Total evaporation estimates from a Renosterveld and dryland wheat/fallow surface at the Voëlvlei Nature Reserve (South Africa)

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Abstract

Accurate quantification of the water balance, in particular evapotranspiration, is fundamental in managing water resources, especially in semi-arid areas. The objective of this study was to compare evaporation from endemic vegetation – Renosterveld – and a dryland wheat/fallow cropping system. The study was carried out in the mid-reaches of the Berg River catchment (South Africa), characterised by dryland salinity. Measurements of total evaporation from these 2 land uses were carried out with large aperture scintillometers during window periods from 2005 to 2007. Total evaporation was measured to be higher in Renosterveld than in wheat during the rainy winter season. In the dry summer season, total evaporation from Renosterveld was limited by soil water supply, and vegetation was under water stress. Spatial variability of total evaporation from both wheat/fallow land and Renosterveld was estimated using the Surface Energy Balance Algorithm for Land (SEBAL) model for 3 climatically different years. The scintillometer measurements were used to determine basal crop coefficients for long-term (20 years) simulations with the HYDRUS-1D model to assess temporal variability in total evaporation. Long-term simulations indicated that well-established, deep-rooted Renosterveld uses 39% more water than the shallow-rooted wheat/fallow system. A change in land use from Renosterveld to dryland annual crops could therefore affect the soil water balance, cause shallow saline groundwater tables and degradation of soil and water resources.

Keywords: evapotranspiration; large aperture scintillometer; Renosterveld; soil water balance; Surface Energy Balance Algorithm for Land (SEBAL); wheat/fallow system

Introduction

Accurate quantification of the water cycle is a fundamental problem in hydrology and water management (Everson, 2001). Amongst the water balance components (Poncea and Shetty, 1995), evaporation from the Earth's surface and vegetation is often the most difficult to measure or estimate. This is particularly important in arid and semi-arid areas where annual rainfall is far below potential evaporation. One such area is the Berg River catchment, an important water supply system for the Western Cape Province of South Africa, where a variety of water users occur (population, industry, agriculture, ecology of the river system).

The source of the Berg River is in the Franschhoek and Jonkershoek mountains. The river flows in a north-westerly direction, eventually discharging into the sea at Velddrif (Fig. 1). The Berg River is approximately 270 km long and has a catchment size of about 900 km^2 (DWAF, 1993). A large part of the catchment comprises semi-arid wheat lands, which receive most of their rain during the winter months (450 mm·a^{-1} on average, mainly from May to October). The geology of the Berg River basin is dominated by the Malmesbury Group shales (western banks) and the Table Mountain Group sandstones (eastern banks). The Malmesbury Group is a Proterozoic marine deposit comprising greywacke and phyllite beds, with beds and lenses of quartz schist, limestone and grit. In previous work, salinisation of the Berg River was attributed to the salt load originating from tributaries draining Malmesbury-shale derived soils (Fourie, 1976). In a cycle of projects funded by the Water Research Commission (Fey and De Clercq, 2004; Gorgens and De Clercq, 2005; De Clercq et al., 2010), it was also found that changes in land use from indigenous, endemic vegetation, i.e. Renosterveld, to extensive pastoral use and dryland wheat farming over the last century or more may have changed the water balance and enhanced the mobilisation of naturally-occurring salts (originated from oceanic deposition through the ages) and salinisation of the Berg River.

Similar occurrences of dryland salinity are widespread throughout semi-arid regions of the world. In Australia, it was proven that clearing of natural perennial scrubland to make way for cultivated crops and pastures resulted in changes in the water balance, rising water tables and mobilisation of fossil connate salts (Greiner, 1998; Stirzaker et al., 1999; Angus et al., 2001; Clarke et al., 2002). Allison et al. (1990) reported that clearing of native vegetation in the western Murray basin of Australia led to increase in groundwater recharge, shallow groundwater tables and increase in salinity of the Murray River. Walker et al. (1999) elaborated on the effectiveness of current farming systems in the control of dryland salinity. Any changes in land use and water balance may cause shallow saline water tables and mobilisation of salinity. It is therefore essential to quantify the soil water balance and, specifically, evaporation from predominant land uses.

In this study, evaporation was estimated from a wheat/fallow land rotation commonly practiced by farmers in the mid-reaches of the Berg River catchment, and from endemic

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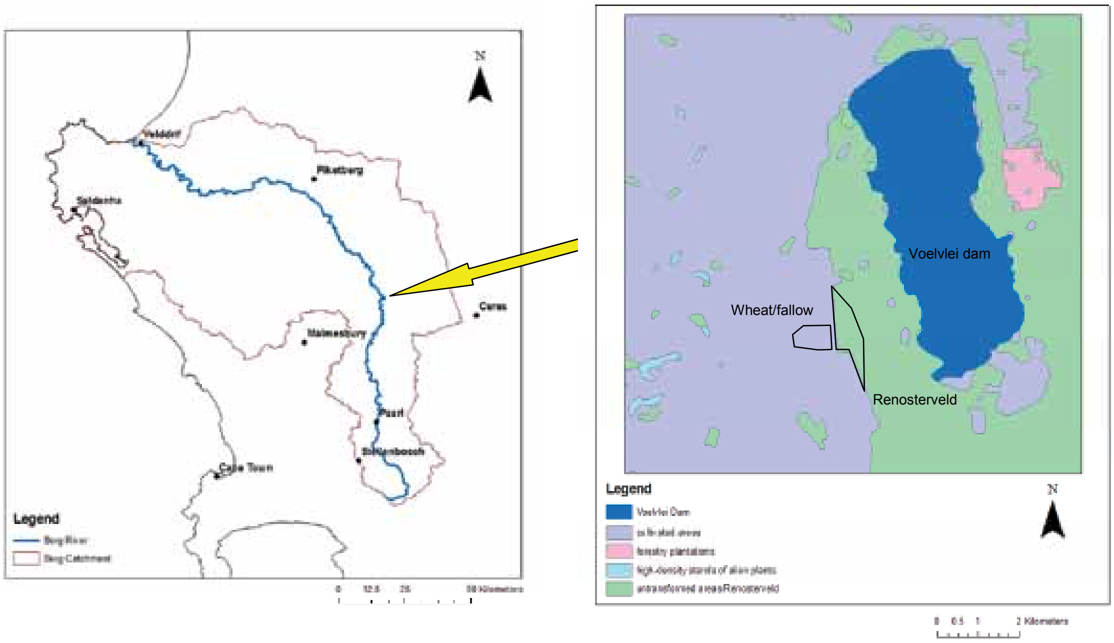

Figure 1
Berg River catchment and location of the evaporation measurement site in the vicinity of the Voëlvlei Dam. The land use map locates the Voëlvlei Nature Reserve and the areas used for scintillometer measurement of total evaporation from Renosterveld and wheat/fallow land

Renosterveld. No measurements of evaporation from Renosterveld have previously been attempted and no information was available on the water use of this vegetation. The hypothesis was that deep-rooted, perennial native vegetation transpiring all year-round produces a different water balance compared to shallow-rooted, annual agricultural plants (e.g. dryland wheat) cropped during the rainy winter season (from May to November) and followed by fallow land in summer. The objective of this paper was to compare evaporation estimates for the 2 different land uses as well as spatial and temporal variabilities in water use.

