Water Resour Manage (2007) 21:1673–1702
DOI 10.1007/s11269-006-9120-5

A Modeling System for the Evaluation of Water Resources Management Strategies in Thessaly, Greece

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Received: 12 October 2005 / Accepted: 30 October 2006 / Published online: 8 December 2006

Abstract A modeling system was developed to evaluate the sustainability of water resources management strategies in the two major basins of Thessaly Region in Greece, namely the Pinios River and the Lake Karla basins. The intense and extensive agriculture of water demanding crops, such as cotton, and the absence of reasonable water resources management have lead to a remarkable water demand increase, which is usually fulfilled by the over-exploitation of groundwater resources. This unsustainable practice has deteriorated the already disturbed water balance and accelerated water resources degradation. The modeling system consists of a hydrological model, a reservoir operation model and methods for the estimation of water demands. The study area was sub-divided into sub-basins and water balance analyses were performed for each sub-basin and each control node of the system for a number of water resources management strategies. Four strategies of hydro-technical project development were coupled with two strategies of groundwater withdrawal and three water demand strategies. In total, more than 24 water management strategies were evaluated. The results showed that, under the existing water resources management, the water deficit of the Pinios River and Lake Karla basins is very large. However, the development of proposed hydro-technical projects in the Pinios River basin coupled with water demand management measures, like improvement of existing water distribution systems, change of irrigation methods, and changes of crop cultivation could alleviate the problem and lead to sustainable and ecological use of water resources in the study area.

Key words water resources · management · strategies · sustainability · hydrological modeling · reservoir operation modeling · Thessaly

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1 Introduction

In recent years, water resources management has become a major issue due to pressure imposed to the natural system by the increasing needs for more and better quality water. It has also become more complicated because of the more sophisticated way the water is used, the antagonistic water uses, and the concept of sustainability. In the past, water was regarded as a natural resource used to satisfy the water needs and it did not need protection. After the definition of the pioneering concept of sustainability by the World Commission on Environment and Development (1987), water has been recognised as an essential component of the living world providing the present and future means of development of not only humans but also all other living organisms.

Water resources management is today regarded as an integrated procedure which "... promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" according to the Global Water Partnership (2000). In this context, water resources management incorporates technical, political, legislative, and organisational components within a river basin, which represents the natural entity of water resources management (Biswas 2004). The technical part of water resources management includes water availability and water supply management, water demand management, water allocation (Karamouz et al. 2004) and decision support (Pallotino et al. 2005). The water availability is assessed for contemporary and future hydrological conditions and water resources development. The water demands are assessed for the contemporary state of water use of the various sectors and stakeholders including the water needs for the sustainability of fauna and flora habitats (Doll and Hauschild 2002) and for future conditions. The future state of water supply and water demands are assessed through the development of scenarios and strategies which can address a broad range of "what if" questions such as questions for: the climatic and hydrological conditions (Varis et al. 2004; Jeong et al. 2005), water resources development (Koch et al. 2005), activities to reduce water demand and improve water use efficiency (Levite et al. 2003; Chen et al. 2005) and others. These scenarios and strategies are developed considering socioeconomic and regional development (Lanini et al. 2004; Mylopoulos et al. 2004; Araujo de et al. 2004) and economic evaluation (Yurdusev and O'Connell 2005).

Examples of most of the world's water resources problems can be found around the Mediterranean basin. Agriculture is still by far the greatest consumer of water in the region, and is well above the world average. More than 80% of water resources are allocated to irrigation, with relatively high losses that exceed 50% (Araus 2004). Furthermore, irrigated agriculture has adverse environmental implications such as soil degradation, salinisation, and water quality. Therefore the application of suitable water resources management strategies and policies is a key priority. These strategies include prediction of demographic and environmental change, increasing freshwater supply, water saving and reducing water losses, reducing water consumption, reducing pollution (Araus 2004), and use of marginal water resources, water reuse and water recycling (Hamoda 2004; Tsagarakis et al. 2004). Water transfer from neighbouring hydrological basins although increases significantly in problematic areas have been severely criticized (Embid 2003). Water management models and decision support systems can play a crucial role in simulation, analysis and adaptation of water management strategies. Such models range from simple models that use a point system, categorization and ranking to evaluate the scores of the various components and strategies of the water resources management (Manios and Tsanis 2006) to more sophisticated decision support systems (Kazeli et al. 2003). However, in any case adequate and high quality hydrological and water resources data as well as estimations on the water availability and water use should be available before the application of these models. These estimates could be available through a physical modelling system of the water resources problem.

The aim of this study is to develop a modeling system for the estimation of water potential of surface water and groundwater resources of the main sub-basins of Thessaly through hydrological modeling, the estimation of the water demands of the sub-basins and water sectors, the evaluation of the water balance of the study area in a sub-basin basis and in significant control nodes for the existing water management condition and for strategies dealing with the development and operation of proposed hydro-technical projects and various water demand management measures. This procedure could reveal the effect of the various water resources management strategies on the water balance of the study area and may lead to sustainable water resources management policies.

Thessaly is a region in central Greece facing the most prominent example of today's water resources problem. Thessaly plain is an intensely cultivated region, the second largest plain of Greece after the Macedonian plain and is traversed by Pinios River (Figure 1). The intense and extensive agriculture of water demanding crops, such as cotton and maize, has lead to a remarkable water demand increase, which is usually fulfilled by the over-exploitation of groundwater. The over-exploitation of groundwater, especially during extended drought periods resulted in deterioration of the already disturbed water balance and acceleration of water resources degradation.

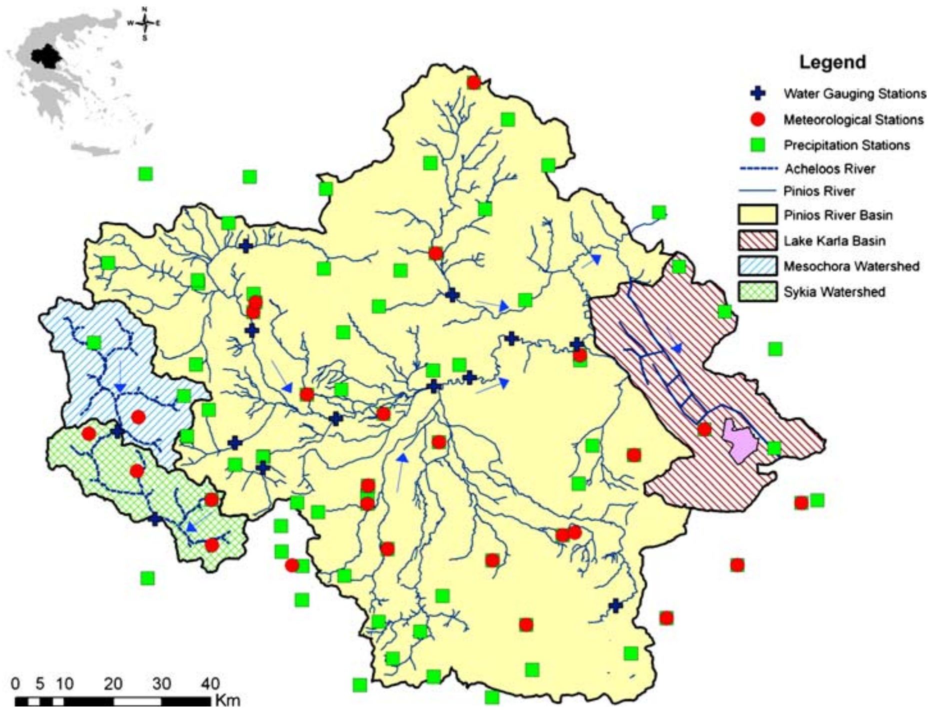

Figure 1 Study basins and locations of meteorological and hydrometric stations.

The above-mentioned problem became more evident during the last two decades. Various water resources management measures have been proposed to deal with the water deficit of Thessaly plain. These measures can be categorized into water demand management measures and water supply management measures (EYDE and ENVECO 1995). The water demand management measures proposed are: (a) drastic reduction of the poorly irrigated areas, where the available water resources do not fully cover the irrigation demand, (b) reduction of the total irrigated area of the region, (c) change and the improvement of irrigated systems to minimize water losses, and (d) change of cultivation species to less water demanding crops (for example from cotton to wheat). The water supply management measures target to increase the availability of surface water in Thessaly by: (a) managing the surface water resources of the region through the development of dams and reservoirs, and (b) diverting water from the nearby Acheloos River basin to Thessaly through a series of dams and reservoirs. Over the years, various locations within Pinios River basin have been proposed for the development of reservoirs, but only the dam of Smokovo has been recently constructed. The only other surface water developments in the region are a few small reservoirs and lagoons on or adjacent to Pinios River system and the diversion of water from the N. Plastiras reservoir (Figure 1). On the other hand, the proposal for the diversion of water from Acheloos River to Thessaly has been criticized for environmental and political reasons.

2 Study Area

Thessaly is located in central Greece and is a plain region surrounded by Mount Kisavos and Mount Pelion in the east, along the coast of the Aegean Sea, Mount Olympus in the north, the Pindus Mountain Range in the west, and the Othrys Mountain Range in the south. Thessaly's total area is about 13,700 km^2. The elevation ranges from sea level at the eastern coastal area to more than 2,800 m at the eastern and western mountain areas, and the mean elevation of the region is nearly 500 m. The two larger basins of region are the Pinios River and the Lake Karla basins.

The climate is continental at the western and central side of Thessaly; the winters are cold, summers are hot and the temperature difference between the two seasons is large. Climate is typical Mediterranean climate at the eastern side of Thessaly. Summers in Thessaly are usually very hot and dry, and in July and August temperatures can reach 40°C. Mean annual precipitation over the whole Thessaly region is about 700 mm and it is distributed unevenly in space and time. Mean annual precipitation varies from about 400 mm at the central plain area to more than 1,850 mm at the western mountain peaks. Generally, rainfall is rare from June to August. Mountain areas receive significant amounts of snow during winter months and transient snowpacks develop.

