Alexandridis, T.K., Panagopoulos, A., Galanis, G., Alexiou, I., Cherif, I., Chemin, Y., Stavrinos, E., Bilas, G., and Zalidis, G.C., 2014. Combining remotely sensed surface energy fluxes and GIS analysis of groundwater parameters for irrigation system assessment. Irrigation Science, 32(2): 127-140.

Combining remotely sensed surface energy fluxes and GIS analysis of groundwater parameters for irrigation system assessment

T.K. Alexandridis[1*], A. Panagopoulos[2], G. Galanis[3], I. Alexiou[4], I. Cherif[1], Y. Chemin[5], E. Stavrinos[6], G. Bilas[3] and G.C. Zalidis[3]

[1] Laboratory of Remote Sensing and GIS, School of Agriculture, Aristotle University of Thessaloniki, Univ. Box 259, Thessaloniki GR54124, Greece

[2] Land Reclamation Institute, Hellenic Agricultural Organisation, Sindos GR57400, Greece

[3] Laboratory of Applied Soil Science, School of Agriculture, Aristotle University of Thessaloniki, Thessaloniki GR54124, Greece

[4] Institute of Soil Classification and Mapping, Hellenic Agricultural Organisation, Larissa GR41335, Greece

[5]International Water Management Institute, PO Box 2075, Colombo, Sri Lanka

[6] Hellenic Ministry of Rural Development and Foods, Directorate of Water Reclamation and Soil-Water Resources Planning, Athens GR10445, Greece

** Author to whom correspondence should be addressed; E-mail:* thalex@agro.auth.gr; Tel: +30-2310-991757; Fax: +30-2310-991778

Abstract

Despite being necessary for effective water management, the assessment of an irrigation system requires a large amount of input data for the estimation of related parameters and indicators, which are seldom measured in a regular and reliable manner. In this work, spatially distributed surface energy balance fluxes and GIS analysis of multiple groundwater parameters were used to estimate water availability, supply and demand, in order to calculate water accounting indicators. This methodology was used to evaluate the performance of an irrigation system in the Pinios River Basin (Greece) at two selected years of high and low water availability. Time series of archived satellite images and groundwater measurements have been used for past years to support comparative analyses, due to the limited availability of actual water measurements. The resulting maps from the proposed methodology show that the performance of the irrigation system varied across space and time due to differences of its characteristics and changes in its operation, driven by fluctuation of water availability and the response of stakeholders to water depletion. Irrigation districts with unsustainable water management were identified, and together with those with slow and/or limited groundwater recharge were brought to the attention of water managers. The observed differences in the system operation between the wet and dry years were attributed not only to the hydrological conditions of each year, but also to the changing behaviour of farmers and the improvement actions of the water managers.

Keywords

agricultural water use, groundwater availability, remote sensing, geographic analysis, SEBAL, water accounting indicators

1. Introduction

To meet demand for increased production, water resources are often overexploited causing severe environmental degradation and social problems (Hamdy et al. 2003). In addition, the changing climate has exacerbated the pressure on water resources by increasing the variability of regional precipitation, diminishing aquifer recharge during the wet season and decreasing soil organic matter. Thus there is an impact on the soils' water holding capacity, a drop in groundwater levels and consequently in groundwater reserves, and further aridification with longer droughts (Kundzewicz et al. 2008). Particularly in the Mediterranean, an already overexploited area which is expected to be severely affected by climate change, excessive use of irrigated water is expected to deteriorate the limited freshwater resources by depleting the aquifers, discharging agri-chemicals and accelerating saltwater intrusion.

As a response, several interrelated European directives and initiatives have been issued to help protect water resources from further deterioration and progressively restore the quantity and quality status of water bodies, amongst which most important are: the European Water Framework Directive (EC 2000) that has the general objectives of improving water quality, guaranteeing provision of sufficient quantities of good quality water for all purposes, and avoiding any long-term deterioration; the Common Agricultural Policy with its reform (EC 2003) focuses on sustainable agriculture to promote environmental safeguards and ensure future yields, including relieving pressures on water resources (Herbke et al. 2006); the groundwater daughter directive (EC 2006) which establishes specific measures in order to prevent and control groundwater pollution; and the nitrates directive (EC 1991) which aims at protecting waters from pollution caused by nitrates of agricultural sources. Among others, EU legislation demands the identification of pressures from agriculture and estimation of water abstractions, with the overall aim to recover the costs of water services, including environmental and resource costs. A crucial step in this direction is the knowledge of water parameters that characterise the utilisation of water resources for agriculture, among other uses.

Irrigation system characterisation is necessary for effective water management, as it provides essential knowledge through performance and accounting indicators (Kassam et al. 2007; Molden and Sakthivadivel 1999). However, a large amount of input data are required to estimate these indicators, which are seldom measured in a regular and reliable manner to cover the entire river basin or even irrigation system (Biggs et al. 2006; Droogers 2002). Recent advances in satellite earth observation can provide several parameters related to irrigation management: mapping the irrigated area (Alexandridis et al. 2008; Biggs et al. 2006), evapotranspiration (Alexandridis et al. 2009; Irmak and Kamble 2009; Singh et al. 2012), biomass and yield estimation (Bastiaanssen and Ali 2003; Basso et al. 2001), irrigation monitoring and management (Bastiaanssen et al. 2000; Santos et al. 2008), irrigation system performance (Santos et al. 2010; Zwart and Leclert 2010) , groundwater management and monitoring (Awan et al. 2012; Castaño et al. 2010). In addition, earth observation can provide unique solutions in cases of complex irrigation systems, where the cost of traditional means of data collection could be prohibitive (Bastiaanssen et al. 2000; Chemin and Alexandridis 2006).

Groundwater modeling is also a valuable tool that assists the characterization of an irrigation system, especially in southern European semi-arid environments where surface water resources are inadequate and irrigation is essentially based on groundwater abstractions form a single or multiple-aquifer system. Such modeling tools may contribute to the assessment of the effects from the operation of an irrigation system to the regional groundwater resources under various alternative management scenarios and climatic regimes (Boskidis et al. 2012; Lambrakis and Kallergis 2001; Koukidou et al. 2010). A relevant work by Paydar et al. (2009), introduced an approach to quantify irrigation losses up scaled to irrigation area level employing a detailed crop-soil-water modelling exercise. Irrigation losses have been considerable, strongly affecting the efficiency of an irrigation network and influencing the overall water balance of a region. Part of the efficiency of an irrigation network relates to the distribution system and delivery schedule used. Hence, Zaccaria et al. (2010) introduced a soil-water balance modeling approach to identify the most efficient water delivery schedule in a semi-arid climatic region suffering by water shortage and groundwater salinisation. However, mathematical groundwater modeling, including the crop-soil-water modeling interaction is often prohibitive due to lack of substantial data sets and/or time series, amongst others. An alternative approach under such conditions is the GIS assisted calculation of basic water balance elements of the entire studied basin.

The use of Geographical Information Systems (GIS) has been successfully combined with hydrological and groundwater models in irrigation water management (McKinney and Cai 2002; Xu et al. 2001; Tsihrintzis et al. 1996), despite the issues of uncertainty that are inherently linked to the overall process (Sui and Maggio 1999). Such issues relate to the data acquisition and availability, model calibration and visualisation. In recent literature, Awan et al. (2012) combined a capillary rise hydrological model and the Penman equation (Penman 1950) using GIS and remote sensing techniques to estimate the crop irrigation requirements and eventually various scenarios of groundwater recharge. In groundwater resources, modeling and GIS certainly offer great assistance in managing data uncertainties, however it is well-acknowledged that large volumes of data are required to obtain meaningful and trustworthy results (Gogu et al. 2001; Refsgaard et al. 1999). Modeling algorithms are nowadays well-developed and provide high precision results. However, in actual terms this precision cannot be utilised since data acquisition, spatial extrapolation and up-scaling techniques are often of limited accuracy (Lubczynski and Gurwin 2005). Groundwater availability and balance, and its spatial and temporal distribution is thus a problem that can be solved with a reasonable degree of accuracy through modeling approaches, provided that enough and trustworthy data are available. Under limited data conditions, a more simplistic approach is required that makes use of the GIS capabilities and resorts to basic and readily available groundwater resources related data, such as water levels, utilising for the calculations a one-off parameterised aquifer system and as variable only the groundwater levels.

