Field quantification of the water footprint of an apple orchard, and extrapolation to watershed scale within a winter rainfall Mediterranean climate zone

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Abstract

Field scale quantifications of the water footprints (WF) of crops, based on actual measurements, provide valuable and detailed information for on-farm water use management. However, watershed-based WF assessments are more appropriate for large-scale water resources management beyond the farm boundaries. In this study, blue, green and grey WF information, using the Water Footprint Network approach up to farm gate level, was determined for an apple (*Malus pumila*) orchard growing under Mediterranean climate conditions in South Africa. WF_{blue} and WF_{green} were determined through measurements of transpiration, total evaporation, rainfall, irrigation and other operational water uses, and WF_{grey} was calculated from fertilizer applications. Combined field-scale blue/green/grey water footprint data were extrapolated to watershed scale by means of representative monthly FAO-56 type reference potential evaporation (ET_o) values and crop coefficients derived from the field scale observations. Resultant water use values were converted to a volumetric equivalent by multiplying by the area under apple orchards in each watershed. The volumetric equivalents were then summed for all QCs in the Water Management Area to calculate the overall water footprint for apple production in the basin. Orchard-scale WF, taking into account all water uses and a fruit yield of 61.5 $t.ha^{-1}$, was 212.1 $m^3.t^{-1}$, comprising 62.7% WF_{blue}, 14.9% WF_{green} and 22.5% WF_{grey}. Irrigation thus contributed the bulk of the WF in the apple production chain. Resultant water productivity (WP) figures for the orchard averaged 4.72 $kg.m^{-3}$. Scaling up the WF estimates to QC level gave an average value of 228.4 $m^3.t^{-1}$ (WP = 4.41 $kg.m^{-3}$). Accurate crop coefficients, representative weather / ET_o data and reliable crop areas within each QC are critical requirements in terms of upscaling WF estimates, where the information has potential application in water allocation decisions, Water-Energy-Food (WEF) Nexus cost-benefit analyses and other water resource management decisions.

Keywords: Water use; Sap flow; Transpiration; Total evaporation; Crop coefficients; Quaternary catchment; Water management area

1 Introduction

South Africa faces a number of water resource challenges common to other semi-arid regions. These include the realities of increasing water scarcity and competition for water due to population expansion, economic growth, climate change and variability (after Falkenmark, 2013; Midgley and Lotze, 2011). Consequently, the issues of water security, water footprints, water productivity and resultant water/energy/food/environment nexus considerations, are receiving increasing attention not only in South Africa but globally (Bazilian et al., 2011; Agholor, 2013). There is therefore an urgent need to improve water productivity, defined in this study as crop yield per unit volume of water used, and to reduce non-beneficial water uses particularly in irrigated agriculture which consumes the largest quantities of water. In South Africa, for example, irrigation uses as much as 62% of the available surface water resources (Reinders, 2013). Consequently, agriculture is one of the greatest potential change agents for improved water management given its significant water allocation.

Past studies (Midgley and Lotze, 2011; Colvin, pers. comm.) have shown that a water risk hot spot lies in the Western Cape Province of South Africa. In particular, the deciduous fruit industry has been highlighted as a key risk, as it is a high water consuming sector per unit mass of fruit produced (Dzikiti and Schachtschneider, 2015). The Irrigation Strategy for South Africa has set a target to increase the area under irrigation in South Africa by more than 50% (DAFF, 2010). However, with only limited new agricultural water supply developments planned, an increase in the area under irrigation will consequently necessitate significant improvements in the water productivity of currently irrigated land to enable this expansion.

As a result of generally low and erratic rainfall and the high value of fruit and vegetable crops, it is estimated that 90% of fruit and vegetables produced in South Africa are grown under irrigation (Nieuwoudt et al., 2004). Under the compulsory registration, authorisation and licensing of water-use, which is being driven by the National Water Resource Strategy (NWRS-2, 2013), implementation of measures to improve water productivity (WP) is at the core of the strategy. However, implementation of WP improvements in this sector firstly requires accurate data on the water requirements of crops. In addition, tools are needed to better manage the actual water use requirements of these crops so that they use less water without compromising fruit quality, yield and profits (Fernández and Cuevas, 2010; Dzikiti et al., 2011).

Up to 96% of the apples exported from South Africa are produced in the Western Cape Province and the country is ranked seventh in terms of global exports of apples (DAFF, 2010). While previous studies have determined the water requirements of apple orchards elsewhere in the world (Naor and Cohen, 2003; Green et al., 2003), studies on the water water use of apple orchards based on actual measurements under Mediterranean climates are rare, and a newly completed study in South Africa has only recently been reported (Dzikiti et al., 2018). As such, irrigation decisions and modelled water use predictions for apple orchards in South Africa are often still based on crop coefficients that were developed in other parts of the world, often under different climatic conditions. To address this we used a novel combination of sap flow monitoring techniques, measurements and modelling of total evaporation, data from mapping exercises, and direct engagement with apple growers to determine both orchard-scale and watershed-scale estimates of the water footprint (WF) of apple production.

WF accounting is a means of conducting comparative water use assessments across various land-uses at wider scales. It indicates the water-use summed over the various steps of the entire production chain. When linked to yield, it has potential to identify existing levels of water productivity and where those may potentially be improved. Various methods for calculating the WF of a product or crop have been proposed and these include the Water Footprint Network (WFN) approach (Hoekstra, 2003; Hoekstra et al., 2011), the Life Cycle Assessment (LCA) approach (Canals et al., 2009; Pfister et al., 2009), and the hydrological-based approach (Deurer et al., 2011), while in 2014 the first International Standards Organization (ISO) standard for water footprint determination was released (ISO, 2014). In a review and investigation of these methods and their ability to improve water management at various scales Le Roux et al. (2018) concluded that the WFN methodology appeared most useful to resource managers due to its quantitative nature and ability to compare blue and green water consumption versus water availability.

As an international water resource management tool, the WF concept has come under some sharp criticism (Wichelns, 2011; Perry, 2014). However, when validated with robust field observations we believe it remains a potentially useful tool to raise consumer awareness, identify relative differences in product water requirements, address over-irrigation tendencies, assist in formulating policy for sustainable local water management decision making, and ultimately improve efficiencies in water use across the entire production process (Aldaya et al., 2010). Further advantages of applying the WF concept include its ability to distinguish between the relative contributions of irrigation and rain water to the crop production process, as well as providing a framework for an assessment of impacts on water quality. On the other hand a WF assessment is only as good as the data on which it is based. The primary objectives of this study were therefore to apply cutting edge measurement and modelling techniques to quantify the actual volumes of water used by apple orchards under current land and water management practices; and to propose a practical methodology for scaling up WF information for irrigated crops from field measurements to watershed scale, to facilitate water resource management decisions.

