VALIDATING ENERGY FLUXES ESTIMATED USING THE SURFACE ENERGY BALANCE SYSTEM (SEBS) MODEL FOR A SMALL CATCHMENT

Report to the
Water Research Commission

by

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Eric Prinsloo from the CSIR is thanked for his help with the field experiment.

Data storage

The energy balance data collected during this project are included in electronic format which appears as a separate Excel-file under the report number KV 290 on the WRC web site

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Symbol list

Symbol	Description	Unit
R_n	Net radiation	W m^{-2}
G	Soil heat flux density	W m^{-2}
H	Sensible heat flux density	W m^{-2}
LE	Latent energy flux density	W m^{-2}
ET	Total evaporation	mm per period
ETo	Reference evapotranspiration	mm per period
Rs	Solar radiation	MJ m-2
VPD	Vapour pressure deficit	kPa
Ta	Air temperature	^{o}C
RH	Relative humidity	%

List of definitions

Evaporation

Evaporation is the "physical process by which a liquid or solid is transferred to the gaseous state" (Huschke, 1959).

Total evaporation

Total evaporation (ET) 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), windspeed and canopy characteristics (canopy resistances) (Rosenberg *et al*., 1983). Others (Kite and Droogers, 2000) refer to total evaporation as evapotranspiration.

In this experiment total evaporation refers to the sum of (a) evaporation from the soil surface, (b) transpiration by vegetation, and (c) evaporation of water intercepted by vegetation.

Transpiration

Transpiration can be defined as evaporation of water that has passed through the plant. Transpiration therefore consists of vaporization of liquid water contained in the plant tissues and vapour removal to the atmosphere (Allen *et al*., 1998).

Reference evapotranspiration

Allen *et al*. (1998) define reference evapotranspiration (ET_0) as "*The evapotranspiration from a reference surface, not short of water …The reference surface is a hypothetical grass reference crop with specific characteristics…The only factors affecting ET_o are climatic parameters. Consequently, ET_o is a climatic parameter and can be computed from weather data. ETo expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors.*" Other definitions specify that the reference surface should fully cover the soil surface. In this document we refer to it as reference evaporation.

Simplified energy balance

The simplified version of the energy balance of a specific surface is given by the equation

$$R_n - G - LE - H = 0$$

where R_n is the net irradiance, *LE* the latent (evaporation) energy flux density, *H* the sensible heat flux density and *G* the soil heat flux density. All terms are in W m^{-2}. The specific latent energy of vapourisation *L* is (2.501-0.00237 T_z) (MJ kg^{-1}), where T_z is the air temperature (^oC) at height z.

Chapter 1: Background

The Water Research Commission funded project, K5/1690 is aimed at assessing the usefulness and applicability of remote sensing technologies as a tool for resource assessment towards the determination of the legal compliance of surface and groundwater use, by spatially calculating the components of the hydrological water balance (rainfall, soil moisture, runoff, groundwater discharge / recharge and total evaporation). For this study, the quaternary catchment G10K, which falls within the Berg River Water Management Area, was selected. The Surface Energy Balance System (SEBS) model was used to estimate total evaporation and the components of the energy balance for the study area over the period of 1 October 2007 to 30 September 2008. High resolution ASTER images were used in the modelling. Since ASTER images are not routinely collected over South Africa, the project team submitted a request for the acquisition of ASTER images for the study area and period in advance.

The use of remote sensing data (like ASTER images) for the estimation of total evaporation (and other components of the water balance) is still a new field in South Africa. It is gaining momentum and capacity is being built in this field in a number of institutions including the Agricultural Research Council and the CSIR. The project team deemed it important to validate some of the hydrological water balance data estimated with the different remote sensing based models, especially the total evaporation, since this is generally a major component of the hydrological water balance. Since validating estimates of ET were not originally part of the project proposal for K5/1690, the project team consulted with the WRC research manager Dr Shafick Adams and he proposed that a validation study be funded through the WRC Consultancy funding. The project team through Mrs Lesley Gibson subsequently approached Dr Caren Jarmain from the CSIR to assist them in this, since the CSIR often conducts studies where the energy balance components and total evaporation are estimated.

This Water Research Commission Consultancy project therefore aims at collecting energy balance and total evaporation data from an apple orchard, using a micrometeorological technique, so that estimates thereof using the Surface Energy Balance System (SEBS) model can be validated.

This Water Research Commission Consultancy project (K8/824), will therefore complement project K5/1690 and provide supporting field data for the remote sensing based total evaporation estimates, to be validated. More information on the latter study can be obtained in Gibson *et al.*, 2009.

