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Numerical assessment of effective evapotranspiration from maize plots to estimate groundwater recharge in lowlands

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ABSTRACT

To maximize the irrigation efficiency and to protect groundwater from agrochemical pollution, two variables must be known with good accuracy: effective evapotranspiration and infiltration, especially in lowland areas were the run-off is minimal. Three different experimental plots cultivated with maize were equipped with tensiometers and soil moisture probes to monitor every day the water movement in the unsaturated zone. Other relevant parameters of the various soil layers, as hydraulic conductivity and water retention curve, were obtained in laboratory experiments, while boundary conditions, as precipitations, temperature and root growth, were obtained on site. Inverse modeling was performed using HYDRUS-1D to assess the degree of uncertainty on model parameters. Results showed a good model fit of water content and head pressure at various depths, in each site, using Penman–Monteith formula for daily potential evapotranspiration calculation, but poor fit applying the Hargreves and Turk formulas. Best performance of model fit was observed for S-shaped equation employed to simulate the root water-uptake reduction with respect to Feddes equation. The soil parameters uncertainty was limited and remained within analytical errors, thus a robust estimation of cumulative infiltration and evapotranspiration has been derived. This study points out that evapotranspiration is the most important variable in defining groundwater recharge for maize crops in lowlands.

1. Introduction

Aquifer recharge assessment is essential to quantify water resources and to estimate contaminants flux towards aquifers (Scanlon et al., 2002). Presently, the most effective tool to quantify recharge flux is to model the unsaturated soil water dynamics; although this process faces many challenges in field conditions (Youngs, 1995). The most important are the soil heterogeneity, the development of aggregations/cracks and pore discontinuity, which causes deviations from Darcy's Law. Despite of these limitations, numerical models are more and more frequently employed to quantify soil water dynamics, often applying several simplifying assumptions to cope with these limitations. Deterministic numerical models require hydraulic conductivity and characteristic curve functions for each soil layer (Jarvis, 1994; Jacques et al., 2002; Suleiman and Ritchie, 2003; Šimunek et al., 2008): in field studies, these parameters are routinely calculated from soil physical properties, because their quantification is often difficult, time consuming and expensive (Suleiman and Ritchie, 2001). Nevertheless, a multiplicity of direct measurement methods have been developed to estimate hydraulic input parameters (Šimunek et al., 1998a; Dane and Topp, 2002; Peters and Durner, 2008). In this study an evaporative method was used to assess hydraulic parameters. Once these parameters have been characterized, other variables had to be addressed such as evapotranspiration, root growth and stress functions.

Several techniques have been developed to measure evapotranspiration: by weighting lysimeters (Gavilan et al., 2007), by field water balance equation (Lenka et al., 2009) or micrometeorological methods (Drexler et al., 2005), but these techniques are threatened to be time consuming and expensive. Evapotranspiration can also be estimated from climatic data, linking evapotranspiration with one or more climatic variables (Sharma, 1985). The performance of various equations has been assessed under a variety of climates (Allen et al., 1998; Berengena and Gavilàn, 2005). The Penman–Monteith equation is now considered the best approximation to estimate evapotranspiration over most of climates (Jensen et al., 1990). This equation is now become the United Nations Food and Agriculture Organization (FAO) standard equation to estimate evapotranspiration (Allen et al., 1998). In addition to evapotranspiration, studies on water stress on plants and roots

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Table 1
Soil legend classification from Servizio Geologico Sismico e dei Suoli of Emilia-Romagna region, based on World Reference Base for Soil Resources (1998).

Group	Description	Subgroup	Description
1	Soils of the deltaic and coastal plains, with hydromorphic characters at shallow depth (*Thionic Fluvisols*, *Thionic Histosols*, *Gypsic Vertisols*, *Eutric Vertisols*, *Vertic Cambisols*, *Haplic Calcisols*, *Calcaric Cambisols*, *Calcaric Arenosols*). Present land use: arable, commercial vegetables, fruit groves, rice-fields	1A	Soils with peaty horizons, frequent acidity from sulphates and salinity (*Thionic Fluvisols*, *Thionic Histosols*)
		1B	Mostly contrasting textured soils (fine over medium), with several characters linked to carbonates redistribution and shrinking-swelling of clays (*Gypsic Vertisols*, *Eutric Vertisols*, *Haplic Calcisols*, *Vertic Cambisols*)
		1C	Soils with biochemical weathering, medium-textured with several characters linked to carbonates redistribution (*Calcaric Cambisols*, *Haplic Calcisols*)
		1D	Coarse textured soils, with low degree of profile differentiation (*Calcaric Arenosols*)
2	Soils in low-lying areas of the alluvial plain, with more or less well-expressed characters due to clay shrinking and swelling (*Eutric Vertisols*, *Gypsic Vertisols*, *Calcic Vertisols*, *Haplic Calcisols*). Present land use: arable (cereals, sugar beet)	2A	Soils with weakly expressed carbonate redistribution, leached of soluble salts in the surface horizons, frequently with gypsum accumulation in depth (*Eutric Vertisols*, *Gypsic Vertisols*)
3	Soils in high-lying areas of the alluvial plain, with biochemical weathering and redistribution of carbonates (*Calcaric Cambisols*, *Haplic Calcisols*, *Chromic Cambisols*). Present land use: arable and high-yield specialized crops (fruit groves, vineyards, vegetable gardens); high urban density	3A	Soils with moderate profile differentiation and very weak carbonate redistribution (*Calcaric Cambisols*)
		3B	Soils with moderate profile differentiation, partially leached of carbonates in surface horizons, with carbonate accumulation in depth (*Haplic Calcisols*)