Thus, due to the unavailability of frequently measured data, the characterisation of groundwater dependent irrigation systems has often been performed statically, disregarding potential deviation because of variable water availability (Javan et al. 2002; Jensen 2007; Dechmi et al. 2003). The aim of this paper is to combine remote sensing and GIS groundwater modeling to characterise the management of an irrigation system under conditions of high and low water availability and highlight the differences between these two regimes in relation to sustainable irrigation management. Three specific steps were followed to reach the objectives: (i) identification of water use from spatially distributed actual evapotranspiration estimates derived from satellite earth observation, (ii) estimation of groundwater availability using geographic analysis of multiple groundwater parameters and 3D GIS modeling, and (iii) characterisation of the irrigation system during irrigation seasons with high and low water availability using water accounting indicators. This work is part of a wider project related to the economic valuation of irrigation water, driven by the implementation of the European Water Framework Directive in Greece.

2. Materials and methods

2.1 Site description

The study area is in the lower part of Tyrnavos basin, a sub-basin of Pinios river (central Greece). The climate is typical Mediterranean, with annual rainfall from 400 to 500mm, distributed almost entirely during the cold season, without any significant precipitation during the hot summer. Thus, several irrigation systems have been developed to support the cultivation of highly productive summer crops.

Agriculture is the dominant economic activity in the study area, covering approximately 16,000 ha (71% of the gross area). Most crops (cotton, alfalfa, sugarbeets, maize, vegetables, orchards and vinyards) are irrigated and on the aggregate represent 65% of the total cultivated area. The remaining agricultural land (35%) is used for cereal production, and is mainly rainfed. The most common irrigation methods are by sprinkler and micro-irrigation. The source of utilised water resources is groundwater.

Three local irrigation organisations cater irrigation water to producers through collective networks within their districts: Tyrnavos, Ampelona, and Aghias Sofias (Fig. 1). Nowadays all operating networks are pressurised, whilst until recently an extensive gravitational network operated on the eastern part of the Ampelona district (subsequently divided into Ampelona East and Ampelona West) tapping the karstic spring of Mati until 1998, when it was abandoned because of diminishing discharge from the spring. Despite the collective irrigation works, several privately owned wells exist and operate to cover irrigation demands of land that does not fall into the jurisdiction of the aforementioned collective networks, mainly in the north and eastern ends of the study area and are named for this work as the Argiropouli and Pinios districts.

The karstic aquifer bounds the alluvial aquifer system along its western edge. On a regional scale, two aquifer units, a superficial unconfined and a deep confined to semi-confined may be distinguished within the alluvial deposits and have a maximum thickness of over 550m towards its central parts (Demitrack 1986). The alluvial aquifer system is predominantly recharged through lateral crossflows along its western margins, and direct infiltration from precipitation at an average rate of 106 Mm^3/y in a dry and 133 Mm^3/y in a wet year (Panagopoulos 1996; Constandinidis 1978). Discharge from the system occurs mainly in the form of abstractions from a vast number of production wells that operate throughout the basin and tap both aquifers at an average rate of 136 Mm^3/y in a dry and 115 Mm^3/y in a wet year. Due to the documented bedrock uplift south-east of the Pinios River (Geophysique 1972; SAS 1974) and mismanagement of the water resources, especially in the past, partial hydraulic cut-off between the upstream and the downstream parts of eastern Thessaly basin exists (Panagopoulos 1995;

Panagopoulos et al. 2008), thus prohibiting recharge of the latter through crossflows. As a result, a severe negative water balance has been established since the mid 1980's (average rate of 30 Mm^3/y) that gave rise to considerable adverse effects to water quality and triggered extensive surface subsidence (Katsilouli et al. 2004; Marinos et al. 1997; Soulios 1997). Nevertheless, during a wet year a surplus has been documented and 18 Mm^3/y can be stored in the system (Panagopoulos et al 2008).

[Fig. 1 about here – Colour on the web only]

2.2 Datasets

The satellite images used were selected on the basis of their ability to map characteristics of irrigated crops and surface energy parameters. Two types of satellite images were used:
(i) Low spatial resolution (ground sampling distance of 1.1 km) but frequently acquired (daily acquisition) images of the AVHRR (Advanced Very High Resolution Radiometer) sensor on board the NOAA (National Oceanic and Atmosphere Administration) satellite. Altogether, 15 images were acquired for each year (1996 and 2002) from the USGS archive (http://edcimswww.cr.usgs.gov/pub/imswelcome/), from which six were selected based on their cloud coverage (cloud free images were preferred) and their temporal distribution (one each month during the irrigation season: April to September).
(ii) A single date high resolution (30x30m) Landsat TM/ETM+ (Enhanced Thematic Mapper) image per year, strategically acquired at the peak of the irrigation season (23/08/1996 and 05/08/2002).

In the absence of water meters in the irrigation well heads, water abstractions were approximated through calculations based on electric consumption, technical specifications of the installed pumping systems and the depth to groundwater.

Since the early 1970s, monthly piezometric data records from approximately 25 piezometers distributed within the study area were used for the assessment of groundwater resources evolution, i.e. changes in water quality and quantity and hence availability for a specific use. Moreover, the distribution of essential hydro-geological parameters was taken into account, namely infiltration percentage (i), specific drawdown (s/Q) and transmissivity values (T), as these were defined in earlier studies conducted in the region (Constandinidis 1978; Panagopoulos 1995) and critically reviewed on the basis of contemporary data where available.

The aquifer system geometry was considered (Geophysique 1972; SAS 1974), and the hydrodynamic evolution model that was proposed in an earlier study (Panagopoulos 1995), including a groundwater budget calculation approach that was adopted and updated accordingly where necessary.

Daily meteorological data were acquired from the Larissa station (N39^o 39', E 22^o 27', elevation 73.6 m amsl). The data used in this work were: air temperature, relative humidity, wind speed, air pressure, solar radiation, and precipitation.

2.3 Surface energy fluxes to estimate irrigation water use

Actual evapotranspiration (ET_a) is a good estimate of irrigation water use in large heterogeneous areas where limited information is available (e.g. no water meters, no regular flow estimates). ET_a in the study area was calculated by applying the Surface Energy Balance Algorithm for Land (SEBAL) on the satellite images which had a thermal band (NOAA AVHRR and Landsat TM/ETM+). SEBAL is a thermodynamically based model, using the partitioning of sensible heat flux and latent heat of vaporisation flux as described in Bastiaanssen et al. (1998). It has been used in hydrological applications from local to regional scales and has been validated in Spain, France, Turkey, Egypt and other Mediterranean countries (Bastiaanssen et al. 2005; Kite and Droogers 2000).

The ratio of heat fluxes (or evaporative fraction: Λ) is an output of SEBAL, and was calculated as:

$$\Lambda = \frac{\lambda E}{R_{net} - G_0} = \frac{R_{net} - G_0 - H}{R_{net} - G_0}$$

where, R_{net} is the instantaneous net radiation (W/m^2), G_0 is the instantaneous soil heat flux (W/m^2), H is the instantaneous sensible heat flux (W/m^2) and λE is the instantaneous latent heat flux (W/m^2).

λE was calculated based on Λ, multiplied by the diurnal net radiation at the surface of the earth (Rn_{day}), calculated spatially from the surface broadband albedo data (ρ_0, calculated from the satellite images) and the single-way transmissivity of the atmosphere (τ_{sw}=0.75).

$$\lambda \mathrm{E} = \Lambda \cdot Rn_{day} = \Lambda \cdot \left[\left((1-\rho_0) \cdot K_{day}^{\downarrow}\right) - 110 \cdot \tau_{sw}\right]$$

Where $K_{day}^{\downarrow}$ is the daily incoming solar radiation (W/m^2).

The actual daily evapotranspiration (ET_a) was calculated by aggregating λE over 24 hours. Moreover, the SEBAL algorithm was initialised with a set of parameters that characterise the conditions at the meteorological station: height of wind measurement (4m), wind speed at satellite overpass time, and vegetation height around the meteorological station (0.5m).