Chapter 2: Materials and Methods

2.1 Site description

Project K5/1690 aims to quantify the components of the hydrological water balance for catchment G10K, which falls within the Berg River Management Area (Figure 1) and therefore a research site was selected within this catchment. The research site selected, an apple orchard, was situated on Mouton's Valley farm, in Bo-Piketberg[1] (Figure 2). On this farm, a range of fruits (deciduous and citrus), flowers and herbs are grown. The cultivated land on the Mouton's Valley farm covers an area of approximately 150 ha, of which the apple orchard selected covered an area of 3.18 ha. The apple orchard was made up of three different apple cultivars – 11 rows of Braestarr (0.77 ha), 16 rows of Royal Gala (1.24 ha) (Fig. 3) and 15 rows of Redchief (1.17 ha). At the time of the energy balance and total evaporation measurements in November 2008, the average canopy height was 3.2 m. The apple trees did not cover the soil surface completely, rather by about 75 %. The inter-row areas were planted \with grass (Fig. 3).

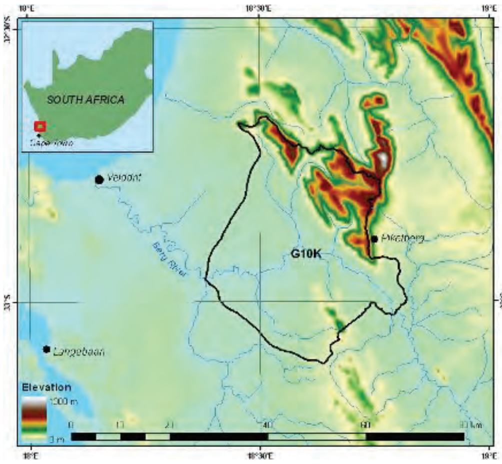


Figure 1 A map showing the extent of the G10K catchment and its location in relation to Piketberg

Figure 2 Location of the validation site (*shown as Piketberg*) on Mouton's Valley Farm

[1] The Bo-Piketberg area consists of an elevated mountainous area which lies approximately 10 km to the west and the northwest of Piketberg, in the Western Cape Province.

Figure 3 The apple orchard as seen from above (left) and from the side (right)

2.2 Energy balance equipment

In this study the aim was to measure the surface energy balance components and the daily total evaporation (ET) of an apple orchard using a field based method, which could be used to validate spatial estimates thereof. A number of techniques can be used to measure the components of the surface energy balance and total evaporation in the field, including the Bowen ratio energy balance, Eddy covariance, Surface renewal and Scintillometry techniques. All these techniques, and the SEBS model, rely on the estimation of the components of the surface energy balance. The simplified energy balance of a surface is described by

$$R_n - G - H = LE \qquad 1$$

where R_n is the net radiation, G the soil heat flux density, H the sensible heat flux density and LE the latent energy flux density. The latter is equivalent to the total evaporation from a surface. The net radiation at a surface is generally partitioned into three components – some energy will go into heating the soil (G), some into heating the air (H) and some energy into driving evaporative processes (LE). In all the techniques listed above, with the exception of the two-sensor type Eddy covariance method, LE is estimated as the *residual* of the energy balance equation, and these techniques hence require that the other three components (Rn, G, and H) be measured.

In this experiment, a one-sensor Eddy covariance system was used for the estimation of the sensible heat flux density. The instrumentation was installed right in the middle of the apple orchard selected, in the part planted with Royal Gala trees. For the eddy covariance (one sensor) systems, we used an RM Young three-dimensional ultrasonic anemometer (model 81000, Traverse city, Michigan, USA – path length of 150 mm) to estimate sensible heat flux density. The sonic anemometer was mounted onto a 7 m tall lattice mast and installed at approximately 7.5 m, right above the apple tree row (Fig. 4). The anemometer was connected to a CR3000 datalogger. The ultrasonic anemometer data was sampled at a frequency of 10 Hz and data processed online in the datalogger and stored for further analysis. Differential voltage measurements on the 5 V range with a settling time of 100 µs and an integration period of 100 µs were used. The anemometer was powered by the datalogger. The high frequency measurements of the three components of wind velocity and sonic temperature were stored on a 1 GB PC card for further analysis. The average windspeeds (u, v, w) and sonic temperature, means of wind vectors, variances of wind vector combinations and the standard deviation of wind direction were all calculated by the logger. Data was output by the datalogger at 30 minute intervals. This data was used to calculate the sensible heat flux density in an Excel spreadsheet.

