Assessing future water supply and demand in a water-stressed catchment after environmental restrictions on abstractions

Alexandros Psomas, Yiannis Panagopoulos, Konstantinos Stefanidis and Maria Mimikou

ABSTRACT

The Ali Efenti catchment is a rural upstream subcatchment of the Pinios river basin in central Greece. The average annual precipitation in this subcatchment is relatively higher and groundwater recharge is relatively faster than in the rest of the river basin. Yet, seasonal water shortages occur due to the rapid increase of water abstractions in the summer months, mainly for crop irrigation. Up until 2030 the gap between water supply and demand is expected to deteriorate, considering the impacts of climate and socio-economic change. The adoption of environmental restrictions on water abstraction, which is a measure foreseen in the local river basin management plan, could decrease water stress substantially from 19.2% to 13.9%. However, this would require enormous (−26%) cuts in the current water abstractions during June–September, lowering water demand coverage from 86% to 68%. Optimal combinations of measures, from an economic and environmental perspective, will need to be designed to bridge the gap between water supply and demand and restore water demand coverage to satisfactory levels. Hydrologic and water resources management modelling has been implemented using the Water Evaluation and Planning system (WEAP), which is a conceptual model based on water balances.

Key words | naturalised flow, water abstraction, water demand, water stress, water supply, WEAP

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INTRODUCTION

The Pinios river basin is a water-stressed rural basin in central Greece, where 90–95% of the total water use is taken up by agricultural activities. Crop irrigation is extensively used to support satisfactory yield formation and quality, since the area suffers from water scarcity and droughts. The agricultural sector is important for the local and national economy and labour market, as this area is the primary producer of agricultural products in the country (Panagopoulos *et al.* 2014a, 2014b; SSW 2014a).

In the summer months, several stretches of the Pinios basin completely dry up. In a recent paper (Stefanidis *et al.* 2016), it was shown that there are significant hydrological alterations in the Pinios river basin, which are impacted from agricultural abstractions. These extreme hydromorphological alterations, which have also been reported in many Mediterranean rivers, affect the concentrations of sediments, nutrients and other chemical substances, as well as the biotic elements of the streams. The resulting low flows impact the composition and the functioning of the aquatic and terrestrial ecosystems which are linked to the respective water bodies (Harrison *et al.* 2008; Benejam *et al.* 2010; Uncles *et al.* 2013).

Climate change is projected to affect the area adversely as hydrologic extremes are expected to become more frequent and more intense (Loukas & Vasiliades 2004). In

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addition, socio-economic change is expected to increase the pressure on water resources, as a growing population and better living standards may drive water demand higher. However, the integration of future technological innovation will partly offset the increase in water demand (Dworak *et al.* 2007). Sustainable water resources management in the catchment needs to address the current and future gap between water supply and demand, while meeting conflicting goals. On the one hand, the groundwater resources should be protected from over-exploitation, while, on the other hand, the economic losses from water shortages should be reduced.

The local river basin management plan (RBMP) (SSW 2014a) estimates water stress of the local water bodies using a hydrologic approach, which is based on the statistical analysis of historical streamflow data. Furthermore, it defines scenarios of environmental restrictions on water abstractions to decrease current water stress. Although alternative and more elaborate approaches exist for determining the ecological flows in the context of the Water Framework Directive (WFD CIS 2015), this paper adopted and tested the above hydrologic approach, which is included in the local RBMP, to assess the practical issues emerging from its use. These issues are related to the following: (a) exploration of the potential to implement the above hydrologic approach for operational purposes using a hydrologic and water resources management model; (b) estimation of the naturalised streamflows in the catchment under climate and socio-economic change; (c) exploration of the current and future water stress conditions in the catchment; (d) estimation of the required reduction in water abstractions to meet the quantitative environmental targets set in the local RBMP; (e) investigation of the impact on water supply and demand from restricting water abstractions.

The applied model is the Water Evaluation and Planning system (WEAP21), which is a conceptual model based on water balances. WEAP's GUI, its flexible and customisable structure and its scenario analysis capabilities constitute its strong features (Yates *et al.* 2005). The pilot area is Ali Efenti catchment, which is an upstream subcatchment of the Pinios river basin, covering north-western Thessaly.

METHODOLOGY

Study area

The Ali Efenti catchment (2,921 km^2) is a rural upstream subcatchment of the Pinios river basin in Greece. The northern and western parts of the catchment are more mountainous, whereas the central and southeastern parts are covered by fertile plains. Forests, pasture, agricultural and urban land account for 33%, 31%, 23% and 2.5% of the total area, respectively. The main cultivated crop is cotton, followed by winter wheat, maize and alfalfa. The average annual rainfall is higher than in the rest of the parts of the Pinios river basin (ca. 860 mm), while reference evapotranspiration is also very high (ca. 1,410 mm). The observed average annual streamflow at the catchment outlet is approximately 40 m^3/s. The alluvial deposits in the plains generally show high hydraulic conductivity, allowing fast groundwater recharge. Irrigated agriculture takes up 90–95% of total water use. The major urban centres in the area are Trikala and Karditsa. Several industries, mainly from the food sector, are based close to them. No major dams exist, but parts of the broader Karditsa area are supplied with water from the Plastiras reservoir, which is considered an outside source. The irrigation infrastructure consists mostly of closed pipes, but an important share of collective networks still operates using open canals, which are responsible for high conveyance losses (30–50%). Drip and sprinkler irrigation systems are widely installed, resulting in limited on-field losses (5–20%) compared to furrow irrigation systems (30–40%). There is an unknown number of non-authorised boreholes for self-supply purposes. For this reason, the estimation of the actual water abstractions from the environment is difficult. Moreover, high conveyance losses are reported in the urban distribution networks (~40%) (Psomas 2012; Panagopoulos *et al.* 2014a).