SEBAL has been used here to estimate ET_a on certain sample dates during the cropping season, giving a very good indication of its spatial distribution. However, it cannot be used directly in water balance studies because of its wide fluctuation from day to day, depending on meteorological conditions and availability of water. Therefore, in order to obtain an accurate estimation of seasonal ET_a, daily values had to be simulated. In this study, the method for temporal integration was a modification of the Λ method, as described in recent literature (Waters et al. 2002; Chemin et al. 2004). Daily ET_o (reference evapotranspiration) was calculated with the standardised Penman-Monteith method (Allen et al. 1998). The fraction $ETrF_j = ET_{aj}/ET_{oj}$, where j refers to the satellite image acquisition date, was considered constant for the time period between two consecutive satellite images. Previous work demonstrated that this assumption holds true for periods with similar rainfall and soil moisture conditions (Farah 2004; Singh et al. 2012). Nevertheless some systematic errors in ET_a estimation are cancelled out while computing seasonal ET_a (Bastiaanssen et al. 2002). The seasonal ET_a (ET_s hereafter) could be simulated with the following equation:

$$ET_s = \sum_j \left(ETrF_j * \sum_{i=t_j}^{t_{j+1}} ETo_j \right)$$

where t_j and t_{j+1} delimit each period.

The above mentioned equation combines the temporal component (expressed by daily ET_o) with the spatial component of ET_a calculation (expressed by ETrF for each satellite image acquisition) to better describe the daily fluctuation of ET_a. Thus, ET_s is accurately estimated as the spatial variation of water availability and is described by the satellite images, which were assumed to be representative for each period, and the temporal variation is described by the daily meteorological observations.

The spatial resolution of ET_s from AVHRR was originally 1.1 km, and was subsequently improved to 30 m, using a simple linear distribution model (Chemin and Alexandridis, 2004). This model re-distributed the original value of ET_s found in a pixel of 1.1x1.1 km to a higher spatial resolution, using the high spatial detail of the Landsat TM/ETM+ image as a guide. The advantage of the model was to keep the initial values of ET_s unchanged, which was an essential prerequisite for estimating water use volumes.

2.4 GIS analysis to estimate groundwater availability

Groundwater resources availability and management should always be considered at a basin scale (Freeze and Cherry 1979; Kallergis 1999; EC 2000). However, for practical reasons related to water logistics, an approach was adopted to estimate the available groundwater resources that could be allocated for use at the irrigation district level of the study area. For this purpose the concept of a water availability index was introduced. This index provides a measure of the availability or non-availability of groundwater in each particular irrigation district of the study area, in terms of volumes of water. In the compiled methodology, a GIS approach was adopted and a set of nine parameters (Table 1) that control groundwater resources evolution were considered. These parameters may be divided in two discrete groups. The first group consists of 5 parameters that describe the characteristics and the hydrodynamic evolution trend of the aquifer system. As such, these are either not time dependent, or an assumption is made that their values do not change dramatically in time. The second group consists of 4 parameters that are time dependent and control groundwater availability on an annual basis.

Each parameter was assigned a weighting factor on a scale of 1-10. Larger weighting factors were selected for the second group as the respective parameters were sensitive and changeable, subject to meteorological phenomena and applied water management practices, thus emphasising that they are critical to the annual cycle of the system (Table 1). For each one of the identified parameters a thematic map of the spatial distribution of values was compiled. The range of values for each parameter was then classified on a scale of 1 to 5. Weighting factors are assigned on the basis of expert opinion, and as such they are somewhat subjective. Classes are established on the basis of equally distributing the range of identified values for every parameter under consideration.

[Table 1 about here]

The Availability Index (AI) was then calculated with the following equation:

$$AI = \frac{\sum_{i=1}^{n}\left(WF_n \cdot CL_n\right)}{\sum_{i=1}^{n} WF_n}$$

Where: *AI* is the dimensionless groundwater availability index, *n* is the number of parameters, WF_n is the weighting factor of the n^{th} parameter and CL_n is the class number of the n^{th} parameter.

In practice, the solution to this algorithm was produced through GIS analysis of nine superimposed thematic layers that described each of the nine considered parameters. Fig. 2 illustrates the results of this analysis for the two considered reference years (1996 and 2002), in terms of weighted values of the water availability index per irrigation district.

[Fig. 2 about here – Colour on the web only]

The water availability index has integrated information regarding the structure, properties and evolution mechanisms that control the aquifer system. However, it does not include any information regarding the actual volume of groundwater available for use and its distribution (in accounting terms) on a fair basis among the irrigation districts, i.e. proportionally to the fraction of the aquifer system within the limits of each irrigation district, assuming uniform distribution of water demands in each one of them. To address this issue, a volumetric approach was followed. This approach was based on the bedrock relief map (Geophysique 1972; SAS 1974) and on April's piezometric map (statistically highest groundwater levels in the study area) from each of the two considered reference years. The total volume of the aquifer system within the study area was calculated using 3D GIS analysis i.e. calculating the volume between the bedrock relief and the piezometric surface for April of each considered year and multiplying the product by the effective porosity of the aquifer system; the latter assumed to be 10% according to previous studies (Panagopoulos 1995; Sogreah 1974). The corresponding volume of each irrigation district within the study basin was calculated on the basis of its spatial extent, and these volumes were expressed as percentages of the total volume of the aquifer system (Table 2). In performing these calculations, an assumption was made that at the regional scale, the effective porosity of the aquifer system is practically uniform, which was confirmed by the available borehole lithological sections. Therefore, the calculated volumetric percentages per irrigation district may also be regarded as actual water volume percentages.

[Table 2 about here]

The distribution of available groundwater amongst the irrigation districts is controlled and should therefore be calculated as a function of both the volumetric percentage and the water availability index of each irrigation district. The two parameters discussed are correlated in the following algorithm that yields the volumetric budget available per year and irrigation district:

$$V_i = \frac{\left(WF_v \cdot f_v\right)_i + \left(WF_{AI} \cdot f_{AI}\right)_i}{\sum \left(WF\right)_i} \cdot V_{tot},$$

where:
V_i : the volume of groundwater available at each identified irrigation district (*i*), in m^3/a,
WF: a weighting factor assigned to each of the two considered parameters: WF_V for volume of aquifer system *V* and WF_{AI} for water availability index *AI*,
f: the percentage of the parametric values (aquifer volume and availability index) at each irrigation district compared to the total value for the entire studied area, and

V_{tot}: the total volume of groundwater available, in m^3/a.

In this algorithm, the sum of the two weighting factors is 10 and the following values were accepted in a partially arbitrary manner: $WF_V=3$, $WF_{AI}=7$. The importance of each of the aforementioned parameters is subjective, however, the water availability index is considered of higher importance since it accounts for a number of well-weighted factors that control the hydrodynamic behaviour of the aquifer system, hence the actual availability of groundwater on an annual basis. This is especially so given the fact that the proposed methodology opts for the utilisation of groundwater that is annually replenished and not for the permanent reserves.

Available groundwater was deduced from the calculated recharge elements of the water budget at the scale of the study area (sub-basin). Inevitably, over dry hydrological years, the natural replenishment is limited and the water budget may be deficient. In such cases, as for example in the reference year 1996, the calculated water deficit is distributed to each irrigation district on the basis of their spatial extent percentage.

2.5 Water accounting indicators

A number of studies have proposed the use of indicators for the characterisation of the performance of irrigation systems, such as irrigation water productivity, adequacy, equity and reliability of water distribution (Bastiaanssen and Bos 1999; Molden and Sakthivadivel 1999; Santos et al. 2010). Performance can be evaluated for various reasons, such as to improve system operations, to assess the sustainability of a system, and to compare actual results to planned targets. In this work, the water accounting indicators used to quantify water use and characterize the operation of the irrigation systems were available water, depleted water, process depleted water, depleted fraction of available water, and process fraction of depleted water (Molden and Sakthivadivel 1999) (Table 3). The process depleted water is the water consumed for beneficial uses, in this case irrigation. The depleted fraction of available water (DF_{avail}) reveals how sustainable a system is and the scope for further use of water resources. The process fraction of depleted water (PF_{depl}) shows the beneficial utilisation of water and connects the amount of water used for all beneficial uses with the depleted water.

[Table 3 about here]

3. Results and discussion

Reports by the local water administrators were taken into account to select two irrigation seasons with extreme water availability conditions: 1996 which was a year of low water availability and 2002 which was a year of high water availability. Thus, the previously described methodology was applied during these two years. The results were reported per irrigation district. In order to facilitate comparison across years and irrigation districts, results were displayed as water height (mm), or dimensionless indicators.

