

# TOTAL EVAPORATION OF NATURAL VEGETATION

C Jarmain<sup>1</sup> CS Everson<sup>2</sup> and PJ Dye<sup>2</sup>

## ABSTRACT

The replacement of natural vegetation with highly productive commercial forestry species and agricultural crops is placing ever-increasing pressure on South Africa's limited water supplies. There is currently a strong focus on identifying forestry and farming activities that result in a reduction in streamflow when compared with the native vegetation (termed Streamflow Reduction Activities or SFRA's). For these reasons it is important to know what the water use of different natural vegetation types are compared to the respective SFRA's. In addition an understanding of the driving mechanisms (plant structure, climate and soil) which result in water use differences between the various vegetation types is needed for extrapolation of results in hydrological models to other regions and plant communities. To date the water use of only a few natural vegetation types have been studied in South Africa.

This study reports on direct measurements of daily evaporation from natural vegetation, determined using the Bowen ratio energy balance technique. Reported measurements are from moist upland grassland (Cathedral Peak and Weatherley research catchments), riparian mountain fynbos (Jonkershoek research catchment), valley thicket (Noodsberg) and coastal bushveld/grassland (Bonamanzi). The seasonal water use patterns of all the vegetation types are similar. Maximum evaporation rates are reached in summer, and minimum evaporation rates during winter. However the daily maximum and minimum evaporation rates for the four vegetation types were different. The moist upland grassland evaporation measured at Cathedral Peak ranged from  $< 1 \text{ mm d}^{-1}$  to  $7 \text{ mm d}^{-1}$  maximum. The minimum evaporation rates measured at Weatherley were similar to those measured at Cathedral Peak ( $< 1 \text{ mm d}^{-1}$ ), but the maximum rates measured at Weatherly were up to  $2 \text{ mm d}^{-1}$  lower. The low minimum evaporation rates during winter were the result of frost which resulted in senescence of the grasses. In comparison, the minimum evaporation rates above the heterogeneous sites (riparian mountain fynbos, valley thicket, and coastal bushveld/grassland), were  $1$  to  $2 \text{ mm d}^{-1}$  higher than that at the moist upland grassland sites during winter ( $1$  to  $3 \text{ mm d}^{-1}$ ,  $\approx 3 \text{ mm d}^{-1}$  and  $1$  to  $2 \text{ mm d}^{-1}$  for the valley thicket, coastal bushveld/grassland and mountain fynbos sites). The evaporation rates at these sites were not influenced by frost. The maximum evaporation above valley thicket ( $7 \text{ mm d}^{-1}$ ), Coastal bushveld/grassland ( $\approx 8 \text{ mm d}^{-1}$ ) and riparian fynbos ( $\approx 8 \text{ mm d}^{-1}$ ) compared well with

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<sup>1</sup> CSIR, Environmentek, P.O.Box 320, Stellenbosch, 7614 [cjarmain@csir.co.za](mailto:cjarmain@csir.co.za),

<sup>2</sup> CSIR, Environmentek, Pietermaritzburg, [ceverson@csir.co.za](mailto:ceverson@csir.co.za), [pdye@csir.co.za](mailto:pdye@csir.co.za)

the maximum evaporation rates measured above the moist upland grassland from Cathedral peak, where very little water stress occurred.

It was concluded that vegetation types that are influenced by frost, will have evaporation rates of  $<1 \text{ mm d}^{-1}$  following the onset of frost until the start of the new rain (and growth) season. In addition, under conditions where water availability is not limited, the maximum evaporation above a plant canopy can reach rates of 7 to 8  $\text{mm d}^{-1}$  irrespective of vegetation structure and climate, as was illustrated by the well watered Cathedral Peak site, the riparian fynbos site, and the coastal bushveld/grassland site.

## 1 INTRODUCTION

A high degree of accuracy in the knowledge of the total evaporation of natural vegetation types is required when the impact of different vegetation types and a change thereof (to commercial or invading species) on the water balance and the availability of water in streams, is assessed (Dye and Bosch, 2000).

In previous years, a lot of streamflow research was focussed in areas where fynbos and grassland was converted to plantations of pine and eucalypt, whereas today the need for information on the total evaporation and streamflow is much wider (Dye and Bosch, 2000). The total evaporation of only a few of the seventy (Acocks, 1988) or sixty eight (Low and Rebelo, 1996) natural vegetation classes occurring within South Africa were estimated since 1915. Land use change-streamflow studies mainly involved paired catchment experiments where grassland or fynbos was converted into plantations (Dye and Bosch, 2000). Versfeld (1993) describes these. However, the differences in the degree of streamflow reduction and the period of streamflow reduction occurrence were not explained by analysing the streamflow data. Therefore, hydrological process studies like that within the Cathedral peak (Everson *et al.*, 1998) and Weatherley catchments (Lorentz, 1999), followed. Hydrological process studies involve measurement of rainfall interception, total evaporation and soil water storage changes. Studies showed that the streamflow is sensitive to changes in total evaporation.

Examples exist where total evaporation of natural vegetation types were measured with the Bowen ratio energy balance system. These include total evaporation measurements for moist upland grassland within the Cathedral peak (Everson, 2001) and Weatherley catchments (Everson and Jarman, unpublished), riparian fynbos and riparian mistbelt grassland (Dye *et al.*, 2000) and valley thicket and coastal bushveld/grassland (Jarman and Everson, unpublished).

## 2 MATERIAL AND METHODS

### 2.1 Introduction

The total evaporation of a number of natural vegetation types occurring across South Africa (Fig. 1) were measured with the Bowen ratio energy balance technique as part of Water Research Commission funded experiments. Some of these Water Research Commission projects focussed on the effect of commercial crops, forestry and invasives on streamflow, through total evaporation measurements.



Fig. 1 Location of natural vegetation research sites<sup>3</sup>

The total evaporation of six natural vegetation types were measured under different conditions (climatic, soil). These vegetation types can be divided into two broad structural classes: multi-layered and single-layered (Table 1). The multi-layered vegetation class includes valley thicket, coastal bushveld/grassland and riparian fynbos, whereas the single-layered vegetation class includes moist upland grassland and riparian mistbelt grassland. These classes can further be divided in terms of their soil water availability: dryland or riparian (Table 1).

Total evaporation of moist upland grassland was measured within the Cathedral Peak VI and Weatherley catchments, the total evaporation of riparian mistbelt grassland in the Karkloof area, and the total evaporation of valley thicket, coastal bushveld/grassland and riparian fynbos at Noodsberg, Bonamanzi and in the Jonkershoek catchment respectively (Fig. 1). Various alien invasives and commercial ‘crops’ occur in close proximity of these natural vegetation research sites, and is listed in Table 2.

<sup>3</sup> Map obtained from [http://www.holidayinsa.com/accommodation/map\\_search/index.asp](http://www.holidayinsa.com/accommodation/map_search/index.asp), and modified.