Using the estimates of sensible heat flux density and that of net irradiance and soil heat flux density, the latent energy flux density was subsequently calculated using the shortened energy balance equation. Two net radiometers were used in this study to measure the net radiation above the apple orchard. One REBS Q*6 net radiometer was installed above the apple tree row, and one NR-Lite net radiometer (Model 240-110, Kipp & Zonen) was installed above the inter-row area (Fig. 4). Both sensors were installed at a height of approximately 7.5 m. The average value of these two sensors was used in the calculation of the ET.

Soil temperature and soil heat fluxes were measured at four different positions between the tree rows and the data was used to estimate the soil heat flux density of the apple orchard. One set of sensors was installed close to the trees within the tree row, a second set in the inter-row area of compaction where the tractor wheels normally pass, a third set in the inter-row grass cover, and the fourth set, again in the tree row. For the soil temperature, type-E soil averaging thermocouples were used and for the soil heat flux REBS heat flux plates were used. In addition, soil water content was measured over the top 80 mm of the soil surface, at two positions, using Campbell CS615 sensors. The soil temperature sensors were installed at depths of 20 and 60 mm, and the soil heat flux plates at 80 mm below the soil surface. The soil sensors were installed as suggested by Campbell (2003) (Fig. 5). The net radiometers and soil sensors were connected to a CR23X datalogger (Campbell Scientific, Logan, Utah, USA) and measurements were performed every 10 s intervals and averages obtained every 2 minutes.

Figure 4 Instrumentation installed at the apple orchard, the sonic anemometer and net radiometers clearly visible above the apple trees

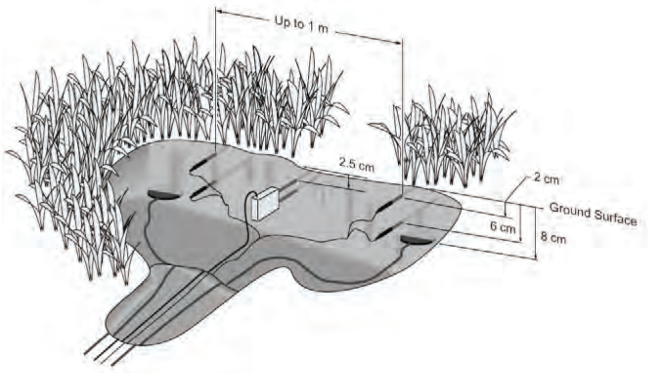


Figure 5 Recommended layout of sensors used to estimate soil heat flux density (Campbell, 2003)

2.3 Additional data

Weather data from an existing Enviromon automatic weather station installed about 0.5 km from the apple orchard, was used in the interpretation of the total evaporation and energy balance data.

Chapter 3: Results

The energy balance and total evaporation (ET) of an apple orchard were measured using a one-sensor type Eddy covariance system from 7 November to 1 December 2008. Since problems were experienced with the RM Young sonic anemometer, some data was lost especially during the latter part of the measurement period. Good quality data was only available from 10 to 21 November 2008 or for Day of year (DOY) 315 to 326. Fortunately this measurement period overlapped with one of the two dates of ASTER satellite image acquisition (10 and 26 November 2008).

3.1 Energy balance of an apple orchard

Figure 6 and 7 show the components of the energy balance. The mid-day maximum net radiation on sunny days was consistent over the measurement period, at about 800 Wm-2. At the beginning of the measurement period, around DOYs 315-319, cloudy conditions existed and lower net radiation values were measured. The low net radiation values on these days were the result of cloud cover and rain over this period, as shown in low solar radiation values (e.g. < 2.5 MJm-2 on DOY 317), high relative humidity values throughout the day (>72 %) (Fig. 8) and the rainfall recorded was 3.4 and 30.8 mm on DOY 317 and 318 respectively (Fig. 9). Night time net radiation values were generally negative as low as -50 Wm-2.

Over the measurement period the soil heat flux density, G, increased to mid-day maximum values of around 100 Wm-2 (Fig. 6). The soil heat flux density diurnal curve shows two peaks, due to the shading of the soil (and subsequently the soil sensors), which affected both soil temperature and soil heat flux density. The soil heat flux density was negative at night time – up to -40 Wm-2 – showing that the soil was losing heat (or energy). G was generally around 12 % of the net radiation (Fig. 10), which is indicative of a canopy that covers the soil completely. The soil heat flux density magnitude was consistent over the measurement period, and this reflects the little change in the canopy cover over this period.

