Hydrol. Earth Syst. Sci. Discuss., 4, 3909–3952, 2007
www.hydrol-earth-syst-sci-discuss.net/4/3909/2007/

Hydrology and Earth System Sciences Discussions

Papers published in *Hydrology and Earth System Sciences Discussions* are under open-access review for the journal *Hydrology and Earth System Sciences*

Analysis of soil and vegetation patterns in semi-arid Mediterranean landscapes by way of a conceptual water balance model

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Received: 28 September 2007 – Accepted: 28 September 2007 – Published: 19 October 2007

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Abstract

This paper investigates the impact of various vegetation types on water balance variability in semi-arid Mediterranean landscapes, and the different strategies they may have developed to succeed in such water-limited environments. Water balance constraints are assumed to dominate the organization of landscapes and a conceptual bucket approach is adopted to model the temporal water balance dynamics, with vegetation water use efficiency being parameterized through the use of empirically obtained crop coefficients as surrogates of vegetation behavior in various developmental stages. Sensitivity analyses with respect to the root zone depth and soil water holding capacity are carried out with the aim of investigating the existence of preferential soil-vegetation associations and, hence, the spatial distribution of vegetation types within the study region. Based on these sensitivity analyses the degrees of suitability and adaptability of each vegetation type to parts of the study region are explored with respect of the soil water holding capacity, and the model results were found to be able to explain the observed affinity patterns. Finally, the existence of such preferential association between soil water holding capacity and vegetation species is verified through an extensive soil survey available in the study region.

1 Introduction

A primary motivation for this study is the development and implementation of a simple water balance model for regional applications in semi-arid Mediterranean landscapes, e.g., study of the impact of climate change on regional water budget, and the assessment of critical climatic and landscape controls over large spatial domains (Entekhabi and Eagleson, 1989; Scholes and Walker, 1993). In such environments, often referred to as water-limited ecosystems, the basic processes of water storage, drainage and evapo-transpiration are controlled by the interaction between climate (seasonality versus inter-annual variability), soil properties (storage capacity and drainage rates), and vegetation dynamics (Farmer et al., 2003) (soil moisture dynamics, plant productivity and security). Consequently, the water balance regime is highly variable in space due to the prevailing spatial heterogeneity of climate and landscape properties (i.e., soils) and the highly complex space-time patterns of vegetation types, density and response. Notwithstanding the process complexity, in scientific literature it has been found that simple models with a single-layered root zone (e.g. bucket models) are quite often adequate to simulate monthly evaporation and water balance, at regional to global scales (e.g. Feddes et al., 2001; Federer et al., 2003).

Several model applications and experimental studies have shown that water balance estimates are sensitive to land cover types, especially vegetation cover and land use, as well as parameters related to soil moisture storage, particularly the rooting depth D_r, and available specific water content θ_{fc}–θ_{wp} (e.g. Finch, 1998). However, most model predictions suffer from the lack of knowledge of the soil water storage capacity, which depends on rooting depth and available water content, whose magnitudes are hard to measure and hence seldom available over large spatial scales. Methods do exist for the estimation of some of these model parameters through the use of regional soil maps which provide suitable estimates (usually in the form of ranges) of soil hydraulic properties. Vegetation characteristics and land-use, combined with multiple regression analyses, are also used to estimate the required soil moisture storage properties (e.g. Santini et al., 1999). However, such methods need suitable geo-databases for testing the robustness of these hypothetical regressions over the study domains.

On the other hand, in the last many years the development of remote sensing has provided extensive and reliable maps of vegetation cover which are always available even in so-called ungauged basins. At the same time in the emerging field of eco-hydrology the role of vegetation in hydrology has been investigated in considerable detail.

Motivated by these considerations we explore for the use of simple models for water balance evaluation and prediction, provided that they are able to correctly represent the role of climate-soil-vegetation (CSV) interactions and the dynamic adaptive behavior of vegetation in controlling the space-time patterns of water balance variability (Scanlon and Albertson, 2003). The analysis and detection of CSV interactions, in fact, may provide a priori information which can be easily exploited, in simple water balance models, in this way helping to reduce parameter uncertainties that arise in absence of accurate soil databases.

It is well known that, during the evolution of native plant species in any environment, a diversity of mechanisms is adopted by plant communities to adapt their progeny to the range of environmental perturbations encountered in nature (Zobel, 1992). There is evidence that plants with different rooting habitats show different seasonal courses of water exploitation, and that the duration of water stress and the distribution of soil moisture with depth will determine whether a species can succeed in a particular environment (e.g. Davis and Mooney, 1986). The depth at which plants are able to grow roots has important implications for the whole ecosystem hydrological balance (as well as carbon and nutrient balances). For example, the water extracted by plants during the wet season often comes from shallow layers where the root density is highest, whereas, as those layers dry, there is a progressive shift towards using water located in deeper layers (Canadell et al., 1996). In this regard, simulations with a simple water balance model across the large area of the United States (Milly, 1994) demonstrated that (estimated) actual values of soil water holding capacity found in places were such that they were large enough to maximize evapo-transpiration and minimize runoff, pointing to an ecologically optimal vegetation response relative to the magnitudes of water and energy supply. In the same vein, we hypothesize that even in heavily human impacted environments such as the Euro-Mediterranean region which is the focus of this study the principles of eco-hydrology continue to play an important role. In particular, the habitats selected for plant domestication are chosen so as to provide reduced competition, improved fertility, and reduced disease incidence to the introduced vegetation, thus allowing increased productivity.

Starting from such kind of reasoning, a key hypothesis in this paper is that vegetation response, and its evolutionary adaptation to the multi-scale climate variability and landscape properties (soils, topography etc.) prevalent in the study region, could be considered as keys to understanding the underlying water balance regimes, with particular reference to agricultural landscapes. Therefore, since soil moisture storage capacity becomes a controlling factor for sustainability and survival of rain-fed agriculture, some selective association between both soil and vegetation features must be recognized in their spatial co-variations, so that the key problem of identifiability of model parameters could be effectively constrained. Thus, land cover information, available at a regional scale, can be further exploited in order to improve the hydrologic evaluation and prediction of water balance and reduce the parametric uncertainty due to scarce information about soil features and hydraulic behavior.

These results are based on the use of a conceptual bucket model which, despite its simplicity, is shown to be able to detect and explain the existence of typical CSV patterns and associations that can be discovered in the available geo-databases of soil features and vegetation characteristics in the study region.

To accomplish this, the hydrologic behavior of each land cover (vegetation) type is explored through sensitivity analysis with respect to soil water storage capacity, and through assessing the effects of climate variability (at intra- and inter-annual time scales) under different soil and vegetation conditions. The adaptation and suitability of each vegetation type to the study region and the sensitivity of plant productivity and vegetation stress (Rodriguez-Iturbe et al., 1999) to are investigated in the absence of irrigation. As an indicator of plant productivity and water stress response, estimated annual values of actual evapo-transpiration, combined with simple statistical indicators, is adopted. Finally, a conceptual validation of this rationale is performed by investigating how the productivity and water stress response produced by the model under different vegetation and soil combinations are reflected in the observable spatial patterns of vegetation types across the study region.

The paper is organized into a methodology section, followed by the results, validation, and conclusions sections. The methodology section includes a background description of the study region with its climatic and landscape peculiarities. Then, the adopted water balance model is briefly described giving an outline of the nature of water balance simulations, and the soil and vegetation data used in the model simulations. The results section is focused on the water balance response under different soil and vegetation conditions, followed by the results of sensitivity analyses carried out to investigate vegetation adaptability. Finally, the validation section analyzes the soil and vegetation patterns observed in the study region and attempts to interpret these through their links to or association with a comprehensive soil database of the study region.

2 Methodology

2.1 Background to the study region

Puglia, a South-Eastern coastal region of Italy (Fig. 1), exemplifies typical features of semi-arid Mediterranean landscapes. Over many centuries, as in several other Mediterranean regions, mild orographic features and high population density have led to intensification of agricultural farming, accompanied by replacement of existing natural vegetation with agricultural crops (Table 1). Some of these crops have originated from native species as in the case of olives, grapes and some varieties of wheat, but exotic species (e.g., some types of vegetables) have also been introduced over time. This is exemplified by a low degree of crop diversity in the region covering an agricultural area of about 14 700 km^2, of which 43% is cultivated with wheat, 32% with olives, 9% with grapes, 3% with citrus and 2% with vegetables (Fig. 1).

