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Assessing Crop Water Demand by Remote Sensing and GIS for the Pontina Plain, Central Italy

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Abstract An estimation of the crop water requirements for the Pontina Plain, Central Italy, was carried out through the use of remote sensing land classification and application of a simple water balance scheme in a GIS environment. The overall crop water demand for the 700 km^2 area was estimated at about 70 Mm^3 year^{-1}, i.e. 100 Mm^3 year^{-1} irrigation requirements when considering an average irrigation application efficiency of 70%. The simplest and least demanding available methodology, in terms of data and resources, was chosen. The methodology, based on remote sensing and GIS, employed only 4 Landsat ETM+ images and a few meteorological and geographical vectorial layers. The procedure allowed the elaboration of monthly maps of crop evapotranspiration. The application of a spatially distributed simple water balance model, lead to the estimation of temporal and spatial variation of crop water requirements in the study area. This study contributes to fill a gap in the knowledge on agricultural use of water resources in the area, which is essential for the implementation of a sustainable and sound water policy as required in the region for the application of the EU Water Framework Directive.

Keywords Evapotranspiration · Remote sensing ·
Geographic information systems · Irrigation

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1 Introduction

Knowledge of the temporal and spatial pattern of irrigation water withdrawals at a regional scale is enormously important for aquifer management purposes, but several methodological difficulties exist and for several important areas in Italy no accurate recent figures are yet available (Bàrberi et al. 2000).

Land use in Italy is still largely dominated by agriculture: recent estimates show that about 19 million ha are occupied by agricultural activities, covering more than 60% of the whole country area (ISTAT 2000).

Estimates from one of the few nation-wide water resources surveys (Passino et al. 1999) indicates that, in Central Italy, 970 Mm^3 of water are used in agriculture out of a total of 4,142 Mm^3 freshwater withdrawals (i.e. about 23%). However, large uncertainties exist for these and other figures at different scales (Passino et al. 1999; Bàrberi et al. 2000).

Most of the water used in agriculture is employed for irrigation when rainfall is not enough to satisfy crop water needs, as it is mostly the case for spring–summer grown crops in Central Italy, where a Mediterranean climate with dry summers prevails.

Groundwater withdrawals for irrigation are therefore highest during the driest months of the year.

Concerning the Latium Department in Central Italy, the lack of data about spatial crop distribution, causes difficulties for the implementation of sustainable water management policies in the agricultural sector. In facts, the first step for a sound water resources planning would be the knowledge of agricultural land use and the availability of reliable estimates on the spatial and temporal distribution of crop water requirements.

For the Pontina Plain, one of the most intensively cropped coastal plains of Central Italy, no detailed information about crop spatial distribution is currently available, since the existing land use classification data (Piemontese and Perotto 2004) are not really suitable for an accurate assessment of the spatial distribution of crop water requirements.

For these reasons, in the context of the European Union Water Framework Directive (European Commission 2000), the Regional Watershed Authority of the Latium Department started a preliminary study to achieve an estimation of crop spatial distribution and their monthly water requirements in the Pontina Plain area.

The main objective was that of providing some first indications on the current spatial and seasonal pattern of irrigation water withdrawals in the area, for aquifer management purposes. In facts, at the present time, the reclamation consortium "Agro Pontino", which supplies water to most of the farmers in the area, is not equipped to provide disaggregated and spatially distributed data on irrigation volumes used by farmers.

Furthermore, although specific information is lacking due to the absence of monitoring, it is suspected that most of the irrigation water is withdrawn by an unknown number of private wells similarly to what happens in other parts of Italy (Todorovic and Steduto 2003).

Thus, uncontrolled and excessive use of groundwater by farmers frequently causes lowering of the groundwater table and intrusion of seawater which leads to serious salinization problems in the area (Sappa et al. 2005). Particularly during the driest months of the year critical conditions for the aquifers, already stressed for climatic conditions, have been reported (Sappa et al. 2005), thus triggering irreversible changes (Coviello et al. 2005).

It was therefore considered important to set up a methodology capable of providing some estimates of the spatial and temporal distribution of irrigation water requirements in the area, under the current crop pattern, in order to make available this information for subsequent hydrogeological studies and evaluate the possible dynamic and temporal evolution of aquifer stress caused by agricultural activities.

Given the extension of the area of about 700 km^2, it was considered that remote sensing would offer several advantages for such a task. Its potential for monitoring water resources are well known and there is a large number of successful applications in operative contexts in the last decades (e.g. FAO 1995; Belmonte et al. 1999; Shultz and Engman 2000; D'Urso 2001; Stehman and Milliken 2007). A review of available remote sensing approaches to water resources estimation was provided by Schmugge et al. (2002). Considering the estimation of crop water use, i.e. evapotranspiration, several methodologies are available. Many are based on the determination, through the use of thermal infrared bands, of radiometric surface temperature, then employed in solving simplified energy balance equations (see e.g. Moran et al. 1990; Sugita and Brutsaert 1992; Kustas and Norman 1996). This type of approaches have been developed into more sophisticated procedures, integrating remotely sensed data into vegetation–atmosphere transfer models (e.g. Bastiaanssen et al. 1998; Allen et al. 2005). However, these methods effectively lead to the estimation of a 'snap shot' of the actual evapotranspiration at the moment of satellite overpass, at best extended to daily values and needing interpolation procedures for the estimation of monthly or seasonal values. In this respect, two alternative strategies are used, both adopting the FAO approach (Allen et al. 1998), in which crop evapotranspiration is obtained by multiplying reference crop evapotranspiration by a specific crop coefficient (Kc). It should be noted that although the FAO approach has been universally accepted and widely applied following its original proposition more than 30 years ago (Doorenbos and Pruitt 1977), it leads to the estimation of evapotranspiration of crops under optimal agronomic conditions, i.e. in the absence of any biotic or abiotic stress, which is not realistic under the current farming practice. Moreover it has been shown that crop coefficients are site-specific (Hanks 1985) and should be determined locally, implying the need of dedicated experimental activities. Therefore the accuracy of the estimates decreases whenever farming or environmental factors cause limitations to crop growth and where local data on crop coefficients are missing. While this inaccuracy can sometimes cause inconveniences when the method is used for irrigation management or scheduling, the FAO approach can be considered adequate for planning purposes or deriving indications on the spatial and temporal evolution of crop water requirements, such as for the present study.

The simplest method available for the spatial estimation of evapotranspiration following the FAO approach, is to derive through remote sensing a crop classification map. Then monthly crop coefficient (Kc) values are associated to each crop class and a reference evapotranspiration map, e.g. derived from meteorological data, is used in order to estimate crop evapotranspiration in a GIS environment (e.g. Stehman and Milliken 2007). This is the procedure followed in the present study. As an alternative, Kc values can be directly estimated from remote sensing using: (1) empirical relationships with vegetation indices (e.g. Ray and Dadhwal 2001); (2) analytical approaches exploiting the relationships existing between vegetation spectral reflectance and some parameters like albedo, leaf area, canopy surface roughness, by which Kc is influenced (e.g. D'Urso 2001), or (3) deriving the Kc from the ratio of actual ET, estimated through remotely sensed surface energy balance models, and reference evapotranspiration (e.g. Tasumi and Allen 2007). The advantage of the first strategy is that, assuming an average seasonal trend of crop development, it is possible to estimate seasonal or monthly Kc values for the whole studied area. However, when only class specific Kc trends are defined, an assumption is made of simultaneous crop development and homogeneity between and within fields under the same crop.

The second strategy can therefore provide more realistic estimates of Kc and take into account its spatial variability. However, providing a static estimate of Kc for the date in which remote sensing data are available, and lacking the knowledge on the type of crops present in each field, it does not allow to extrapolate to seasonal trends unless remote sensing data are available for several dates throughout the growing season: for example Tasumi and Allen (2007) employed 12 cloud-free Landsat images for 1 year. Moreover, regional evapotranspiration mapping, based on crop classification, derived from the first strategy, can be more valuable for subsequent planning and scenario studies, where hypotheses on the evolution of cropping systems can be compared. For these reasons this strategy, which is also the least expensive in terms of remote sensing data requirements, was selected in the present study. Indeed this process allows to increase the land use knowledge and to understand the correlations with local aquifer stress conditions helping to identify sensible land use policy solutions.