Material and methods

Estimation of spatially-averaged total evaporation: Scintillometry

The study was done in the mid-reach of the Berg River catchment and in the vicinity of the Voëlvlei Dam (Fig. 1). Total evaporation (ET) was measured from a dryland wheat field and from an area under Renosterveld. Total evaporation can be defined as the total process of water movement into the atmosphere. Soil evaporation (E) and transpiration (T) occur simultaneously and are determined by the atmospheric evaporative demand (available energy and water vapour pressure deficit), soil (soil water availability) and canopy characteristics (canopy resistances) (Rosenberg et al., 1983). Total evaporation is also referred to as evapotranspiration (Kite and Droogers, 2000). In this study, total evaporation refers to the sum of evaporation from the soil surface, transpiration by vegetation, and evaporation of water intercepted by vegetation, as estimated with large aperture scintillometers (Jarmain et al., 2009).

Two large aperture scintillometer (LAS) systems were used to estimate total evaporation from a Renosterveld and a dryland wheat surface: a Micromet Scientific large aperture scintillometer system, with a Fresnel lens; and a Scintec boundary layer scintillometer (BLS900). Measurements were made during selected window periods (representative of different seasons) from August 2005 to September 2007. Table 1 provides information on the different field campaigns and the way the equipment was used. During the field campaign at the Renosterveld site in August and September 2005, the Micromet LAS was used. For the remaining field campaigns at the Renosterveld site, the Scintec boundary layer scintillometer was used. Total evaporation was estimated at the wheat field with the Micromet LAS.

The LAS systems measure the path-averaged structure parameter of the refractive index of air (C_N^2) over a horizontal path. Measurements of C_N^2, together with standard meteorological observations (air temperature, wind speed and air pressure) collected with an automatic weather station, are used to derive the sensible heat flux density (H). The latent heat flux density (LE and hence total evaporation) is subsequently calculated using the simplified energy balance:

$$LE = Rn - H - G \tag{1}$$

where:
Rn is net irradiance (Rn)
G is the soil heat flux density (all terms are in W·m^{-2})

In this study, Rn was measured with a net radiometer and G with soil heat flux plates. The LAS systems determine C_N^2 and total evaporation over distances of 400 m to 5 km. Estimates of total evaporation are spatially averaged over the area between the transmitter and receiver sensors. The energy balance theory and methods for measurement of ET have been discussed extensively by Savage et al. (2004) and Jarmain et al. (2009).

An extensive stand of mature Renosterveld (> 30 years in age), situated in the Voëlvlei Nature Reserve (33.396083°S, 19.024833°E) (Fig. 1), was selected for this study. The altitude over the research area ranges between 70 and 79 m, with a mean slope of less than 1%. Renosterveld vegetation was relatively uniform in density and covered the soil by about 80%. The average height of the vegetation throughout the study was 0.9 m (Table 1). A wheat field adjacent to the Renosterveld site was selected for this study (Fig. 1). Altitude and slope were very similar to those at the Renosterveld site. Winter wheat is usually planted in May in this area and harvesting is in November. The land is left fallow in the dry summer season.

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Table 1
Total evaporation measurement periods, scintillometry systems used and vegetation description for Renosterveld and dryland wheat

Measurement period	2 August to 8 September 2005	31 January to 22 February 2007	13 to 17 June 2007	19 to 30 September 2007
Vegetation	Renosterveld	Renosterveld	Renosterveld	Mature wheat (complete canopy cover)
Scintillometry system	Micromet LAS	BLS900	BLS900	Micromet LAS
Installation (effective) height (m)	2.47	2.47	2.47	3.20
Path length (m)	610	610	610	640
Vegetation height (m)	0.9	0.9	0.9	1
Other measurements	Net irradiance, soil heat flux, rainfall, temperature, humidity, wind speed and direction, solar radiation	Net irradiance, soil heat flux, rainfall, temperature, humidity, wind speed and direction, solar radiation, temperature gradient		Net irradiance, soil heat flux, rainfall, temperature, humidity, wind speed and direction, solar radiation

During the September 2007 field campaign, the wheat had matured and covered the soil 100%, and was about 1 m tall (Table 1).

A full automatic weather station was installed in the vicinity of the scintillometer measurement sites in open field. All weather data and components of the energy balance were recorded at 10 min time intervals. As it was not possible to measure *ET* of Renosterveld and wheat simultaneously for comparative purposes, the *ET* measurements were normalised for atmospheric conditions by dividing daily measured *ET* with the reference evapotranspiration calculated with the Penman-Monteith equation (*ETo*) (Allen et al., 1998). The ratio *ET*/*ETo* yields *Kc*, which is commonly known as the crop coefficient, because the methodology is mainly used to predict crop water requirements (Allen et al., 1998). The soil at the experimental site is a 0.5 m deep sandy loam overlying semi-weathered Malmesbury shale. Volumetric soil water content at field capacity is 26.8% and 14.5% at permanent wilting point, based on soil physical analyses and measurements of soil water content (De Clercq et al., 2010).

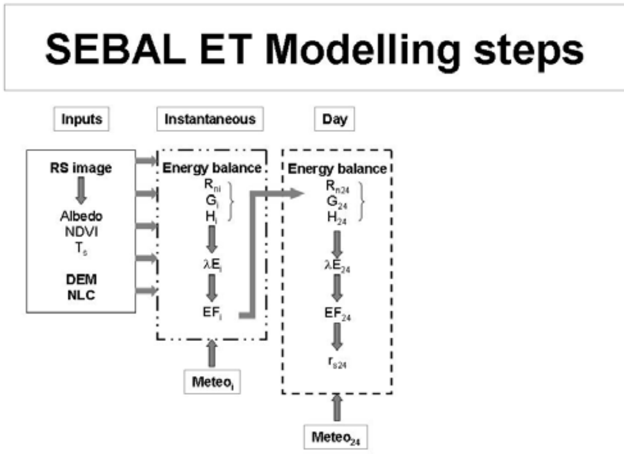

Figure 2
A summary of the SEBAL modelling steps performed to estimate daily total evaporation. RS image refers to the satellite images used, whether Landsat or MODIS. NDVI refers to the Normalised Difference Vegetation Index, T_s to the surface temperature, DEM to the digital elevation map and NLC to the National Land Cover. In the energy balance calculations, R_n, G, H and λE are net irradiance, soil heat flux density, sensible heat flux density and latent energy flux densities, EF is the evaporative fractation, with EF_i referring to instantaneous estimates and EF_{24} to daily estimates. r_s is the surface resistance and Meteo are the meteorological data required in the modelling

Modelling total evaporation spatially: Surface Energy Balance Algorithm for Land (SEBAL) model

Algorithms and methods making use of remotely-sensed satellite images are becoming powerful tools to estimate total evaporation spatially over wide areas. Examples of such tools are the Surface Energy Balance System (SEBS) (Su, 2002; Gibson et al., 2010), the METRIC (Mapping EvapoTranspiration at high Resolution with Internalized Calibration) (Allen et al., 2007) or the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998a; 1998b). In our study, total evaporation of Renosterveld and a wheat/fallow surface estimated using scintillometers over short periods was extended both in space and time, using data sets generated in 2 separate studies (Klaasse et al., 2008; Meijninger and Jarmain, 2010) where SEBAL was applied.