A major distinction can be made between permanent and seasonal crops. In fact, a marked differentiation exists between seasonal (e.g. winter wheat) and permanent native vegetation (e.g. olives) in terms of their physiological features (e.g. root apparatus) to deal with variable soil moisture storage (Zobel, 1992). Seasonal crops, represented here by wheat crops, are usually characterized by an almost complete vegetation ground cover with a high root density and shallow root depth. These features make seasonal vegetation able to maximize soil water exploitation only during and immediately after the wet season (Canadell, 1996). On the other hand, permanent tree crops, represented by olives, grapes, and citrus, have lower percentages of vegetation ground cover, deeper roots and lower root density, which have all evolved over time to withstand the expected soil moisture deficits during the dry season.

Besides physiological features of plants, the spacing of trees, which in turn controls vegetation ground cover, is affected by local agricultural practices aimed at maximizing productivity and reducing disease exposure. Typical ground cover conditions observed in the region are presented in Table 2 (Allen et al., 1998) for the permanent crops used in the study.

As shown in Fig. 2, the climate variables in this region exhibit marked inter-annual variability (especially in rainfall, Fig. 2a), as well as strong annual seasonality (Fig. 2b) where the observed seasonal rainfall pattern is out of phase with that of potential evapo-transpiration.

A comprehensive geo-database is available, including the results of over 4000 soil samples covering the entire study region. Direct measurements of soil thickness were performed during field surveys, which also provided estimates of the available water content AWC (mm), thus permitting the analysis of the aforementioned eco-hydrological associations and the validation of the conceptual model. For each soil sample the AWC is estimated by accounting for all soil layers available within the root zone. The soil moisture storage capacity S_{bc} is the corresponding model parameter on the assumption of a single homogeneous soil layer within the root zone, and is simply defined as $S_{bc}=D_r\left(\theta_{fc}-\theta_{wp}\right)$, where θ_{fc} and θ_{wp} represent the specific soil moisture values at field capacity and wilting point respectively.

2.2 Description of the water balance model

Our main interest is in the role of soil and vegetation in regulating the landscape water balance. In particular, we focus on vertical fluxes of evapo-transpiration to the atmosphere, and evaluate drainage from the root zone, including any surface or subsurface flow. Therefore, modeling a single-layer root zone is deemed adequate to simulate monthly water fluxes, through ignoring several processes of water movement which become more important at the daily time scale (Federer et al., 2003).

The role of soil and vegetation in controlling these processes is expressed through simple parameterizations. The hydrologic behavior of agricultural landscapes can be reasonably modeled by way of literature parameterizations (Allen et al., 1998), used as surrogate for the various vegetation development stages that can be effectively surveyed from LAI (and/or NDVI monitoring systems).

In the single-layer root zone, soil moisture state variable $S(t)$ is continuously updated on the basis of known or estimated net inflows and outflows to and from an associated control volume. The resulting dynamic water balance equation is given by:

$$S(t+1) = S(t) + P - E_T - Y \tag{1}$$

where, P is the rate of precipitation, E_T is the rate of actual evapo-transpiration, and Y is the net drainage yield, the rate at which water is leaving the root zone, and t is the generic time step. The magnitudes of the other fluxes on the right-end-side of Eq. (1), namely, E_T, and Y, are all controlled by the soil water storage $S(t)$. To estimate these fluxes in terms of $S(t)$ (with the assumed mathematical expressions being summarized in Appendix A) the field capacity threshold is the only parameter in these expressions, and is estimated as $S_{fc} = D_r\theta_{fc}$ (e.g. Milly, 1994; Struthers et al., 2003; Federer et al., 2003). Such a model structure is specifically adopted in order to control soil moisture behavior and concentrate its variability into one single parameter, S_{bc}. The sensitivity of model predictions to the parameter S_{bc} will be reported later on.

Monthly evapo-transpiration is modeled on the basis of the Penman-Monteith equation, after the FAO calculation method (Allen et al., 1998). The influence on evapo-transpiration exercised by canopy architecture and leaf cover density is embedded into empirical crop coefficients K_c describing vegetation development stages with respect to some standard vegetation type. Similarly, the influence of soil water availability on the stomatal resistance considered in the Penman-Monteith formulation is taken into account through an empirical water stress conceptualization on the basis of the available water in the root zone, again as suggested by the FAO method (Allen et al., 1998) (see Appendix A).

Both for seasonal and permanent crops K_c values are variable during the year reflecting the seasonal developmental stages of plants. A database of crop coefficients for typical Mediterranean crops was provided by Doorenbos and Pruitt (1977), which was later supplemented by Allen et al. (1998) (Table 2). Lengths of development stages are themselves variable according to plant variety, local climate and cultural conditions. Consequently, as suggested by the FAO method (Allen et al., 1998), local observations of seasonal plant development are incorporated into the monthly crop coefficients adopted in the model (Table 2) by way of the expected durations of vegetation stages observed in the study region (Caliandro et al., 2005).

Four typical crops are investigated, namely wheat, olives, grapes, and citrus. These selected crops are representative of most of the agricultural areas within the Mediterranean region, including Puglia, since they are considered native to the Mediterranean region, at least in the sense that they have been established in the region for several centuries.

The allowable limits of root depth for each species are taken from Doorenbos and Pruitt (1977), and supplemented by Allen et al. (1998) and local observations (Caliandro et al., 2005). The estimates of D_r are expressed in terms of ranges of variability (up to ±30%) observed in the region (Table 3). Similarly, θ_{fc} and θ_{wp} are highly variable between the different soil types that exist in the study region. The possible range of values defining soil water holding capacity is reported in Table 3 as obtained from the regional soil database. Consequently, the variability of the soil storage capacities can cover a range of about ±70% if any dependence between root depth and soil properties is neglected.

For all vegetation species, the water balance simulations are initially carried out for central values of the soil water storage capacity, S_{bc}, estimated using central values of D_r, θ_{wp} and θ_{fc} in their respective variability ranges. With this parameter set, the model was run for a 50-year data set (1951–2000) of monthly climate records in order to capture specific water balance responses to the intra-annual and inter-annual climate variabilities that can be related to landscape attributes in the study region. The climate records are taken from a meteorological station that is centrally located and is considered climatically representative of most of this territory. Each vegetation species in the simulations is assumed to be under stationary conditions, repeating their annual development cycle as represented by the adopted crop coefficients. In the case of permanent tree crops, we refer to mature plants with no biomass growth through the years.

Subsequently, the simulations were repeated covering the full range of possible values for the bucket capacity and recording estimates of the water balance fluxes (evapotranspiration and drainage) and the soil moisture storage. A comparison between model simulations resulting from daily and monthly formulations is presented in Appendix B to demonstrate the limited bias of the monthly water flux predictions and their reasonable applicability for regional studies.

3 Results and discussion

3.1 Climate-soil-vegetation impacts on water balance

The selection of the results presented below is aimed at recognizing and conveying differences among the various vegetation species in terms of hydrologic response and climate adaptation which can be useful to explain observed spatial occurrence of vegetation and soil features. The vegetation response to intra-annual and inter-annual variability of climate is presented in the form of associated behavior patterns, or signature plots (Atkinson et al., 2002; Farmer et al., 2003). Differences between the signatures are interpreted in terms of vegetation functioning in respect of landscape properties and climate.

The central values of root depths and soil properties in their respective variability ranges (Table 3), used in the initial simulations, are not significantly different between the various crops: it is either 100 cm (olives, wheat) or 110 cm (grapes, citrus), and the remaining soil properties are in fact identical. Hence, the differences in the average drainage yields between different crops, and the differences in drainage yields between different years that may yet have similar rainfall totals, can only be explained in terms of differences in plant water use (i.e., crop coefficients and moisture dynamics). This is confirmed by considering the values of the crop coefficients presented in Table 2.