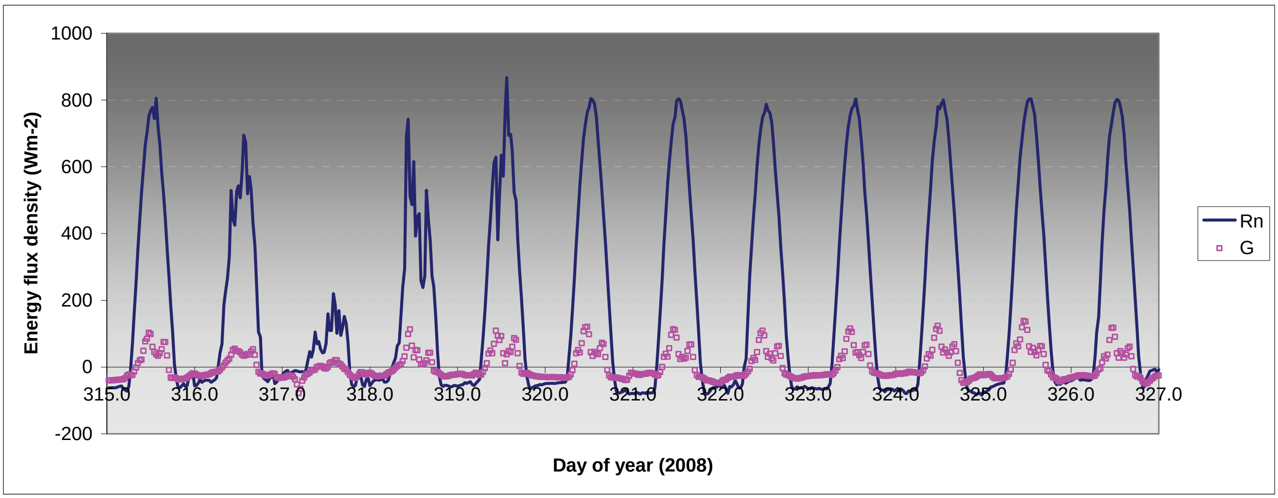


Figure 6 Net radiation (R_n) and soil heat flux density (G) measured for an apple orchard over the period 10 to 21 November 2008

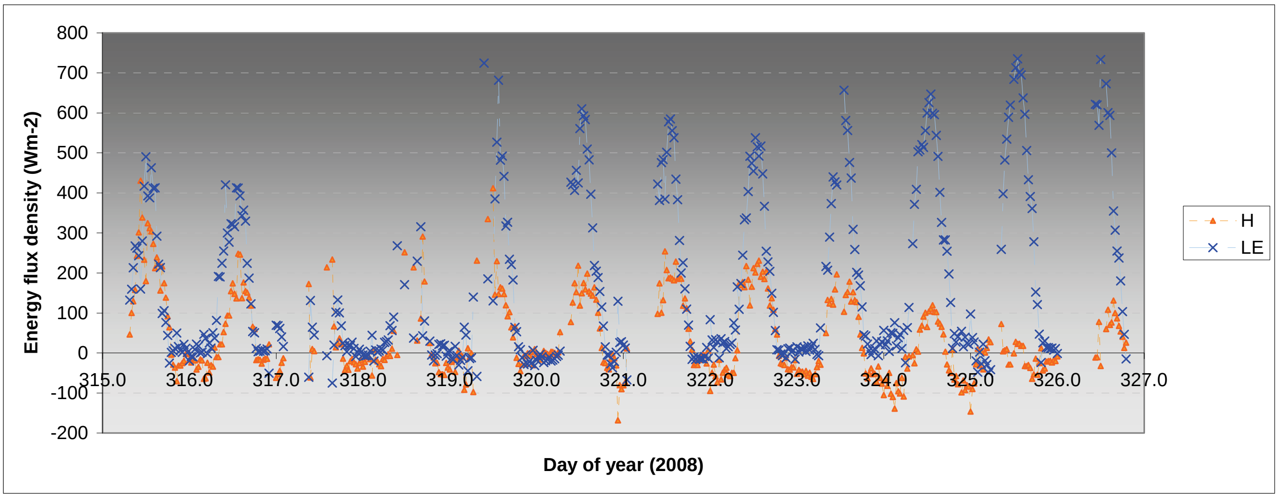


Figure 7 Sensible (H) and latent energy flux density (LE) measured of an apple orchard over the period 10 to 21 November 2008