The SEBAL model uses the simplified energy balance to estimate total evaporation, biomass production, water deficit and soil moisture, spatially. Land surface characteristics used in the SEBAL modelling, such as broad band surface albedo, the normalised difference vegetation index (NDVI) and surface temperature, are derived from satellite imagery and combined with spatially-representative meteorological data (wind speed, humidity, solar radiation and air temperature), a digital elevation map (DEM) and a land cover map, to provide estimates of total evaporation spatially (Fig. 2).

Klaasse et al. (2008) used 20 Landsat 7-ETM images to estimate the seasonal grape water use (September to April) for table and wine grapes produced in the winelands of the Western Cape of South Africa. These satellite data were combined with meteorological data from 189 mainly automatic weather stations, which were spatially extrapolated using Meteolook (Voogt, 2006), a digital elevation map (DEM), and a land cover map, which were generated using 2 ASTER images. Monthly and seasonal grape water use was estimated for 3 seasons (2004/05, 2005/06 and 2006/07), at a spatial resolution of 30 m. These evaporation maps overlap with the Voëlvlei study area (Fig. 1) and were used to illustrate differences in total evaporation between Renosterveld and cultivated areas, for months when fields were predominantly fallow.

Meijninger and Jarmain (2010) used 70 Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images to estimate the total evaporation for 3 climatically different years

(2000/01, 2002/03 and 2006/07) for the entire Western Cape Province of South Africa. In this study, a year extended over the period from 1 July to 30 June. Winter wheat was cropped in all 3 years (May to November), followed by fallow land (November to April). Total evaporation was estimated at a spatial resolution of 250 m. These total evaporation data sets were used to illustrate differences in the annual total evaporation of Renosterveld and adjacent wheat/fallow land, which are in close proximity to the Voëlvlei Dam (Fig. 1).

Long-term modelling of the soil water balance: HYDRUS-1D

Measurements of total evaporation with scintillometry were made to determine the effects of different land uses (Renosterveld to wheat) on *ET*, and hence the hydrological water balance, over short window periods. Information from field measurements obtained during these window periods was used to estimate the long-term water balance (20 years) with the HYDRUS-1D v. 4.0 model (Simunek et al., 2009).

HYDRUS-1D is a 1-dimensional water flux, heat and solute transport model for variably-saturated soil conditions. It uses Richards' equation for simulating variably-saturated flow and a Fickian-based advection-dispersion equation for heat and solute transport. In this study, only water flow was considered. The water flow equation incorporates a sink term to account for water uptake by plant roots (Feddes et al., 1978). Potential transpiration and soil evaporation are inputs (time variable atmospheric boundary conditions). HYDRUS-1D v. 4.0 can be used to predict water flows in the vadose zone between the soil surface and the groundwater table.

The graphical user interface includes data pre-processing and presentation of output results. The pre-processing stage is used to specify inputs, to discretize the soil profile into finite elements and to define vertical distribution of hydraulic parameters and root system. The output results are displayed in graphical format and written to output files at user-specified time intervals. The graphical user interface, written in C^{++} using the Microsoft Visual C/C^{++} compiler, operates in Windows 95, 98, 2000, NT, XP and Vista environments. The Hydrus-1D software package was downloaded from www.hydrus2d.com, accessed on 4 January 2010.

Results

Estimation of spatially-averaged total evaporation: Scintillometry

Total evaporation was calculated from Eq. (1) by integrating 10 min interval measurements of *H*, *Rn* and *G*. Estimates of total evaporation from Renosterveld on sunny days were conservative and generally ranged between about 1 mm·d^{-1} and 5 mm·d^{-1} during the measurement periods (Figs. 3a and 3b). Maximum daily *ET*'s were measured in spring (September 2005) and summer (February 2007) following rainfall. *ET*'s generally increased following rainfall (Fig. 3a) and as solar irradiance values (*Rs*) increased (Fig. 3b). In summer, the vapour pressure deficits (VPD) increased up to 2.8 kPa, which were higher than those in winter (August 2005) and early spring (September 2005). The increase and decrease in *ET*'s in summer (February 2007) followed changes in VPD more closely than in spring (September 2005) (Fig. 3b). In late winter 2005 and spring 2005, the Renosterveld *ET*'s consistently exceeded the reference evapotranspiration (*ETo*) values (Fig. 3a). However, in summer (February 2007) the *ET*'s were significantly lower than the reference evapotranspiration (*ETo*). In early winter (June 2007), at the beginning of the rainfall season, *ET*'s and *ETo*'s were very similar (Fig. 3a).

Crop coefficients (*Kc*) are used to account for specific vegetation and relate its *ET* to *ETo.* For Renosterveld, *Kc*'s exceeded 1 in late winter and spring (August and September 2005) and were as high as 2.4 (Fig. 3c). The high *Kc*'s may be because the *ET*'s estimated with the scintillometers include evaporation of any water intercepted by the canopy. After drying of the canopy, *Kc* values stabilised at around 1.5 (average *Kc* = 1.49, straight line in Fig. 3c). The *Kc* value of 1.49 was therefore obtained taking into account predominantly sunny days with high *Rs* (Fig. 3b). On days when rainfall occurred (Fig. 3a), *Rs* was generally low (Fig. 3b) and unrealistically high *Kc*'s were calculated (Fig. 3c) as measured total evaporation included water evaporating from the wet canopy. These days were omitted from the

