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An ecohydrological modelling approach for assessing long-term recharge rates in semiarid karstic landscapes

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NDVI;
Hydrological equilibrium hypothesis

Summary An ecohydrological water balance method based on the hydrological equilibrium hypothesis was developed to estimate long-term annual recharge rates in semiarid karstic landscapes. Recharge was predicted from the difference between long-term annual precipitation and evapotranspiration rates. A multiple regression interpolation approach was used to compute precipitation. Evapotranspiration was quantified from the deviations between the observed local value of the normalised difference vegetation index (NDVI) and, the predicted minimum and maximum NDVI values for two hydrologically-well defined reference conditions representing the minimum and maximum vegetation density given a local long-term water availability index. NDVI values for the reference conditions ($NDVI_{min}$ and $NDVI_{max}$) were estimated from an empirically-based boundary analysis. Evapotranspiration rates for the reference conditions were estimated using a monthly water budget model that integrates the roles of the soil water holding capacity and a climate-driven evaporative coefficient (k) representing the mean annual conductance of the vegetation canopy. The methodology was tested in Sierra de Gádor (SE

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Spain), where predicted evapotranspiration and recharge rates compared well with local and regional scale estimates obtained from independent methods. A sensitivity analysis showed that $NDVI_{max}$ and k are the parameters that mostly affect our model's evapotranspiration and recharge estimates.

Introduction

A quantification of available water resources is a requisite for any water management plan. In semiarid regions where precipitation is typically highly variable in space and time, this quantification is difficult and may be a major source of uncertainty in the regional water balance. A primary goal of water management plans is maintaining a long-term balance between groundwater consumption and recharge rates. This is particularly critical in those semiarid regions where key socio-economic activities heavily rely on groundwater resources, such as in south-eastern Spain and other dry zones of the Mediterranean Region (European Commision, 2000; Scanlon et al., 2006). Where groundwater resources are over-exploited, enhancing recharge rates may be one of a set of measures to re-establish sustainable water use.

The semiarid zones of the Mediterranean Basin are often characterised by rugged topography. Favourable conditions for enhancing recharge in those landscapes are most likely met in the mountainous headwater areas of the catchments (Wilson and Guan, 2004) where precipitation and diffuse recharge rates are usually higher than in the lowlands. However, quantification of recharge rates in headwater areas is difficult due to the high spatial and temporal variability of precipitation, the heterogeneity of terrain, soil and surface cover conditions, and a general scarcity of spatially explicit data (Wilson and Guan, 2004). In spite of the fact that the vegetation is known to have strong control over local and regional water balances in dryland environments (Eagleson, 2002; Scanlon et al., 2005) and the existence of well-established methodologies to quantify a range of vegetation attributes through remote sensing, the vegetation cover has not received enough attention in the regional hydrological modelling exercises undertaken to underpin water management plans.

For its apparent simplicity, many of the existing methods to estimate long-term recharge rates in semiarid mountainous regions are based on the soil water balance (e.g. Scanlon et al., 2002; Carter and Driscoll, 2006). In semiarid karstic landscapes, where long-term surface runoff can be considered negligible, recharge from infiltration of precipitation, also termed diffuse recharge, is essentially the residual between precipitation (P) and evapotranspiration (E). Spatial estimates of P are usually computed from point measurements and well established spatial interpolation techniques (Tabios and Salas, 1985; Marquínez et al., 2003). However, the spatially-distributed estimation of E, which can be as high as 95% of P in semiarid regions (Wilcox et al., 2003), is difficult and therefore subject to a high uncertainty.

Several models have been developed to estimate evapotranspiration ranging from empirical or semi-empirical equations (see review by Arora, 2002) to theoretical models based on the Bouchet's complementary relationship (Hobbins et al., 2001) or ecohydrological equilibrium criteria (Eagleson, 1982; Neilson, 1995). Empirical models typically explain up to about 70% of the evapotranspiration ratio (E/P), but uncertainty of estimated evapotranspiration estimates tends to increase with aridity (Milly, 1994; Zhang et al., 2001). Potential causes for relatively poor performance of these models in arid environments include the assumed independence between actual and potential evapotranspiration (Hobbins et al., 2001) or failure to take important climate or terrain attributes into account (Potter et al., 2005). Physically-based water balance models (Eagleson, 1978; Milly, 1994) can be attractive to use in ungauged basins or in regions with scarcity of data, but often the complexity of the analytical solutions or excessive parameterization advises against their use. For example, attempts by Eagleson (1982) to simplify the complexity of his physically-based model (Eagleson, 1978) by incorporating the ecological optimality hypothesis have been severely criticized in ecological terms by Kerkhoff et al. (2004).

The goal of the present study is to develop an ecohydrological modelling framework for assessing annual recharge rates across semiarid karstic mountainous landscapes. The ecohydrological water balance (EWB) model developed here estimates recharge in an indirect way as the difference between precipitation and evapotranspiration. Based on the hydrological equilibrium hypothesis (Nemani and Running, 1989), which suggest that vegetation adjusts to maximize its growth while minimizing water stress, the model uses a regionalized vegetation density index and basic climate attributes to drive a simple monthly water budget model. The EWB model improves upon the empirical or semi-empirical approaches to estimating evapotranspiration based on the Budyko's curve by incorporating the role of the vegetation, the soil, and the seasonality of the climate variables in the water balance while avoiding the complexity that characterizes physically-based water balance models. The EWB model was developed and tested in a mountain range of Southeast Spain (Sierra de Gádor, Almería) over three years of contrasting annual precipitation (average, dry and wet). Predicted evapotranspiration and recharge rates were verified at different spatial scales (plot and regional) using independent and complementary approaches. A sensitivity analysis was performed to assess the model's sensitivity to variation in parameter values.

Theoretical framework

Rationale

Long-term water balance methods are based on the mean annual water balance equation which for a given soil volume can be written as

$$P = E + R \tag{1}$$

where P is the precipitation, E is the evapotranspiration and R represents the recharge, all in mm yr^{-1}. This formulation assumes that long-term surface runoff and changes in the soil water store are negligible, which is considered reasonable in semiarid karstic landscapes (Carter and Driscoll, 2006). R is the fraction of precipitation available for water production; it can be computed indirectly as the residual of P and E.

In semiarid regions, where by definition the annual potential evapotranspiration (E_p) exceeds the annual precipitation (P), the hydrological equilibrium hypothesis (Nemani and Running, 1989) assumes a linear relationship between E, and the leaf area index (LAI) for values below 4–5 m^2 m^{-2}:

$$E = a\mathrm{LAI} + b \tag{2}$$

where a and b are parameters that define two boundary or reference conditions. The parameter b corresponds to the evaporation from a site with no vegetation cover (LAI = 0) whereas the parameter a represents the rate of change of E with respect to LAI. Both, a and b, are local parameters that depend on climate and soil properties (e.g. soil water holding capacity).

Eq. (2) has been found to hold by other authors for experimental and simulated data (Greenwood et al., 1985; Nemani and Running, 1989; Hoff and Rambal, 2003; Contreras, 2006); it constitutes the cornerstone of our EWB model. From the hydrological equilibrium hypothesis, it follows that the mean long-term water balance can be assessed by quantifying the deviation of observed LAI values from two boundary LAI values that correspond to hydrologically-defined reference conditions, namely

$$E = \frac{E_{\max} - E_{\min}}{\mathrm{LAI}_{\max}}\mathrm{LAI} + E_{\min} \tag{3}$$

where $E_{\max}$ and $E_{\min}$ are the long-term evapotranspiration rates in mm yr^{-1} for a site with a maximum leaf area index, $\mathrm{LAI}_{\max}$, and for a site with no vegetation (LAI = 0), respectively.

As ground-based measurements of LAI are unaffordable for areas of regional extent, remote sensing is the preferred method to quantify vegetation density. The normalized difference vegetation index (NDVI) is one of the most commonly used spectral vegetation indices; it has a demonstrated capacity as an indicator of physiological and structural vegetation properties including LAI (Pettorelli et al., 2005). Several authors have demonstrated that the relationship between LAI and NDVI can be considered linear for ecosystems with low LAI values (Turner et al., 1999; Soudani et al., 2006) such as those found in semiarid Mediterranean landscapes with typical LAI values of 1.0–1.5 m^2 m^{-2} or less (Myneni et al., 2002). According to those results, we can substitute the linear relationship between LAI and NDVI for LAI in Eq. (3)

$$E = (E_{\max} - E_{\min})\frac{\mathrm{NDVI} - \mathrm{NDVI}_{\min}}{\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}} + E_{\min} \tag{4}$$

where the paired values ($\mathrm{NDVI}_{\min}$, $E_{\min}$) and ($\mathrm{NDVI}_{\max}$, $E_{\max}$) correspond to NDVI and E values for the two boundary/reference conditions defined above.