Table 1 Structural and soil water availability classes of the natural vegetation types studied

Single-layered		Multi-layered	
Type	Soil water availability	Type	Soil water availability
Moist upland grassland (Cathedral peak)	Dryland	Valley thicket	Dryland
Moist upland grassland (Weatherley)	Dryland	Coastal bushveld/grassland	Dryland
Mistbelt grassland	Riparian	Fynbos	Riparian

## **2.2 Site descriptions**

### **2.2.1 Moist upland grassland<sup>4</sup>**

Total evaporation of moist upland grassland was measured at the Cathedral Peak Forestry Research Station which lies in the northern part of the Natal Drakensberg Park (29° 00'S, 29° 15'E) (Figs 1 and 2). Cathedral Peak Catchment VI is a natural grassland catchment receiving a biennial spring burning treatment. Elevations range from 1860 m a.m.s.l. at the basin outlet to 2070 m a.m.s.l. at the highest point. The terrain has an average slope of 19 % (Everson, 2001).

Winters at Cathedral Peak are cold and dry, while summers are hot and wet (Scott *et al.* 2000). Bosch (1979) provides a detailed description of the weather in these catchments. The mean annual precipitation is 1299 mm. Catchment VI falls within the summer rainfall region, with 85 % of the rain falling in the months October to March. Occasional snowfall occurs in winter, mostly on the upper parts of the catchments (Scott *et al.* 2000).

The soils of the catchment are classified as Lateritic Red and Yellow earths, grading into heavy black soils (Katspruit and Champagne) in saturated zones and along the stream banks (Granger, 1976).

The total evaporation of moist upland grassland was measured from 1/10/1990 to 30/09/1994.

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<sup>4</sup> Moist upland grassland is synonymous to highland sourveld grassland and Dohne sourveld grassland.

Table 2 Alien invasives and commercial crops within close proximity of research sites on total evaporation of natural vegetation

<b>Natural vegetation type</b>	<b>Alien invasive</b>	<b>Commercial crops</b>	<b>Location</b>
Moist upland grassland	<i>Pinus halepensis</i> <i>Pinus patula</i> <i>Acacia dealbata</i> <i>A mearnsii</i> <i>Populus canescans</i> (riparian) <i>Salix babylonica</i> (riparian)	<i>Eucalyptus</i> spp. <i>Pinus</i> spp. Others	Cathedral peak
Moist upland grassland	<i>Pinus halepensis</i> <i>P pinaster</i> <i>Acacia dealbata</i> <i>A mearnsii</i> <i>Populus canescans</i> (riparian) <i>Salix babylonica</i> (riparian)	<i>Eucalyptus</i> spp. Others	Weatherley
Riparian mistbelt grassland	<i>A. mearnsii</i> <i>A dealbata</i> <i>A decurrens</i> <i>Solanum mauritianum</i> <i>Jacaranda mimosifolia</i> <i>Lantana camara</i> <i>Populus canescans</i> <i>Salix babylonica</i>	<i>Acacia mearnsii</i> <i>Eucalyptus</i> spp. Others	Karkloof
Valley thicket	<i>Jacaranda mimosifolia</i> <i>A. mearnsii</i> <i>Melia azedarach</i> <i>Rubus spp</i> <i>Lantana camara</i> <i>Solanum mauritianum</i> <i>Chromolaena odorata</i> <i>Eucalyptus</i> species <i>Opninta</i> species (prickly pears)	Dryland sugarcane <i>Eucalyptus</i> spp. Others	Noodsberg
Coastal bushveld/grassland	<i>Chromolaena odorata</i> <i>Solanum mauritianum</i> <i>Lantana camara</i> <i>Psidium guajava</i> <i>Caesalpinia decapetala</i> <i>Schinus terebinthifolius</i> Others	<i>Eucalyptus</i> spp. Irrigated sugarcane Others	Hluhluwe
Riparian fynbos	<i>Acacia longifolia</i> <i>A saligna</i> <i>A mearnsii</i> <i>Pittosporum undulatum</i> <i>Rubus</i> species	<i>Pinus</i> spp. Others	Jonkershoek





Fig. 2 Natural vegetation research sites. From top: Moist upland grassland at Cathedral peak and Weatherley, Valley thicket at Noodsberg, Coastal bushveld/grassland at Bonamanzi and Riparian fynbos at Jonkershoek

## 2.2.2 Moist upland grassland

Total evaporation of moist upland grassland was measured within the Weatherley catchment (31°06'S, 38°21'E; 1300 m a.m.s.l) situated approximately 5 km south west of Maclear, and covers an area of approximately 1.5 km<sup>2</sup>.

Sixteen different soil forms were identified within the 1.5 km<sup>2</sup> catchment, and include the Hutton, Clovelley, Kroonstad, Katspruit, Wesleigh, Oakleigh and Tukulus soil forms (Lorentz, 2001).

The mean annual precipitation of this site was 740 mm and the mean annual A-pan evaporation 1488 mm. The average daily winter and summer temperatures is 11 and 20 °C respectively. Severe frost occurs at this site, with snow falls during winter at the high altitudes (Lorentz, 2001).

The total evaporation of moist upland grassland was measured from 01/07/2001 to 31/12/2001.

## 2.2.3 Riparian mistbelt grassland<sup>5</sup>

This site was situated on the Mondi property Gilboa, which lies on the top of the Karkloof hills north of Howick in the KwaZulu-Natal midlands (Figs 1 and 2). The altitude of the site is 1532 m a.m.s.l, and the mean annual precipitation is 867 mm. The Bowen ratio energy balance system was situated near the centre of the Inyamvubu vlei (29° 15' S; 30° 15' E). This vlei is flat and extensive, providing a wind fetch in excess of 150 m in all directions.

The soil surface remained wet throughout the summer, with occasional shallow inundation after heavy rainfall, but dried during the winter months.

The predominant plant species in the vicinity were *Andropogon appendiculatus*, *Helictotrichon turgidulum*, *Tristachya leucothrix*, *Harpechloa falx*, *Helichrysum aureonitens* and *Aristida congesta*.

The total evaporation of riparian mistbelt grassland was measured from 01/09/1998 to 31/08/1999.

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<sup>5</sup> Mistbelt grassland is synonymous with short mistbelt grassland and Natal mistbelt Ngongoniveld.

### 2.2.4 Valley thicket<sup>6</sup>

The valley thicket experimental site (29° 19'S, 30° 49'E; 838 m a.m.s.l) is located near Noodsberg, and covers an area of approximately 0.25 km<sup>2</sup> (Figs 1 and 2).

The lowest average minimum temperature of occurs in June and July (7.5°C), while the highest average maximum temperature occurs in February (26.7°C).

The valley thicket at this site consists of approximately 62% of various tree species clusters and 38% grass patches. Granger (unpublished) gives a description of the various species found at this site.

The soil at the valley thicket site was classified as of the Cartref soil form, and is characterised by being very sandy. The fraction of sand within the different layers ranged between 69 and 88 %.

The total evaporation of valley thicket was measured from 01/05/2002 and measurements are still ongoing.

### 2.2.5 Coastal bushveld/grassland<sup>7</sup>

The coastal bushveld/grassland experimental site is located in the Bonamanzi Nature Reserve (29° 01'S, 32° 16'E; 57.4 m a.m.s.l) (Figs 1 and 2) and covers an area of approximately 0.47 km<sup>2</sup>.