2 Materials and methods

2.1 Study site and water management area

Field measurements were conducted in a 12-year old apple orchard (*Malus pumila*) at a commercial farm (“Nooitgedacht”) located near the town of Ceres in the Western Cape Province of South Africa (S33° 12 03.57″; E19° 20′ 15.06″; 1089 masl). The orchard was 134 m by 172 m (2.3 ha) in extent (Fig. 1). It was planted to ‘Cripps’ Pink’ (‘Pink Lady’) apples on M793 rootstock, with every 8th tree in each row being a ‘Hillary’ crab-apple pollinator. Row orientation was north – south and the trees were spaced at 1.25 m by 4 m, giving a planting density of 2000 stems per ha, with a short grass cover between rows. Average tree height was 5.1 m and average stem diameter at 0.3 m from the base of the tree was 0.1 m. Irrigation water and fertiliser (‘fertigation’) were applied by means of short-range micro-sprinklers, with scheduling based on daily soil moisture and weather data. The discharge rate of each micro-sprinkler was 30 $L.h^{-1}$, equivalent to 5 mm per hour for emitters which were positioned every 1.5 m within the tree rows, with a wetted radius of approximately 08-–1.0 m. Trees were irrigated once or twice a week at the beginning of the season in October-November when there was still residual moisture from the winter rains, increasing to approximately once every two days during the hot summer weather in January and February. Typically, each irrigation event lasted between one and one and half hours. Soils were gravel, with a high sand and stone content, well drained and with an effective rooting depth of approximately 0.6 m. Based on soil analyses in the area (Dzikiti et al.,

2018) the soils had a water holding capacity of approximately 174 mm.m⁻¹. Annual orchard yields were 54 t.ha⁻¹ in the 2008/2009 season and 69 t.ha⁻¹ in the 2009/2010season, with an average of 61.5 t.ha⁻¹ over the two seasons.

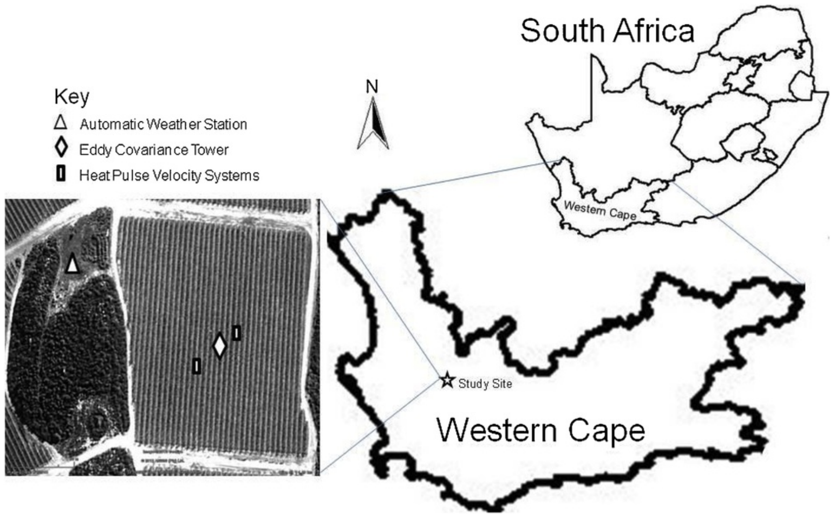

Fig. 1 Location of the study orchard. The Google Earth extract (extreme left) provides the details of the study site.

The study site falls within the Koue Bokkeveld region of the Olifants/Doorn Water Management Area (WMA) in the Mediterranean-type winter rainfall region of the Western Cape Province (Fig. 2). This WMA was one of an original 19 WMAs subsequently consolidated to 9, and now forms part of the new Berg-Olifants WMA comprising the original Berg WMA and the Olifants-Doorn WMA (NWRS-2, 2013). However, for the purposes of this study it was analyzed in its original capacity. There are 89 watersheds (termed Quaternary Catchments / QCs as 4th-order hydrological response units under South Africa water resource management legislation) included in the Olifants-Doorn WMA, and climatic conditions vary considerably as a result of the variation in topography. The mean annual precipitation ranges from approximately 1 500 mm in the Cederberg Mountains in the south-west, decreasing sharply to about 200 mm to the north, east and west thereof, and to less than 100 mm in the far north (DEA&DP, 2011). The WMA depends heavily on surface water (76%) and groundwater (16%) as respective sources of supply. The major river contributing to the surface flow in the WMA is the Olifants River, of which the Doring River (draining the Koue Bokkeveld and Doring area) and the Sout River (draining the Knersvlakte area) are the main tributaries. The Olifants and Doring Rivers are perennial and have high flows in winter, while the Sout River is ephemeral and flows seasonally. Surface water in the Olifants River is regulated by the Clanwilliam Dam and the Bulshoek Barrage. There are no large dams on the Doring River, although a large number of farm dams have been constructed on the upper tributaries.

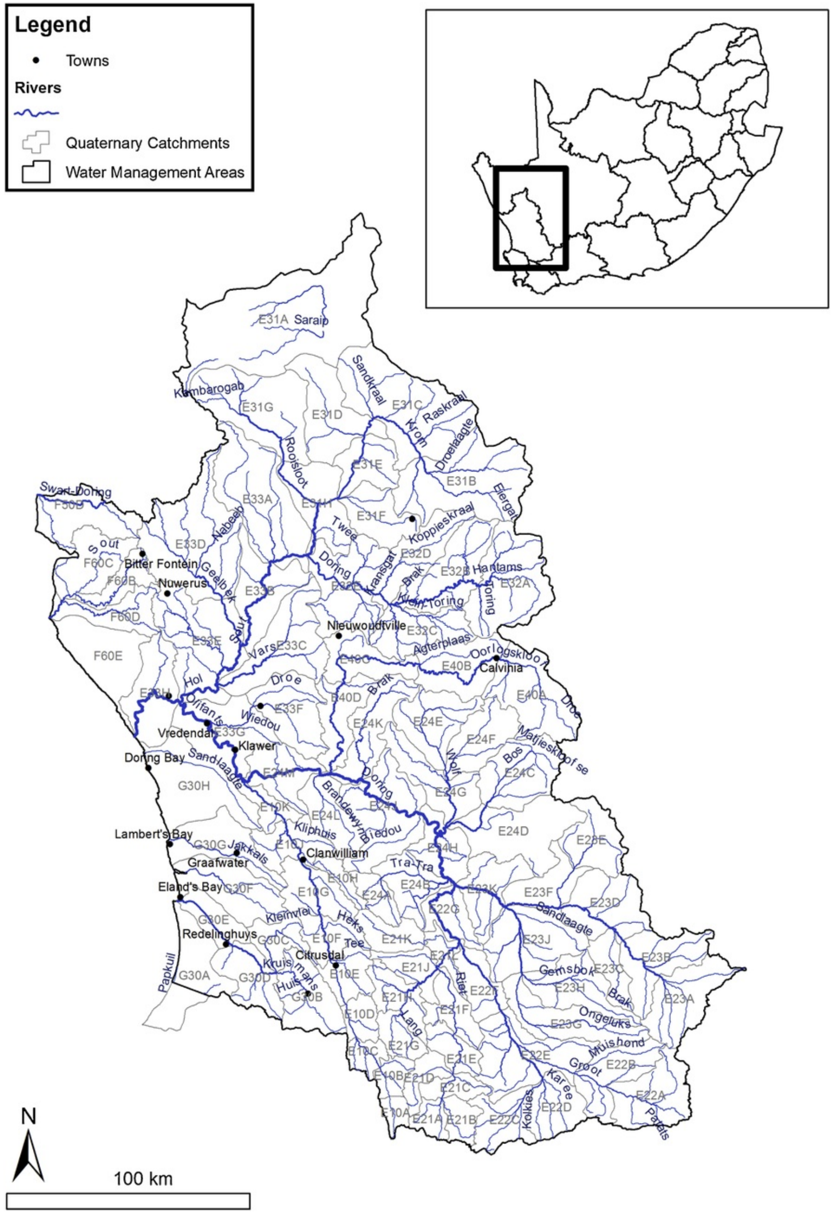

Fig. 2 Locality map of the Olifants/Doorn Water Management Area showing the main towns, rivers and the watersheds / quaternary catchments.