Modelling procedure

To apply Eq. (4) over a study area we take a four-step approach (Fig. 1): (i) firstly, an index of long-term water availability is computed that represents the averaged local climate conditions for plant growth; (ii) using the local soil moisture availability index as a predictor variable, vegetation density values representing two reference conditions, $\mathrm{NDVI}_{\max}$ and $\mathrm{NDVI}_{\min}$, are estimated for each grid cell; (iii) in the next step, reference values of annual evapotranspiration rates, $E_{\max}$ and $E_{\min}$, are estimated and associated to each simulated reference vegetation cover condition and; (iv) finally, the long-term evapotranspiration rate is computed for every grid cell as the deviation between the observed local vegetation density (NDVI) and the two sets of reference values ($\mathrm{NDVI}_{\max}$, $\mathrm{E}_{\max}$) and ($\mathrm{NDVI}_{\min}$, $\mathrm{E}_{\min}$) defined in steps (i) and (ii).

To estimate $\mathrm{NDVI}_{\max}$ and $\mathrm{NDVI}_{\min}$ values, we follow Boer and Puigdefabregas' (2003) empirical approach based on a regional boundary analysis between observed NDVI values and Specht's evaporative coefficient, k (Specht, 1972; Specht and Specht, 1989), which is in our case used as the long-term water availability index. The evaporative coefficient k is defined (Specht, 1972) to set the maximum monthly evapotranspiration rate that allows an evergreen perennial vegetation cover to thoroughly use the local water resources without ever completely depleting the soil moisture store. In ecophysiological terms, k can be interpreted as an indicator of the maximum long-term canopy conductance, g_c, and can therefore be expected to be closely related to LAI (Jones, 1992). Specht and Specht (1989) showed k to be strongly correlated to LAI of evergreen perennial vegetation communities in Australia, while Boer and Puigdefábregas (2003, 2005) demonstrated its suitability as a predictor of potential vegetation density in semiarid Mediterranean environments. An additional advantage of using k as a long-term water availability index, rather than for example the aridity index E_p/P, is the fact that the evaporative coefficient incorporates the seasonality of P and E_p. Specht's k is computed from monthly precipitation and potential evapotranspiration records using a simple water budget model (Fig. 2A) and two simplifying assumptions: (i) a non-limiting water holding capacity, such that all local rainfall is stored in the soil and losses due to

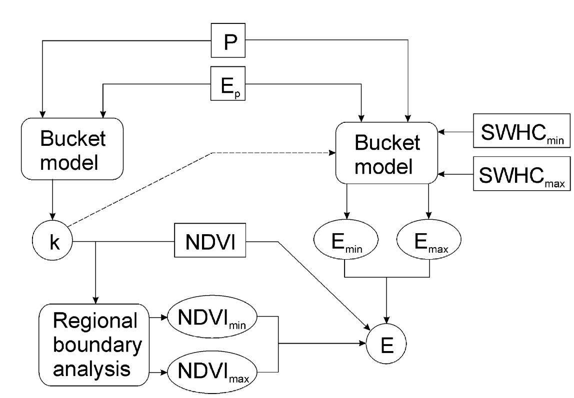

Figure 1 Flow diagram of the methodological approach used to estimate long-term annual evapotranspiration rates.

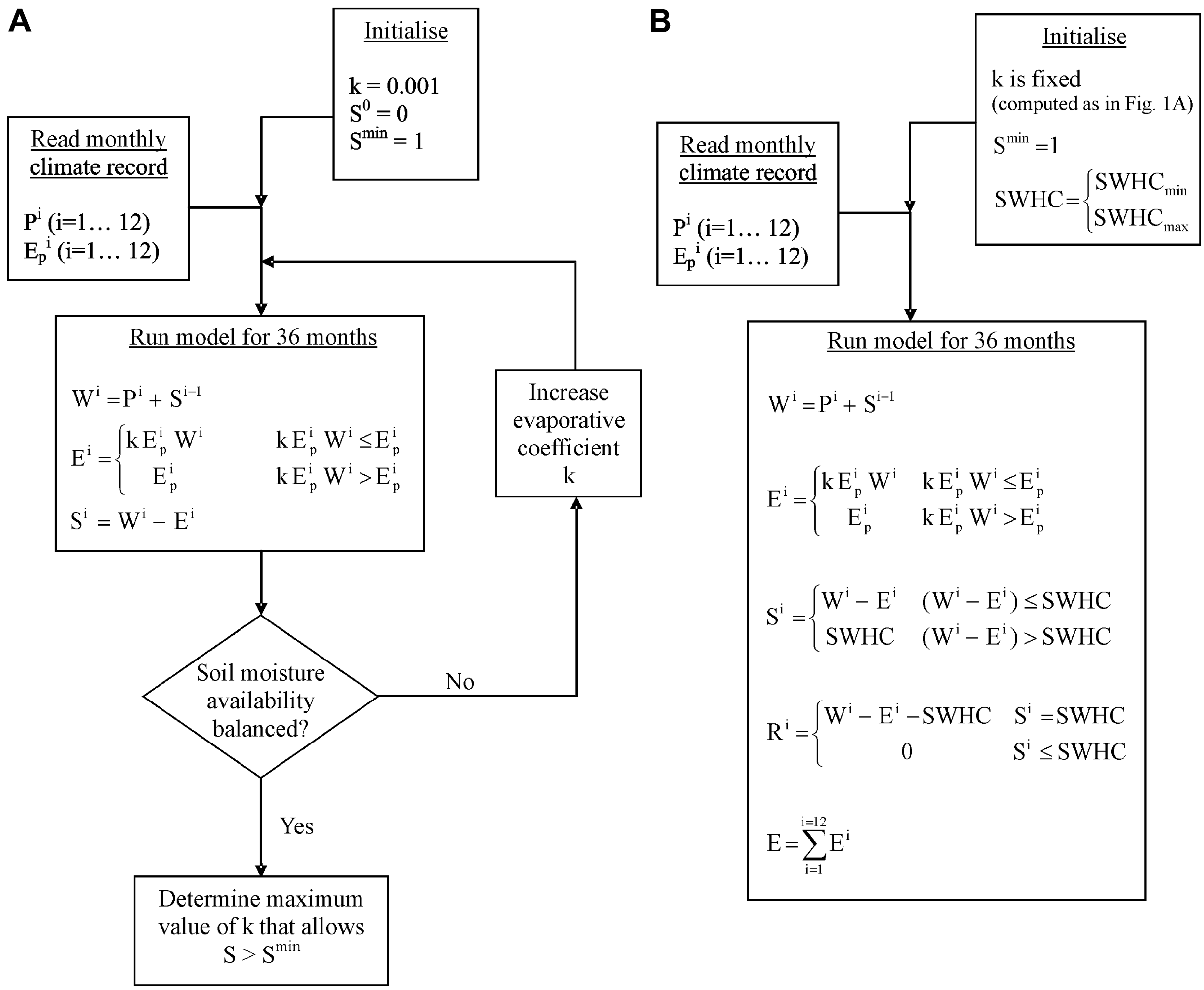

Figure 2 (A) Specht (1972) hydrological budget model to calculate the evaporative coefficient k; (B) modified Specht's hydrological budget model to calculate annual evapotranspiration for the boundary/reference conditions. P: precipitation; E_p: potential evapotranspiration; E: evapotranspiration; W and S represent the soil moisture content at the initial and final monthly period. S^0: initial soil moisture content, in mm. S^{min}: minimum soil moisture content required in the root zone to guarantee the survival of the vegetation, in mm.

lateral or deep drainage are neglected, (ii) an evergreen perennial vegetation cover that 'aims' at optimising mean annual rather than short-term water uptake (i.e. conservative water-use). By assuming a non-limiting soil water holding capacity we use the evaporative coefficient as a climate index (Boer and Puigdefábregas, (2003, 2005)) and deviate from Specht's original approach (Specht, 1972). The parameter S^{min} in Fig. 2A represents the minimum soil moisture content required in the root zone to guarantee the survival of the vegetation. The computation of k starts by assuming a small initial value for k and increasing that value until the water balance shows the soil moisture content in the driest month to be equal to S^{min}, which we arbitrarily set at 1 mm. Boer and Puigdefábregas (2003, 2005) estimated the NDVI reference values ($NDVI_{max}$, $NDVI_{min}$) from two functions fitted to the boundaries of the data envelop formed by the computed values of Specht's evaporative coefficient k and the percentile NDVI values observed for a large sample of grid cells without water inputs by irrigation, runon or groundwater influence. Based on these considerations, we are confident that the grid cells from which the NDVI reference values are derived correspond to sites where vegetation cover is near the maximum or minimum density given the long-term local P and E_p.