The lowest average minimum temperature occurs in June and July (11°C), while the highest average maximum temperature occurs in January (30.7°C).

The soil at the coastal bushveld/grassland site was a clay loam soil of the Willowbrook soil form. This soil form consists of a Melanic A layer (0-30cm) overlying a G horizon (30 to 270cm) overlying parent material.

Coastal bushveld/grassland at this experimental site consists of approximately 41% bush of various species and 59% grass patches. Granger (unpublished) gives a description of the various species found at this site.

The total evaporation of coastal bushveld/grassland was measured from April 2002 and measurements are still ongoing.

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<sup>6</sup> Valley thicket is synonymous to valley bushveld, kaffrarian thicket and xeric kaffrarian thicket.

<sup>7</sup> Coastal bushveld/grassland is synonymous to coastal forest and thornveld.



## 2.2.6 Riparian fynbos<sup>8</sup>

Total evaporation of fynbos within a riparian site was measured in the upper reaches of the Jonkershoek valley (33° 59.336'S, 18° 57.65'E; 325 m.a.m.s.l) (Figs 1 and 2). This area has a mean annual precipitation is 1324 mm.

The soils are of the Rietfontein family of the Champagne form (Ch2200) with a mineral fraction of coarse sand. The profile is between 0.8 m and 1.5 m deep with very few rocks and stones in the upper half.

Dominant plant species included *Pteridium aquilinum*, *Elegia capensis*, *Cannomois virgata* and *Ischyrolepis gaudichaudiana*. Projected canopy cover of the plant community was approximately 95%, with a mean plant height of 0.5 to 0.75 m.

The total evaporation of riparian fynbos was measured from September 1998 to August 1999.

## 2.3 Bowen ratio energy balance technique

### 2.3.1 Theory

The Bowen ratio energy balance technique estimates the components of the energy balance and therefore the total evaporation above a surface.

The main components of the energy balance above a surface are:

$$R_n - G = LE + H \quad 1$$

where  $R_n$  is the net radiation,  $G$  soil heat flux density,  $LE$  latent heat flux density and  $H$  sensible heat flux density. Solution of equation 1, requires the measurement of the available energy flux density ( $R_n - G$ ) and the air temperature and water vapour pressure profile differences above a surface. The available energy flux density consists of the net irradiance (net incoming and outgoing long and short wave irradiance) and the soil heat flux density (energy that goes into heating the soil). The available energy flux density is partitioned into latent heat flux density

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<sup>8</sup> Fynbos is synonymous to mountain fynbos, false fynbos, Cape fynbos shrubland, Cape shrubland, heathland, macchia, dry fynbos, mesic fynbos, wet fynbos and arid fynbos.

(energy driving evaporation), and sensible heat flux density (energy heating the air). The latent heat flux density is a function of the water vapour pressure profile difference and the sensible heat flux density is a function of the air temperature profile difference.

### 2.3.2 Instrumentation

The net radiation is measured with a net radiometer, installed above the vegetation (Fig. 3). The soil heat flux density is calculated from the average soil temperature, soil water content and soil heat flux measured up to 80 mm below the soil surface. Two Bowen ratio system arms are installed above the grass canopy: the lower area approximately 1 m above the vegetation surface. The separation distance between the arms is approximately 1 m. The air temperature profile difference is calculated from the air temperatures measured with fine wire, type-E thermocouples with a high resolution ( $0.006^{\circ}\text{C}$ ). The water vapour pressure difference between the arms is calculated from the water vapour pressure measured with a dew-10 hygrometer with a resolution of 0.01 kPa.

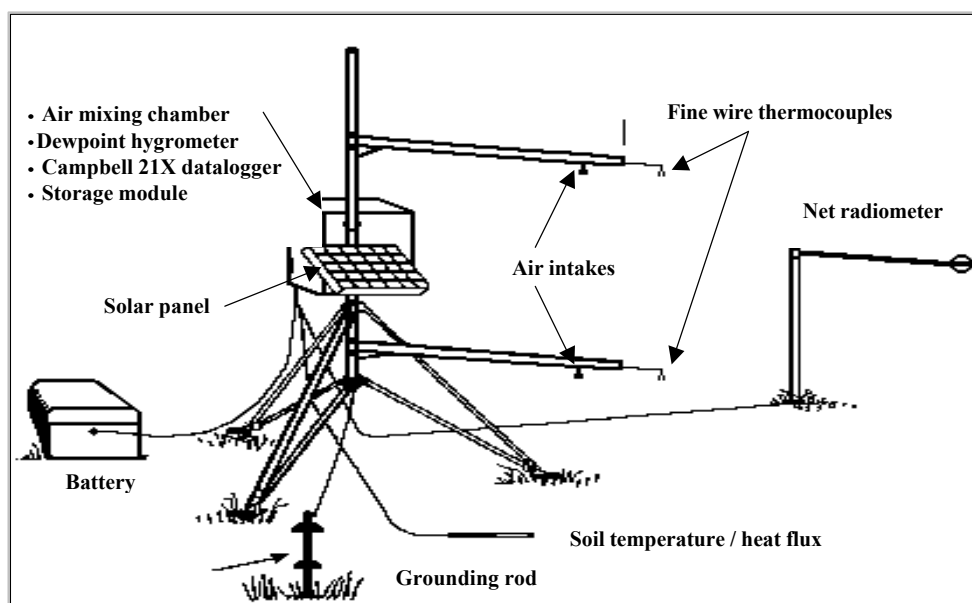


Fig. 3 A diagrammatic representation of the Bowen ratio system

### 3 RESULTS AND DISCUSSION

#### 3.1 Introduction

Calder (1986) lists determining factors (limits) for transpiration of *Eucalyptus* spp. and most other vegetation types as atmospheric demand, physiological mechanisms, canopy structure and the availability of soil water to roots. Differences in the total evaporation of different vegetation types (e.g. single- vs multi-layered or short and tall) can be attributed to differences in the leaf area index (Greenwood *et al.*, 1985; Dunin, 2002), height (Greenwood *et al.*, 1985; Dunin, 2002; Le Maitre and Scott, 1997), length of growing season or seasonality (Greenwood *et al.*, 1985; Dunin, 2002), soil water availability (Silberstein *et al.*, 2001; Dunin, 2002; Calder, 1998; Sharma, 1984; Olbrich *et al.*, 1994) and rooting depth and depth of soil water extraction (Greenwood *et al.*, 1985; Dunin, 2002).

It is hypothesized that the differences in total evaporation of dryland and riparian vegetation will be the result of differences in soil water availability, length of growing season, rooting depth, depth of soil water extraction and leaf area index. The differences in total evaporation of the single- and multi-layered vegetation types will possibly result from differences in height, seasonality, rooting depth, depth of soil water extraction and soil water availability differences.