3.1 Water supply and use

In general, process depleted water was slightly higher during the dry year (study area mean was 621 mm in 1996 and 600 mm in 2002), as factors that favour reference evapotranspiration had higher values than the wet year. However, Argiropouli district showed a slight increase of process depleted water (from 552 mm to 578 mm) which could be due to changes in cropping pattern (shift from trees to high consumption annual crops). The geographic distribution of process depleted water (Fig. 3) shows that values were higher at the eastern districts of the study area in both years (> 650 mm in East Ampelona and Pinios), indicating that higher water consuming crops dominated (cotton and maize).

Despite the very slight increase of process depleted water, depleted water (Fig. 4) was considerably higher during the dry year (1123 mm in 1996) than in 2002 (748 mm), due to excessive groundwater abstractions. Farmers responded to the increased crop water requirements with disproportionately high irrigation applications, which had no effect on crop development (based on crop statistics, not reported here). The highest levels of depleted water were noted at the south-eastern half of the study area (1012 mm in Pinios, 1025 mm in West Ampelona and 1293 mm in East Ampelona). The extreme value at East Ampelona was due to the high losses of the gravity irrigation system that was still operating in 1996, while the high values at the other two districts in 1996 were an indication of inefficient water management during a dry year. In the wet year, 2002, the Pinios and Argiropouli districts were the highest users of irrigation water, while the other four districts (which operated under a collective irrigation system) were on the lower side. This could be an indication that a collective irrigation system operates well under high water availability, while this occurs rarely under low water availability regimes, such as in the Tyrnavos district in 1996).

[Fig. 3 and 4 about here – Colour on the web only]

3.2 Water availability

Available water (Fig. 5) was higher in the wet year (study area mean was 1057 mm in 1996 and 1129 mm in 2002). However, the difference was lower than expected, probably due to the combined and cumulative effects of the dry years preceding 1996 and 2002 on the hydrogeological system (Panagopoulos et al. 2008). Across the study area, water availability was higher at the northwest reaches (> 2000 mm in Argiropouli) because of recharge from the karstic domain, as well as the eastern end because of recharge from the river Pinios (> 1500 mm in the Pinios district).

Compared with process depleted water, the available water was higher in both years (considerably higher in the wet year). This means that available water resources can meet the crop water requirements even during prolonged dry periods. However, compared with depletion, water availability was lower in the dry year. Taking into account the higher crop water requirements for this year, this is the effect of inefficient water management during a dry year (districts of Aghias Sofias, West and East Ampelona). To cover the excessive water depletion, withdrawals were made from resources committed to downstream users (eastern Thessaly basin in Fig. 1) or the permanent reserves of the aquifer system.

[Fig. 5 about here – Colour on the web only]

3.3 Water accounting indicators

PF_{depl} was considerably lower in the dry year (study area mean was 0.55 in 1996 and 0.8 in 2002), indicating that supplied water was not utilised by crops but lost due to low irrigation efficiency. The spatial distribution of PF_{depl} (Fig. 6) shows that most irrigation districts had constant values across the two years, except for East and West Ampelona that have higher values in the wet year (0.90 and 0.89, respectively) as compared to the dry year (0.37 and 0.63, respectively). In these two irrigation districts several improvement works had occurred, such as abandonment of the gravity canals and improvement of irrigation application methods, which were not observed in the other irrigation districts.

DF_{avail} was considerably higher in the dry year (study area mean was 1.06 in 1996 and 0.66 in 2002) indicating that most or all of the available water resources were diverted to agricultural use. Moreover, a value higher than 1.0 during the dry year implied that the study area was a closed basin, i.e. all available water was depleted. The additional depleted water was withdrawn from commitments to downstream users or the permanent reserve. During the wet year, DF_{avail} returned to low values, indicating that the system is sustainable and recharging the aquifer. The spatial distribution of DF_{avail} (Fig. 7) displayed that several districts with collective irrigation systems had values greater than 1.0 in 1996 (1.18 in Aghias Sofias, 1.52 in West Ampelona, and 1.60 in East Ampelona). These are unfavourable areas for groundwater recharge, and combined with low efficiency irrigation systems have lead to depletion of locally available water resources. Except for the privately operating irrigation districts (DF_{avail} ranged from 0.43 to 0.62 in Argiropouli and Pinios), Tyrnavos had persistently low DF_{avail} (0.59 in 1996 and 0.46 in 2002), indicating efficient water management.

The inverse trend of PF_{depl} and DF_{avail} between the two years confirms that in a dry year, although most of the available water was diverted to irrigation, this was not utilised beneficially by the crops (due to low irrigation system efficiency, or because the plants simply didn't need that amount).

[Fig. 6 and 7 about here – Colour on the web only]

3.4 Discussion and implications for irrigation management

Groundwater modeling is important in irrigation system characterisation, mainly in groundwater dependent systems. Remote sensing can only be used indirectly for groundwater monitoring (Awan et al. 2012; Castaño et al. 2010). This work presented an alternative groundwater modeling approach under limited data conditions, which was a GIS assisted calculation of basic water balance elements of the entire studied basin. In doing so, simple and easily measured and/or calculated parameters are only considered so that local stakeholders and decision makers be able to perform regardless of their scientific capacity and data collection infrastructure. Relevant combinations of hydrological models and GIS have been presented in various hydrological conditions, ranging from semi-arid Uzbekistan where recharge rates were estimated for a small irrigation district (Awan et al. 2012), to monsoon driven India where groundwater resources were assessed in large irrigation systems (Chowdary et al. 2003).

Spatial variability of water accounting indicators in the study area was dictated by topography and the hydrogeological setting of the basin, favouring certain areas (Argiropouli and Pinios districts) with high availability of water resources (karstic recharge, proximity to the river Pinios). Also, preference to highly productive annual crops in the central and eastern side of the study area (East Ampelona and Pinios districts) has resulted to extreme water depletion. Such large variability of neighbouring irrigation districts (e.g. Tyrnavou vs. West Ampelona) can lead to rapid deterioration of overall water resources, as all districts share in fact the same surface and groundwater water bodies. The differences noted between the wet and dry years were driven by hydrologic conditions (water availability) and the response of farmers and water managers to the long term water regime, who adapted to the declining water resources. Optimistically, there were cases of irrigation districts with improved water management (Tyrnavos district), bearing actions such as upgrading of irrigation application methods, organisational improvements and raising public awareness to reduce wasted water (Administration of Tyrnavos Irrigation District, personal communication, 2008).

Water management was proven inadequate during the dry year by displaying low irrigation efficiencies. Farmers responded in the dry year with excessive water applications and other practices that promoted high consumption, such as irrigating during the warm hours of the day, use of sprinklers, not conforming to the water distribution system, etc. However, it seems that districts with collective irrigation systems (Tyrnavos, Ampelona, and Aghias Sofias) operated well under high water availability, while during the dry year privately operating irrigation systems were more efficient (districts of Argiropouli and Pinios). Similar difficulty to manage efficiently the irrigated water was noted in Indus basin (Alexandridis et al. 1999), in Spain (Rocamora et al. 2012), South Africa (Hellegers et al. 2009) and Yellow river (Liu et al. 2008). Inversely to the previously reported high irrigation efficiencies during dry years, the high PF_{depl} noted during the wet year in the study area was probably influenced by the prolonged water shortage of the previous dry years, or due to improved distribution efficiency (better management by district administrations).

Although available water resources in the study area could meet irrigation demands, water abstractions were higher than the available water in the dry year, which is the outcome of inefficient water management during a difficult year. To meet increased abstractions, water was withdrawn from resources committed to downstream users or from the permanent reserve. This situation can lead to social instability (Kijne 2010), and when it appears in transboundary basins, political issues are raised (Gleditsch et al. 2006; Kliot et al. 2001). Long term overexploitation of water resources for irrigation has lead to deterioration of water quality (Karpouzas et al. 2006; Khalil and Hanna 1984; Nikolaidis et al. 2008), land degradation and desertification (Biswas 1987; Zalidis et al. 2002), and river basin closures (Falkenmark and Molden 2008; Molle et al. 2010).

Overall, the results indicate the need for improved irrigation management in various districts of the study area. The districts of Pinios, West and East Ampelona could decrease their depleted water by shifting to low water requirement crops (orchards and vines) and also shifting to higher efficiency irrigation methods (Panagopoulos 1995; Panagopoulos 1996). The irrigation network of Aghias Sofias could be renewed to improve irrigation efficiency (MinEnv 2012). Finally, artificial groundwater recharge in Aghias Sofias, West and East Ampelona irrigation districts, in the form of aquifer storage recovery wells utilising the winter time discharge of Mati karstic springs, could increase groundwater replenishment (Koukidou et al 2010; MinEnv 2012).