Conventional simple monthly soil water budget models can be employed to calculate E_{max} and E_{min} values using precipitation, potential evapotranspiration and soil water holding capacity as input variables. These bucket models have shown their efficiency in reproducing the seasonal and interannual water balance in semiarid regions and are considered suitable for estimating long-term mean annual evapotranspiration rates (Milly, 1994; Farmer et al., 2003). In this study, we modified the procedure schematized in Fig. 2A by assigning particular values of the soil water holding capacity (SWHC) to the two reference conditions (Fig. 2B). In this second step, we limit the plant-available soil water by specifying a value for the SWHC, which is computed as the difference between the volumetric water contents at matrix potentials of −33 kPa and −1.5 MPa integrated over the soil profile depth.

Material and methods

Study area

The study area is located in the South East of the Iberian Peninsula (Fig. 3). It is characterized by strong relief with elevations ranging from sea level up to 3342 m.a.s.l. in Sierra Nevada. The rugged topography is responsible for strongly contrasting precipitation and temperature regimes. Annual precipitation is lowest in the Tabernas desert (i.e. <200 mm yr^{-1}) and highest in the mountains (i.e. 400–700 mm yr^{-1}), where it sustains forest growth. Two geological complexes belonging to the Betic Domain are represented in the study area: the Alpujárride Complex and the Névado–Filábride Complex. In the former, which comprises Sierra de Gádor and Sierra de las Estancias, the permeable lithologies (limestones and dolomites) are better represented than in the latter (mainly micaschists) which appears in Sierra Nevada and Sierra de los Filabres. These mountain ranges are deeply dissected by three permanent rivers (Río Andarax, R. Adra and R. Guadalfeo from East to West) and other ephemeral rivers or *ramblas* (e.g. Rambla de Tabernas, Rambla de Nacimiento). Perennial streams are sparse in the region and are associated with snowmelt in the high elevations of Sierra Nevada or the discharge from permanent springs. The groundwater flow system can be compartmentalized into local and regional flow systems depending on tectonic and lithologic features. Usually the regional carbonate rock aquifers belonging to the Alpujárride Complex present a regional system of groundwater flow with deeper phreatic levels and long residence times. However, metapelitic lithologies are usually associated with local systems of groundwater flow controlled by a shallow recharge–discharge interaction and shorter residence times.

Sierra de Gádor is located in the centre of the study area just west of the city of Almería (Fig. 3). It is a mountain range reaching 2246 m.a.s.l. and consisting of a thick series of Triassic carbonate rocks (limestones and dolomites) that are highly permeable and fractured with intercalated calcschists of low permeability underlain by impermeable metapelites of Permian age (Pulido-Bosch et al., 2000). The southern edge of this mountain range is potentially the main source of recharge for the deep Triassic aquifers of Campo de Dalías (Vallejos et al., 1997), a coastal plain with a highly profitable horticulture and tourist industry (Pulido-Bosch et al., 2000). The current total groundwater extraction rate in Campo de Dalías is 130 $hm^3\,yr^{-1}$, of which 110–115 $hm^3\,yr^{-1}$ is extracted from the deep Triassic aquifers (Pulido-Bosch et al., 2000). The northern and eastern edges of Sierra de Gádor drain to the Andarax river basin while the western edge drains to the Adra river basin.

Sierra de Gádor and the surrounding area have a Mediterranean climate characterized by dry-hot summers and wet-mild springs, autumns and winters. There are strong altitudinal gradients in annual precipitation and temperature. Mean annual precipitation is 260 mm in Alhama de Almería (520 m.a.s.l.) and approximately 650 mm near the summit (2246 m.a.s.l.). Mean annual precipitation increases by about 23 mm for every 100 m increase in elevation. Mean

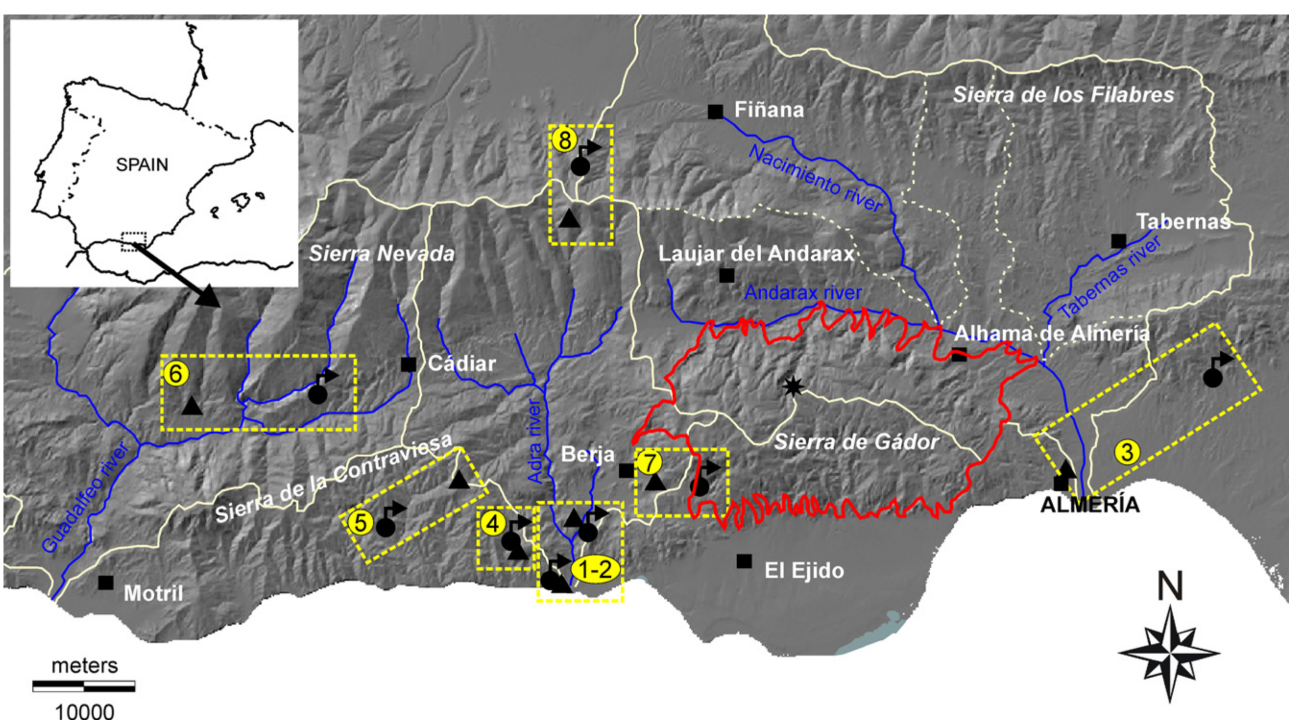

Figure 3 Study area showing the Sierra de Gádor contour (red line) and the main hydrological basins (white lines). Spatial distribution of the totalising raingauges used to calculate the total deposition of Cl (triangles) and of the non-modified recharge sample sites (circles with arrows). Data pairs inside the dashed yellow boxes are used jointly to estimate average recharge rates. Numbers in boxes are in accordance with the number identification site in Table 2. The Llano de los Juanes experimental site is shown with a star.

annual temperatures are 9 °C near the summit and 18 °C at the foot of the range. The thermal gradient is about −0.4 °C/100 m.

Historically, especially during the 18th and 19th centuries, Sierra de Gádor was subjected to an intense and widespread deforestation for ship construction and lead mining. As a consequence, the current vegetation cover is mostly sparse and soils are very thin and rocky. The main land cover (73% of Sierra de Gádor) is a sparse perennial shrubland with a vegetation cover of less than 50% mixed with grasses, rock or bare soil. Agriculture, mostly in the form of rainfed tree crops, represents 9% of the area. The rest of the area is covered with reforested pine woodlands (1%), shrublands with pines (15.5%) and other land cover uses (2.5%) (Junta de Andalucía, 1999).

NDVI reference values

NDVI values were calculated from four Landsat7 ETM+ images acquired for different seasonal periods representing both maximum and minimum vegetation density (autumn, winter, spring and summer): path/row 199/34 and 200/34 for 20/01/2000, 12/04/2001, 02/06/2002 and 06/09/2002. Images were rectified using (GPS-based) ground control points, and topographically and atmospherically corrected using a 30 m resolution digital elevation model (DEM) as described by Gónima and Alados (2003). The mean NDVI value computed from the four images was used as indicator of the average vegetation density (Fig. 4A).