Due to the fact that the seasonal variability of rainfall and potential evapo-transpiration are perfectly out of phase, soil moisture storage and consequently drainage yield are expected to show strong intra-annual variability. Firstly, we express this intra-annual variability in terms of drainage duration curves, in the same fashion as flow duration curves are normally used in the analysis of streamflow variability (Atkinson et al., 2002; Farmer et al., 2003). The drainage duration curves, of a 50-years simulation run, with median values of storage capacities are presented in Fig. 3, and exhibit features of the ephemeral flow regimes typical of semi-arid regions exhibiting out-of-phase seasonality of rainfall and potential evapo-transpiration. In particular, grape crops show negligible drainage yield (less than 10 mm/month) for 66% of the time, olives 70% of the time, citrus 76%, and wheat 77%, with much of the deep drainage occurring over the peak winter season, wet period. Significant differences between the crops are highlighted, with grapes having the greatest water yield on average, followed by olives. Wheat and citrus, although representing very different vegetation types, exhibit almost identical hydrological responses, but with lower annual yields than grapes and olives.

The simulations also highlighted significant inter-annual variability of drainage, ranging from less than 50 mm/year to about 600 mm/year for the various crops. Evidently, much of this variability can be attributed to the corresponding huge inter-annual variability of annual rainfall (ranging from less than 400 to about 950 mm/year). Nevertheless a significant inter-annual variability of drainage yield, of the order of 100 to 150 mm/year, is exhibited also between years with similar annual rainfall totals. This component of the total inter-annual variability can be explained by the intra-annual (deterministic and random) variability of rainfall, interacting with intra-annual variability of potential evapo-transpiration, to produce variable soil moisture storage and drainage yield within and between years.

Further insights into the intra-annual (especially random) variability of the land surface response are needed to explain these inter-annual variabilities. Always using central values of root zone depth and soil properties, the model estimates the mean monthly drainage yields, which are presented in Fig. 4 (continuous lines). In general, these mean curves reflect the average seasonal water use patterns. These trends are governed by the seasonal patterns of climate (rainfall and potential evapo-transpiration) and the seasonal cycle of plant water use (as reflected in the crop coefficients). Wheat crops, for example, exhibits the lowest average water yield during winter months since they correspond to its growth period, whereas for permanent crops (e.g., olives, grapes) the highest water yields are obtained by the concurrence of high winter rainfall and relative plant dormancy.

Figure 4 also presents measures of the inter-annual variability of monthly drainage yield, in the form of excursions above and below the mean curve. One can see that the inter-annual variability is particularly high during winter months for all of the vegetation species, clearly reflecting the inter-annual variability of wet season rainfalls. In the early autumn period, however, the wheat crop shows the greatest variability, since this period corresponds to pre-seedling and early development of that crop when its evapo-transpirative demand is reduced, as seen in Table 2. The effects of rainfall deficit conditions (below average rainfalls) are also evident in Fig. 4, with deep drainage falling quickly to negligible values in dry years for all (including winter) months.

The ability of soil-vegetation interactions to alter the intrinsic variability of water balance, and in particular the drainage yield, is further investigated for the winter season, this being the most critical period for the annual replenishment of water resource supplies. In Fig. 5 the coefficients of variation (CV), characterizing the inter-annual variability of monthly rainfalls and drainage yields, are compared. It is clear that, for each crop, the intra-annual soil-vegetation interactions produce a larger inter-annual variability of hydrological response (i.e., drainage yield) than that of rainfall. In fact, the CV of drainage yield is always higher than that of rainfall also during the months of December, January and February (peak winter months), when the soil moisture would be expected to be at or near field capacity, suggesting little filtering by the soil moisture storage. Outside of this 3-month period, the CV of drainage yield becomes even larger than that of rainfall. This suggests that that the CV of drainage yield is governed not only by inter-annual variability (CV) of rainfall, but also its *intra-annual* variability, since the latter will be expected to have an impact on the inter-annual variability (CV) of antecedent soil moisture storage, which helps to increase the CV of drainage yield further.

3.2 Vegetation adaptive strategies and hydrological descriptors

In this section we explore the adaptive strategies that may have been employed by the various vegetation species to survive and succeed in the semi-arid Mediterranean landscape. The basic hypothesis is that the vegetation species develop strategies to maximize their productivity within the limited resources available (energy, water, nutrients etc.), and, on the other hand, they withstand periodic shortages of these resources that arise due to the natural variability of climate (Zobel, 1992). In other words, the assumption is that the species that are naturally adapted to the local conditions are those that concurrently maximize mean productivity and minimize the variance of the productivity. With respect to the water uptake, the strategies they have under their disposal are 1) maximize the reach of the root apparatus to access more of the annual rainfall, and 2) maximize security against water stress by adopting a seasonal plant water use pattern that is aligned with the climate (water and energy). In model simulations, both strategies are accounted for by varying the root zone depth and soil moisture storage parameters within the expected range of soil properties that are present in the study region and by comparing the evapo-transpiration performance of different crops (essentially represented by the seasonal patterns of the specific crop coefficients K_c in

Table 2). In fact, the mean monthly potential evapo-transpiration turns out to be larger than mean monthly rainfall for a significant period of the year for all of the investigated crops (though with considerable differences between crop types), with wheat having its period of maximum evapo-transpiration from late winter till mid-spring (February to May), while tree crops (particularly grapes and olives) maximize their water exploitation from spring to summer (March to September). In other words, for all plants water stress conditions are likely to occur over considerable (though different) periods in the absence of irrigation. The impact of these adaptation strategies are investigated in terms of the mean and variance of actual evapo-transpiration, these being used as surrogate measures of plant productivity and security against water stress, respectively.

The model sensitivity to effective soil moisture storage capacity, S_{bc}, is explored next. The results of the analysis are first presented in terms of mean annual and mean monthly variations of the water balance fluxes, and inter-annual variability of monthly fluxes. Figure 6 shows the sensitivity of mean annual evapo-transpiration and drainage yield to the range of soil storage parameters defined in Table 3. As expected, the increase of S_{bc} produces a beneficial increase in actual evapo-transpiration, and a corresponding decrease of drainage yield, by assisting plants to capture a larger fraction of the annual rainfall. This sensitivity of the hydrological response to S_{bc} may also be taken as an indication of the heterogeneity of actual evapo-transpiration and drainage yield estimates across the region, arising from the heterogeneity of soil storage properties (root depth, field capacity and wilting point).

Due to the intra-annual (seasonal) variability of climate and vegetation response, the above sensitivity of the hydrological responses to soil storage capacity is not uniform throughout the year. Figure 7 presents results of sensitivity analyses carried out with respect to S_{bc}, where the solid lines represent the mean monthly yields for central soil storage properties (same as Fig. 4). In addition to these, the results corresponding to the maximum and minimum values of S_{bc} in the ranges defined Table 3, are presented as points, to represent the ranges of variability in the mean monthly yields that can be expected due to soil storage properties. The results presented in Fig. 7 indicate that the greatest variability in drainage yield is achieved in the late autumn period (November), as this corresponds to the period of moisture recovery after the summer deficit, when the superposition of variability of S_{bc} and intra-annual rainfall variability combines together to cause this effect. On the other hand, it is clearly evident that the effect of changes in S_{bc} on drainage yield progressively reduces in the winter, and from late winter till late summer it is almost negligible. In late winter field capacity conditions are reached on average for all realistic values of S_{bc}, and hence the water yield does not depend on S_{bc}. In summer, on the other hand, soil moisture status is considerably low regardless of the soil storage capacity, and therefore drainage yield is, once again, not in any way impacted by the assumed maximum value of S_{bc}.

A comparison of the results presented Figs. 4 and 7 also indicate that in such an environment the variability of the hydrological responses due to variability of S_{bc} values is considerably smaller than that due to the inter-annual fluctuations of climate, which were previously reported, especially during winter months. Consequently, it can be argued that in order to assure plant survival and security in the Mediterranean region, vegetation must develop more effective strategies to adapt to the large inter-annual variability of climate than those needed to be successfully adapted to other landscape features controlling soil moisture storage (i.e., through increases of root depth). In particular, they must focus on adjusting their plant water use to be more closely aligned with the temporal patterns of rainfall and the resulting patterns of soil moisture.