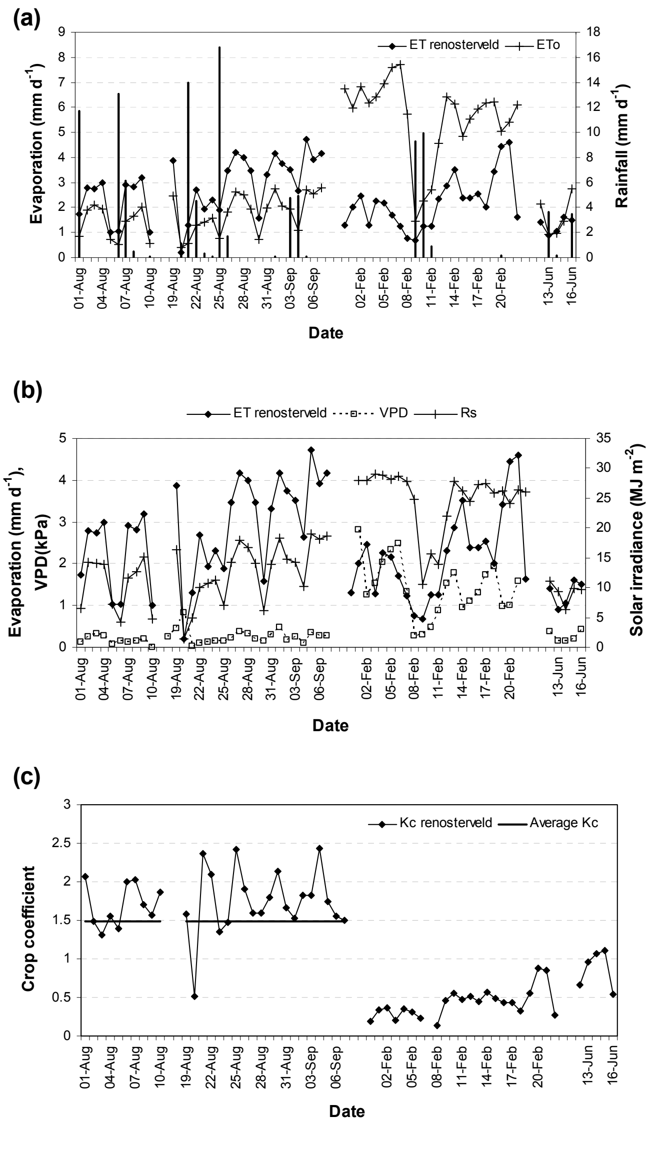

Figure 3

Total evaporation from a Renosterveld surface for selected window periods, representative of different seasons, over the period from August 2005 to June 2007: (a) Daily total evaporation (ET Renosterveld), grass reference evapotranspiration (ETo) and rainfall (bars); (b) Daily total evaporation (ET Renosterveld), vapour pressure deficit (VPD) and solar irradiance (Rs); and (c) Crop coefficients for Renosterveld (Kc Renosterveld)

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calculation of average *Kc*. In the dry summer season (February 2007), the vegetation was subject to water stress for most of the measuring period due to prolonged drought conditions and *Kc*'s ranged between 0.13 and 0.88 (Fig. 3c). Crop coefficients estimated for early winter (June 2007) were much lower than those for late winter (August 2005) and ranged between 0.55 and 1.11 (Fig. 3c). The highest *Kc* of 1.11 in June 2007 was calculated following rainfall. It should be noted that the weather station from where *ETo* was derived was installed in the same field in the vicinity of the scintillometer measurement site, and was not surrounded by well-watered grass.

Figure 4 shows the components of the energy balance for the Renosterveld canopy in winter 2005. Data refer to daytime instantaneous records taken every 10 min from approximately 7:00 to 19:00. It is evident that a large portion of the energy available (*Rn*) was used for evaporation (*LE*). The ratio *H*/*LE* was 0.25 for the period of measurement indicating that soil water supply conditions were favourable and the Renosterveld canopy was meeting atmospheric evaporative demand, nearly in full. Soil heat flux (*G*) was a negligible component of the energy balance during the period of measurement (1% of *Rn*). Negative *LE* values (condensation) were calculated, especially in the late afternoon hours, on some days. During the dry summer season (measurement campaign from 31 January to 22 February 2007), *H*/*LE* was 0.85, indicating that water stress conditions occurred due to limited soil water supply and G was 2% of *Rn*. During the autumn measurement campaign from 13 to 17 June 2007, the Renosterveld evaporation was meeting, almost entirely, the atmospheric evaporative demand (*H*/*LE* = 0.33), and *G* was 6% of *Rn*.

Evapotranspiration measured from a wheat field in spring (September 2007) ranged between 1.8 and 5.2 mm·d^{-1} (Figs. 5a and 5b). *ET* and *ETo* values were very similar, with *ETo*'s ranging between 1.8 mm·d^{-1} (on a cloudy/rainy day) and 5.1 mm·d^{-1} (on a sunny day) (Figs. 5a and 5b). *ET* from the wheat field reflected changes in solar irradiance (*Rs*) (Fig. 5b), suggesting that it was mainly limited by available energy.

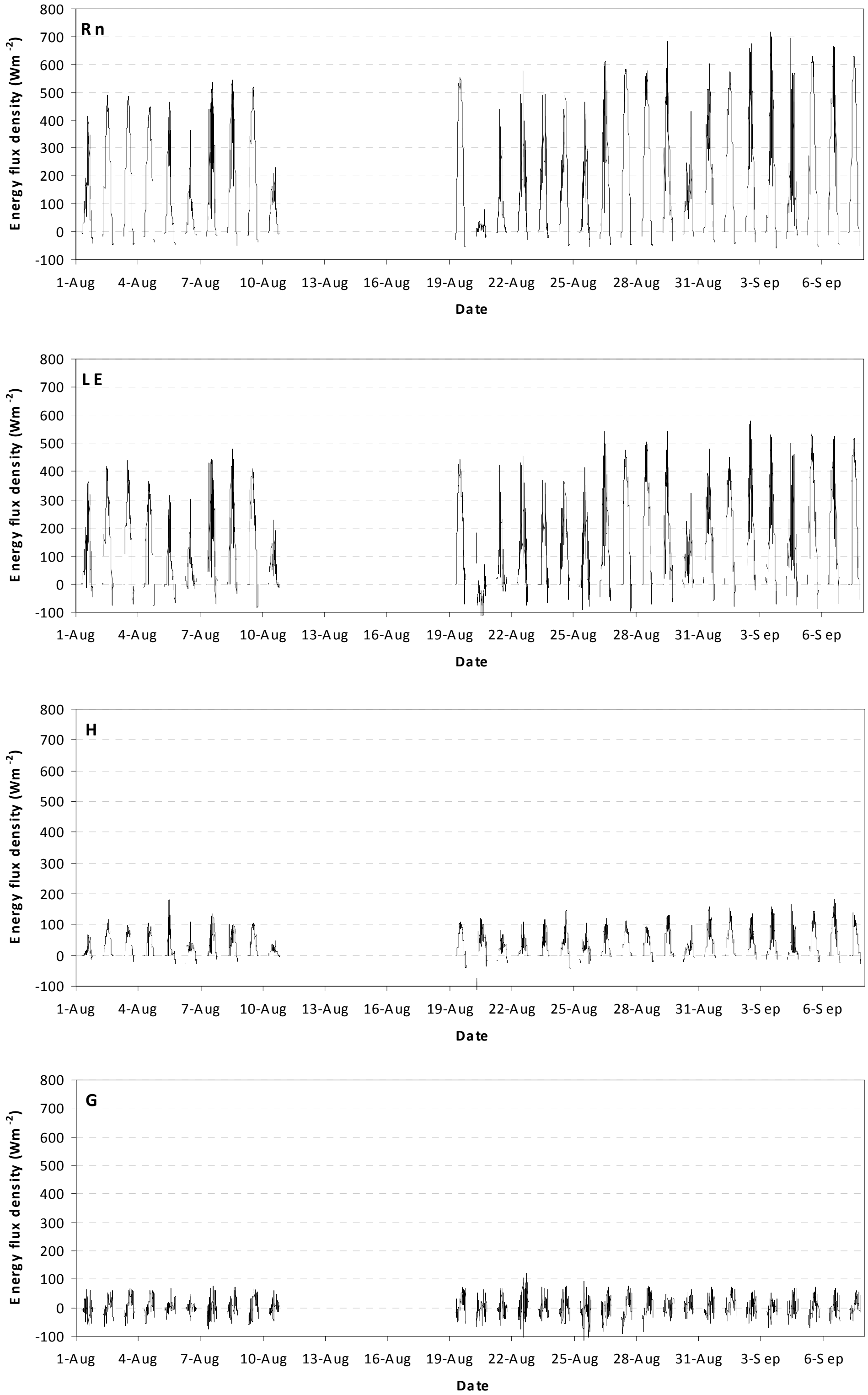

Figure 4
Energy balance components (Rn – Net radiation; LE – Latent heat of vaporization; H – Sensible heat flux; G – Soil heat flux) of a Renosterveld canopy measured every 10 min from 2 August to 8 September 2005