To compute continuous surfaces of k, E_{max} and E_{min} for the study area we required input data layers of mean monthly precipitation and potential evapotranspiration (E_p). The twelve monthly E_p surfaces were computed using the Hargreaves–Samani equation (Hargreaves and Samani, 1982), which has been found to perform well in other semiarid environments where meteorological information is scarce (Gavilán et al., 2006). According to this method, E_p is calculated as

$$E_p = nR_a(T_{avg} + m)(T_{max} - T_{min})^{0.5} \tag{5}$$

where R_a is the monthly solar radiation in equivalent evaporated water-depth (mm month^{-1}), T_{avg} is the monthly average temperature (°C), T_{max} and T_{min} are the monthly maximum and minimum average temperatures (°C) and m and n are regionally-calibrated parameters.

Different techniques were evaluated (multiple regression, ordinary kriging, modified residual kriging, a minimum curvature – spline interpolator and, multiple regression with interpolation of residuals with the spline interpolator) were used to generate mean monthly precipitation and temperature surfaces. Monthly rainfall and temperature series from a total of 35 and 16 meteorological stations close to Sierra de Gádor respectively, were selected in order to investigate spatial precipitation and temperature patterns. Additionally, an independent set of 10 additional meteorological stations with short monthly data series were used to test the accuracy of the methods employed. From all the techniques tested, multiple regression yielded the best overall accuracy as quantified by smaller errors. Some geographical and independent variables computed from the 30 m DEM were tested in developing the multiple regression equations used to estimate the monthly maps of precipitation and temperature (Marquínez et al., 2003). Altitude and, longitude in winter and distance to the coast or continentality in summer, were the variables that explained the greatest proportion of the observed variance in monthly rainfall. Latitude and local aspect did not significantly increase the predictive power of the final regression equations employed. Altitude was the only variable used to generate the monthly surfaces of temperature. Surfaces for monthly potential short wave radiation were computed from the DEM using POTRAD5 (van Dam, 2000).

Calibration of the Hargreaves–Samani equation was based on monthly Penman–Monteith reference evapotranspiration values measured at 6 meteorological stations close to Sierra de Gádor over three years (i.e. January 2003–December 2005). The non-linear fitting procedure was based on the least-squares criterion, resulting in values of $n = 0.00317$ and $m = 36.45$ ($R^2 = 0.97$, $p < 0.001$; standard error = 8.6 mm). For detailed descriptions of the mean monthly climate surfaces for Sierra de Gádor, see Contreras (2006).

Finally, to identify the NDVI reference values the mean NDVI values were plotted against the evaporative coefficient k for a large sample of grid cells ($n = 140807$), all in positions that exclude water inputs by irrigation or by runon from areas upslope. The influence of regional groundwater on the productivity of the vegetation on the slopes is negligible because levels are too deep (Pulido-Bosch et al., 1991). To derive equations for the upper and lower boundary, interpreted as the maximum and minimum NDVI reference values, the sample of 140807 grid cells was grouped into 46 equal range intervals according to the k value with the exception of the first and the last interval. We defined the upper and lower boundaries of the data envelop by the 95th and 5th percentiles of the median NDVI and the middle of the k interval for each sub-sample (Contreras, 2006). Those percentile values are reasonable approximations of the boundaries of the data envelop and make it possible to minimize the influence of those 'outlier' grid cells, where our assumptions regarding vegetation-climate relations may not hold.

The form of the two boundary functions consisted of a second-order polynomial equation with a maximum threshold

$$\mathrm{NDVI}_{ref} = \begin{cases} a\,k^2 + b\,k - c & k \leqslant \lambda \\ d & k > \lambda \end{cases} \tag{6}$$

where a, b and c are fitted parameters and d is the maximum NDVI_{ref} value expected for each reference condition (NDVI_{min} and NDVI_{max}) once a k threshold, represented as λ, is reached.

Evapotranspiration reference values

Reference evapotranspiration rates corresponding to the NDVI reference conditions were estimated for three hydrological years, representing dry, average and wet conditions, using the modified monthly water budget model initially proposed by Specht (1972) (Fig. 2B).

In order to choose the SWHC values corresponding to the reference conditions in Sierra de Gádor, we used soil depth and water retention measurements extracted from an

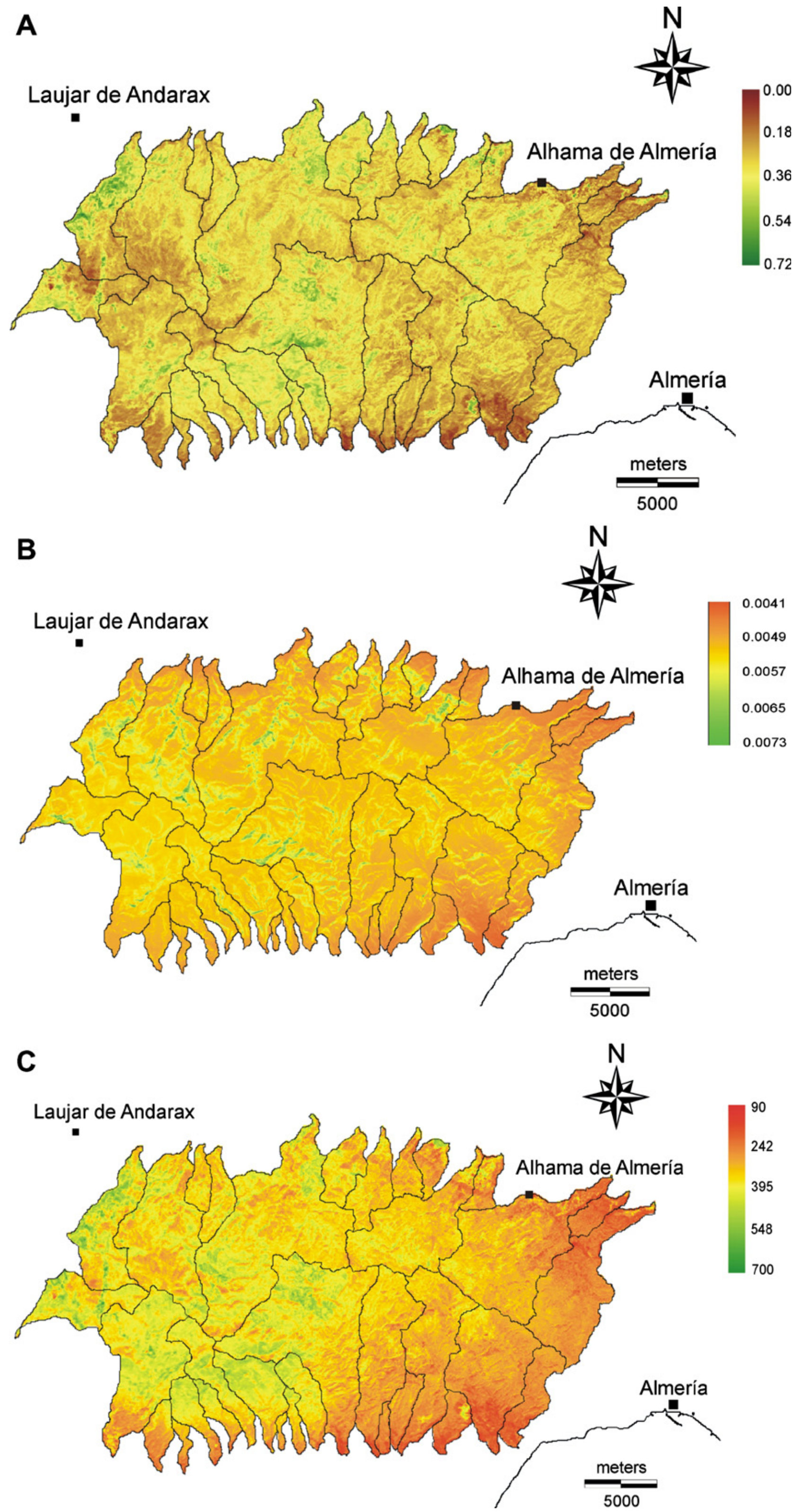

Figure 4 (A) Mean annual NDVI; (B) evaporative coefficient, in mm^{-1}; and (C) estimated mean annual evapotranspiration, in $mm\ yr^{-1}$ for the Sierra de Gádor study area.