have been performed at various scales, from microscopic to field sites and ecosystems (Passioura, 2002; Duchemin et al., 2006). These studies reveal that maize exerts a very high water demand mainly in the upper soil horizons (Lenka et al., 2009; Doorenbos and Pruitt, 1977) and that an important variable is the plants stress function due to water deficit and salinity stress (Maas, 1986; Katerji et al., 2000). There is a close connection between groundwater depth and crop evapotranspiration, in fact plants can use shallow groundwater, if present during the growing season, which can improve or threaten crop performance as recently demonstrated (Nosetto et al., 2009).

To simulate the abovementioned processes, numerical models have often been implemented and employed in the recent past (Azzaroli Bleken et al., 2009; Lopez-Cedron et al., 2005). Overall, the model accuracy depends on the accuracy of the input data and on the assumptions made to simplify the complex modeled environment (Panigrahi and Panda, 2003). Here residuals, i.e. differences between simulated and measured values, were used to evaluate the accuracy of each model run. The most common statistical tools, used to compute model accuracy are the average mean residual error and the root-mean square residual error (Whitmore, 1991). These statistics were used in this work to assess the effect of different potential evapotranspiration (PET) formulas and root water-uptake reduction functions on actual groundwater recharge in the Ferrara province, an area located in the Po Plain lowlands, characterized by a flat topography and by a temperate humid climate. The main goal of this study were to assess whether simple approaches to calculate the PET, like Hargreves and Turk ones, can substitute complex ones like Penman–Monteith and to assess the variability of the groundwater recharge estimated with different PET formulas. The same assessment was performed for root water-uptake reduction functions. In addition, simulations were run with minimum and maximum observed saturated hydraulic conductivities, to quantify its influence on groundwater recharge flux. To achieve these aims, three field sites consisting of different soils representative of the Po Plain lowlands were monitored for 400 days and modeled with HYDRUS-1D.

2. Materials and methods

2.1. Field sites characterization and setup

Po Plain lowlands are intensively farmed due to the flat topography and to the abundance of surface water for irrigation; the primary land use is maize cropping. In the study area, located in Ferrara province (Italy) at an altitude ranging from 5 to −3 m above sea level, three sites (named SAP, CCR and MEZ) were selected to monitor and model the water movement in the unsaturated zone. For the research it was chosen a medium maturing maize hybrid (*Zea mays* L., FAO 500, 125 days), commonly employed in the studied area, at density of 7 plants m^{-2}. Five replicate plots of 10 m × 20 m were cultivated at each of the three sites and used to derive the grain yield and its standard deviation.

The surface area of the plot in each site was 1 ha, its slope was less than 0.5% (and mostly less than 0.05%). For this reason, it was assumed surface run-off was minimal and water movement in the unsaturated zone dominantly vertical.

Meteorological stations recording rainfall, wind speed, solar radiation, temperature and humidity are located from 0.5 to 5 km far from the field sites. Data are available on-line from meteorological regional service (www.dexter.it) and from local web service (www.meteoveneto.com). A rain gauge was installed in each site to record daily rainfall. The linear correlation of daily data between the rain gauges and the nearest regional weather stations ($R^2 > 0.9$ for all sites), consented to extend the data measured by the on-line weather stations to the field sites. As shown in Table 2 the average meteorological parameters recorded in the three sites are typical of coastal plain environments, with a sub-coastal temperate climate characterized by cold winters and warm summers, with moderate precipitations, elevated humidity, low wind speed, moderate daily and seasonal temperature excursions. In Ferrara province the agricultural schedule suggests two above-canopy sprinkler irrigation times of 30 mm before and during the milking stage of maize crops (approximately June and July 2008). Fig. 3 shows that during