WEAP model

Model description

WEAP was developed by the Stockholm Environment Institute's US Center (SEI-US). Due to major advances, the current version is officially labelled as WEAP21 to distinguish it from previous versions. WEAP21 attempts to combine an integrated modelling tool for water resources planning and management with a selection of conceptually simple models for watershed hydrology. It operates on the basic principle of a water balance and can be applied to a single watershed or a complex transboundary river basin system (Yates *et al.* 2005). WEAP21 is considered a conceptual model taking into account the schematisation approach for the physical system and the nature of the models used for describing the hydrological processes (Riepl 2013). The components of the natural system (e.g., catchments, aquifers, rivers and lakes) and the components of the technical system (e.g. reservoirs, boreholes, diversions, pipes, canals, cities, wastewater treatment plants, hydropower facilities and irrigated farms) are schematised using a network of inter-connected model elements without geographical reference. Model elements can fall into two main categories: nodes, where water is demanded or made available for supply, and links, which transfer water between the nodes. The water management model is driven by user-defined demand priorities, supply preferences and environmental requirements for the various nodes. The water allocation problem is solved using linear programming on a daily or monthly basis. The catchment nodes offer a selection of simplified hydrologic models, such as a runoff-coefficient method or a two-bucket groundwater model. Evapotranspiration, runoff, interflow, baseflow and percolation are estimated using empirical equations. Crop growth and yields can also be estimated at catchment level. WEAP21 allows for the introduction of user-defined variables and scripts, dynamic links to spreadsheets, coupling with water quality, groundwater and energy models, flexible scenario building and analysis and visualisation of model variables or output results (Sieber & Purkey 2015).

Model set-up, calibration and validation

Relevant datasets for the Ali Efenti catchment were collected and organised in a database. The geospatial information was processed using geographic information system (GIS) tools. Data included information on topography, geology/hydrogeology, land use, climate/hydrometeorology, water supply/demand/consumption, water efficiency, wastewater treatment, management practices, administration and socioeconomic affairs. The data originate from various sources, such as the Greek Ministry of Environment, the Public Power Corporation, the National Institute of Geology and Mineral Exploration, the National Institute of Soil Mapping and Classification, CORINE Land Cover, Eurostat and previous studies conducted in the Pinios river basin.

A GIS map of the area was used as reference background to schematise the river network, the subcatchments, the main groundwater bodies and other physical elements of the Ali Efenti catchment in WEAP21. The schematisation (Figure 1) led to 23 subcatchment nodes, eight

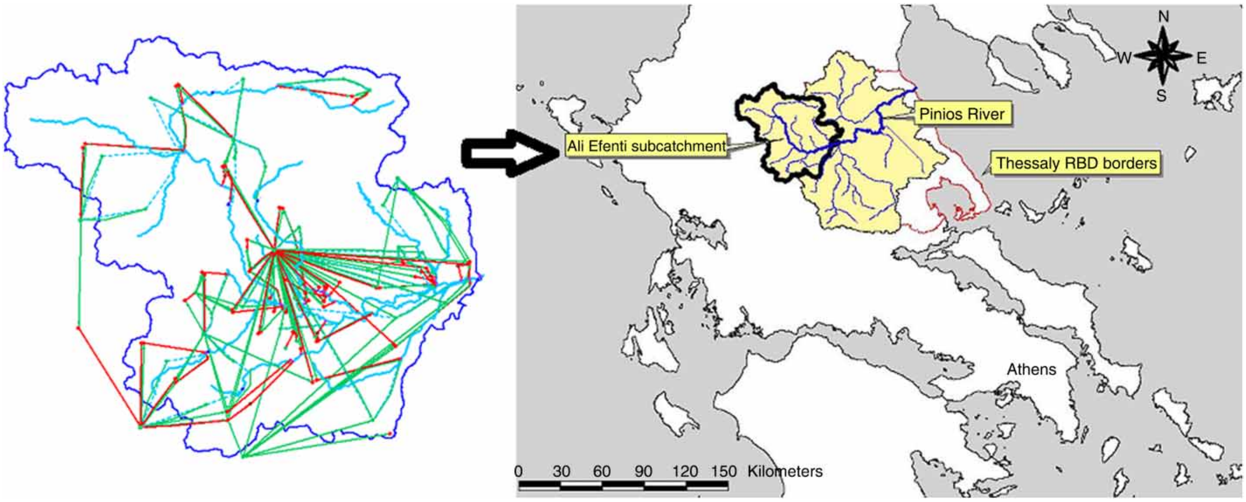

Figure 1 | Schematisation of the WEAP model for the Ali Efenti catchment in the Pinios river basin.

groundwater nodes, three spring nodes and one outside source node (Plastiras reservoir). Demand-site nodes were added in each municipality dealing with domestic, tourism, livestock and industrial water use. Special nodes were added for the wastewater treatment plants. All nodes were linked with transmission and return elements to account for water transfers between the water sectors and the environment or between the water sectors. Catchment rainfall–runoff modelling followed an approach based on runoff-coefficients. Irrigation needs were estimated using the approach of FAO (Allen *et al.* 1998).