existing database with more than 100 soil profiles describing textural, chemical and hydraulic parameters and a digitised soil map representing different soil cartographic units (Oyonarte, 1992). No spatial correlation was found between the characteristic SWHC values of the soil map units and the corresponding average values of terrain attributes such as elevation, slope gradient or slope aspect. We therefore assigned SWHC values to the reference situations that are

Table 1 Model parameters, range and reference values ('standard condition') for Sierra de Gádor study area as used in the sensitivity analysis

	Parameter value range		Reference value	Change in evapotranspiration	
	Min	Max		±1%	±5%
Soil parameters					
S^{min}	1	25	1	+20.1 (−)	+61.1 (−)
$SWHC_{min}$ (mm)	5	25	10	+13.6 (+)	+78.3 (+)
$SWHC_{max}$ (mm)	60	150	75	+9.4 (+)	+50.0 (+)
Climate parameters					
k (mm^{-1})	0.0027	0.0071	0.0050	+2.7 (+)	+11.2 (+)
Vegetation parameters					
$NDVI_{min}$	0.135	0.225	0.180	−5.9 (+)	−25.7 (+)
$NDVI_{max}$	0.310	0.520	0.415	−1.3 (+)	−8.0 (+)

Percentage changes in the model parameters that produces changes of 1% and 5% in the mean-averaged annual evapotranspiration from the 'standard condition'. The sign of the change in the parameter is between parentheses.

consistent with the generally degraded status of Sierra de Gádor and correspond to the most common soils in the area, i.e. *Typic Haploxerolls* and *Lithic Haploxerolls*, with typical depths of 40–50 cm (SWHC = 75 mm) and 10 cm (SWHC = 10 mm), respectively.

It should be noted that the evaporative coefficient k is an indicator of long-term bioclimatic conditions, in particular the amount of climatically available moisture to evergreen plants (Specht, 1972; Specht and Specht, 1989). Therefore, k was assumed to remain constant while estimating E_{max} and E_{min} for the dry and wet hydrological years. To guarantee a steady state condition for the soil moisture content at the beginning of the hydrological year the model was run for 36 months (Fig. 2B).

To compute mean monthly precipitation surfaces characterizing dry and wet hydrological years, we proceeded in three steps: (i) from the annual precipitation series for each meteorological station, we calculated the 25% and 75% values as representative values for the dry and wet conditions; (ii) annual precipitation surfaces for those conditions were computed using a multiple regression model with the altitude, longitude and/or distance to the coast as independent variables; (iii) finally, annual precipitation values were distributed over the twelve months of the year according to the mean fractions recorded in a particular meteorological station during either dry (annual precipitation less than the 25% value) or wet (annual precipitation greater than the 75% value) hydrological years. We assume that monthly potential evapotranspiration values for dry and wet hydrological years do not differ from those computed for long-term average conditions.

Sensitivity analysis

A sensitivity analysis was performed to assess the effects of variation in parameter values on model predictions of mean annual evapotranspiration rates. Following Finch (1998), these impacts are assessed relative to a 'baseline' output value (E_{ref}). In our study, E_{ref} is computed as the spatially-averaged mean annual evapotranspiration rate calculated from the same population sample of grid cells (n = 140807) used to estimate the NDVI in the reference conditions. During the assessment, one parameter is varied at a time. Sensitivity to a given parameter is assessed by plotting the changes in the parameter versus the ratio between the model output normalized by the 'baseline' value, E_{ref}. Additionally, the percentage change in a parameter from their reference value required to produce a 1% and 5% variation over the 'baseline' output value is calculated to allow for a simple comparison between the parameters. Although a one-at-a-time design does not allow assessment of the distribution of possible output values, due to interactions between the parameters, this approach was preferred over the more complex and computationally more demanding global sensitivity analysis based on random sampling methods (e.g. Monte-Carlo simulations). The model parameters, their reference values and the values ranges tested in the sensitivity analysis are listed in Table 1.

Verification procedures

The main result of the EWB model consists of long-term annual evapotranspiration rates. Assuming surface runoff is negligible, recharge rates can be estimated in an indirect way as the difference between precipitation and evapotranspiration. In order to assess the reliability of the model, the evapotranspiration or recharge rates were verified at different spatial scales (plot and regional) using independent and complementary approaches. In complex arid and semiarid landscapes, where quantifying recharge is difficult due to scarcity of data, using more than one verification technique is common and advisable (Scanlon et al., 2002).

Plot scale — the annual water balance at Llano de los Juanes

Model predictions were compared with direct observations of precipitation and evapotranspiration at the plot scale (i.e. 10^1–10^2 m). The instrumented site was located at Llano de los Juanes (Fig. 2), a relatively flat area at about 1660 m.a.s.l., which is part of a much larger well-developed and dissected karstic plateau between 1400 and 1800 m.a.s.l. According to previous isotopic studies this morpho-structural domain constitutes the main source of recharge to the deep aquifers of Campo de Dalías (Vallejos et al., 1997). This makes Llano de los Juanes an adequate site for the collection of hydrological observations and verification of our model's predictions. Annual precipitation and actual evapotranspiration were measured for two hydrological years (2003/2004 and 2004/2005) in a flat area where surface runoff is negligible. Since March 2003, rainfall has been measured with a normalized raingauge (Davis, model 7852M) while actual evapotranspiration has been measured by the Eddy covariance method. The measurement systems consists of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., USA) for measuring the three components of the wind speed and a krypton hygrometer KH20 (CSAT3, Campbell Scientific Inc., USA) for measuring the water vapour concentration. Both devices are located on a tower at 3 m above the ground surface. Eddy flux corrections for density perturbations (Webb et al., 1980) and coordinate rotation (Kowalski et al., 1997) were carried out in post-processing. Hygrometer measurements were corrected for absorption of radiation by oxygen, according to Tanner et al. (1993). Measurements were stored at 20 Hz in a Campbell CR23X data logger and averaged every 30 min. According to the historical monthly precipitation data collected at the nearby meteorological station of La Zarba (at 10.4 km from the Llano de los Juanes field site), the hydrological year 2003/2004 can be considered as an average year in terms of total precipitation while 2004/2005 was a dry year.

Regional scale — estimating recharge using the chloride mass balance method

Chloride is the most appropriate environmental tracer to estimate the recharge rate per unit area under a wide range of climatic conditions, especially in arid and semi-arid landscapes (Wood and Sanford, 1995; Scanlon et al., 2006). In steady state conditions and assuming that surface runoff from recharge areas is negligible, the chloride-mass balance method assumes the conservation of mass between the input of atmospheric chloride to the soil profile, $P \cdot C_p$, and the output chloride flux through the upper part of the saturated zone in a regional or local system of groundwater flow, $R \cdot C_r$, for an annual period

$$P\ C_p = R\ C_r; \quad R = \frac{A_p}{C_r} \tag{7}$$

where R and P are the rates of recharge and precipitation, respectively, both in mm yr^{-1}, C_p, and C_r are the average chloride concentrations in atmospheric bulk deposition (wet and dry) and groundwater recharge. A_p is the annual rate of atmospheric bulk deposition of chloride, in g m^{-2} yr^{-1}, obtained by cumulative samples of deposition over a specific interval of time.

The knowledge of the enrichment chloride gradient with altitude observed from precipitation and recharge waters linked to a local system of groundwater flow allows establishing a regional relationship between recharge and altitude in the study area. Similar to Minor et al. (2007) an elevation-dependent chloride mass-balance approach (EDCMB) is established to obtain a spatially-distributed estimate of the altitude-dependent recharge rate for the study area that can be compared with the estimated recharge surface derived from the EWB method.

To estimate A_p in Eq. (7), (5) totalising raingauges were installed in the study region (Fig. 3). Total rainfall and atmospheric dust were sampled in time intervals of 2—3 months from December 2002 to September 2006 (Table 2) and the chloride concentration of each sample was determined using the high pressure liquid chromatography technique. To complete the database three more A_p values were derived from a bibliographic review by Alcalá (2006) (Table 2).

As for A_p, two data sources were used for the quantification of C_r. A set of groundwater samples was collected from four sites during the period March 2002—August 2004 and another four appropriate C_r were found in the literature (Alcalá 2006) (Table 2). In order to minimise the modification of the chloride local signature as a consequence of the mixing of recharge water coming from other altitudes, all the groundwater samples were collected in springs with a well-defined recharge area and with discharges associated to local systems of groundwater flow. Finally, corresponding A_p and C_r values were found following criteria of proximity and similar altitude, geological setting, and effective connectivity between recharge and discharge areas. Using the paired A_p—C_r values, Eq. (7) could be used to calculate annual recharge rates along a wide range of elevations.