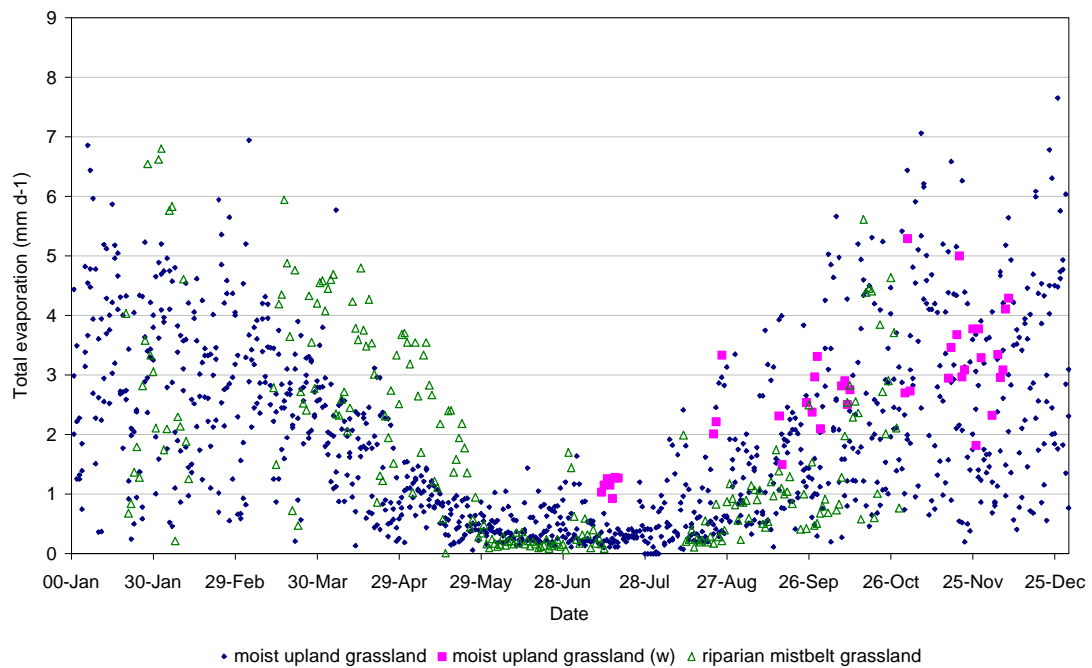
#### 3.2 Total evaporation of 'single layered' natural vegetation types

The moist upland grassland research sites at Cathedral peak and Weatherley respectively, and the mistbelt grassland site were situated within summer rainfall areas, the latter within a riparian area. The seasonal trend in total evaporation was similar for all three vegetation types. Minimum total evaporation ( $< 1 \text{ mm d}^{-1}$ ) was reached during winter and maximum total evaporation during summer (4 to 6  $\text{mm d}^{-1}$ , occasionally  $> 6 \text{ mm d}^{-1}$ ) (Fig. 4). The maximum total evaporation rates during summer coincided with maximum leaf area indices, canopy height, soil water availability and atmospheric demand (reference total evaporation). The minimum total evaporation of moist upland grassland and riparian mistbelt grassland followed frost and senescence of grass during autumn and coincided with minimum atmospheric demand. Soil water was not necessarily limiting the total evaporation during winter.

However, differences existed in the total evaporation of the three vegetation types during autumn and spring, specifically between the dryland (moist upland grassland) and riparian (mistbelt grassland) vegetation types (Fig. 4). Following the maximum

total evaporation during summer, the riparian mistbelt grassland maintained higher total evaporation rates (about 1 to 2 mm d<sup>-1</sup> higher) (Fig. 4) for a longer period (March to end of May) compared to moist upland grassland. This was due to the availability of soil water within the riparian strip. However, the higher total evaporation of riparian mistbelt grassland ended as soon after the occurrence of the first frost of the season and the senescence of the mistbelt grassland. The total evaporation at all sites was low and less than 1 mm d<sup>-1</sup> (Fig. 4). Therefore, rainfall distribution and the termination thereof during summer and autumn, and the subsequent soil water availability to dryland vegetation types determine the total evaporation rates until the onset of frost.

However, during spring, the total evaporation of moist upland grassland exceeded 1 mm d<sup>-1</sup> from the beginning of August, whereas the total evaporation of mistbelt grassland only exceeded 1 mm d<sup>-1</sup> towards the end of September (Fig. 4). The delay in the increase in total evaporation from winter minimum rates of riparian mistbelt grassland depended on physiological differences and seasonality (growth responses of different grasses different), the subsequent increases in leaf area index, height, and differences in the atmospheric demand.



**Fig. 4 Total evaporation of single-layered natural vegetation types**

### 3.3 Total evaporation of ‘multi-layered’ natural vegetation types

Although the valley thicket and coastal bushveld/grassland sites were situated within the summer rainfall region, and the riparian fynbos site within the winter rainfall region of South Africa, the seasonal trends of total evaporation were similar. Maximum total evaporation (6 to 8 mm d<sup>-1</sup>) was reached during summer, and minimum total evaporation (< 1 to 3.5 mm d<sup>-1</sup>) during winter (Fig. 5). The maximum total evaporation of coastal bushveld/grassland and riparian fynbos during summer (6 and 8 mm d<sup>-1</sup>) generally exceeded that of valley thicket generally by about 1 mm d<sup>-1</sup> (Fig. 5). The differences in total evaporation of coastal bushveld/grassland and fynbos, and valley thicket, were due to differences in atmospheric demand, physiological differences in species composition, soil water availability, height, leaf area index and rooting depth. Maximum total evaporation coincided with maximum atmospheric demand and soil water availability, and maximum height and leaf area indices for all vegetation types.

The minimum total evaporation of coastal bushveld/grassland during winter exceeded that of valley thicket and riparian fynbos by 1 to 2 mm d<sup>-1</sup> (Fig. 5). This was mainly the result of differences in atmospheric demand (coastal bushveld/grassland vs fynbos) and soil water availability, root water extraction and grass senescence (coastal bushveld/grassland vs valley thicket).