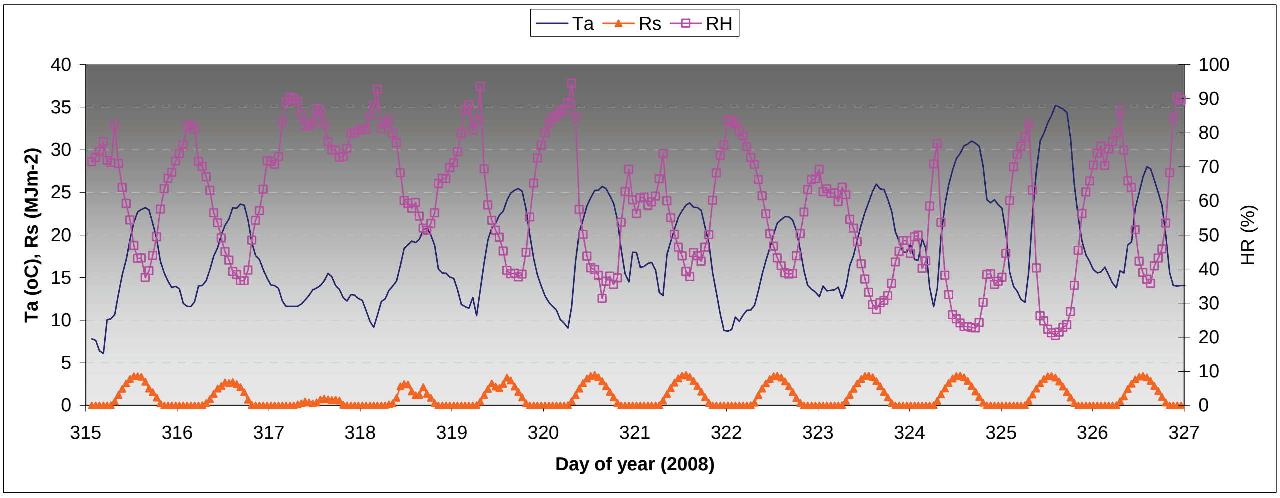


Figure 8 Climatic conditions over the period of energy balance and total evaporation measurements at the apple orchard site, where T_a is the average temperature in °C, R_s the solar radiation in MJ m^{-2}, and RH is the average relative humidity (%) at an hourly time interval for the period 10 to 21 November 2008

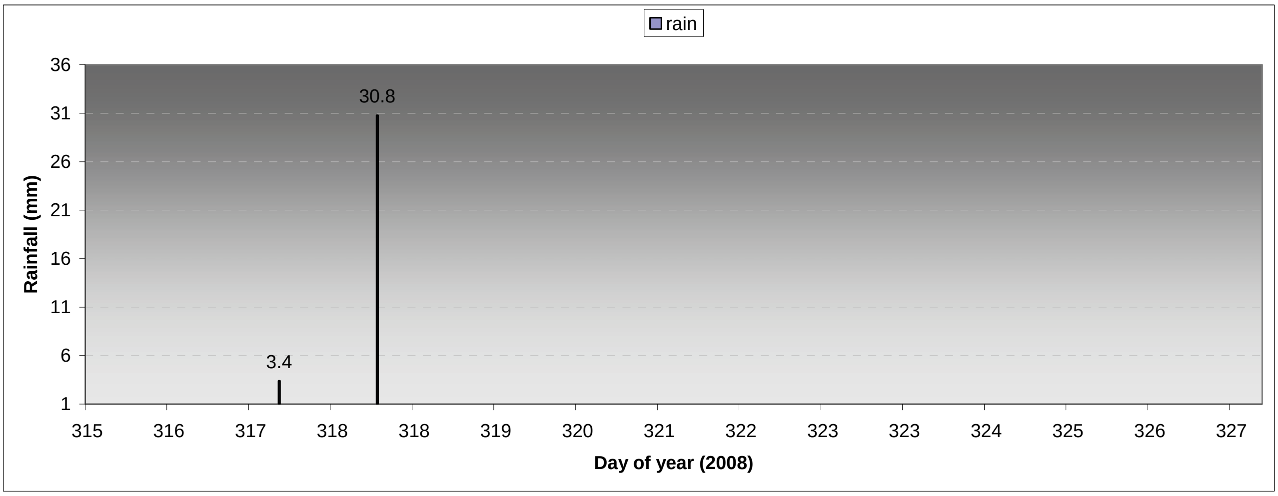


Figure 9 Rainfall (rain) as measured at the apple orchard over the period 10 to 21 November 2008

Figure 7 shows the diurnal trend in the latent and sensible heat flux density, where H was estimated from the sonic anemometer high frequency windspeed data and the latent energy flux density calculated as the residual of the energy balance equation (eq. 1). From Figure 7 it is clear that most of the available energy (Rn-G) at the apple orchard was paritioned into the latent energy flux density. This is also shown in the Bowen ratio[2] values (Fig. 11) which were generally less than 1, and the evaporative fraction[3] which on sunny days approached 1 (ranged between 0.7 and 1) (Fig. 11). The latent energy flux density showed a gradual increase over the sunny period (DOYs 320 to 327) to maximum mid-day values ranging from 600 to 700 Wm-2, whereas the sensible heat flux densities were generally around 200 Wm-2 or less.