The accuracy of the regional scale recharge rates predicted by the EWB model was assessed by comparing them

Table 2 Bulk deposition of chloride (A_p, in g m^{-2} yr^{-1}) and saturated zone chloride concentration (C_r, in mg L^{-1}), and estimated annual recharge rate (R, in mm yr^{-1}) using the chloride mass balance method

Id	Site	Reference elevation (m.a.s.l.)	Precipitation		Groundwater		R
			Sampling date	A_p	Sampling date	C_r	
1	Adra (1)	5	Dec 02—Jan 04	7.91	Jun 02	697.0	11.3
2	Adra (2)	180	Aug 04—Sep 06	5.00	Nov 03	249.4	20.1
3	Almería	510	Feb 01—Aug 02	5.30	Sep 92[a]	135.0	39.3
4	La Parra	840	Aug 04—Sep 06[a]	2.13	Aug 04	27.4	77.7
5	Albuñol	1200	Aug 04—Sep 06	1.59	Mar 99[a]	17.0	93.5
6	Órgiva	1650	Feb 90—Mar 91[a]	1.47	Jun 92[a]	9.0	163.3
7	Celín	1950	Aug 04—Sep 06	0.65	May 01[a]	3.3	197.0
8	Las Yeguas	2400	Mar 04—Sep 04[a]	0.27	Mar 02	1.0	270.0

Location of sites appears in Fig. 3.
[a] Data from Alcalá (2006).

with the rates obtained from the EDCBM method. We used the altitude (or annual precipitation) as a common predictor for both methods. Averaged annual recharge rates by ranges of altitude were calculated for both methods. Finally, stepwise linear regression models were fitted to the data in order to obtain empirical equations for the relationship between altitude and estimated recharge rate.

Results and discussion

Water balance and vegetation density

Fig. 4B shows the spatially distributed value of Specht's evaporative coefficient, *k*. The values range from 0.0041 mm^{-1} for the drier areas located in the north-eastern sector to 0.0073 mm^{-1} on some north-facing slopes at higher elevations. The spatially-averaged value of *k* for Sierra de Gádor study area is 0.0050 mm^{-1}. The mean annual NDVI values in Sierra de Gádor range from 0.09 to 0.20 in areas of sparse vegetation or bare soil/rock to 0.40—0.50 in areas of dense vegetation. The highest values are frequent in reforested areas with values between 0.45 and 0.55 and, in irrigated fields where NDVI values were close to 0.70. Note that in this paper the evaporative coefficient *k* has the dimension of mm^{-1} rather than cm^{-1} as in previous work by Specht (1972) and Boer and Puigdefabregas (2003, 2005).

The scattergram of the observed mean annual NDVI values against the evaporative coefficient in Sierra de Gádor is shown in Fig. 5, while the values and statistics for all the parameters in Eq. (6) are presented in Table 3. The $NDVI_{max}$ values estimated for the upper boundary range from 0.20 in

Table 3 Parameter values and statistics for the NDVI reference conditions

Parameter	Upper boundary ($NDVI_{max}$) Value ± Error Std.	Lower boundary ($NDVI_{min}$) Value ± Error Std.
a	−71999.0 ± 7652.9	−44237.7 ± 5947.61
b	867.514 ± 83.07	528.242 ± 64.56
c	−2.13265 ± 0.22	−1.34838 ± 0.17
d	0.4805	0.2285
λ	0.00602	0.00597
No samples	46	46
R^2	0.90	0.84
Error Std.	0.022	0.017
MAE	0.015	0.014

MAE: mean absolute error.

Table 4 Spatially-averaged evapotranspiration values estimated in Sierra de Gádor for three characteristic precipitation periods

Precipitation year condition	Evapotranspiration ($mm\ yr^{-1}$)	Evapotranspiration ratio
Dry	231 ± 61	0.71 ± 0.13
Average	284 ± 75	0.69 ± 0.13
Wet	320 ± 84	0.65 ± 0.12

Evapotranspiration ratio is computed dividing the long-term annual evapotranspiration by the long-term annual precipitation.

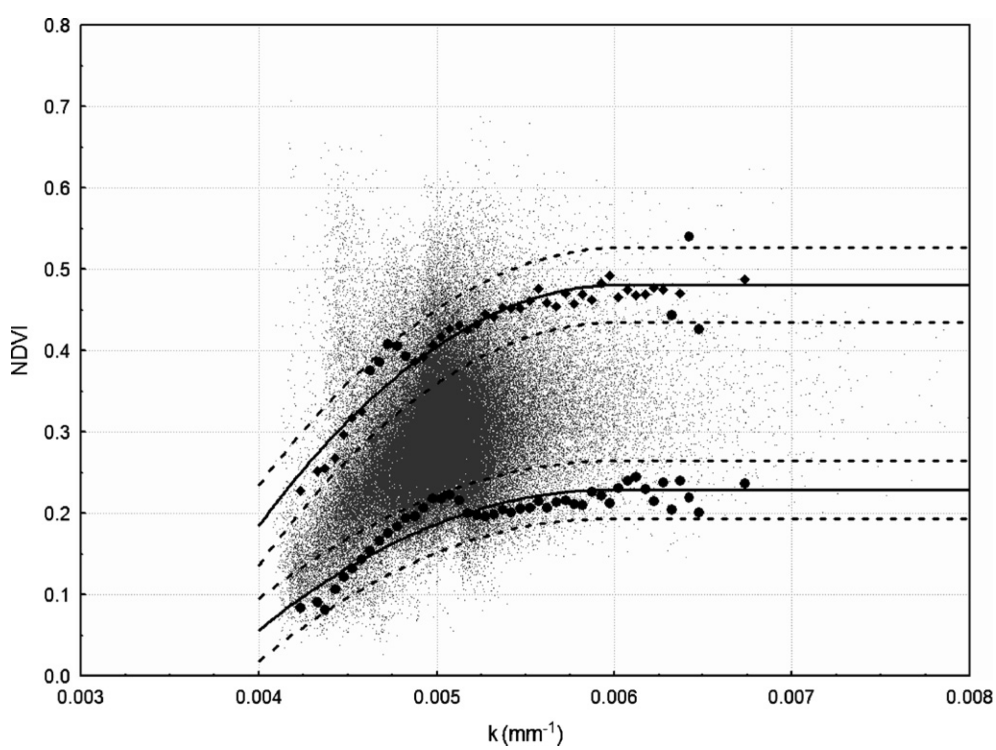

Figure 5 Scatterplot of *k*-NDVI values and boundary limits for the vegetation density reference conditions. Dashed lines represent the 95% predictions intervals.

the drier sites to a maximum value of 0.48 for sites with k values greater than $0.006\,mm^{-1}$. These relatively low $NDVI_{max}$ values fitted for the upper boundary are characteristic of the degraded low vegetation cover resulting from widespread deforestation for mining activities in the middle of 19th century. Another explanation for the relatively low $NDVI_{max}$ values could be the predominantly karstified nature of the landscape which favours deep percolation through dissolution cracks or fractures limiting the water availability to plants.

The NDVI values of the lower boundary (i.e. $NDVI_{min}$, bare areas) range from 0.08 in the drier sites to 0.23 in the wetter ones, being similar to bare soil values reported by other authors (e.g. Kustas et al. 2000). The non-linearity observed