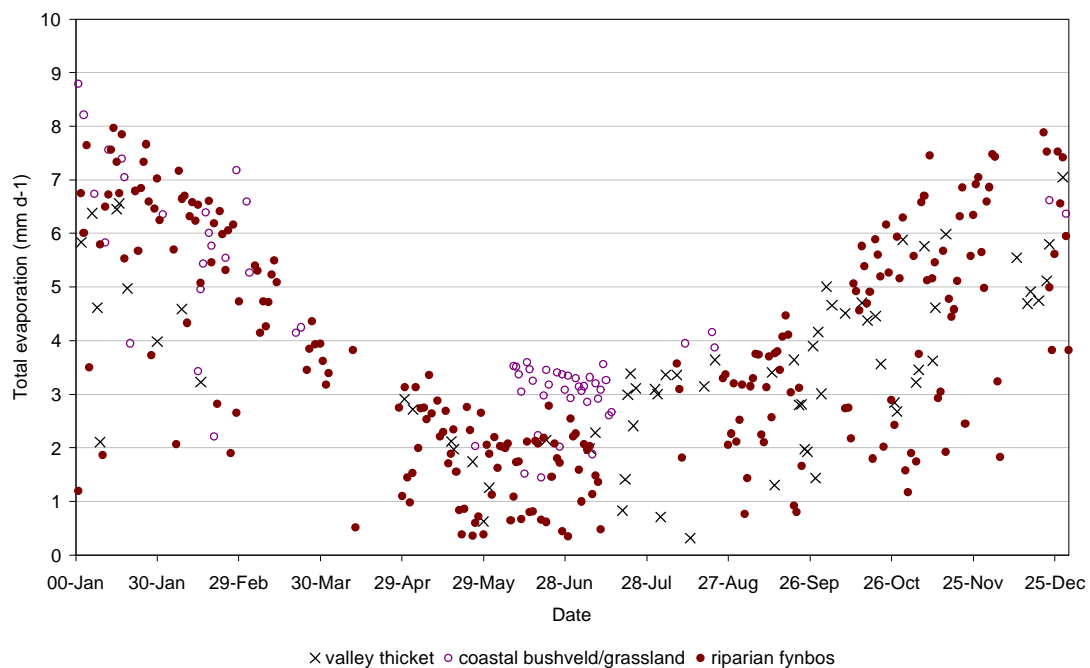


Fig. 5 Total evaporation of multi-layered natural vegetation types

However, from the available and corresponding total evaporation data sets for all three vegetation types during autumn (2 to 5 mm d<sup>-1</sup>) and spring (< 1 mm d<sup>-1</sup> during cloudy days to 5 mm d<sup>-1</sup>), it is clear that the total evaporation rates of all three vegetation types were similar and changed with atmospheric demand (Fig. 5).

Therefore, differences in total evaporation of coastal bushveld/grassland, valley thicket and fynbos are a result of differences in atmospheric demand, and soil water availability between sites, as well as seasonality, height, leaf area indices and possible rooting depths and depth of soil water extraction of different species within the vegetation types.

### **3.4 Comparison of total evaporation for ‘single layered’ and ‘multi-layered’ natural vegetation types**

The maximum total evaporation of the multi-layered vegetation types, valley thicket, coastal bushveld/grassland and riparian fynbos measured during summer exceeded that of the single-layered moist upland grassland and riparian mist belt grassland by 1 to 2 mm d<sup>-1</sup> (Fig. 6). However, the total evaporation of riparian mistbelt grassland was occasionally similar to that of multi-layered natural vegetation types. The higher total evaporation of valley thicket, coastal bushveld/grassland and riparian fynbos were the result of the greater height, broader root distribution and subsequent better utilization of soil water over the whole soil profile and higher atmospheric demand.

A similar trend was found in the total evaporation measured for during winter: the total evaporation of the multi-layered vegetation types exceeded that of the single layered vegetation types by 0.5 mm d<sup>-1</sup> (cloudy days) to 3 mm d<sup>-1</sup> (Fig. 6). The main reason for the lower total evaporation for single layered vegetation types compared to multi-layered vegetation types (< 1 mm d<sup>-1</sup> vs < 1 to 3.5 mm d<sup>-1</sup> respectively) during winter, were seasonality and senescence following the first frost during autumn or winter.

However, during autumn, before the onset of frost and the subsequent senescence of the grasses, the total evaporation of riparian misbelt grassland were similar to the total evaporation of valley thicket, coastal bushveld/grassland and riparian fynbos and exceeded the total evaporation of moist upland grassland by about 1 mm d<sup>-1</sup>. The total evaporation differences were due to differences in atmospheric demand, and soil water availability (Fig. 6).

However, during spring, the total evaporation of moist upland grassland was similar to that of riparian fynbos, valley thicket and exceeded that of the riparian mistbelt

grassland<sup>9</sup>. This was mainly due to differences in atmospheric demand and physiological differences between these vegetation types.

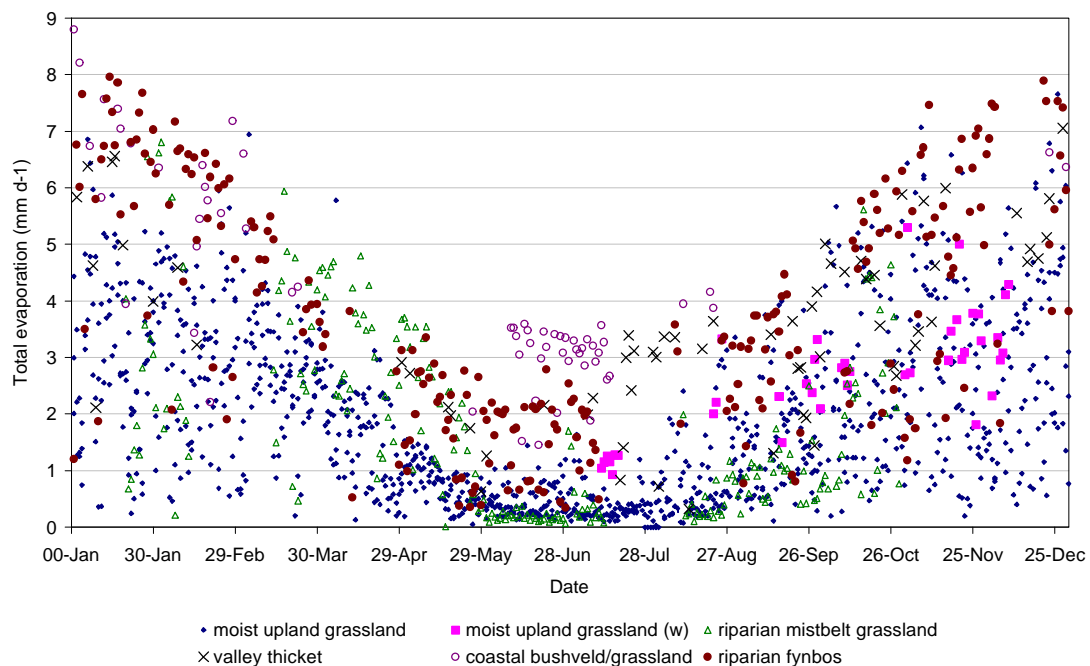


Fig. 6 Total evaporation of moist upland grassland at Cathedral peak, and Weatherley, riparian mistbelt grassland, valley thicket, coastal bushveld/grassland and riparian fynbos