2 Description of the Study Area

The Pontina Plain is one of the largest coastal plains in Central Italy and is situated in the Latium Department, covering an area of about 70,000 ha (Fig. 1). Mean rainfall is about 600 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$ with a direct infiltration rate of about 80 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$. In order to evaluate the volume of total annual groundwater inflows, these recharge volumes must be added to the groundwater inflows from adjacent karstic aquifers, estimated at 17 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$ (Regione Lazio 1992; Rossi 2005). Therefore, a volume of about 100 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$ can be assumed as the average total amount of renewable water resources in Pontina Plain.

From a morphological point of view, the territory is mostly flat with a mean elevation of about 30–35 m a.m.s.l.; some areas are situated below the sea level. In the past century, comprehensive land reclamation and drainage works have been carried out on this land, formerly largely covered by marshland, allowing a subsequent process of human and productive settlement (Stabile 1985).

Farming has particular importance from a social and economic point of view in the Pontina Plain. Data on the distribution of the main agricultural crops are available from the last National Agricultural Census (ISTAT 2000), though aggregated at the county level and merging several crop types into rather broad categories.

More detail is provided in a recent study (Tulipano et al. 2004), in which these data are combined with local empirical data obtained from local technicians and farm extension personnel.

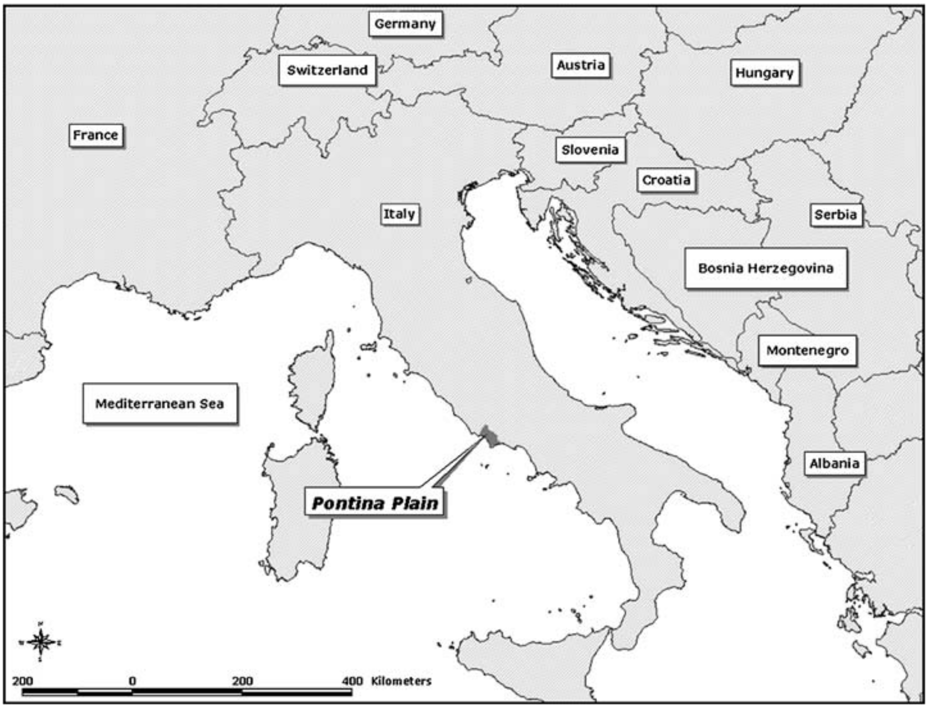

Fig. 1 Location of the Pontina Plain in Central Italy

A further important information source is provided by the digital Land Use Map of the Latina Province (Piemontese and Perotto 2004), derived from photointerpretation of July 1998 colour ortophotos, using the Corine level (Bossard et al. 2000) classification. From these data it results that agricultural areas cover overall 69,390 ha, i.e. almost 80% of the total surface of the study area (88,856 ha). In particular, arable crops in non irrigable areas occupy 29,142 ha, i.e. 33% of the area, while another 33% (29,351 ha) is covered by arable crops classified as potentially irrigable due to the presence of irrigation systems infrastructures. These irrigable areas include important horticultural growing areas close to the coastline, while tree crops, mainly kiwi fruit and vineyards, cover 6.8 thousand ha in more inland locations.

Yearly mean water used for irrigation has been estimated as almost 110 Mm^3 year^{-1} (Tulipano et al. 2004; Sappa and Rossi 2006), i.e. 113% of the total yearly aquifers inflows, though mostly concentrated in summer months.

Non-uniform distribution of irrigation withdrawals throughout the year has gradually brought about some critical environmental phenomena typical of overexploited coastal aquifers, like saline intrusion, potentiometric levels lowering trends on pluriannual series, local subsidence phenomena (Coviello et al. 2005; Sappa et al. 2005; Bono 1995; Brunamonte and Serva 2004). Consequently aquifers in the study area have been classified as highly vulnerable in a recent study (Gerardi et al. 2004). However local correlations between irrigation withdrawal and environmental effects on aquifers are only known from a qualitative point of view. In fact, up to now no detailed studies were carried out in order to evaluate the spatial and temporal variability in irrigation water requirements at regional scale for this area.

3 Methodology

The overall procedure adopted to evaluate the spatial distribution of monthly crop water requirements is presented in Fig. 2. Crop water requirements were assumed to equal a simplified hydrologic "root zone" water balance, taking into account crop evapotranspiration (ET_c), monthly rainfall values and plant available soil water (AWC), thus following a widely adopted methodology (see e.g. Custodio and Llamas 1996).

In order to evaluate ET_c, the method suggested by FAO was adopted (Allen et al. 1998):

$$ET_c = ET_0 \cdot Kc \qquad (1)$$

where Kc is a crop coefficient related to the crop type and to its vegetative stage, and ET_0 is the reference evapotranspiration. ET_0 is defined as the "evapotranspiration of an hypothetical reference crop with a height of 0.12 m, a surface aerodynamic resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water" (Allen et al. 1998). The meteorological data available for the study area included limited series (1996–2002) for rainfall and temperature in five different stations, annually published by Hydrometeorological Regional Service. The availability of complete meteorological data sets, simultaneously for all the five weather stations, constrained the choice of the temporal series. However, despite the fact that a longer time series could confer higher statistical confidence to the results, for the aim of this study it was assumed that using only recent data could take better into account the currently observed climate change trends, particularly evident for rainfall in the Mediterranean area (Brunetti et al. 2000; Norrant and Douguédroit 2006).

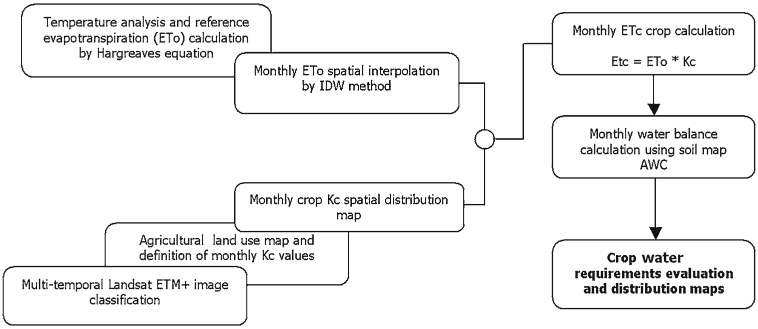

Fig. 2 Flow chart of the methodology adopted for the present study

3.1 Mapping Reference Evapotranspiration (ET_0)

Though FAO recommends the Penman–Monteith equation for the estimation of ET_0 (Allen et al. 1998), the unavailability of complete sets of meteorological parameters for the study area hindered its application. Therefore the Hargreaves equation was used (Hargreaves 1994) since it only requires temperature and extraterrestrial solar radiation and it has been shown to provide accurate estimates for monthly time steps (Allen et al. 1998; Droogers and Allen 2002).

The Hargreaves equation is the following:

$$\mathrm{ET}_0 = 0.0023 \cdot (T_\mathrm{m} + 17.8) \cdot (T_\mathrm{max} - T_\mathrm{min})^{0.5} \cdot R_\mathrm{a} \tag{2}$$

where ET_0 is the daily reference evapotranspiration (millimeter per day), T_m, T_max and T_min are respectively the daily mean, maximum and minimum air temperature (°C) and R_a is the extraterrestrial solar radiation (millimeter per day). Monthly temperature data available for five weather stations located inside the study area were used to calculate ET_0 punctually. To obtain ET_0 monthly values, monthly mean temperatures were assumed to correspond to that of an average monthly day, so that Eq. 2 could be applied and the result multiplied by the number of days of the respective month.

