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

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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

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