The intensive agricultural activity of the study area is a severe pressure on the water resources. During the dry year, water abstractions were excessive, predominantly in the East Ampelona district operated by gravity canals. Similar pressures on water resources have appeared worldwide, in places where the increasing population or economic development has demanded constant increases to the irrigated area, or higher agricultural intensity, or increased competition between water users (Rockström and Barron 2007; Seckler et al. 1999; Shiklomanov 2000). Moreover, the intensive irrigation and associated fertilisation in the study area have resulted in peaking nitrate concentrations in the remaining groundwater reserves, and several pending penalties from the EU court according to the Nitrates Directive (Karyotis et al. 2001; Karyotis et al. 2002). Also, as a result of the excessive abstractions in the study area and its vicinity, permanent damage to the south-eastern extension of the aquifer system have been reported due to aquifer compaction (Kaplanidis and Fountoulis 1997; Soulios 1997).

The study area may not reach the required status according to the European Water Framework Directive. Indeed, the wider study area has recently been characterized as a groundwater body in poor status due to its quantitative condition, although its chemical quality is at good status (MinEnv 2012). More specifically, a clear groundwater head decline at an average rate of 0.5 m/y has been documented since the mid 1980's as a result of the applied poor water resources management practices. The results of this work may contribute towards a reasonable water pricing policy which would provide incentives for water saving. The combined effect of additional groundwater resources protection and restoration measures such as sensitisation of farmers and managers, modernisation of the irrigation system, and groundwater artificial recharge, would result in mid-term visible recovery signs within the next 10-15 years (Koukidou et al 2010). However, even though within this time frame a reverse of the groundwater head decline trend could be achieved, full recovery of the system to its designated baseline would require more than 25 years.

The suggested methodology has several benefits for the local and regional water managers. First, it takes into consideration key hydrogeological aspects that relate directly to groundwater resources replenishment and availability, as well as the crops conditions and energy interactions as depicted in regularly acquired satellite images in multiple wavelengths. Second, it can be applied effectively in basins with limited availability of water volume measurements, using as main source of inputs the archived satellite images, routine groundwater measurements and standard meteorological data, without resorting to extravagant, high tech approaches that are data consuming and require non-existent infrastructure. Third, the costs associated with this work are low, as is often when remote sensing and GIS technology is given preference to ground data collection methods. Finally, the spatial location of identified problems may help to focus on site specific improvements in the operation of irrigation systems and higher possibilities for water savings.

Some weights of the hydrogeological model have been assumed in a somewhat arbitrary manner. A sensitivity analysis of the algorithm was performed revealing that the values assigned to the weighting factors of the two considered parameters were only important during hydrologically deficient years and especially in the irrigation districts of Aghias Sofias, West and East Ampelona that were distant from the main recharge zones and were characterised by high abstraction rates and relatively low values of aquifer hydraulic parameters (compared to the regional average). In such cases, selection of a high weighting factor for the water availability index, lead to more conservative (i.e. lower) estimates of water availability. Hence, accepting a reasonably high weighting factor value for the water availability index has lead to estimates that essentially safeguard rational water use, towards the direction of resource sustainability, and is in accordance with the European Water Framework Directive.

4. Conclusion

In this work, a combination of spatio-temporal energy balance fluxes and GIS analysis of multiple groundwater parameters were used to estimate irrigation water demand, supply, and water accounting indicators, in order to evaluate the differences in irrigation system characterisation between years of high and low water availability. The methodology provided the parameters needed for irrigation system characterisation, despite the limited availability of actual water measurements. Historical data were retrieved for past years to support comparative analyses.

The performance of the irrigation system varied across space and time due to differences of its characteristics and changes in its operation, driven by fluctuation of water availability and the response of stakeholders to water depletion. Examples of irrigation districts with efficient and others with unsustainable water management have been identified. The observed differences in system operation between the wet and dry years were attributed not only to the hydrological conditions of each year, but also to the changing behaviour of farmers and the actions of the water managers of Tyrnavos district. Practices leading to poor performance were easily depicted thus leaving space for suggestions towards improvements hence better and more efficient water management.

The presented methodology provided information that covers the temporal and spatial dimensions, thus enhancing the understanding of the irrigation system. This alternative approach to viewing patterns of water parameters could assist water managers to organise the system more efficiently and provide the means for raising awareness to increase stakeholders' participation. Finally, this quantitative information on the human pressures on water resources and their impact at the basin level can be further used in retrieving the cost of water services, thus satisfying the relevant articles of the European Water Framework Directive.

The advantages of the presented methodology include the consideration of key hydrogeological parameters, the use of frequently acquired satellite images to monitor the crop conditions and energy interactions, its applicability in basins with limited availability of water volume measurements, and its low cost as compared to ground data collection methods.

The in-depth analysis of the irrigation system’s effectiveness that was based on dynamic evolving parameters of the water providing (water bodies) and the water consuming system (irrigation patterns) is thought to be essential in developing an understanding of the water needs, the system's sustainability and its scope for further development. In turn, these elements are of paramount importance in building strong foundations in the direction of preparedness and capacity building in the context of the expected climate change, especially in the semi-arid regions of the planet.

Acknowledgements

Authors express their gratitude to the local irrigation organisations of Tyrnavos, Ampelona, and Aghias Sofias for providing data and expertise, and to the anonymous reviewers for their help to improve the manuscript. The work described has been funded by the Hellenic Ministry of Rural Development and Foods. Satellite images courtesy of U.S. Geological Survey.

References

Alexandridis T, Asif S, Ali S (1999) Water performance indicators using satellite imagery for the Fordwah Eastern Sadiqia (South) Irrigation and Drainage Project. International Water Management Institute - Pakistan Research Rep. R-87,

Alexandridis TK, Cherif I, Chemin Y, Silleos GN, Stavrinos E, Zalidis GC (2009) Integrated Methodology for Estimating Water Use in Mediterranean Agricultural Areas. Remote Sens 1 (3):445-465

Alexandridis TK, Zalidis GC, Silleos NG (2008) Mapping irrigated area in Mediterranean basins using low cost satellite Earth Observation. Computers and Electronics in Agriculture 64 (2):93-103

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper, vol 56. Food and Agriculture Organization of the United Nations, Rome.

Awan UK, Tischbein B, Martius C (2012) Combining hydrological modeling and GIS approaches to determine the spatial distribution of groundwater recharge in an arid irrigation scheme. Irrigation Science:(in press)

Basso B, Ritchie JT, Pierce FJ, Braga RP, Jones JW (2001) Spatial validation of crop models for precision agriculture. Agricultural Systems 68 (2):97-112

Bastiaanssen WGM, Ahmad MUD, Chemin Y (2002) Satellite surveillance of evaporative depletion across the Indus Basin. Water Resources Research 38 (12) 91-99.

Bastiaanssen WGM, Ali S (2003) A new crop yield forecasting model based on satellite measurements applied across the Indus Basin, Pakistan. Agriculture, Ecosystems and Environment 94 (3):321-340

Bastiaanssen WGM, Bos MG (1999) Irrigation performance indicators based on remotely sensed data: A review of literature. Irrigation and Drainage Systems 13 (4):291-311

Bastiaanssen WGM, Menenti M, Feddes RA, Holtslag AAM (1998) A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. J Hydrol 212-213 (1-4):198-212

Bastiaanssen WGM, Molden DJ, Makin IW (2000) Remote sensing for irrigated agriculture: Examples from research and possible applications. Agricultural Water Management 46 (2):137-155

Bastiaanssen WGM, Noordman EJM, Pelgrum H, Davids G, Thoreson BP, Allen RG (2005) SEBAL model with remotely sensed data to improve water-resources management under actual field conditions. Journal of Irrigation and Drainage Engineering 131 (1):85-93

Biggs TW, Thenkabail PS, Gumma MK, Scott CA, Parthasaradhi GR, Turral HN (2006) Irrigated area mapping in heterogeneous landscapes with MODIS time series, ground truth and census data, Krishna Basin, India. Int J Remote Sens 27 (19):4245-4266

Biswas AK (1987) Water development and management for desertification control. A review of the past decade. Land Use Policy 4 (4):401-411

Boskidis I, Pisinaras V, Petalas C, Tsihrintzis VA (2012) Monitoring and modeling of two alluvial aquifers in lower Nestos river basin, Northern Greece. Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering 47 (12):1849-1868