This hypothesis is further investigated by exploring the effectiveness of increasing S_{bc} for stabilizing plant productivity, and in particular, for reducing the inter-annual variability of actual evapo-transpiration. Figure 8 presents the coefficients of variation of the annual actual evapo-transpiration (CV_{Et}), which is used as a measure of the inter-annual variability of plant productivity. The results indicate, in general, that increases of S_{bc}, besides clear improvements in the mean annual evapo-transpiration as reported before (Fig. 6), also produce substantial decreases in the inter-annual variability once some threshold of S_{bc} is exceeded. This is due to more of the water being carried over to subsequent months and being available for plant water use, and not lost through deep drainage. Native permanent species, i.e., olives and grapes, show the greatest sensitivity to soil moisture storage capacity, and reach the same degree of residual variability, which suggests the potential use of soil moisture storage capacity as an adaptation strategy to deal with climate variability. For winter seasonal crops (e.g., wheat) the sensitivity to soil moisture storage capacity is not as strong as olives and grapes, since their growth period coincides with the period of low rainfall variability, helping to ensure that they are less dependent upon the carryover of soil moisture storage. In fact, the coefficient of variation for wheat presents an almost constant value for S_{bc} values greater than 150 mm, indicating a substantial non-sensitivity of the inter-annual variability to any increase of storage capacity. On the other hand, citrus appears less sensitive to the soil moisture storage capacity, with the highest residual variability among the studied crops, suggesting that citrus crop is not as well suited to the local climate.

The analysis of CV_{Et} can be used to estimate expected values of S_{bc} needed to optimize plant performance in terms of both productivity and conservation. In all four cases, in fact, the rising limb of the CV_{Et} curve represents unfavorable conditions of stable but low evapo-transpiration from year to year that determine the occurrence of frequent water stress conditions as a consequence of limited moisture storage within the soil. Consequently, specific suitability ranges for S_{bc} can be recognized for the modeled vegetation types (Fig. 8), thus providing an explanation for the existence of spatial patterns of vegetation and soil properties arising from the highlighted variable degrees of affinity. According to the performed sensitivity analysis, grape and olive crops seem to be adaptable to the climatic conditions in the study region for soil moisture capacities above 75–100 mm, whereas wheat and citrus would have good performances for S_{bc} values greater than 140–150 mm (Fig. 8).

Besides CV_{Et} a second important hydrological descriptor is the mean annual value of the actual evapo-transpiration E_T scaled by the annual potential crop evapo-transpiration E_{Tc} (Fig. 9). This ratio is a measure of the annual plant productivity, representing the variable degree of adaptation in response to the water storage capacity of the soil. In Fig. 9, wheat and olive crops show better performances among the considered species, whereas grapes and citrus are far below, thus appearing to be less adapted.

4 Conceptual validation through analysis of soil geo-database

We can investigate, at this point, if the co-occurrence of plant species and soil features, being the ultimate effect of adaptation mechanisms (both naturally and human-induced), might be adopted as a robust, though non-conventional, validation of the model-based hypotheses regarding the spatial patterns of vegetation. The validation of such principles represent a way forward to the internal verification of water balance models, which may be used to explain observed patterns of vegetation more than just reproducing hydrological time-series.

Such kind of reasoning is tested in this paper through the analysis of about 4 000 soil samples covering the entire study region (covering almost 20 000 km^2). This data collection, although focused only on agricultural landscapes (Caliandro et al., 2005), provided a valuable source of information on soil depth and water holding capacity. The soil samples cover a range of statistically significant land-uses, at least for wheat, olive and grape crops (Table 4).

These data represent a sample of a multi-dimensional variable in which each element is a vector of soil parameter values including (among the others) the soil use, soil depth, AWC, specific water content SWC (mm/m), etc. We chose the land-use as the characteristic for the statistical analysis of some of the remaining parameters, namely soil depth, AWC and SWC, to investigate the affinity between soil properties and spatial patterns of vegetation. As already mentioned, AWC is the data-set measure corresponding to model parameter S_{bc}.

The frequency analysis of the soil samples with respect to the AWC values can be related to the results coming from the sensitivity analysis of the water balance model simulations. First of all, the range of values for the soil AWC observed in the real data

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(Fig. 10) is coherent with those values estimated on the basis of literature ranges of root depths and soil textural properties (Table 3). Nevertheless, by assuming a gamma probability distribution function for the AWC sub-sets, as in Milly (1994), marked differences are revealed between their shapes. Olive plants seem well suited even to small values of the AWC parameter, while wheat and grape appear less tolerant. This observation is consistent with the above reported considerations about Fig. 8.

Moreover, the respective AWC sample averages in Fig. 10 (75 mm for olive, 150 mm for wheat and 165 for grape) correspond to a narrow range between 0.62 and 0.69 for the ratio of actual to potential evapo-transpiration (Fig. 9), with wheat crops showing the best performance (0.69), followed by olives (0.65) and then grapes (0.62).

These features of the frequency distributions of water holding capacity very well represent the selectivity (grapes and wheat) and conversely the adaptability (olives) of different vegetation types to various landscape conditions.

Furthermore, the dependence between spatial occurrence of land-use types and soil attributes across the landscapes is clarified in terms of patterns of relative abundance of the considered land-uses in any given class of soil water holding capacity. Based on the soil samples, Fig. 11 presents the relative frequencies of each land-use varying the class of the soil AWC. The use of frequencies of occurrence normalised by the relative abundance of each soil class within the entire sample assures more significant and unbiased signals of soil-vegetation affinity (Fig. 11). The observed regular patterns show that increasing the available water content of the soil implies a gradual transition (or substitution) from less water-consuming crops (more adaptable) to more exigent ones (more selective).

Therefore, the shapes of these curves (and their slopes) provide an explanation of the affinity patterns between land-use and water holding capacity. In fact, according to Fig. 11, wheat crops tend to dominate above 150 mm of AWC with noticeable improvements as this threshold is exceeded. Similarly grape crops reach a stable condition for AWC values above 150 mm (Fig. 11). On the other hand, olive groves that are adaptable to a wider range of landscape conditions in the study region appear gradually substituted by other more profitable crops.

Hence, the preferential soil settings summarized in Fig. 11 for the three dominant agricultural species in the region are in good agreement with productivity performances predicted with the water balance model. In fact, the overall abundance of olive and wheat crops with respect to grapes is exactly what the annual plant productivity measure shows in Fig. 9. On the other hand, the substitution of less remunerative cultures such as the olives with more rewarding ones, such as wheat, seems to be controlled by the available soil moisture storage, which helps in stabilizing the annual productivity as highlighted in Fig. 11.

Therefore, all the results from the analysis of field data appear in good agreement with the hypothesis of vegetation adaptability formulated from the sensitivity analysis of water balance simulations. The co-occurrence of land-use and soil properties provides evidence that eco-hydrological principles play a crucial role even in human-modified landscapes that are strongly characterized by agricultural vegetation in a water limited environment. The observed distributions support the role of the soil water holding capacity as a limiting factor for vegetation development and suggest the principle of maximum landscape productivity as the key to interpret the spatial patterns of vegetation in which successful species take the place of less productive ones, thus providing a useful guidance for model parameterization and constraint.

5 Discussion and conclusions

This research was carried out under the basic conjecture that, the interaction between human (or socio-economic) and natural processes, in a challenging natural environment, has led to the adoption of typical "naturally" selected crops, combined with agricultural practices developed in an ad hoc manner. It then pursued a dual goal. The first one was to assess the role of the eco-hydrological concepts of natural selection and productivity optimization to landscapes deeply affected by human intervention and dominated by agricultural vegetation species. The second one is to assess the applicability of simple hydrological models for water balance evaluation and prediction. A monthly bucket model is proven to be able to fairly reproduce the aforementioned eco-hydrological processes, providing a simple scientific explanation of the observed patterns of vegetation cover and associations between vegetation and soil types. The model also had the advantage of simple process parameterizations which assisted in containing the uncertainty of prediction. In fact, the above mentioned "eco-hydrological" associations permitted the evaluation of probability distributions of soil hydraulic properties conditional on the vegetation cover (see Fig. 10). Such information, within a Bayesian context of model uncertainty evaluation can be highly informative when considering that soil properties are rarely available at regional scale while nowadays vegetation and land cover information is one of the products that can be most effectively obtained by remote sensing observation.

The monthly water balance model (bucket model) used explicitly incorporates the key processes of evapo-transpiration and deep drainage (or drainage yield) allowing one to obtain reasonable estimates as compared to the daily model formulation. Model simulations are utilized to explain and explore differences in the soil moisture response due to different vegetation types and their impact on the temporal variability of water balance, and in this way explaining the spatial patterns of soil-vegetation occurrences extracted from the statistical analysis of available data over the study region.

The following comments can be made regarding the vegetation impact on water balance which is characteristic of a Mediterranean water limited environment:

- Much of the inter-annual variability is due to the inter-annual variability of rainfall. Nevertheless, there are significant differences between vegetation types in the way their phenology is adapted to the climate, as exemplified by the assumed crop coefficients.