Thessaly plain is the most productive agricultural region of Greece with an area of about 4,000 km^2. The main crops cultivated in the plain area are cotton, wheat and maize whereas apple, apricot, cherry, olive trees and grapes are cultivated at the foothills of the eastern mountains. Pinios river and its tributaries traverse the plain area, and the basin total drainage area is about 9,500 km^2 (Figure 2). The waters of Pinios River are used primarily for irrigation. The intense and extensive cultivation of water demanding crops has lead to a remarkable water demand increase, which is usually fulfilled by the over-exploitation of groundwater resources. The over-exploitation of the groundwater, especially during extended dry periods, has lead to the deterioration of the already disturbed water balance and the degradation of water resources. Over the years, various locations within the Pinios

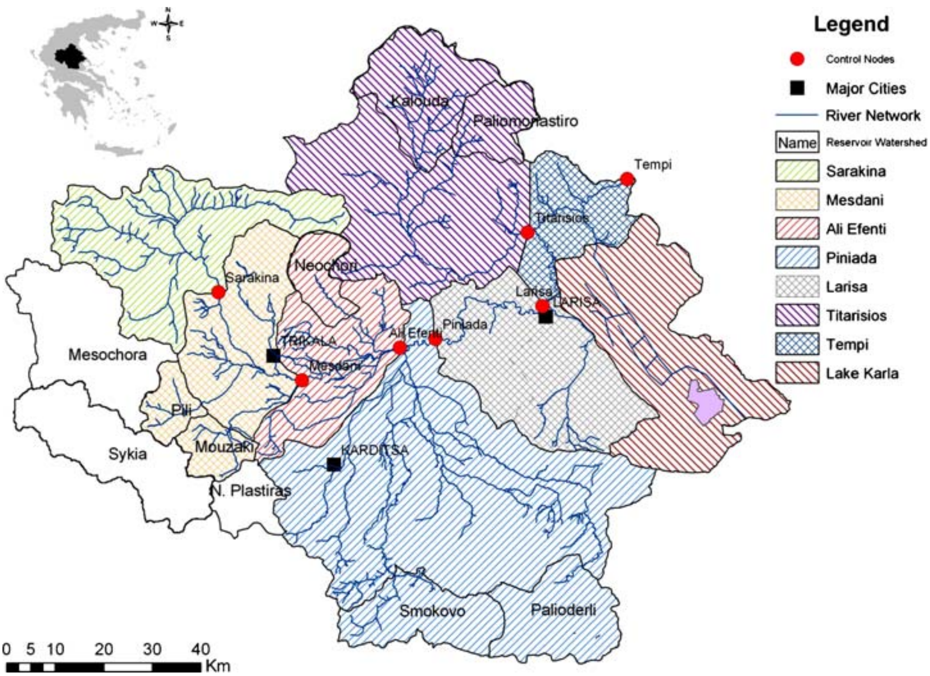

Figure 2 Sub-basins of the study area and watersheds with existing and proposed reservoirs.

River basin have been proposed for the development of reservoirs, but only the dam of Smokovo has been recently constructed. The only other major surface water storage projects in Thessaly region are a few small reservoirs and lagoons on or adjacent to Pinios River system and the diversion of water from the N. Plastiras reservoir, which is located outside of the Pinios River basin. Over the years, the development of reservoirs within the area of Pinios River basin, the partial diversion of Acheloos River through a series of four reservoirs, and water demand management measures have been proposed to alleviate the water problem of Thessaly (Loukas and Mylopoulos 2004).

Lake Karla occupied, until 1962, most of the eastern part of Thessaly plain in central Greece. It was one of the most important wetlands in Greece and a natural reservoir, which provided significant water storage and recharge to groundwater. The basin surface runoff and the overflowing floodwaters of the Pinios River sustained Lake Karla. The lake area fluctuated from 40 to 180 km^2 due to the very gentle land slope and the inflow–outflow balance. For this reason, significant area of the surrounding farmland was often inundated facing soil salinity problems.

Various technical studies proposed measures for flood protection and the revelation of agricultural fields. These studies recommended to build flood control dykes on Pinios River, constructed a drainage network, which would have drained the lake overflows through a tunnel into the sea, and develop a reservoir in the location of the natural lake. This reservoir would have been used to store the winter surplus surface runoff and the diverted floodwater of the Pinios River for irrigation during spring and summer. However, only the mountain collector ditches, the draining tunnel, and the Pinios River embankments, which cut off the river floodwater inflows to the lake, were constructed. The reservoir and its associated works were never built creating a series of environmental problems: (1) the lake area diminished and the natural wetland deteriorated, (2) the limited natural recharge of the aquifer and the uncontrolled pumping of the groundwater has caused a dramatic drawdown of the water table, which, today, is more than 200 m below the land surface at the southern area of the basin, (3) areas with small land slope were often flooded, (4) large areas remained uncultivated due to salt concentration and soil degradation, (5) the large loads of agrochemicals washed of the fields polluted the Pagasitikos Gulf (Greek Ministry of Environment, Regional Planning and Public Works 1999).

The decision to restore part of the former lake has been taken in the early 1980s by the Greek government but the construction works started few years ago. The project, today, is near completion. The suggested plan for the restoration of Lake Karla proposes the creation of a reservoir in the lowest depression plain of the former lake Karla that will occupy a maximum area of about 38 km^2, through the construction of two embankments, one in the eastern part and one in western part of the lake (Figure 1). Four collector channels will concentrate the surface runoff from the higher elevation zones of the watershed and directly divert it into the reservoir. The surface runoff of the lower elevation areas will be pumped into the reservoir. After the construction of these works, the drainage area of the restored Lake Karla will be 1,171 km^2 (Figure 1). The partial restoration of the former Lake Karla is one of the most important environmental projects in the region, possibly in the whole country, that has been planned to reverse the adverse environmental conditions, caused by the lake drainage.

3 Database

3.1 Geographical Data

A GIS database, with all the available spatial and attribute information of the study area was developed. The available data were digitized elevation contours with a contour interval of 100 m, topographical maps of 1:50,000 and 1:250,000 scales acquired from Greek Army Geographical Service, co-ordinates and elevations of meteorological and water-gauging stations, co-ordinates of the locations of reservoirs and digitized boundaries of municipalities. These geographical data were used for the development of the digital elevation models (DEMs) of the total study area and the sub-basins, the delineation of the sub-basins, the digitization of Pinios River system, the estimation of sub-basins characteristics (e.g. area, mean elevation, elevation range, mean land slope, etc.), and the identification of the municipalities laying within the sub-basins. Geological maps of 1:50,000 scales were used for the digitisation of the major geological formations in the study area. Data from the CORINE database were also used for the evaluation of land cover-land use of the study basins.

3.2 Meteorological and Hydrological Data

The available data for the estimation of the water resources were precipitation data, temperature data, and discharge data. The original meteorological and discharge measurements were collected by regional and prefecture water resources agencies and the Greek Power Authority. These measurements have been checked for errors, homogenized and processed according to the World Meteorological techniques and standards (Sevruk 1982;

World Meteorological Organization (WMO) 1994). Processed monthly precipitation data from 69 stations (Figure 1) for the period October 1960 to September 2002 were available. The mean areal precipitation of the sub-basins was estimated by the Thiessen polygon method modified by the precipitation gradient using the stations, which are within and in the vicinity of each sub-basin. According to this method, the mean annual precipitation estimated by the Thiessen polygons is adjusted by using the precipitation gradient calculated by the stations located within or in the vicinity of the watershed.

The mean monthly temperature of each sub-basin was estimated using the mean monthly temperature data from 26 meteorological stations (Figure 1) for the period October 1960 to September 2002 and the method of temperature gradient. One temperature gradient was used for all study area. Mean areal potential evapotranspiration has been calculated using the well-known Thornthwaite method (Thornthwaite 1948).

Finally, monthly discharge data from 13 water-gauging stations (Figure 1) were used for the calibration of the hydrological model. The records of the water gauging stations were discontinuous with large gaps.

4 Modeling System – Methodology

This study aimed to evaluate the surface water and the groundwater resources potential and the water demand of the study area in a sub-basin basis. A modeling system has been developed consisting of a hydrological model, a reservoir operation model and methods for the estimation of water demands for each water use sector. The components of this system are presented in the next paragraphs.

4.1 Hydrological Model

A monthly conceptual hydrological model (UTHBAL) for the calculation of surface runoff and groundwater recharge has been used. The model has been proposed by Loukas and his associates (Loukas et al. 2003b). The UTHBAL model has been successfully applied to watersheds in Cyprus (Loukas et al. 2003b), Crete (Christodoulaki et al. 2003; Christodoulaki et al. 2004), Thessaly (Loukas et al. 2005a; Loukas et al. 2006), and the transboundary Nestos/Mesta River basin (Kampragou 2006). The description of the hydrological model is presented in Appendix.

Originally, the Pinios river basin was separated into 11 sub-basins according to the available water gauging stations, namely, Gabros, Sarakina, Pili, Mouzaki, Mesdani, Ali Efenti, Skopia, Piniada, Amigdalea, Larisa, and Mesochori (Figure 1). The runoff of the two Acheloos river sub-basins, namely, Mesochora and Sykia, was also simulated, because they are part of the Acheloos River partial diversion project. The above Pinios River and Acheloos River sub-basins were used for the calibration of the UTHBAL model using the available runoff data. Table I presents the runoff calibration statistics for the 13 sub-basins.