The model calibration was executed via a WEAP21–Matlab conjunction (Psomas 2012; Tsoukalas & Makropoulos 2013) using simulated annealing as optimisation algorithm. The calibration and the validation were implemented using the observed streamflow at gauge stations within the catchment starting from upstream to downstream. The calibrated parameters included model variables for direct runoff and percolation. Such variables are highly site-specific and cannot be obtained through literature. Three fitness criteria were estimated: Efficiency/Nash–Sutcliffe coefficient (NSE) (Equation (1)), correlation factor (r) (Equation (2)) and mean value bias (PBIAS) (Equation (3)). The calibration (1981–1984) and the validation (1984–1988) results for the catchment outlet at Ali Efenti gauge show very good fit of the model, given the complexity of the study area (Table 1).

$$NSE = 1 - \frac{\sum_{i=1}^{n} (Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n} (Q_{obs,i} - \bar{Q}_{obs})^2} \tag{1}$$

$$r = \frac{\sum_{i=1}^{n} (Q_{obs,i} - \bar{Q}_{obs})(Q_{sim,i} - \bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n} (Q_{obs,i} - \bar{Q}_{obs})^2 (Q_{sim,i} - \bar{Q}_{sim})^2}} \tag{2}$$

Table 1 | Calibration and validation results of WEAP21

	Fitness criterion		
Ali Efenti gauge process	**Efficiency/Nash–Sutcliffe coefficient (NSE)**	**Correlation factor (r)**	**Mean value bias (%) (PBIAS)**
Calibration	0.626	0.800	−11.6
Validation	0.571	0.765	8.4

$$PBIAS\ (\%) = \frac{\sum_{i=1}^{n} (Q_{obs,i} - Q_{sim,i}) * 100}{\sum_{i=1}^{n} (Q_{obs,i})} \tag{3}$$

Future climate change

Climate change projections for the SRES A1B scenario (i.e., moderate emissions; balanced use of fossil and non-fossil fuels) have been obtained from the National Observatory of Athens (NOA), which was a partner of the EU project ENSEMBLES (http://ensembles-eu.metoffice.com/). The driving Global Climate Model (GCM) was ECHAM5, while dynamic downscaling was carried out using the Regional Climate Model (RCM) RACMO2.1 (van Meijgaard *et al.* 2008). The physics package of RACMO2 is based on the ECMWF model (White 2003). The gridded data are available at 50 km resolution.

The time series of the climate projections at the grid nodes were matched to the existing hydrometeorological stations in the area and they have been compared to the historical observations of the same stations for a long reference period (1980–2010), which included both wet and dry periods. The climate projections were corrected using the 'delta' method (Loukas & Vasiliades 2004; Chen *et al.* 2011; Psomas 2012; Kossida 2015).

The interpretation of the corrected time series reveals that during 2015–2030 the temperature may increase by 0.5 °C and the precipitation may increase by 0.8%. Temperature increases for all seasons, whereas precipitation decreases in winter and summer and increases in spring and autumn. It should be highlighted that during the typical irrigation season in the area (April to September), precipitation is estimated to fall significantly by 8.5%. The reduction of precipitation and the simultaneous increase of temperature (and evapotranspiration) during the irrigation season could cause the increase of crop irrigation needs by 2.7–3.9%, provided that crop patterns remain similar.

Future socio-economic change

Future developments in the society and the economy, worldwide and regionally, are expected to influence the local environment, including the consumption, management and protection of local water resources. The trends in demographics, global trade, policy-making, income levels, wealth distribution and the societal values towards environmental goods and services could affect the future water management policies and practices. Such considerations have been integrated in the water scenarios for Europe, which have been developed during the EU project SCENES (http://www.peer.eu/projects/peer-flagship-projects/scenes/), after extensive consultation with experts (Kok *et al.* 2011). The respective narrative for the Mediterranean region has inspired a local water scenario for the Pinios river basin, named P1 (Psomas 2012). It is assumed that the world is heading towards faster globalisation and liberalisation of markets, enhancement of decision-making at the supra-national level, more decisive influence of markets and businesses in policy-making and more balanced exploitation of fossil fuels and renewable energy sources. Furthermore, P1 has been developed to take into account the particularities and the local trends of the Greek society and economy within the global context, making use of numerous foresight studies developed by Greek and international institutions and historical trends from Greek and European statistics. Regarding agriculture, which is the primary water user in the area, the foresight study included in the local RBMP (SSW 2014a) and the extensive stakeholder consultation organised during the EU project i-adapt (http://i-adapt.gr/) have been considered.

The water-related assumptions of the local water scenario P1 can be summarised in Table 2. In general, water demand for the urban, livestock and industrial sectors is expected to increase, while water demand for the irrigated agriculture is expected to depend only on climate variability and change.

