latter land use, which would increase $WA_{blue}$. And if natural vegetation is replaced by urban areas with lower ET, and the stormwater is directed through artificial recharge to the aquifer, this will also increase $WA_{blue}$. For our case study the green water sustainability assessment indicated that there is $WA_{green}$ currently not utilised. This $WA_{green}$ may present an opportunity either to expand rainfed cropping based on a natural vegetation conservation target of 24%, or to improve irrigation efficiency to utilise more green water under irrigated agriculture, thus alleviating pressure on blue water.

According to Gleeson et al. (2012), long term multigenerational (50 to 100 years) sustainability targets in terms of water quality and quantity must be set for the management of groundwater resources. Policies must then be developed through backcasting, which as opposed to forecasting, starts with a future sustainability target and works backwards to determine shorter term aims and policies that will get you from the present state to the future target. The emphasis of Gleeson et al. (2012) is on ongoing monitoring and adaptation of strategies to ensure that progress is made towards the long term sustainability target. The catchment WF framework can potentially be applied within this framework. For example, long term sustainability targets can be set for groundwater levels of the Steenkoppies Aquifer, specifying a range of acceptable groundwater levels for both the long term and, through backcasting, targets can be set to ensure shorter term increases in groundwater levels. Once the long-term sustainability target has been reached, a suitable range for groundwater levels should be specified within which groundwater levels are to be maintained. For this purpose, it will be extremely useful for a catchment water resource manager to know how much agricultural production can be permitted to achieve these objectives. For example, 7 $Mm^3$ of water can be used to produce x tonnes of carrots, y tonnes of cabbage and z tonnes of maize, or different combinations thereof. Our proposed approach links the total yields from the aquifer with WFs to determine total agricultural water use on the aquifer. This can be done in reverse (determining production based on water availability), to determine and more easily regulate maximum agricultural yields from an aquifer when water for agriculture is restricted as specified by a sustainability target.

## 6.5 CONCLUSION

In this chapter the catchment WF framework is proposed for the first time and is an important contribution to the current scientific knowledge. It is envisaged that the catchment WF framework proposed here can be used to improve the water resource management of similar aquifers around the world. The framework proposes that volumetric blue and green WFs are linked to crop yields to provide a catchment manager with a relatively simple way to quantify and regulate water use of agriculture in the catchment. The framework could potentially be applied in catchments where surface water is the main source of irrigation, as long at the excess water abstracted for irrigation (where irrigation > crop ET) is returned to the same surface water resource in the same time period. In some cases, natural areas (which defines $WA_{green}$) may serve a function in recharging the aquifer (thus increasing the blue water availability), and in such cases green water availability should not be interpreted in isolation from blue water availability, as they are closely linked.

The potential use of the catchment WF framework has been tested in a case study on the Steenkoppies Aquifer. This assessment is the first attempt to quantify total ET on a catchment level for the Steenkoppies Aquifer using water footprinting. The lack of sustainability of blue water use on the Steenkoppies Aquifer is worrisome, with results being confirmed with observed reductions in groundwater levels and Maloney's Eye outflows. The water balance gave insights into the geohydrology of the aquifer, which indicated possible water movement across the boundaries of the aquifer, which was previously thought not to occur. The correlation between estimated and measured outflows from Maloney's Eye indicates that a method such as this can potentially be developed to estimate outflows from an aquifer using the WF approach. Despite the good correlation between estimated and measured outflows, however, the estimated outflows exceed measured outflows before irrigated agriculture became a significant user. The WF approach is therefore still in development and does not replace hydrological assessments and monitoring. In other areas, hydrological information may be even more important, because the Steenkoppies Aquifer is relatively simple from a hydrological perspective (with no surface runoff into or out of the catchment and only one known natural outlet). Future research required to refine and further develop the catchment WF framework should include:

- Record actual crop yields produced by the farmers over the long term.
- Improve the quantification of water use by natural vegetation.
- Improve the interplay between WF accounting and hydrological assessments to improve the understanding of the dynamics and sustainable water use for the system.
- Conduct a catchment scale grey WF assessment.

# 7 CHAPTER 7: WATER FOOTPRINTS OF VEGETABLE CROP WASTAGE PRODUCED ON THE STEENKOPPIES AQUIFER

## 7.1 INTRODUCTION

The water footprints (WFs) of vegetable crops on the Steenkoppies Aquifer during cultivation and in the packhouse were determined in **Chapters 3** and **4**, respectively. In **Chapter 6** it was estimated that the catchment scale blue WFs of irrigated agriculture exceeds sustainable limits for the Steenkoppies Aquifer. In this chapter the WFs of vegetable waste produced on the Steenkoppies Aquifer is calculated.

Phenomenal amounts of food wasted along the supply chain have been reported. Lundqvist et al. (2008) reported that up to 50% of production is lost from ‘field to fork’. There is limited information published on wastage of specific vegetables. Nahman et al. (2012) determined the cost of household waste in South Africa. Gustavsson et al. (2011) determined food wasted for different commodity groups, including roots and tubers, and fruits and vegetables for different region across the world, including sub-Saharan Africa. Oelofse and Nahman (2013) determined the average annual food wastage of these commodity groups along the supply chain in South Africa.

Production on the Steenkoppies Aquifer is mainly driven by market demands, and if less wastage occurs along the supply chain, it could potentially lead to reductions in demands. The question is asked as to whether reductions in food wastage, with concomitant reductions in vegetable production could provide a way to improve the degree of sustainability with which water is used on this water stressed aquifer.

## 7.2 MATERIALS AND METHODS

### 7.2.1 OBTAINING DATA ON PERCENTAGE WASTAGE ALONG THE SUPPLY CHAIN

Measured or estimated data was obtained on wastage of carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*) and lettuce (*Lactuca sativa*) at different stages along the supply chain. For each stage the percentage wastage was determined in terms of the volumes of vegetables delivered to the particular stage. Therefore, the percentages did not represent total wastage along the supply chain, but for that stage only. Total production figures on the Steenkoppies Aquifer in 2005 (**Chapter 6**) was then used to determine total wastage from field to fork. For each stage along the supply chain, wastage was determined by subtracting wastage at all preceding stages from total production and multiplying the remainder with the percentage wasted in the particular stage. This was done for each crop in each of the four seasons.

At farm level, wastage is mostly due to pests and diseases or because crops have unmarketable properties (**Figure 7-1 A and B**). The farm that was assessed was the sole provider for a large supermarket group and there have not been any cases reported where vegetables were wasted because of low demands or flooded markets. Wastage at the retailers mostly occurs when vegetables reach the end of their sell-by date or shelf-life. Offcuts, such as those shown in **Figure 7-1 C** are not counted as wastage, because they are not considered fit for human consumption and are not included in total production figures. Considering that these offcuts are fit for livestock consumption complicates the calculations, because it can be considered to reduce the WFs of the crops and if it is not used for another beneficial purpose it could increase the wastage.

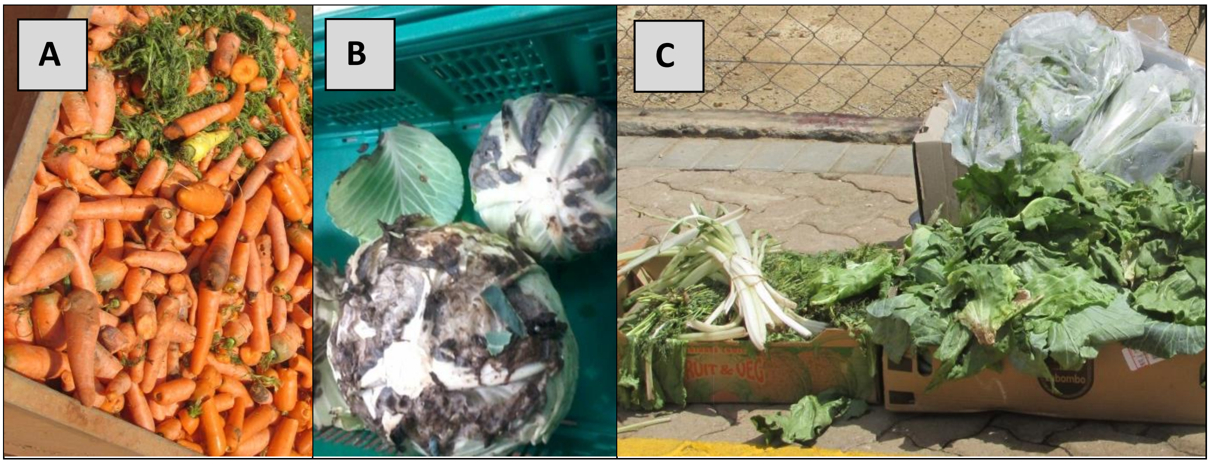

**Figure 7-1: Vegetables produced on the Steenkoppies Aquifer that are wasted along the supply chain. A and B, respectively, shows carrots and cabbage wasted at the farm level; C represents vegetable offcuts including the outer leaves of cabbage that have been cut and removed at a green grocer. Offcuts are not counted as wastage, because they are not considered fit for human consumption.**

#### *7.2.1.1 Wastage at the packhouse*

At farm level, there are three stages during which crop material can be discarded, namely:

- Discards at planting stage, which represents seedlings that don't grow.
- Discards during growing stages, which represents crops that don't develop into a harvestable product.
- Discards at harvest which represent vegetables that are not marketable.

Discards during planting and growing are not considered wastage, because these plants never develop into an edible product and are also not recorded as production. The seedlings use relatively little water and therefore do not have a significant impact on water resources. Vegetables wasted at harvest represent an edible product, and should therefore be considered as food wastage.

Daily production reports for the year 2015 for a packhouse on one of the farms on the Steenkoppies Aquifer were obtained which indicated the input and output volumes of carrots, cabbage and lettuce (Production Report, 2016). The difference between input and output volumes equals the wasted material. Beetroot and broccoli are not currently packed on the Steenkoppies Aquifer, and data on wastage in the packhouse was therefore not available for these two crops. Recording data for these crops in the packhouse are recommended for future research. Wastage of beetroot in the packhouse was assumed to be the same as carrots, because both are subsurface crops and treatment in the packhouse will be similar. Wastage of broccoli in the packhouse was assumed to be the same as cabbage, because the two crops are closely related. However, the quality of the produce will also play an important role, and therefore it is important to quantify wastage of these crops in future research. Although cabbage and lettuce data was given in terms of crop heads, it was used to calculate a percentage wastage at the packhouse, which was multiplied by total yields measured in weight for the total production in 2005 to provide a total wastage in terms of weight. Therefore, calculations on wastage in the remainder of the supply chain was done in terms of weight.

The question was asked whether data on total weights of crops received by the packhouse might have included non-edible portions of the crops, which would have wrongfully increased total food wastage of crops with a lower harvest index. This potential problem was not relevant to cabbage and lettuce, because the data for the packhouse was reported in terms of crop heads, instead of weight. For carrots, this was also not a problem, because the leaves of the carrots are cut during harvest and left in the fields as mulch.

#### *7.2.1.2 Wastage at the fresh produce market or distribution point*

The Tshwane Fresh Produce Market provided data on all crops that were received daily from the Steenkoppies Aquifer as well as those sold and discarded by them from July 2011 to July 2014 (Tshwane Fresh Produce Market, 2014). The data was detailed and reflected masses of each vegetable received, sold and discarded for each farm on the Steenkoppies Aquifer specifically. The percentage of each vegetable received from all farms of the Steenkoppies Aquifer that were discarded was calculated per season.

#### *7.2.1.3 Wastage at the retailer level*

Quantitative data on wastage at the retail level was not available, because retailers do not normally record food losses. Retailers that do record losses are often unwilling to disclose the data. Theoretically, it can be assumed that the difference between products bought and sold by the retailer will be equal to the wastage. In reality it is more complicated, because although the processing of vegetables reduces the percentage of food losses, it also complicates estimations of food losses. It is not always recorded how much of a particular vegetable, like carrots, are used in each of these pre-packed products and is therefore not possible to record exactly how much of the particular vegetable was sold. Even if wasted products are weighed, there is the challenge that the vegetables that are wasted often have much lower water contents than the fresh products, potentially underestimating the wastage in terms of mass of fresh product that was bought. Estimations of wastage at retail level are based on information obtained during several semi-structured interviews with experienced retailers.

#### *7.2.1.4 Wastage by consumers*

Estimating wastage by consumers is outside the scope of this study. Percentage wastage by consumers in South Africa was therefore taken from relevant literature sources.

### 7.2.2 ESTIMATING THE WATER FOOTPRINTS OF WASTAGE OF SELECTED VEGETABLES

The volume of blue plus green water lost due to the wastage of the selected vegetables produced on the Steenkoppies Aquifer in 2005 was estimated using the crop WFs estimated in **Chapter 3**. Water footprints were determined for wastage, for each season specifically, at each step of the supply chain by multiplying the total wastage at each step with the crop WFs.

## 7.3 RESULTS

#### *7.3.1.1 Wastage at the farm level*

Percentages of carrots, cabbage and lettuce wasted at the packhouse level in each season are given in **Figure 7-2**. Compared to carrots and lettuce, percentage wastage of cabbage in the packhouse was very low. Wastage during this stage was not closely correlated with seasons, because the wastage was not so much due to rotting during this first stage, but due to unmarketable traits.

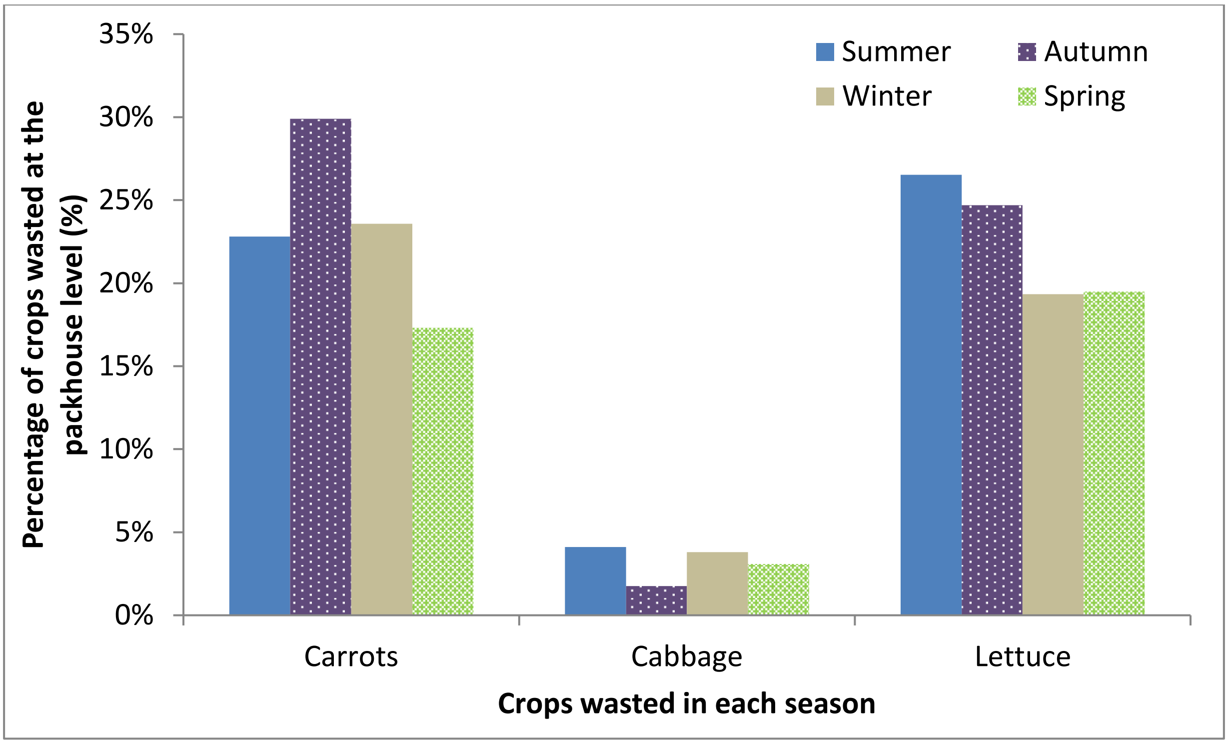

**Figure 7-2: Wastage of carrots, cabbage and lettuce in each season in 2015 in a packhouse on the Steenkoppies Aquifer**

The carrot production report is in kilograms of the harvest index, while cabbage and lettuce are reported in 'heads'. Carrots that were not marketable or sold include broken pieces that were too short to be marketed in a low value pack as well as grossly mis-formed, cracked, extremely thick or thin carrots. In the case of cabbage and lettuce, most waste heads were edible except those with serious insect infestation and those that were rotten or decayed. Cabbage heads that were not marketable include those that had decay, worm damage, black rings, discolouration, dehydration, *Anthropoda* infestation and those with incorrect head sizes. Lettuce heads that were not marketable include those that had browning, decay, worms, sun scorch, deep cuts, incorrect sizes, malformation and bruising. The trimmed leaves and non-marketable vegetables were fed to the cattle on the farm.