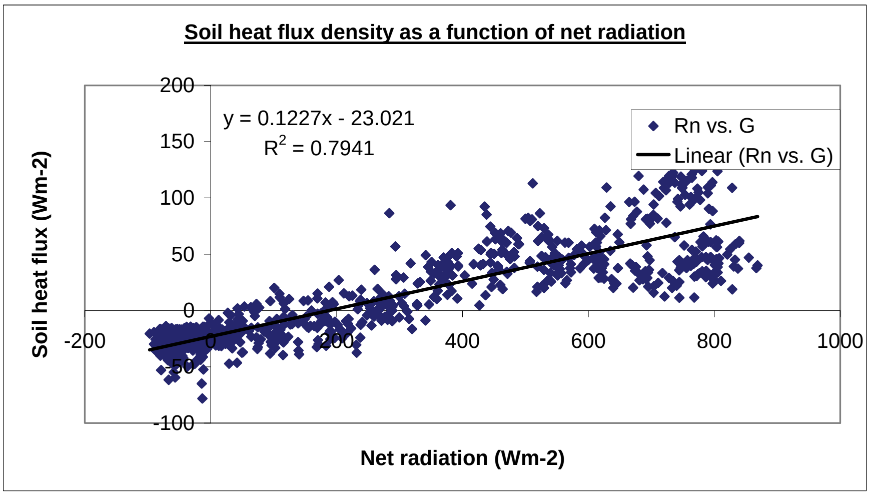


Figure 10 Soil heat flux density (G) as a function of net radiation (R_n) for an apple orchard and as measured over the period 10 to 21 November 2008

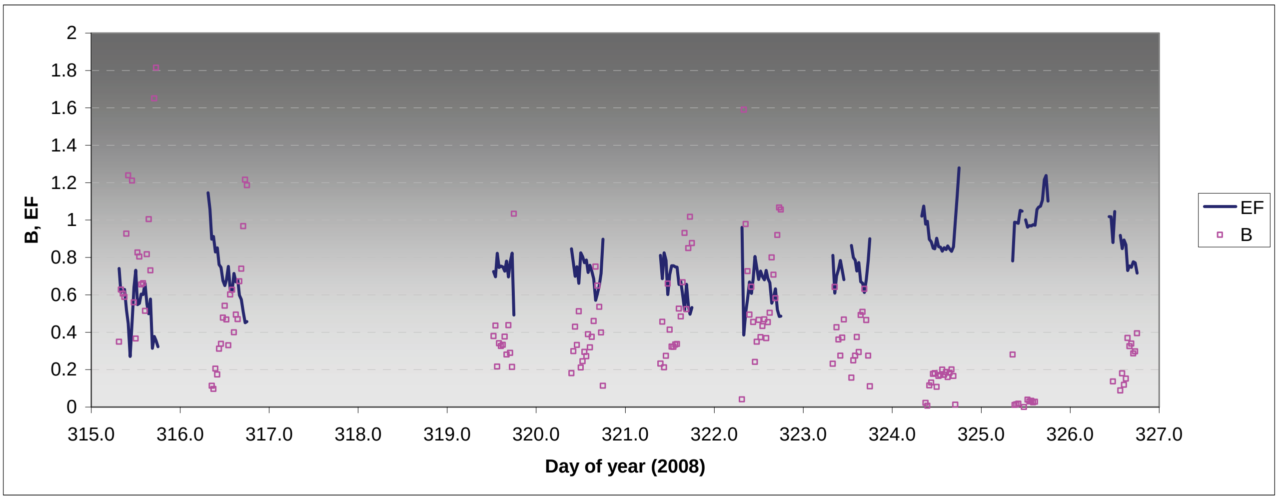


Figure 11 B the Bowen ratio (B=H/LE) and the evaporative fraction EF (EF=LE/R_n-G) for an apple orchard and as measured over the period 10 to 21 November 2008

[2] The Bowen ratio (B) is the fraction of sensible to latent energy flux density (B=H/LE)

[3] The evaporative fraction (EF=LE/(Rn-G)) is calculated as the fraction of available energy (Rn-G) that is partitioned into latent energy flux density

3.2 *Total evaporation from an apple orchard*

Daily total evaporation (ET) was subsequently estimated from the latent energy flux density estimates for the period DOY 315 to 325 and is shown in Fig. 12. Total evaporation rates measured at the beginning of the period were around 4 mm/d (Fig. 12) (DOY 315) and increased to values exceeding 5 mm/d following two rainfall events (totalling to 34.2 mm on DOY 316 and 317) (Fig. 9). After the rainfall events the vapour pressure deficit (e_s-e) and solar radiation values also further increased (to 1.8 and 28 MJ m-2 d-1 respectively) which led to a further increase in the daily ET's - up to 7.3 mm/d (Fig. 12).

