Evaluating the long-term water balance of arid zone stream bed vegetation using evapotranspiration modelling and hillslope runoff measurements

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Abstract

The difference between long-term actual evapotranspiration (AET) and precipitation (P) provides a useful indication of the extent to which a site retains or loses water resources, and therefore of the likely occurrence of specific land degradation processes. Sink areas (AET ≫ P) receive lateral water inputs from other parts of the catchment. In arid and semi-arid environments these areas are frequently found in, or next to, the stream beds of ephemeral rivers and are often characterised by intensive land use or high conservation values. For both types of land use it is important to know if, and how much, AET exceeds P, and where the lateral water inputs come from. Thick sedimentary fills in the stream bed, variable climate conditions and ephemeral flow conditions pose specific difficulties to the evaluation of the water balance of these sites. The objective of this study was to develop an approach to explore the relative importance of lateral water inputs to shrub stands growing in thick sedimentary fills of semi-arid ephemeral rivers. The approach is based on (i) estimating long-term AET balances in the channel sediments and (ii) assessing whether these inflows originate mainly from surrounding hillslopes or from the upstream part of the catchment. A physically based evapotranspiration model for sparse vegetation was used to estimate the long-term AET rates. The relative importance of hillslope runoff and channel flow was evaluated in a semi-quantitative fashion from a combination of surface area estimates and mostly published values of soil hydrological parameters. The approach was developed and tested in a selected stand of Retama sphaerocarpa shrubs in a stream bed at the Rambla Honda field site (Tabernas, Almería, SE Spain). Predictions from the evapotranspiration model, which were found to be accurate during previous studies at Rambla Honda, show that actual evapotranspiration (AET) largely exceeds precipitation (P) at annual scales. The estimated deficit may be compensated by: (a) infiltration of local rainfall during extreme events; (b) runon from the surrounding hillslopes; or (c) infiltration of channel flow during flash floods originating from the upper part of the catchment. Results show that possibilities (a) and (b) cannot explain the water deficit. Deep storage of water during floods in the main channel, however, can be as much as 60–150 mm per event, and may have been 160–400 mm per year during the study period (1994–1997). This amount is large enough to replenish the annual deficit of ca. 100 mm per year found in the R. sphaerocarpa stand. These results imply that under current climate conditions land use changes in the upper sections of the Rambla Honda basin are more important for the persistence of the stream bed vegetation of our site than the land cover and runoff from surrounding hillslopes. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Retama sphaerocarpa; Evapotranspiration modelling; Dry river bed; Semi-arid environment; Flash flood; Lateral water input

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1. Introduction

In dryland environments, site water balance may provide very useful information to land managers. The long-term difference between actual evapotranspiration (AET) and precipitation (P) is particularly relevant because it indicates to what extent water is retained and used (e.g. for primary production) on site or is lost from the site. Where $P \gg AET$, water losses through runoff or deep drainage are likely to be important, land condition can be expected to be poor, and associated processes such as soil erosion may be active (Ludwig et al., 1997; Boer, 1999). On the contrary, where $P \ll AET$, water inputs by overland or sub-surface flow can be expected to outweigh the losses by runoff and deep drainage. These sites act as sinks for water and other resources in the landscape, and provide favourable conditions for high productivity and groundwater recharge, but also for specific problems such as water logging and salinization (Barrow, 1991; Farrington and Salama, 1996; Greiner, 1997). The ‘over-performance’ of the vegetation in sinks, as compared to areas where $AET = P$, provides opportunities to identify their locations on satellite imagery (Boer, 1999).

Owing to the local richness and reliability of resources, in arid and semi-arid environments intensive land use often focuses on sink areas, particularly on the channels of ephemeral rivers and the areas immediately adjacent to the stream bed. In non-agricultural areas, stream bed ecosystems are frequently characterised by high biological diversity and are important for conservation by providing pathways for species dispersal. The stream bed may receive lateral water inputs from the upstream part of the catchment as well as from surrounding hillslopes. Knowledge of the relative importance of these sources is important to evaluate the possible impacts of land use changes elsewhere in the catchment on the stream bed ecosystems. The ephemeral character of the flow conditions and the usually large depth of the sedimentary fills pose specific difficulties to the direct measurement of these lateral inputs, and to the assessment of site water balance in general. As an alternative, the lateral inputs can be estimated indirectly by comparing long-term AET rates with P.