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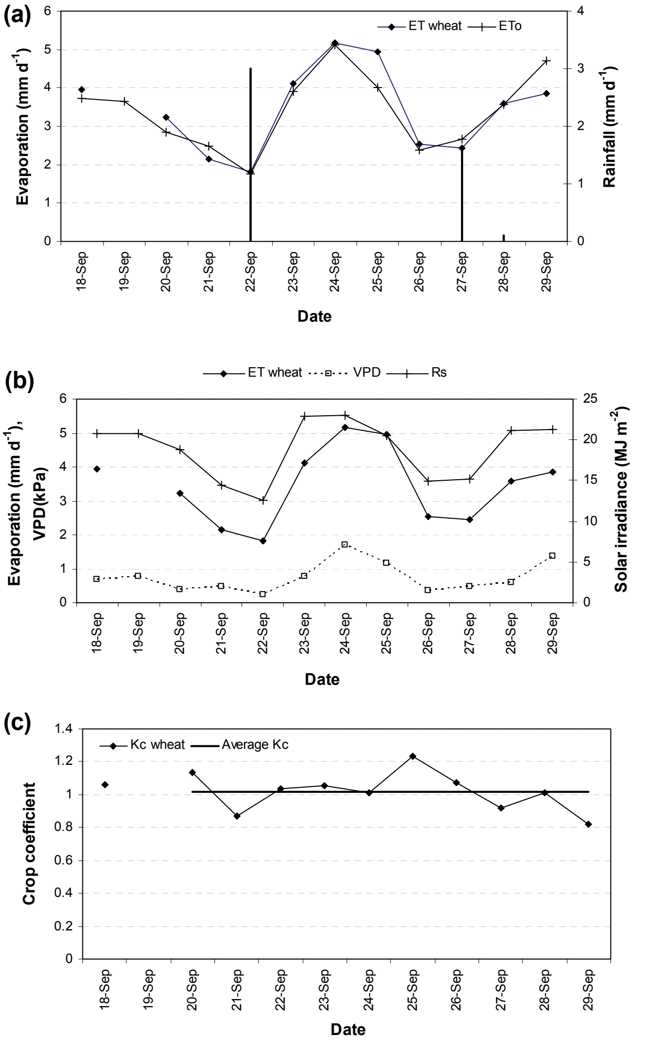

Figure 5
Total evaporation from a wheat field for a window period from 19 to 30 September 2007: (a) Daily total evaporation (ET wheat), grass reference evapotranspiration (ETo) and rainfall (bars); (b) Daily total evaporation (ET wheat), vapour pressure deficit (VPD) and solar irradiance (Rs); and (c) Crop coefficients of wheat at 100% canopy cover

Crop coefficients in spring (September 2007), towards the end of the rainy season, were around 1 (from 0.82 to 1.23) (average Kc = 1.02, straight line in Fig. 5c). The revised FAO methodology (Allen et al., 1998) splits the crop coefficient Kc into a basal coefficient related to transpiration (Kcb) and a soil evaporation component (Ke). If one had to split Kc into a basal and a soil evaporation component ($Kc = Kcb + Ke$) for the wheat field in September 2007, the total contribution to the Kc was from Kcb as the wheat field covered the soil completely at this stage and the soil evaporation contribution was almost negligible. Allen et al. (1998) recommended a Kcb of 1 for wheat during the vegetative stage and full canopy development.

Figure 6 represents the components of the energy balance for a wheat canopy in September 2007. This window period represents the end of the rainy winter season when full canopy cover occurred. A large portion of the energy available (Rn) was used for evaporation (LE). The ratio H/LE was 0.51 for the period of measurement indicating that soil water supply conditions were favourable and that the wheat canopy was meeting the atmospheric evaporative demand almost completely. Soil heat flux (G) was negligible (0.2% of Rn). Negative LE values (condensation) were calculated occasionally in the mornings and afternoons.

Modelling total evaporation spatially: SEBAL

Spatial variations in total evaporation estimated with SEBAL, using both Landsat and MODIS satellite images (Figs. 7 and 8, respectively), are displayed for cultivated land and adjacent Renosterveld. The high resolution of the Landsat satellite images (30 m) clearly distinguishes the cultivated land and the Renosterveld in terms of total evaporation for the period September to April (Fig. 7). The period from September to April represents the time when there are great differences in total evaporation between cultivated land and Renosterveld, since the total evaporation from the cultivated land represents fallow conditions for most of this period, and therefore evaporation from the soil only.

Total evaporation estimated using SEBAL and MODIS images over a 12 month period differed between wheat/fallow land and adjacent Renosterveld indigenous vegetation (Figs. 7 and 8). Annual total evaporation showed distinct spatial differences, and the lower spatial resolution of MODIS images compared to Landsat is reflected in these spatial total evaporation estimates (Fig. 8). Annual estimates of total evaporation for wheat/fallow land over 3 climatically different years were on average 401 mm, or 39% lower than total evaporation from Renosterveld (655 mm, Fig. 9). Total evaporation for 3 climatically different years was similar for wheat/fallow land as well as Renosterveld, with the highest total evaporation estimate from Renosterveld observed during the climatically wettest year (2006/07) (Fig. 9).

Long-term modelling of the soil water balance: HYDRUS-1D

Scenarios were simulated with HYDRUS-1D v. 4.0 to assess differences in the yearly water balance of Renosterveld and dryland wheat/fallow land. The main processes simulated with HYDRUS-1D were water flow and root water uptake on a daily time step. The depths of soil profiles were 2 m for wheat/fallow and 9 m for Renosterveld. A groundwater depth of approximately 9 m was measured in monitoring boreholes in the vicinity of the study site (De Clercq et al., 2010). The lower boundary condition (bottom of the soil profile) was set at a constant pressure value of 0 kPa (groundwater table at 9 m depth) for Renosterveld, and at free drainage for wheat/fallow land. The van Genuchten-Mualem hydraulic model was used; no dual porosity, hysteresis and runoff were considered. Hydraulic parameters for a sandy loam were used, and Feddes root uptake model included in HYDRUS-1D was used with a critical stress index of 1 (Feddes et al., 1978). The time-variable atmospheric boundary condition at the soil surface included daily precipitation, potential evaporation and potential transpiration.

Weather data are the main inputs driving the water flux processes calculated with HYDRUS-1D. Simulations were run from 1 January 1988 to 31 December 2007 using daily maximum and minimum temperatures as well as daily rainfall data obtained from the South African Weather Service for the station in Langgewens (No. 0041347 X). This weather station was the closest to the area of the Voëlvlei Nature Reserve with at least 20 years of historic data. A time series of 20 years was deemed to be long enough to comprise unusually wet and dry years.