### ***3.5 Comparison of the total evaporation of natural vegetation types under dryland and riparian conditions***

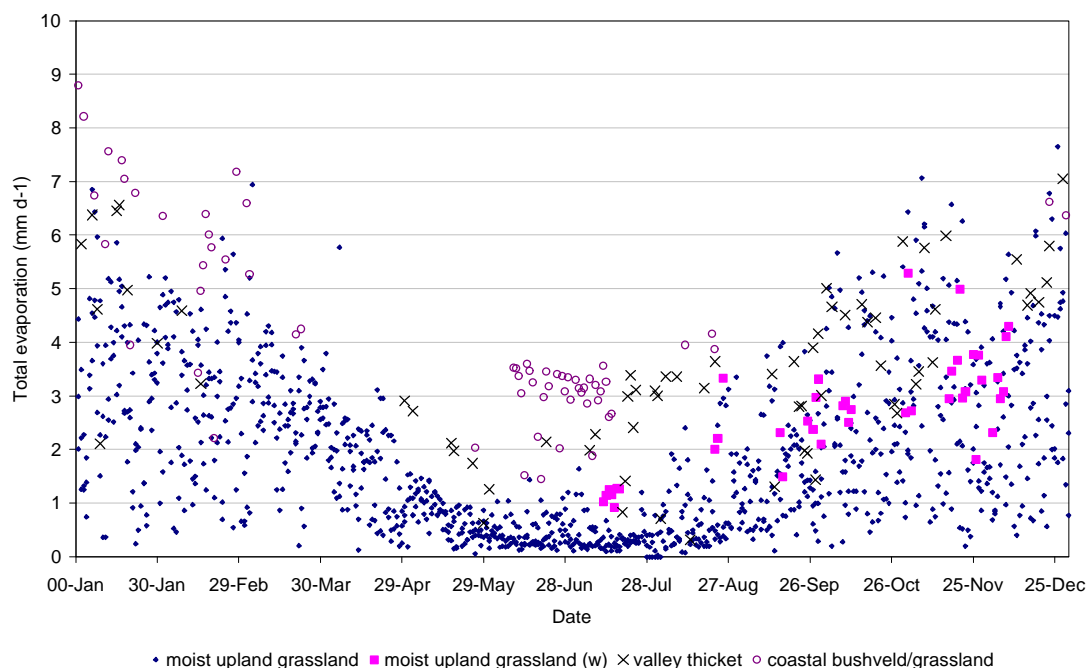
The total evaporation of coastal bushveld/grassland exceeded that of valley thicket and moist upland grassland during summer, autumn and winter by 0.5 to 2 mm d<sup>-1</sup>.

However, during spring the total evaporation of these vegetation types were similar and ranged between 2 and 4 mm d<sup>-1</sup> (Fig. 7). The high and similar total evaporation of moist upland grassland and valley thicket and coastal bushveld/grassland were due to the start of the new growing season, with the grasses of moist upland grassland growing actively (LAI increase). The distinct higher total evaporation of coastal bushveld/grassland and valley thicket, compared to that of moist upland grassland during autumn and winter (following frost) are the result of differences in seasonality of these vegetation types and atmospheric demand. Moist upland grassland reached senescence following the first frost in autumn, which reduces the total evaporation from this vegetation type to only soil evaporation. However, the tree and shrub species within the valley thicket and coastal bushveld/grassland vegetation types continued

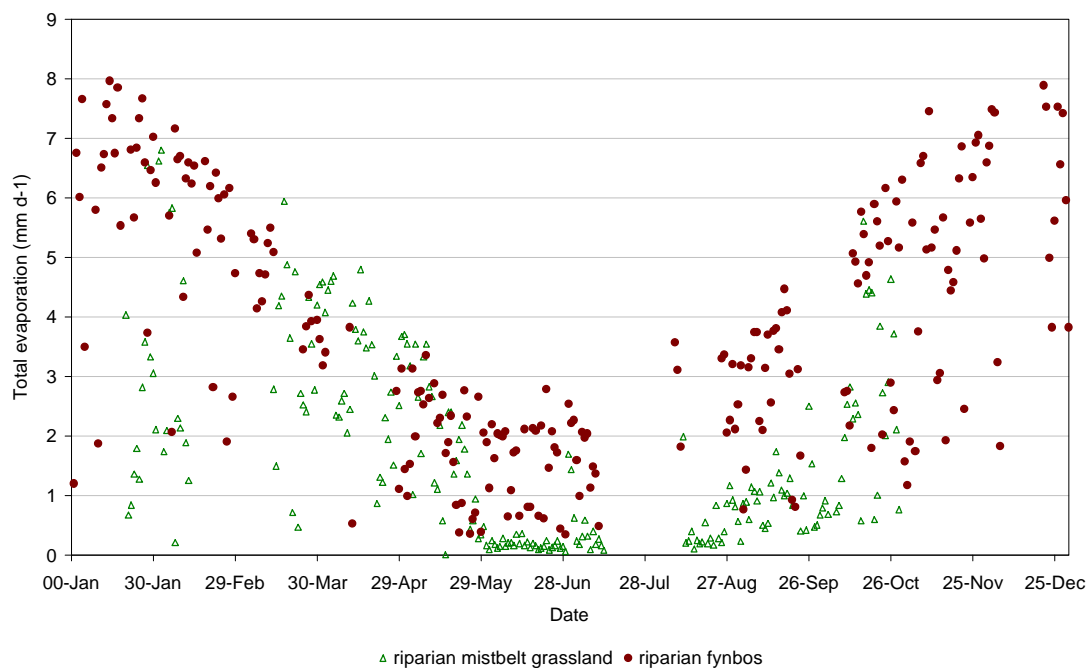
<sup>9</sup> Total evaporation of coastal bushveld/grassland during spring was not available.



transpiration throughout autumn and winter, although some of the grass species within these vegetation types reached senescence.



**Fig. 7** Total evaporation of dryland natural vegetation types: moist upland grassland at Cathedral peak (moist upland grassland) and Weatherley (moist upland grassland (w)), valley thicket, coastal bushveld/grassland



**Fig. 8** Total evaporation of natural vegetation types occurring in riparian zones

The difference in total evaporation between these vegetation types during autumn was possibly due to soil water availability limitations, affecting the shallow-rooted moist upland grassland more than the deep-rooted valley thicket and coastal bushveld/grassland. The total evaporation differences are also the result of differences in atmospheric demand (highest at valley thicket and coastal bushveld/grassland), and the associated physiological responses of the vegetation types to these differences. Therefore, seasonality, and the associated physiological differences, the atmospheric demand and soil water availability for the different vegetation types determine the total evaporation of dryland vegetation types.

The riparian sites, mistbelt grassland and fynbos, were situated within different seasonal rainfall zones: the mistbelt grassland within the summer rainfall region and the fynbos within the winter rainfall region. The seasonal differences in total evaporation between these two sites will be determined mainly by climatic and plant physiological differences. During summer ( $6$  to  $8 \text{ mm d}^{-1}$ ) and autumn ( $2$  to  $4 \text{ mm d}^{-1}$ ) high and similar total evaporation rates were measured until the occurrence of frost at the mistbelt grassland site during autumn. Thereafter, the total evaporation of fynbos exceeded that of the mistbelt grassland by up to  $2 \text{ mm d}^{-1}$  (Fig. 8). Despite the availability of soil water at the mistbelt grassland site, the total evaporation is reduced to less than  $0.5 \text{ mm d}^{-1}$ , following the senescence of grass. The differences in total evaporation between these two sites are maintained during spring, with the total evaporation of fynbos exceeding that of mistbelt grassland by up to  $2 \text{ mm d}^{-1}$ . The higher total evaporation at the fynbos site is the result of the differences in the physiology of the species within these vegetation types, and the slower response/growth of the mistbelt grassland during spring compared to the immediate response of the fynbos to the change in atmospheric demand. Therefore, the total evaporation of natural vegetation within riparian zones and differences between, are the result of atmospheric demand differences, and physiological and seasonality differences.