The objective of this study was to develop an approach for exploring the relative importance of lateral water inputs to shrub stands growing in thick sedimentary fills of semi-arid ephemeral rivers. The approach is based on: (i) estimating long-term AET – P balances in the channel sediments; and (ii) assessing whether these inflows originate mainly from surrounding hillslopes or from the upstream part of the catchment. To this purpose we used a physically based evapotranspiration model for sparse vegetation (Domingo et al., 1999) to estimate the long-term AET rates. The relative importance of hillslope runoff and channel flow was evaluated using mostly published values of soil hydrological parameters. The approach was developed and tested at the Rambla Honda field site in Southeast Spain (Puigdefabregas et al., 1996). At this site the AET model was originally developed and parameterised, and supplementary field information was available to check the published values of the main soil hydrological parameters. The Rambla Honda field site is operated by EEZA-CSIC within the framework of the MEDALUS project and other research projects.

2. The approach

In a general form, the long term water balance of a particular site in the landscape (Rockström et al., 1998) can be written as:

$$P + (R_{on} - R_{off}) - D - AET = \Delta S$$

(1)

where $P$ is precipitation, $R_{on}$ and $R_{off}$ are, respectively, runon and runoff by overland flow or sub-surface flow, $AET$ is actual evapotranspiration, $D$ is deep drainage or percolation, and $\Delta S$ is the change in soil water storage.

Focusing on a section of an ephemeral channel, Eq. (1) can be re-written as follows:

$$P + (Q_{ui} - Q_{uo}) + (Q_{si} - Q_{so}) - AET - Q_p + \Delta S_u + \Delta S_s = 0$$

(2)

where $S_u$ and $S_s$ are unsaturated and saturated storage in the sediment fill. $Q_{ui}$ and $Q_{si}$ are inflows to these stores. $Q_{uo}$ and $Q_{so}$ are the outflows. $Q_p$ is deep percolation to ground water.

Assuming that the channel section and its vegetation are hydrologically in long term steady state, storage changes can be regarded as negligible.
Fig. 1. Location and topographic map of the Rambla Honda field site showing the position of the three H-type gauging flumes. The upper flume (AHF3) drains a S. tenacissima-covered area of 0.29 ha, the middle flume (AHF2) drains an area of 3.88 ha, covered by Anthyllis cytisoides, while the catchment area draining to the lower flume (AHF1) is 4.65 ha. Also shown are the location of the permanent weather station (●) and of the instrumented stand of R. sphaerocarpa (★).
Accepting a further assumption that net inputs to the unsaturated storage are provided by infiltration in the channel during floods \((Q_f)\) and net changes due to lateral unsaturated flow through the channel sediment fill are negligible, Eq. (2) can be simplified to:

\[ P + Q_l + (Q_{si} - Q_{so}) - AET - Q_p = 0 \]  

(3)

If the phreatic level is located deeply, beyond reach of plant roots, or does not exist, as is often the case in arid zone stream channels, saturated fluxes can be disregarded. If the permeability of the channel bedrock, beneath the sediment fill is negligible, the term \(Q_p\) can also be neglected. In such conditions the equation can be further reduced to:

\[ P + Q_l - AET = 0 \]  

(4)

\(Q_l\) can be calculated as:

\[ Q_l = Q_{fh} + Q_{fd} \]  

(5)

the sum of infiltrated runon from lateral contributions from adjacent hillslopes \((Q_{nh})\) and from flash floods through the main channel \((Q_{fd})\). Eq. (4) therefore becomes:

\[ Q_{fh} + Q_{fd} = AET - P \]  

(6)

To evaluate Eq. (6) we measured \(P\) and estimated AET with a parameterised and validated evapotranspiration model (Domingo et al., 1999, 2000) for a continuous period of three hydrological years (1994–1997). Contributions from adjacent hillslopes \((Q_{nh})\) were estimated from the published values of hillslope runoff parameters, and checked using hydrological records of a small instrumented catchment. The lateral contributions of flash floods from the upper sections of the drainage basin \((Q_{fd})\) were estimated from the observed frequency, duration and depth of flooding in the main channel, and measured soil hydraulic properties.