For the spatial interpolation of ET_0, the Inverse Distance Weight (IDW) method was chosen (Burrough and McDonnell 1998; Matheron 1962), since it had already been applied in similar situations (e.g. Ray and Dadhwal 2001). In fact, because of the scarce quantity of meteorological stations, all with an elevation close to the sea level, other more complex and effective methods like cokriging (Kurtzman and Kadmon 1999; Li et al. 2003) or the inclusion of the elevation parameter in IDW method (Zimmerman et al. 1999) gave unsatisfactory results. The operation led to monthly maps of the spatial distribution of ET_0, on grid layers with a 30 m mesh in agreement with the resolution of land classification (see the following section).

3.2 Mapping Crop Coefficients (Kc) Monthly Distribution

The methodology chosen for obtaining monthly maps of Kc values was the simplest available, i.e. that of developing a crop classification map, identifying homogeneous crop classes in terms of water use and assigning to each class a monthly Kc value. As already mentioned, a digital land use map (Piemontese and Perotto 2004) was already available for the study area. However, insufficient detail was provided for most agricultural crops, grouping them into very broad classes. For example, all the field crops plus horticultural crops were included in only two classes, based on the presence or not of irrigation infrastructures as observed from ortophotos. Therefore, it was decided to use additional remote sensing data in order to better discriminate between the different crop classes. As a reference year for this study the 2001–2002 growing season was chosen. LANDSAT ETM+ images were acquired for the following dates: 9th June 2001, 2nd December 2001, 4th February 2002 and 15th August 2002. The images were already orthorectified and geometrically corrected by the suppliers using digital terrain models and ground control points, with a declared Root Mean Squared Error ranging between <25 m (June image) and 250 m (August image). All images were resampled to a pixel size of 30 m for the multispectral bands and geometric co-registration of all the images to the June 2001 image was carried out, as the latter had the highest georeference accuracy. Radiometric normalisation of all the images was carried out using the method of "invariant points" (e.g. Furby and Campbell 2001). Subsequent preprocessing operations included the building of masks for excluding clouds and their shadows (occurring only in the December 2001 and August 2002 images), using ISODATA unsupervised classification. A mask was also built, using the land use map (Piemontese and Perotto 2004), in order to exclude non-agricultural areas from further processing.

In order to carry out multitemporal classification of the images, a training set of ground control points was obtained. For permanent tree crops it was assumed that they had remained in the same plots between satellite image acquisition dates (years 2001–2002) and the time this study was carried out (spring 2005). Therefore, a field survey was carried out in April 2005, identifying 80 ground truth points which were digitised and georeferenced in site, using a laptop with digital ortophotos and topographic maps. For the non-permanent crops the information was extracted from the databases of farmers' declarations for eligibility to Common Agricultural Policy (CAP) and Structural Funds subsidies, maintained by the Italian state agency AGEA. The agency, in addition to the databases, holds a GIS including ortophotos of the entire Italian territory, used for checking the truthfulness of the declarations, therefore a high reliability of the databases was assumed. Several databases (CAP, Structural funds, Vineyards Cadastre, Olives Cadastre) for the years 2001 and 2002 were obtained and were used for the identification and delineation, using cadastral information included in the database, of 2,209 polygons comprising 46 crop types. These ground truth points were chosen by extracting a sample of 59 Cadastre sheets homogeneously distributed across the study area and including the widest crop diversification. The polygons layer was used to obtain the regions of interest (ROI) to use for multitemporal supervised classification carried out using ENVI 4.0 (RSI, Boulder Colorado, USA). To this end, for each crop type, ROIs were analysed comparing false colour images, Tasseled Cap Transformation (TCT) images (Crist and Cicone 1984) and digital ortophotos, in order to verify the compatibility to the declared crop and to select only pure pixels. Image classification was then carried out using a mix of strategies, employing decision-trees based on TCT greenness differences between dates and testing several supervised classification algorithms. The results were assessed in terms of overall accuracy using error matrices in order to select the best strategy for each crop type. Finally a classification map including 17 crop types was obtained.

The monthly Kc values assigned to each crop class were obtained from Allen et al. (1998) and Ravelli and Rota (1999). Average Kc monthly values were estimated, based on farming practices of the study area (Table 1). Information on the timing of farming operations, particularly planting and harvesting dates, were obtained from a field survey and interviews of farmers and extension service personnel, while information on development phases of crops were obtained mainly from a phenological atlas (Borin et al. 2003). A Kc value of 0.2 was assumed for the months in which herbaceous crops were not actively vegetating (presence of bare soil or crops residues), while for tree crops this value was increased accordingly to the crop type in order to take into account soil vegetation cover.

Table 1 Average monthly crop coefficient (Kc) values used for the computation of monthly crop water requirements

Crop type	Average monthly Kc values											
	January	February	March	April	May	June	July	August	September	October	November	December
Annual forage crops	0.52	0.70	0.90	1.03	1.00	0.50	0.30	0.20	0.20	0.20	0.30	0.40
Citrus	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Fruit trees	0.50	0.50	0.60	0.70	0.90	1.00	1.00	1.00	0.80	0.70	0.60	0.50
Grain legumes	0.67	0.80	1.15	1.15	0.82	0.40	0.20	0.20	0.20	0.20	0.20	0.50
Grain maize	0.20	0.20	0.20	0.30	0.46	1.05	1.20	1.04	0.61	0.20	0.20	0.20
Kiwi fruit	0.50	0.50	0.50	0.60	0.90	1.00	1.00	0.90	0.90	0.80	0.60	0.50
Olives	0.60	0.60	0.65	0.65	0.65	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Permanent forage crops	0.68	0.68	0.68	0.74	0.82	0.93	0.93	0.93	0.93	0.80	0.68	0.63
Set-aside	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Silage maize	0.20	0.20	0.20	0.30	0.46	1.05	1.20	0.20	0.20	0.20	0.20	0.20
Sugarbeet	0.58	0.92	1.18	1.20	1.20	0.94	0.70	0.30	0.20	0.20	0.30	0.36
Summer horticultural crops	0.20	0.20	0.37	0.53	0.66	0.58	0.50	0.46	0.36	0.37	0.29	0.20
Sunflower	0.20	0.20	0.20	0.36	0.87	1.10	0.77	0.20	0.20	0.20	0.20	0.20
Tomato	0.20	0.20	0.20	0.60	0.81	1.13	1.14	0.92	0.20	0.20	0.20	0.20
Vineyard	0.50	0.50	0.50	0.60	0.80	0.80	0.80	0.80	0.70	0.70	0.60	0.50
Winter cereals	0.57	0.88	1.05	1.11	0.85	0.50	0.29	0.20	0.20	0.20	0.20	0.20
Winter horticultural crops	0.58	0.62	0.64	0.47	0.28	0.23	0.33	0.35	0.50	0.70	0.80	0.63

3.3 Mapping Crop Evapotranspiration (ET_c) and Estimation of Monthly Irrigation Requirements

Using GIS functionality, Eq. 1 was applied and the pixel-wise product of ET_0 monthly maps by monthly Kc maps yielded monthly ET_c maps.

These ET_c maps represent the crop evapotranspiration under standard conditions, i.e from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions (Allen et al. 1998).

But in order to estimate irrigation requirements, soil water availability needs to be taken into account, because theoretically only when the plant-available water is insufficient it would be necessary to supplement this amount with irrigation.

Many methods used in literature make use of the "effective rainfall" concept, using different estimation procedures (Dastane 1974). A widely adopted one is the USDA Soil Conservation Service method (see e.g. Tsanis et al. 2002; Tsanis and Naoum 2003; Loukas et al. 2007).

Nevertheless, this highly empirical procedure seems not much linked to soil hydraulic conditions and can only be used as a first approximation (Dastane 1974). Therefore, a procedure was chosen which takes into account the nature of the soils in the study area, more in agreement with hydrogeological studies.

The methodology was based on the knowledge of soil available water content (AWC) distribution throughout the study area and by the implementation of a simplified soil water balance, in order to estimate crop water demand.

AWC, defined as the range of plant available water storable in the upper layer of the soil (root zone), is obviously strongly dependent on the soil type (Richards and Wadleigh 1952).

By linking, in a GIS environment, pedological classes distribution data (Provincia di Latina 2003) with corresponding reference AWC values, as found in the literature (Sevink et al. 1991), a digital cartography for the AWC spatial distribution was obtained.

In order to estimate soil water content the following equation was then used:

$$U_e = U_s - ET_c + P \tag{3}$$

where U_s and U_e are the soil water content respectively at the start and at the end of the month; P is the monthly rainfall, ET_c the crop maximum evapotranspiration. The procedure for the calculation of monthly water balance terms is summarised in Fig. 3. In short it was assumed that for each month, if the total quantity of water available, given by the sum of monthly rainfall and water stored in the root zone, is sufficient to satisfy the monthly crop water requirements (ET_c), no irrigation is needed. Otherwise, if the rainfall is insufficient and soil water storage is depleted, the difference between monthly water requirement (ET_c) and the total available water is the deficit that should be supplied by irrigation.