Castaño S, Sanz D, Gómez-Alday J (2010) Methodology for Quantifying Groundwater Abstractions for Agriculture via Remote Sensing and GIS. Water Resources Management 24 (4):795-814

Chemin Y, Alexandridis T (2006) Water productivity at different geographical scales in Zhanghe Irrigation District, China. International Journal of Geoinformatics 2 (2):9-19

Chemin Y, Platonov A, Ul-Hassan M, Abdullaev I (2004) Using remote sensing data for water depletion assessment at administrative and irrigation-system levels: case study of the Ferghana Province of Uzbekistan. Agricultural Water Management 64 (3):183-196

Chowdary VM, Rao NH, Sarma PBS (2003) GIS-based decision support system for groundwater assessment in large irrigation project areas. Agricultural Water Management 62 (3):229-252

Constandinidis D (1978) Hydrodynamique d' un système aquifère hétérogène. Hydrogeologie de la Thessalie orientale., Ph.D. diss. Université Scientifique et Médicale de Grenoble, Grenoble,

Dechmi F, Playan E, Faci JM, Tejero M (2003) Analysis of an irrigation district in northeastern Spain I. Characterisation and water use assessment. Agricultural Water Management 61 (2):75-92

Demitrack A (1986) The Late Quaternary geologic history of the Larissa plain, Thessaly, Greece: tectonic, climatic, and human impact on the landscape. Ph.D. thesis, Stanford University, 117 p. (unpublished),

Droogers P (2002) Global irrigated area mapping: Overview and recommendations, Working Paper 36. International Water Management Institute, Colombo, Sri Lanka

EC (1991) Council Directive 91/676/EEC of 12 December 1991 concerning the protection of water against pollution caused by nitrates from agricultural sources. Official Journal of the European Communities. L 375, 1-8.

EC (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Union, 1-73.

EC (2003) European Council Regulation 1782/03: Reform of the CAP, which introduces a single payment scheme, cross compliance and Farm Advisory System. Official Journal L 270, 21/10/03, p.1.

EC (2006) Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration. Official Journal of the European Union, L 372,19-31.

Falkenmark M, Molden D (2008) Wake up to realities of river basin closure. Int J Water Resour D 24 (2):201-215

Farah HO, Bastiaanssen WGM, Feddes RA (2004) Evaluation of the temporal variability of the evaporative fraction in a tropical watershed. International Journal of Applied Earth Observation and Geoinformation (5) 129-140.

Freeze RA, Cherry JA (1979) Groundwater. Prentice-Hall, Englewood Cliffs, N.J

Geophysique CGd (1972) Reconnaissance par prospection electrique dans la plaine de Thessalie (Grece), France.

Gleditsch NP, Furlong K, Hegre H, Lacina B, Owen T (2006) Conflicts over shared rivers: Resource scarcity or fuzzy boundaries? Political Geography 25 (4):361-382

Gogu RC, Carabin G, Hallet V, Peters V, Dassargues A (2001) GIS-based hydrogeological databases and groundwater modelling. Hydrogeology Journal 9 (6):555-569

Hamdy A, Ragab R, Scarascia-Mugnozza E (2003) Coping with water scarcity: Water saving and increasing water productivity. Irrigation and Drainage 52 (1):3-20

Hellegers PJGJ, Soppe R, Perry CJ, Bastiaanssen WGM (2009) Combining remote sensing and economic analysis to support decisions that affect water productivity. Irrigation Science 27 (3):243-251

Herbke N, Dworak T, Karaczun Z (2006) WFD and Agriculture - Linkages at the EU Level, Analysis of the policy and legal linkages between CAP and WFD. Ecologic – Institute for International and European Environmental Policy, Berlin, Germany

Irmak A, Kamble B (2009) Evapotranspiration data assimilation with genetic algorithms and SWAP model for on-demand Irrigation. Irrigation Science 28 (1):101-112

Javan M, Sanaee-Jahromi S, Fiuzat AA (2002) Quantifying management of irrigation and drainage systems. Journal of Irrigation and Drainage Engineering 128 (1):19-25

Jensen ME (2007) Beyond irrigation efficiency. Irrigation Science 25 (3):233-245

Kallergis G (1999) Applied-Environmental Hydrogeology. Technical Chamber of Greece Publications., Athens, Greece (in Greek)

Kaplanidis A, Fountoulis D (1997) Subsidence phenomena and ground fissures in Larissa, Karla basin, Greece: Their results in urban and rural environment. In: Marinos, P.G., Koukis, G.C., Tsiambaos, G.C., Stournaras, G.C. (Eds.), Proceedings of International Symposium on Engineering Geology and the Environment, 23-27 June 1997, Athens, Greece, 1, 729-735.

Karpouzas DG, Capri E, Papadopoulou-Mourkidou E (2006) Basin-scale risk assessment in rice paddies: An example based on the Axios river basin in Greece. Vadose Zone Journal 5 (1):273-282

Karyotis T, Panagopoulos A, Kosmas C, Pateras D, Panoras A, Danalatos N, Yassoglou N (2001) Guidelines for establishing a code for good agricultural practice in the river Pinios sedimentary basin, southern Greece. In Proceedings of 12th World Fertilizer Congress, 3-9 August 2001, Beijing, v.III, 1594-1601.

Karyotis T, Panagopoulos A, Pateras D, Panoras A, Danalatos N, Angelakis C, Kosmas C (2002) The Greek Action Plan for the mitigation of nitrates in water resources of the vulnerable district of Thessaly. J Mediterr Ecol 3 (2-3):77-83

Kassam AH, Molden D, Fereres E, Doorenbos J (2007) Water productivity: Science and practice - Introduction. Irrigation Science 25 (3):185-188

Katsilouli I, Karyotis T, Georgiou T, Mitsimponas T, Panagopoulos A, Panoras A, Pateras D, Haroulis G, Argyropoulos G, Toulios M (2004) Nitrates in soils and water originated from agricultural sources: a case study in Thessaly, central Greece. In: Hatch D., Chadwick D., Jarvis S., Roker J. (Eds), Proc. 12th Nitrogen Workshop "Controlling nitrogen flows and losses", Wageningen Academic Publishers, 447-448.

Khalil JB, Hanna FS (1984) Changes in the quality of Nile water in Egypt during the twenty-five years, 1954-1979. Irrigation Science 5 (1):1-13

Kijne JW (2010) Tushaar Shah: Taming the anarchy: groundwater governance in South Asia. Irrigation Science 28 (3):281-284

Kite GW, Droogers P (2000) Comparing evapotranspiration estimates from satellites, hydrological models and field data. J Hydrol 229 (1-2):3-18

Kliot N, Shmueli D, Shamir U (2001) Institutions for management of transboundary water resources: their nature, characteristics and shortcomings. Water Policy 3 (3):229-255

Koukidou E, Panagopoulos A, Arampatzis G, Hatzigiannakis E (2010) Groundwater flow modelling as a tool for assesing aquifer restoration using artificial recharge. The case of Tirnavos alluvial basin, central Greece. Paper presented at the 10th International Conference of Protection and Restoration of the Environment, Corfu, Greece,

Kundzewicz ZW, Mata LJ, Arnell NW, Doll P, Jimenez B, Miller K, Oki T, Sen Z, Shiklomanov I (2008) The implications of projected climate change for freshwater resources and their management. Hydrological Sciences Journal 53 (1):3-10

Lambrakis N, Kallergis G (2001) Reaction of subsurface coastal aquifers to climate and land use changes in Greece: Modelling of groundwater refreshening patterns under natural recharge conditions. J Hydrol 245 (1-4):19-31

Liu C, Golding D, Gong G (2008) Farmers' coping response to the low flows in the lower Yellow River: A case study of temporal dimensions of vulnerability. Global Environmental Change 18 (4):543-553

Lubczynski MW, Gurwin J (2005) Integration of various data sources for transient groundwater modeling with spatio-temporally variable fluxes - Sardon study case, Spain. J Hydrol 306 (1-4):71-96

Marinos P, Kavvadas M, Perleros V (1997) Investigation of the over-exploitation of a major alluvial aquifer in Thessaly, Greece. Proceedings of 3rd USA/CIS Joint Conference on Environmental Hydrology and Hydrogeology: Water sustaining a critical resource: a selection of papers presented by hydrologists, Tashkent, Uzbekistan, September 22-27, 1996, 29-38.