3. Materials and methods

3.1. Site description

3.1.1. The Rambla Honda field site

Field work was conducted at the Rambla Honda field site, near Tabernas, Almería, Spain \((37°\ 8′\ N, 2°\ 22′\ W, 630\ m\ altitude)\). Tabernas is partially surrounded by the Betic cordillera and leeward of the Sierra de los Filabres, Sierra Nevada and Sierra de Gádor ranges (Fig. 1). A detailed description of the field site is given by Puigdefábregas et al. (1996). The climate is semi-arid, with a mean annual temperature of 16°C. Mean annual rainfall is 279 mm (10-year record) which falls mainly in the winter season, followed by a dry period centred on the months of June–September. A hillslope sector of 18 ha with a median slope angle of 22° is operating as field site within the framework of the MEDALUS project (Brandt and Thornes, 1996) and other research programmes. The hillslope stretches from the dry bed of an ephemeral river (Rambla Honda), at 630 m altitude to the water divide at 800 m (Fig. 1). The area is characterised by a catena of soils and associated vegetation types. In the upper hillslope Typic Torriorthent soils and Stipa tenacissima L. tussocks occur on micaschist bedrock, while Typic Torrifluvent soils with Anthyllis cytisoides L. and Retama sphaerocarpa(L.) Boiss. shrubs are dominant, respectively, in the upper and lower parts of the alluvial fan sectors. R. sphaerocarpa is also abundant in the dry stream bed. The sedimentary fill of the stream bed is about 30 m thick, no saturated layer has ever been detected, and the permeability of the underlying micaschist bedrock can be assumed to be very low. In the upper hillslopes, S. tenacissima used to be harvested for cellulose, while the footslope sedimentary fill was used for the rainfed cultivation of cereals. Both types of land use ceased about 35 years ago.

3.1.2. The Retama sphaerocarpa stand

Evaluation of Eq. (6) was carried out in a representative stand of R. sphaerocarpa situated in the middle of the stream bed. R. sphaerocarpa is a woody leguminous evergreen shrub, that grows up to 4 m tall and 6 m diameter, with cylindrical photosynthetic stems (cladodes) and covers about 30% of the river bed (Domingo et al., 1999). Physiological research on R. sphaerocarpa revealed a very open canopy (Domingo et al., 1996, 1997) and an extensive root system capable of extracting water from more than 25 m depth (Haase et al., 1996a). R. sphaerocarpa was also found to have a low rainfall interception rate and a canopy structure that optimises drainage of the effective rainfall as stemflow at the expense of canopy drip (Domingo et al., 1998). These traits could play...
an important role in directing rainfall to deeper soil layers adjacent to the plant roots. The open canopy and extensive root system of *R. sphaerocarpa* are an indication of a water use strategy that aims at maximising transpiration by creating access to large volumes of soil water. *R. sphaerocarpa* shrubs are distributed randomly, with distances of 1.0–2.0 m between shrubs and inter-shrub clearings of 2.7–6.1 m diameter (Haase et al., 1996b).

Micro-meteorological variables described below were measured at a reference height ($z_r$) of 5.0 m. The average height of the *R. sphaerocarpa* individuals ($h$) was approximately 2.0 m and the assumed mean surface flow height ($z_m$) was 0.75$h$ (Brenner and Incoll, 1997; Domingo et al., 1999).

3.2. Precipitation measurements

Precipitation was measured by a tipping bucket raingauge which provided readings of intensity and total rainfall volume per storm event. The raingauge is part of an automatic weather station (Fig. 1) at approximately 100 m from the selected *R. sphaerocarpa* stand.

3.3. Evapotranspiration assessment

The evapotranspiration model used in this study (Domingo et al., 1999) is an extension form of a previous model developed by Brenner and Incoll (1997). Brenner and Incoll’s model combined the approach of Shuttleworth and Wallace (1985), in which the vegetation is assumed to be uniformly distributed over a surface, and the approach of Dolman (1993) in which energy is partitioned over plants/shrubs and bare soil on the basis of their respective fractional covers. Brenner and Incoll extended Dolman’s approach by explicitly quantifying evaporation from both the soil surface under the plant canopy and from the soil surface in the open. Parallel energy balances were calculated, for shrub canopy, soil under shrub and bare soil surfaces.

The original Brenner and Incoll model was refined, parameterised and validated through a series of field experiments by Domingo et al. (1999, 2000) carried out in a representative stand of *R. sphaerocarpa* at the Rambla Honda field. Parameterisation of the new model was concerned with three components of the original model that still required further field support: (a) net radiation absorbed by each component of the land cover mosaic; (b) soil aerodynamic resistances; and (c) soil surface resistances (Domingo et al., 1999, 2000). Model predictions were compared with evapotranspiration, measured by a Bowen Ratio Energy Balance (BREB) and transpiration, measured by sap flow of the stems of the shrubs. In this study we assume that the parameters and equations described and validated by Domingo et al. (1999, 2000) are valid for the whole period of time analysed here (i.e. 1994–1997).