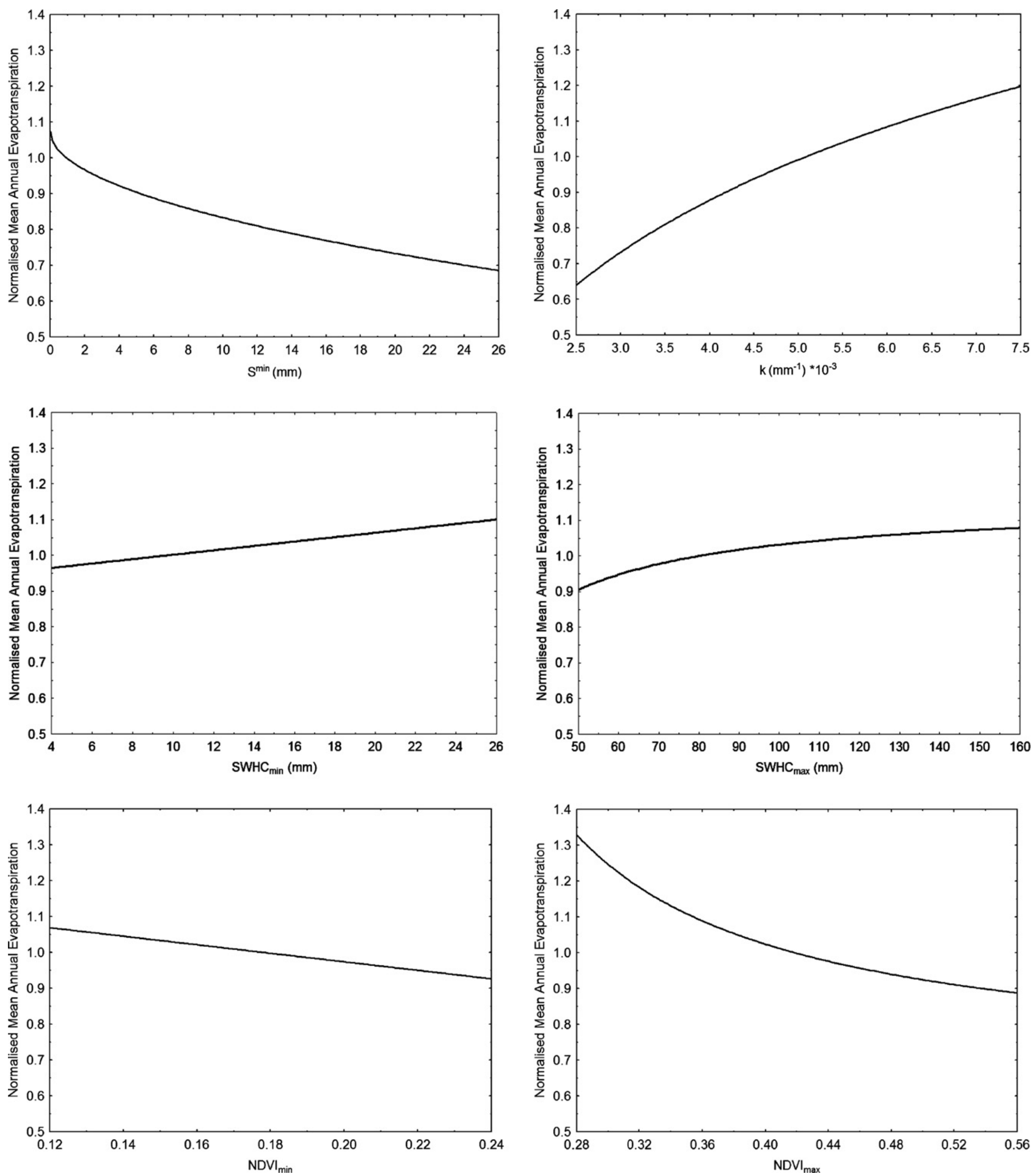

Figure 6 Variation in normalised mean annual evapotranspiration with soil (S^{min}, $SWHC_{min}$, $SWHC_{max}$), vegetation ($NDVI_{min}$, $NDVI_{max}$) and climate parameters (k). Data for the graphs are from the sensitivity analysis.

for the lower boundary function may be the result of systematic variation in the background soil colour in areas with no or very sparse vegetation cover. As was previously pointed out by García-Haro et al. (1996) dark soil surfaces tends to have higher NDVI values than light soil surfaces. Variation in soil background colour is not random in our study area. Light-coloured surfaces correspond to areas dominated by marly limestones, phyllites and marls that occur mainly at lower elevations (which are more arid and have low *k* values), while dark-coloured surfaces represent dolomitic limestones and dolomites that make up the medium and higher elevation zones of the range that have a relatively humid climate and higher *k* values.

The spatially-averaged long-term mean annual evapotranspiration rate (Fig. 4C) in Sierra de Gádor is estimated at 284 mm yr^{-1} which represents 69% of the mean annual precipitation (Table 4). Given that surface runoff is negligible at mean annual time scales, the non-evapotranspired fraction of the annual precipitation (i.e. 31%) could be considered as recharge. This percentage translates into an estimated total recharge of 74.2 $hm^3\ yr^{-1}$ for the entire Sierra de Gádor study area, which is close to the value (i.e. 63.8 $hm^3\ yr^{-1}$) estimated by Vanderlinden et al. (2005) using a semi-empirical relationship based on Milly's modelling approach (Milly, 1994). We estimate the contribution of the southern edge of Sierra de Gádor to the total recharge to be close to 40 $hm^3\ yr^{-1}$, which implies a recharge rate that is 2.5 times less than the pumping rate from the Triassic aquifers of Campo de Dalías.

Our assumption of negligible surface runoff in Sierra de Gádor, necessary in considering the simplified Eqs. (1) and (7), are supported by field observations and modelling results obtained at a range of different spatiotemporal scales. Low rates of surface runoff have been registered under natural rainfalls events at the hillslope scale by continuously measuring the water level inside '*aljibes*', traditional cisterns strategically located at the base of hillslopes for the harvesting of runoff water (Van Wesemael et al., 1998). In the *aljibe* of Llano de los Juanes with a drainage area of 0.91 ha., total annual runoff collected for a period of 18 months (from September 2003 to March 2005) was less than 1% of the total rainfall, with a maximum rate per event of 6.3% for a storm of 65 mm and a maximum intensity of 7.5 mm h^{-1} (Contreras, 2006). Similar results have been found by Frot and Van Wesemael (unpublished field data) for La Chanata (drainage area, 2.52 ha) and El Calabriar (drainage area, 7.84) *aljibes* located in Sierra de Gádor with an average annual runoff rate of 0.18% and 2.53%, respectively, of the total rainfall collected for the hydrological years between 1999/2000 and 2003/2004. Using the HEC-HMS code for a design storm with a return period of 5 yrs (i.e. 76 mm fallen in 6 h), Martín-Rosales et al. (2007) predicted an average runoff rate for the southern edge of Sierra de Gádor of 19.5%, with values ranging from 31% for the most impermeable basins to 14% for the most permeable ones. Under the assumption of average annual rainfall conditions (i.e. 400 mm/yr) for the entire area and assuming that rainfall events with a return period of less than 5 yrs do not yield surface runoff, predicted annual runoff rates did not exceed 5% of the total annual rainfall.

We also computed annual evapotranspiration rates for dry and wet hydrological years under the assumption that the ratio between the observed mean annual NDVI and the reference NDVI values computed for each grid cell would remain unchanged (Table 4). Our model estimates that, annual evapotranspiration and recharge rates are reduced to 81% and 77%, respectively, of the long-term annual rates for a dry hydrological year, while they increase to 113% and 134%, respectively, for a wet hydrological year.

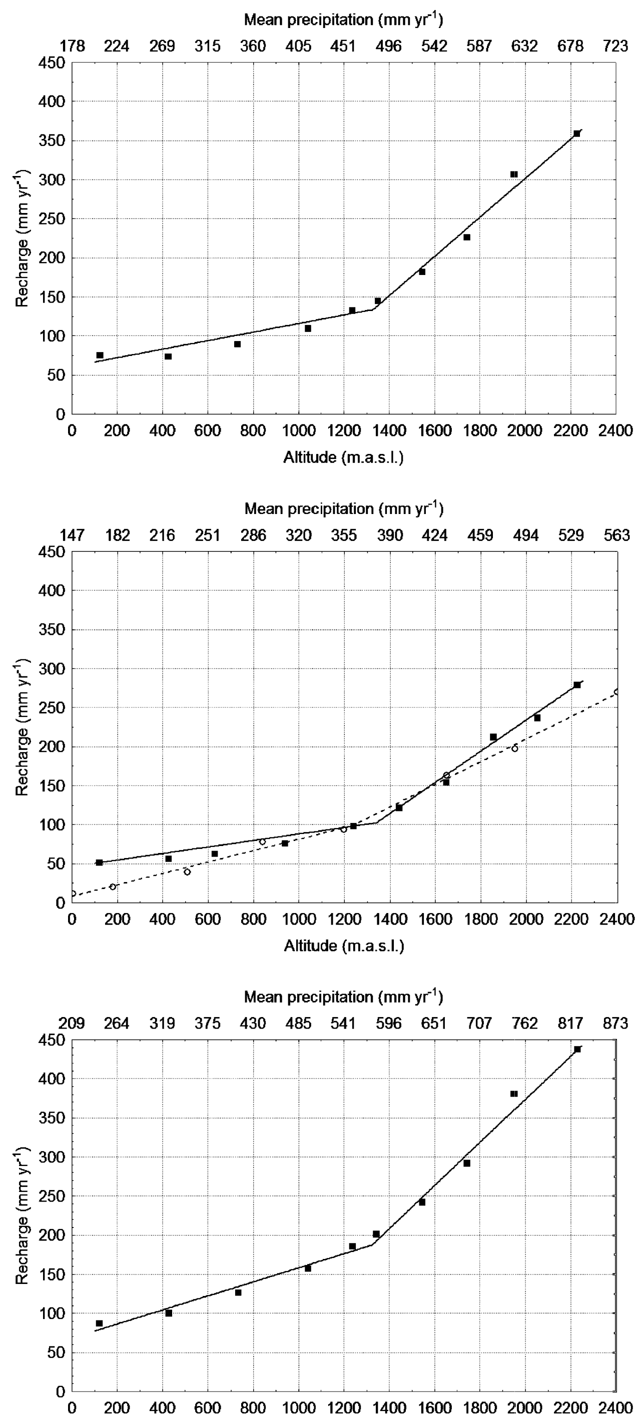

Figure 7 Altitudinal recharge domains estimated in Sierra de Gádor for: (A) hydrological year of average precipitation; (B) dry hydrological year (dashed line has been derived from the EDCMB approach); and (C) wet hydrological year.