McKinney DC, Cai X (2002) Linking GIS and water resources management models: An object-oriented method. Environmental Modelling and Software 17 (5):413-425

MinEnv (2012) Compilation of management plans for the river basins of the water districts of Thessaly, Epirus and western Sterea Hellas in accordance to Directive 2000/60/EC and in implementation of A. 3199/2003 and PD 51/2007: Water Management Plan-Water District of Thessaly. Official report. Ministry of Environment, Energy and Climate Change, Special Secretariat for Water, Athens

Molden D, Sakthivadivel R (1999) Water accounting to assess use and productivity of water. Int J Water Resour D 15 (1-2):55-71

Molle F, Wester P, Hirsch P (2010) River basin closure: Processes, implications and responses. Agricultural Water Management 97 (4):569-577

Nikolaidis C, Mandalos P, Vantarakis A (2008) Impact of intensive agricultural practices on drinking water quality in the EVROS Region (NE GREECE) by GIS analysis. Environmental Monitoring and Assessment 143 (1-3):43-50

Panagopoulos A (1995) A methodology for groundwater resources management of a typical alluvial aquifer system in Greece. Ph.D. thesis, The university of Birmingham, U.K.,

Panagopoulos A (1996) Groundwater resources management study of the Tyrnavos alluvial basin using mathematical models. Proceedings of the 2nd panhellenic Conference on land reclamation works and water resources management. Larissa, 393-404 (in Greek)

Panagopoulos A, Vrouhakis Y, Pechlivanidou S, Stathaki S, Alexandridis TK, Karyoti K (2008) Evaluation of two alternative methods for the calculation of groundwater balance at basin scale. In: Proceedings of 8th International Hydrogeological Congress of Greece, 8-10 October 2008, Athens, Greece, 683-692.

Paydar Z, Gaydon D, Chen Y (2009) A methodology for up-scaling irrigation losses. Irrigation Science 27 (5):347-356

Penman HL (1950) The water balance of the Stour catchment area. Journal of the Institution of Water Engineers and Scientists 4:457-469.

Refsgaard JC, Thorsen M, Jensen JB, Kleeschulte S, Hansen S (1999) Large scale modelling of groundwater contamination from nitrate leaching. J Hydrol 221 (3-4):117-140

Rocamora C, Vera J, Abadía R (2012) Strategy for Efficient Energy Management to solve energy problems in modernized irrigation: analysis of the Spanish case. Irrigation Science:1-20

Rockström J, Barron J (2007) Water productivity in rainfed systems: overview of challenges and analysis of opportunities in water scarcity prone savannahs. Irrigation Science 25 (3):299-311

Santos C, Lorite IJ, Tasumi M, Allen RG, Fereres E (2008) Integrating satellite-based evapotranspiration with simulation models for irrigation management at the scheme level. Irrigation Science 26 (3):277-288

Santos C, Lorite IJ, Tasumi M, Allen RG, Fereres E (2010) Performance assessment of an irrigation scheme using indicators determined with remote sensing techniques. Irrigation Science 28 (6):461-477

SAS SC (1974) Groundwater development project of the plain of Thessaly: Final Report. Grenoble, France. (in Greek).

Seckler D, Barker R, Amarasinghe U (1999) Water scarcity in the twenty-first century. Int J Water Resour D 15 (1-2):29-42

Shiklomanov IA (2000) Appraisal and assessment of world water resources. Water Int 25 (1):11-32

Singh R, Liu S, Tieszen L, Suyker A, Verma S (2012) Estimating seasonal evapotranspiration from temporal satellite images. Irrigation Science 30 (4):303-313

Soulios G (1997) Subsidence de terrains alluviaux dans le sud-est de la plaine de Thessalie. In proceedings of a symposium on International Engineering Geology and the Environment, 1067-1072.

Sui DZ, Maggio RC (1999) Integrating GIS with hydrological modeling: Practices, problems, and prospects. Computers, Environment and Urban Systems 23 (1):33-51

Tsihrintzis VA, Hamid R, Fuentes HR (1996) Use of Geographic Information Systems (GIS) in water resources: A review. Water Resources Management 10 (4):251-277

Waters R, Allen R, Tasumi M, Trezza R, Bastiaanssen WGM (2002) SEBAL (Surface Energy Balance Algorithms for Land): Advanced Training and Users Manual. Idaho Department of Water Resources,

Xu ZX, Ito K, Schultz GA, Li JY (2001) Integrated hydrologic modeling and GIS in water resources management. Journal of Computing in Civil Engineering 15 (3):217-223

Zaccaria D, Oueslati I, Neale CMU, Lamaddalena N, Vurro M, Pereira LS (2010) Flexible delivery schedules to improve farm irrigation and reduce pressure on groundwater: A case study in southern Italy. Irrigation Science 28 (3):257-270

Zalidis G, Stamatiadis S, Takavakoglou V, Eskridge K, Misopolinos N (2002) Impacts of agricultural practices on soil and water quality in the Mediterranean region and proposed assessment methodology. Agriculture, Ecosystems and Environment 88 (2):137-146

Zwart SJ, Leclert LMC (2010) A remote sensing-based irrigation performance assessment: A case study of the Office du Niger in Mali. Irrigation Science 28 (5):371-385

Tables

Table 1 Considered parameters for the calculation of water availability index

	Description of parameter	Assigned weighting factor
Characteristics-particularities of system and hydrodynamic trends		
1	Transmisivity (m^2/d)	3.5
2	Specific drawdown ($m/m^3/d$)	3.5
3	Average rate of groundwater level variation (20 years) (cm/a)	4.5
4	Direct infiltration from precipitation (%)	1
5	Aquifer recharge zones (origin and importance)	5
Temporal variation of groundwater availability		
6	Domestic water abstractions per unit area ($m^3/d/km^2$)	6
7	Agricultural water abstractions per unit area ($m^3/d/km^2$)	8
8	Deviation of annual from mean-annual (20 years) precipitation (%)	9
9	Deviation of maximum annual depth to groundwater (April) from mean (20 years) maximum depth to groundwater (%)	10

Table 2 Volumetric percentage of each identified irrigation district within the study basin

Irrigation district	Volumetric percentage
East Ambelona	26.23
West Ambelona	29.89
Aghias Sofias	15.06
Tyrnavos	15.54
Pinios	4.91
Argiropouli	8.38
Total	100.00

Table 3 Definition of the water accounting parameters and indicators

Water accounting parameter or indicator (units)	Equation used
Available water (mm)	$Available = GW_{res} + R'$
Depleted water (mm)	$Depleted = Qirr + R'$
Process depleted water (mm)	$Process\ depleted = ET_s$
Depleted fraction of available water (-)	$DF_{avail} = Depleted/Available$
Process fraction of depleted water (-)	$PF_{depl} = Process\ depleted / Depleted$

Where
GW_{res}: groundwater resources,
Q_{irr}: irrigation water,
R': effective rainfall,
ET_s: seasonal evapotranspiration

Figure legends

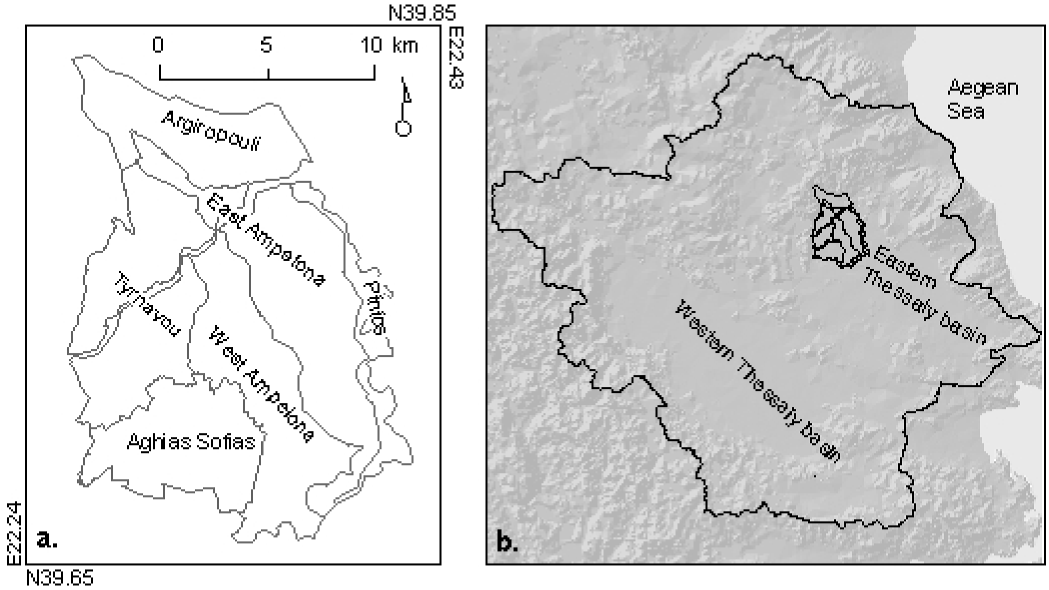

Fig. 1 Irrigation districts of the study area (a), and its location in the Pinios river basin (b)