The driving variables required to run the evapotranspiration model consist of measurements of air temperature, wind speed, air humidity and net radiation at reference height ($z_r = 5$ m), as well as the soil water content (both for bare soil and soil under shrub), plant leaf area index and fractional vegetative cover. We also obtained estimates of potential evapotranspiration (PET) with the model by setting the vegetation and soil surface resistances equal to zero. Model simulations were carried out using Borland Pascal for Windows version 7.0 for the period from September 1994 to August 1997. This period is representative of the long-term climate conditions in the region (Lázaro et al., 2000), and was assumed to be sufficiently long to evaluate the terms of Eq. (6). The meteorological driving variables where obtained as follows:

(A) From 5 April 1997 to 28 May 1997, divided in two sub-periods (named campaigns 1 and 2) AET estimates were calculated by running the model with input measurements taken at the selected *R. sphaerocarpa* stand.

(B) From 1 September 1994 to 31 August 1997, AET estimates were calculated by running the model with meteorological input data from the automatic weather station of the Rambla Honda field site at ca. 100 m from the studied *R. sphaerocarpa* stand (Fig. 1). The meteorological records of this weather station overlapped with the measurements
obtained in the *R. sphaerocarpa* stand during campaigns 1 and 2, so that correlations between the measurements for net radiation, air temperature, wind speed and air humidity at both weather stations could be analysed.

Therefore measurements (A) served to inter-calibrate AET estimates obtained with the permanent weather station at Rambla Honda which can be used for long-term AET monitoring.

### 3.3.1. Measurements of net radiation, wind speed and air temperature and humidity

In the *R. sphaerocarpa* stand aspirated humidity sensors (MTH-A1, ITC, Almería, Spain) measured air temperature and humidity at reference height ($z_r$). A cup anemometer (A100, Vector Instruments, Rhyl, UK) measured wind speed at $z_r$. A net radiometer (Q7, REBS, Seattle, WA, USA) measured net radiation ($R_n$) from the whole surface at reference height. All measurements were recorded every 1 s by a CR10 datalogger (Campbell Scientific Ltd, Logan, Utah, USA) and averaged every 20 min.

The automatic weather station of the Rambla Honda field site (Fig. 1) measured wind direction (potentiometric wind vane W200P, Vector Instruments, Rhyl, UK), wind speed (A100, Vector Instruments, Rhyl, UK), air temperature (LM35CZ, National Semicond.), solar radiation (CM6B, Kipp and Zonen, Delft, Holland) and relative humidity (EE Electronik HC500). Measurements were taken every second and averaged every 5 min. For air temperature, vapour pressure deficit, wind speed and net radiation, we found the following relationships between the values measured by the permanent weather station and the ones observed within the *R. sphaerocarpa* stand during campaigns 1 and 2 (sub-script ‘Stand’ is used for measurements in the stand and sub-script ‘WS’ for measurements from the automatic weather station).

Air temperature ($t$):

$$t_{\text{Stand}} = 0.94 \ t_{\text{WS}} + 1.22$$

($r^2 = 0.948; n = 417; p < 0.05$)

Vapour pressure deficit ($D$):

$$D_{\text{Stand}} = 1.014D_{\text{WS}} + 0.18$$

($r^2 = 0.901; n = 420; p < 0.05$)

Wind speed ($u$):

$$u_{\text{Stand}} = 0.83u_{\text{WS}} + 0.69$$

($r^2 = 0.552; n = 600; p < 0.05$)

Net radiation ($R_n$):

$$R_{n\text{ Stand}} = 0.9913R_{n\text{ WS}} + 18.045$$

($r^2 = 0.989; n = 656; p < 0.05$).

### 3.3.2. Soil water content

Measurements of soil water content ($\theta$) were obtained in two ways:

(a) Since 1996, continuous measurements of volumetric soil water content ($\theta$) have been made with Self Balanced Impedance Bridge (SBIB) probes positioned at 0.25 m depth both under the plant and in clearings with bare soil surface. This soil humidity sensor was developed at the Estación Experimental de Zonas Áridas (CSIC) in Almería, Spain (Vidal, 1994) and has been calibrated against TDR probes, gravimetric moisture measurements and laboratory experiments for a wide range of soil salinity levels and soil temperatures (Vidal et al., 1996). For other applications of the SBIB sensor at Rambla Honda see Puigdefábregas and Sanchez (1996), Puigdefábregas et al. (1998) and Domingo et al. (1999).