- The combination of seasonal variations of soil moisture storage and plant water uptake has a measurable impact on the drainage yield production with remarkable differences between vegetation types. For example, where vegetation activity is in phase with rainfall the water yield is reduced as happens for wheat crops. On the contrary, if the wet season corresponds to the plant dormancy period, as for grape crops, the water yield is maximized.

– The inter-annual variability of the drainage yield is particularly high during winter, especially during late winter months of December, January and February, since soil moisture storage is at or near field capacity, and the variability of rainfall during these months is immediately passed on to the drainage yield. Nevertheless, a significant fraction of the inter-annual variability of drainage yield is due to random intra-annual (within year) variability of rainfall, especially with rainfall amounts falling during the wetting up period between summer and winter combined with the effects of random variability of antecedent soil moisture.

In the second part of the results section, model sensitivity analysis is reported in order to explore the vegetation response to variable soil properties, namely soil type and root depth. In particular, the impact of soil properties on the overall water balance is clarified. Depending on the different types of vegetation,

– increasing values of the soil moisture storage capacity, S_{bc}, leads to an increase of actual evapotranspiration and a decrease of the drainage yield, due to the increase in the carry-over of soil moisture from wet to subsequent dry periods;

– variations of S_{bc} can indeed contribute significant variability to the hydrological responses at the annual scale, although it is most important during the autumn, wetting up period.

– During periods when the soil moisture is at field capacity (winter), or during periods when it is much lower than field capacity (summer), the storage capacity has a negligible impact on the hydrological responses.

– For the range of values of S_{bc} used, the model simulations also showed that the variability of hydrological response caused by the soil parameters is much smaller than the variability caused by climate (rainfall) fluctuations in this region.

Subsequently, the concepts of maximum plant productivity and security are employed in the context of soil moisture storage to discuss the suitability and adaptation of these vegetation types to the semi-arid Mediterranean climate and landscapes. In this way we have gained some insights into relevant correspondences between vegetation distribution and soil water holding capacity which are deemed extremely useful for large scale water balance studies.

It is assumed that to survive in water-limited environments plants adapt their physiology in such a way as to exploit water during periods of abundance and restrict it during periods of shortage, and, secondly adjust their root depth and thus the extent of soil moisture storage capacity. Both strategies help to carry over soil moisture from wet to dry periods. Indeed, it is interesting to note that well-adapted native vegetation types (e.g. olive groves) are not the ones that maximize water exploitation but are the ones that are able to successfully manage the inter-annual variability of climate.

The effectiveness of soil moisture storage capacity in improving evapo-transpiration performances helped to assess the suitability of a given species to different landscape conditions (e.g. spatial variability of soil attributes prevalent across the region). Olive, for example, exhibited the smallest minimum allowable value of soil moisture storage capacity among all crops, proving its adaptability to different soil settings (including shallow soils), as exemplified by the exceptional spreading of olives throughout the region. The other crops were shown to be more selective in terms of soil settings as they require larger storage capacities to survive under drought conditions. The results of the sensitivity analysis are confirmed by the observed spatial patterns of vegetation and soil water holding capacity in the study region thus enabling to interpret the variability occurring in the Mediterranean landscape in terms of their eco-hydrological controls. Spatio-temporal patterns of vegetation coverage across the study region are usefully interpreted in terms of the underlying climatic (mean annual rainfall and potential evaporation, and their seasonal and inter-annual variabilities), and soil (soil depth, texture etc.) distributions.

This kind of pattern interpretation could provide a powerful guide for the development of large scale water balance models in which the critical point of spatial distribution of soil water storage can be constrained from the recognized soil-vegetation affinity patterns. In this sense, the knowledge of vegetation functioning, and in particular, their possible adaptation to the climatic and landscape characteristic, can be utilized effectively to effectively reduce model uncertainty in regional scale water balance studies.

Appendix A

Model equations

Threshold storage and bucket capacity are defined as follows:

$$S_{fc} = D_r \theta_{fc} \tag{A1}$$

$$S_{wp} = D_r \theta_{wp} \tag{A2}$$

$$S_{bc} = D_r \left(\theta_{fc} - \theta_{wp}\right) \tag{A3}$$

Actual evapo-transpiration is modelled according to recommendations by the FAO (UN's Food and Agricultural Organization). Therefore, when the soil moisture is abundant (moisture content is at or above θ_{fc}, or in other words $S(t) \geq S_{fc}$), actual evapo-transpiration is equal to a potential crop evapo-transpiration, E_{Tc} of each vegetation type. This procedure involves estimating a reference (i.e. potential) evapo-transpiration (E_{T0}) for a "standard crop" through application of the Penman-Monteith equation, and then multiplying it by a crop coefficient (K_c) for the crop in question, thus yielding:

$$E_T = E_{Tc} = K_c E_{T0} \qquad \text{if } S(t) \geq S_{fc} \tag{A4}$$

Note that the rate of actual evapo-transpiration (E_T) is estimated for a unit total ground area, with no distinction being made between vegetated and bare soil fractions, with the relative areas of vegetation and bare soil being effectively incorporated within the assumed crop coefficients.

Moreover, Eq. (A4) refers to evapo-transpiration rate under conditions of abundant soil water availability (i.e., a potential rate). However, as the soil moisture decreases, the evapo-transpiration flux is proportionately reduced below this potential rate. The constant of proportionality (Allen et al., 1998), denoted as the water stress effect $K_s(\theta)$, is expressed as a function of the average soil moisture content in the root zone, θ, which is related to the soil moisture storage $S(t)$ through $\theta = S/D_r$. The actual evapo-transpiration for a given crop, under water-limited conditions, is then given by:

$$E_T = K_s(\theta)\ K_c E_{T0} \qquad D_r\theta\ (t) = S(t) \leq S_{fc} \tag{A5}$$

The function $K_s(\theta)$ takes on a value of 1 for $\theta \geq 0.75\theta_{fc}$, and reduces linearly to zero as the soil water content θ approaches wilting point θ_{wp}. The functional expression adopted for the water stress coefficient $K_s(\theta)$ is reported below in Eq. (A6).

$$E_T = K_s(\theta) K_c E_{To} = \left(\frac{S(t) - S_{wp}}{S_{fc} - S_{wp}}\right) K_c E_{To} \qquad \text{if } S(t) < 0.75$$

$$S_{fc} E_T = K_c E_{To} \qquad \text{if } S(t) \geq 0.75\ S_{fc} \tag{A6}$$

Actually, the estimation of $K_s(\theta)$ suggest daily water balance computation (Allen et al., 1998), but, as demonstrated from the basic comparison between daily and monthly calculations (see Appendix B), such an approach to model evapo-transpiration below the potential rate is equally valuable for monthly calculations, at least for the conditions of this study.

$$Y = 0; \qquad \text{if } S(t) \leq S_{fc}$$

$$Y = S(t) - S_{fc} \qquad \text{if } S(t) \geq S_{fc} \tag{A7}$$

Appendix B

Comparison between monthly and daily model formulation

Compared with the monthly model adopted, the daily formulation of the soil water balance, regardless of the adopted flow model, would involve additional hydraulic parameters such as, for example, the saturated hydraulic conductivity, the total porosity, the pore size distribution, and the residual water content, that are likely to increase the parametric uncertainty of the model. Therefore, as a proof of the validity of the monthly water balance model results, a daily formulation of the vertical fluxes was also implemented and tested. For the daily predictions of soil water fluxes a Brooks and Corey formulation was adopted for the un-saturated flow with hydraulic parameters from the literature (Rawlset al., 1992).

All of the results describing the hydrologic response of the Mediterranean landscape at the monthly scale are compared with water balance predictions resulting from a daily model. In order to compare the prediction of the two model formulations hydraulic parameters from silty-loam soils were considered as they cover the widest range of possible soil water holding capacities among all soil textures. The daily predictions of water fluxes were then aggregated at the monthly scale to enable the comparison.