The iterative procedure was referred to the hydrologic year, assuming October as the starting time for the soil moisture recharge (American Metereological Service 2000).

This balance procedure was implemented in a GIS environment by ESRI ArcGis 9.0 software to automate the computations and it led to the production of monthly distribution maps of crop water requirements on a 30 m pixel grid.

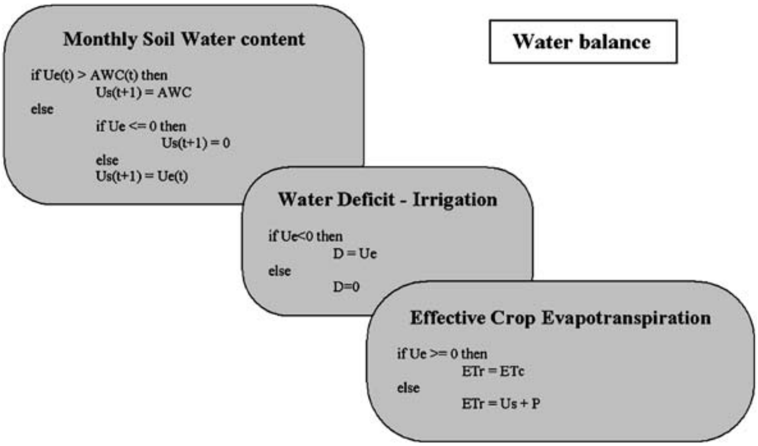

Fig. 3 Monthly water balance calculation algorithm. U_s = soil water content at the start of the month; U_e = soil water content at the end of the month; AWC = available water content; D = soil water deficit, assumed equal to the irrigation requirement; P = rainfall; ET_c = maximum crop evapotranspiration; ETr = actual crop evapotranspiration

4 Results and Discussion

4.1 Reference Evapotranspiration (ET_0)

Reference evapotranspiration maps showed that higher evaporative conditions occurred in the Northern and more inland parts of the study area, while coastal areas tended to have lower values (Figs. 4 and 5).

The isocurves trend is typical of deterministic local interpolation methods like the IDW (Burrough and McDonnell 1998), strongly locally depending on observed values. However the morphological characteristics of the Plain and the maritime influence on temperatures, cause ET_0 values to be fairly homogeneous throughout the study area, with yearly total values included in the 950–1,150 mm range (Fig. 4).

In Fig. 5 the peak month (July) mean values in are shown, with values centered around 5 mm day^{-1} and all within a range of ±0.5 mm day^{-1}.

The reference evapotranspiration maps shown in Figs. 4 and 5 can be compared with those reported by Ravelli and Rota (1994).

In both cases ET_0 annual maps show values under 1,100 mm for most of the plain area, though mapping resolution provided by this paper is higher than for Ravelli and Rota (1994), who covered the whole Southern Italy territory.

The peak month ET_0 values presented in this paper are around 5 mm day^{-1}. These values are lower compared to the ones obtained by Ravelli and Rota (1994), but this can be explained by the fact that these authors report the 75% percentile of monthly ET_0 values, while in the present case the map shows mean values.

4.2 Agricultural Land Use and Crop Coefficients (Kc) Monthly Distribution

The accuracy of the crop classification map was assessed by obtaining a confusion matrix (Table 2), showing a class-by-class comparison between ground truth data

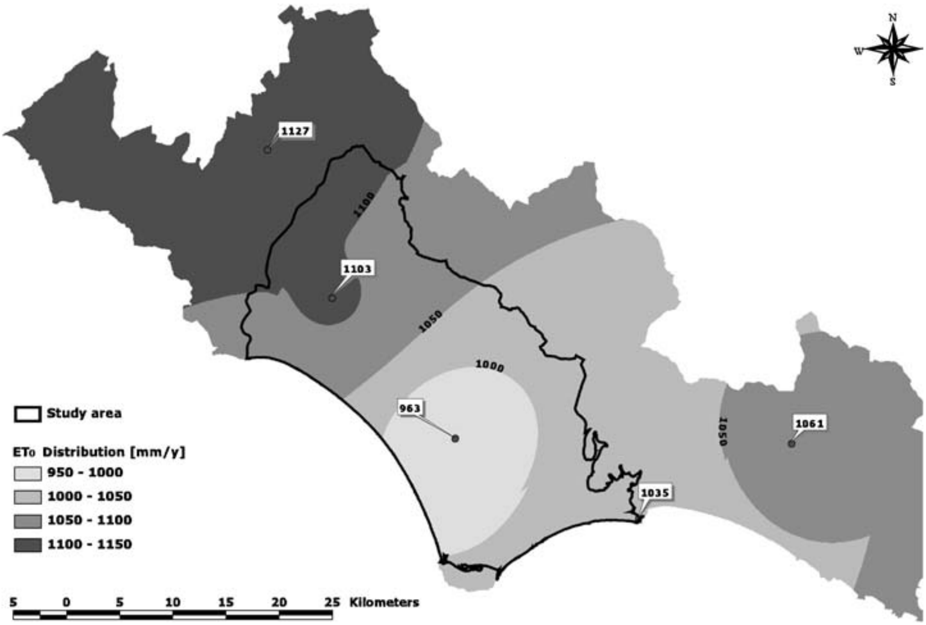

Fig. 4 Mean reference evapotranspiration (ET_0) annual values (millimeter per year). *Points highlighted* indicate location and values estimated at the weather stations

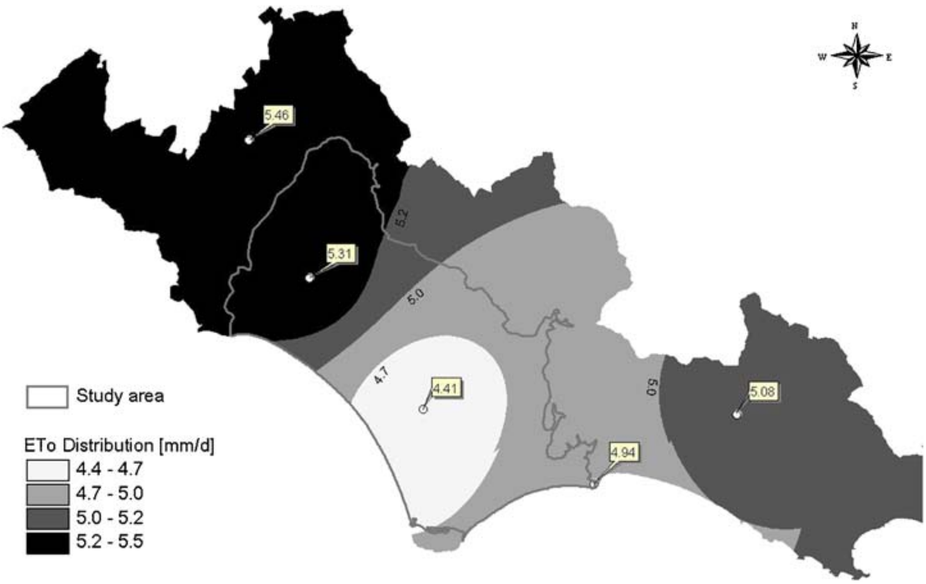

Fig. 5 Mean reference evapotranspiration (ET_0) peak month (July) values (millimeter per day). *Points highlighted* indicate location and values estimated at the weather stations

and classification results (Lillesand and Kiefer 1999). Commission error, representing the number of pixels belonging to other classes and erroneously assigned to a given class, ranged from quite small values, e.g. for winter cereals and horticultural crops, to rather high values such as for perennial forage crops and fruit trees (Table 3). Overall the high commission error found is largely due to a great abundance of mixed pixels, i.e. including more than one crop class. This is due to the spatial resolution of the satellite data (30 m pixel size) and the agricultural land fragmentation structure in the study area, in which small fields (less than 0.5 ha) are particularly abundant.