(b) In parallel to the monitoring of soil moisture content with the SBIB sensors, non-continuous measurements have been made since 1992 using the gravimetric method, starting just after rainfall and continuing at increasing time intervals of 1, 2, 3, 5, 10, 14, … days until the next rain event. Soil samples for moisture measurements are taken at 0.10, 0.15 and 0.20 m depth.
3.3.3. Leaf area and fractional vegetative cover

Leaf (cladode) area of *R. sphaerocarpa* was estimated from measurements of the transmission of direct beam radiation (DEMON, CSIRO, Canberra, Australia), as described by Brenner et al. (1995) for the same species. Average leaf area index per shrub (*L*a*), defined as the leaf area of the shrub divided by the projected area of the canopy, was 3.03 ± 0.37 in June 1993, and 2.00 ± 0.29 in June 1994 (Brenner and Incoll, 1997). DEMON measurements made on 22 shrub individuals in 1997 produced a *L*a of 2.5 ± 0.15 (Domingo et al., 1999). The average fractional cover (*f*) for the *R. sphaerocarpa* stand, calculated by image analysis of aerial photographs was 0.34 in February 1994 (Brenner and Incoll, 1997) and 0.30 in April 1996 (Domingo et al., 1999). The leaf area index for the plot (*L*), obtained by combining the *f* of the plot with the *L*a of the measured shrubs, was estimated at 0.75 for 1997 and assumed to be constant during the whole modelled period (from September 1994 to April 1998). The potential error in the AET estimates due to the assumption of *L* being constant was assessed by running the model for *L* values in the range 0.68–0.75. This range of *L* values covers the minimum and maximum values for *L*a (2.0–2.5) and *f* (0.34–0.3) observed in 1994 and 1997.

3.4. Lateral water flux

3.4.1. Hillslope runon (*Q*<sub>fh</sub>)

For the estimation of the lateral water inputs from the hillslopes on both sides of the stream bed we considered a 1670 m long section of the stream course (Fig. 1). Because of the topography, hillslopes outside this section are unlikely to deliver runoff directly to the stream bed. Stream lengths and surface areas were determined from a digitised topographic map (1:10,000) of the Rambla Honda area using AUTO-CAD 14 for Windows (Autodesk, Inc.). In this section of the Rambla Honda, the total surface area of the hillslopes on both sides of the stream bed is 167 ha, while the actual stream bed where *R. sphaerocarpa* grows has an area of 71 ha.

The input of lateral water flows from the hillslopes to the stream bed was estimated by assuming a uniform runoff coefficient for the whole hillslope area. This runoff coefficient was estimated in two ways: (i) based on regional runoff estimates published by Thornes and Gilman (1983) taking into account the assumption that hillslope runoff is a continuous phenomenon; and (ii) based on field observations from a first-order basin at the Rambla Honda site. Thornes and Gilman (1983) used simple hydrological models developed by Kirkby (1976) and Scoging and Thornes (1980) to predict annual and extreme event excess water production for different rock types from daily rainfall, annual PET, runoff from other gauged river basins and infiltration parameters. Continuous measurements of hillslope runoff have been made since 1994 for a small part of the area that potentially contributes to the studied stream bed section by three H-type gauging flumes (Fig. 1) equipped with capacitive sensors. For this study we only used the runoff coefficients recorded at the middle flume (AHF2 in Fig. 1). It drains an area of 3.88 ha, and by being located at the intersection of the rocky upperslope and the apex of the alluvial fan this flume provides most insight into the contribution of lateral water flow from the hillslope to the stream bed. Measurements from gauging flume AHF2 presented here cover the period from 17 May 1994 to 5 October 1997.