After the calibration, the UTHBAL model was used to produce the synthetic monthly runoff for the period October 1960 to September 2002 at the 13 sub-basins of Pinios River and Acheloos River basins. The Pinios River sub-basins, then, were aggregated into seven sub-basins, namely, Sarakina, Mesdani, Ali Efenti, Piniada, Larisa, Titarisios and Tempi (Figure 2), forming the seven major control nodes of the river system where the upstream water potential and demands were considered. These nodes were selected in such

Table I Calibration statistics of UTHBAL model

Sub-basin	Eff	DV%	R^2
Gabros	0.727	3.15	0.728
Mouzaki	0.718	−0.40	0.711
Pili	0.723	0.96	0.725
Sarakina	0.622	2.54	0.623
Mesdani	0.755	−3.91	0.804
Ali Efenti	0.783	−1.06	0.780
Piniada	0.688	1.37	0.688
Skopia	0.694	−7.31	0.695
Amygdalea	0.628	3.66	0.636
Larisa	0.700	−4.78	0.702
Mesochori	0.550	−9.34	0.552
Mesochora	0.712	−0.68	0.716
Sykia	0.723	−1.09	0.724

a way to indicate major junctions of the Pinios river tributaries as well as major water demand changes. Furthermore, the watershed boundaries and DEMs of the existing and proposed major dams and reservoirs, namely, Lake Karla, N. Plastiras, Pili, Mouzaki, Smokovo, Palioderli, Neochori, Kalouda, Paliomonastiro, Mesochora and Sykia (Figure 2) were delineated with GIS. The simulation of the runoff of ungauged sub-basins and reservoir watersheds was achieved using regional estimates of model parameters based on their topographical, geological and land cover-land use characteristics.

4.2 Reservoir Operation Model

In order to simulate the usable renewable surface water resources in the study area, the existing reservoirs, the reservoirs and dams that are under construction as well as the proposed reservoirs were modeled and incorporated in the simulation procedure. In this study, the reservoirs were classified into two categories: (a) large and major reservoirs with volume storage larger than 5 hm^3 and (b) small reservoirs and lagoons with volume storage smaller than 5 hm^3. The operation of large reservoirs was simulated considering the natural runoff inflows from their watershed area, any water transfers from nearby water resources, the water withdrawals, and the net water losses. The natural surface runoff has been simulated as presented by the hydrological model, the historical withdrawals from the N. Plastiras reservoir have been used as they are considered as representative for the region, and the net water losses of the reservoir were calculated as the subtraction of precipitation from evaporation from the reservoir water surface, and the percolation losses. Table II presents the main characteristics of the major existing and proposed reservoirs in the study area. Two different plans for the construction of reservoirs at the mouth of Pili and Mouzaki watersheds have been proposed. The first plan is the construction of two independent reservoirs, whereas the second plan is the construction of two reservoirs as part of the series of four reservoirs for the partial diversion of Acheloos River, having different water storage characteristics (Table II).

A large number of small reservoirs and lagoons exist in the study area. Most of them are small lagoons located adjacent to Pinios River and they are distributed over the study area. The procedure for the simulation of their operation was the following: (a) the location of each one of the small reservoirs was identified and digitized in the GIS, (b) the total volume of the small reservoirs located into a sub-basin of the Pinios River basin and Lake

Table II Characteristics of existing and proposed major reservoirs

Reservoir	Basin area (km^2)	Mean basin elevation check amsl (m)	Maximum useable storage capacity (hm^3)	Sub-basin mainly affected	Remarks
N. Plastiras	161	1,459	286	Piniada	Existing, located outside Pinios River basin
Smokovo	375	634	232	Piniada	Existing, located inside Pinios River basin
Lake Karla	1,171	257	127	Lake Karla	Existing, located inside Lake Karla basin
Mouzaki	144	827	280	Mesdani	Proposed, located inside Pinios River basin
Pili	132	949	47	Mesdani	Proposed, located inside Pinios River basin
Palioderli	410	657	129	Piniada	Proposed, located inside Pinios River basin
Neochori	171	645	65	Ali Efenti	Proposed, located inside Pinios River basin
Kalouda	467	763	130	Titarisios	Proposed, located inside Pinios River basin
Paliomonastiro	210	1,009	70	Titarisios	Proposed, located inside Pinios River basin
Mesochora[a]	615	1,401	502	Mesdani	Proposed, located outside Pinios River basin
Sykia[a]	540	1,161	228	Mesdani	Proposed, located outside Pinios River basin
Pili[a]	132	949	47	Mesdani	Proposed, located inside Pinios River basin
Mouzaki[a]	144	827	530	Mesdani	Proposed, located inside Pinios River basin

[a] Part of Acheloos River partial diversion project

Karla basin was estimated, and (c) their operation was modeled as the operation of one large reservoir having the total storage volume of the small reservoirs and located at the mouth of the sub-basin.

The model used for the simulation of the operation of reservoirs is a simple model (Tsakiris 1995). The general equation of the model that describes the operation of a reservoir in a monthly time step is:

$$V(J) = V(J-1) + Q(J) - E(J) - A(J) - Y(J) \tag{1}$$

where, $V(J)$ και $V(J-1)$ are the stored water volume in the reservoir for the months J and $J-1$, $Q(J)$ is the inflow in the reservoir for the month J, $E(J)$ is the net water loss from the reservoir for the month J, $A(J)$ is the real withdrawals during month J, $Y(J)$ is the overflow during month J.

The reservoir storage and overflow were calculated at each monthly time step using Eq. 1. The monthly net water loses of the reservoir are estimated from the equation:

$$E(J) = E_o(J) - P_o(J) + L(J) + Q(J) \tag{2}$$

where, $E(J)$ are the net water loses of month J, $E_o(J)$ is the evaporation from the reservoir water surface of month J, $P_o(J)$ is the direct precipitation on the reservoir during month J, $L(J)$ are the estimated deep percolation loses to groundwater, and $Q(J)$ is the natural surface runoff that would have been generated from the area of the reservoir if the reservoir does not exist. The deep percolation loses are usually estimated by field geological measurements before the development of the reservoir and they are included in the dam development study. In case that such measurements do not exist, estimates of the deep percolation loses are used or the deep percolation loses are taken equal to zero. All the above quantities are expressed in millimeters.

The above quantities are expressed to volume units (hm^3) by multiplying them with the reservoir surface area. The water level and the reservoir surface area were estimated using the reservoir storage-water level and surface area-water level curves. Using these curves, an expression was developed relating the reservoir water surface area, F, to reservoir storage, V:

$$F = a + bV^c \tag{3}$$

The coefficients a, b and c are determined through regression.

The direct precipitation, P_o, and the mean monthly temperature at the reservoir water surface were estimated from the reservoir watershed mean areal precipitation and temperature adjusted to the mean monthly elevation of the water surface of the reservoir using the precipitation and the temperature gradients of the basin, respectively. The evaporation from the reservoir surface was estimated using the Thornthwaite method increased by an average of 40% as previous studies in the region have shown (Efstratiadis et al. 2002; Loukas et al. 2005b).

4.3 Renewable Water Potential

Following the above described hydrological and reservoir operation modeling procedures, the renewable water resources potential in a sub-basin was evaluated. The renewable groundwater resources were assumed to be the volume of natural groundwater recharge estimated by the Eq. 25 of the UTHBAL model (in Appendix). A basic assumption made was that the groundwater movement is minimal within a period of a month, so that the total recharge of the groundwater is available for use in the sub-basin. Detailed simulation of groundwater was not considered, in this study, due to data limitations.

The renewable and usable surface water resources in a sub-basin were assumed to be the available water withdrawals from the large and small reservoirs and lagoons located in each sub-basin. The addition of the renewable groundwater and surface water resources withdrawals estimated the total renewable water potential of each sub-basin.

4.4 Water Demands

The water demands were estimated for the five major water uses, namely, urban, agricultural, industrial, tourism and animal production water use. The river flow and the lake storage, which is necessary for the ecological sustainability of Pinios River and Lake Karla ecosystems, was also considered. The methods used for the estimation of water demand per sub-basin for each water use are presented in the next paragraphs.

4.4.1 Urban Water Demand

The population census data for the year 2001, provided by the Greek National Statistical Service, were used for the estimation of the total population of each sub-basin. Furthermore, data of annual urban water consumption and population for the years 1991–2001 were available for seven municipalities of Thessaly, namely, Trikala, Karditsa, Sofades, Kalampaka, Farkadona, Kleinovou, and Gomfon. By analyzing these data, the average specific water demand was found to be 330 l/capita/day, which was adjusted to 400 l/capita/day considering 20% water losses (Loukas and Mylopoulos 2004). Then, the annual water supply demand for each sub-basin was estimated by multiplying the sub-basin population with the average specific water demand (400 l/capita/day) and integrated over the year. The monthly urban water supply demand for each sub-basin was estimated by distributing the annual water supply demand over the year using the results of a recent study for the City of Volos (Mylopoulos et al. 2001) (Table III).

4.4.2 Agricultural Water Demand

The agricultural water demand for irrigation per sub-basin was estimated as follows. Firstly, data of the irrigated agricultural areas per crop and municipality for the year 2002, provided by the Greek Ministry of Agriculture, were used to estimate the irrigated agricultural areas for each sub-basin and each crop. The major crops in the study area were cotton, wheat, alfa-alfa, corn, tobacco and orchards. The monthly reference evapotranspiration for each crop (ET_o) was estimated using the Blaney–Criddle method (Blaney and Criddle 1950) and the monthly crop coefficients proposed by FAO (Allen et al. 1998) for Mediterranean climate conditions:

$$ET_o = K_{crop}(0.457T + 8.13)p \tag{4}$$

where, K_{crop} is the monthly crop coefficient, T is the mean monthly temperature and p is the monthly percentage of daylight hours to the total annual daylight hours.

The monthly agricultural water demand for each crop in a specific sub-basin was estimated using the monthly Near Irrigation Requirement (NIR) of the US Soil Conservation Service method (Dastane 1974):

$$NIR = ET_o - P_{eff} \tag{5}$$

where, P_{eff} is the effective precipitation calculated as:

$$P_{eff} = \begin{cases} P\dfrac{125 - 0.2P}{125}, & \text{when } P \leq 250\,\text{mm} \\ 125 + 0.1P, & \text{when } P > 250\,\text{mm} \end{cases} \tag{6}$$

where, P is the monthly precipitation.