Some results of this comparison are reported in Fig. B1 and Fig. B2 concerning both the soil water fluxes at monthly scale and sensitivity of model predictions to variable conditions of soil storage capacity. In particular, Fig. B1 shows the comparison between monthly flow duration curves obtained from the two model formulations in which the differences appear indeed quite limited. The results of the sensitivity analyses of the mean annual soil water balance estimates to variable conditions of soil storage capacity (Fig. B2) appear to be very similar. Probably the negligible differences in the estimation of drainage and evapo-transpiration can be explained by the attenuation of the episodic nature of rainfall caused by the buffering effect of the soil water storage. This attenuation effect is even more evident when the daily calculations are aggregated to months and the typical seasonal pattern is revealed in soil drainage and evapo-transpiration. The comparison between the two water balance models of contrasting complexity, at least for the adopted soil setting, show a consistent agreement for longer time scales as reported by other authors (e.g. Federer et al., 2003).

Acknowledgements. This work was completed while the senior author (IP) spent a period of study leave at the Centre for Water Research. This study leave was made possible and was supported in part by the Water Research Institute of Italy (Bari). This support is gratefully acknowledged. The authors thank S. Schymanski for critically reviewing an early version of the manuscript and offering many constructive suggestions.

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Table 1. Land-use summaries of Puglia region (Southern Italy).

	Area, km^2	Area, %	Area, % of antecedent figure
Study site	19 332	100	–
Human-modified	15 776	81.6	–
Natural	3556	18.4	–
Vegetation cover	18 243	94.4	–
Agricultural use	14 687	76.0	80.5
Simulated species	12 779	66.1	87.0
Irrigated crops	2175	11.3	17.0

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Table 2. Water use efficiency parameters, modified from Allen et al. (1998).

Crop K_c	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wheat	0.90	0.98	1.10	1.15	1.15	0.30	0.30	0.30	0.30	0.60	0.70	0.80
Olives[a]	0.50	0.50	0.65	0.60	0.55	0.50	0.45	0.45	0.55	0.60	0.65	0.50
Grapes[b]	0.30	0.30	0.30	0.45	0.60	0.70	0.70	0.65	0.55	0.45	0.35	0.30
Citrus[c]	0.70	0.70	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.70	0.70	0.70

[a] Values with ground cover equal to 50%;
[b] Values with ground cover equal to 35%;
[c] Values with ground cover equal to 70%.

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Table 3. Central values and expected variability bounds of model parameters.

Parameter	Wheat	Olive	Grape	Citrus
Root Depth (cm)	80÷100	70÷130	90÷130	100÷120
$b_c = \theta_{fc} - \theta_{wp}$ (% vol.)	6.4÷19.5	6.4÷19.5	6.4÷19.5	6.4÷19.5

Field capacity $=\theta_{fc}$; wilting point $=\theta_{wp}$.

Table 4. Composition of land-use types and numbers of soil samples classified by their land-use attributes.

	Area [km^2]	Area [%]	Soil Samples	Soil Samples [%]
Total	19 332	100	3967	100
Wheat	6850	35.5	1202	30.3
Olive	4828	25.0	1575	39.7
Vineyards	1266	6.6	246	6.2
Other land-uses	6388	33.0	940	23.7

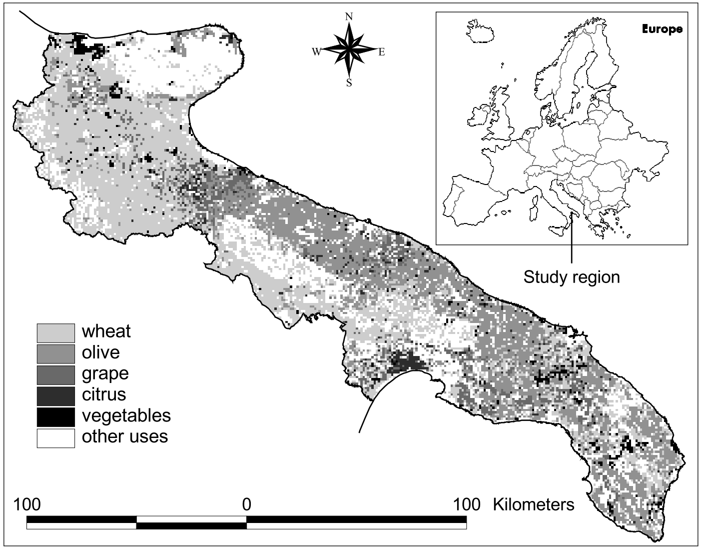

Fig. 1. Map of study area with spatial distribution of crops under consideration. The notation "other uses" refers to natural areas, other agricultural uses and urban areas.

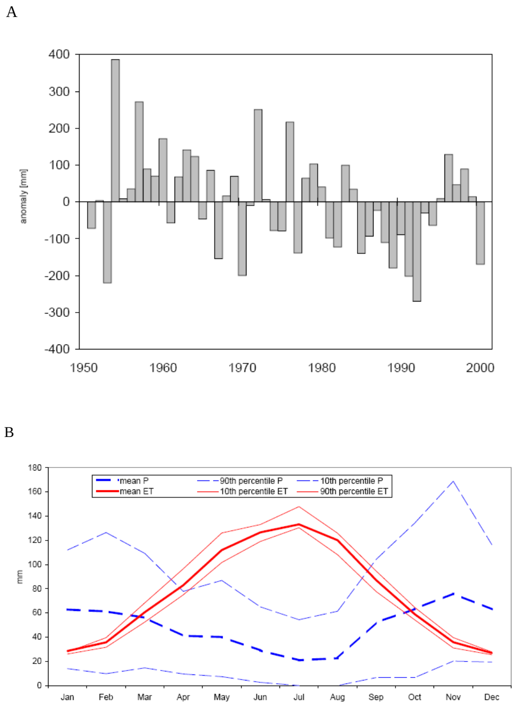

Fig. 2. Inter-annual (top) and intra-annual (bottom) variability of climate: **(a)** fluctuations of annual rainfall totals above and below mean annual rainfall; **(b)** mean monthly values (tick lines) of rainfall and the potential evapo-transpiration and their inter-annual variability range expressed as 10th and 90th percentiles. The average annual rainfall is 588 mm, while the average annual reference evapo-transpiration is 1136 mm.

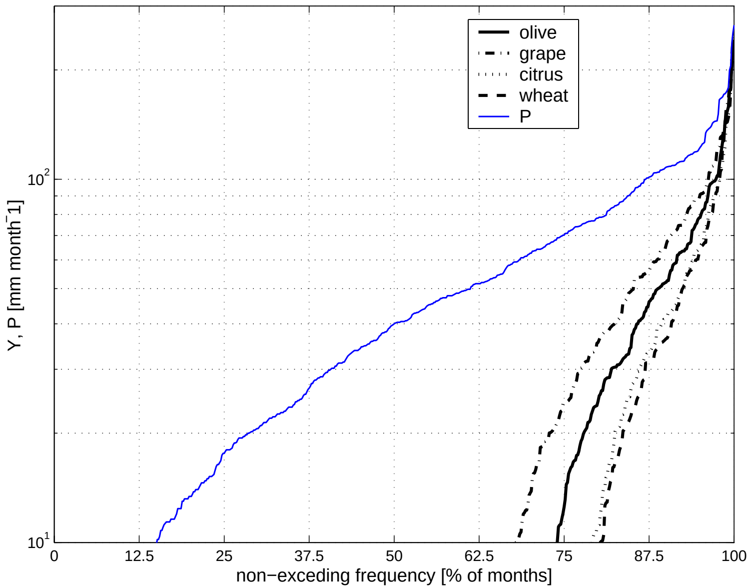

Fig. 3. Rainfall and drainage yield duration curves for the experimented vegetation types. The duration curves refer to the percentage of time that monthly drainage yield, Y, and monthly rainfall, P, remain less than or equal to a specified value.