3.4.2. Infiltration in the channel from flash floods (*Q*<sub>fd</sub>)

We used field information on the long-term infiltration rate (41 mm h<sup>−1</sup>), and saturated hydraulic conductivity (*K*<sub>sat</sub>) (65 mm h<sup>−1</sup>) of the soil at the base of the alluvial fan (Puigdefabregas et al., 1998) to estimate the deep water storage in the river bed during flood events between May 1994 and October 1997. Alternatively, published values for soil hydrological parameters of coarse sandy soils could be used. Flash floods were assumed to have an average duration of 4 h. This figure is based on observations by Harvey (1984), who observed a flood duration of 6–12 h during a 150 mm, 5 h storm in Rambla Honda on 28–29 September 1980, our own visual observations and information from local people. Our estimate of the potential depth reached by the infiltration front is based on measurements of the water holding capacity of the soils on the alluvial fan, which are highly similar to those of the river bed. Puigdefabregas et al. (1998) measured a water content of 0.16 and 0.07 cm<sup>3</sup> cm<sup>−3</sup> at field capacity and a total pore volume of 0.34 and 0.25 cm<sup>3</sup> cm<sup>−3</sup>, for the 0–5 cm and 5–20 cm soil layers, respectively. These figures
agree with published values for coarse sandy soils (Marshall and Holmes, 1979).

The depth to which soil water could be extracted by evaporation from the soil surface was estimated by using an exponential function proposed by Van Keulen (1975):

\[
a_i = \theta_i \exp(-K_e z_i)
\]

where \(a_i\) is the relative contribution of the \(i\)th soil layer to the total water loss through evaporation, \(\theta_i\) the volumetric moisture content of the \(i\)th soil layer, \(z_i\) the depth of the centre of the \(i\)th soil layer (m), and \(K_e\) is an extinction coefficient for the withdrawal of water from the soil. The coefficient \(K_e\) depends on the relationship between moisture content and conductivity of the soil (van Keulen, 1975) and, hence, varies with texture. Van Keulen found a value of \(K_e = 5\) to work well for loess, while Floret et al. (1982) used \(K_e = 12.5\) to model water relations of a desert plant community on sandy clay soil in Tunisia. The value of \(K_e\) for the sandy soils of the stream bed is not known, but can be assumed to be at least 12.5.

4. Results

4.1. \((AET - P)\) values

Precipitation during the study period was 261 mm for the hydrological year 1994–1995, 221 mm for 1995–1996 and 393 mm for 1996–1997 (Table 1). Total rainfall during the first year was slightly lower than the mean annual value measured at Rambla Honda over the last 10 years (i.e. 279 mm), the second year was drier while the third was relatively more rainy. In terms of rainfall timing the three hydrological years had in common that a major proportion of the annual precipitation fell in large events in September–October (1994, 1996 and 1997) which produced flash floods in the main channel.

The combination of measurements taken in the \(R. \text{sphaerocarpa}\) stand and measurements taken by the permanent weather station at Rambla Honda permitted the comparison of \(AET\) and \(P\) for 3 hydrological years (from 1994–1995 to 1996–1997). Results show a continuous deviation between local rainfall \((P)\) and evapotranspiration \((AET)\) (Table 1), reaching an accumulated \(AET - P\) deficit of 302 mm.
that is at an average rate of around 100 mm per year. This deficit is caused by the high and steady transpiration rates of the shrubs. Evaporation from bare soil surfaces was considerable but less than the local rainfall, evaporation from soil under the shrub was very small, while transpiration from the shrub, when expressed by projected area $f = 0.3$, was more than twice the precipitation (Table 1).

The potential error resulting from the assumption that the leaf area index of the *R. sphaerocarpa* stand was constant during the 3 hydrological years $L = 0.75$, which was assessed by running the model for $L = 0.68$ and 0.75, was estimated at 7%.

As described above (Materials and Methods), the meteorological input data to the model recorded by the permanent weather station at Rambla Honda overlapped with the measurement campaigns in the *R. sphaerocarpa* stand. The relationships found between both series of values for variables that drive the evaporation model were all significant ($p < 0.05$). A comparison of model outputs calculated with stand data and with data from the weather station for that coincident period showed that the differences in estimated AET are small. The accuracy was checked through correlation analysis between both sets of AET estimates and showed a very high correlation ($y = 0.9735x + 0.0042; r^2 = 0.9171; p < 0.05$) (Fig. 2). Hence, in spite of these two simplifications, the AET estimates for the three hydrological years (Table 1) are rather accurate.

During the two campaigns rainfall caused wetting and drying cycles in the soil at 0.25 m depth (Table 2). Modelled total evapotranspiration for the *R. sphaerocarpa* stand and for each source (shrub, soil under shrub and bare soil) are shown also in Table 2.