Table 2 | Summary assumptions of local water scenario P1 (2015–2030)

Key scenario parameters	Change: 2030 vs. 2010
Population	+10.6%
Water use per capita	+5.9%
Nights spent per tourist	+30%
Number of sheep	+10%
Number of pigs	+30%
Number of cattle	+40%
Industrial production	+30%
Urban land	+6.7%
Prairies	−0.5%
Agricultural-irrigated area	No change
Dams/Reservoirs	No change
WWTPs	+4 new installations/+ 2 extensions

Environmental restrictions on water abstractions

Human activities interact with the natural components of the hydrological cycle and result in the modification of the routes and the biochemical composition of water. Examples of anthropogenic interventions to natural watershed hydrology include the construction of dams and artificial reservoirs, the extraction of groundwater for drinking water or for crop irrigation, the use of desalinated water for inland activities, the withdrawals from rivers for cooling purposes in thermal power plants, the disposal of (treated or non-treated) wastewater in rivers and the contamination of soil water with chemicals.

From the water quantity perspective, the 'naturalised streamflow' represents the hypothetical river streamflow without the influence of the human activities. The water abstractions and returns from/to river bodies and the artificial works for river regulation impose hydromorphological alterations to river segments. The resulting higher or lower flows and river diversions affect the transfer of water, sediments, nutrients and other chemical substances downstream and, consequently, they impact the aquatic and terrestrial ecosystems which are linked to the respective water bodies (Harrison *et al.* 2008; Yang *et al.* 2008; Benejam *et al.* 2010; Uncles *et al.* 2013).

On catchment scale, *naturalised streamflow*, *net water abstraction* and *water stress* can be calculated using Equations (4)–(6), respectively. For those catchments where dams and reservoirs exist, their impact on catchment hydrology should be integrated into the calculation of the naturalised streamflow. In addition, for those catchments where hydrogeology allows extensive connectivity and strong interaction between surface water and groundwater bodies, the calculation needs to consider both the abstractions from rivers and aquifers. In such cases, higher abstractions from the rivers may lead to lower recharge of the aquifers and, vice versa, higher abstractions from the aquifers may lead to lower baseflow in the rivers.

$$\text{Naturalised streamflow} = \text{Reference streamflow}_{(\text{observed or simulated})} + \text{Net water abstraction} \quad (4)$$

$$\text{Net water abstraction} = \text{Gross water abstraction} - \text{Return before use} - \text{Return after use} \quad (5)$$

$$\text{Water stress} = \frac{\text{Net water abstractions}}{\text{Naturalised streamflow}} \quad (6)$$

The RBMP of the River Basin District (RBD) of Thessaly sets out local empirical thresholds for the characterisation of water stress following a hydrological approach (SSW 2014a). The thresholds have been determined using a statistical analysis of a long sample of local streamflows (1960–1993). Following this approach, if the water stress exceeds 50% on a monthly or a seasonal basis, then the pressure on the water body is considered 'severe'. The rest thresholds for the characterisation of water stress are shown in Table 3. The water stress is calculated for two temporal scales and the worst characterisation determines the characterisation of the overall water stress of the water body.

Furthermore, the RBMP of Thessaly sets out two scenarios of environmental restrictions on water abstractions from surface water and groundwater bodies to relieve water stress in the RBD. The scenario of *moderate environmental restrictions* requires that the water stress of the surface water bodies does not exceed 50% in the dry period and pumping from groundwater bodies is capped at 300 hm^3 per year. Similarly, the scenario of *high environmental restrictions* requires that the water stress of the surface water bodies does not exceed 35% in the dry period and pumping from groundwater bodies is capped at 250 hm^3 per year.

The adoption of any scenario of environmental restrictions on water abstractions will mean that the current level of water abstractions will need to be truncated for the portion that exceeds the maximum allowed water abstractions. The scenario of moderate environmental restrictions on water abstractions is already very ambitious for this water-stressed Greek RBD. Therefore, between the two proposals, the moderate scenario is assumed to be the most likely to be adopted in the future.

Moreover, since the surface water bodies and the groundwater bodies in the Ali Efenti catchment (especially the alluvial deposits in the lowlands) have a strong hydraulic interaction between them, the calculation of the naturalised streamflow should integrate both the net abstractions from rivers and aquifers in the lowlands. Therefore, the estimated water stress in the catchment should not distinguish between surface and groundwater bodies. This allows us to use only one equation for both types of water bodies.

In WEAP, the environmental restrictions on water abstractions may be modelled in various ways by combining its built-in capabilities: the *maximum flow* for the transmission links between water bodies and demand sites; or the *maximum groundwater withdrawal* for total abstractions from groundwater model elements; or the *minimum flow requirement* to ensure a minimum monthly streamflow at the catchment outlet.

Table 3 | Characterisation of water stress in the RBD of Thessaly (SSW 2014a)

Characterisation of water stress (WS)	Reference temporal scale	
	Annual	**Dry period**
Severe	WS > 50%	WS > 50%
Moderate	30% < WS < 50%	35% < WS < 50%
Low	15% < WS < 30%	20% < WS < 35%
Negligible	WS < 15%	WS < 20%

Baseline and future scenarios

The selected baseline period is 1995–2010. The input climate data represent historical observations at the key hydrometeorological stations within and around the catchment. Thiessen polygons have been used to estimate the average precipitation over each catchment. Precipitation has been corrected for the altitude of the respective stations. The input socio-economic data collected for this period were not available on an annual scale. Therefore, logical assumptions and extrapolations have been applied to complete the temporal gaps.