#### *7.3.1.2 Wastage at the market / distribution point*

**Figure 7-3** gives the percentage discard in terms of what the market received from the Steenkoppies Aquifer for each crop in each season. At this stage of the supply chain wastage is due to rotting of the crops, which is why waste percentages are higher in summer and higher for more perishable crops, like lettuce. Wastage of beetroot is particularly low for all seasons, except for summer. Wasted products at the market are used to make compost in a digester on site, which is a more recent development that was launched in 2014.

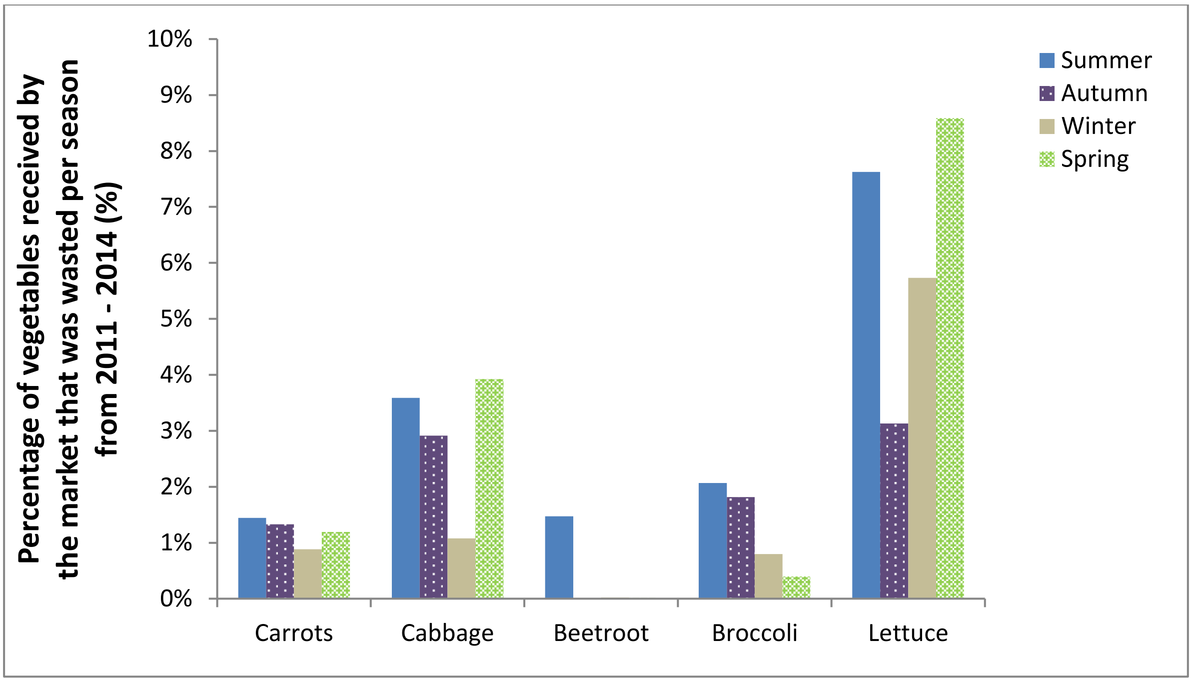

**Figure 7-3: Percentage of crops received by the Tshwane Market from 2011 – 2014 that was discarded**

#### *7.3.1.3 Wastage at retailers*

Weather conditions impact on food wastage at the retailer level, but management decisions also play an important role in terms of percentage food losses. Retailers that order too many vegetables once or twice a week generally have more losses than retailers that order less vegetables more often, or even daily. Most green grocers cut and combine vegetables that approach the end of their shelf life into pre-packed products for salads, soups or stir-fry vegetables. In supermarkets ageing vegetables are used to make salads and sandwiches in the supermarket delis. This greatly reduces food losses at the retail level, but in the case of lettuce, for example, there is a limit to how much salad can be sold in a deli and wastage cannot be completely avoided. Wastage from the retailer is often given to soup kitchens, or livestock farms or used for composting.

Carrots, cabbage, beetroot and broccoli have a relatively long shelf-life and wastage is generally low. According to experienced retailers (dos Santos, 2014, Gathino, 2016, Mentis, 2016), wastage of these vegetable at retail level is between 1% and 5%. It was therefore assumed that wastage of these vegetables at the retailer is 5% in summer, 3% in autumn and spring and 1% in winter. Lettuce is more perishable and according to experienced retailers average wastage of lettuce at retail level is between 7% and 10%. It was therefore assumed that wastage of lettuce at the retailer is 10% in summer, 9% in autumn and spring and 7% in winter.

#### *7.3.1.4 Wastage by consumers*

According to Gustavsson et al. (2011), as cited by Oelofse and Nahman (2013), wastage of roots and tubers in South African households is 2% and wastage of fruit and vegetables in South African households is 5%. Thus, the wastage of carrots and beetroot was assumed to be 2% and wastage of cabbage, broccoli and lettuce was assumed to be 5% at the household level. Data was not available on total food wastage per household in South Africa, but according to Nahman et al. (2012) most wastage in South Africa occurs in low income communities (**Figure 7-4**). This is, however, because of the number of low income households in South Africa, which is much more compared to high income houses and does not reflect higher wastage per household in low income communities.

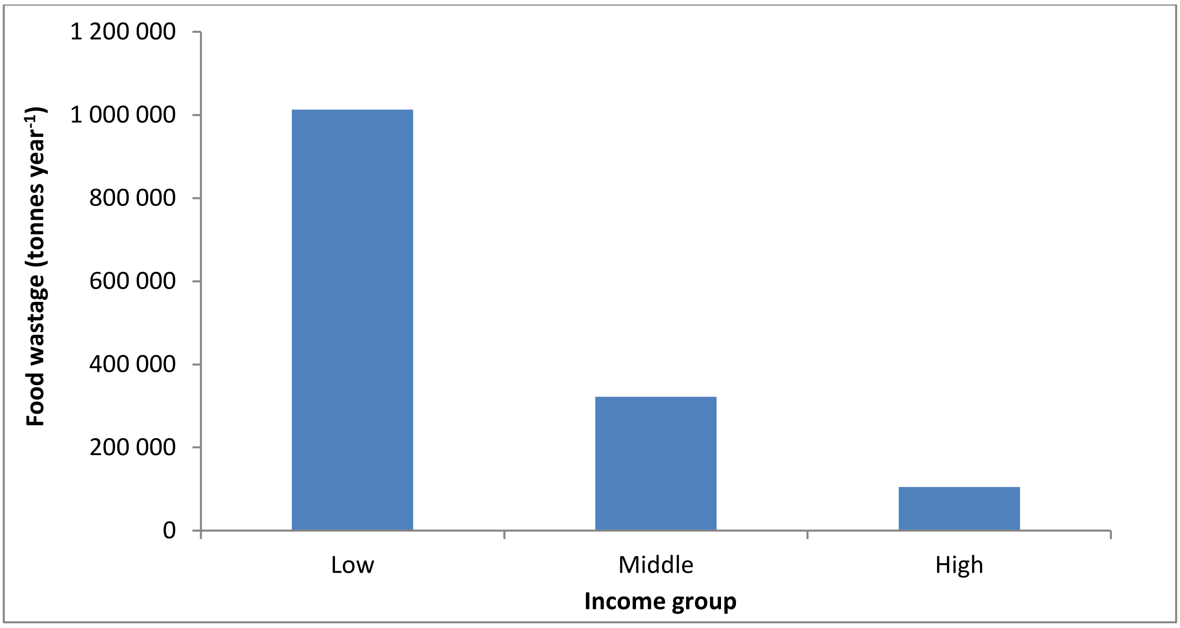

**Figure 7-4: Total food wastage generated by different income groups in South Africa (Nahman et al., 2012)**

### *7.3.2 Total wastage of vegetables from the Steenkoppies Aquifer along the supply chain to the consumer*

**Table 7-1** summarises wastage at each stage of the supply chain to the consumer in terms of annual production of each vegetable on the Steenkoppies Aquifer in 2005. Wastage of cabbage and broccoli was relatively low, because of low percentage wastage in the packhouse and the general longer shelf lives of these crops. Lettuce had the highest percentage wastage for all seasons, because of high percentage wastage in the packhouse and the short shelf life of the crop. As indicated in **Table 7-1**, an estimated 29% of the annual production of carrots and beetroot (root vegetables) and 32% of the annual production of cabbage, broccoli and lettuce was lost due to wastage. This is much lower than indicated by Oelofse and Nahman (2013), who estimate annual wastage of 44% of roots and tubers and 51.5% of other vegetables in terms of average annual food production. The percentage wastage estimated by Oelofse and Nahman (2013) was based on percentage wastage given by Gustavsson et al. (2011) for sub-Saharan Africa. The percentage contribution to total wastage (including all five vegetables) by each step along the supply chain, as calculated in this study, is given in **Figure 7-5,** and compared to the findings of food wastage along the supply chain in South Africa as published by Oelofse and Nahman (2013) and given in **Figure 7-6**. Oelofse and Nahman (2013) estimated that 79 % of total wastage occurs before distribution during agricultural production, post-harvest handling and storage, and processing and packaging. Our packhouse level data included all three of these losses combined. The average percentages wastage in the packhouse on the Steenkoppies Aquifer were 70% of total food wastage along the supply chain, which correlates well with estimates from Oelofse and Nahman (2013). Oelofse and Nahman (2013) also reported wastage during distribution, which included our market and retail stages. Our percentage wastage for the market and retail stages was 9% and 12% in terms of total wastage along the supply chain, respectively, the sum which correlated well with the 17% wastage during distribution as reported by Oelofse and Nahman (2013). We estimate 8% wastage at the household level in terms of total wastage, compared to 4% estimated by Oelofse and Nahman (2013). There was, however, variation in average annual wastage between different crops, which varied from 13% for broccoli to 38% for lettuce, as illustrated in **Figure 7-7**.

**Table 7-1: Summary of wastage of carrots, cabbage, beetroot, broccoli and lettuce along the supply chain from the farm to the consumer in terms of total production on the Steenkoppies Aquifer in 2005**

| Crop | Season | Total production for 2005 (tonnes) | Percentage wastage in terms of mass received by each stage (%) | | | | Total wastage at each stage (tonnes) | | | | | Total percentage wastage (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Farm | Market | Retail | Consumer | Farm | Market | Retail | Consumer | Total | |
| **Carrots** | Summer | 13487 | 23% | 1% | 5% | 2% | 3076 | 150 | 513 | 195 | 3934 | 29% |
| | Autumn | 8455 | 30% | 1% | 3% | 2% | 2527 | 79 | 175 | 114 | 2895 | 34% |
| | Winter | 9194 | 24% | 1% | 1% | 2% | 2167 | 62 | 70 | 138 | 2437 | 27% |
| | Spring | 3222 | 17% | 1% | 3% | 2% | 558 | 32 | 79 | 51 | 720 | 22% |
| **Beetroot** | Summer | 3094 | 23% | 2% | 5% | 2% | 706 | 35 | 118 | 45 | 903 | 29% |
| | Autumn | 4769 | 30% | 0% | 3% | 2% | 1425, | 0 | 100 | 65 | 1591 | 33% |
| | Winter | 4218 | 24% | 0,02% | 1% | 2% | 994 | 1 | 32 | 64 | 1091 | 26% |
| | Spring | 2586 | 17% | 0,01% | 3% | 2% | 448 | 0 | 64 | 42 | 553 | 21% |
| **Subtotal 1 *** | | **49023** | | | | | **11901** | **359** | **1151** | **712** | **14124** | **29%** |
| **Cabbage** | Summer | 3700 | 3% | 4% | 5% | 5% | 125 | 128 | 172 | 164 | 589 | 16% |
| | Autumn | 1369 | 2% | 3% | 3% | 5% | 22 | 39 | 39 | 63 | 164 | 12% |
| | Winter | 2705 | 4% | 1% | 1% | 5% | 100 | 28 | 26 | 128 | 281 | 10% |
| | Spring | 2373 | 3% | 4% | 3% | 5% | 81 | 90 | 66 | 107 | 344 | 15% |
| **Broccoli** | Summer | 1016 | 3% | 2% | 5% | 5% | 34 | 20 | 48 | 46 | 148 | 15% |
| | Autumn | 62 | 2% | 2% | 3% | 5% | 1 | 1 | 2 | 3 | 7 | 11% |
| | Winter | 482 | 4% | 1% | 1% | 5% | 18 | 4 | 5 | 23 | 49 | 10% |
| | Spring | 672 | 3% | 0% | 3% | 5% | 23 | 3 | 19 | 31 | 76 | 11% |
| **Lettuce** | Summer | 15855 | 27% | 8% | 10% | 5% | 4205 | 889 | 1076 | 484 | 6654 | 42% |
| | Autumn | 2965 | 25% | 3% | 9% | 5% | 732 | 70 | 195 | 98 | 1095 | 37% |
| | Winter | 9918 | 19% | 6% | 7% | 5% | 1918 | 459 | 528 | 351 | 3255 | 33% |
| | Spring | 6858 | 19% | 9% | 9% | 5% | 1337 | 474 | 454 | 230 | 2495 | 36% |
| **Subtotal 2 **** | | **47977** | | | | | **8597** | **2205** | **2630** | **1727** | **15159** | **32%** |