Actual evapotranspiration from the stand exceeded local rainfall over the same period. Again as observed at the annual scale, this evapotranspiration excess could only be accounted for by transpiration since bare soil evaporation per unit area ranged between 0.3 and 0.7 of plant transpiration (Table 2). The water deficit that builds up progressively during the summer drought is only partially replenished by the rains that usually fall in autumn (Lázaro et al., 2000) and is sustained from one year to another (Table 1).

4.2. Lateral water inputs

The contribution of lateral water inputs from the hillslopes on both sides of the stream bed ($Q_{h}$) was
based on our estimates of their respective surface areas, and the regional overland flow figures for bare ground on different lithologies in Murcia and Almería (SE Spain) published by Thornes and Gilman (1983) (Table 3). The rock types present at Rambla Honda (i.e. micaschists and quartzites) fit between the categories ‘micaschists’ and ‘mixed metamorphics’ used in that report. Looking for the maximum values, we take the latter category and the estimates for Almería (4.0 mm per year) and Murcia (15 mm per year). This amount of runoff is produced by 167 ha of hillslopes and is delivered to 71 ha of stream bed, so that the total water input to the latter would range from 9 to 35 mm per year. If we consider the estimated water excess of ca. 21 mm that is produced by an extreme event of 60 mm h\(^{-1}\) with a recurrence interval of 100 years (Table 3), the lateral input from the hillslopes to the stream bed would be about 49 mm per century, that is 0.49 mm per year. This rough assessment suggests that runoff inputs from the lateral hillslopes could maximally account for one third of the recorded annual water deficit of the R. sphaerocarpa stand.

This result can be tested against measured records of hillslope from the Rambla Honda field site. Table 4 shows measured rainfall and runoff coefficients for all events that produced discharge at flume AHF2 during the period May 1994–October 1997. Table 4 also indicates which events produced flash floods in the main channel of the Rambla Honda.

If we assume that the entire hillslope area has the same runoff coefficient as the monitored micro-catchment of flume AHF2, the input of lateral water from the hillslopes to the stream bed would only be about \(Q_{\text{fh}}\) over a period of more than three years (from May 1994 to October 1997), that is about 5 mm per year (Table 4). As expected the runoff figures obtained experimentally from vegetated hillslopes are much lower than those based on regional models for bare ground surfaces. The conclusion that lateral water inputs from surrounding hillslopes cannot balance the water deficit that builds in the stream bed deposits, is therefore strengthened.

The second possibility for water inputs to the sedimentary fill is by floods over the main channel bed. This has occurred 8 times since May 1994 (Table 4). Assuming an average duration for flash floods of 4 h, a long-term infiltration rate of 41 mm h\(^{-1}\) and a saturated hydraulic conductivity of 65 mm h\(^{-1}\), infiltration into the river bed could be as much as 164–258 mm per flash flood. If we further assume a water holding capacity of 0.34 mm mm depth\(^{-1}\) (Puigdefábregas et al., 1998), the water could infiltrate to 0.5–0.8 m depth. This is of course an average figure, local infiltration depths could be considerably more or less due to spatial variation in soil hydrological properties.

In coarse sandy substrates, only the water from the upper soil layers can be evaporated. Using Eq. (7) (Van...
Keulen, 1975) with a $K_e$ value of 12.5 suggests that more than 99% of the water evaporated from the soil surface would be withdrawn from the upper 30 cm of the soil. If so, deep-water storage ($Q_{fd}$) after a 4 h flood event could range from around 60 mm to 150 mm (Table 3). Under the same assumptions we estimated the total infiltrated water input from the 8 flash floods that occurred during the period May 1994–September 1997 at $Q_{fd} = 480–1200$ mm. At roughly 120 mm per year to 400 mm per year these lateral inputs are the most likely water source that allow the $R. sphaerocarpa$ stand to function at AET rates that exceed local rainfall by 100 mm per year.

### 5. Discussion and conclusions

Our assessment of the water balance components (Eq. (6)) shows that actual evapotranspiration (AET) of the stream bed shrub stand largely exceeds local precipitation ($P$). As Domingo et al. (1999) pointed out daily evaporation rates from the stand remain relatively constant despite of substantial variations in soil water content ($\theta = 0.04 \rightarrow \theta = 0.13 \rightarrow \theta = 0.06$ kg kg$^{-1}$) of the upper soil layer (0–0.25 m). The same pattern was found in the present study which confirms that access to deep water stores enables the $R. sphaerocarpa$ stand to maintain steady transpiration rates independently of variations in soil moisture conditions of the upper soil layers. These results agree with previous studies at Rambla Honda that showed $R. sphaerocarpa$ to extract water from more than 25 m depth (Haase et al., 1996a).