With the mean annual precipitation over much of the WMA being less than 200 mm, the result is that, except in the wetter south-west, the climate is not suitable for dryland farming on a large scale. It is a region experiencing extreme water scarcity, with a particularly high dependence upon groundwater (as a direct source of supply) in the Sandveld region. Consequently, more than 90% of the land in the Olifants-Doorn WMA is used as grazing for livestock, predominantly for sheep and goats. However, the principal economic activity in the WMA is irrigated agriculture, and 87% of total water use is for irrigation (DEA&DP, 2011). A recent estimate (Bailey and Pitman, 2016) puts the total area under irrigation in this WMA at 730 km^2.

2.2 Field measurements

2.2.1 Meteorological measurements

An automatic weather station (AWS) equipped with a CR1000 data logger (Campbell Scientific Inc., Logan, UT, USA), and measuring rainfall (TE525-L, Texas Electronics, Dallas, Texas, USA), solar radiation (LI-200SA, LI-COR Inc., Lincoln, NE, USA), temperature and humidity (HMP50, Vaisala, Helsinki, Finland), wind speed and wind direction (Model 03001, RM Young, Traverse City, Michigan, USA) was installed in an open area approximately 200 m from the study orchard. Sensors were mounted 2 m above the ground, and variables were scanned at 10 s intervals and stored in the logger at hourly intervals for the two-year monitoring period (2008-09 and 2009–2010). Hourly values were further processed into daily averages or totals, and the data were used to calculate daily reference evaporation (ET_o) for the site according to the FAO-56 approach (Allen et al., 1998).

2.2.2 Sap flow /transpiration

The heat ratio method (HRM) (Burgess et al., 2001) of the heat pulse velocity (HPV) technique was used to measure sap flow in this study. Six individual apple trees were instrumented with the HRM / HPV technique, comprising four mature ‘Cripps Pink’ trees and two ‘Hillary’ crab-apple pollinators. Further details of the theory and application of the HPV equipment utilised in this study are provided by Taylor and Gush (2014). Monitoring of sap flow in the instrumented trees spanned two full growing seasons (801 days) between May 2008 and July 2010. Measurements of tree attributes influencing transpiration, namely stem diameters, tree heights, canopy dimensions, and sapwood characteristics (xylem depth, density and moisture content) were recorded, while Leaf area index (LAI) measurements were taken periodically with a LI-2000 Plant Canopy Analyser (LI-COR Inc., Lincoln, NE, USA).

Measured heat-pulse velocities were corrected for sapwood wounding caused by drilling, using wound correction coefficients described by Burgess et al. (2001). The corrected heat-pulse velocities were then converted to sap-flux densities according to the method described by Marshall (1958). Finally, the sap-flux densities were converted to whole-tree total sap flow volumes by calculating the sum of the products of sap-flux density and cross-sectional area for individual tree stem annuli (ring-shaped areas determined by below-bark individual probe insertion depths and sap-wood depth). Hourly sap-flow volumes were aggregated into daily, monthly and annual totals for each tree, and were assumed to equate to transpiration (T).

2.2.3 Total evaporation

An extended open path eddy covariance (OPEC) system was used to measure total evaporation (ET) of the orchard during short-term seasonal measurement campaigns. Measurements took place on four separate occasions, namely autumn (13–16 May 2008), summer (3–17 December 2008), spring (9–12 October 2009) and winter (28 July–4 August 2010). On each occasion the instruments were fixed at 6.2 m above ground (1.1 m above average canopy height) on a lattice mast, installed in the centre of the orchard, where the fetch was 110 m from the prevailing north-west winds. Details on the sensors comprising the OPEC system deployed for this study are provided in Gush and Taylor (2014).

2.2.4 Irrigation

Irrigation was monitored by means of a water pressure sensor (IRROMETER Company Inc., Riverside, CA, USA), fixed on the irrigation line and connected to a CR10X data logger (Campbell Scientific Inc., Logan, Utah, USA), which was programmed to record the duration (in minutes) of individual irrigation events. Corresponding irrigation volumes were subsequently calculated based on the delivery rate of the micro-sprinklers.

2.3 Evaporation modelling

Observed orchard ET data captured during seasonal measurement campaigns were extrapolated to the full monitoring period through modelling. We adopted a two-layer Shuttleworth-Wallace type model (Shuttleworth and Wallace, 1985) as modified for cherry orchards by Li et al. (2010). According to this model, ET was calculated as the algebraic sum of separate tree transpiration and soil evaporation submodels. The transpiration submodel utilised the Penman-Monteith approach (Green et al, 2003; Zhang et al., 1997) wherein tree transpiration (E_{tree} in kg m^{-2} s^{-1}) was calculated as:

$$E_{tree} = LAI\left(\frac{\Delta Rn_{tree} + 0.93\rho c_p VPD/r_b}{\lambda(\Delta + 0.93\gamma(2 + r_s/r_b))}\right) \quad \mathbf{(1)}$$

where LAI ($m^2 . m^{-2}$) is the orchard leaf area index, Rn_{tree} (in $W . m^{-2}$) is the net radiation absorbed by the tree canopies, Δ (in $Pa.K^{-1}$) is the slope of the vapour pressure – temperature curve, ρ (in $kg . m^{-3}$) is the density of air, c_p ($J . kg^{-1} . K^{-1}$) is the specific heat capacity of air at constant pressure, VPD (Pa) is the vapour pressure deficit of the air, λ ($J . kg^{-1}$) is the latent heat of vaporisation of water, γ ($Pa.K^{-1}$) is the psychrometric constant, r_s ($s . m^{-1}$) is the mean stomatal resistance, and r_b ($s . m^{-1}$) is the leaf boundary layer resistance. The net radiation absorbed by the canopies was modelled according to Beer’s law as:

$$Rn_{tree} = Rn(1 - \exp^{-kLAI}) \quad \mathbf{(2)}$$

where Rn is the net radiation absorbed by a reference surface (Monteith and Unsworth, 2013) and k is the extinction coefficient which was taken to be 0.5 (Li et al., 2010). The canopy conductance, g_c was modelled using the approach by Jarvis (1976) in which maximum conductance (g_{cmax}) is reduced by temperature (T), solar irradiance (S), soil water content (SWC) and vapour pressure deficit (VPD) stress functions, such that:

$$g_c = g_{c\max}.f(T).f(S).f(SWC).f(VPD) \tag{3}$$

The functional form of the irradiance, SWC and VPD stress functions (Eq. 3) are given for apple trees in Green et al. (2003). Model performance was significantly enhanced by including the temperature stress function *f(T)* to Green's original formulation and the functional form of the temperature stress function is given in Zhang et al. (1997). The stomatal conductance data used for deriving the parameters in the conductance stress functions was obtained by inverting the Penman-Monteith equation (Eq. 1) using measured sap flow (assumed equal to transpiration), net radiation and climate data collected during the March and December 2008 campaigns. Model optimisation was carried out using the "ModelMaker" software package (Cherwell Scientific, Ltd., UK) using the Marquardt iterative procedure. Parameters that minimized the squared differences between the measured and modelled stomatal conductances were selected and typical values for the study orchard were determined. Soil evaporation (E_s, in kg m^{-2} s^{-1}) was estimated from a modified Priestely and Taylor evaporation model proposed for cherry orchards by Li et al. (2010) in which:

$$E_s = \alpha_E \tau \frac{\Delta}{\lambda(\Delta + \gamma)}(Rns - G) \tag{4}$$

where α_E is the Priestley and Taylor coefficient, Rns is the net short wave radiation on the orchard floor, G is the soil heat flux (assumed to be 10% of Rns) and τ is the ratio of Rns to Rn and the full equation is given in Li et al. (2010). Rns was formulated as:

$$Rns = \exp^{-kLAI} \cdot Rn \tag{5}$$

The model was run on an hourly time step, and at the completion of the modelling exercise monthly basal/transpiration (K_{cb}) and full crop coefficients (K_c) were derived for the orchard using the FAO-56 approach (Allen et al., 1998), by dividing daily transpiration and ET totals with corresponding daily reference evaporation (ET_o) values, and calculating monthly averages for the orchard.