Three different scenarios have been developed for the future (2015–2030). The CC scenario only includes the impact of climate variability and change, assuming no additional change. The CCP1 scenario includes the impact of both climate and socio-economic change, based on the local water scenario P1. The CCP1ENV scenario combines the impact of climate and socio-economic change with the adoption of environmental restrictions for water abstractions, based on the moderate scenario described in the local RBMP of Thessaly (see the section 'Environmental restrictions on water abstractions').

After the simulation of each scenario, the *water supply* from all sources to all users and the *water demand* from all sources by all users are calculated. The gap between water supply and demand can be approached by using the *unmet water demand* from all sources by all users (Equation (7)) and the *water demand coverage* in the catchment (Equation (8)). Calculations can be further elaborated to reflect the various water uses (i.e., urban and tourism, irrigated agriculture, livestock, industry) to explore the gap between water supply and demand by economic activity. Water stress is estimated using Equation (6).

$$\text{Unmet water demand} = \text{Water demand} - \text{Water supply} \tag{7}$$

$$\text{Water demand coverage} = \frac{\text{Water supply}}{\text{Water demand}} \tag{8}$$

RESULTS AND DISCUSSION

Monthly naturalised streamflow and water stress in the catchment

Following the methodology described in the section 'Environmental restrictions on water abstractions', naturalised streamflow and water stress in the catchment have been estimated for the baseline and future scenarios CCP1 and CCP1ENV.

The annual naturalised streamflow in the baseline is approximately 1,420 hm^3, which is very similar to the estimation provided in the local RBMP (1,399 hm^3). In the future (2015–2030), after integrating the impact of climate and socio-economic change (scenarios CCP1/CCP1ENV), the annual naturalised streamflow shows a slight reduction by 1% overall. This slight reduction occurs because the increase in the average evapotranspiration is almost balanced by the increase in the average precipitation in the timeframe of the analysis (2015–2030). Given the uncertainties included in the analysis, the estimated reduction is negligible. It should be highlighted, though, that on a monthly scale (Figure 2) there is a significant reduction in the naturalised streamflows of the driest months of the year, which are August (−20%) and September (−45%).

The annual water stress in the baseline is 19.2% ('low' annual stress), which is very similar to the estimation provided in the local RBMP (19.6%). In future scenario CCP1 (no restrictions on abstractions), the water stress is expected to remain almost the same on an annual scale. Despite the rise of the water demand, which is foreseen in water scenario P1 (see the section 'Future socio-economic change'), most of the additional demand is not satisfied, because it occurs in the severely water-stressed season. Hence, it adds up to the existing unmet demand in the catchment (see the section 'Gap between water supply and demand'). On a monthly scale (Figure 3), the situation is expected to deteriorate if no measures are considered. The months with severe water stress (>50%) are expected to increase from three (June–August) to four (June–September). In addition, the highly water-stressed conditions in July, August and September are expected to worsen. In scenario CCP1ENV (restrictions on abstractions), the annual water stress is expected to fall sharply to 13.9% ('negligible' annual stress). On a monthly scale (Figure 3), a huge improvement is also detected. After truncating the water abstractions exceeding the monthly limit that indicates severe water stress (50%), no month is in severe water stress.

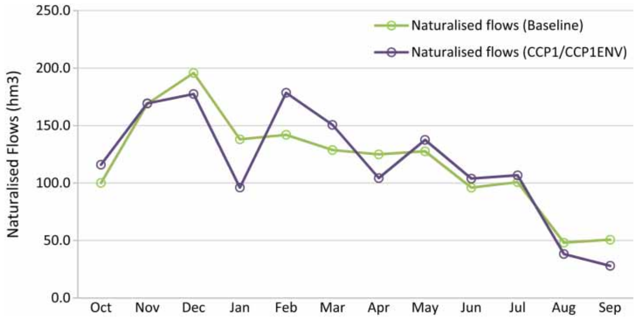

Figure 2 | Mean monthly naturalised streamflow in the Ali Efenti catchment for baseline, CCP1 (future without environmental restrictions) and CCP1ENV (future with environmental restrictions) scenarios.

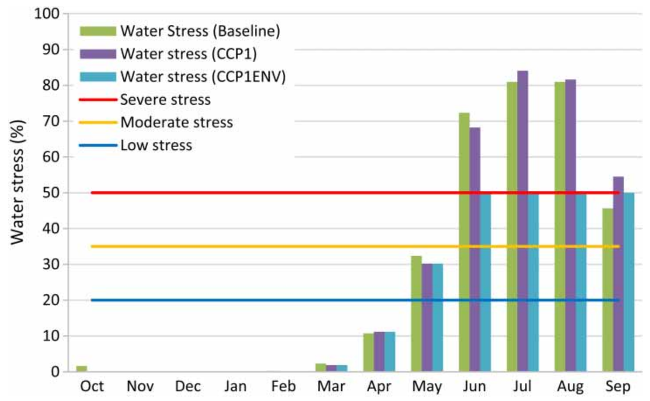

Figure 3 | Mean monthly water stress in the Ali Efenti catchment for baseline, CCP1 (future without environmental restrictions) and CCP1ENV (future with environmental restrictions) scenarios.