The monthly irrigation requirement per crop in a specific sub-basin was estimated by multiplying the crop cultivation area in the sub-basin with NIR of that particular crop in the

Table III Monthly percentage distribution of annual water supply demand (Mylopoulos et al. 2001)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
%	8	5	5	5	5	6	8	10	12	13	13	10

specific sub-basin. The total monthly irrigation water requirement per sub-basin was, then, simply the summation of the monthly irrigation requirements for all crops cultivated in the sub-basin. Figure 3 shows the estimated annual irrigation requirement for each crop and sub-basin of the study area for the year 2002. It is clear that the largest irrigation requirements are in the Piniada, Ali Efenti, Larisa sub-basins and the Lake Karla basin. Also, over 70% of the irrigation water volume is used for the irrigation of cotton cultivated areas.

The irrigation water requirements do not determine the agricultural water demands because there are water losses during the transfer of water from the water source to the field and the application or irrigation method used in the field. The efficiency of the system of water transfer and distribution depends on the type of network. The open channel surface distribution networks have efficiency, E_{open}, that ranges from 0.20 to 0.75 depending on the condition of the network whereas the pressure distribution systems have efficiency, E_{pres} which ranges from 0.80 to 0.95 (Papazafiriou 1999). The efficiency of the irrigation methods ranges from 0.50 to 0.80 for the surface irrigation methods, E_{surf}, from 0.60 to 0.90 for the sprinkle irrigation methods, $E_{sprinkle}$, and from 0.80 to 0.95 for the drip irrigation, E_{drip} (Papazafiriou 1999).

In this study, the irrigated areas per municipality and per water sources for the year 2002 were available from the Greek Ministry of Agriculture. A basic assumption was made for the assessment of the water transfer efficiency. According to this assumption the water transferred from surface water sources was distributed by open channel surface networks to irrigated areas, whereas the water transferred from groundwater was distributed by pressure distribution networks to irrigated areas. The open channel surface distribution network efficiency, E_{open}, was assumed to be equal to 0.60 and the pressure distribution systems

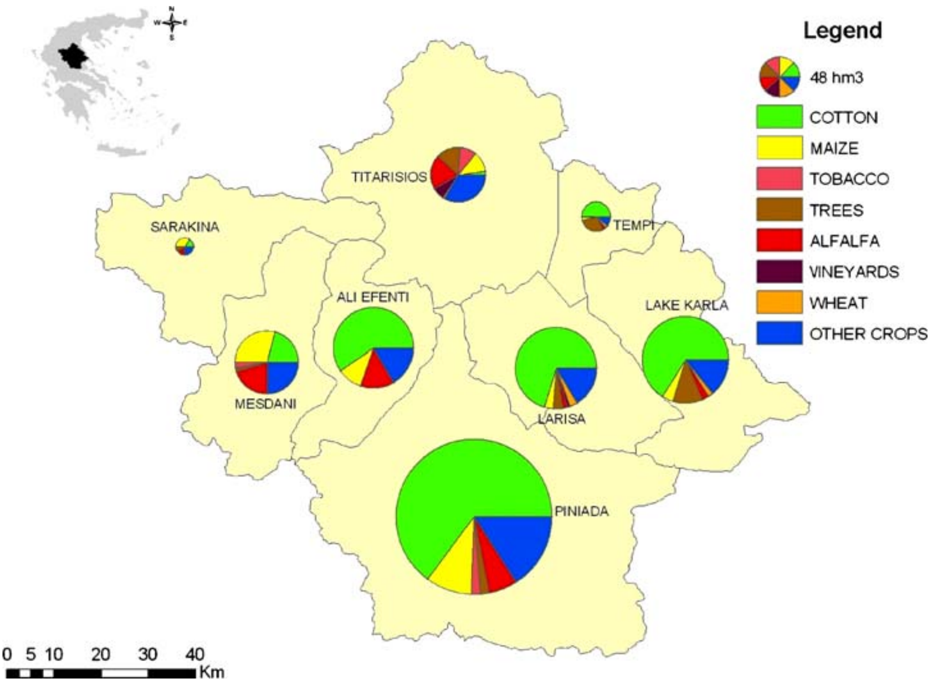

Figure 3 Distribution of mean annual irrigation requirements (in hm^3) per sub-basin and cultivated crops.

efficiency, E_{pres}, was assumed to be equal to 0.90. The average efficiency of water transfer and distribution network, E_{trans}, for each sub-basin was estimated as the weighted average of E_{open} and E_{pres}:

$$E_{trans} = M_{open}E_{open} + M_{pres}E_{pres} \tag{7}$$

where, M_{open} and M_{pres} are the percentages of the total irrigated area of the sub-basin irrigated from surface water sources and groundwater, respectively.

The commonly used irrigation methods in the Thessaly plain are the various sprinker irrigation methods. However, detailed information on the irrigation methods for the Thessaly region was not available. For this reason, the percentage of the areas irrigated with the various methods reported from the Greek Ministry of Agriculture for the whole country were considered to be representative also for Thessaly. This assumption is not far from true because Thessaly plain is the second largest agricultural plain of Greece. According to these data, the sprinkle irrigation methods are used at the 63% of the total irrigated area of Greece, whereas the surface irrigation and the drip irrigation methods are equally used at the rest 37% of the irrigated area. Over the last 10 years, the use of the drip irrigation and sprinkler irrigation methods has been increased in dispense of surface irrigation methods. The efficiencies of the sprinkler irrigation methods, $E_{sprinkle}$, drip irrigation methods, E_{drip}, and surface irrigation methods, E_{surf}, were assumed to be equal to average values of 0.80, 0.90, and 0.65, respectively. The average efficiency of irrigation methods, E_{irr}, for each sub-basin was estimated as the weighted average of $E_{sprinkle}$, E_{drip}, and E_{surf}:

$$E_{irr} = M_{sprinkle}E_{sprinkle} + M_{drip}E_{drip} + M_{surf}E_{surf} \tag{8}$$

where, $M_{sprinkle}$, M_{drip}, and M_{surf} are the percentages of the total irrigated area of the sub-basin irrigated with sprinkler, drip, and surface irrigation methods, respectively.

Finally, the monthly agricultural water demand per sub-basin was estimated from the total monthly irrigation water requirements of the sub-basin multiplied by the adjustment factor:

$$K_{adj} = \frac{1}{E_{trans}E_{irr}} \tag{9}$$

4.4.3 Industrial Water Demand

Two major industrial areas exist in the study basins located near the cities of Trikala and Larisa within the sub-basins of Mesdani and Larisa, respectively. The industries are mainly food processing industries. Monthly water supply and consumption data from these two industrial areas were available for the years 2001 to 2004. These data were analyzed and used for the estimation of the monthly industrial water demands.

4.4.4 Tourism Water Demand

The water demand for tourism was estimated using monthly overnight stay (persons/night) data from Greek National Tourist Organization for the years 1999 and 2000. These data refer to number of monthly overnight stays in hotels and camping facilities for the prefectures of Karditsa, Trikala and Larisa. The monthly tourism water demands were calculated assuming: (a) the specific water consumption is 400 l/tourist/day, and (b) tourism was concentrated on the three major cities of Karditsa, Trikala, and Larisa. The city of Karditsa is located within the Piniada sub-basin, the city of Trikala is located in the Mesdani sub-basin, and the city of Larisa is located in the Larisa sub-basin.

4.4.5 Animal Production Water Demand

The water demands for animal production were calculated using the animal production data from the Greek National Statistical Service for the year 2000. These data were available for each municipality and animal species. The major animal species in the study areas are sheeps, goats, cows, pigs and poultry. The average specific water demand per species was taken from bibliography (Markantonatos 1990). Then, the annual animal production water demand for each sub-basin and animal species was estimated by multiplying the sub-basin population of the animal species with the average specific water demand of the species and it was evenly distributed over the months. The total monthly animal production water demand per sub-basin is, then, simply the summation of the monthly water demands for all animal species produced in the sub-basin.

4.4.6 Ecological Water Demand and Criteria

The modifications of flow regime in rivers such as development of large reservoirs, small dams and water abstractions, may result in significant impacts on the river hydrological regime and consequently on the ecological sustainability of the river ecosystem. The reduction in number of events, the reduction in size of events (high and low flow), the reduction in the duration or quantity of in-channel pool storage, the reduction in streamflow variability, the changes in water quality, the change of biodiversity, the extinction of species, are some of the impacts on the river resulted by the flow regime change (Hughes 2005).

According to a previous study (EYDE and ENVECO 1995), to sustain the Pinios River ecosystem consisting of the main stem of Pinios River, its major Pinios River tributaries and the Pinios River delta, it is necessary a minimum continuous discharge of 5 m^3/s. However, this a quite general rule applied to the Greek rivers and it has not been properly justified. More scientifically based is the definition of the instream environmental flow requirements (IFR) which could be seen as a function of hydrological regime characteristics, ecological functioning (i.e. biotic composition, structure and function of aquatic, wetland, and riparian ecosystem), and the relationships between flow and ecology (Poff and Ward 1989; Richter et al. 1997). An initial estimation of the IFR in a river cross-section, due to the lack of ecological data regarding the natural flora and fauna of the river system, could be done by analyzing observed or simulated flows. Various methods have been proposed for the characterization of streamflow regimes and the estimate of IFR using various parameters of flow to characterize the high and low flows as well as their seasonal and interannual variation (Hughes and Hannart 2003; Sanz and Del Jalon 2005). Some of these flow parameters could be extracted by the flow duration curve. A flow duration curve is one of the most informative methods of displaying the complete range of river discharges from low flows to high flood events. Among others, the flow parameters that could be extracted from the flow duration curve are the flow that is exceeded only 5% of time (Q_5) which represents the magnitude of high flows, the flow that is exceeded 95% of time (Q_{95})

which represents the low flows and the flow that is exceeded 50% of time (Q_{50}) which defines the "the low flow section" of a flow duration curve (Smakhtin 2001). The variation of flows could be represented by the monthly coefficient of variation (CV_{month}), and interannual coefficient of variation (CV_{inter}) (Hughes and Hannart 2003; Sanz and Del Jalon 2005).