2.4 Water footprint determination (study site)

The total WF associated with the apple growing process (i.e. m^3 water used per tonne of apples produced) was calculated according to the Water Footprint Network (WFN) method of Hoekstra et al. (2011). This was determined for the study orchard by accounting for all processes using water over a calendar year (July to June), which incorporated the full growing season until produce was ready for distribution at the farm gate. The field measurements provided accurate quantification of the different components of crop water use (CWU).

CWU_{blue} ($m^3.ha^{-1}$) was calculated as orchard ET associated with irrigation applications over the summer growing season (October to April), and was determined using the daily irrigation observations from the site. CWU_{green} ($m^3.ha^{-1}$) was determined by subtracting the CWU_{blue} from the total annual ET of the orchard determined from measurements and modelling, and consequently accounted for the fraction of orchard ET associated with the use of rainfall. CWU_{blue} constituted the primary water use component, however, information on all other CWU_{blue} uses in the fruit production chain was obtained through additional field measurements and interviews with managers on the farm. These comprised quantities of water used for spraying operations in the orchard (micro-nutrients, fungicides, pesticides, herbicides, chemical fruit thinning agents), packhouse operations (fruit washing, cleaning of equipment), orchard worker water use (5 $L.person^{-1}.day^{-1}$ for drinking and hand-washing) and evaporative water losses from irrigation storage dams. These additional / supplementary orchard water use volumes were added to the CWU_{blue} component. WF_{blue} and WF_{green} were then calculated by dividing CWU_{blue} and CWU_{green}, respectively by the fruit yield of the orchard ($t.ha^{-1}$).

WF_{grey} was calculated using application rates of nitrogen (N) determined from on-farm data, by means of the Hoekstra et al. (2011) equation (Eq. 6):

$$WFgrey = \frac{(\alpha \times AR)\,(Cmax - Cnat)}{Y} \tag{6}$$

where α is the leaching fraction (fraction of applied chemical reaching freshwater bodies), AR is the application rate ($kg.ha^{-1}$), c_{max} is the maximum acceptable concentration of the applied chemical in water according to guidelines or standards ($mg.L^{-1}$), c_{nat} is the natural concentration of the applied chemical in water ($mg.L^{-1}$), and Y is the average crop yield ($t.ha^{-1}$). According to Franke et al. (2013) and Franke and Mathews (2013), the maximum concentration (c_{max}) for N is 13 $mg.L^{-1}$, with an ambient N concentration (c_{nat}) of 4.33 $mg.L^{-1}$. A leaching fraction of 10% was assumed for N, which was applied at 250 $kg.ha^{-1}$. Nitrogen is the most common agricultural pollutant that has been used for calculating grey WFs (Hoekstra et al., 2011; Mekonnen and Hoekstra, 2011; Mekonnen and Hoekstra, 2011), which enables comparisons with a wide range of other WF studies reported in the literature. We consequently used N as the critical pollutant during the cultivation phase to determine WF_{grey} for this study. We recognise that other pollutants, including P and pesticides, might be more appropriate in other studies. However, South Africa does not have any maximum contaminant levels for pesticides (they are not supposed to be present at all) and the maximum concentration applied in the WFgrey equation has a significant impact on the final grey WF calculation, therefore making this method unusable for certain pollutants locally.

The system produced only one product (i.e. apples), and consequently the total WF ($m^3.t^{-1}$) could be fully attributed to this crop, and was thus calculated as the sum of the respective components, such that:

$$WF = WF_{blue} + WF_{green} + WF_{grey} \quad \textbf{(7)}$$

Yield was also used to calculate the Water Productivity (WP) of the crop ($kg.m^{-3}$), essentially the inverse of its Water Footprint. The water consumed was considered to be Total Evaporation (ET), combining both stand transpiration (T) and soil evaporation (E).

2.5 Water footprint determination (watersheds)

Site specific (farm-scale) WF results were subsequently upscaled to QC and WMA scales. This was done using the monthly crop coefficients (K_c) determined for the apple orchard from the field study estimates of ET and ET_o. Each monthly K_c value was partitioned into a $K_{c\text{-}blue}$ and $K_{c\text{-}green}$ component based on the average monthly proportions of CWU_{blue} and CWU_{green} observed from the field study data. Each monthly $K_{c\text{-}blue}$ and $K_{c\text{-}green}$ crop coefficient was subsequently multiplied by the corresponding monthly ET_o value (mm) for each QC within the WMA (determined from Schulze et al., 2007) to calculate QC-specific monthly CWU_{blue} and CWU_{green} values (mm). Monthly 'blue' and 'green' orchard CWU values were summed for the year and then converted to a volumetric equivalent (m^3) by multiplying them by the area under apple orchards in each QC obtained from the Cape Farm Mapper product (http://gis.elsenburg.com/apps/cfm/). Volumetric CWU values were then divided by a representative orchard yield to derive WF_{blue} and WF_{green} values ($m^3.t^{-1}$) for each QC. To these were added the WF_{grey} component, which was assigned a fixed value linked to yield (based on the field study results), in order to determine the total WF for each QC ($m^3.t^{-1}$). QC-specific CWU values were summed for all QCs in the WMA to determine the overall water requirement for apple production in the basin.

3 Results and discussion

3.1 Weather

Monthly variations in mean maximum and minimum temperatures, total rainfall and average daily total solar radiation for each month measured at the field study site over the two year monitoring period reflect typical Mediterranean climatic conditions with cool wet winters and warm dry summers (Fig. 3). Temperatures ranged from daily minimums of -2.5 °C in winter (July) to maximums of 37.8 °C in summer (February), with a mean annual temperature of 14.0 °C. Below zero temperatures were registered approximately 10 days in a year, with occasional snowfalls on high-lying mountains. Daily solar irradiance ranged from 0.6 to 33.7 $MJ.m^{-2}.day^{-1}$, with average daily totals of 9 $MJ.m^{-2}.day^{-1}$ in winter (June) and 30 $MJ.m^{-2}.day^{-1}$ in summer (December). While precipitation patterns were typical of a Mediterranean climate, total annual rainfall differed substantially between the first and second year of study. From July to June, rainfall amounted to 1198 mm in 2008/2009, but just 560 mm in 2009/2010, of which approximately 16% fell during the summer growing season (October to March) of both years. Conversely, ET_o totals calculated using hourly AWS data and the FAO56 method (Allen et al., 1998) were similar for the two years, totaling 1580 mm in 2008/2009 and 1578 mm in 2009/2010 (Table 1). Monthly average windspeeds ranged from 1.9 to 3.2 $m.s^{-1}$ over an annual period, with the strongest winds experienced in August / September. Daily ET_o values ranged from a maximum of 8–9 mm in summer, when the atmospheric evaporative demand was at it's peak, down to approximately 1 mm in winter in both years. Given the relatively shallow root systems of the trees (<0.7 m), use of water from a shallow watertable was improbable, and due to the high dependence on irrigation over the dry summer months it is highly unlikely that the variation in rainfall between the years had an effect on the observed plant transpiration rates.