In order to extend the daily total evaporation estimates from 9 days to a 4 week period (28 days), various relationships between total evaporation and climatic parameters, were investigated. The linear relationship between daily ET and ET_o and the exponential relatiohship between daily ET and the product of solar radiation and vapour pressure deficit (R_s*vpd) were subsequently found to described daily ET's from the apple orchard to within 73 % (Fig. 13).

Figure 14 shows the total evaporation calculated using these relationships for a 28 day period. It is clear that the relationships used yielded agreeable daily total evaporation rates. The total evaporation estimated over this period (ET(ET_o) and ET(R_s*vpd)), showed a similar trend to the measured ET (Fig. 14). The ET's calculated and measured over the 9 day period using the different methods, yielded exactly the same results – 46.6 mm (or a daily average of 5.2 mm/d). The 28-day estimate of ET subsequently calculated using the two approaches, differed by only 5 mm (125.9 mm vs. 130.6 mm with the ET_o and R_s*vpd relationships respectively).

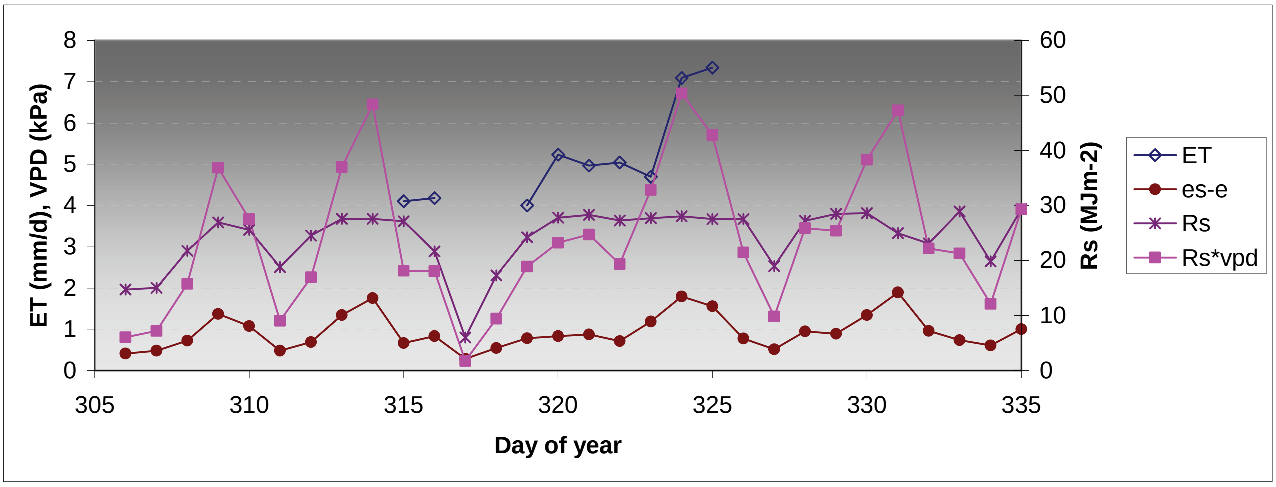
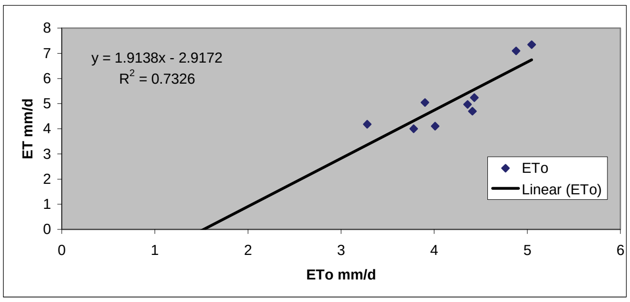


Figure 12 Total evaporation (ET) from an apple orchard, vapour pressure deficit (e_s-e), solar radiation (R_s) (secondary Y axis) and the product of solar radiation and vapour pressure deficit (R_s*vpd) (secondary Y axis)