Omission error, taking into account pixels really belonging to a given class that were wrongly assigned to another class, was particularly high for grain maize and again permanent forage crops. Producer accuracy, indicating the probability that a given pixel belonging to a class is really assigned to that class, was reasonably high for most classes with the exception of grain maize and permanent forage crops. User accuracy, indicating the probability that a pixel classified as belonging to a class really belongs to it, was high for some classes such as winter cereals, horticultural crops, vineyards and sunflower, while rather low values were found for permanent forages and tree crops. Inspection of the confusion matrix (Table 2) revealed that a problem occurring with these two classes was that high percentages of their pixels in the training set remained unclassified (57% for permanent forage crops and 39% for fruit trees), because these fell into areas that were covered by clouds in two of the four images available. In summary the overall classification accuracy, calculated from the confusion matrix, had a value of 62.5% and a kappa coefficient of 0.59 (Jensen 1986).

The truthfulness of the classification results was assessed by comparing, on a county basis, total surface areas attributed to the different crop classes by the present study, with results from the last National Agricultural Census (ISTAT 2000) and by the data reported in a previous study (Tulipano et al. 2004). For tomato the data used were those provided by the AGEA database, considered more reliable. The crop classification map (Fig. 6) shows that kiwi fruit and other tree crops are mostly located in the North–West part of the study area, horticultural crops are mainly along the coastline, while maize and other extensive field crops are especially abundant in the central part of the Pontina plain. The classification results were overall in agreement with crop area statistics reported by ISTAT (2000) on a county basis, although classification provided higher crop area estimates in most cases (Fig. 7). Analysis of the data revealed that for some counties the total crop area estimated exceeded the used agricultural surface area reported by ISTAT. This suggests that non cropped areas (i.e. hedges, roadsides, woodlots etc...) were erroneously attributed to the crops, thus contributing to the commission error. It should be noted that ISTAT (2000) data are provided in a form aggregated at the whole county level, while the study area considered here included only partially the county of Sezze. This explains an outlier in Fig. 7, where ISTAT data for Sezze report a much higher surface area for permanent forage crops than the present study, which only considered about half of the total county area (i.e. only the flatland).

From an overall crop area estimates comparison (Table 4) it appears that the largest discrepancies appear for horticultural crops, for which this study estimates an area almost double than that reported by ISTAT, but still largely smaller that the estimate from Tulipano et al. (2004). Also for other crops these estimates seem to fall in between the values reported by ISTAT (2000) and by Tulipano et al. (2004).

Table 2 Confusion matrix of the classification results using ground control points: columns report the percentages of ground truth pixels assigned to the various classes (rows)

Class	Ground truth (percent)																
	Winter cereals	Kiwi fruit	Citrus	Sugarbeet	Fruit trees	Annual forage crops	Perennial forage crops	Sunflower	Grain legumes	Grain maize	Silage maize	Olives	Tomato	Vineyard	Horticultural crops	Set-aside	Total
Unclassified	1	5	3	2	39	0	57	1	7	7	6	1	4	24	11	0	13
Winter cereals	96	0	0	0	1	2	0	1	0	1	0	0	0	1	0	24	15
Kiwi fruit	0	78	0	0	4	0	0	11	0	0	0	0	0	7	0	0	6
Citrus	0	0	85	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sugarbeet	0	0	0	81	0	3	0	1	0	3	8	0	0	0	0	0	4
Fruit trees	0	0	0	0	46	0	0	0	0	0	0	2	0	11	0	0	4
Annual forage crops	2	0	0	0	0	82	4	14	70	1	14	0	11	1	0	17	7
Perennial forage crops	0	5	12	3	0	11	24	12	0	22	3	0	57	6	5	4	9
Sunflower	0	0	0	0	0	0	2	56	0	1	0	1	0	2	0	0	4
Grain legumes	0	0	0	3	0	0	0	1	21	1	0	0	0	0	0	0	1
Grain maize	0	0	0	0	3	0	1	0	0	30	4	0	1	0	0	0	3
Silage maize	0	0	0	12	2	0	10	0	0	15	45	0	2	6	3	2	10
Olives	0	0	0	0	0	2	1	0	0	0	0	96	0	1	0	0	7
Tomato	0	0	0	0	0	0	0	0	0	3	3	0	10	0	0	0	1
Vineyard	0	9	0	0	3	0	0	0	0	1	4	0	0	34	0	0	8
Horticultural crops	0	0	0	0	0	0	0	1	1	4	4	0	16	1	80	0	5
Set-aside	1	1	0	0	2	0	0	1	1	11	8	0	0	6	0	54	4
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 3 Classification error from the confusion matrix of crop classification results

Classes	Commission (%)	Omission (%)	Producer accuracy (%)	User accuracy (%)
Winter cereals	4.0	4.0	96.0	96.1
Kiwi fruit	44.6	21.4	78.6	55.4
Citrus	39.6	3.0	97.0	60.4
Sugarbeet	38.4	18.9	81.1	61.6
Fruit trees	68.5	18.7	81.3	31.5
Permanent forage crops	76.3	67.3	32.7	12.7
Annual forage crops	51.0	18.0	82.0	49.0
Sunflower	16.6	32.0	68.0	83.4
Grain maize	21.2	72.3	27.7	78.8
Silage maize	18.8	45.6	54.5	81.2
Olives	44.7	46.7	53.4	55.3
Tomato	29.1	17.6	82.4	70.9
Vineyard	20.3	57.7	42.3	79.7
Horticultural crops	8.0	20.4	79.6	92.0
Set-aside	63.8	53.7	46.3	36.2
Grain legumes	37.4	10.2	89.8	62.6

Overall accuracy = 62.45%. Kappa coefficient = 0.59

It should be noted that part of the differences could be attributed to year to year variation of crop areas.

By combination of the crop classification map (Fig. 6) with the table of monthly crop coefficients (Table 1), monthly crop evapotranspiration (ET_c) maps were obtained. The annual total ET_c map (Fig. 8) shows that the highest values are found in the North and North–East parts of the Pontina Plain, corresponding to the highest occurrence of tree crops and particularly kiwi fruit. In the most Southern area of the Plain high annual ET_c values are mostly associated to the occurrence of permanent forage crops such as alfalfa.

4.3 Irrigation Requirements

The analysis of the water balance results show that soil water deficits start to appear in April and last until September (Fig. 9).

The total irrigation requirement for the Pontina Plain was estimated at about 70 Mm^3 $year^{-1}$, equal to 11% of the annual rainfall amount and 70% of the effective infiltration (Regione Lazio 1992; Rossi 2005).

Table 5 reports the estimated irrigation requirements for the whole study area according to the crop class. These are data resulting from the simplified water balance computations and therefore represent estimated soil water deficits, not necessarily matching actual irrigation practices in the area. For example, for economic reasons, winter cereals are not usually irrigated, as well, obviously, land used as set-aside. Currently irrigation is mostly applied to high value horticultural crops, kiwi fruit and tree crops, sugar beet and maize.

Monthly irrigation requirements for each crop (Table 5) show that, as expected, most of the water is required in the June–August period as about 50% of the total water deficit is concentrated in July while no irrigation is needed from October until March.