The comparison of scenarios CCP1 and CCP1ENV (Figure 4) shows that the gross abstractions from surface water and groundwater bodies in the lowland areas (alluvial deposits) will need to be reduced by 8–41% on a monthly scale or 26% on an annual scale, due to the environmental restrictions adopted for CCP1ENV. This amounts to approximately 90 hm^3. The annual gross water abstractions in the lowland areas are expected to fall from 356 to 265 hm^3. The cuts are applied to the four months with water stress over 50% (June–September).

Gap between water supply and demand

Table 4 | Gap between water supply and demand in the baseline and future scenarios CC (climate change), CCP1 (climate and socio-economic change) and CCP1ENV (climate change, socio-economic change and environmental restrictions)

Parameter	Baseline	Difference: CC-baseline	Difference: CCP1-CC	Difference: CCP1ENV-CCP1
Water demand (hm^3)	508.4	+10.5	+2.7	±0.0
Water supply (hm^3)	436.2	+7.4	+2.0	−90.7
Unmet water demand (hm^3)	72.1	+3.1	+0.7	+90.7
Water demand coverage (%)	85.8	−0.4	−0.1	−17.4

The simulation results (Table 4) of the baseline and the future scenarios CC, CCP1 and CCP1ENV suggest that the initial unmet demand, which is 72.1 hm^3, is expected to grow by 3.1 hm^3 because of the impact of climate change and 0.7 hm^3 because of the impact of socio-economic change. The adoption of environmental restrictions on water abstractions is expected to increase unmet demand enormously by 90.7 hm^3, because the available water supply will be reduced dramatically. Overall, water demand in the catchment is expected to exceed water supply by 166.6 hm^3 in CCP1ENV. The most significant driver for this gap seems to be the reduction of water abstractions, which aims at relieving the water stress in the catchment. Driving water stress from 19.2% to 13.9% (see the section 'Monthly naturalised streamflow and water stress in the catchment') impacts the water demand coverage largely, since it is expected to fall from almost 86% in the baseline to 68% in CCP1ENV (after the restrictions).

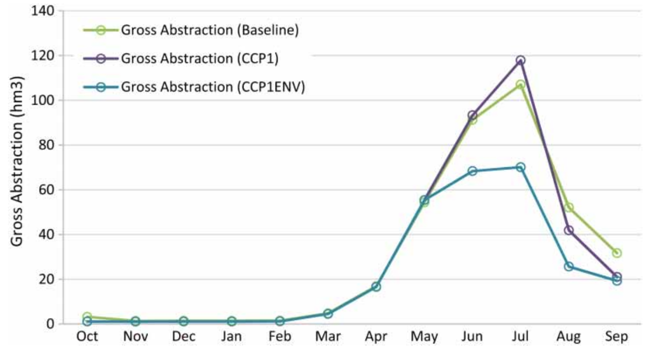

Figure 4 | Mean monthly gross abstractions in the lowlands of Ali Efenti catchment for baseline, CCP1 (future without environmental restrictions) and CCP1ENV (future with environmental restrictions) scenarios.

On a monthly scale, the highest unmet water demand and the lowest water demand coverage occurs during July–September. In the CCP1ENV scenario, the situation worsens, because the reductions in water abstractions decrease the water supply to the consumers, while water demand is the same as in CCP1.

The simulations also indicate that 99% of the unmet demand occurs in the lowland areas of the catchment. This is explained by the fact that the majority of the fields under collective or individual irrigation systems and the majority of the livestock is located in this part of the catchment. Agriculture (including irrigation and livestock breeding) is the major water user in the catchment and almost all of the unmet demand comes from this sector (>99.5%). The share of the urban (including tourism) or the industrial sector in total unmet demand is significantly lower (<0.5%). However, taking into account the socio-economic context and the risks behind these two water uses, it should be highlighted that even the smallest cuts could cause serious damages in these sectors.

Discussion of the results

On the one hand, the above results indicate that the adoption of environmental restrictions on water abstractions may drive water stress in the catchment from 19.2% to 13.9%. On the other hand, this will cause a significant decrease in the water demand coverage from 86% to 68%. A large proportion of future water demand will remain unmet and this will have a harsh impact on the agricultural sector of this rural catchment. Lower productivity and lower revenues for agricultural holdings, due to limited water availability, will have a knock-on effect on the local economy and labour market. Therefore, practical and cost-efficient solutions need to be sought in order to bridge the estimated gap between water supply and demand.

There are three socio-technical challenges associated with the decision to reduce water abstractions in the catchment. The first is the feasibility to monitor and control the compliance of the water users, either as individuals or as collective entities. The second is the feasibility to improve the water demand coverage in terms of available technology and/or methodology. The third challenge is to assess and combine the various measures to develop optimal bundles of them, in terms of economic and environmental performance.