***Subtotal 1 for carrots and beetroot (root vegetables), ** Subtotal 2 for cabbage, broccoli and lettuce**

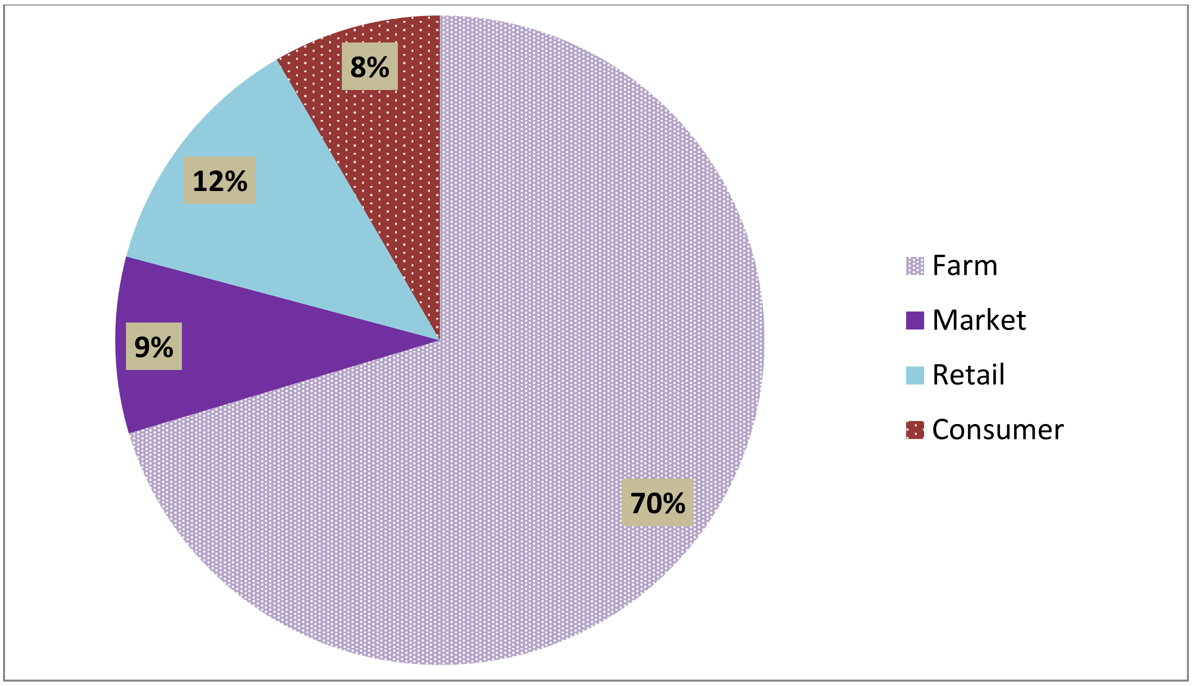

**Figure 7-5: Average percentages of total annual wastage of carrots, cabbage, beetroot, broccoli and lettuce produced on the Steenkoppies Aquifer at different stages along the supply chain from 'field to fork'**

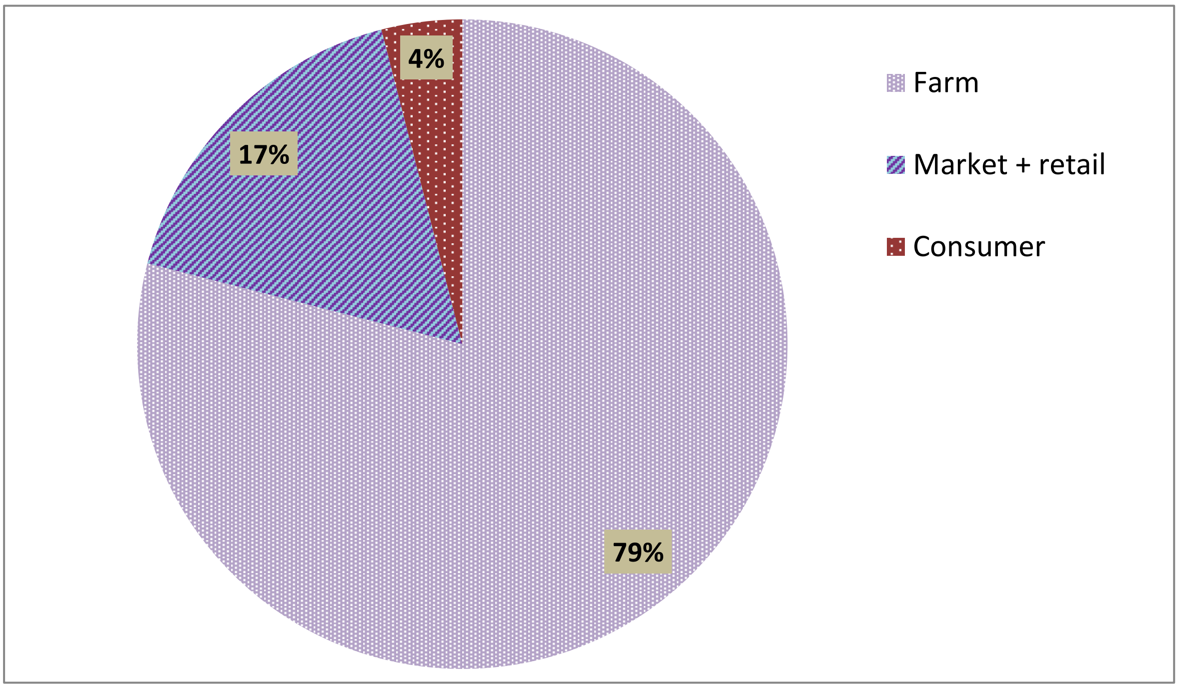

**Figure 7-6: Wastage of food along the supply chain in South Africa as estimated by Oelofse and Nahman (2013)**

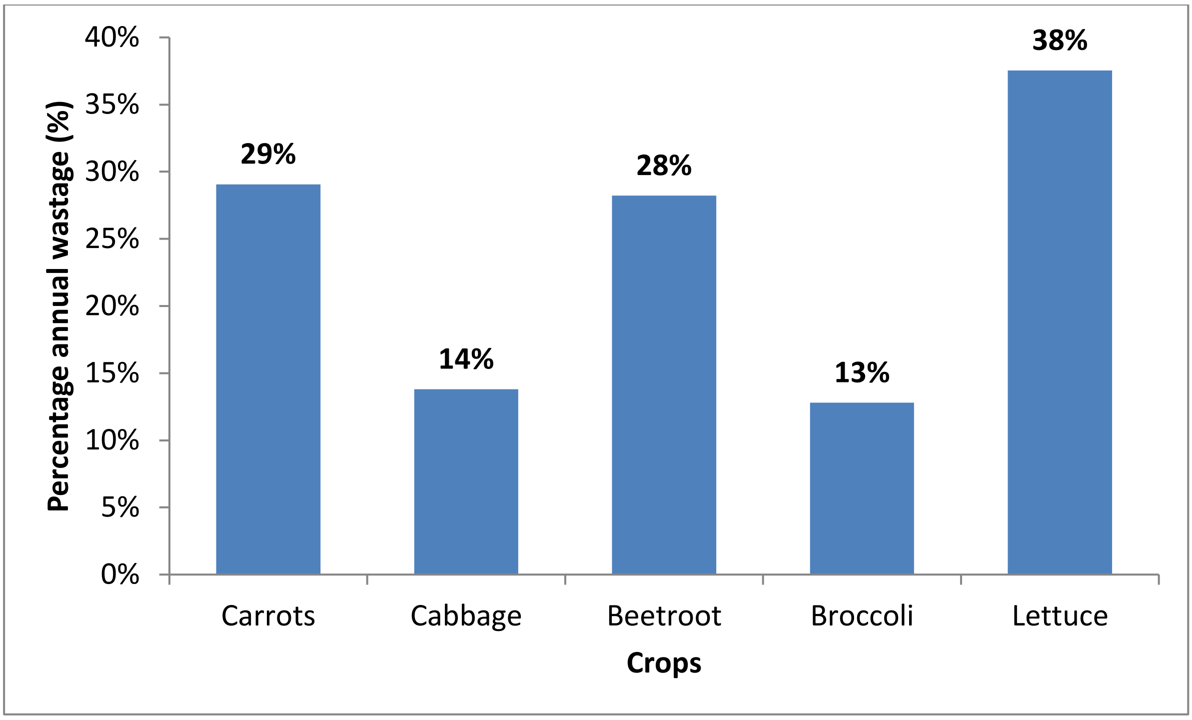

**Figure 7-7: Percentage annual wastage from 'field to fork' of the five selected vegetable crops in terms of total production on the Steenkoppies Aquifer in 2005**

### *7.3.3 Water footprint of wastage of selected vegetables*

The blue plus green WFs of seasonal discards along the supply chain to the consumer of the selected vegetable crops produced on the Steenkoppies Aquifer in 2005, are given in **Table 7-2** and **Figure 7-8.** In 2005, an estimated 2.4 Mm$^3$ blue plus green water was lost due to this wastage of the selected vegetable crops, of which 1.9 Mm$^3$ was blue water. Most of the wastage occurred in the packhouse, and due to wastage of lettuce along the whole supply chain.

**Table 7-2: Blue plus green water lost due to wastage of vegetables produced on the Steenkoppies Aquifer in 2005**

| Crop | Season | Blue plus green water lost due to wastage (Mm$^3$) | | | | Total |
|---|---|---|---|---|---|---|
| | | Farm | Market | Retail | Consumer | |
| **Carrots** | Summer | 0.188 | 0.009 | 0.031 | 0.012 | **0.24** |
| | Autumn | 0.294 | 0.009 | 0.020 | 0.013 | **0.34** |
| | Winter | 0.206 | 0.006 | 0.007 | 0.013 | **0.23** |
| | Spring | 0.035 | 0.002 | 0.005 | 0.003 | **0.04** |
| **Cabbage** | Summer | 0.008 | 0.009 | 0.011 | 0.011 | **0,04** |
| | Autumn | 0.001 | 0.003 | 0.003 | 0.004 | **0,01** |
| | Winter | 0.008 | 0.002 | 0.002 | 0.010 | **0,02** |
| | Spring | 0.006 | 0.007 | 0.005 | 0.008 | **0,03** |
| **Beetroot** | Summer | 0.070 | 0.003 | 0.012 | 0.004 | **0.09** |
| | Autumn | 0.144 | 0.000 | 0.010 | 0.007 | **0.16** |
| | Winter | 0.123 | 0.000 | 0.004 | 0.008 | **0.13** |
| | Spring | 0.053 | 0.000 | 0.008 | 0.005 | **0.07** |
| **Broccoli** | Summer | 0.009 | 0.005 | 0.013 | 0.012 | **0,04** |
| | Autumn | 0.000 | 0.000 | 0.001 | 0.001 | **0,00** |
| | Winter | 0.006 | 0.001 | 0.002 | 0.007 | **0,02** |
| | Spring | 0.005 | 0.001 | 0.004 | 0.007 | **0,02** |
| **Lettuce** | Summer | 0.234 | 0.049 | 0.060 | 0.027 | **0.37** |
| | Autumn | 0.052 | 0.005 | 0.014 | 0.007 | **0.08** |
| | Winter | 0.179 | 0.043 | 0.049 | 0.033 | **0.30** |
| | Spring | 0.083 | 0.029 | 0.028 | 0.014 | **0.15** |
| **Total** | | **1.71** | **0.18** | **0.29** | **0.21** | **2.38** |

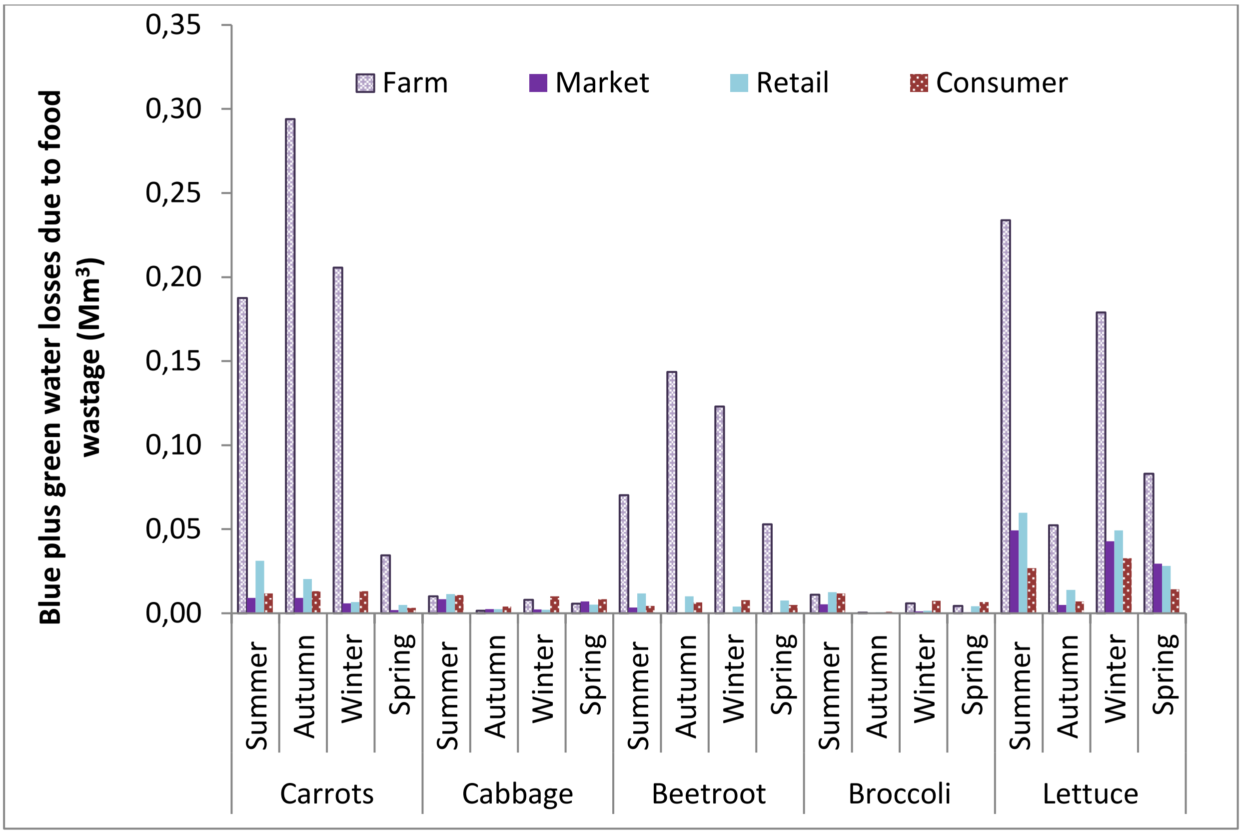

**Figure 7-8: Water footprint of vegetables produced on the Steenkoppies Aquifer in 2005 that was wasted along the supply chain from the farm to the consumer**

## 7.4 DISCUSSION

Average wastage for carrots, cabbage, beetroot, broccoli and lettuce along the supply chain that was calculated in this study was lower than estimates from the literature for sub-Saharan Africa (Oelofse and Nahman, 2013). The results also indicated that there is a large variation in food wastage between different crops, which translates to significant differences in WFs of wastage of the different crops. For example, literature sources indicating that 51.5% of vegetables are wasted along the supply chain overestimate wastage of cabbage which ranges between 10.4% in winter and 15.9% in summer.

The results also indicated high inter-seasonal variation in vegetable wastage. For carrots and beetroot, there is 12% difference between highest food wastage in autumn and lowest food wastage in spring. Maximum wastage of lettuce in summer was 10% more than minimum wastage of lettuce in winter. Large differences in total production may affect the percentage wastage, where lower production may be easier to manage and have less wastage. For all crops percentage wastage was higher in summer compared to winter, partly because of shorter shelf lives when temperatures are higher.