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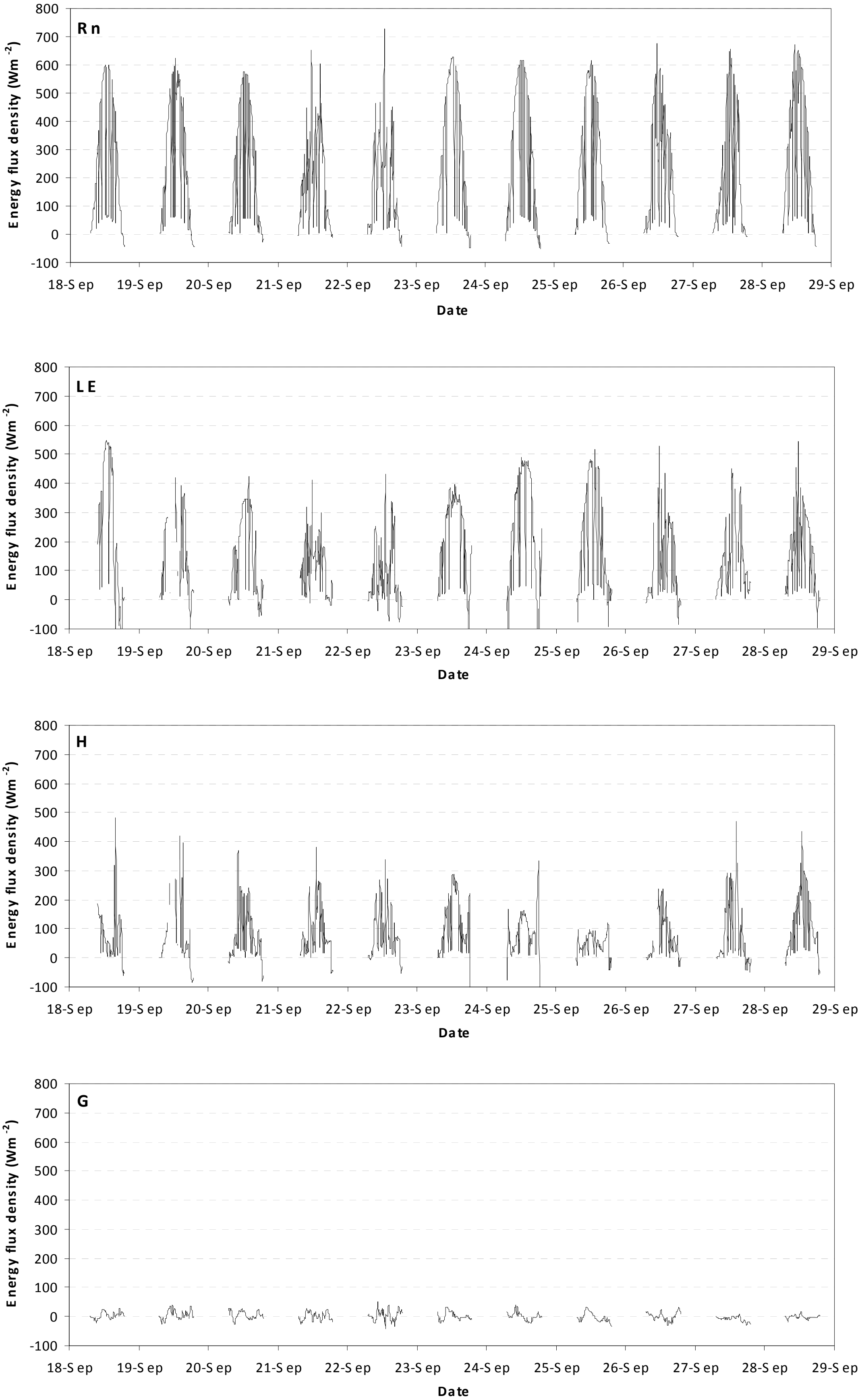

Figure 6
Energy balance components (Rn – Net radiation; LE – Latent heat of vaporisation; H – Sensible heat flux; G – Soil heat flux) of a mature wheat canopy measured every 10 min from 19 to 30 September 2007

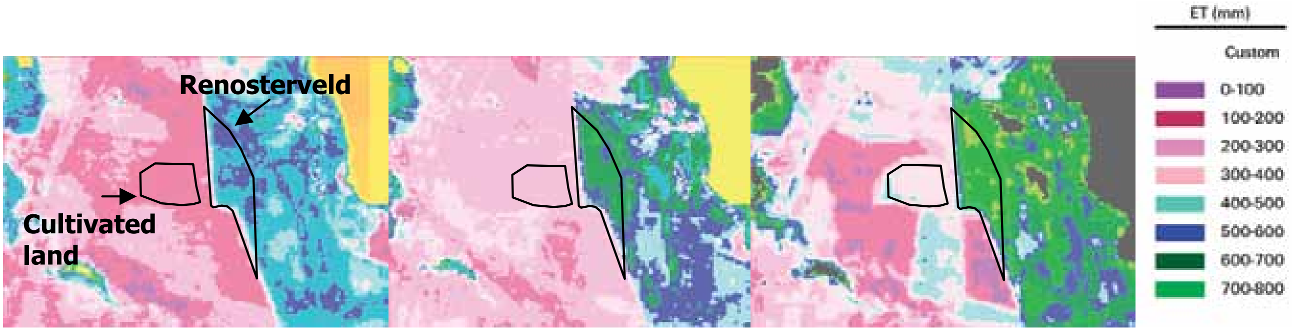

Figure 7
Spatial maps of total evaporation estimated for the Voëlvlei area using the SEBAL model with Landsat images for the period September to April for 3 climatically different years: 2004/05 (left), 2005/06 (middle) and 2006/07 (right)

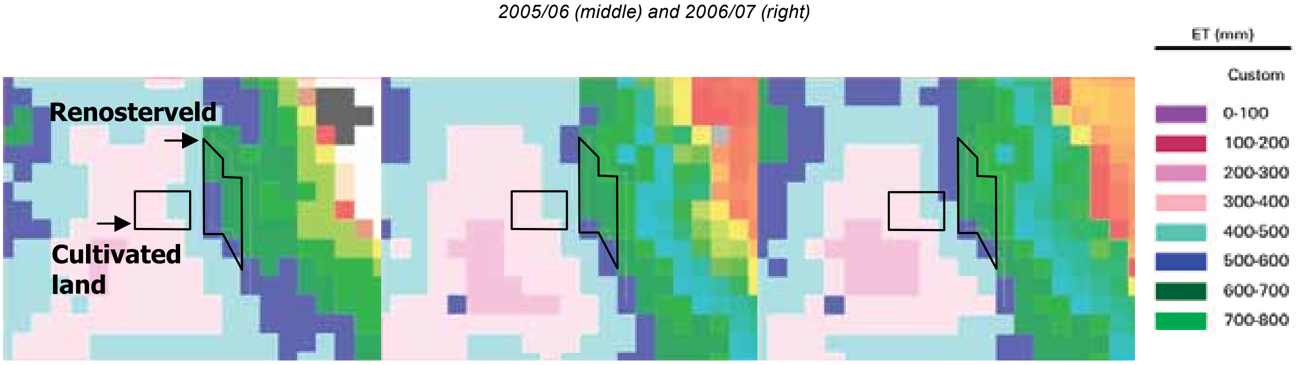

Figure 8
Spatial maps of total evaporation estimated using SEBAL and MODIS images for the Voëlvlei area, for 3 climatically different years (July to June): 2000/01 (left), 2002/03 (middle) and 2006/07 (right)