The impact of the various water supply management strategies on the river flow was evaluated at the control nodes of Pinios River, considering apart from the natural runoff, the overflows and releases of the existing and proposed reservoirs and the effluent flows from the wastewater treatment plants of the three major cities of Thessaly, namely Karditsa, Trikala, and Larisa. The flow parameters used for the analysis were, Q_5, Q_{95}, Q_{50}, CV_{month}, CV_{inter}.

For the Lake Karla reservoir, the minimum allowable water level for the wetland preservation has been defined to +46.4 m of absolute elevation (Greek Ministry of Environment, Regional Planning and Public Works 1999). This elevation corresponds to a water volume of 57.01 hm^3 stored in the reservoir and a reservoir surface area equal to of 34.65 km^2. Thus, as soon as the water level reached the minimum allowable water level for wetland preservation (+46.4 m), the water withdrawals from the reservoir stopped. This ecological criterion has been incorporated in the Lake Karla reservoir operation model and represents a limiting criterion.

4.5 Water Resources Management and Strategies

After the calculation of the renewable water resources potential and the water demands, the water balance was estimated as the subtraction of water demands from the water resources potential for various water resources management strategies. The procedure followed for the estimation of the water balance of the two study basins was:

1. Estimation of water balance of each Pinios River sub-basin
2. Estimation of water balance at each control node of Pinios River system
3. Estimation of monthly discharge at each control node of Pinios River system
4. Assessment of the ecological criterion of minimum discharge at the control nodes of Pinios River system
5. Estimation of water balance of the Lake Karla basin

Two types of water resources management strategies were investigated: (a) water supply management strategies, and (b) water demand management strategies. Two types of water supply management strategies were assessed referring to the level of groundwater use and the development and operation of surface water storage projects. The first strategy of groundwater use assumed the use of the total volume of renewable groundwater as this assessed by the estimated groundwater recharge. The second strategy assumed the pumping and use of the 70% of the groundwater recharge water volume. For this second groundwater use strategy, the estimated 30% of the groundwater recharge volume was left aside for the restoration of the overexploited and degraded groundwater.

Four strategies of development and operation of surface water storage projects have been examined. The first strategy represented the present or near future state of surface water storage project development. It considered the operation of the existing reservoirs of N. Plastiras, Smokovo, the restored Lake Karla reservoir, which is under construction, and the operation of the existing small reservoirs and lagoons in the Pinios River and Lake Karla basins. The second strategy simulated the operation of the reservoirs of the first strategy and the proposed large reservoirs within the Pinios River basin, namely, the reservoirs of Pili, Mouzaki, Palioderli, Neochori, Paliomonastiro, and Kalouda (Figure 2).

The third surface water management strategy simulated the operation of the existing reservoirs (first water supply strategy) and the contribution of the partial diversion of Acheloos River project. The project of the partial diversion of Acheloos River to the Thessaly plain includes the construction of four reservoirs, two on Acheloos River, namely, the reservoirs of Mesochora and Sykia and two in the sub-basins of Pinios River basin, namely Pili and Mouzaki reservoirs (Loukas and Mylopoulos 2004). The Mesochora reservoir can operate as a single reservoir but its operation is essential for the operation of diversion. The inflow to reservoir is only the natural runoff from Mesochora basin. The Sykia reservoir will be located downstream of Mesochora on Acheloos River and it will be the control reservoir for the diversion. The inflow to Sykia reservoir will be the natural runoff from the Sykia basin, the withdrawals for hydropower generation from Mesochora reservoir and the overflow from Mesochora reservoir. The outflow from Sykia reservoir will be the withdrawals for hydropower generation and the overflows. The Sykia reservoir will control the diversion of water to a tunnel, which will transfer water to Mouzaki reservoir. The average annual volume of water diverted to Thessaly has been estimated to be 600 hm^3. The Mouzaki reservoir will represent the storage project of the diversion and it will be the reservoir with the largest storage volume (Table II). This reservoir will receive the water diverted from Acheloos River, the natural runoff from Mouzaki watershed, and the overflow of the Pili reservoir. The Pili reservoir will satisfy local irrigation demands (22 hm^3), but its major contribution to the diversion project is to overflow water to Mouzaki reservoir through a tunnel. The Mouzaki reservoir will be used for irrigation and hydropower generation. The Pili and Mouzaki reservoirs, which are part of the Acheloos diversion project, have different storage characteristics from the respective reservoirs of the second surface water management strategy (Table II). This project has been seriously criticized for environmental, political, and legal issues and it is doubtful whether it will be ever fully constructed. At this moment, only the Mesochora dam has been constructed. Also, this project does not conform with the concept of water sustainability within a river basin of the European Union Water Framework Directive.

Finally, the fourth strategy simulated the operation of the existing and proposed reservoirs of the second strategy and the partial diversion of Acheloos River. Figure 4 schematically presents the water resources system of the study area for the four strategies of development and operation of surface water projects.

Three water demand management strategies have been evaluated. The first strategy, representative of the existing conditions, considered the existing level of water demand estimates in the study area, as previously presented. The second strategy evaluates the effects of the improvement of the efficiency of the surface water transfer and distribution system from 0.60 to 0.75 and replacement of surface irrigation methods with drip irrigation methods. The third strategy considered that 10% of the irrigated areas were set aside according to the European Union Common Agricultural Policy and 50% of the cotton cultivation area was converted to wheat cultivation.

The water supply management strategies were combined along with the water demand strategies to produce 24 water resources management strategies of Pinios River and Lake Karla basins. The various surface water supply management strategies of Pinos river basin might affect also the availability of water resources of Lake Karla basin. The inflows to the Lake Karla reservoir are the surface runoff of the watershed, the diversion of Pinios River flood flows, and the direct precipitation on the reservoir surface. The water volume of

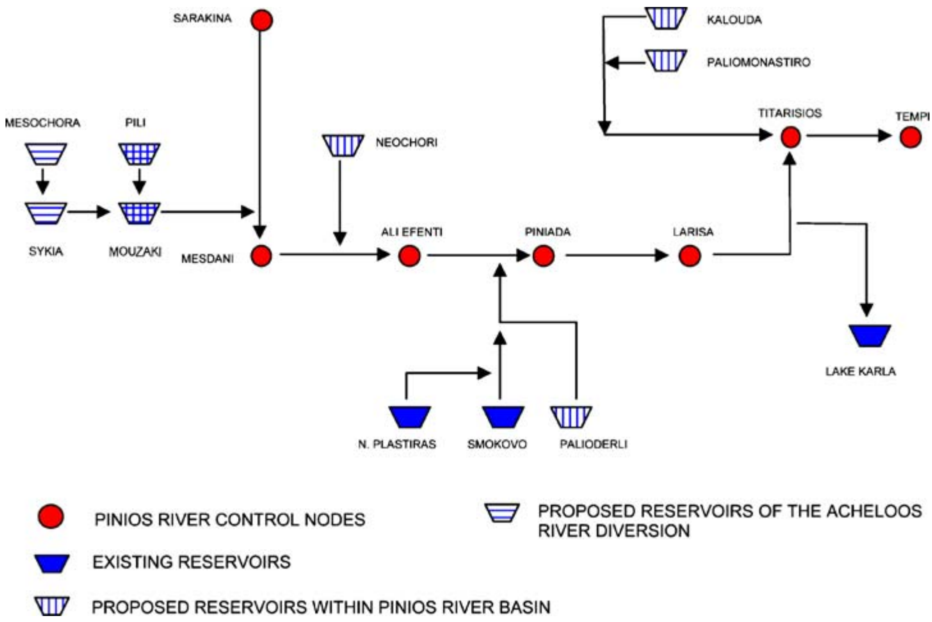

Figure 4 Schematic diagram of modeling system.

Pinios River flood flows diversion has been found to be the major inflows to the Lake Karla reservoir and critical during dry periods (Loukas et al. 2003a). The volume of water abstractions were estimated considering a pumping threshold when the river discharge exceeded 30 m^3/s (Loukas et al. 2003a). The existing pumping stations, which will be used for the withdrawal of floodwater from the river and divert them through a channel into the reservoir, have an average capacity of 14 m^3/s. This discharge is also the maximum capacity of the diversion channel. With this diversion capacity and pumping for 18 h/day, it was then calculated that it is possible to divert from Pinios River a maximum water volume of 27.2 hm^3 per month. Using the simulated flow at Larisa control node (Figure 4) plus the return flow from the Larisa wastewater treatment plant and considering the above limitations, the possible diverted floodwater volume to the reservoir was calculated.

5 Application – Results and Discussion

The methodology described above was applied on a monthly basis for the period October 1960–September 2002. However, the presentation of the results will be focused on three characteristic hydrological years of record: (a) the wettest hydrological year 1962–1963, (b) the average hydrological year 1978–1979, and (c) the driest hydrological year 1989–1990. These three years were selected according to the average annual precipitation over the whole study area. For example, the mean annual precipitation for the study area is about 720 mm, whereas the study area received for the three selected hydrological years, 1,044, 719, and 517 mm, respectively.

5.1 Pinios River Basin

The results indicated that the largest water resources potential was observed on the mountainous sub-basins of western Pinios river basin, namely, Sarakina, Pili and Mouzaki sub-basins. On the other hand, the largest water demands were estimated in the Pinios River agricultural plain sub-basins of Mesdani, Ali Efenti, Piniada, Larisa, and Titarisios. Agriculture is the largest consumer of water in the study area and irrigation water demand accounts for 94.5% of the total water demand. The urban water supply amounts to 4.7% of the total water demand, whereas all the other water demands account for only 0.8% of the total.