The main challenge in quantifying food wastage is to classify waste. Offcuts, which includes non-edible parts of the crops, was not considered wastage. These offcuts were also not included in total production figures, because for cabbage and lettuce the figures were given in head counts, and the leaves of carrots are cut in the field. Most of the wastage reported in this chapter was not simply discarded. Wastage at the farm level is fed to livestock, wastage at the Tshwane Market was used for composting, and wastage at many of the green grocers that were contacted was given to charity organisations or livestock farmers. The beneficial use of these vegetables could disqualify them from being classified as waste, especially if they substitute better quality foods used for livestock feed. However, in the face of food insecurities it is still worth considering these losses from the food supply chain. Another challenge in quantifying vegetable wastages is the loss of water content as the vegetables age, which results in low masses wastage compared to what was bought. If products are measured in terms of vegetable counts, like cabbage heads with more or less standard sizes, that problem could potentially be overcome.

It could be argued that the reduction in food wastage may be one of the simpler ways to address food insecurities and water scarcities. Potential savings in green water used through reductions in food wastage was assumed to be negligible, because these wasted crops replaced natural vegetation that would also use green water. According to the 2005 crop areas a total of 6 $Mm^3$ of blue water was required to grow the five selected vegetables, of which an estimated 2 $Mm^3$ was used to produce the wastage. According to the 2005 crop areas 12 $Mm^3$ blue water was used to grow maize and wheat on the Steenkoppies Aquifer. The wastage of maize and wheat has not been determined, but Gustavsson et al. (2011) reported 19% wastage of cereals in sub-Saharan Africa, therefore it is estimated that wastage of maize and wheat would use 2 $Mm^3$ of blue water. Total wastage on the Steenkoppies Aquifer would use an estimated 4 $Mm^3$ of blue water, which is 25% of the estimated volume of the 17 $Mm^3$ $yr^{-1}$ blue water that exceeded sustainable limits. However, not all wastage can be prevented. For example, considering the intensive use of pesticides on modern farms, further reductions in losses due to pests come with associated ecological impacts. Refrigeration extents the life of vegetables, but indirectly releases carbon to the atmosphere through using electricity, which, on the Steenkoppies Aquifer, is mainly generated by coal-fired power stations. Future research focusing on quantifying the causes for vegetable wastage would be valuable, because it may be that only a small percentage of total wastage has causes of which the solution has adverse ecological impacts. For example, a simple solution to vegetables with unmarketable properties in terms of what they look like, given that they are of high quality otherwise, could be to sell these vegetables in a pre-cut or grated form. If the majority of current wastage consists of vegetables with unmarketable properties, it may be relatively simple to address a large proportion of wastage. In a global study on food losses the minimum wastage recorded for fruits and vegetables was 37%, which was recorded in industrialised Asia and the minimum of 33% wastage of root and tubers was recorded in northern Africa, western and central Asia (Gustavsson et al., 2011). Losses recorded for this study were therefore below the recorded minimum and with current technologies further reductions may be difficult. Thus, by reducing food wastage to reduce total production may be difficult and is likely to have a relatively low impact on addressing the sustainable use of the aquifer. Addressing food wastage must be considered as one of multiple management objectives that will have to be implemented to achieve sustainability targets for the Steenkoppies Aquifer.

## 7.5 CONCLUSION

It was observed that wastage of different types of vegetables can be variable, with small fractions of some crops, like cabbage, and high fractions of other crops, like lettuce, being wasted. Care should therefore be taken when using published data on wastage of fruits and vegetables in general. The results have shown that the highest percentage of wastage occurs during the production stage for a number of reasons, including damage by pests and diseases, and unmarketable properties of some crops, so efforts to limit wastage should focus on this stage. Accounting for food wastage is complicated by the fact that vegetables that are classified as wasted are often used for other purposes such as animal feed and compost.

Further reductions in recorded food wastage to achieve sustainability targets for the Steenkoppies Aquifer does not seem to be feasible given the current technologies and is complicated by the associated ecological impacts, for example through the increased use of pesticides or electricity. Household based cultivation may present a better opportunity to reduce the high wastage of vegetables, because people are more likely to eat crops with unmarketable properties that are grown in their gardens, and crops like lettuce will be eaten directly after it is harvested, which will prevent the decay that happens along the supply chain.

The information generated by the WF calculations using the WFN methodology thus indicates that addressing food wastage through improved technologies is important, but other management objectives must also be implemented to achieve sustainability targets, such as limiting total production or selecting crops and cultivars with lower water requirements. In the next chapter, crop parameters are developed for two ‘fancy’ lettuce cultivars, namely cos and butterhead lettuce, that are also cultivated on the Steenkoppies Aquifer. The WFs of cos and butterhead lettuce are then assessed to determine whether alternative cultivars can potentially be used to reduce the catchment scale WF on the Steenkoppies Aquifer.

# 8 CHAPTER 8: ESTIMATING THE WATER FOOTPRINT OF FANCY LETTUCE (*LACTUCA SATIVA*) CULTIVARS COS AND BUTTERHEAD

## 8.1 INTRODUCTION

In **Chapter 3** water footprints (WFs) were estimated for the most important crops on the Steenkoppies Aquifer, namely carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*) and Robbenson lettuce (*Lactuca sativa*), which is an iceberg (or crisp head) type of lettuce, using crop parameters developed by Vahrmeijer (2016). It was observed that WFs differ notably between crops and growing seasons, but the variation between the WFs of different cultivars for these crops have not been considered yet. There are several cultivars of the fancy lettuce type that are grown on the Steenkoppies Aquifer. These fancy lettuce cultivars are becoming more popular, which is indicated by a steady production increase of 152% from 5.5 tons between July 2011 and June 2012 to 13.9 tonnes between July 2013 and June 2014 in butterhead lettuce received by the Tshwane Fresh Produce Market (2014).

There are a few published studies on the water use of fancy lettuce cultivars. Pollet et al. (1998) used the Penman-Monteith model to calculate evapotranspiration (ET) of butterhead lettuce in glasshouses and highlighted the importance of good water management, because for this cultivar both over- and under-irrigation zhave undesirable effects on the quality of the crop. Jovanovic et al. (1999) developed crop parameters for the Great Lakes lettuce cultivar, which is a head forming cultivar, at the Roodeplaat dam, Gauteng, South Africa. Gallardo et al. (1996) proposed a relatively simple model to accurately assess the growth and water use for lettuce in California.

The sustainability assessment for the Steenkoppies Aquifer in **Chapter 6** indicated that the catchment scale blue WF of irrigation exceeds sustainable limits by 17 Mm$^3$ per year. In **Chapter 4** the use of water in the packhouse was evaluated in terms of its relative importance compared to cultivation blue WF. **Chapter 7** evaluated the potential of achieving blue WF sustainability through the reduction in food wastage. It was concluded that limited opportunities exist to achieve a sustainable blue WF on the Steenkoppies Aquifer through reductions in packhouse water use and through reductions in wastage of vegetables. Using fancy lettuce cultivars as an example, this chapter asks the question whether alternative cultivars might have notably lower WFs, which could replace cultivars with higher WFs to achieve sustainability targets on reducing the pressure on water resources. The hypothesis is that open cultivars will be more photosynthetically efficient than head forming cultivars, because their large flat leaves that can intercept maximum solar radiation (Rs), whereas the inner leaves of the head forming cultivars are shaded by the outer leaves.

## 8.2 MATERIALS AND METHODS

Cos and butterhead lettuce are fancy lettuce cultivars that are cultivated on the Steenkoppies Aquifer. These have not been included in the catchment WF (**Chapter** 6), because crop areas data that was available for 1998 and 2005 did not include these cultivars and these cultivars were less popular before 2012; according to the (Tshwane Fresh Produce Market, 2014) fancy lettuce cultivars from the Steenkoppies Aquifer that was sold to the market in 2011 were less than 10% of iceberg lettuce sold to the market. Cos lettuce have an open structure, while butterhead lettuce is a head forming cultivar. Crop parameters for crop growth simulations were not available for these cultivars and were therefore developed for use in the Soil Water Balance (SWB) model using a field trial.

### 8.2.1 SOIL WATER BALANCE CROP GROWTH MODEL

Crop ET, irrigation and yield are key components of WF calculations. Such variables can be measured directly, but this is labour intensive, expensive and not practical for multiple seasons. The other alternative is to obtain the necessary data from a crop model. The Soil Water Balance (SWB) crop model (Annandale et al., 1999) was used for this purpose. Crop parameters required by the SWB model is discussed in **Chapter 3.2.1.3**.

### 8.2.2 FIELD TRIAL

To determine the crop parameters of cos and butterhead lettuce (**Figure 8-1 A and B**), a trial was established at the University of Pretoria Experimental Farm (Lat 25.75° S, Long 28.26° N; altitude 1360 mamsl). The area is located in a summer rainfall region with a subtropical climate and winter occurs between May and August. Weather data was taken daily at an automatic weather station located within 60 m of the trial. According to the data from this station average maximum temperatures from January 2013 to December 2015 ranged from 19°C in winter (May to July) to 26°C in summer (November to February) and average minimum temperatures range from 8°C in winter to 18°C in summer. Average annual precipitation from January 2013 to December 2015 was 796 mm. The trial was located on a sandy loam Hutton soil (Soil Classification Working Group, 1991) with a clay content ranging from 26% in the top 0.2 m to 38% at 0.6 m depth.

**Figure 8-1: Cos (A) and butterhead (B) lettuce grown on the University of Pretoria Experimental Farm**

Cos and butterhead lettuce seed were sourced from Rijk Zwaan seed distributers, based in Krugersdorp, South Africa, and were planted in seedling trays in a greenhouse and watered daily with nutrient enriched water (Hygroponic as the main component with Solu-cal, produced by Hygrotech based in Pyramid, Pretoria, South Africa) using watering cans. The volume of water used during this stage was recorded to determine the water applied per seedling.

The trial consisted of two treatments, one for cos and one for butterhead lettuce, each with three replicates (six plots) with each plot having a surface area of 4 $m^2$ (**Figure 8-2**). Cos and butterhead lettuce seedlings were transplanted on 22 July 2015 at a density of approximately 12 seedlings $m^2$. Weeds were removed by hand throughout the duration of the trial.

The plots were irrigated using a high-density drip irrigation system. Two flow meters were installed, one in each main irrigation pipe servicing each crop species, to measure the volume of water applied. In each plot, Decagon 10HS soil moisture sensors were installed at 0.25 m and 0.5 m depth, linked to a Decagon EM50 logger (Pullman, Washington, USA). Soil water content was automatically recorded by the Decagon 10HS soil moisture sensors on a daily basis, and manual recordings were made using a Decagon ProCheck (Pullman, Washington, USA) regularly for irrigation scheduling purposes. Irrigation was applied when the soil water content was at 50% plant available water and the crop growth was assumed to be water non-limiting. Field capacity (FC) of the soils was 0.25 $m^3$ $m^{-3}$ and permanent wilting point (PWP) was 0.15$m^3$ $m^{-3}$. Irrigation was applied to restore the soil water content to field capacity.

**Figure 8-2: Cos and butterhead lettuce trial at the University of Pretoria Experimental Farm.**

A fertilization schedule was determined based on soil nutrient analyses for the trial and according to guidelines for lettuce in the Fertilization Manual (Misstofvereniging van Suid Afrika, 2007). Fertilisers were applied at planting and three weeks after planting according to the schedule given in **Table 8-1**. The fertilisers LAN (Limestone Ammonium Nitrate), KCL (Potassium chloride) and super phosphate were applied to ensure nutrient non-limiting conditions.

**Table 8-1: Fertiliser schedule for the fancy lettuce trial at the University of Pretoria**

| Fertiliser | Quantity applied at planting | Quantity applied after three weeks |
|---|---|---|
| **Nutrients required (kg $ha^{-1}$)** | | |
| **Nitrogen** | 60 | 60 |
| **Potassium** | 120 | |
| **Phosphorus** | 100 | |
| **Fertilisers applied (kg $ha^{-1}$)** | | |
| **LAN (28% N)** | 210 | 210 |
| **KCL (50% K)** | 240 | |
| **Super phosphate (14% P)** | 710 | |

### 8.2.3 SAMPLING AND MEASUREMENTS

Weather data, consisting of precipitation and minimum and maximum temperatures, was measured for the duration of the experiment at the automatic weather station located within 60 m of the trial. The weather station did not monitor other variables like solar radiation (Rs) and wind speed, and these parameters are estimated in SWB according to FAO 56 recommendations (Allen et al., 1998). The effect of estimated Rs data was not corrected as suggested in **Chapter 5**, because this trial was done during winter, which is the time of the year when Rs estimations were accurate. Soil samples were analysed to determine soil texture. Soil water measurements over the season were used to estimate volumetric soil water content at field capacity and permanent wilting point, which are required input data for SWB per soil layer.

Sampling of the crops should ideally be done throughout the growth season during each phenological stage of the crop. For lettuce, however, phenological stages are less well distinguished and harvesting occurs before the crop flowers. Thus, sampling was done one month after planting and thereafter every second week until the crop started flowering. During a sampling event, destructive harvesting was done by removing the aboveground material of four representative plants adjacent to each other. The four plants were weighed immediately to obtain fresh mass, then dried in an oven at 60°C, until it reached a constant mass to determine dry matter. During the sampling event measurements were taken for each of the six plots with a Decagon sunfleck ceptometer (Pullman, Washington, USA) to determine FI and LAI. For each plot three reference readings were taken above the canopy, and six readings were taken below the canopy, at ground level. Gallardo et al. (1996) noted that it is more appropriate to use canopy cover instead of LAI to determine crop ET for lettuce, because of the number of leaf layers overlapping each other in the canopy structure. The LAI results at harvesting were 19.7 and 19.6 for cos and butterhead, respectively, when determined destructively, which is unrealistically high. Measured by the ceptometer proved less sensitive to the number of leaf layers of the lettuce plants and provided reasonable LAI measurements. However, sensor distance should be at least four times the size of the largest object (leaf), which was not possible here, given the low height of the lettuce plants. This could have resulted in high LAI results, due to excessive shading which are expected close to the leaves. Finding the appropriate tool to determine the LAI of lettuce should therefore be addressed in future research. Final harvesting was done on 16 September 2015 (57 days after transplanting).

### 8.2.4 MODEL CALIBRATION

Crop parameters were calibrated using measured data from the trial. Measured data for soil water content at 0.25 m and 0.5 m, LAI, irrigation applied and aboveground dry matter for the duration of the experiment were compared to the SWB simulated results and adjustments were made to the Vahrmeijer (2016) parameters for Iceberg lettuce to obtain a good fit between simulated and measured data. The coefficient of determination ($R^2$) between measured and simulated data of LAI and yield was calculated as an indicator of how closely the simulated data matched the measured data. Base temperature was not measured and the values were assumed to be the same as iceberg lettuce as given by Vahrmeijer (2016).