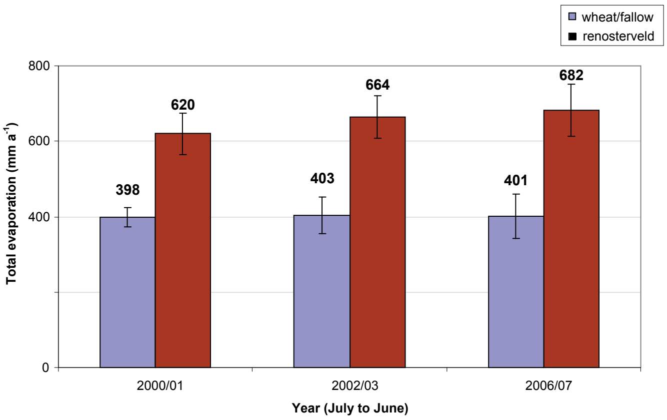

Figure 9
Annual total evaporation (mm·a^{-1}) estimated using SEBAL and MODIS images for wheat/fallow land and Renosterveld, for 3 climatically different years

Maximum and minimum temperatures from Langgewens were used to calculate *ETo* according to the internationally standardised Penman-Monteith methodology (Allen et al., 1998). Solar radiation, wind speed and relative humidity were estimated according to the guidelines for estimation of missing data in the Penman-Monteith equation (Allen et al., 1998; Annandale et al., 2002). Daily vegetation- or crop-specific potential evapotranspiration (*PET*) was then calculated as:

$$PET = ETo\ Kc_{max} \qquad (2)$$

where:

Kc_{max} is the maximum value for *Kc* following rain (or irrigation), and is calculated as a function of weather data and vegetation height (Allen et al., 1998). Vegetation heights are reported in Table 2 for Renosterveld and wheat.

The basal crop coefficient *Kcb* can be used to partition *PET* into potential transpiration (*PT*) and potential evaporation from the soil surface (*PE*) (Jovanovic and Annandale, 1999). Values of *ET* measured with scintillometry after rainfall and estimated canopy cover (*C*) were used to determine *Kcb* coefficients for Renosterveld. The relation between *C* and *Kcb* is:

$$Kcb = PET/ETo\ C = Kc_{max}\ C \qquad (3)$$

The lengths of stages for Renosterveld were not assigned as the vegetation is perennial (Table 2). The *Kcb* for Renosterveld was estimated based on the *Kc* determined from measurements of total evaporation during 1 window period in winter 2005 (Fig. 3c), and using Eq. (3):

$$Kcb = Kc_{max}\ C = 1.49 \times 0.8 = 1.2$$

where:

Kc_{max} was taken from Fig. 3c (average *Kc* during the August-September 2005 winter campaign) and canopy cover was estimated to be 80%.

Although the *Kcb* was derived using only 1 window period in winter when evaporative demand was low, the value of 1.2 was used throughout the year, bearing in mind that soil

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Table 2 **Length of stages, *Kcb*, vegetation height and canopy interception of wheat and Renosterveld**			
Inputs		**Wheat**	**Renosterveld**
Length of stages (d)	Initial	30	-
	Development	60	
	Mid-	30	
	Late	65	
	Total	185	365
Kcb	Initial	0.15	1.2
	Mid-	1.0	
	Late	0.15	
Vegetation height (m)	Initial	0.2	0.9
	Maximum	1.0	
Canopy interception (mm)		1.0	1.2

water supply is the limiting factor in the dry summer season. Vegetation water stress is likely to occur in summer and this was simulated with the root water uptake subroutine of the HYDRUS-1D model. Low evaporation was therefore simulated during periods of water stress, even though the evaporative demand was high.

The estimated values of *Kcb* for different stages of wheat are shown in Table 2. The length of stages was estimated based on common knowledge of practices in the area. Similar values for length of stages were reported in various databases (Allen et al., 1998; Annandale et al., 1999). In the model simulations, planting date of wheat was 1 May of each year and harvest date at the beginning of November. Fallow conditions, with only soil evaporation occurring from the top soil, were simulated for the period from November to April of the following year. The *Kcb* factor for mid-stage of wheat was taken from Fig. 5c (September 2007 winter campaign) assuming full canopy cover ($C = 1$), whilst the initial value and that for the late stage were obtained from the literature (Allen et al., 1998; Annandale et al., 1999). Although wheat monoculture is not a common practice in the area, a 20-year wheat/fallow land rotation was simulated in order to assess the temporal variability in water balance for this land use.

Canopy interception for Renosterveld was estimated from Fig. 3 (corresponding to increased *Kc* between rainfall event and drying off of canopy), whilst it was assumed to be 1 mm for wheat (Annandale et al., 1999) (Table 2). Root depth of the well-established Renosterveld was assumed to be 9 m, corresponding to the groundwater table depth, thereby allowing the root system to tap water in the capillary fringe. Although scarce data are available on rooting depth of Renosterveld, such deep root systems were previously measured (Scott and Breda, 1937). Maximum root depth for wheat was assumed to be 1 m, with a vertical linear distribution from the soil surface to the bottom of the profile. Such shallow root systems for annual crops commonly occurs in the area, given that many soils are poorly developed, overlying semi-weathered Malmesbury shale (De Clercq et al., 2010).

Twenty-year simulations were carried out to compare the soil water balance of the 2 land uses. Table 3 presents a comparison of *ET* estimates obtained using SEBAL and MODIS images with HYDRUS-1D estimates for 3 climatically different years, namely 2000/01, 2002/03 and 2006/07. The

Table 3
Comparison of SEBAL (MODIS) and HYDRUS-1D estimates of total evaporation for years 2000/01, 2002/03 and 2006/07; summary of 20-year soil water balance simulated with the HYDRUS-1D model for Renosterveld and dryland wheat/fallow land with weather data from Langgewens (1988 to 2007). All values are in mm·a^{-1}.