The annual water balances for the three characteristic years are showing in Table IV for the existing level of development and operation of surface water storage projects, 100% withdrawal of the renewable groundwater recharge and water demands. These results showed that there is surplus of water in the Sarakina sub-basin, even for the driest hydrological year (1989–1990). On the other hand, large water deficits were estimated for the sub-basins located on Thessaly plain, namely the sub-basins of Mesdani, Ali Efenti, Piniada and Larisa even for the wettest hydrological year (1962–1963). The sub-basins of Titarisios and Tempi indicated a water surplus during the wettest hydrological year (98.51 and 8.05 hm^3, respectively) and water deficits during the average and driest historical hydrological years. The estimated water deficits in every sub-basin are satisfied by excess and unsustainable pumping of groundwater and in that sense there is no water deficit. However, this continuous practice has lead to a large decline of groundwater and deterioration of its quality.

The water balance for the existing conditions and for all sub-basins of Pinios River basin has the same monthly variation being positive (water surplus) during the autumn and winter months and negative (water deficit) during the late spring and summer months (Figure 5). Agriculture is by far the major consumer of water and due to cultivation of large areas of cotton and maize, the largest water demands are concentrated during the summer months. Also, the water potential at each sub-basin is at minimum level during the summer period. This temporal variation of water demands and water potential could explain the monthly variation of water balance found in this analysis (Figure 5).

The development and operation of reservoirs within the Pinios River basin, the partial diversion of Acheloos River, the level of withdrawals from the renewable groundwater resources, the change of cultivation species, the improvement of water transfer system, and the change of irrigation methods would significantly affect the water balance of Pinios River sub-basins. The major effect of surface water resources projects (reservoirs and

Table IV Annual water balance (in hm^3) of the seven major Pinios River sub-basins for existing water resources management for three representative hydrological years

Sub-basin	1962–1963 wettest for Thessaly	1978–1979 average for Thessaly	1989–1990 driest for Thessaly
Sarakina	340.09	166.36	33.07
Mesdani	−74.44	−103.62	−145.33
Ali Efenti	−149.09	−171.84	−221.03
Piniada	−203.74	−371.65	−538.60
Larisa	−172.88	−210.49	−222.01
Titarisios	98.51	−55.67	−77.49
Tempi	8.05	−20.87	−40.35

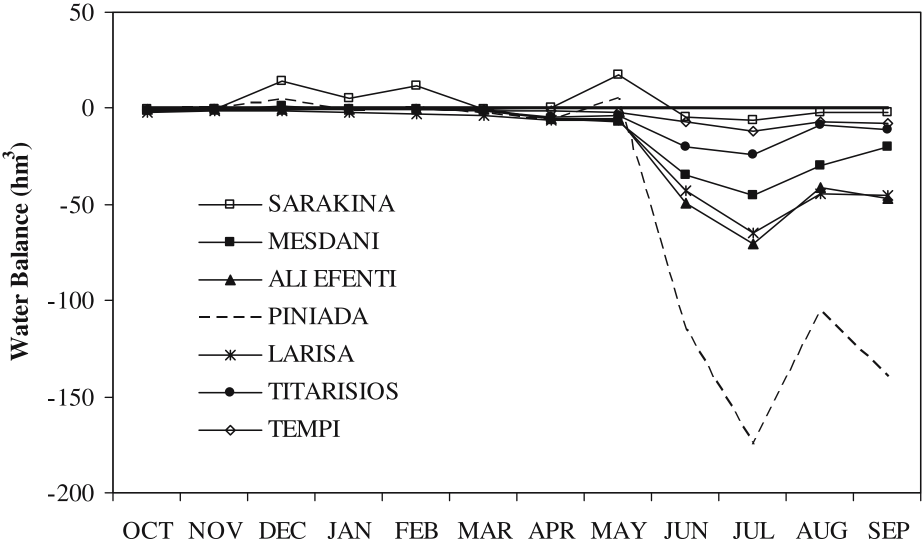

Figure 5 Variation of monthly water balance at the seven Pinios River sub-basins for existing water supply and demand management strategies (Driest hydrological year 1989–1990).

diversion of Acheloos River) development is expected in the Mesdani, Ali Efenti, Piniada and Titarisios sub-basins because the proposed projects are located within the area of these sub-basins and directly supply water to these sub-basins (Table V). The major impact on water balance from the development of reservoirs within the Pinios River basin would be in the Mesdani and Titarisios sub-basins where the annual water deficit would be reduced by about 139 and 73 hm^3, respectively, for the driest hydrological year in record (Table V). These figures represent a 95% change from the existing conditions. Smaller changes have been found for the Ali Efenti and Piniada sub-basins. However, the largest change has been observed in Mesdani sub-basin for the third and fourth surface water supply management strategies, which examined the partial diversion of Acheloos River and the combination of the Acheloos River diversion and the development of major reservoirs within the Pinios

Table V Annual water balance (in hm^3) of the seven major Pinios River sub-basins for the four surface water supply management strategies and the existing water demand management – driest hydrological year (1989–1990)

Pinios River sub-basin	Surface water supply management strategies			
	First	Second	Third	Fourth
Sarakina	33.07	33.07	33.07	33.07
Mesdani	−145.33	−6.33	701.67	701.67
Ali Efenti	−221.03	−196.73	−221.03	−196.73
Piniada	−538.60	−496.14	−538.60	−496.14
Larisa	−222.01	−222.01	−222.01	−222.01
Titarisios	−77.49	−4.21	−77.49	−4.21
Tempi	−40.35	−40.35	−40.35	−40.35

River basin. According to these strategies, the Mesdani sub-basin would have a very large volume of water surplus which amounts to more than 700 hm^3 of water (Table V).

The improvement of water transfer system and the change of irrigation methods (second water demand management strategy) mainly affect the water balance of the Piniada sub-basin which is the sub-basin with the largest area by surface irrigation methods. The improvement of water balance in the Piniada sub-basin found to be 16% for the driest hydrological year in record, whereas it is smaller in the other sub-basins (Table VI). The restructure of cultivation according to the third water demand strategy would affect mainly the sub-basins, where cotton is the major cultivation, namely Mesdani, Ali Efenti, Piniada and Larisa sub-basins (Table VI). The largest improvement in the water deficit and for the driest hydrological year was found in the Piniada sub-basin (20%), which is the sub-basin with the largest cotton cultivated area (Figure 3).

As has already been mentioned, apart from the water balance analysis in sub-basin basis, the water balance of Pinios River basin has been studied in characteristic control nodes (Figure 4). This analysis assumes that the upstream water potential and the water demands were concentrated in the control node and presents the evolution of water balance from the upstream to downstream areas. This type of analysis is necessary because the development of large water resources projects, such as major reservoirs and water diversion projects, affect the whole region and not a specific area or sub-basin. Table VII presents the annual water balance of control nodes for the existing water supply and water demand management conditions for the three characteristic hydrological years and for the two groundwater withdrawal strategies. Using 100% of the renewable groundwater recharge, water surplus has been estimated at the upstream control nodes of Sarakina and Mesdani for the wettest and average hydrological years. Water deficit has been calculated at the downstream control nodes starting from the Piniada node for the wettest year and Ali Efenti for the average year. The water deficit decreases at the Titarisios and Tempi control nodes for the wettest hydrological year mainly due to the water contribution from the northeastern mountainous areas. The water balance was found to be negative at all control nodes except for the upstream Sarakina node for the driest hydrological year.

The reduction of groundwater withdrawals to 70% of the renewable groundwater recharge has a significant effect on the water balance of the control nodes especially during wet and average conditions (Table VII). The contribution of groundwater, during these hydrological conditions, is significant and the reduction of pumping would decrease the water potential and water deficits appeared at the upstream control nodes. On the other hand, the contribution of groundwater to water potential, during dry hydrological

Table VI Annual water balance (in hm^3) of the seven major Pinios River sub-basins for the three water demand management strategies and the existing water supply management – driest hydrological year (1989–1990)

Pinios River sub-basin	Water demand management strategies		
	First	Second	Third
Sarakina	33.07	34.26	34.95
Mesdani	−145.33	−134.45	−128.67
Ali Efenti	−221.03	−203.13	−188.30
Piniada	−538.60	−452.00	−430.19
Larisa	−222.01	−205.16	−196.15
Titarisios	−77.49	−70.34	−71.22
Tempi	−40.35	−37.12	−37.68

Table VII Annual water balance (in hm^3) of the seven control nodes of Pinios River for the existing surface water supply and water demand management conditions and 100% (70%) renewable groundwater withdrawal

Control node	1962–1963 wettest	1978–1979 average	1989–1990 driest
Sarakina	340.09 (232.90)	166.36 (111.49)	33.07 (18.16)
Mesdani	265.65 (135.84)	62.74 (−2.82)	−112.26 (−128.28)
Ali Efenti	116.56 (−33.59)	−109.10 (−183.27)	−333.29 (−349.31)
Piniada	−87.18 (−293.82)	−480.75 (−573.02)	−871.89 (−889.57)
Larisa	−260.06 (−485.82)	−691.24 (−789.94)	−1,093.88 (−1,111.57)
Titarisios	−161.55 (−439.17)	−746.91 (−852.85)	−1,171.39 (−1,189.05)
Tempi	−153.49 (−446.24)	−767.37 (−880.28)	−1,211.74 (−1,229.50)

conditions, was found to be significantly reduced, due to small groundwater recharge and its effect is reduced on the water balance of the control nodes (Table VII).

The effect of the combination of the water resources supply and demand management strategies were applied and analyzed in all Pinios River sub-basins and characteristic nodes. The results are presented for the Tempi control node, which is the last downstream node and integrates the water balance for the whole Pinios River basin (Table VIII). These results indicated that for the existing level of water demands (first water demand management strategy) and water resources project development (first water supply management strategy), the water balance of the Pinios River basin is negative even for the wettest hydrological year (1962–1963) and with withdrawal of the 100% of the renewable groundwater resources. For this case, the maximum water deficit was observed during the driest hydrological year (1989–1990) and amounts −1,212 hm^3.