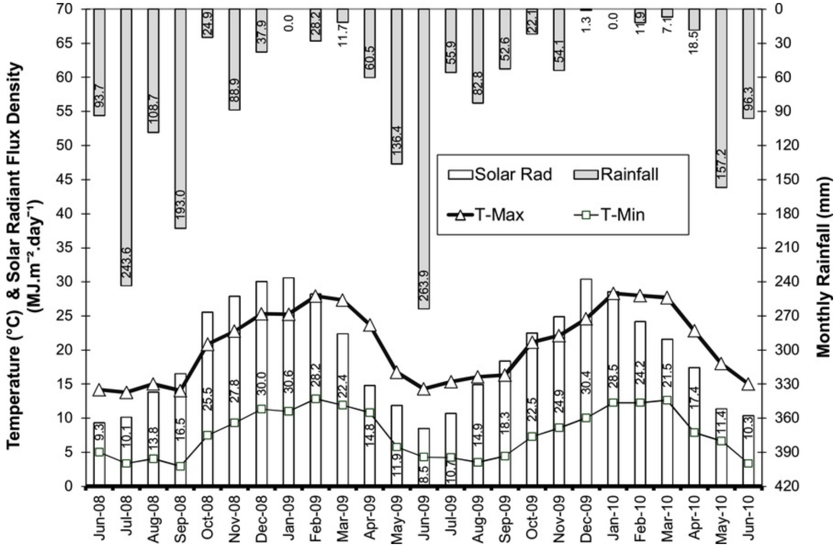

Fig. 3 Monthly values of rainfall (mm), mean daily maximum and minimum temperatures (°C) and mean daily radiant flux density ($MJ.m^{-2}.day^{-1}$) recorded at the apple orchard between June 2008 and June 2010.

alt-text: Fig. 3

Table 1 Monthly FAO-56 reference total evaporation (ET_O) totals (mm) for the orchard calculated from hourly automatic weather station data over two consecutive years.

alt-text: Table 1

	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
2008/’09	67.9	80.1	99.1	154.6	176.4	205.9	207.0	186.2	169.3	114.3	70.8	48.61	**1580.1**
2009/’10.	67.6	85.1	99.9	146.4	168.4	205.6	217.3	173.7	163.0	114.1	75.7	60.84	**1577.7**

3.2 Transpiration

Distinct seasonal trends in transpiration (T) were observed in the apple trees of the study orchard due to the deciduous nature of the species. Following winter dormancy where no observable T was measured, summer T rates of these 12-year old ‘Cripps’ Pink’ apple trees peaked at up to 42 $L.tree^{-1}.day^{-1}$, with an average of 16 $L.tree^{-1}.day^{-1}$ (Fig. 4). These results are similar to those obtained by Green et al. (1989) who observed average T rates of 25 $L.tree^{-1}.day^{-1}$, measured in 10-yr old apple trees over a 15 day period (17 February to 3 March, 1987) during the summer growing season in New Zealand. Over the same 15-day period in our study average ‘Cripps’ Pink’ apple tree T was also 25 $L.tree^{-1}.day^{-1}$ in the 2008/2009 season and 18 $L.tree^{-1}.day^{-1}$ in the 2009/2010season.

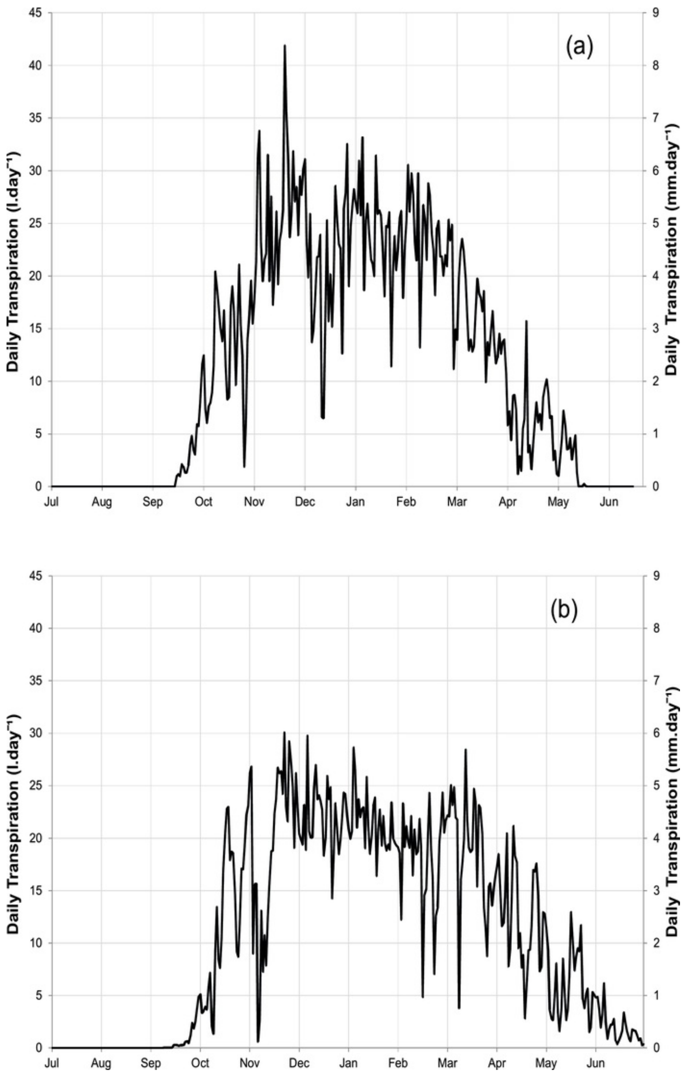

Fig. 4 Observed daily sap flow (transpiration) volumes (L.day^{-1} and mm) for 12-year old ‘Cripps’ Pink’ apple trees, measured over the 2008/2009 (a) and 2009/2010 (b) growing seasons.

On the other hand, the pollinator trees used much less water, with maximum daily T rates of just 13 L.tree^{-1}.day^{-1}, and an average of 5 L.tree^{-1}.day^{-1} in summer. On an annual time scale (June to July) each ‘Cripps’ Pink’ apple tree transpired 3980 l of water on average in 2008/2009 (average of four trees), and 3994 l during the same period in 2009/2010. In contrast, the ‘Hillary’ crab apple pollinators used a far more conservative 1326 L.tree^{-1} in 2008/2009 and 1471 L.tree^{-1} in 2009/2010 (average of two trees). Converting these T rates into the equivalent water depth for the entire orchard, while accounting for planting density (2000 stems per ha) and the representative proportions of ‘Cripps’ Pink’ and pollinator trees, transpiration equated to 683 mm (6828 m^3.ha^{-1}) in 2008/2009 and 691 mm (6912 m^3.ha^{-1}) in 2009/2010.

3.3 Total evaporation measurements and modelling results

ET measurement data from the four eddy covariance campaigns represented the seasonal changes in ET from the orchard (Fig. 5). During May 2008 (autumn) the orchard was losing leaves and approaching dormancy, with typical clear-sky ET rates of 2.7 mm.day^{-1}. In December 2008 (summer) trees were at maximum leaf area and transpiring at peak rates, with observed ET values of up to 8.5 mm.day^{-1}. In October 2009 (spring) trees were in blossom with some signs of bud break and young leaves emerging. However, observed ET values were only in the region of 1.8 mm.day^{-1}, while in July / August 2010 (winter) the trees were completely leafless and tree transpiration would not have contributed to the typical ET values of 0.7 mm.day^{-1} observed at this time. Evaporation from the soil and vegetated inter-row surfaces would have accounted for the measured ET values during this period, especially since significant rainfall shortly before this measurement campaign provided ample water for evaporation.