Evapotranspiration (ET) over the growing season was also calculated with the soil water balance equation:

$$ET = P + I - R - D \pm \Delta S$$

**Equation 8-1**

where *P* is precipitation, *I* is irrigation, *R* is runoff, *D* is deep drainage and $\Delta S$ is change in soil water content. The assumption was made that *R* and *D* are negligible, and $\Delta S$ was calculated from the daily soil water content measurements. The ET result was compared to simulated ET from the SWB model. Although D was not measured based on the assumption that it would be negligible, excessive irrigation to ensure good establishment of the seedlings during the first two weeks of the trial would have resulted in some drainage. Thus, any discrepancies between measured and simulated ET was likely due to this drainage. The blue plus green water footprint equals crop ET, because it is assumed that any excess water applied will drain into an aquifer or form runoff to a blue water resource and therefore is not considered used. Thus, over-irrigation and subsequent drainage will not impact the blue plus green WF and is therefore not a big concern in this study. However, if the proposed **Equation 2-4 b** is used to calculate WFs, it must be kept in mind that over-irrigation during the trial will result in a zero green WF and the blue plus green WF will consist of entirely blue water.

### 8.2.5 VERIFICATION OF THE PARAMETERS

The crop parameters were verified with yield data measured for a trial done in summer 2015, in which seedlings were transplanted on 6 February 2015. During the summer trial the high-density drip irrigation system was out of order and the crops were mostly irrigated manually using watering cans. This irrigation method used much less water than an irrigation system, due to it being labour intensive. But this method was also less efficient to get adequate water to the roots and many of the seedlings did not survive. For this reason, the irrigation data from the February trial was considered incomparable to the data from the July trial. However, the crops that did survive developed normally and the dry matter accumulation of these crops were used to determine yield for verification.

The GDD, as specified in the crop parameters that were developed for cos and butterhead lettuce, were adjusted for summer crops, based on the actual GDD relevant to the summer trial. If the GDD that were relevant to the winter trial was used, the crop was harvested within less than a month, before the plants matured.

### 8.2.6 WATER FOOTPRINT CALCULATIONS

The crop parameters for cos and butterhead lettuce (developed in this study), and iceberg lettuce (developed by Vahrmeijer (2016)) was used to simulate growth of these cultivars at the University of Pretoria Experimental Farm in summer and winter over three years (2013 to 2015), which is the time that weather data was available. The simulated data was used to calculate blue and green water footprints (WFs) according to the WFN approach (**Chapters 2 and 3**). The blue and green WFs of cos and butterhead lettuce were compared to the WFs of iceberg lettuce to determine whether these cultivars may have notably lower WFs that can be used as alternative crops.

## 8.3 RESULTS

### 8.3.1 SEEDLING WATER USE

Total water applied to raise seedlings in the glasshouse was measured to be one liter per seedling. With approximately 12 seedlings planted per square meter, the water used to raise seedlings was therefore approximately 12 mm. The total irrigation requirement in the winter trial in 2015, as simulated by SWB was 319 mm (equivalent to 3190 $m^3\ ha^{-1}$) for cos and 326 mm (equivalent to 3260 $m^3\ ha^{-1}$) for butterhead lettuce in winter. Thus, water used to raise cos and butterhead seedlings was 4% of total irrigation required by these crops.

### 8.3.2 MEASURED DATA

Measured I, P, ΔS, ET calculated with measured data according to the soil water balance equation, SLA and LAI at harvesting, aboveground dry matter and fresh mass of each lettuce cultivar is given in **Table 8-2**. Iceberg lettuce yields in fresh mass measured by Vahrmeijer (2016) was 3 kg $m^2$, which is lower than the yields obtained for cos and butterhead (5.3 kg $m^{-2}$ and 5.2 kg $m^{-2}$, respectively), which may be explained by the possibility that the lettuce in this trial was harvested later than what is normally done on commercial farms; the trail was harvested 57 days after planting as opposed to farmers on the Steenkoppies Aquifer that harvest these lettuce cultivars after approximately 30 to 45 days.

**Table 8-2: Measured data for cos and butterhead lettuce used for crop model parameterisation and water footprint calculations**

| Measurements | Cos lettuce | Butterhead lettuce |
|---|---|---|
| **Irrigation (mm)** | 364.2 | 357.4 |
| **Precipitation (mm)** | 49.0 | 49.0 |
| **Average reduction in soil water content for the top 0.5 m (mm)** | 29.4 | 24.7 |
| **Evapotranspiration (mm)** | 442.6 | 431.1 |
| **Average above ground fresh mass at day of harvest (kg $m^{-2}$)** | 5.3 (0.38) * | 5.2 (0.49) * |
| **Average above ground dry matter at day of harvest (kg $m^{-2}$)** | 0.3 (0.02) * | 0.3 (0.03) * |
| **Average leaf area index at day of harvest** | 4.2 (0.54) * | 2.8 (0.64) * |
| **Average specific leaf area at harvesting ($m^2$ $kg^{-1}$)** | 15.9 (1.12) * | 18.1 (0.46) * |
| **Days from transplanting to harvesting** | 57 | 57 |

* Figures in brackets indicate standard deviation

### 8.3.3 CROP PARAMETERS

The crop parameters that were determined for cos and butterhead lettuce are provided and compared to iceberg lettuce determined by Vahrmeijer (2016) in **Table 8-3**. Generally, the crop parameters for cos and butterhead are very similar to that of iceberg lettuce, which can be expected considering the close relation between the crops. Both cos and butterhead lettuce had higher GDD for emergence, flowering, maturity, transition and leaf senescence as compared to the crop parameters for iceberg lettuce. This could be explained by the possible differences in crop age at harvesting between the trial and commercial farms. There is a notable difference between GDD in summer and winter, which may be an indication that the crops are sensitive to daylength. For cos lettuce, SLA values used to parameterise the crop were increased slightly from what was measured to obtain the higher yields that were observed.

**Table 8-3: The Soil Water Balance crop growth model crop parameters for cos and butterhead lettuce**

| **Parameters** | **Cos lettuce** | | **Butterhead lettuce** | | **Iceberg lettuce**** |
|---|---|---|---|---|---|
| | **Winter** | **Summer** | **Winter** | **Summer** | |
| **Extinction coefficient** | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 |
| **Dry-matter-water ratio (Pa)** | 9 | 9 | 9 | 9 | 9 |
| **Conversion efficiency (kg MJ$^{-1}$)** | 0.0009 | 0.0009 | 0.0009 | 0.0009 | 0.0009 |
| **Base temperature (°C)** | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 |
| **Temperature optimal light (°C)** | 15 | 15 | 15 | 15 | 15 |
| **Cut off temperature (°C)** | 23.9 | 23.9 | 23.9 | 23.9 | 23.9 |
| **Emergence day degrees (GDD)** | 190 | 190 | 190 | 190 | 71 |
| **Flowering day degrees (GDD)** | 710 | 1257 | 710 | 1257 | 175 |
| **Maturity day degrees (GDD)** | 710 | 1257 | 710 | 1257 | 529 |
| **Transition day degrees (GDD)** | 710 | 1257 | 710 | 1257 | 475 |
| **Maximum leaf age (GDD)** | 710 | 1257 | 710 | 1257 | 529 |
| **Max height (m)** | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| **Maximum root depth (m)** | 0.3 | 0.3 | 0.3 | 0.3 | 0.6 |
| **Stem to grain translation** | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| **Canopy storage (mm)** | 1 | 1 | 1 | 1 | 1 |
| **Minimum leaf water potential (kPa)** | -1500 | -1500 | -1500 | -1500 | -1500 |
| **Maximum transpiration (mm day$^{-1}$)** | 9 | 9 | 9 | 9 | 9 |
| **Specific leaf area ($m^2$ kg$^{-1}$)** | 22 | 22 | 18 | 18 | 20 |
| **Leaf stem partition ($m^2$ kg$^{-1}$)** | 6.33 | 6.33 | 6.33 | 6.33 | 6.33 |
| **Top dry mass at emergence or transplanting (kg m$^{-2}$)** | 0.0008 | 0.0008 | 0.0008 | 0.0008 | 0.0008 |
| **Root fraction** | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| **Root growth rate** | 8 | 8 | 8 | 8 | 2 |
| **Stress index** | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 |

***Crop harvested before commencement of flowering; ** Taken from Vahrmeijer (2016)**

### 8.3.4 SWB SIMULATED RESULTS FOR LETTUCE

**Figure 8-3** shows the measured soil water contents of two plots for each lettuce cultivar compared to SWB results at 0.25 m and 0.50 m, respectively. During the early part of the season, simulated soil water content closely reflected the average soil water content of measured data over time, although it differed in terms of the variation (simulated data showed no variation). Towards of the end of the season simulated data closely reflected measured data in terms of average values and variation. The measured soil water content in Plot 4 (cos lettuce) and Plot 6 (butterhead lettuce) drops below field capacity at 0.25 m after 6 September (**Figure 8-3 A and B**), which can be explained by the lettuce roots extending into this layer at that time. This is an indication that the roots of both cultivars have a relatively shallow distribution, and a maximum rooting depth of 0.3 m at harvesting was therefore assumed (**Table 8-3**).

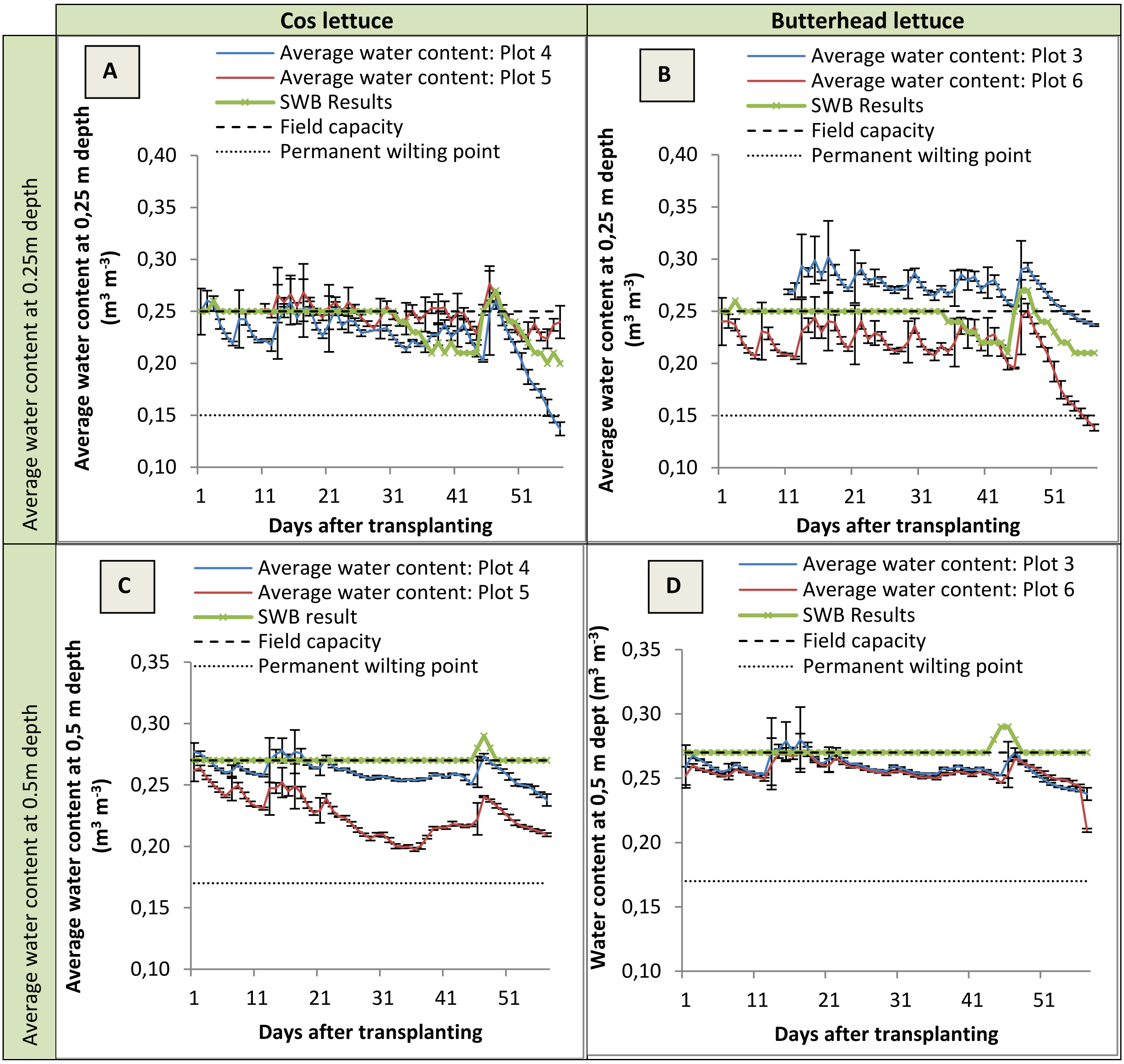

**Figure 8-3: Average measured versus Soil Water Balance (SWB) simulated water contents for A: cos at 0.25 m; B: cos at 0.50 m; C: butterhead at 0.25 m and D: butterhead at 0.50 m depths transplanted on 22 July, harvested 16 September (57 days). Standard deviations indicated as error bars represent hourly variation over a day in the measured data.**

The parameters given in **Table 8-3** simulated LAI and yield for cos and butterhead lettuce that correlated well with measured data. The best-fit logarithmic trendline for measured and simulated LAI had $R^2$ values of 0.83 and 0.98 for cos and butterhead, respectively. Although simulated and measured LAI values correlated well, the LAI values are slightly underestimated for both cultivars. **Figure 8-4** shows the comparison between measured and simulated aboveground dry matter accumulation, respectively. The best fit linear trendline for measured and simulated yield had $R^2$ values of 0.95 and 0.98 for cos and butterhead, respectively. Low temperatures that occurred between 41 and 48 days after planting (DAP) resulted in plant growth switching off and no increase in yield during that time.