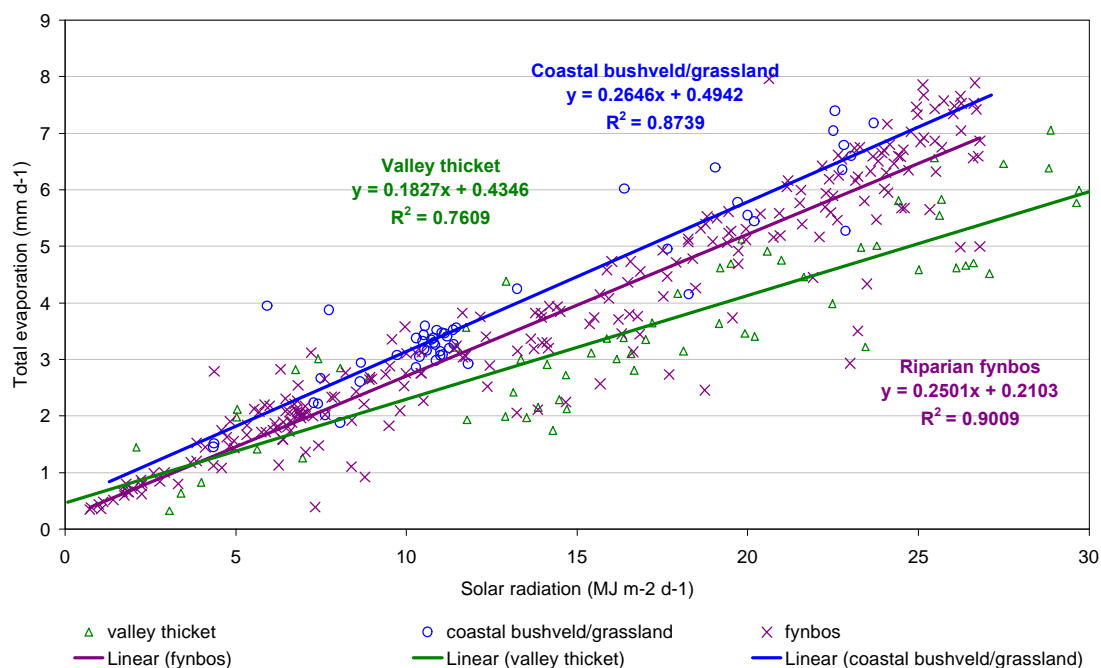
### **3.6 Relationship between total evaporation and solar irradiance**

Linear relationships ( $r^2$ 's  $0.76$ ,  $0.87$  and  $0.90$  for valley thicket, coastal bushveld/grassland and riparian fynbos respectively) were found between the total evaporation of all three multi-layered vegetation types and the solar irradiance measured at these sites<sup>10</sup> (Fig. 9). However, linear relationships were not distinct for the single-

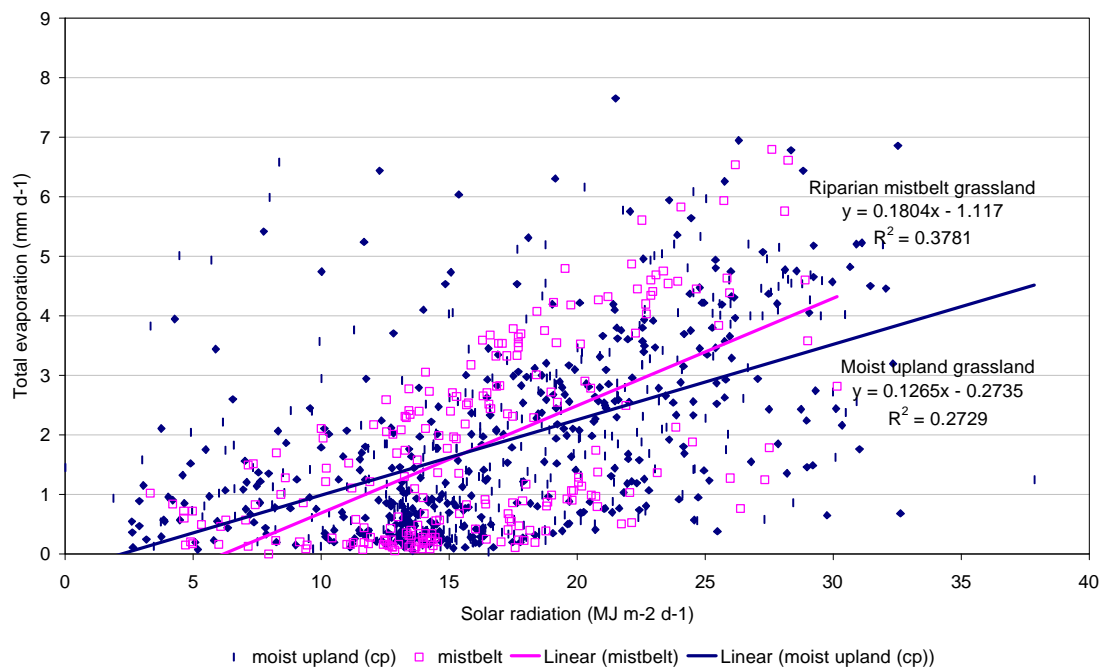
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<sup>10</sup> The total evaporation for valley thicket and coastal bushveld/grassland were patched with data from SASEX.

layered vegetation types ( $r^2$  of 0.2729 and 0.3781 for moist upland grassland and riparian mistbelt grassland respectively) (Fig. 10).



**Fig. 9 Relationships between total evaporation and solar irradiance at the valley thicket, coastal bushveld/grassland and riparian fynbos**



**Fig. 10 Relationships between total evaporation and solar irradiance of moist upland grassland site at Cathedral peak (moist upland), and mistbelt grassland site (mistbelt)**

The strong linear relationships for valley thicket, coastal bushveld/grassland and riparian fynbos suggest that the total evaporation were governed by solar radiation and were not limited by soil water availability. The lower  $r^2$  for valley thicket compared to that of coastal bushveld/grassland and riparian fynbos could suggest that the total evaporation of valley thicket was occasionally limited by soil water availability (Fig. 9), whereas the high  $r^2$  for riparian forest ( $r^2 = 0.9009$ ) (Fig. 9), suggest hardly any limitation on the total evaporation by soil water availability. This is expected as the fynbos is situated within a riparian zone.

Therefore these linear relationships between total evaporation and solar irradiance for valley thicket, coastal bushveld/grassland and riparian fynbos might be of use in the estimation of annual water use (total evaporation) of these vegetation types. However, no independent data set was available to test this.

### **3.7 Comparison of the total evaporation of natural vegetation types and other vegetation types (commercial, riparian) under dryland and riparian conditions**

Various alien invasives and commercial ‘crops’ occur in close proximity of the research sites for total evaporation of natural vegetation (Table 2). Some total evaporation data is available for these invasives and commercial crops in comparative areas (Fig. 11 and Table 3). A few examples are discussed below and illustrate the differences between the total evaporation of natural and other vegetation types.

Dye *et al.* (2001) compared the water use of riparian fynbos and riparian mistbelt grassland with the riparian invading *Acacia mearnsii* within the Jonkershoek and Karkloof (Gilboa) areas respectively. At both sites, the total evaporation of the natural vegetation types within the riparian area was 143 and 535 mm yr<sup>-1</sup> respectively lower than the total evaporation of the invading *A. mearnsii*.