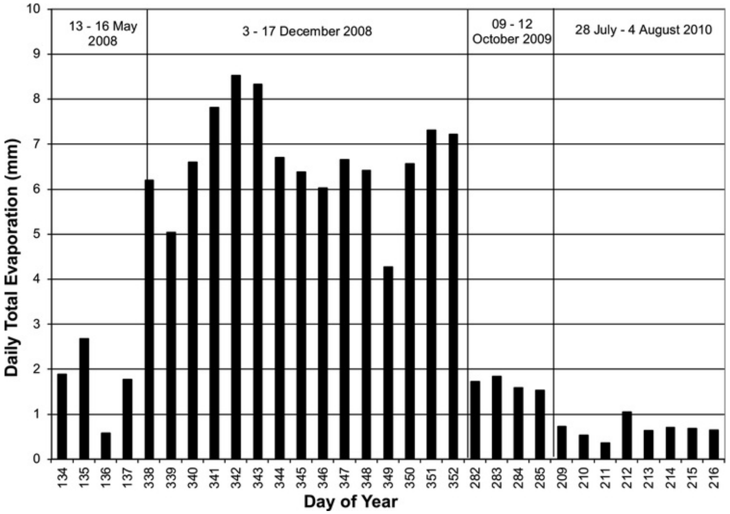

Fig. 5 Daily total evaporation rates measured over a 12-year old ‘Cripps’ Pink’ apple orchard during seasonal campaigns in May 2008, December 2008, October 2009 and July / August 2010.

To scale up the ET data from a few days’ measurements to the annual scale we used the two layer model described earlier. Outputs from the T submodel were first compared against observed T data, and the simulations accounted for 84% of the variation in observed values (Fig. 6). Following the addition of the soil evaporation component and subsequent comparison of modelled orchard ET against measured ET for periods not used in model calibration, it was evident that there was reasonable correlation between simulated and observed values (Fig. 7). However, the scatter tended to be larger during the spring campaign, which was attributed to smaller fluxes and rainy conditions, and resultant increased margins of error . After extrapolation, the annual ET for our study orchard was found to be 952 mm (9520 m^3.ha^{-1}) in 2008/2009 and 966 mm (9660 m^3.ha^{-1}) in 2009/2010 (Fig. 8).

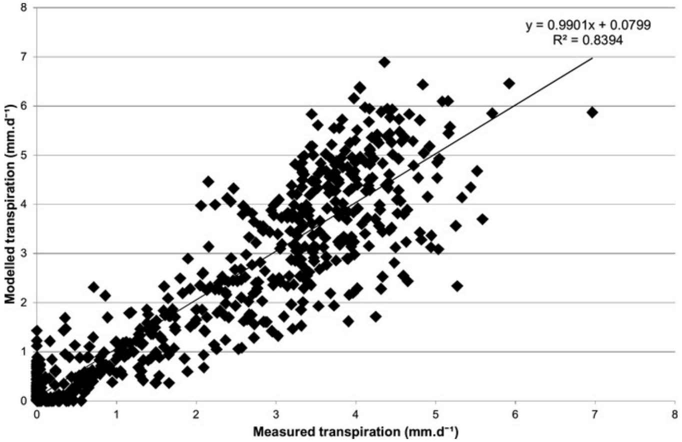

Fig. 6 Validation of the transpiration sub-model using observed daily sap flow data from the orchard.

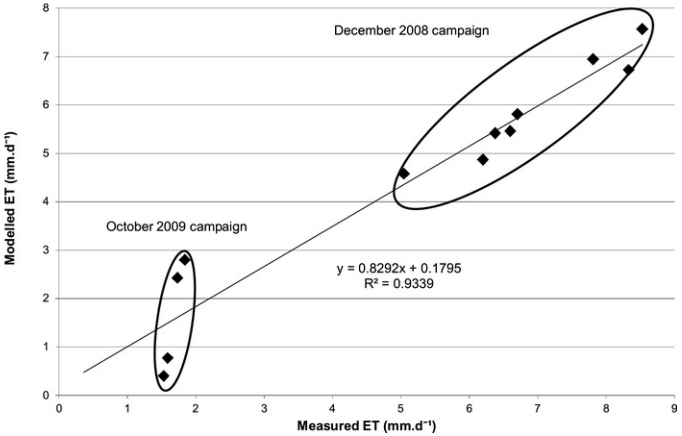

Fig. 7 Validation of the daily apple orchard ET model against observed ET data from December 2008 and October 2009.

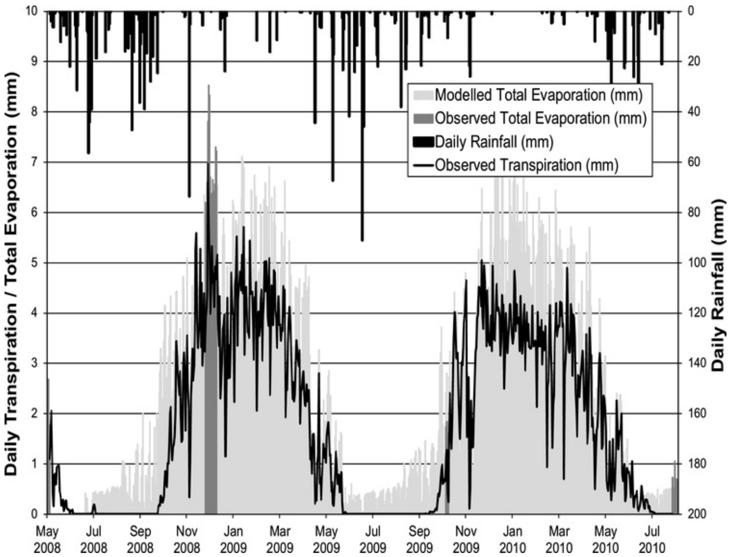

Fig. 8 Relationship between modelled ET using a dual-source model (light grey bars), and continuously observed daily transpiration rates (black line). Corresponding daily rainfall totals, as well as measured daily total evaporation (ET) during 31 sample days (dark grey bars), are also illustrated (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

The annual water balance of the orchard for 2008/2009 (Fig. 9) illustrates the relationship between orchard water ‘gains’ and ‘losses’ over the year. Overall it is evident that total annual water application (irrigation plus rainfall) exceeded total annual ET, but this is to be expected given that rainfall occurred primarily during the winter when the orchard was leafless and dormant. This winter period represented the bulk of the ‘green water’ component of the total WF, particularly as ‘blue water’ irrigation volumes supplied the majority of the water required by the actively growing orchard during the summer months. Growing season water applications were generally well balanced against water losses (particularly T), only deviating somewhat towards the end of the season when trees were dropping leaves and slowing in their T rates, providing opportunity for reduced irrigation applications and potential water savings at this stage.

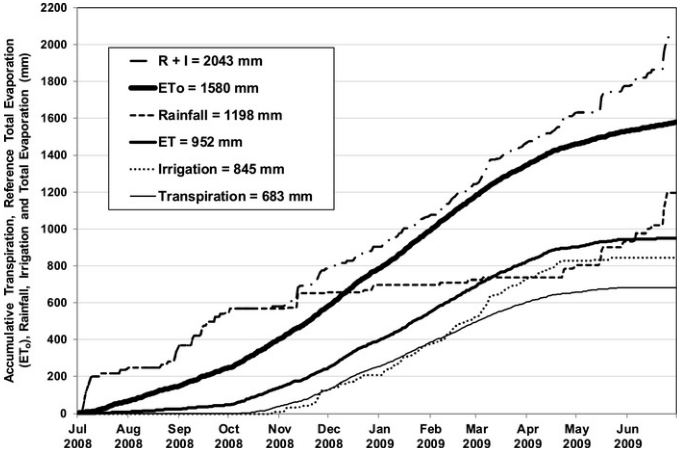

Fig. 9 Cumulative applied water (irrigation, rainfall and irrigation + rainfall), transpiration, total evaporation and reference total evaporation for the 2008/2009 season (July – June 2009).