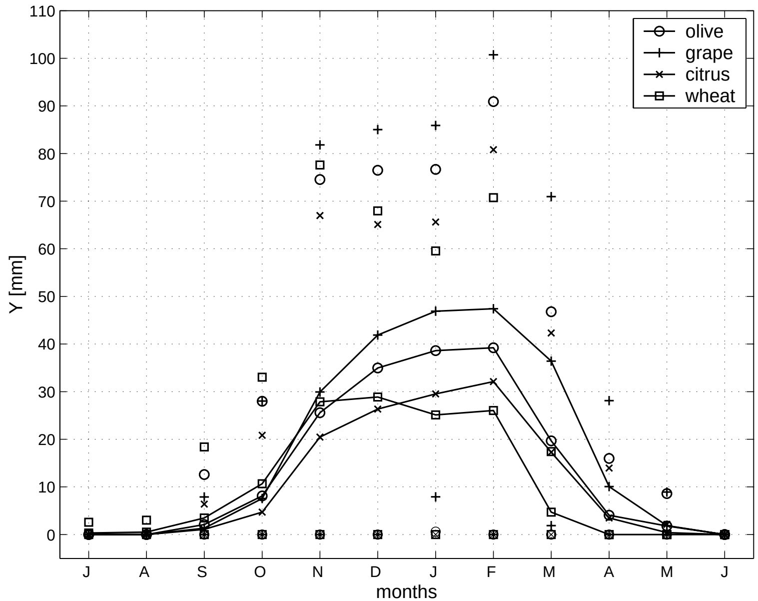

Fig. 4. Drainage response at the intra-annual scale and variability due to climate fluctuations. Continuous lines represent mean monthly drainage yields based on 50-year of simulations. The magnitude of inter-annual variability for each month is marked with dots shifted from the mean curves by as much as one times the standard deviation of the monthly simulation results.

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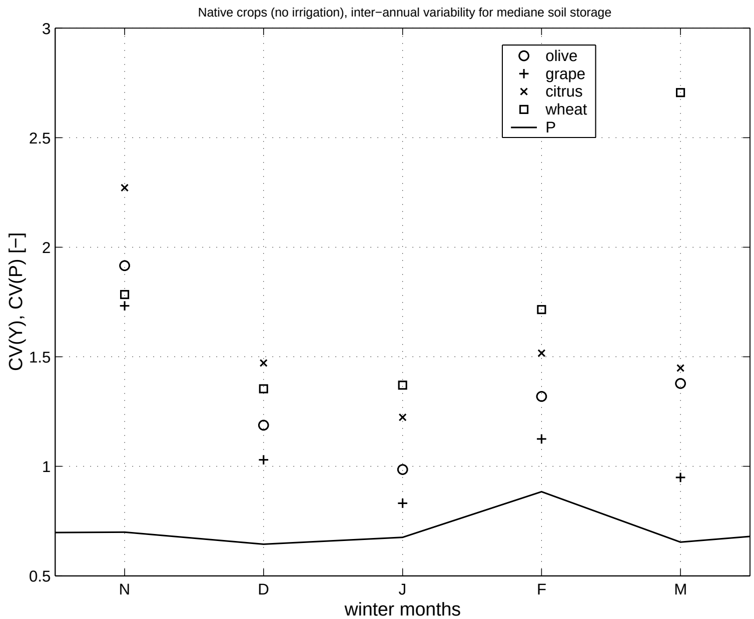

Fig. 5. Inter-annual variability of the monthly drainage yield Y, expressed in terms of the coefficient of variation, CV(Y), compared against the corresponding variability measure of the monthly rainfall, CV(P). The continuous line refers to monthly rainfall and dots to the predicted drainage yield when median soil storage properties are adopted.

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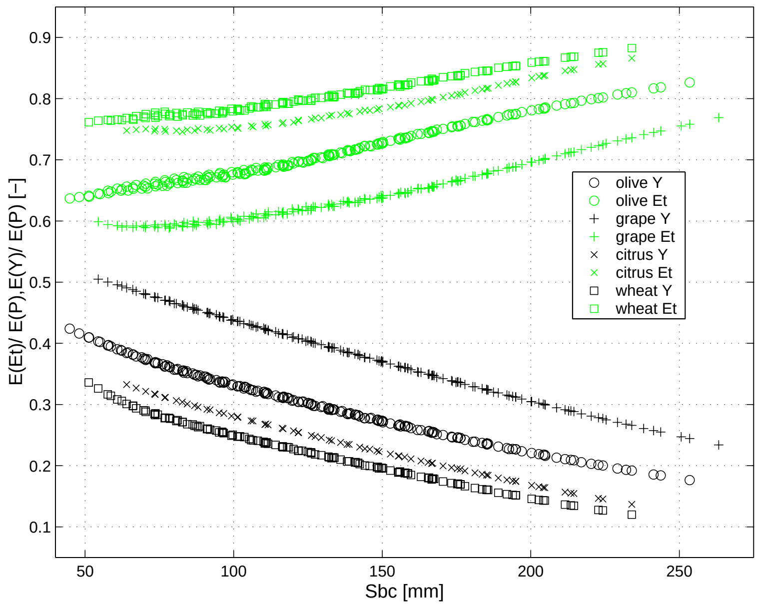

Fig. 6. Sensitivity of the mean annual evapo-transpiration $E(E_T)$ and drainage yield $E(Y)$ to changes in soil moisture storage capacity, $S_{bc} = S_{fc} - S_{wp}$. The various curves refer to mean annual values scaled by the mean annual rainfall, $E[P]$, based on 50-year water balance simulations.

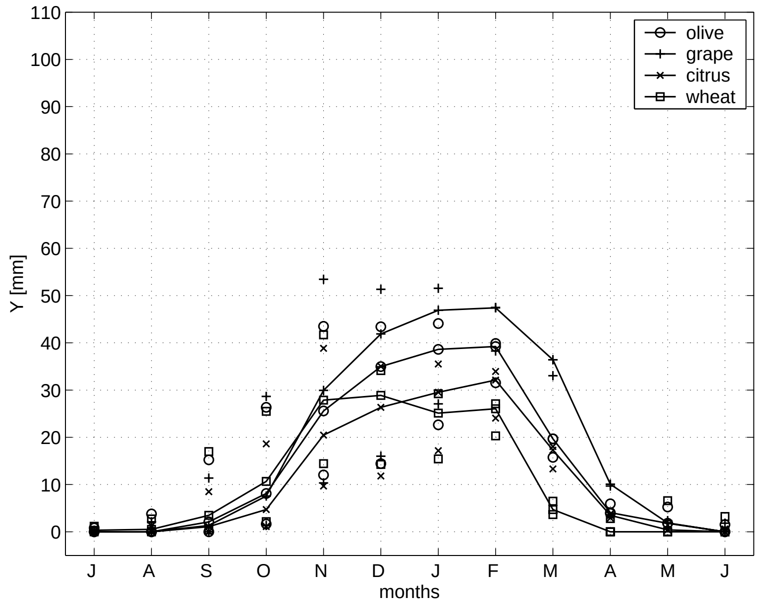

Fig. 7. Sensitivity of the mean monthly drainage yield (based on 50-years simulations) to soil moisture storage capacity, $S_{bc} = S_{fc} - S_{wp}$. Continuous lines refer to median soil storage conditions and dots correspond to the use of minimum and maximum values of $S_{fc} - S_{wp}$ found within the region.

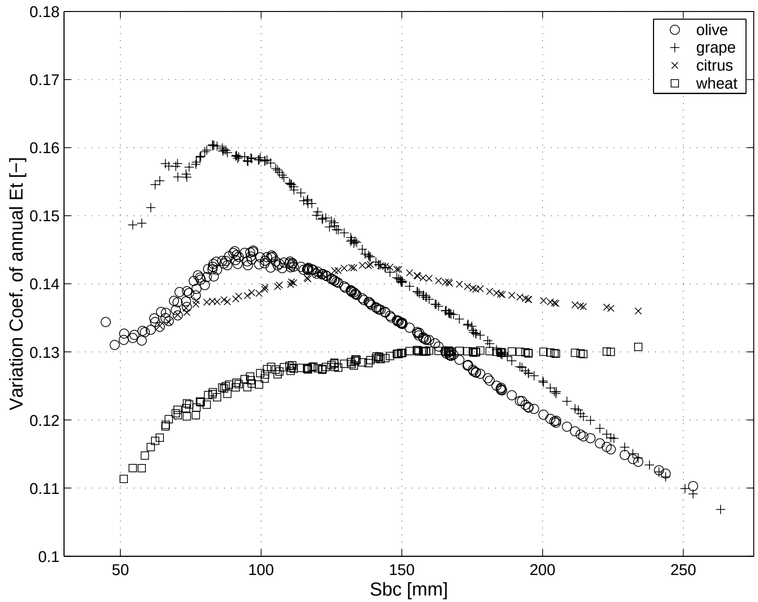

Fig. 8. Influence of soil moisture storage capacity $S_{bc} = S_{fc} - S_{wp}$ on the coefficient of variation of the estimates of annual actual evapo-transpiration.