This water use strategy also becomes apparent when we plot actual evaporation from bare soil and plant transpiration against the PET (Fig. 3).
Plant transpiration shows a significant relationship \((p < 0.05)\) with PET, while evaporation from bare soil shows a highly scattered distribution. This implies that plant evaporation is energy-limited while evaporation from bare soil is limited by the availability of water.

Water level records from deep bore holes at the Rambla Honda site show that permanently saturated layers do not occur in the sedimentary fill of the stream bed (Puigdefàbregas et al., 1999). The deep soil water store that enables the *R. sphaerocarpa* stand to maintain a steady evapotranspiration rate must therefore be occasionally recharged during extreme events. The estimated deficit of 100 mm per year may be balanced by (a combination of): (a) infiltration of local rainfall during extreme events; (b) runon from the surrounding hillslopes; or (c) infiltration of channel flow generated by the upper section of the basin.

Looking at the event scale, the deficits on the annual water balance are too substantial (Table 1) to be explained by the occasional recharge that might be achieved during very large rainstorms. Extreme events (e.g. \(>100\) mm) occur with very low frequency (Lázaro et al., 2000; Elias Castillo and Ruiz Beltran, 1979). Even if an extreme rainfall event of 50–100 mm day\(^{-1}\) would completely infiltrate to the deep soil layers, this would only account for 3–10 mm per year which obviously does not compensate for the observed deficit between AET and \(P\).

At annual time scales the compensation of the water deficit by extremely rainy years can also be excluded because AET only approaches \(P\) at annual rainfall values larger than 500 mm, as can be deduced from Table 1. As shown by Lázaro et al. (2000) annual rainfall amounts of ca. 500 mm have only been recorded twice in the region over the last 30 years.

Discarding deep infiltration of local rainfall as the principal recharge process, the additional water inputs to the sedimentary fill must come from runoff. Runoff generation mechanisms and boundary conditions for hillslope-channel connectivity from the Rambla Honda have been analysed by Puigdefàbregas et al. (1998) and Puigdefàbregas et al. (1999). They identified two runoff generation mechanisms, near surface and sub-surface saturation, and concluded that when the latter condition builds up, moderate rainfall intensities can produce widespread runoff on the hillslopes. This runoff is delivered to the bottom sedimentary fill through first order channels. Occasionally, small saturated lenses build up in the sediment deposits at the outlet of these small channels, but they are ephemeral and disappear within a few days by diffusion into the sediments of the main channel. Rainfall events that lead to widespread runoff do not occur frequently enough to compensate for the deficit between long-term precipitation and evapotranspiration from the stand.

By far the most likely source of lateral water inputs to the stream bed sediments are the floods coming...
from the upstream sector of the basin. Flooding over the main channel bed has occurred eight times from May 1994 to October 1997. Combination of reasonable figures for flood duration, and soil hydrological parameters suggests that the infiltration into the river bed could have been 160–400 mm per year during the study period, which is an amount that could easily replenish the annual deficit observed in the channel (Table 3).

Assessment of local values of \((AET - P)\) is a straightforward approach to identify runoff sources and sinks in the landscape, but requires a reasonably accurate and low cost procedure to estimate long-term AET rates. In sites with thick sedimentary deposits, where sub-surface flow may be an important component of the water balance, long-term AET rates cannot be derived from the difference between surface runoff or discharge and precipitation. AET must then be calculated from micro-meteorological variables. Our approach has the advantage of being based on physiological and aerodynamical properties of the plant canopy, which allows the method to be relatively easily applied in other vegetation types. The driving variables are obtained indirectly through their relationships with conventional meteorological data or can be obtained during specifically designed short field campaigns. For sites that are found to receive significant amounts of lateral water inputs \((AET > P)\), semi-quantitative assessments, based on regional runoff and flood frequency estimates, allow the relative importance of the different sources to be evaluated.

Although this approach only provides insight in the orders of magnitude of recharge by hillslope runoff or channel flow, such qualitative assessments are significant to the understanding of plant–water relations in general and to the management of vegetation in ephemeral channels in particular. In the case of the study area, for example, knowing that channel flow from upstream parts of the catchment is the dominant recharge pathway enables us to predict that under current climate conditions the persistence of the channel vegetation is more dependent on land use changes in the valley head than on changes in adjacent hillslopes.

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