Application of the various water resources supply and demand management strategies increased the availability of water resources and decreased the volume of water demands. The development of the partial diversion of Acheloos River diversion project (third surface water supply management strategy) has the major impact on the availability of water resources. For this surface water supply water management strategy, the potential and the

Table VIII Annual water balance (in hm^3) of the Pinios River basin (Tempi control node), for various surface water supply (SWSS), water demand (WDS) and groundwater withdrawal (GWS) management strategies (100% (70%))

		1962–1963 wettest	1978–1979 average	1989–1990 driest
First WDS	First SWSS	−153 (−446)	−767 (−880)	−1,212 (−1,230)
	Second SWSS	165 (−128)	−465 (−578)	−933 (−951)
	Third SWSS	694 (401)	80 (−33)	−365 (−383)
	Fourth SWSS	873 (580)	243 (130)	−225 (−243)
Second WDS	First SWSS	−7 (−300)	−625 (−738)	−1,068 (−1,086)
	Second SWSS	311 (18)	−323 (−436)	−789 (−807)
	Third SWSS	840 (547)	222 (109)	−221 (−239)
	Fourth SWSS	1,019 (726)	385 (272)	−81 (−99)
Third WDS	First SWSS	201 (−92)	−444 (−557)	−1,018 (−1,036)
	Second SWSS	519 (226)	−142 (−255)	−739 (−757)
	Third SWSS	1,048 (755)	403 (290)	−171 (−189)
	Fourth SWSS	1,227 (934)	566 (453)	−31 (−49)

sustainable surface water resources withdrawals were increased by 850 hm^3, on the average year (Table VIII). On the other hand, development of only the proposed reservoirs within the Pinios River basin (second surface water supply management strategy) increased, on average, the sustainable surface water resources withdrawals by only about 300 hm^3. The development of all hydro-technical projects within the Pinios river basin and the partial diversion of Acheloos River (fourth surface water supply management strategy), would increase, on average, the availability of surface water potential by about 1,000 hm^3. Withdrawal of 70% of the renewable groundwater led, as expected, to smaller groundwater potential. However, the effect of such action was found to be small especially during the driest hydrological year (1989–1990), since the renewable recharge of groundwater was limited.

Application of the water demand management strategies indicated that on an average hydrological year (1978–1979) the water demand can decreased by about 315 hm^3 by restructuring and changing the cultivation (third water demand management strategy). Improvement of water distribution systems and changing of irrigation methods to less water consuming methods (second water demand management strategy) may decrease the water demands by about 140 hm^3 for the total Pinios River basin (Table VIII).

Combination of the above water resources supply and demand management strategies indicated that during the driest hydrological year (1989–1990) the water demands would increase due to higher temperatures, whereas the water potential would diminish to a limited volume. As a result, water deficit was estimated for all combinations of water resources management strategies. In contrast, water surplus was estimated for most combinations of strategies for the wettest hydrological year (1962–1963) and the average hydrological year (1978–1979), when the strategy of the Acheloos River partial diversion was accounted for (Table VIII).

The project of the partial diversion of Acheloos River has been seriously criticized and it is doubtful whether if will be ever completed. For this reason, the effect on the water balance of Pinios River basin of the conjunctive application of the two water demand management strategies combined with the second water supply management strategy (development of the proposed reservoirs within the Pinios River basin) has been evaluated. The results are presented on Table IX and indicate that the water balance of Pinios River basin was positive for the wettest hydrological year (1962–1963) for both groundwater withdrawal strategies. The water demands were balanced with the sustainable water supply during the average hydrological year (1978–1979) for 100% withdrawal of renewable groundwater. However, water deficit (−113 hm^3) was estimated for the average hydrological year when the withdrawal from groundwater amounted to 70% of the renewable resources. The water deficit during the driest hydrological year estimated to be −595 and −613 hm^3, for the two groundwater withdrawal strategies, respectively. These results indicate that the water potential could balance the water demands if the proposed reservoirs within the Pinios River basin were developed, the efficiency of water distribution system and irrigation methods were improved, the cultivation species were changed, and the groundwater pumping was adjusted according to hydrological conditions.

The impact of hydro-technical projects on the discharge of Pinios river was analyzed using the flow parameters Q_5, Q_{95}, and Q_{50} estimated by the flow duration curves. The flow duration curves have been built using the simulated flows for the four surface water supply strategies. Furthermore, the changes in the flow variation were analyzed by estimating the coefficients of variation for the mean monthly flow, CV_{month}, and the coefficients of variation for the mean annual flow, CV_{inter}. The estimated flow parameters are shown on

Table IX Annual water balance (in hm^3) of the Pinios River basin (Tempi control node) for the combination of the second surface water supply management strategy and the second and third water demand management strategies

Hydrological year	Water demand	Sustainable groundwater withdrawal – 100% (70%)	Sustainable surface water withdrawal	Water balance
1962–1963	1,006	977 (695)	695	666 (372)
1978–1979	1,003	376 (262)	628	1 (−113)
1989–1990	1,142	59 (41)	488	−595 (−613)

Table X for the control nodes of Mesdani, Larisa and Tempi. The coefficient of variation of mean monthly flow were represented on Table X with the coefficient of variation for the wettest month (February) and the driest month (August).

The results indicate that the variation of flow remains, essentially, unchanged at the upstream and downstream control nodes. The flow variation did not change in any control node for all four surface water supply strategies. Furthermore, it seems that the development of reservoirs within the Pinios River basin (Second Surface Water Supply Strategy) would have essentially no impact on river flow in all control nodes (Table X). This finding could be explained by the fact that the portion of the flow and the area of the river regulated by the proposed reservoirs are considered small and thus minimizing the effect on the river flow regime. On the other hand, the partial diversion of Acheloos River to Pinios River basin (third SWSS) would reduce the high flows, represented by Q_5, by 7 to 10% and the low flows, represented by Q_{95}, by about 10% at all control nodes. The development of a large reservoir in the Mouzaki watershed and a small at Pili watershed may explain this finding. Finally, the effects of partial diversion of Acheloos River diversion on river flow overshadowed the effects of the proposed reservoirs within Pinios River basin (fourth SWSS) (Table X).

Application of measures targeting at the reduction of the water required for irrigation would increase the availability of water, as previously has been shown. This, in return,

Table X Flow duration curve parameters and flow variation at three control nodes for the four surface water supply management strategies (SWSS)

Control node	Q_5 (m^3/s)	Q_{95} (m^3/s)	Q_{50} (m^3/s)	CV_{Feb}	CV_{Aug}	CV_{intra}
Mesdani control node						
First SWSS	79.9	1.8	12.2	0.44	0.35	0.32
Second SWSS	79.9	1.8	12.1	0.44	0.35	0.32
Third SWSS	72.2	1.6	12.0	0.40	0.36	0.30
Fourth SWSS	72.2	1.6	12.0	0.40	0.36	0.30
Larisa control node						
First SWSS	210.5	6.3	39.9	0.42	0.30	0.35
Second SWSS	210.4	6.3	38.8	0.43	0.30	0.35
Third SWSS	196.2	5.7	34.9	0.44	0.31	0.37
Fourth SWSS	196.1	5.6	33.7	0.45	0.30	0.37
Tempi control node						
First SWSS	234.4	8.5	41.4	0.45	0.33	0.37
Second SWSS	231.6	8.4	40.3	0.46	0.30	0.38
Third SWSS	216.5	7.6	37.0	0.47	0.34	0.40
Fourth SWSS	214.4	7.5	35.9	0.48	0.34	0.40

would allow more water to be used to sustain the ecological flow during dry hydrological conditions.

5.2 Lake Karla Basin

The Lake Karla basin for the three characteristic hydrological years exhibited small water deficits for existing water management conditions (Table XI). However, it should be mentioned that the selected hydrological years are not characteristic years for the Lake Karla basin. For this basin the wettest historical hydrological year was the year 1990–1991, the average hydrological year was the year 1988–1989 and the driest hydrological year was the year 1999–2000. For these years, the lake Karla basin had a water surplus of 35.44 hm^3, and water deficits of −14.42 and −80.07 hm^3, respectively, for the wettest, average and driest hydrological years (Table XI).

The various water supply management strategies (water resources project development strategies) may affect the discharge of Pinios River. Application of the surface water supply management strategies and analysis of the simulated flows indicated that the effect on Pinios River hydrograph would be minimal, because the reservoirs affect only a small percentage of the total basin area and thus the runoff generated from it. As a result, the major effect on the water balance of Lake Karla basin would be the application of water demand management strategies since the surface water supply management strategies would have no effect on Pinios River water withdrawals for Lake Karla reservoir. Figure 6 presents the annual water balance for the existing condition (first water demand strategy) and the other two water demand management strategies (second and third water demand strategies). Water deficits were estimated for about half of the years for the historical period 1960–2002 under the existing water demand management strategy. Restructuring and changing the crop cultivation (third water demand management strategy) significantly improved the water balance and water deficits were estimated only for three hydrological years (1976–1977, 1987–1988, and 1999–2000, Figure 6). Combination of the third water demand management strategy with the second water demand strategy allowed the reduction of the groundwater renewable recharge to 70% without significant water deficits. Water deficit was estimated for the hydrological years 1976–1977 (−18.50 hm^3) and 1999–2000 (−3.22 hm^3) (Figure 6). The reduction of groundwater pumping is critical for the Lake Karla basin because the largest drawdown of groundwater table in Thessaly has been observed in the southern part of this basin. Today, the groundwater table is more than 200 m below the land surface. Also, it should be mentioned that the ecological criterion for the sustainability of Lake Karla ecosystem has been incorporated into the model of the operation of Lake Karla reservoir as a limiting criterion and it has been preserved during simulations.