Crop coefficient results derived for the orchard over the two years were averaged and illustrate the seasonal variation in ET and T within the orchard (Fig. 10). K_{cb} values reflect phenological changes in the trees from winter dormancy (July / August / September, $K_{cb} = 0$), through bud-break (October $K_{cb} = 0.3$) to full bloom ($K_{cb} = 0.5$), followed by fruit set and fruit growth (November $K_{cb} = 0.55$), and corresponding increases in leaf area. Between December and February K_{cb} values are relatively consistent ($K_{cb} \approx 0.6$), followed by increased transpiration in March ($K_{cb} \approx 0.63$) prior to harvest in April and subsequent leaf drop and senescence during May and June ($K_{cb} \approx 0.1$). The significant contribution of inter-row vegetation and wetted soil surface to the overall ET of the orchard is evident from the difference between the K_{cb} and K_c values, particularly in winter (July / August) when trees are leafless (K_{cb} is zero) but there is frequent rainfall and associated evaporation (K_c values of 0.1 – 0.2), as this is a winter rainfall site. Overall, the observed trends in our K_c values correspond very closely with lysimeter-derived K_c values on 10-year old trees, reported by Marsal et al. (2013).

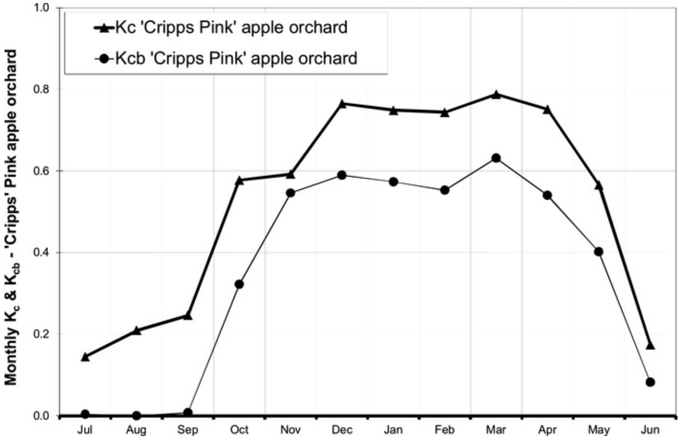

Fig. 10 Monthly basal (K_{cb}) and full (K_c) crop coefficient values determined for the apple orchard (average of the 2008/2009 and 2009/2010seasons).

Monthly crop coefficient (K_c) values for the orchard were partitioned into $K_{c\text{-blue}}$ and $K_{c\text{-green}}$ components (Table 2) based on the average monthly proportions of CWU_{blue} and CWU_{green} observed from the field study data.

Table 2 Monthly fractional partitioning (based on CWU_{blue} and CWU_{green}) of $K_{c\text{-}blue}$ and $K_{c\text{-}green}$ crop coefficients for the apple orchard.

alt-text: Table 2

	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
K_c	0.14	0.21	0.25	0.58	0.59	0.77	0.75	0.74	0.79	0.75	0.57	0.17
$K_{c\text{-}blue}$ fraction	0	0	0	0.21	0.92	1	1	1	1	0.9	0.33	0
$K_{c\text{-}green}$ fraction	1	1	1	0.79	0.08	0	0	0	0	0.1	0.67	1

3.4 Water footprints at farm scale

Observed data from the field measurements over the full production periods (one year each) indicated that the ET of the apple orchard was 9520 $m^3.ha^{-1}$ in 2008/2009 and 9660 $m^3.ha^{-1}$ in 2009/2010. Summing additional water uses associated with orchard and farm management (spraying, pack-house use, evaporation from dams etc.) supplementary water use was calculated to be approximately 380 $m^3.ha^{-1}$. After assessing the volumes of daily orchard ET that could be directly attributed to irrigation applications over the two growing seasons, and adding these to the supplementary water uses, it was found that CWU_{blue} accounted for an average of 8064 $m^3.ha^{-1}$. CWU_{green} (i.e. volumes of daily orchard ET associated with rainfall events) accounted for an average of 1907 $m^3.ha^{-1}$ over the two seasons (Table 3). Combining these water use values with yield data from the orchard resulted in the water footprint of the apples produced at the study site equating to 236.8 $m^3.t^{-1}$ in 2008/2009 and 187.3 $m^3.t^{-1}$ in 2009/2010, giving an average of 212.1 $m^3.t^{-1}$. This comprised 62.7% WFblue (surface and groundwater), 14.9% WF_{green} (rainwater) and 22.5% WF_{grey} (polluted water). Based on the above yield and water footprint results, crop water productivity figures for the orchard averaged at 4.72 $kg.m^{-3}$.

Table 3 Observed water footprint and water productivity results for ‘Cripps’ Pink’ apples over two growing seasons.

	2008/2009	2009/2010	Average
Crop Yield ($t.ha^{-1}$)	54.0	69.0	61.5
CWU_{blue} ($m^3.ha^{-1}$)	7941.9	8186.7	8064.3
CWU_{green} ($m^3.ha^{-1}$)	1961.6	1853.2	1907.4
WF_{blue} ($m^3.t^{-1}$)	147.1	118.6	132.9
WF_{green} ($m^3.t^{-1}$)	36.3	26.9	31.6
WF_{grey} ($m^3.t^{-1}$)	53.4	41.8	47.6
Total WF ($m^3.t^{-1}$)	**236.8**	**187.3**	**212.1**
Crop water productivity ($kg.m^{-3}$)	**4.22**	**5.34**	**4.72**

Orchard yield was 54 $t.ha^{-1}$ in 2008/2009 and 69 $t.ha^{-1}$ in 2009/2010, and relative to orchard tree density, this translated to fruit production of 27 $kg.tree^{-1}$ in 2008/09 and 34 $kg.tree^{-1}$ in 2009/10. Using an average fruit mass of 160 g per apple in 2008/2009 and 158 g per apple in 2009/2010, annual CWU volumes yielded a requirement of 38 l of water per apple (237 $m^3.t^{-1}$) produced in 2008/09 and 30 l of water per apple (187 $m^3.t^{-1}$) produced in 2009/10. Mekonnen and Hoekstra (2011) report that as a global average, 125 l of water is required to produce a single 150 g apple (822 $m^3.t^{-1}$). Our study showed a substantially lower estimate which could either be attributed to higher production figures observed in our study (relative to those used by Mekonnen and Hoekstra, 2011), or lower water use, or both. As our study used field-based observations and verified modelled estimates of actual orchard ET in the WF calculations, it is possible that our water use values were lower than those used by Mekonnen and Hoekstra (2011). However differences between the studies are more clearly attributable to the substantial yield differences between our study (54–69 $t.ha^{-1}$) and their study (11 $t.ha^{-1}$), possibly as this value was for a global average, including low / marginal production zones. Nevertheless, similarly low values of 8.9 $t.ha^{-1}$ and 15.9 $t.ha^{-1}$ were given by Mekonnen and Hoekstra (2011) for average rainfed and irrigated regions respectively, giving rise to substantially higher WF estimates. A further difference is in the relative proportions of the WF components. Unlike the Mekonnen and Hoekstra (2011) findings, our study indicated that the major proportion of the WF of apples constituted WFblue, largely due to the high dependence on irrigation during the summer months of the growing season in this Mediterranean area, where rainfall is minimal but ET rates are at their maximum. The WF$_{green}$ component dominates the rainy winter months, however, its relative proportion is lower as the apple trees are largely dormant (leafless) and ET rates are at their lowest during this period. It is also worth noting the annual variation in results over the two growing seasons. Crop water use volumes were similar for both years, resulting in consistent proportions of WF$_{blue}$, WF$_{green}$ and WF$_{grey}$ over both seasons. However, the more pronounced differences in annual yield between years (alternate bearing tendencies) had a disproportionately greater influence on the total WF and WP estimates, with higher yields resulting in lower WF values and higher WP values.