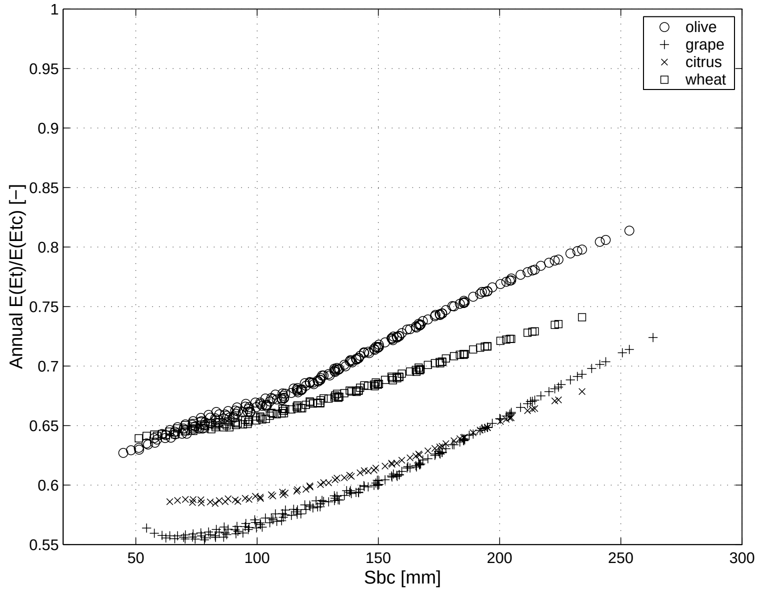

Fig. 9. Influence of soil moisture storage capacity $S_{bc} = S_{fc} - S_{wp}$ on the ratios between actual and potential annual evapo-transpiration for the experimented crops.

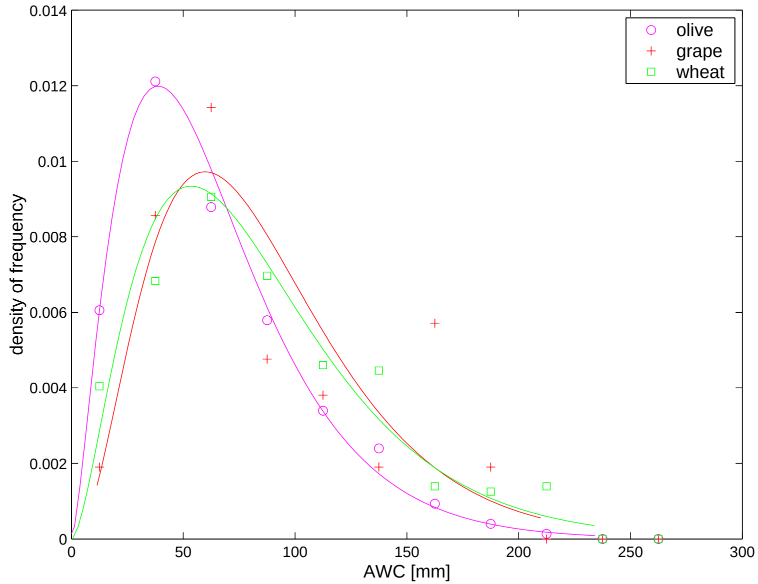

Fig. 10. Empirical and fitted probability density functions for olive, wheat, and vineyards.

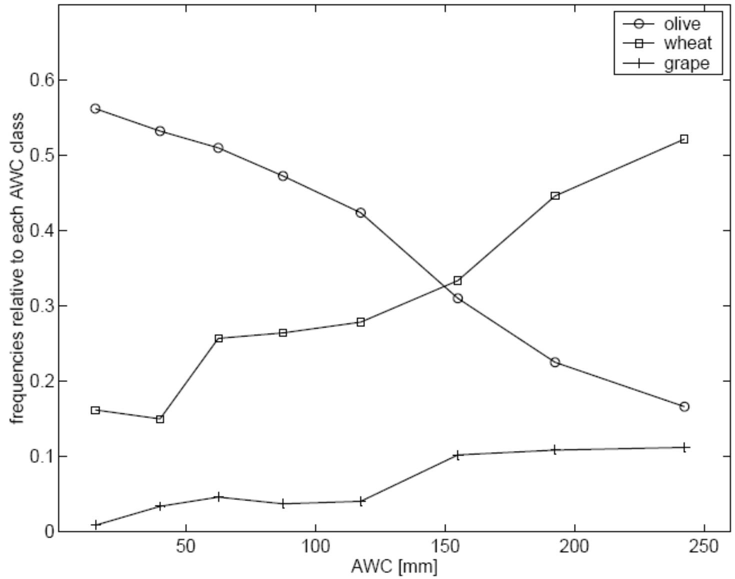

Fig. 11. Relative frequencies of soil samples conditional on soil use with respect to AWC classes.

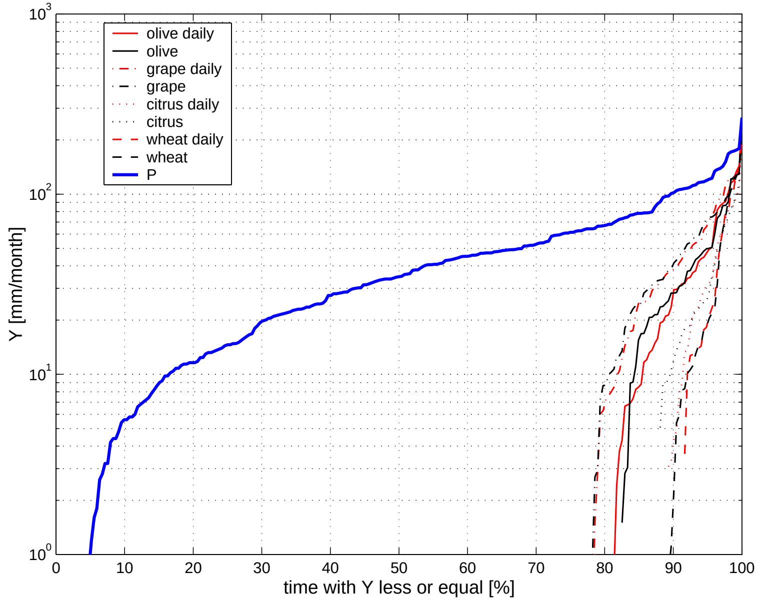

Fig. B1 Comparison between daily and monthly estimation of mean annual water fluxes in response to variable soil moisture storage capacity, $S_{bc} = S_{fc} - S_{wp}$. Simulations were conducted with soil hydraulic parameter in the typical ranges of the silty-loam. Red marks refer to the daily model while black marks to the monthly one. Drainage response is in the lower part of the figure (decreasing patterns) and evapo-transpiration in the upper part.

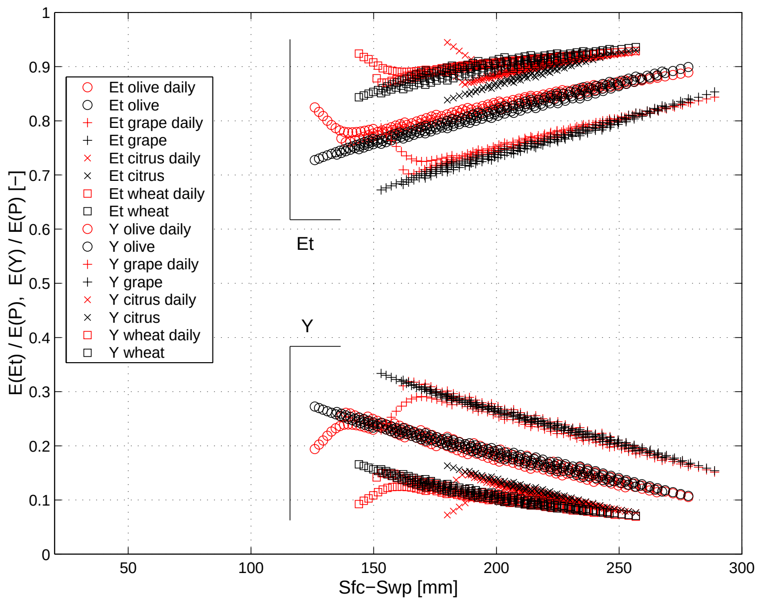

Fig. B2 Comparison between monthly drainage duration curves obtained from the daily (red lines) and monthly (black lines) formulations of the water balance model.

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