Table XI Annual water balance (in hm^3) of the Lake Karla basin, for existing water resources management for three representative hydrological years

1962–1963 wettest for Thessaly	1978–1979 average for Thessaly	1989–1990 driest for Thessaly
−4.65	−2.79	−7.03
1990–1991 wettest for Karla	1988–1989 average for Karla	1999–2000 driest for Karla
35.44	−14.42	−80.07

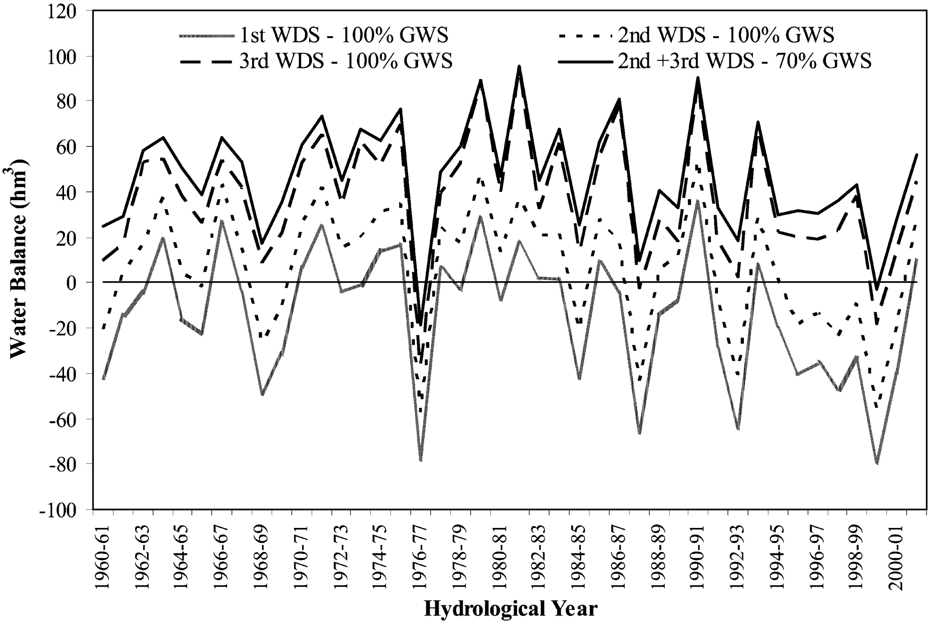

Figure 6 Annual water balance of Lake Karla basin for various water demand management (*WDS*) and groundwater withdrawal (*GWS*) strategies.

6 Conclusions

A systematic modeling procedure has been presented for the evaluation of water resources management strategies in the two largest basins of Thessaly, namely the Pinios River basin and the Lake Karla basin. The modeling procedure incorporates a hydrological model, a reservoir operation model, methodologies for the estimation of water demands and constrains.

This study evaluated various water resources management strategies that have been proposed for reversing the large water deficit of the two basins. These strategies target at the surface water potential increase of the area, the reduction of the extreme and unsustainable groundwater pumping, and the decrease of the water volume required for crop irrigation. The results obtained from the analysis lead to the following conclusions:

(a) The existing reservoirs are unable to supply enough water to satisfy the present water demands. As a result, unsustainable pumping of groundwater has been used to cover the large water deficit.
(b) The proposed surface water storage projects in the Pinios River basin would reduce the large water deficit but they would be unable to totally satisfy the water demand.
(c) The partial diversion of Acheloos River would largely increase the water availability and would improve the water balance, especially, during average hydrological conditions. However, negative water balance would be expected during dry hydrological years.
(d) The development and operation of the proposed hydro-technical projects would have a small effect on the Pinios River flow, and, in return, the sustainability of Pinios River ecosystem and the water withdrawals from Pinios River to the Lake Karla would not be affected.
(e) Thus, water demand management measures, which would target to the reduction of agricultural water demand, should be taken. Combination of two water demand

measures could allow the reduction of groundwater pumping to sustainable levels helping the recovery of the degraded groundwater resources.

Appendix

The hydrological model UTHBAL uses as inputs, monthly time series of precipitation, mean temperature and potential evapotranspiration. These time series were estimated using the methods presented in the previous paragraphs. The water balance model separates the total precipitation into rainfall and snowfall. The snow percentage of the total monthly precipitation is estimated using a logistic relationship based on mean monthly air temperature (Semadeni-Davies 1997; Knight et al. 2001):

$$\%S = 0 \quad \text{if} \quad T \geq 12.22^\circ\text{C}$$

$$\%S = \frac{1}{(1.35^{T} * 1.61) + 1} \quad \text{if} \; -10^\circ\text{C} \leq T \leq 12.22^\circ\text{C} \tag{10}$$

$$\%S = 1 \quad \text{if} \quad T \leq -10^\circ\text{C}$$

where, $\%S$ is the monthly percentage of precipitation which is falling in the form of snow and T the mean monthly temperature.

The snowmelt of month J, SM(J) is estimated using the simple degree-day method (World Meteorological Organization (WMO) 1986):

$$\text{SM}(J) = C_{\text{m}} T(J) \tag{11}$$

where, T is the mean monthly temperature and C_{m} is the monthly melt rate factor (mm/°C per month).

The snow water equivalent of the accumulated snowpack, SWE_{sp} is estimated by:

$$\text{SWE}_{\text{sp}}(J) = \text{SWE}_{\text{sp}}(J-1) + S(J) - \text{SM}(J) \tag{12}$$

where, $S(J)$ is the snow fallen during month J equals to:

$$S(J) = \%SP(J) \tag{13}$$

where, $P(J)$ is the total precipitation of month J.

The model divides the total watershed runoff into three components: the surface runoff, the interflow, and the baseflow using a soil moisture mechanism. The first priority of the model is to fulfill the actual evapotranspiration. The monthly actual evapotranspiration E_{a} of month J depends on the available soil moisture and the average surface potential evapotranspiration E_{p} of month J. The monthly actual evapotranspiration is estimated using a relationship proposed by Vandewiele and Win (1998):

$$E_{\text{a}}(J) = \min\left\{E_{\text{p}}(J)\left(1 - \alpha^{S_{\text{moist}}(J)/E_{\text{p}}(J)}\right), S_{\text{moist}}(J)\right\} \tag{14}$$

where, $S_{\text{moist}}(J)$ is the available soil moisture of month J for the fulfillment of the actual evapotranspiration, α is a parameter for the actual evapotranspiration ($0 \leq \alpha \leq 1$), and $E_{\text{p}}(J)$ is the potential evapotranspiration of month J.

The surface runoff, SR of month J is calculated as:

$$\mathrm{SR}(J) = (1-K)(\mathrm{AS_{moist}}(J) - S_{\max}) \quad \text{if } \mathrm{AS_{moist}}(J) > S_{\max} \tag{15}$$

or

$$\mathrm{SR}(J) = 0 \quad \text{if} \quad \mathrm{AS_{moist}}(J) \leq S_{\max} \tag{16}$$

where, $\mathrm{AS_{moist}}(J)$ is the remaining soil moisture of month J after the fulfillment of the actual evapotranspiration ($S_{\mathrm{moist}}(J) - E_{\mathrm{a}}(J)$), $S_{\max} = \frac{25{,}400}{\mathrm{CN}} - 254$, the maximum soil moisture, CN is the Curve Number of the US Soil Conservation Service (1972), and K the deep infiltration parameter.

The deep infiltration, D of month J is calculated by the equation:

$$D(J) = K(\mathrm{AS_{moist}}(J) - S_{\max}) \quad \text{if} \quad \mathrm{AS_{moist}}(J) > S_{\max} \tag{17}$$

or

$$D(J) = 0 \quad \text{if} \quad \mathrm{AS_{moist}}(J) \leq S_{\max} \tag{18}$$

The available soil moisture of month J, N_{moist}, is calculated by the relation:

$$N_{\mathrm{moist}}(J) = \mathrm{AS_{moist}}(J) - \mathrm{SR}(J) - D(J) \tag{19}$$

The interflow from the soil moisture, MR, of month J is calculated as:

$$\mathrm{MR}(J) = \beta[N_{\mathrm{moist}}(J-1) + N_{\mathrm{moist}}(J)] \tag{20}$$

where, β the interflow parameter ($0 \leq \beta \leq 1$).

The remaining soil moisture at the end of month J, $\mathrm{NS_{moist}}$, is calculated by the relation:

$$\mathrm{NS_{moist}}(J) = N_{\mathrm{moist}}(J) - \mathrm{MR}(J) \tag{21}$$

The available soil moisture for the fulfillment of the actual evapotranspiration for the subsequently month (J+1) is:

$$S_{\mathrm{moist}}(J+1) = \mathrm{PSM}(J+1) + \mathrm{NS_{moist}}(J) \tag{22}$$

where,

$$\mathrm{PSM}(J+1) = R(J+1) + \mathrm{SM}(J+1) \text{ and } R(J+1) = [1 - \%S(J+1)]P(J+1) \tag{23}$$

The baseflow, Q_{g}, of month J is calculated by the deep infiltration, D, of the previous month $J-1$, from the relation:

$$Q_{\mathrm{g}}(J) = \gamma D(J-1) \tag{24}$$

where, γ a parameter for the baseflow ($0 \leq \gamma \leq 1$).

The groundwater recharge, R_{g},could be estimated from Eq. 23 as:

$$R_{\mathrm{g}}(J) = D(J-1) - \gamma D(J-1) \tag{25}$$

Finally, the total surface runoff, Q_{sim}, is the sum of the three components of runoff, the surface runoff, interflow and baseflow:

$$Q_{\mathrm{sim}}(J) = \mathrm{SR}(J) + \mathrm{MR}(J) + Q_{\mathrm{g}}(J) \tag{26}$$

The UTHBAL model has six parameters to be optimized in order to estimate watershed runoff, namely, Cm, CN, K, α, β, and γ. The optimization of the UTHBAL model parameters was performed using the Simplex Downhill Algorithm and the Nash–Sutcliffe Model Efficiency (Eff) (Nash and Sutcliffe, 1970) was used as the objective function. Apart of the Eff, two more statistical measures of the quality of runoff simulation were used: (a) the percentage runoff volume difference (DV%), and (b) the coefficient of determination (R^2) between the observed and simulated runoff.

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