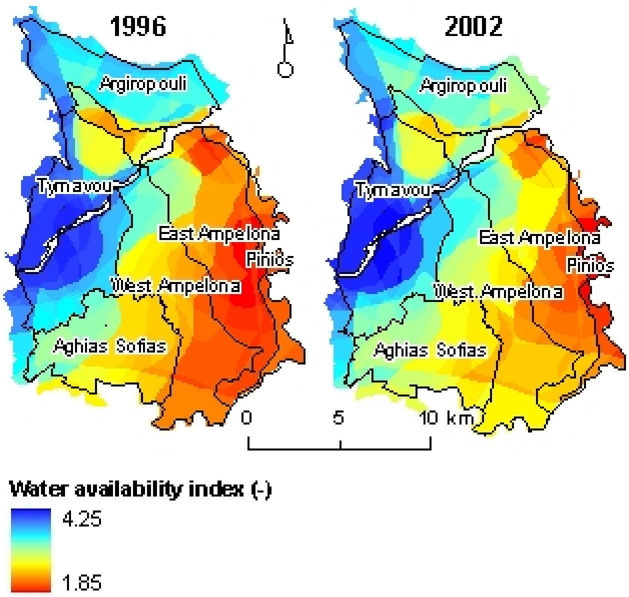

Fig. 2 Weighted values of calculated water availability index

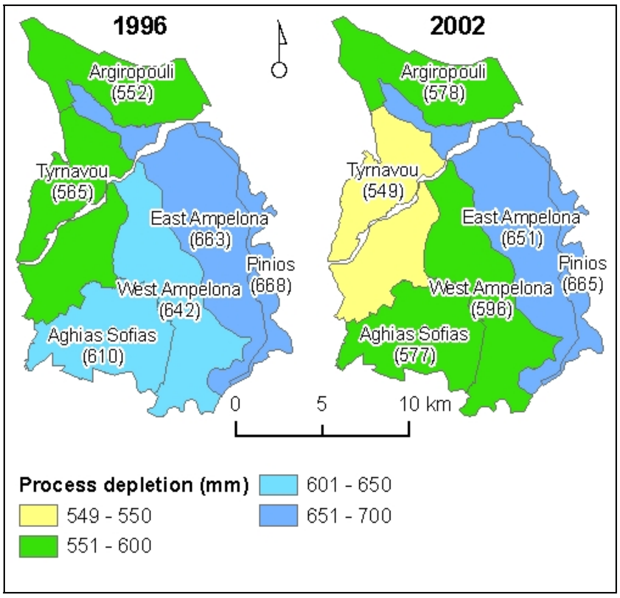

Fig. 3 Process depletion per irrigation district and year

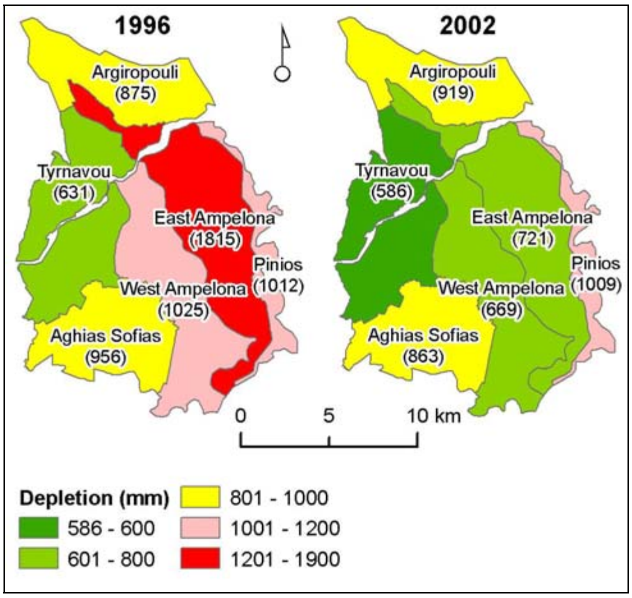

Fig. 4 Depletion per irrigation district and year

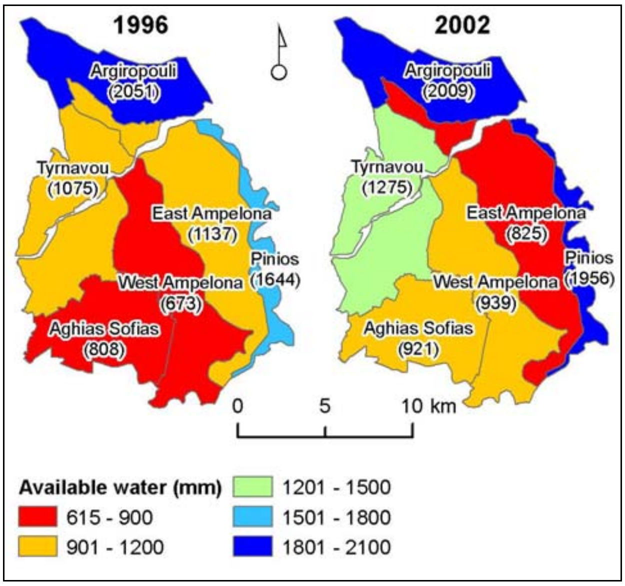

Fig. 5 Available water per irrigation district and year

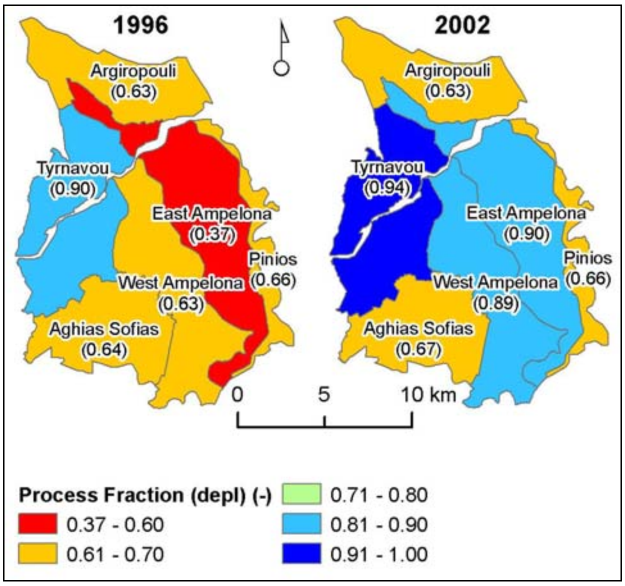

Fig. 6 Process fraction of depleted water per irrigation district and year

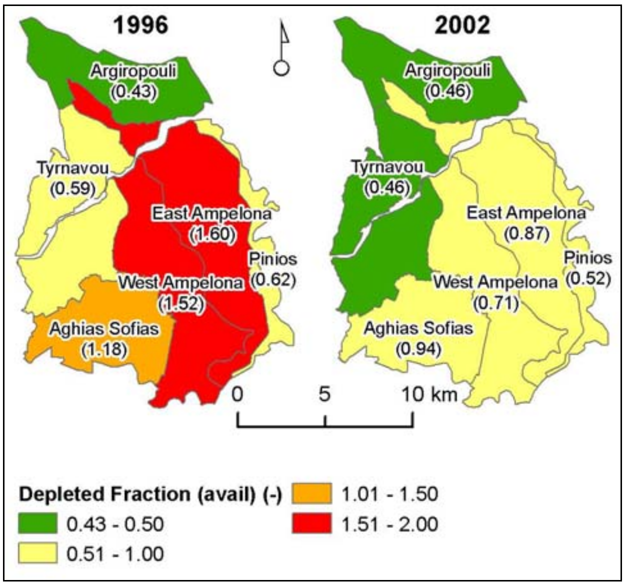

Fig. 7 Depleted fraction of available water per irrigation district and year