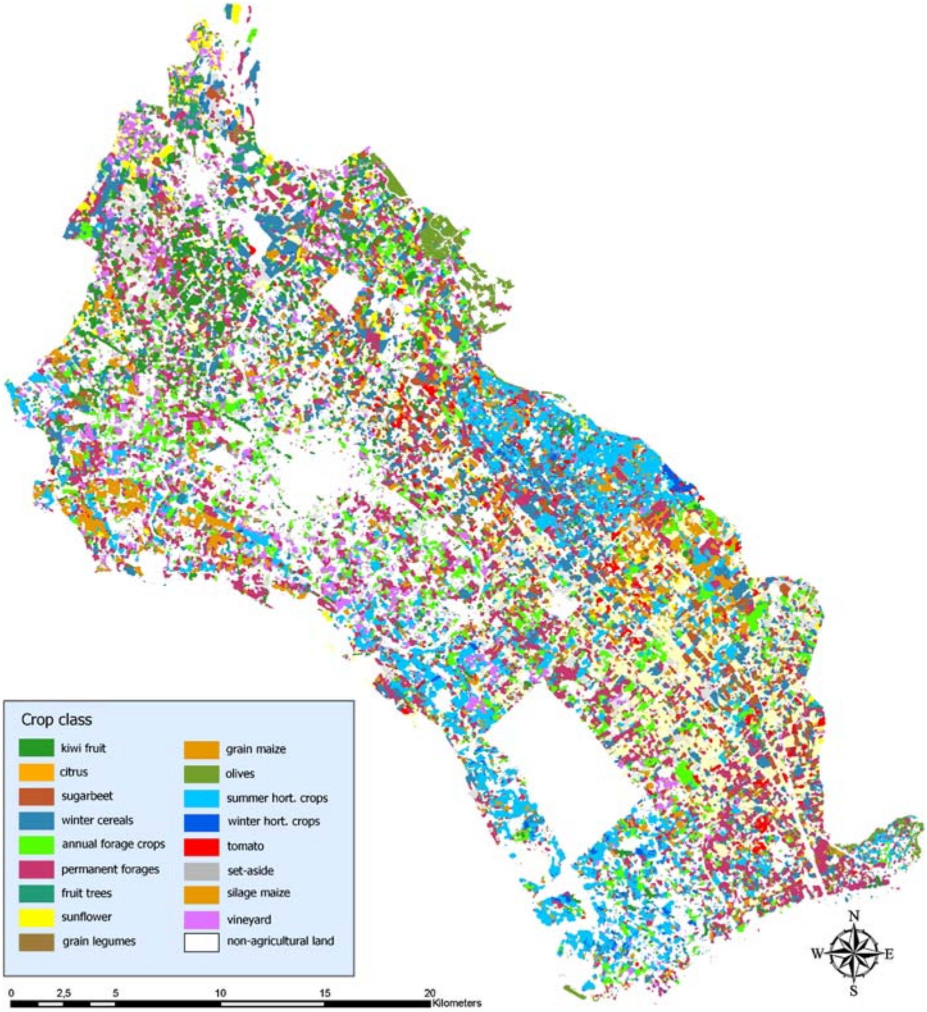

Fig. 6 Crop map of the study area obtained from multitemporal LANDSAT ETM+ image classification

Permanent forages, typically alfalfa or permanent ryegrass, are on the whole study area the crops requiring most of the overall water resources, accounting for a monthly water demand of 31% in June, 25% in July and of 41% in August out of the total irrigation requirements of the area. This results from combined high unitary crop water requirements and the large surface area occupied by this class in the Pontina plain.

Also silage maize reaches a deficit of more than 8 Mm^3 in July but the harvest in August causes the requirements to decrease to very small values. With a total seasonal irrigation requirement of about 21 Mm^3 year^{-1}, permanent forage crops would absorb about 30% of the total annual irrigation requirements of the study

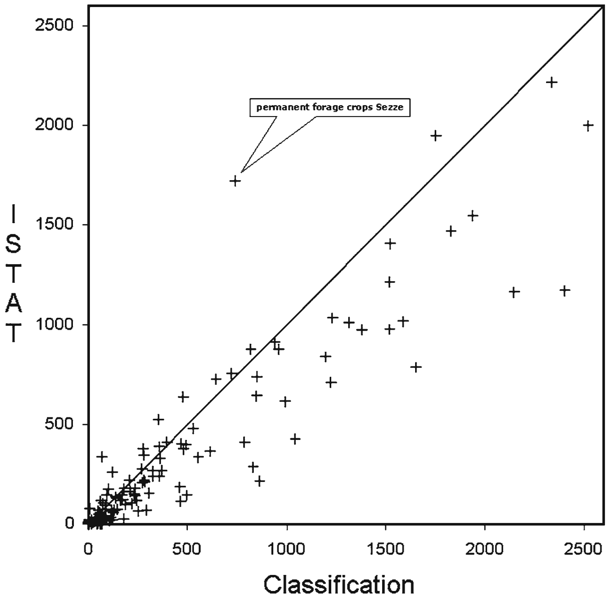

Fig. 7 Comparison between crop area estimates obtained from LANDSAT ETM+ multitemporal image classification (present study) and those provided by ISTAT (2000) on per crop and per county basis

area, followed by silage maize with more than 10 Mm^3 $year^{-1}$, i.e. about 15% of the total for the area.

The most water demanding crops grown in the study area were found to be grain maize, tomato, fruit trees and kiwi fruit, with seasonal requirements in the order of 3,000 m^3 ha^{-1}. These values are considerably lower than those reported elsewhere. For example Ravelli and Rota (1999) report water deficit values of 5,430 m^3 ha^{-1}

Table 4 Comparison between crop surfaces estimated by the present study (through LANDSAT ETM+ classification), ISTAT (2000) and Tulipano et al. (2004) for the Pontina Plain territory

Crop type	Present study (ha)	ISTAT (2000) (ha)	Tulipano et al. (2004) (ha)
Kiwi fruit	3,456	22,147	5,115
Citrus	26	29	–
Sugarbeet	1,897	1,670	1,151
Winter cereals	5,121	4,683	6,239
Annual forage crops	4,882	4,131	–
Permanent forage crops	9,318	8,470	6,264
Fruit trees	1,081	646	1,795
Sunflower	1,352	854	–
Grain legumes	1,392	674	–
Grain maize	3,734	2,692	5,972
Olives	1,420	1,354	603
Horticultural crops	8,280	4,653	11,924
Tomato	950	706	1,376
Set-aside	4,210	3,144	–
Silage maize	5,668	4,863	–
Vineyard	3,507	2,322	1,603
Total	56,296	43,038	42,042

Fig. 8 Annual crop evapotranspiration (ET_c) map in millimeter per year

for maize, 4,760 for tomato and 6,560 for fruit trees, for a test site in the same study area, although these data are calculated for a probability of non-exceeding the 75% percentile. In their study the most water demanding crop was a permanent forage (*Festuca*) with a seasonal requirement of 7,610 m^3 ha^{-1}.

These discrepancies could result partly from the fact that Ravelli and Rota (1999) used a simple effective rain methodology (Dastane 1974), not taking into account the soil water availability. Moreover they used the 75% probability of non exceeding mean climatic values rather than actual mean values. This corresponds to adopting a safer scenario concerning crop water availability, i.e. what would happen in a dry year. Therefore, a test was carried out for the weather station of Borgo S.Michele (Latina), in the centre of the study area, using the 75% probability of non exceeding monthly ET_0 values and the 75% probability of exceeding monthly rainfall values, calculated from 20 years of climatic data. For Borgo S. Michele, in which mean ET_0 is 959 mm $year^{-1}$ and mean rainfall is 857 mm $year^{-1}$, there is a 75% probability that 1,005 mm $year^{-1}$ ET_0 will not be exceeded and that 395 mm $year^{-1}$ of rainfall will be exceeded. Using the same Kc values and sowing dates as for the computations of Table 5, the seasonal water requirement of grain maize was estimated, using the

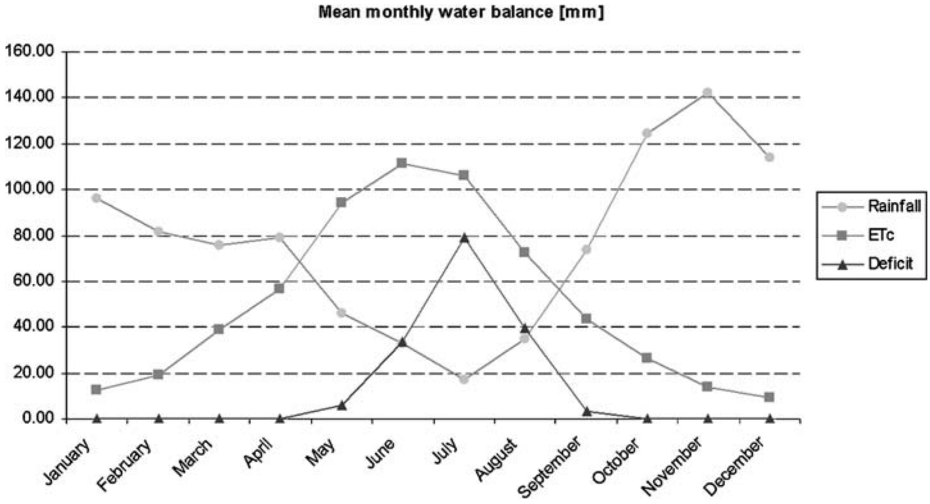

Fig. 9 Average monthly water balance terms for the whole study area

FAO Cropwat software (Clarke et al. 1992) as 4,930 m^3 ha^{-1} (net irrigation) for this "dry year" scenario as compared to 3,530 m^3 ha^{-1} calculated using actual mean ET_0 and rainfall values.

The behavior of the current crop pattern and the sensitivity of the water balance model estimates to climatic variability, was investigated by calculating the spatial distribution of soil water deficits under two different climatic scenarios, chosen within the historical series of weather data available for the whole study area (1996–2002). The total rainfall amount for the irrigation period (April–September) was minimum in 2001 (183 mm) and maximum in 2002 (434 mm), i.e. respectively 35% less and 53% more than the average 283 mm. Therefore 2001 can be considered a "dry" year and 2002 a "wet" year.