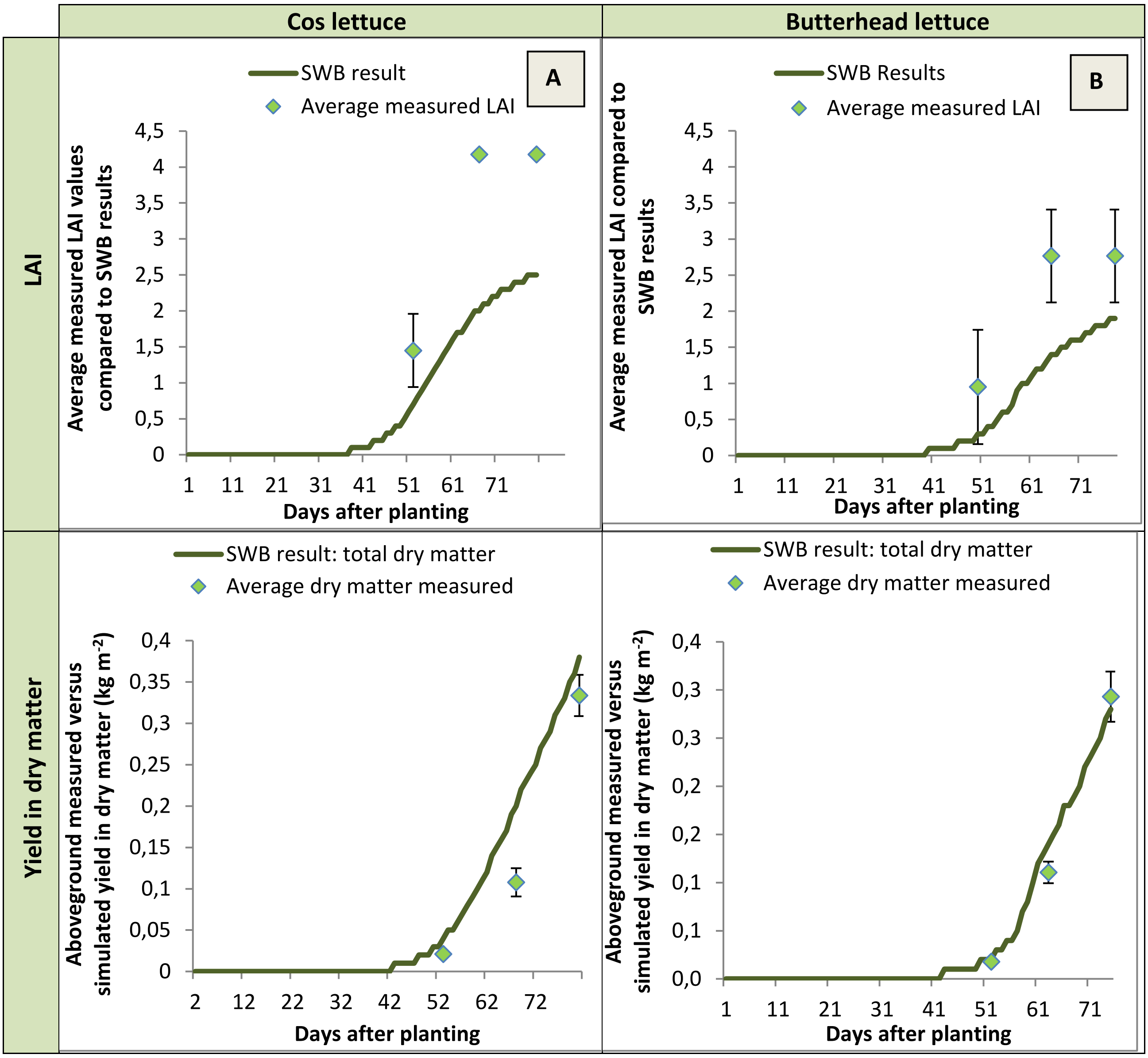

**Figure 8-4: Measured versus Soil Water Balance (SWB) simulated leaf area index (LAI) for A: cos and B: butterhead lettuce and dry matter yield for A: cos and B: butterhead lettuce transplanted on 22 July, harvested 16 September (57 days). Error bars indicate standard deviation for the three replicates of each lettuce cultivar.**

Simulated ET (328 mm for cos and 323 mm for butterhead) was lower than the ET calculated from measured data (**Table 8-2**). This discrepancy can be explained by drainage below the rootzone that was not accounted for in the manual calculation, because of excessive irrigation in the first two weeks to ensure good seedling establishment resulting in drainage which was confirmed by the SWB simulations. Actual irrigation (364mm for cos and 357mm for butterhead) was much more than simulated irrigation (268mm for cos and 326mm for butterhead), because of initial high volumes given early in the trial during seedling establishment.

The measured yields for cos lettuce in the summer trial (0.36 kg m$^{-2}$ with a standard deviation of 0.02 kg m$^{-2}$) successfully validated yields for this cultivar simulated to be planted in summer (0.35 kg m$^{-2}$). Validation of the butterhead lettuce was, however, not as successful, with the measured data being 0.23 kg m$^{-2}$ compared to simulated yields of 0.31 kg m$^{-2}$. Low butterhead yields obtained in the summer trial might be explained by heat stress or water stress due to the irrigation system that were out of order at the time, and may be an indication that butterhead is more sensitive to heat and drought than cos lettuce.

### 8.3.5 WATER FOOTPRINTS OF COS AND BUTTERHEAD LETTUCE

**Figure 8-5** indicates the irrigation and yield results for SWB simulated crops grown annually in summer and winter from 2013 to 2015 at the University of Pretoria Experimental Farm. For both cultivars irrigation was higher (because rainfall received in summer fulfills part of the water requirements of the crops) and yield is lower in winter. For both cultivars, the standard deviations for irrigation and yields were higher in summer, which is expected because of variations in rainfall during summer.

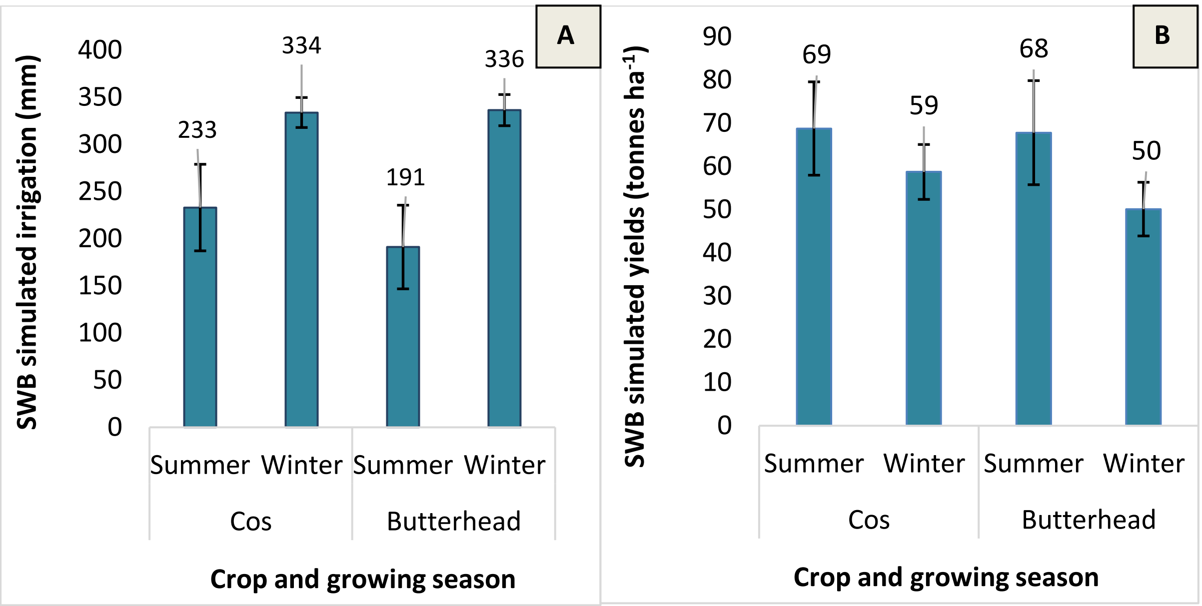

**Figure 8-5: Average of three year's simulated A: irrigation and B: yield (2013 to 2015) with standard deviations (shown as error bars) of cos and butterhead lettuce in summer and winter.**

The blue and green WFs of cos and butterhead lettuce are shown in **Figure 8-6**. The blue plus green WFs of these cultivars in summer are similar, but blue WF of cos is higher than the blue WF of butterhead. Green WFs are very small in winter, because of the absence of rainfall. Blue plus green WFs of both cultivars are higher in winter, even though green WFs are small. The blue WF of butterhead lettuce is higher than the WF of cos lettuce in winter, because of higher yields in cos lettuce. The standard deviation in green WFs in summer were relatively high, due to variation in rainfall.

In **Figure 8-7** blue and green WFs of cos and butterhead lettuce are compared to the WFs of iceberg lettuce for the winter growing season. The WFs of iceberg lettuce is 42% and 23% higher than cos and butterhead lettuce, respectively. Iceberg lettuce was harvested earlier, resulting in lower ET and yields. The differences in WFs between the fancy lettuce cultivars, cos and butterhead, and iceberg lettuce mostly arises due to differences in their harvesting dates, because the GDD are the main difference in the parameters of these crops. It is expected that the longer the crop is on the land, the lower the WF, firstly because more water evaporates at the beginning as compared to the end of the growing season when the crops cover most of the surface and secondly because yield initially increases exponentially and later linearly (**Figure 8-4**).

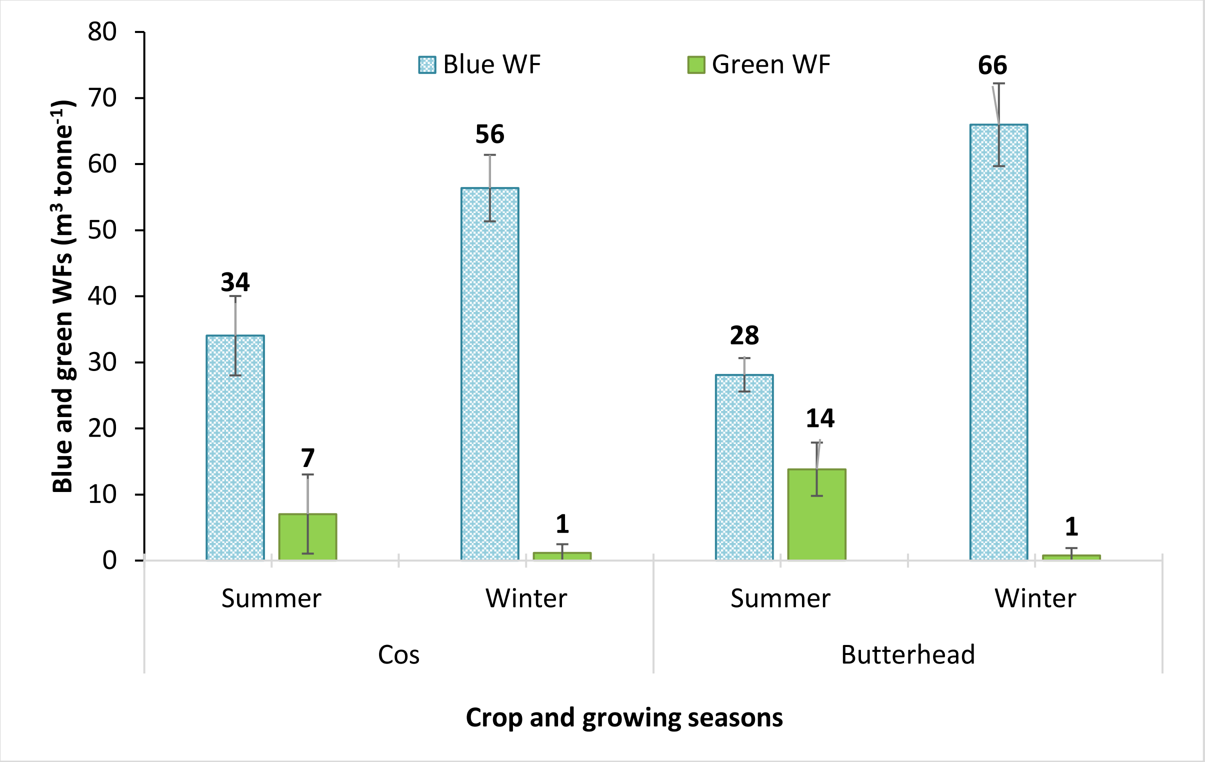

**Figure 8-6: Average of three year's (2013 to 2015) blue and green water footprints (WF) with standard deviations (shown as error bars) of cos and butterhead lettuce in summer and winter growing seasons using one tonne fresh mass as a functional unit**

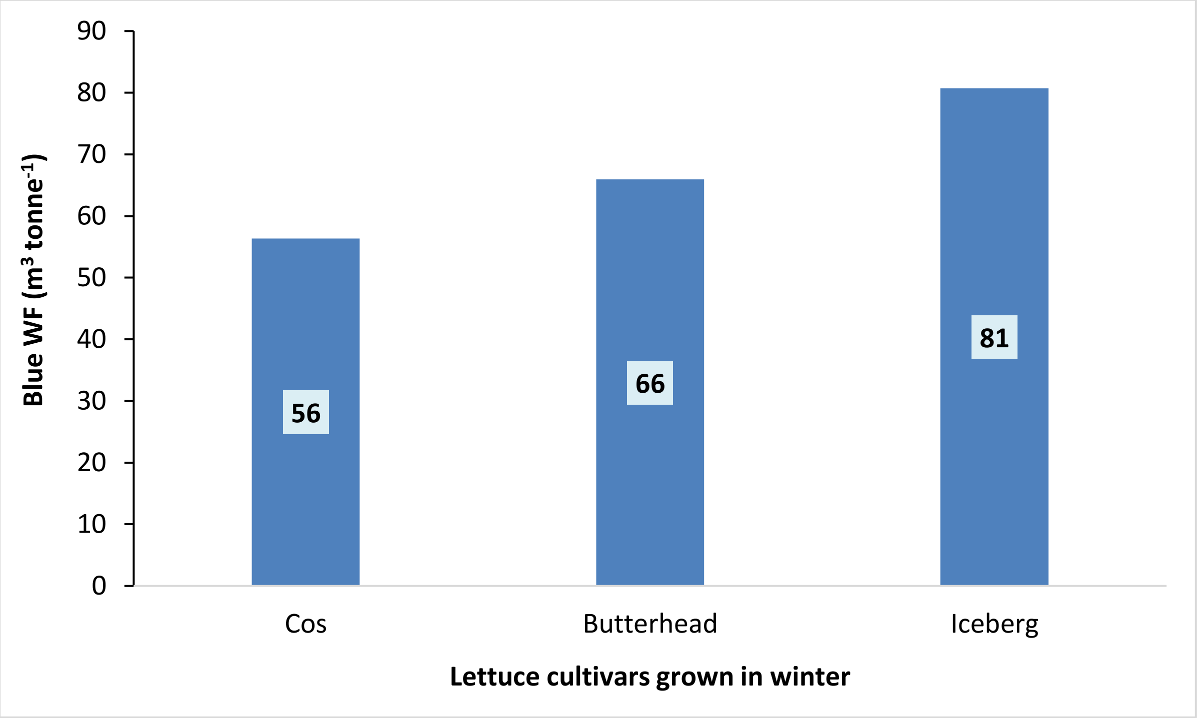

**Figure 8-7: Average of three years' (2013 to 2015) blue and green water footprints (WF) of cos and butterhead lettuce compared to iceberg lettuce in the winter growing seasons using one tonne of fresh mass as a functional unit**

## 8.4 DISCUSSION

Blue plus green WFs of cos (58 $m^3$ tonnes$^{-1}$) and butterhead (67 $m^3$ tonnes$^{-1}$) lettuce grown in winter are lower compared to the iceberg lettuce grown in winter, which had a blue plus green WF of 93$m^3$ tonnes$^{-1}$ for the Steenkoppies Aquifer and of 81$m^3$ tonnes$^{-1}$ for the University of Pretoria Experimental Farm. The difference in WFs between cos and butterhead, compared to iceberg, can mainly be explained by the differences in harvesting dates, because more biomass is produced later in the growing season per unit of water. According to SWB simulated data, if cos, butterhead and iceberg lettuce were planted at the University of Pretoria in the winter and harvested according to iceberg lettuce parameters (GDD 529), the yields in dry matter would be higher for cos lettuce (0.2 tonnes ha$^{-1}$) than for butterhead (0.14 tonnes ha$^{-1}$) and for iceberg lettuce (0.13 tonnes ha$^{-1}$). Biophysically, the reason for this could be due to the open structure of cos lettuce and its large flat leaves that can intercept more Rs, compared to the cultivars that form heads of which only the outer leaves can photosynthesize. However, measured water content for cos lettuce (94%) was lower than for iceberg (96%) which gave rise to similar WFs in terms of fresh mass for these two crops, if harvested at the same time. Similar to the results found in **Chapter 5**, this again highlights the importance of differences in water content between crops and the potential impact of this on WFs. This indicates that the main reason for measured differences in WFs between iceberg lettuce and the fancy lettuce cultivars must be explained by differences in growing period. Future research could be focused on determining whether WFs may be lower for crops that are harvested later. Harvesting dates are currently determined by market demand and the price that a farmer can get for his produce. It is therefore possible that crops are sometimes harvested early and in such cases a delay in harvesting will not result in lower quality produce.