3.5 Water footprint at watershed scale

For all the QCs of the Olifants / Doorn WMA where apples are cultivated (14 in total) the average total water footprint (WF) for this crop was 228.4 m^3.t^{-1} (Table 4). Of this, WF$_{blue}$ accounted for 65.2% (149 m^3.t^{-1}), WF$_{green}$ for 13.9% (31.8 m^3.t^{-1}) and WF$_{grey}$ for 20.8% (47.6 m^3.t^{-1}). WF values across the WMA ranged from 198.9 m^3.t^{-1} to 268 m^3.t^{-1}. Equivalent crop water productivity ranged from 3.73 kg.m^{-3} to 5.03 kg.m^{-3}, with an average of 4.4 kg.m^{-3}. Based on crop coefficients derived from the field study described here, QC-specific ET$_o$ data and the latest available figures on apple orchard area per QC, the associated water (blue, green and grey) required to sustain this industry across the WMA as a whole was estimated at approximately 57.3 million m^3.yr^{-1}. Of this, 37 million m^3.yr^{-1} (64.5%) represents the irrigation water required by the industry.

Table 4 Water footprint and water productivity estimates for ‘Cripps’ Pink’ apples in all the QCs of the Olifants / Doorn WMA where this crop is cultivated.

QC	Blue WU (m^3)	Green WU (m^3)	Grey WU (m^3)	Total WU (m^3)	Blue WF (m^3.t^{-1})	Green WF (m^3.t^{-1})	Grey WF (m^3.t^{-1})	Total WF (m^3.t^{-1})	WP (kg.m^{-3})
E10A	5413172.7	1186059.4	2076844.0	**8676076.1**	124.1	27.2	47.6	**198.9**	5.0
E10B	4257190.0	892291.0	1427592.5	**6577073.5**	141.9	29.8	47.6	**219.3**	4.6
E10C	186173.3	39519.7	58422.5	**284115.4**	151.7	32.2	47.6	**231.5**	4.3
E21A	5145420.4	1106462.4	1855541.2	**8107423.9**	132.0	28.4	47.6	**208.0**	4.8
E21B	855345.0	180364.6	301114.6	**1336824.2**	135.2	28.5	47.6	**211.3**	4.7
E21C	537347.9	112914.4	176043.1	**826305.4**	145.3	30.5	47.6	**223.4**	4.5
E21D	8172512.5	1720839.9	2717014.1	**12610366.4**	143.2	30.1	47.6	**220.9**	4.5
E21E	187.7	39.6	59.7	**287.0**	149.7	31.5	47.6	**228.9**	4.4
E21F	81926.5	17443.0	25447.1	**124816.6**	153.2	32.6	47.6	**233.5**	4.3
E21G	10374399.1	2168625.6	3264385.7	**15807410.4**	151.3	31.6	47.6	**230.5**	4.3
E21H	1284426.8	272332.4	433627.7	**1990386.8**	141.0	29.9	47.6	**218.5**	4.6
E22C	617711.6	131752.0	183996.6	**933460.3**	159.8	34.1	47.6	**241.5**	4.1
G30B	925.7	202.5	243.6	**1371.8**	180.9	39.6	47.6	**268.0**	3.7
G30D	30931.3	6790.8	8343.0	**46065.2**	176.5	38.7	47.6	**262.8**	3.8
Total	**36957670.5**	**7835637.2**	**12528675.4**	**57321983.1**					
Average					**149.0**	**31.8**	**47.6**	**228.4**	**4.4**
%	**64.5%**	**13.7%**	**21.9%**	**100.0%**	**65.2%**	**13.9%**	**20.8%**	**100.0%**	

It should be borne in mind that the results generated using this scaling-up approach assume consistency between the conditions under which the field-scale crop coeffients used were generated, and the conditions of the watersheds to which they were subsequently applied. This would assume comparative soils, rainfall amounts and distribution, irrigation methods and scheduling, and orchard architecture (age, pruning, spacing) for example. Whilst this proviso clearly has shortcomings in terms of representing spatial heterogeneity of growing conditions across the wider study area, the method is nevertheless grounded on actual field observations of the water use, yield and water footprint of a “typical” apple orchard. Considering the paucity of relevant field observations, and limitations of modelling approaches, the method is proposed as a pragmatic approach (with simple data requirements) for assessing the water resources impacts or requirements of a particular product over a larger spatial scale.

4 Conclusions

Water availability and climate-related issues are some of the greatest crop production risks to irrigated agriculture as a whole. Deciduous fruit produced in Mediterranean regions is highly dependent upon irrigation, so the industry is one of the major water users, yet it is facing increased competition for water. As competition for water heightens, so does the need to improve the efficiency with which water is utilised. Consequently, studies aimed at increasing the efficiency or productivity of water use, such as through improved quantification and qualification of crop water use and resultant water footprints, have merit. This study has attempted to highlight that observations on volumes of water actually used by a particular crop will greatly improve the accuracy of water footprint calculations for products of that crop. Detailed field measurements are necessary for more realistic subsequent calculations of watershed WFs. The particular scale at which the assessment is done (farm or watershed) consequently has the potential to facilitate both on-farm water management planning and irrigation scheduling, as well as crop-specific water use allocation guidelines and sustainability improvements within watersheds. Potential applications of the latter include the provision of data for water stewardship (Alliance for Water Stewardship, 2012) and / or Global Gap assessments, or even future water-use related certification schemes. South Africa's National Water Resources Strategy (NWRS-2, 2013), calls for substantial water savings in agriculture and has the implementation of water-use efficiency (water productivity) measures as one of its core strategies. Research on the water use of irrigated fruit tree orchards is one means of facilitating more efficient and productive use of water within the sector. Benefits include more sustainable water use and reduced operating costs on farms, specifically savings from lower electricity usage as a result of reduced pumping of irrigation water. However, in order to add value to the detailed field data, so that it may have wider scale impact, realtively simple methods of upscaling to watersheds are required.

The deciduous fruit industry in South Africa is a significant contributor to the Gross Domestic Product of the country, with increasing levels of income generation and job creation. However, in order to grow in a sustainable manner, and in parallel to numerous other competing water users, water requirements for the industry need to be carefully considered, allocated and utilised in the most efficient ways possible. The importance of accurate observations of actual orchard water requirements is critical in this regard, not only for improved on-farm irrigation scheduling accuracy, but also for local and regional water resource planning and allocation. This study has illustrated the differences between so-called “transpirational” and “evaporational” water requirements at orchard scale (Gerbens-Leenes and Nonhebel, 2004; Cammalleri et al., 2013), and in so-doing has highlighted the beneficial (T) and non-beneficial (ET minus T) components of orchard water use (after Perry, 2007). The provision of T and ET data for fruit trees and orchards, that is as accurate as possible, will facilitate more efficient water use. Furthermore, the incorporation of this data into water footprint and water productivity assessments, as illustrated in this study for example, will provide more accurate information on the true water use associated with the production of a particular product.

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Highlights

- 2 Years of sap flow and total evaporation data from apple trees are presented
- Water use, irrigation and yield data are used to determine apple water footprints.
- Novel partitioning of K_c values into ‘blue’ and ‘green’ WF components.

- Field data substantially improves accuracy of WF calculations & facilitates extrapolation.
- Results show a water footprint of 187~~-~~–237 m^3 per tonne of apples produced.