Water balance model results showed that cumulative crop evapotranspiration for the area was almost insensitive to the different climatic scenarios, decreasing by only 3% (471 mm) in the dry year and 1% (479 mm) in the wet year as compared to the average year. This was due to the small temperature variations between years and the use of the Hargreaves equation to calculate evapotranspiration.

The different climatic scenarios affected the temporal and spatial pattern of water deficit. Although the deficit peak values were always recorded in month of July, differences were found in the response to rainfall changes between the dry and the wet year. The cumulative deficit for the irrigation season in the dry year was increased by 35% (90 Mm^3) as compared to the average year, i.e. almost proportionally to the rainfall decrease. Conversely in the wet year the deficit was decreased by 24% (52 Mm^3), i.e. much less than the rainfall increase of 53%.

This behaviour highlights a non-linear response of deficit to rainfall, clearly due to the role of the soil and its limited water storing capacity defined by the AWC value.

The spatial distribution of the deficit in the area (Fig. 10), depends however on the complex combination of soil, crop and climatic factors. The areas where the highest deficit tends to develop correspond mostly to inland zones in the southern part of the

Table 5 Monthly and seasonal irrigation requirements for the study area

Crop type	Monthly irrigation requirement (thousand m^3)						Seasonal total (thousand m^3)	Seasonal average[a] ($m^3 ha^{-1}$)	Total crop area (ha)
	April	May	June	July	August	September			
Grain maize	0	1	1,658	4,681	3,142	0	9,481	3,235	2,931
Tomato	0	5	654	1,328	818	0	2,804	3,175	883
Fruit trees	0	24	347	820	663	29	1,883	3,077	612
Kiwi fruit	0	71	622	1,785	1,251	185	3,913	2,952	1,326
Permanent forage crops	0	258	4,522	8,450	6,843	1,113	21,186	2,877	7,363
Vineyard	0	85	834	1,725	1,488	5	4,138	2,230	1,855
Silage maize	0	4	2,332	8,113	0	0	10,449	1,989	5,252
Citrus	0	0	8	20	16	0	44	1,857	24
Sunflower	0	6	419	764	0	0	1,188	1,611	738
Sugarbeet	0	474	17	1,494	101	0	2,086	1,241	1,681
Summer horticultural crops	0	54	1,080	2,772	2,171	0	6,076	914	6,648
Olives	0	5	81	351	362	0	799	895	893
Annual forage crops	1	895	1,046	856	0	0	2,798	705	3,970
Grain legumes	7	202	152	90	0	0	450	477	943
Winter cereals	1	325	696	672	0	0	1,693	452	3,745
Winter horticultural crops	0	0	0	2	27	0	29	40	745
Set-aside	0	0	0	0	0	0	0	0	3,010
Total	9	2,407	14,467	33,923	16,881	1,332	69,020	1,619	42,618

[a] For this column the last row reports average seasonal irrigation requirement in cubic meter per hectare

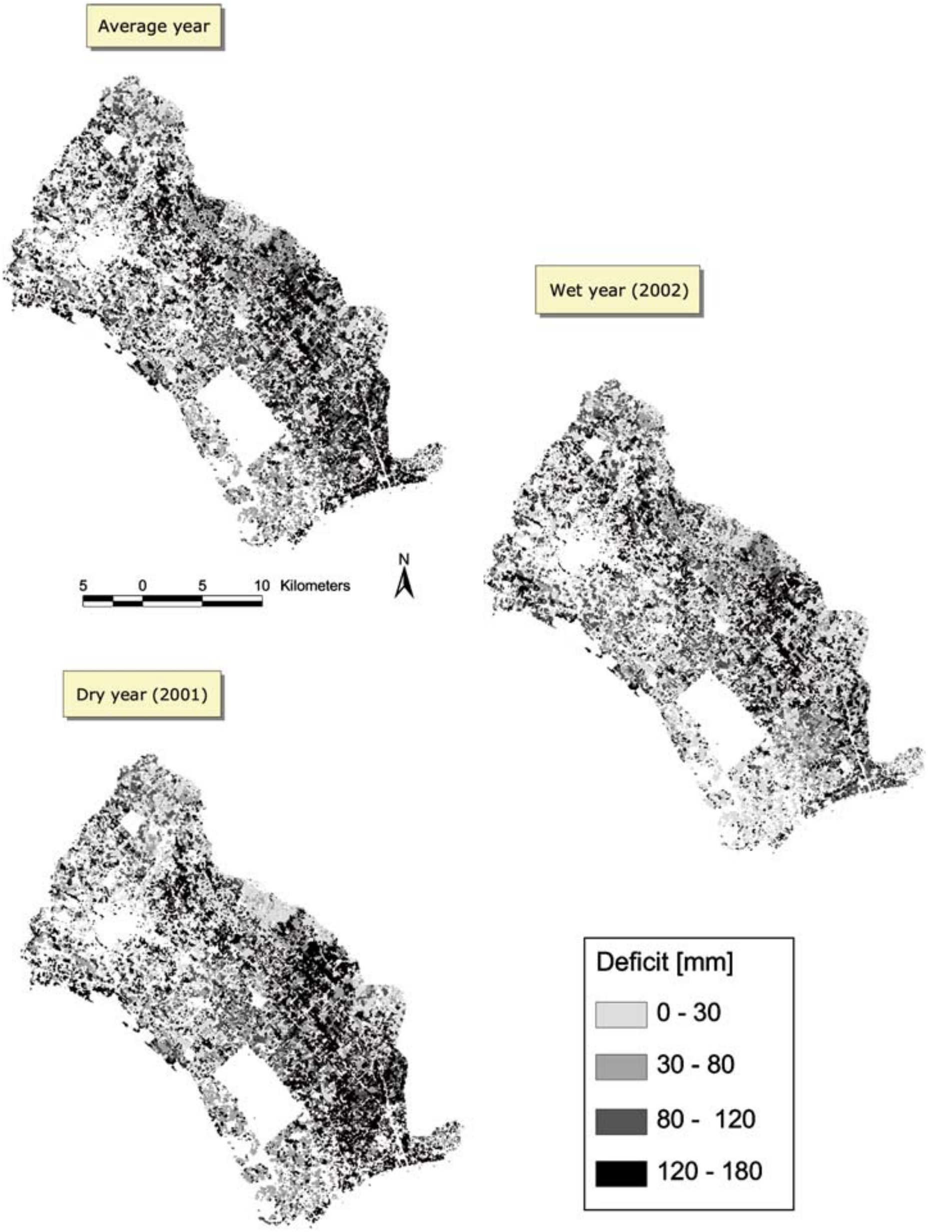

Fig. 10 Spatial distribution of soil water deficit for the peak month (July) calculated using average climatic data (average year) as well as data from a dry year (2001) and from a wet year (2002)

plain, especially where maize and permanent forages are cultivated and soils have a relatively low AWC.

It should be noted that the water balance model (3) calculates soil water deficit for each pixel on a monthly basis as a function of climatic data of the current and the previous month, as well as monthly Kc and AWC. Even keeping constant the latter two factors, a wide range of responses to climate is possible, for example because of different temporal and spatial rainfall distribution patterns, making a thorough model sensitivity analysis a rather complex task.

4.4 Comparison with Previous Estimates for the Study Area

The water balance results from the present study have been compared with the information collected in the Pontina Plain from specific focus groups organised with different stakeholders and farmer associations (Tulipano et al. 2004). The data available include mean water amounts used for irrigation and the techniques used in the Pontina Plain (Tulipano et al. 2004; Sappa and Rossi 2006).

Although the methodology of data collection and the spatial data aggregation scale is very different, these data are the only ones available concerning spatial and temporal distribution of agricultural water use in the Pontina Plain. The total amount of water used for irrigation in the whole area amounts to 110 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$ according to Tulipano et al. (2004), a value much higher than the one obtained in the present study (about 70 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$).

Based on homogeneous agronomic basin polygons (referred to as BAO) used in the reference works (Tulipano et al. 2004; Sappa and Rossi 2006) and shown in Fig. 11, a more detailed comparison was carried out.

The results resumed in Fig. 12 show a spatial constant ratio of about 60% between the crop water requirements estimated, in the present study, by considering soil water deficit and the water amount assumed to be used for the irrigation.