The winter blue plus green WFs for the fancy lettuce cultivars are also much lower than the blue plus green WFs of carrots (95 $m^3$ tonne$^{-1}$), cabbage (79 $m^3$ tonne$^{-1}$), beetroot (124 $m^3$ tonne$^{-1}$) and broccoli (327 $m^3$ tonne$^{-1}$) for the Tarlton area grown in winter. Water content of these crops were lower compared to lettuce, but the WFs in dry matter of lettuce (913 $m^3$ tonne$^{-1}$) was still lower compared to that of carrots (929 $m^3$ tonne$^{-1}$), cabbage (1118 $m^3$ tonne$^{-1}$), beetroot (947 $m^3$ tonne$^{-1}$) and broccoli (2589 $m^3$ tonne$^{-1}$). Cabbage is also a head-forming crop, similar to iceberg lettuce, and differences in Rs interception can potentially also explain differences in biomass accumulation. Furthermore, crops that produce seeds with high protein and fat content also require relatively more energy for biomass production (Steduto et al., 2012), while these lettuce plants grow only vegetatively throughout the growing season, and are harvested before flowering, therefore requiring relatively less energy for the synthesis of more complex molecules. The relatively low WFs of lettuce can also be explained by the large harvestable portion (harvest index) that these crops have, which includes most of the aboveground biomass of the plants. It is acknowledged that comparisons with iceberg lettuce, carrots, cabbage, beetroot and broccoli may be less accurate, because these crop parameters were developed in a different trial, albeit in the same Tarlton area.

Lettuce plants have a canopy structure with several leaf layers, which complicated the crop growth modelling. When calculated as total leaf surface area divided by ground area, the LAI at the harvesting date was 20 $m^2$ $m^{-2}$ for both cultivars, which is exceptionally high, relative to other crops. Because of this layering in lettuce, Gallardo et al. (1996) and Pollet et al. (1998) stated that LAI is not a suitable indicator of the potential transpiration of plants, because not all the leaves transpire and canopy cover percentage is more appropriate for modelling water use. Thus, for this study an LAI based on canopy cover was used.

Simulated LAI was underestimated when using the measured SLA values for parameterisation. This can possibly be explained by sampling errors when LAI measurements were made, which is possible, considering the large standard deviations between different measurements and possible bias where the ceptometer might have been more likely to be placed under denser leaf material. However, SLA is known to be a dynamic parameter, while SWB assumes a single value for the whole growing season, which could also give rise to such errors. Presnov et al. (2005), for example, recorded SLA in lettuce changing from 20 $m^2$ $kg^{-1}$ to 50 $m^2$ $kg^{-1}$ during the lifetime of the crop. The crop parameters for cos lettuce proposed here used higher SLA values than what was measured (22 $m^2$ $kg^{-1}$ instead of 16 $m^2$ $kg^{-1}$), but simulated LAI values were still lower than the measured values (2.5 instead of 4.2). This was done for cos lettuce to obtain the higher yields that were observed, because maximum values for $E_c$, DWR and K values were already assumed. For butterhead lettuce, measured SLA values (18 $m^2$ $kg^{-1}$) were used, which simulated lower LAI values than measured (1.9 instead of 2.8). It is acknowledged that crop growth and water use modelling is a complex exercise with an interplay between different crop and soil parameters. For example, it could also have been assumed that measured LAI values are correct and therefore increase SLA values for parameterisation to a minimum of 35 $m^2$ $kg^{-1}$ (to obtain the measured LAI values) requiring reductions in $E_c$ or K to correct the subsequent increase in yields.

If all the lettuce grown on the Steenkoppies Aquifer in 2005 was replaced by cos lettuce with a delay in harvesting time (at approximately 710 GDD in winter), the total blue WF for cultivating all crops on the catchment would be reduced to 24.4 $Mm^3$, a reduction of 4% from the currently estimated 25.4 $Mm^3$ (**Chapter 6**) when iceberg lettuce is used for the WF calculations. This saving is much more than the estimated 0.03 $Mm^3$ of blue water that would be used to clean and pack lettuce produced on the Steenkoppies Aquifer in 2005 in the packhouse. The cultivation of lettuce consumed 1.9 $Mm^3$ of blue water on the Steenkoppies Aquifer in 2005, and an estimated 0.7 $Mm^3$ of blue water is lost indirectly due to wastage of lettuce. If wastage could have been reduced to zero, this would still result in lower blue water savings compared to potential reductions of water use during cultivation, such as switching to cultivars with a lower WF and delaying harvesting dates. If alternative cultivars or even species for all crops are available with similarly reduced WFs, this can potentially play a role in achieving blue water sustainability targets for the aquifer, while producing the same quantity and constitution of food products. It is, however, acknowledged that the nutritional content of the produce, and other factors such as market prices and farmer profitability, would need to be taken into account.

## 8.5 CONCLUSION

As hypothesized the WFs of cos and butterhead lettuce is therefore notably lower than the WFs of other vegetable crops, including iceberg lettuce. It is concluded that alternative cultivars with lower WFs can play an important role towards achieving sustainable water use on the Steenkoppies Aquifer, and in catchments in general. Alternative crops can be assessed in future research, which may include indigenous species or crops that are more drought resistant, for example the African sweet potato versus the Irish potato. The length of the growing season can also potentially reduce the WFs of the crop, because in this case the crops produced more biomass per ET at the end of the growing season. This matter should receive attention in future research.

# 9 CHAPTER 9: DISCUSSION

This study was conducted to better understand the usefulness of water footprint (WF) information for vegetable crops to farmers (local level), water resource managers (catchment/basin level), policy makers (regional/national level), and consumers, although the latter two were beyond the immediate scope of this project from a research perspective. In addition to a literature review (**Chapter 2**), a WF methodology comparison using actual data was made, WFs were calculated for selected important vegetable crops during cultivation (**Chapter 3**) and in the packhouse (**Chapter 4**). Complexities in calculating WFs for vegetable crops were discussed (**Chapter 5**). WF accounting was up-scaled to the catchment level using the Steenkoppies Aquifer as a case study (**Chapter 6**), and important ways to utilise this information were identified. **Chapters 7** and **8** quantify WFs of food wastage and for the fancy lettuce cultivars, cos and butterhead. The potential of achieving sustainable blue water use on the Steenkoppies Aquifer by reducing food wastage or by using alternative cultivars was evaluated. In the following section, the results are discussed section by section in a manner envisaged to be useful to other stakeholders in the water and agricultural sectors.

## 9.1 COMPARISON BETWEEN WATER FOOTPRINT METHODS

The methodologies proposed by the Water Footprint Network (WFN) (Hoekstra et al., 2011), the Life Cycle Assessment (LCA) communities (i Canals et al., 2009, Pfister et al., 2009), and the hydrological-based WF communities (Deurer et al., 2011) were evaluated in a literature review. Three methodologies were further compared in a case study on the cultivation of carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*), lettuce (*Lactuca sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*) on the Steenkoppies Aquifer, Gauteng, South Africa. A key aim was to identify one or more simple yet effective method(s) that can be applied in South Africa for various purposes, including decision-making and through the raising of consumer awareness.

Although the WFN methodology's volumetric WFs are not considered appropriate as is for awareness raising, for example by simply stating that it takes 100 ℓ to produce a kg of carrots, it was selected as the key methodology for this research project. Reasons for this include the following:

- The methodology is well-developed, and WFs are relatively simple to calculate and understand
- The quantitative nature of these WFs can potentially be used in different information systems, such as water use licensing services and up-scaling to a catchment level and quantifying water consumed by different users for allocation purposes.
- By altering the functional units, these metrics can be used for applications such as understanding WFs per nutritional unit produced, economic gain or labour opportunities provided.
- These WFs can reveal impacts on water resources in different seasons of a hydrological or calendar year.
- It can indicate high WFs of certain crop species, such as broccoli, or certain growing regions, such as those which experience relatively high vapour pressure deficits or with poor soils.
- It allows for local contextualisation if there is suitable information to conduct the sustainability assessment

The hydrological-based methodology was considered useful in improving understanding of water use in a cropping system, but at this stage it still has a number of shortcomings that may limit its widespread application. For example, because it calculates WFs of one or more crop products over a hydrological year, it potentially conceals seasonal water scarcities and the high WFs of specific crops when several are rotated, as observed for vegetables. Determining WFs of crop sequences also complicates up-scaling to a catchment level, because of the number of crop sequences that are likely to occur on an aquifer. The idea of a negative blue WF, when recharge is greater than irrigation is interesting. However, it does not reflect the opportunity cost in the consumption of blue water resources. Downstream requirements are not accounted for in this methodology, for example a zero blue WF according to the hydrological methodology would mean no net recharge of the aquifer and, eventually, zero outflows. It furthermore does not reflect the irrigation and associated environmental impacts that are taking place (although it is acknowledged that neither do the other methods when reported simply as a WF). Blue WFs estimated according to the hydrological-based method will often be lower than the WFN approach, but impact on water quality must be assessed simultaneously and this is an even more complex exercise than estimating water consumption. For example Witthueser et al. (2009) indicated that initially more rainfall increases pollution due to leaching, but above a certain threshold (~900 mm $yr^{-1}$ for the Steenkoppies Aquifer) the recharge is enough to dilute the contaminants.

Clear advantages exist for calculating the WF of a product, entity or activity within a LCA framework. For example, simultaneous estimations of the carbon footprint and other environmental impacts allow for more informed management decisions and the screening for any 'pollution swapping' (Thorburn and Wilkinson, 2012) or 'problem shifting' (Finnveden et al., 2009). This has led LCA groups to propose modified methodologies that are compatible with LCA, but these methodologies have their own weaknesses that will potentially prevent their widespread application. According to the knowledge hierarchy, data (a volume of water used to produce a product) can be calculated by a computer, while higher orders of the hierarchy such as wisdom (knowing whether a water use is good or bad) cannot (currently) be calculated by a computer or programmed (Rowley, 2007). The methodology does not account for green water, but if less green water is used by a specific land use it may lead to increased blue water in rivers and aquifer as a result of higher levels of runoff or drainage. The International Standards Organization (ISO) published a global WF standard (ISO 14046) in August 2014, closely resembling the LCA methodology proposed by Pfister et al. (2009). The widespread adoption of ISO 14046 remains to be seen.

The complexity of the ecological, social and economic factors which must be considered when assessing the impact of water use and the trade-offs that are required to choose between one water use and another, highlights the complexity or even impossibility of calculating a WF as a single numerical value that will assist consumers to make wise decisions about their water use. It is recognised that change in consumer behaviour is key to achieving sustainable water use, but it is unlikely that a single numerical value can be developed to inform consumers to make wise decisions on their water use, which is a key aim of the LCA WF methodology. Other options, such as education, advertising and government subsidies should be considered in addition to creating consumer awareness, but the WF is not yet that far developed. Essentially, the choice of WF method selected will be based on the objectives of the exercise.

Future research is required to determine the most suitable ways to change consumer behaviour. Water footprints aim to provide the consumers with information that will assist them to make decisions to achieve sustainable water use. Other options, such as marketing and incentives, could also be considered.

## 9.2 PACKHOUSE WATER FOOTPRINTS

Packhouse WFs were calculated to quantify the volume of water used in cleaning and/or packaging a unit yield of carrots, cabbage and lettuce in a packhouse on the Steenkoppies Aquifer according to the WFN methodology. As observed in previous studies, packhouse WFs were relatively low compared to the WFs linked to the cultivation phase (ET) (1.9% of the total for carrots, 0.5% for cabbage and 1.6% for lettuce). If it is assumed that packing and cleaning of beetroot, broccoli, maize and wheat, which are not included in the packhouse assessment requires as much water as carrots (1.3 $m^3$ $tonne^{-1}$), the catchment scale water use for cleaning and packing selected crops based on 2005 production (**Chapter 6**) is estimated to be 0.12 $Mm^3$. By extrapolating this water use to all crops cultivated on the Steenkoppies Aquifer, it is estimated that packing all vegetables produced in 2005 on the Steenkoppies Aquifer will require 0.17 $Mm^3$. This volume is only 0.7% of the total blue WF of cultivation in 2005, which highlights the relatively high water use during cultivation (ET) as a priority for management actions towards sustainable water use. Considering the current management practices in the packhouse that were evaluated, which includes the recycling and purification of water, further potential reductions of the impacts of the water use at the packhouse level is limited. However, the major reductions in blue WFs that are necessary to achieve sustainable blue water use necessitates savings at all levels and the water use in the packhouses should be incorporated as one of several measures to reduce total blue WF on the catchment.

Using phosphorus (P) as the critical pollutant, packhouse grey WFs were estimated to be larger than the packhouse blue WFs. For carrots, cabbage and lettuce, packhouse grey WFs were 44%, 12% and 16%, respectively, of the grey WF linked to the cultivation of these crops. The inclusion of recycling and filtration systems, final fate of the disposed water and associated pollutants, and assimilation capacity of the natural environment make the estimation and interpretation of grey WFs challenging.

It was unfortunate that a number of big producers approached as part of this research project were unwilling to share data from their packhouse or allow monitoring by the team, for example, using flowmeters. This was most likely due to two reasons, a perceived threat of bad publicity, and case of managers just being too busy to give this request attention. The WWF (2017) also experienced a lack of data, or unwillingness of companies to share their data, during a survey that involved food retailers in South Africa. What is needed for improving data collection is policies that require transparency on food wastage during all stages of the supply chain, a central database where data can be recorded and actively involved agencies that take responsibility of collecting the necessary data. Life Cycle Assessment (LCA) methodologies can also assist in the interpretation of environmental impacts of food wastage and a good understanding of the methodology can improve the quality of data on food wastage that is collected in the future (WWF, 2017). Recording data for beetroot and broccoli at the packhouse level is recommended for future research.

## 9.3 COMPLEXITIES INVOLVED IN CALCULATING WATER FOOTPRINTS

Even though the WFN presented the most simplified methodology to calculate WFs, the following challenges were encountered in a crop production context:

- The vegetable crops grown on the Steenkoppies Aquifer are mostly short season crops and are grown in different seasons. In addition to differences caused by natural inter-annual weather variability, the growing season and planting date had an impact on crop WFs. For example, the summer blue plus green WFs of carrots is 61 $m^3$ $tonne^{-1}$, compared to 116 $m^3$ $tonne^{-1}$ in autumn. And summer blue plus green WFs of lettuce was 56 $m^3$ $tonne^{-1}$, compared to 93 $m^3$ $tonne^{-1}$ in winter. In winter, blue WFs are higher and green WFs are lower for all crops, simply because the study area is a summer rainfall region.
- Compared to measured solar radiation, estimated values according to FAO 56 (Allen et al., 1998) for 1983 to 2003 were observed to result in noticeably different daily summer and spring ETo and yield estimates, in turn impacting the WF estimates (which use cumulative crop ET values and yield in their calculation). This effect was less significant for crops planted in autumn and winter. The reason why this effect is more prominent in summer and spring can possibly be explained by the fact that the study area is a summer rainfall region, because it is expected that solar radiation is more accurately estimated in the absence of cloud cover. It is recommended that the weather data that is used for crop parameterisation, whether specific variables are estimated or

measured, must be used consistently over the simulation period to estimate WFs, assuming that the variation in the error in Rs estimates are insignificant for a particular season.