Monitoring and controlling the compliance of the water users with the targets for water abstractions is very challenging in the Ali Efenti catchment. It is estimated that the irrigated areas under collective irrigated networks do not exceed 30% of the total (Psomas 2012), whereas large areas are being irrigated with non-authorised individual systems. In recent years, Greek national and local authorities have initiated various measures to support their efforts in mapping and reducing water abstractions in the Pinios river basin (SSW 2014b). They have proposed the restructuring of the local/general organisations for reclamation works, which operate the collective irrigation networks, and the specification of trustworthy irrigation schemes by their members. Generally, this is described as a low cost measure and strict water metering would be much easier in this case than for the individual systems. Moreover, the Ministry of Environment has revaluated and revised the national regulation on water abstraction permits. It has established the national registry of abstraction points and it is updating the regional limits of irrigation needs per crop category. The licensed water users are required to install water meters and the abstractions from major users have to be registered by the competent agencies. Any abstraction not included in the registry is considered illegal, it is punished with penalties and the non-authorised boreholes are closed. On-site inspections are also foreseen twice a year for the major water users. Most of these measures have low implementation cost, except for the development of the national registry, which has a budget of 2.6 M€ co-funded with EU funds. In addition to the above measures, the mapping of non-authorised abstractions could be facilitated by using Earth Observation technologies in combination with other ground data sources (Bea Martínez *et al.* 2003; Castaño *et al.* 2010).

Regarding the gap between water supply and demand in the catchment, there are currently many technological and socio-economic tools available to close it (Dworak *et al.* 2007; EEA 2012). In general, the measures may target increasing water supply or decreasing water demand. The current options of increasing water supply in the Ali Efenti catchment are rather limited, since no major dams and reservoirs have been planned. The local Programme of Measures (PoM) (SSW 2014b) describes a series of demand-side measures, which focus on cutting the water needs directly or cutting the accompanying losses. These include the repair and upgrade of the urban water networks to reduce leakages, the promotion of water efficiency schemes in the industrial sector, the promotion of water efficiency audits in buildings, the promotion of wastewater treatment and reuse in irrigated agriculture and groundwater recharge, the promotion of rainwater harvesting, the promotion of water recycling, the banning of irrigation during hot mid-days, the upgrade of irrigation canals and pipelines, the promotion of drip irrigation, the adaptation of water pricing to ensure higher cost recovery and to incentivise water saving, the educational/training programmes and the awareness campaigns.

The estimated budget for the implementation of the above measures exceeds 80 M€ for the whole RBD. It should be highlighted, though, that the response of the consumers to the expected water efficiency gains is difficult to predict. A rebound effect, which could partially offset the positive impacts of the measures, is possible, as water users may take advantage of the saved water to expand their activities (Pfeiffer & Lin 2014). Therefore, it is important to have in place a strict framework for monitoring, assessing and fine-tuning the measures in close collaboration with the local communities and stakeholders to avoid similar trends.

There are various mixtures of measures which could succeed in driving water demand in the catchment at lower levels. However, not all measures are suitable across all areas. For example, the application of deficit irrigation depends greatly on the crop resistance against water stress. From an economic perspective, it is important to assess the monetary costs and benefits from implementing each measure across the various suitable locations. Also, from an environmental perspective, it is important to evaluate the externalities which emerge from implementing a measure (e.g., indirect impacts on ecosystems and their services). The selection and combination of measures in a cost-effective and environmentally responsible way is crucial for achieving a sustainable water management in the catchment. For the Pinios river basin, such efforts are described in Panagopoulos *et al.* (2014b), Kossida (2015) and Psomas *et al.* (2016). Unfortunately, the local PoM lacks structured and science-based evidence on these issues, since it focuses on listing measures, whereas it should seek optimal combinations and spatial distribution of them from an economic, environmental and social perspective.

It should be noted that the water stress in the catchment has been determined following a hydrologic method, which is based on the naturalised streamflows. In general, the hydrologic methods assume that the natural variability of the hydrological regime is crucial for the ecosystem functioning. These methods are often easy to apply due to their simplicity in logic and good availability of historical data. The present study aims at gaining insight into the practicalities and impacts from implementing the environmental restrictions using this method, since this is the only one adopted in the local RBMP. Nevertheless, alternative and more elaborate approaches exist for determining the ecological flows (WFD CIS 2015).

The selected climate and socio-economic scenarios include a wide range of assumptions, which increase the uncertainty of the present analysis. Nevertheless, the impact of these assumptions in the final results is expected to be low for two reasons. First, these assumptions have been harvested from official reports or foresight studies and many of them have been discussed in workshops with local stakeholders. Second, the impact of climate and socio-economic change on future water supply and demand in the catchment was found to be relatively small within the timeframe of the analysis (2015–2030). Thus, the uncertainty bound in these assumptions plays a small role in the final findings.

It should be highlighted that the timeframe of the analysis is limited up to 2030, because the scope of the current study is focused on: (a) the implementation of environmental restrictions on abstractions in the short term and (b) the investigation of the impacts on water resources and water management in the mid term. Therefore, the above timeframe is adequate for the purpose of the analysis. Although climate change is small in the respective period, the long-term analysis of the climate projections shows that precipitation in the Eastern Mediterranean is expected to drop significantly after mid-century. Although it is difficult to forecast the technological and socio-economic advances that might have occurred by then, the trends indicate that the gap between water supply and demand will grow. Thus, additional adaptation efforts will be needed at a later period. Moreover, the current study could be further improved if the most updated RCP scenarios for future progress (AR5) were used. However, the respective data for Pinios river basin were not available at the beginning of this study, and the elaborated SCENES water storylines, at the level of European regions (e.g., the Mediterranean), were built based on the GEO-4 storylines (AR4).