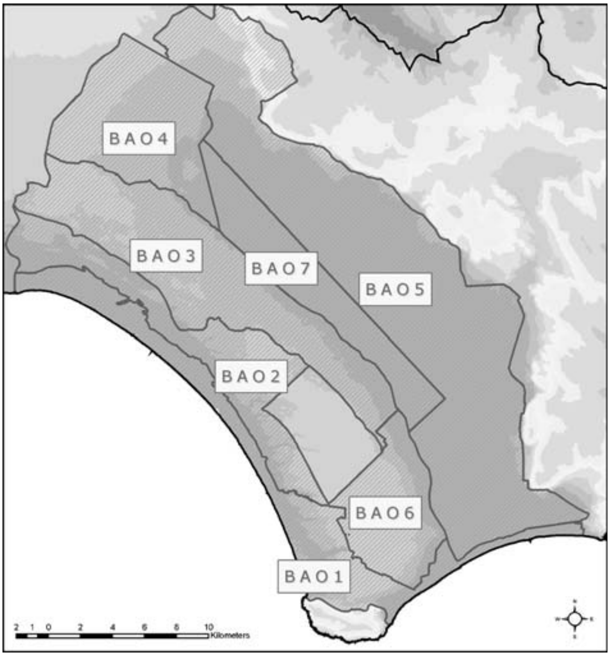

Fig. 11 Homogeneous Agronomic Basins (BAO) delimitation on Pontina Plain (Tulipano et al. 2004; Sappa and Rossi 2006)

Minimum and maximum values have been found respectively in BAO 3 and BAO 6. The first one is characterized by widespread diffusion of forage crops and maize, whereas more than 60% of the BAO 6 surface is occupied by horticultural crops (Tulipano et al. 2004; Sappa and Rossi 2006).

Referring to the classifications results in Table 4, it can be noted that the total crop surfaces estimated in the present work are greater than those in Tulipano et al. (2004) for maize (more than 2,000 ha in excess) and smaller for horticultural crops (about 3,000 ha less).

Additionally, the differences in estimates can be explained by considering that the present study reports estimated soil water deficits, assumed to be equal to crop water requirements calculated from a simplified water balance, while in Tulipano et al. (2004) the irrigation amounts estimates were based on information collected in focus groups organized with representative of local farmers associations. It should be noted that water metering devices are not generally available to farmers of the area, so their estimate of the amount of irrigation supplied can be sometimes only approximate.

The most widespread irrigation method in the Pontina Plain is through high-pressurised sprinkler systems, in particular traveling guns, needing high threshold flow values for correct functioning, sometimes greater than the effective crop water requirements (Hsiao et al. 2007). Additionally sprinkle irrigation leads to water losses by evaporation and runoff, so that its efficiency is generally estimated to be within the 65–80% range (FAO 1996; Hsiao et al. 2007; Rogers et al. 1997). Drip irrigation, a more efficient technique, is used in the area only for part of the horticultural crops, especially processing tomato. However the high efficiency values (up to 80–90%) attainable with this technique, are only possible where proper irrigation management and sound scheduling criteria are adopted (Hsiao et al. 2007).

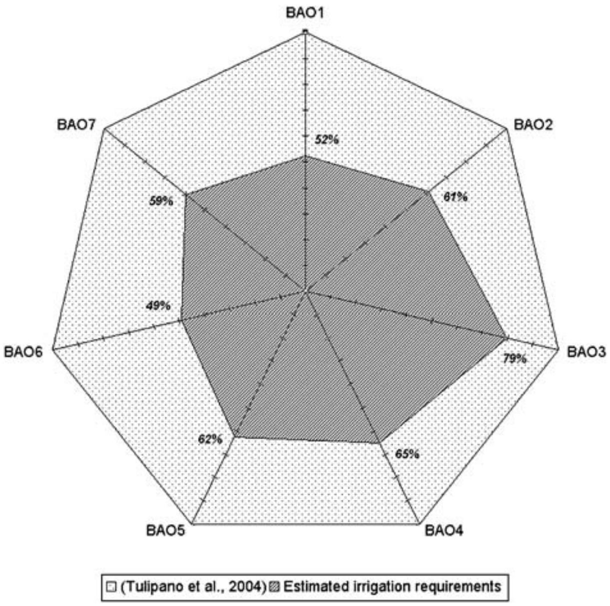

Fig. 12 Comparison between estimated irrigation requirements from the present study and water used for irrigation (Tulipano et al. 2004) on a HAB scale

In the Pontina Plain, irrigation applications are usually based on simple observations of meteorological conditions or by visual assessment of crop and soil water status and no proper irrigation management based on water balance scheduling (FAO 1996) is practiced in the area (Tulipano et al. 2004).

Therefore, assuming an average irrigation efficiency of 70% for the whole study area, the irrigation requirement would be of around 100 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$, from the estimated crop water needs of about 70 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$.

5 Conclusions

The present work aimed at providing a preliminary estimate of irrigation water requirements for the Pontina Plain, useful for inferring the temporal and spatial patterns of groundwater withdrawals due to agricultural use, to be employed in further hydrological studies. Considering the importance of agricultural water use on the hydrological balance of the area, and given the present economic and time constraints of regional institutions, this study was aimed at identifying and testing an inexpensive and rapid methodology for this task.

For this reasons a simple and economic approach, in terms of data and resources, based on remote sensing and GIS, was chosen.

Employing only 4 Landsat images and a few meteorological and geographical vectorial layers, the integrated use of GIS allowed the elaboration of monthly maps of crop evapotranspiration for an area of about 700 km^2. The application of a spatially distributed water balance model, allowed the estimation of temporal and spatial variation of crop water requirements in the study area.

The accuracy of the estimates provided in the present study is influenced by several factors.

Classification error can have an impact on crop evapotranspiration mapping, especially when crops having contrasting water use behaviour are confused (Stehman and Milliken 2007). A particular problem encountered in the study area was the widespread occurrence of small sized fields, causing high commission errors in the classification. Increased accuracy would be achieved by using a per-field rather than a pixel-based classification method (De Wit and Clevers 2004), should digitised field boundaries become available for the study area.

Another source of error in crop evapotranspiration maps was the assumption of standardized Kc seasonal curves throughout the study area, though the reasonably uniform climatic and soil conditions of the Pontina Plain entail a fairly homogeneous farming practices calendar, as confirmed by interviews with local farmers and extension service personnel (Tulipano et al. 2004).

The use of an extremely simplified root-zone water balance adopted in this study, although an improvement compared to the simpler effective rain methodologies, still introduced some gross approximations by not considering in detail several terms of the water balance, such as drainage and runoff, and ignoring even basic crop growth terms such as the root uptake of readily available soil moisture and water stress related evapotranspiration reduction. On the other hand considerable more information would have been required in order to adopt more detailed agro-hydrological models (Boegh et al. 2004), considering the temporal constraints and the spatial scale of the present application.

Nevertheless, the results provided by this work make available to further hydrological modelling activities, more detailed and accurate spatial data, on water requirements of the existing cropping pattern, than those which are usually employed in similar planning studies (e.g. Bonomi 1995; Capelli et al. 2005).

Actually the crop classification work carried out to build Kc maps, contributed important information on agricultural land use, potentially useful to elaborate different scenarios in subsequent studies for the definition of sustainable water management policies.

It was not within the scope of the present work to explore possible alternative crop allocation patterns in the area, aimed at minimizing water deficit, or alternatively provide the highest economic net benefit. However the results provided by this study could be used, for example, as inputs of spatially distributed linear optimisation models, capable of providing suggestions for planning authorities on more suitable cropping patterns for the conservation of water resources while safeguarding farmers' income.

The increasing availability of high resolution remote sensing data and the recent set-up of a comprehensive network of weather stations in the Latium Department, gives the Regional Watershed Authority powerful tools for updating and improving the accuracy of the present work, for an efficient monitoring and planning of water resources use.

The present study estimated crop water demand for the whole area to be about 70 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$, i.e. 100 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$ irrigation requirements when considering an average irrigation application efficiency of 70%. A previous estimate of current irrigation amounts used in the area, though following very different methodologies (Tulipano et al. 2004), reported a figure of 110 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$, suggesting scope for substantial irrigation water savings. Improvements are expected to stem from the diffusion of water metering devices and sound water balance based irrigation scheduling criteria (FAO 1996), or by policies encouraging less water demanding cropping systems.

It should be noted that the calculation of irrigation requirements from the simplified water balance implemented in the present study, allows plant uptake of the whole available water content, implying the possibility of occurrence of crop water stress and yield reduction. Full irrigation scheduling criteria would, more cautiously, allow depletion of only the fraction of readily available soil water (Allen et al. 1998; Clarke et al. 1992).

For these reasons, the overall irrigation water requirement for the Pontina Plain, estimated in this work, can be considered as an absolute minimum net amount of water resources necessary for allowing current farming practices to be sustained.

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