- The functional unit, for example, yield in fresh mass or dry matter, used to calculate WFs can have a notable impact on the relative size of a crop's WF. For example, the grain crops with low moisture content in the harvested grain have relatively high WFs in terms of fresh mass, but in terms of dry matter these crops have relatively low WFs, as compared to vegetable crops (which can have around 90% moisture content). Other functional units, such as nutritional content and economic gain are potentially more useful, because they connect the volume of water use to a specific benefit derived from the crop.
- The WFs of crops with a small harvest index, such as broccoli over all seasons are high, because of the small harvestable portion used in the WF calculation. However, these high WFs could be misleading if the rest of the broccoli plant is used for other beneficial purposes, such as composting and animal feed.
- The relatively high grey WFs do not match the good quality water of the Steenkoppies Aquifer with regard to nitrate levels. This highlights the uncertainties regarding the fate of N after application to the field.

The following opportunities for future research have been identified:

- Development of methodology to incorporate the beneficial uses of crop residues in the WF estimation.
- Further developing WF methodologies using alternative functional units, such as crop nutritional content, and economic gain and job creation per unit water used.
- Investigations to better understand the N balance of these intensive cropping systems and the whole aquifer.
- Improve the understanding of how initial soil water content at planting and where this water originated from impacts the blue and green WF, specifically for models that can only do simulations for one season. This issue is not important for models, such as SWB, that do long-term simulations.
- Determine how significant the variation in WFs is between different crop cultivars.

## 9.4 CATCHMENT SCALE WATER FOOTPRINTS

In **Chapter 6** WFs according to the WFN were used to develop the catchment WF framework, in which total ET from agriculture was estimated by linking WFs of crops with total yields produced on the aquifer. Catchment scale agricultural water use were then used together with other water flows to calculate a catchment water balance. According to the catchment water balance, water flowing into the aquifer exceeds water losses, which is an important question arising from this study. This can either be explained by errors in the assumptions made for this study, or by the possibility that other losses may occur from the aquifer boundaries that are currently not known. There was, however, a good correlation between estimated and measured outflows from Maloney's Eye, and water outflows (crop ET plus natural vegetation ET plus Maloney's Eye outflows) are very similar to precipitation inflows during years with low rainfall and / or high agricultural water use. Through this framework, total ET estimates of a catchment can potentially be used to improve hydrological models. Using WFs to determine a water balance of the catchment is, however, also considered to be part of a process towards developing a simplified and more cost-effective approach to understanding water dynamics of an aquifer, in contrast to complex and expensive hydrological assessments. The water balance requires relatively little information for an agriculture-dominated catchment, including rainfall data, the total yield of different crops cultivated and their respective WFs, and the WF of natural vegetation. The crop WFs were used to estimate the water balance of the catchment, and these WFs was calculated with data derived through crop modelling. Crop modelling may increase the difficulty of applying the framework, depending on which model is used, the variation in soil properties (particularly where crops have deeper root systems) or rainfall throughout a catchment, and what data is available for the catchment. The sustainability assessment given by the WFN requires the ecological flow requirements (EFR), and these are only available through hydrological assessments. However, in this study the unsustainable use of water on the aquifer was also reflected by the water balance, which does not require any complex hydrological studies.

The blue WF sustainability assessment indicated that irrigated agriculture became unsustainable after 1986, which is in line with measured reductions in the outflows from Maloney's Eye, as well as reductions in groundwater levels during this time. The green WF sustainability assessment indicates that there is still further opportunity to expand rainfed crops based on a natural vegetation conservation target of 24%. It is expected that more efficient irrigation systems can also be implemented to optimise the use of green water by irrigated crops, to alleviate pressure on blue water sources, but this possibility has not been tested in this research.

Whether this framework can be applied to other catchments depends on the specific characteristics of that catchment. The WFN WFs do consider the difference between over-irrigation and ET, assuming that any excess water applied will recharge the blue water source. This framework only therefore applies to situations where the difference between over-irrigation and ET can be considered unimportant or as recharge to the same water resource. For example, the framework will definitely apply to aquifers where the deep drainage caused by over-irrigation will recharge the aquifer and become available to the same users in the future. Impacts on water quality will, however, need to be addressed simultaneously. If water is discharged into a river, the blue water will become available to downstream users including the environment and/or flow into the sea (which also plays an important role in estuary ecology), in which case the framework may not apply as effectively. However, if water was taken from the same river and would have left the catchment even if abstraction did not take place, this framework could apply. It is also important to emphasize that when using this framework, green WF proportions must be maximised as an indication that irrigation is applied effectively. This will also reduce other ecological impacts associated with over-irrigation and the impact of lags (due to temporary unavailability in the vadose zone) on blue water availability in systems like the Steenkoppies Aquifer.

The following opportunities for future research for the Steenkoppies Aquifer (and similar aquifers or catchments) have been identified:

- Further refine the catchment WF framework to estimate outflows from the aquifer more accurately (assuming these can be accurately measured).
- Linked to the point above, estimations of ET of the natural vegetation must be improved and verified.
- Record actual production within the catchment for the estimation of WFs. This will require a willingness of farmers to share their production records.
- Future geohydrological assessments are required to confirm the hypothesis of an unknown outlet.
- Using catchment scale WFs to determine maximum allowable production on an aquifer to achieve multi-generational sustainability targets as proposed by (Gleeson et al., 2012).

- The blue and green WF sustainability assessments can be further improved in future research, specifically with regards to determination of natural runoff, additional components that can be included in the calculation of blue water availability (such as water allocated to downstream users), and accounting for recharge of the aquifer under natural vegetation, which may be defined as available blue water.

## 9.5 WATER FOOTPRINTS OF WASTAGE

Water footprints of food wastage between harvesting and the consumer present opportunities to reduce water use. However, reductions or even elimination in wastage of crops produced on the Steenkoppies Aquifer alone will not be sufficient to achieve blue water sustainability targets. Furthermore, the percentage wastage calculated here is already much lower than what has been recorded in other studies for other parts of the world and for sub-Saharan Africa. Food wastage is still important and should therefore be considered as only one of several measures to be implemented to reduce the WFs on the Steenkoppies Aquifer.

Classifying waste is complex, because wasted food all along the supply chain up to the retailer are used for other beneficial purposes such as composting and animal feed. Lettuce has relatively high wastage rates along the supply chain, partly because the crop has a short shelf-life, and because it cannot be preserved or frozen. This information should motivate some awareness raising among consumers to plant these crops in homestead gardens. Further reductions in food wastage may come at a cost, for example ecological impacts due to pesticide application, or carbon emissions associated with energy use or refrigeration. Buying less food more often requires more frequent transporting and increased carbon emissions. Future research studies are, therefore, required to:

- Improve classification of wastage to account for other beneficial uses of produce that is not suitable for selling.
- Compare the increased ecological and carbon footprints with the gains of reducing water footprints when implementing different strategies to reduce food wastage.
- Quantifying the causes for vegetable wastage, especially at the packhouse level.

## 9.6 WATER FOOTPRINTS OF FANCY LETTUCE CULTIVARS

New crop parameters were developed for the fancy lettuce cultivars, cos and butterleaf for application in the SWB model. Water footprint results for cos and butterleaf were lower than all the other crops that were investigated in this study. This is partly because they are very efficient in producing biomass and the harvestable portion is high considering that the entire aboveground biomass is harvested. But most notably, longer growing seasons were found to decrease the WF, because crops produce more dry matter per volume of water later in the growing season. Future research can focus on:

- Assessing alternative cultivars or species, for example, indigenous species that are drought resistant, to find crops with lower WFs. Finding alternative crops with lower WFs could therefore become an important measure in which sustainability can be achieved.
- Determining the impact of the length of the growing season on WFs of other crops.

# 10 CHAPTER 10: CONCLUSION

The Water Footprint Network (WFN) methodology proposed by Hoekstra et al. (2011) was selected as the most appropriate for water footprint (WF) calculations on the Steenkoppies Aquifer. The value of their approach can be seen on different levels.

## 10.1 VALUE OF WATER FOOTPRINT NETWORK WATER FOOTPRINTS ON A LOCAL LEVEL

On a local or farm level, the WFN methodology makes it possible to:

- Calculate WFs for well-managed farms which can be used as benchmarks for other farmers in the region.
- Determine whether efficient irrigation management practices were used, which are reflected by maximum green WFs and minimum blue WFs.
- Determine which crops and cultivars have low WFs, so that these can be selected during dry years when water limitations are enforced.
- Make decisions about what a farmer wants to achieve with the available water, for example in terms of economic gain, nutritional value or job creation.

From this study there are some specific recommendations that can be given to the farmers on the Steenkoppies Aquifer, for example that current agricultural water must be reduced to be within sustainable limits. This could potentially be achieved by:

- Reducing production,
- Reducing the WFs of the crops that are produced, for example by delaying harvesting dates or selecting cultivars with lower WFs.
- Avoid growing crops during seasons when they have high WFs, such as broccoli in winter,
- Reduce total production by reducing food losses at the packhouse level,
- Make better use of available green water

However, it should be noted that given the current conditions that dictates farmers' decision making, farmers would often not implement these recommendations. For example, farmers select crops and determine harvesting dates based on market demands. If the price of lettuce is high, farmers will harvest their lettuce immediately, rather than delaying harvest dates for two weeks to produce lettuce with a low WF. This further highlights the importance of raising consumer awareness to change market demands. Furthermore, reducing total production on the aquifer will also require a combined effort from all the farmers on the aquifer and a single farmer will not consider reducing his production as an isolated effort to achieve sustainable water use on the aquifer.

However, some complexities of calculating WFs according to the WFN approach must be kept in mind.

- Water footprints can differ depending on the growing season, between years and between different locations. Water footprints must therefore be calculated with local data, and be specific to the growing season and year in which they are applied.
- The quality of data used for crop water use modelling can have notable impacts on the WF outcomes. If estimated solar radiation data was used to develop crop parameters, estimated data should also be used when using these crop parameters to do simulations, otherwise $ET_o$

outcomes could potentially be underestimated, which will impact yield and WF outcomes. The same consistency should be applied when using measured data.

- The functional unit that is used to calculate WFs can impact the outcomes, for example WFs of grain crops calculated in fresh mass are higher than the vegetables, but when calculated with dry matter these WFs are lower than the vegetables. This is because of the low water contents of the grains relative to the vegetables. Using other functional units, such as nutritional content, economic gain or job creation may therefore be more useful.
- Crop residues that are normally used for other purposes, such as composting and animal feed, are not included in WF calculations, which may cause an overestimation of WFs.
- Grey WF results were not successfully verified by groundwater quality analyses. Improving the estimations of nutrient loads, which requires an understanding of the fate of the nutrients, is necessary to improve grey WF results.

## 10.2 VALUE OF WATER FOOTPRINT NETWORK WATER FOOTPRINTS ON A REGIONAL LEVEL

For aquifers and catchments in general, the WFN methodology is considered to be most useful, because it is quantitative and can be interpreted within a catchment manager's information systems. Water footprints that are calculated according to the WFN methodology provide a simple way to estimate the total evapotranspiration (ET) of agriculture and to assess the sustainability of this ET. The conclusion in this study was made that agricultural water uses between 1986 and 2012 were unsustainable, as determined by the WFN methodology. This conclusion was supported by the fact that groundwater levels and outflows from Maloney's Eye were consistently reduced during this period.

In this study the methodology proposed by Hoekstra et al. (2011) for assessing the WF of crops, has been expanded by providing the framework in which the WF methodology can best be applied. According to this framework total production on an aquifer can be multiplied by the WFs of the crops to obtain the agricultural water use (ET) on the aquifer. The total ET of agriculture, together with precipitation, WFs of natural vegetation, other water uses and in- and outflows from the aquifer, can be used to estimate the water balance of an aquifer and in this case study it improved the understanding of the geohydrology of the aquifer. This framework is simple because it requires relatively little information, of which the crop WFs, total production and natural vegetation are the most important. Future research could further develop the catchment WF framework to determine how accurate the results would be if average WF values are used, compared to locally generated WFs. Average WF values may proof to be accurate enough for crops with a low variation in WFs. It must be noted that estimations with average crop WFs may provide less accurate results that should not be used when more detailed results are necessary.

Water footprints, according to the WFN, were able to provide the quantitative data needed to prioritise actions and measures that are required to achieve sustainable water use on the Steenkoppies Aquifer, which will apply to aquifers in general. For example, potential water savings in the packhouses and the reduction of food wastage are very important, but will not be sufficient measures to achieve sustainable water uses on the Steenkoppies Aquifer and must be applied together with other measures. Selecting alternative cultivars with lower WFs, could however be successfully used to achieve sustainable water use on the Steenkoppies Aquifer, or aquifers in general. Cos and butterhead lettuce varieties, for example, had lower ET compared to the more common iceberg lettuce and these varieties could result in lower catchment scale WFs. Longer growing seasons can also potentially reduce the WFs of the crop, because later in the growing season the crops produce more biomass per volume of water. For example, in **Chapter 8** it was found that the water required to produce one tonne of cos lettuce, harvested 82 days after planting, was 70% of the water required to produce one tonne of iceberg lettuce, which was harvested 66 days after planting. Therefore, alternative cultivars and longer growing seasons may reduce the volume of water required while maintaining current production of lettuce.

## 10.3 USE OF WATER FOOTPRINTS ON A NATIONAL LEVEL

In the modern world consumers are often unaware of the environmental impacts associated with the production of the products they buy and are therefore unable to respond in an appropriate way. It is therefore recognised that changing consumer behaviour and demands are key to reaching sustainable water use targets. The term virtual WF has been proposed as a way to inform water users and policy makers of a WF of a product that is produced in another location or country. Virtual water is therefore applicable on a national level where decisions must be made on exports and imports, and it also applies to raising awareness of consumers. However, WFs according to the WFN without a sustainability assessment are not considered suitable for awareness raising or labelling of products, because the data is not informative outside the local environmental context. Because of the complexity of the ecological, social and economic systems in which water is used, methods that aim to provide information that will enable a distant consumer or policy maker to make wise decisions about their virtual water use are difficult to obtain. Alternative ways to influence consumers or countries where products are exported to, such as education, advertising and subsidies, should be considered in future research. It is expected that WFs can play an important role in generating the required information and knowledge that will ultimately lead to wise decisions being made in terms of sustainable water use.

Water footprints, calculated according to the WFN, but with alternative functional units could, however, be very useful to policy makers. For example, this data can inform them of which crops in which seasons will use the least amount of water for each job that was created, or each person that was provided with the required nutrition. Water can then be allocated to increase the production of those crops that will use the least amount of water to achieve specified priorities. Water will often be an important limiting factor in a water scarce country like South Africa, and using WFs in this way will most likely be very useful to policy makers.

From this study it is concluded that WFs according to the WFN methodology can provide reliable and useful data on the use of water. This data must be interpreted according to the local knowledge of the ecological, economic and social environment in which the water is used to provide information for those who must make decisions. Decision makers need knowledge and experience to know how to respond to the information provided and the wisdom on how to achieve sustainable water use. Without good data, we do not have reliable information or knowledge, and will not be able to make wise decisions, as T.S. Eliot (1934) said in his poem ‘The Rock’.

> *Where is the wisdom that we have lost in knowledge?*
> *Where is the knowledge that we have lost in information?*

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