Jarman and Everson (2000) reported on the total evaporation of dryland sugarcane, *Eucalyptus mcarthurri*, and *Acacia mearnsii* at a site approximately 50 km from the valley thicket site. The total annual evaporation of valley thicket (1241 mm yr<sup>-1</sup>), as estimated as a function of the solar irradiance (Fig. 7), were between 220 and 481 mm yr<sup>-1</sup> higher than that of dryland sugarcane, between 5 and 377 mm yr<sup>-1</sup> lower than *E. mcarthurri*, and between 193 and -127 mm yr<sup>-1</sup> higher than *Acacia mearnsii*.

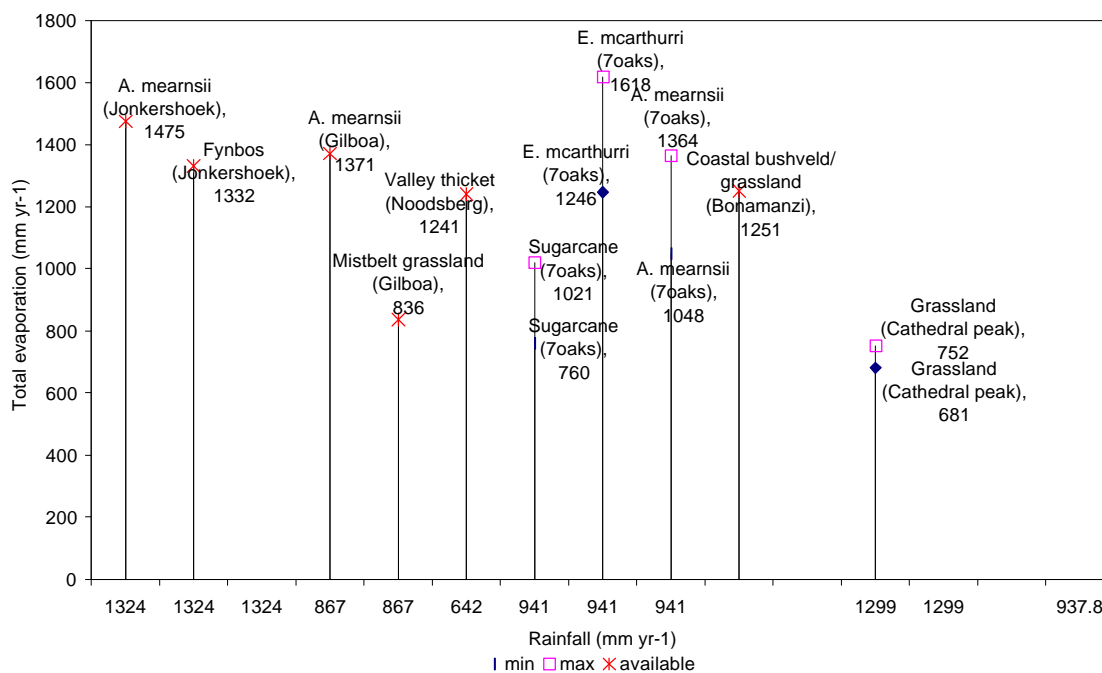


Fig. 11 Total evaporation natural vegetation types and commercial ‘crops’ within similar areas where min, max and available refer to the minimum, maximum and only available total data for a specific site

Table 3 Total evaporation rate ranges during different seasons measured for different vegetation types – natural vegetation types, invaders and commercial crops

Vegetation type	Total evaporation (mm d <sup>-1</sup> )				Location
	Summer	Autumn	Winter	Spring	
Riparian fynbos	5.5 to 8	2 to 4.5	0.5 to 2.5	1.2 to 7.5	Jonkershoek
<i>A. mearnsii</i>					Karkloof
Riparian mistbelt grassland	4.5 to 6.8	1.5 to 5	< 0.5	0.5 to 5.5	Karkloof
Valley thicket	5 to 7	2 to 3	1 to 3.5	1.5 to 6	Noodsberg
Dryland sugarcane	2 to 7.8	0.5 to 2.5	0.5 to 2	1 to 5	7oaks
<i>E. mcarthurri</i>	4 to 10	2 to 4	2 to 3.5	2 to 7	7oaks
<i>A. mearnsii</i>	4 to 9	1 to 2	0.5 to 2	1.5 to 7	7oaks
Coastal bushveld/grassland	5 to 8.2	2 to 4.2	1.5 to 3.5	3.8 to 6.5?	Hluhluwe
Moist upland grassland	4 to 6	0.5 to 4	< 1	0.5 to 5.8	Cathedral peak
Moist upland grassland	n/a	n/a	± 1	1.5 to 5.5	Weatherley

## 4 CONCLUSIONS

The six natural vegetation types studied (moist upland grassland, riparian mistbelt grassland, valley thicket, coastal bushveld/grassland and riparian fynbos) can be divided in terms of their structure (single-layered vs multi-layered), and the soil water availability (riparian vs dryland).

The seasonal trends within total evaporation of moist upland grassland, riparian mistbelt grassland, valley thicket, coastal bushveld/grassland and riparian fynbos are the same, with minimum total evaporation rates reached during winter and maximum total evaporation rates during summer.

Maximum total evaporation reached during summer for multi- and single-layered vegetation types, under both riparian and dryland conditions were similar, with the total evaporation of multi-layered vegetation types exceeding that of single-layered vegetation types by at least  $1 \text{ mm d}^{-1}$ . Differences in total evaporation was caused by differences in atmospheric demand.

Differences existed in the minimum total evaporation of multi- and single-layered vegetation types during winter, following frost (up to  $3 \text{ mm d}^{-1}$ ). This was the result of grass (moist upland grassland and riparian mistbelt grassland) senescence during winter following frost, whilst the shrub and tree species within the multi-layered vegetation types continued transpiration.

Total evaporation differences between multi- and single-layered (seasonal) vegetation types during autumn were dependent on soil water availability, atmospheric demand and the onset of frost and subsequent grass senescence. However, before the onset of frost, the total evaporation from a single-layered riparian vegetation type like mistbelt grassland, was similar to that of the multi-layered vegetation types and exceeded the total evaporation of a dryland single-layered vegetation type (moist upland grassland).

The total evaporation differences between different vegetation types during spring were dependent on soil water availability, atmospheric demand, plant physiology and increased leaf area index. The total evaporation of single-layered dryland vegetation like moist upland grassland was similar to the total evaporation of multi-layered vegetation types during spring.

Good relationships were found between the total evaporation of multi-layered vegetation types and the solar irradiance measured at these research sites. This suggests that the total evaporation of multi-layered vegetation types is governed by solar irradiance and that it is not limited by soil water availability.

## 5 RECOMMENDATIONS

The possible use of linear relationships between total evaporation and solar irradiance for the estimation of total evaporation of multi-layered natural vegetation types like valley thicket, coastal bushveld/grassland and riparian fynbos need to be investigated further.

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- WRC report no. K5/808 (Riparian fynbos, Riparian mistbelt grassland).

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