Sensitivity analysis

Results of the sensitivity analysis are shown in Fig. 6. Model parameters exerting most influence on the estimated mean annual evapotranspiration rates are $NDVI_{max}$ and k (Table 1). Model results are affected in a non-linear fashion by variation in these parameters. The results of the sensitivity analysis show, that in general model predictions are likely to have greater uncertainty in the drier sectors of the study area (i.e. lower k and $NDVI_{max}$). This result is consistent with the conclusions drawn previously by Arora (2002) who stated that the drier the site, the more sensitive its water balance to variation in climate conditions.

Verification of model predictions

At the plot scale in Llano de los Juanes, our model estimated a mean annual evapotranspiration rate of 315 mm yr^{-1} while the actual evapotranspiration measured with the eddy correlation technique during the hydrological year 2003/2004 was 307 mm yr^{-1}, which is only 3% lower than the estimated value. The observed evapotranspiration for the relatively dry year 2004/2005 was 194 mm yr^{-1} while the estimated value from the EWB model is 248 mm yr^{-1}. The greater deviation between estimated and measured evapotranspiration rates are probably due the extremely dry conditions prevailing during that year. The total precipitation recorded during the 2004/2005 was only 210 mm yr^{-1}, while we computed our evapotranspiration estimate for a dry year on the basis of an annual precipitation of 421 mm yr^{-1}, corresponding to the 25% value of the average annual precipitation at Llano de los Juanes.

The regional altitude-recharge relationship for the study area using the EDCMB method is derived from the eight local recharge estimates presented in Table 2 and is shown in Fig. 7 jointly with the relationships extracted for Sierra de Gádor using the EWB method. Although non-linear relationships between annual recharge and altitude (or annual precipitation) have been described and used as empirical methods by other authors in arid and semiarid landscapes (e.g. Hevesi et al., 2002) we only extract these regional relationships in Sierra de Gádor for comparative purposes to assess the consistency of the EWB method. Table 5 shows the total recharge rates estimated for Sierra de Gádor using both methods as well as the different linear domains of annual recharge with altitude or annual precipitation. In both cases there is a breakpoint in the recharge rate at about 1200–1300 m.a.s.l. A preliminary assessment based on deuterium excess values measured in composite bi-monthly rainfall samples and recharge water collected in springs representing local recharge systems, suggests that this breakpoint might be associated with the origin of the frontal air masses from which the precipitation falls (data not shown). The samples collected at altitudes greater than 1100–1200 m.a.s.l. show a isotopic composition that is typical for Mediterranean air masses as opposed to the samples collected at altitudes of less than 1100 m.a.s.l. which show the typical isotopic signal of precipitation falling from Atlantic air masses. In addition to the higher mean annual precipitation rates at high altitudes and the generally greater rainfall intensities during rainfall events associated with Mediterranean air masses, the geomorphological and ecological conditions at higher altitudes (i.e. a relatively flat topography associated with the Sierra de Gádor plateau and relatively low vegetation cover due to deforestation practices during the XIX century) may also contribute to the observed altitudinal change in the mean annual recharge rate. A more intensive field measurement campaign was initiated two years ago in order to confirm this hypothesis and to obtain a better understanding of the contribution of precipitation from Mediterranean and Atlantic air masses on the recharge processes in the region.

Results from the application of the EDCBM approach are shown in Table 5. Total recharge estimated for Sierra de Gádor using the EWB approach is 57.6, 74.9 and 99.4 $hm^3\ yr^{-1}$ for dry, average and wet hydrological years, respectively. The recharge rate computed using the EDCMB approach is 53.6 $hm^3\ yr^{-1}$, which is close to the recharge rate estimated for a dry hydrological year using the EWB method. The similarity between estimates suggests that the measured mass fluxes of chloride in precipitation and groundwater samples were characteristic of dry conditions. This statement is consistent with the regional drought that the area is suffering from 2002 until now (data not shown).

It is important to note that all A_p–R_c data pairs applied to estimate recharge using the EDCMB approach were obtained from sites near to but outside the Sierra de Gádor study area. This is because the carbonated lithology dominating in Sierra de Gádor favours deep phreatic levels and the mixing of infiltration water recharged at different altitudes, which makes it difficult to find springs with discharges that are representative of local ground water flow systems. For that reason, we have only used this method as a first attempt to assess the reliability of our predictions at the regional scale and the results should thus be interpreted with caution. Currently, efforts are being made in

Table 5 Recharge-altitudinal gradients (R_{g1} and R_{g2}, in mm/100 m) and total recharge estimated in Sierra de Gádor using different methods and for periods with different amount of precipitation

Method	Precipitation year type	R_{g1}	R_{g2}	Altitudinal threshold m.a.s.l.	Precipitation threshold (mm yr^{-1})	Total recharge Sierra de Gádor ($hm^3\ yr^{-1}$)
EWB	Dry	4.2	20.0	1340	379	54.7
	Average	5.5	25.0	1320	478	74.2
	Wet	9.0	27.5	1320	574	99.9
EDCMB	Dry	7.3	14.5	1230	360[a]	53.6

[a] Estimated from the relationship found between annual precipitation and altitude for a dry hydrological period.

Sierra de Gádor to identify suitable sites for expanding the sampling network of precipitation and local springs at different altitudes.

Conclusions

This paper develops an ecohydrological approach based on the hydrological equilibrium hypothesis to estimate spatially-distributed mean annual recharge rates in semiarid karstic landscapes. Recharge (*R*) is quantified in an indirect way as the difference between precipitation (*P*) and evapotranspiration (*E*). The model was tested in Sierra de Gádor, a semiarid mountainous region located in south-eastern Spain. Results are in agreement with annual evapotranspiration rates measured at the local scale with an eddy covariance system, and at the regional scale with recharge rates derived from the application of the elevation-dependent chloride mass balance method.

Results from a sensitivity analysis show that model predictions of mean annual evapotranspiration and recharge are most sensitive to the $NDVI_{max}$ values that characterise the reference condition of maximum vegetation density, and to the evaporative coefficient, *k*. There was also a general tendency for increasing sensitivity of model predictions with increasing aridity. In Sierra de Gádor, evapotranspiration was found to represent ~69% of the long-term average annual precipitation. The remaining fraction, corresponding to 74.2 $hm^3\,yr^{-1}$, can be considered recharge. The annual recharge rate is reduced by 23% relative to the mean annual rate for dry years and is increased by 34% for wet hydrological years. The long-term annual recharge rate estimated for the southern edge of Sierra de Gádor represents about half the pumping rate of ground water from the Triassic aquifers of Campo de Dalías.

The EWB modelling framework has potential applications in other environments where: (i) mean annual potential evapotranspiration exceeds mean annual precipitation (i.e. drylands), (ii) LAI is less than 4–5 $m^2\,m^{-2}$, so that we can assume a linear relationship between NDVI and LAI, (iii) the vegetation largely consists of evergreen perennial vegetation in agreement with assumptions underlying the evaporative coefficient *k*, and (iv) surface runoff represents a very small fraction of the mean annual water balance. However, estimating long-term recharge rates in non-karstic landscapes may require quantification of surface runoff to close the annual water balance. In general, our results with the EWB model are promising, but further research is nonetheless required to verify and increase the predictive capacity of the model. Priorities for further work include: (a) comparing EWB estimates with other complementary and independent water balance approaches and; (b) increasing the temporal resolution of the model, for example using a top-down approach (from long-term annual scale to daily temporal scale) (e.g. Farmer et al., 2003).

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