Land use	Method, season and statistics		Rainfall	Transpiration (T)	Soil evaporation (E)	Canopy interception	Total evaporation	Water balance	Reference evapotranspiration
Wheat/fallow land (free drainage)	SEBAL (MODIS)	2000/01	384	-	-	-	398	-	1 339
		2002/03	304	-	-	-	403	-	1 379
		2006/07	474	-	-	-	401	-	1 338
	HYDRUS-1D	2000/01	384	159	185	25	369	15	1 339
		2002/03	304	197	159	25	381	-77	1 379
		2006/07	474	213	226	27	466	8	1 338
		Total	8 036	3 701	3 776	518	8 065	-29	26 531
		Average	402	189	189	26	403	-1	1 327
		Maximum	553	234	266	36	533	31	1 394
		Minimum	289	111	127	20	290	-46	1 137
		Median	403	197	193	25	451	0	1 340
		SD	76	39	37	4	69	19	54
Renosterveld (water table at 9 m)	SEBAL (MODIS)	2000/01	384	-	-	-	620	-	1 339
		2002/03	304	-	-	-	664	-	1 379
		2006/07	474	-	-	-	682	-	1 338
	HYDRUS-1D	2000/01	384	429	67	70	567	-183	1 339
		2002/03	304	549	63	67	679	-375	1 379
		2006/07	474	533	68	78	679	-205	1 338
		Total	8 036	10 501	1 149	1 506	13 155	-5 119	26 531
		Average	402	525	57	75	658	-256	1 327
		Maximum	553	868	67	93	999	-132	1 394
		Minimum	289	427	44	60	559	-644	1 137
		Median	403	496	58	76	638	-237	1 340
		SD	76	94	7	10	96	110	54

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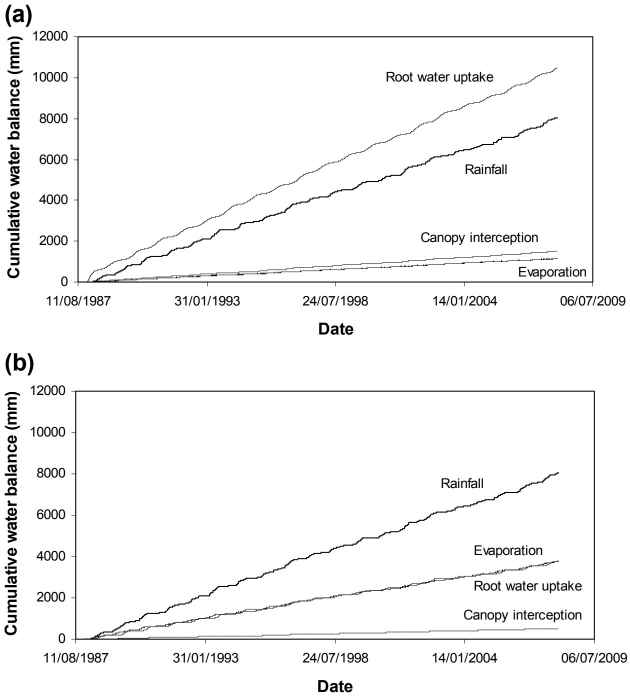

Figure 10
Cumulative rainfall, root water uptake, soil evaporation and canopy interception simulated with the HYDRUS-1D model for Renosterveld (a) and wheat/fallow rotation (b)

average yearly estimates were very close for both wheat/fallow land (401 mm with SEBAL and 405 mm for HYDRYS-1D) and Renosterveld (655 mm with SEBAL and 642 mm with HYDRUS-1D). HYDRUS-1D, however, displayed larger variations in estimated *ET* compared to SEBAL, depending on rainfall. Total rainfall for these 3 years varied between 304 and 474 mm, with an average of 387 mm. Estimated *ET* depended not only on total amounts of rainfall, but also on rainfall distribution and evaporative demand. The highest reference evapotranspiration value was calculated in 2002/03.

Table 3 also presents the summary of the 20-year soil water balance simulated with the HYDRUS-1D model. The cumulative values are presented in Fig. 10, where the proportion of the soil water balance components can be seen. With the deeper root system and the larger *Kcb* throughout the year, Renosterveld transpired much more, compared to the dryland wheat/fallow system. The soil evaporation component was higher for the dryland wheat/fallow system, as wheat has a smaller canopy cover compared to Renosterveld for most of the growing season, and fallow land occurs for 6 months of the year. Canopy interception was higher for Renosterveld because of the larger canopy cover compared to wheat/fallow for most of the year. Total evaporation represents the sum of transpiration (root water uptake calculated with HYDRUS-1D after Feddes et al., 1978), soil evaporation and canopy interception. Total evaporation was higher from Renosterveld compared to the wheat/fallow rotation. The water balance in Table 3 represents the difference between rainfall and total evaporation and accounts for soil water storage, drainage and capillary rise. Drainage outflux through the bottom soil profile boundary (positive sign of the water balance in Table 3), which can be approximated with deep percolation, was simulated to occur occasionally after heavy rainfall events and depending on rainfall distribution. With an average annual rainfall of 402 mm, most of the rain water was consumed by the vegetation during the winter rainy season. Very low (negative) values of the water balance in Table 3 are indicative of upward water influx through the bottom soil profile boundary and root water uptake from the groundwater table by Renosterveld. It should be noted that, even in the case of the root system reaching the groundwater table and tapping water in the capillary fringe, vegetation stress may occur under conditions of high evaporative demand and depending on root distribution, rainfall dynamics, soil water redistribution and soil properties.

Higher transpiration, soil evaporation and canopy interception values were calculated in wetter years compared to drier years (maximum and minimum values in Table 3). Total evaporation values for both land uses were well below the reference evapotranspiration levels (Table 3), indicating that vegetation was under water stress for large parts of the year. Temporary and shallow groundwater tables, an occurrence that is rather common in the area, could be an additional source of water for deep-rooted Renosterveld and this vegetation could therefore contribute to regulating the natural water and salt balance.

Conclusions

Considering the *ET* data series measured with scintillometry in a wheat and a Renosterveld field, and comparing *ET* estimates for these 2 sites with the reference evapotranspiration, the following conclusions can be made:

- During winter, the Renosterveld canopy tended to exhibit *ET*'s equal to, or higher than, evapotranspiration calculated with the Penman-Monteith equation (*ETo*). A large component of evaporation of water intercepted by the canopy increased *ET* on rainy days.
- In mid- to end of summer (e.g. February 2007), *ET*'s from Renosterveld were much lower than *ETo*'s, showing that this surface had total evaporation below reference rates and the vegetation was under water stress.
- *ET*'s of wheat measured during the rainy season at full canopy development (September 2007) were very close to reference values, displaying characteristics of a well-watered grass canopy.

Total evaporation estimates for wheat/fallow land and Renosterveld differed spatially, but differences in total evaporation were consistent over different years, with total

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evaporation from Renosterveld estimated with SEBAL (MODIS) exceeding that from wheat/fallow land by, on average, 39%. Total annual spatial evaporation estimates using SEBAL and MODIS compared well to simulations run with the HYDRUS-1D model at a point scale (in a vertical dimension). With regard to the long-term (20 years) estimates with HYDRUS-1D, the following considerations can be made:

- Total evaporation of wheat/fallow land was 39% lower compared to Renosterveld.
- Deep-rooted Renosterveld and dryland wheat/fallow are likely to use almost all the water available from rainfall
- The transpiration component of *ET* was dominant in perennial Renosterveld (525 $mm \cdot a^{-1}$ on average, including groundwater contributions to root water uptake), whilst a considerable volume of water evaporated directly from the soil cultivated to annual wheat (189 $mm \cdot a^{-1}$ on average)
- Evapotranspiration from both land uses was far below evapotranspiration rates calculated with the Penman-Monteith equation (or *ETo*), given the semi-arid climate (<50% of *ETo* for both land uses)

It is concluded that change in land use from Renosterveld to dryland wheat cropping can considerably affect the soil water balance. The dryland wheat/fallow cropping system may result in increased runoff and groundwater recharge, shallow saline water tables and consequently the development of dryland salinity, loss of agricultural production and salinisation of the Berg River.

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