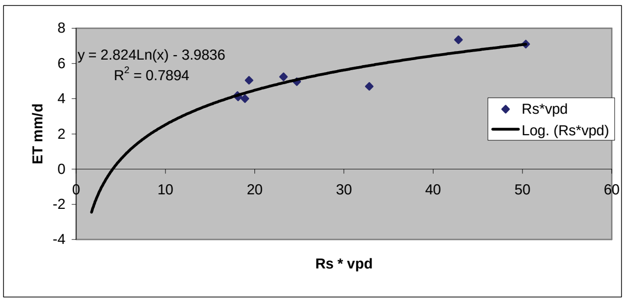


Figure 13 Relationships derived for estimating daily total evaporation (ET) rates from estimates of reference evaporation (ET_o) (*left*) and the product of solar radiation and vapour pressure deficit (R_s*vpd) (*right*)

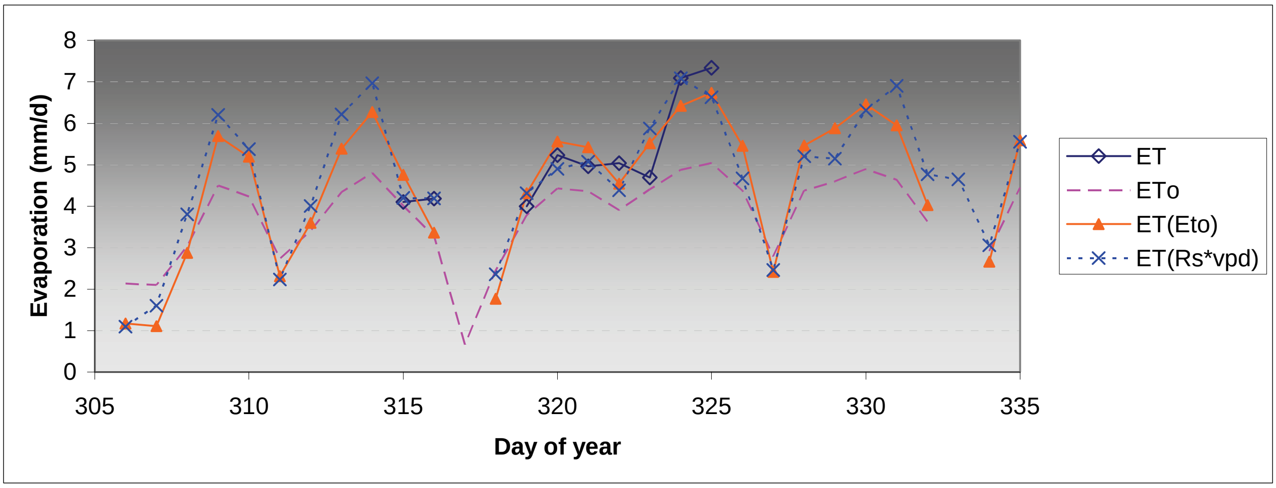


Figure 14 Daily total evaporation (ET) and reference evaporation (ET_o) as measured at the apple orchard. ET (ET_o) and ET(R_s*vpd) refers to the total evaporation calculated as a function of reference evaporation and the product of solar radiation and vapour pressure deficit respectively.

The daily total evaporation rates estimated for the apple orchard at Mouton's Valley were within the range measured in another WRC funded project, focussing on Tree orchard water use (K5/1770). ET's measured in December 2008, at an pink lady apple orchard in Ceres ranged between 4.3 (cloudy) and 8.5 mm/d (sunny) with an average total evaporation of 6.7 mm/d (Gush et al., unpublished). The rates measured at Ceres were slightly higher than those measured at the Mouton's Valley farm at Bo-Piketberg (4.5 mm/d). This could be due to larger vapour pressure deficits and slightly higher solar radiation values. Figure 12 suggest that even higher ET estimates than those measured at the apple orchard at Bo-Piketberg is possible with increases in both solar radiation and vapour pressure deficit.

Chapter 4: Conclusion

The one-sensor Eddy covariance system was successfully applied at an apple orchard in Bo-Piketberg and total evaporation and energy balance data was collected over the period 7 November to 1 December 2008, which coincided with one ASTER satellite overpass date which will be used in project K5/1690. The data sets will be used to validate the SEBS estimates of evaporation and the components of the energy balance for the apple orchard.

Most of the available energy was partitioned into latent energy flux density, as was expected at this irrigated orchard. Daily total evaporation rates as high as 7.3 mm/d were measured and exceeded the reference evapotranspiration rates.

Chapter 5: References

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