CONCLUSIONS

The Ali Efenti catchment suffers from seasonal water shortages, which lead to high gaps between water supply and demand. Almost all the unmet demand comes from the agricultural sector, which accounts for 90–95% of the water use in the area. The local RBMP for the Pinios river basin describes two scenarios of future environmental restrictions on water abstractions, which aim at relieving the existing water stress. Based on the moderate scenario, the water abstractions will need to be reduced to eliminate severe water stress in the dry period. This means that the net abstractions will need to be restrained below half of the volume of the naturalised flow at the catchment outlet. Catchment hydrology and water resources management have been modelled using a conceptual model based on water balances, the Water Evaluation and Planning system (WEAP21).

The simulation results indicate that future climate and socio-economic changes in the region are expected to have a relatively small impact on the local water stress, at least in the timeframe of the analysis (2015–2030). On the contrary, restricting the water abstractions to satisfy the environmental goals will cause a substantial drop in the annual water stress from 19.2% to 13.9%. To make this feasible, an enormous reduction in water abstractions will be required, which amounts to 90 hm^3 (−26%) during the dry period (June–September). Without the restrictions, the months with severe water stress (>50%) are expected to increase from three (June–August) to four (June–September). After the restrictions, the situation improves greatly, as no month is expected to have severe water stress. The key negative impact from the environmental restriction on water abstractions is the dramatic deterioration of the gap between water supply and demand. The unmet water demand will rise, since less water supply will be delivered for the same water demand. Hence, the water demand coverage will decrease from 86% to 68%.

The PoM of the RBMP of the Pinios river basin describes numerous measures, which are currently implemented or will be funded as a priority in the future. Regarding the Ali Efenti catchment, these include mainly demand-side measures, which focus on monitoring and controlling water use, enhancing water efficiency in the urban, agricultural and industrial sector, and raising public awareness on the issue of water scarcity and drought. The local PoM lacks structured and science-based evidence on how best to combine and distribute these measures spatially in a cost-efficient, target-effective, environmentally responsible and socially acceptable manner.

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REFERENCES

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration: Guidelines for Computing Crop Requirements*. Irrigation and Drainage Paper No. 56, Food and Agriculture Organization (FAO), Rome, Italy.

Bea Martínez, M., Montesinos Aranda, S. & Benítez Navío, A. 2003 Application of remote sensing techniques for groundwater extractions management in Mancha occidental aquifer. In: *6th Inter-Regional Conference on Environment-Water*, 3–5 September 2003, Albacete, Spain.

Benejam, L., Angermeier, P. L., Munné, A. & García-Berthou, E. 2010 Assessing effects of water abstraction on fish assemblages in Mediterranean streams. *Freshwater Biology* **55**, 628–642.

Castaño, S., Sanz, D. & Gómez-Alday, J. J. 2010 Methodology for quantifying groundwater abstractions for agriculture via remote sensing and GIS. *Water Resources Management* **24**, 795–814.

Chen, J., Brissette, F. P. & Leconte, R. 2011 Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. *Journal of Hydrology* **40**, 190–202.

Dworak, T., Berlund, M., Laaswer, C., Strosser, P., Roussard, J., Grandmougin, B., Kossida, M., Kyriazopoulou, I., Berbel, J., Kolberg, S., Rodriguez-Diaz, J. A. & Montesinos, P. 2007 *EU Water Saving Potential*. Final Report ENV.D.2/ETU/2007/0001r, Ecologic (in cooperation with ACTeon, NTUA and University of Cordoba), Berlin, Germany, 247 pp.

EEA (European Environment Agency) 2012 *Towards Efficient Use of Water Resources in Europe*. EEA Report No. 1/2012, European Environment Agency, Copenhagen, Denmark, 74 pp.

Harrison, P. A., Berry, P. M., Henriques, C. & Holman, I. P. 2008 Impacts of socio-economic and climate change scenarios on wetlands: linking water resource and biodiversity meta-models. *Climatic Change* **90** (1), 113–139.

Kok, K., van Vliet, M., Barlund, I., Dubel, A. & Sendzimir, J. 2011 Combining participative backcasting and exploratory scenario development: experiences from the SCENES project. *Technological Forecasting & Social Change* **78**, 835–851.

Kossida, M. 2015 *Methods and Tools Supporting Operational Drought Risk Management in Water Stressed Areas*. PhD Dissertation, School of Civil Engineering, National Technical University of Athens, Athens, Greece.

Loukas, A. & Vasiliades, L. 2004 Probabilistic analysis of drought spatiotemporal characteristics in Thessaly region, Greece. *Natural Hazards and Earth System Sciences* **4**, 719–731.

Panagopoulos, Y., Makropoulos, C., Gkiokas, A., Kossida, M., Evangelou, E., Lourmas, G., Michas, S., Tsadilas, C., Papageorgiou, S., Perleros, V., Drakopoulou, S. & Mimikou, M. 2014a Assessing the cost-effectiveness of irrigation water management practices in water stressed agricultural catchments: the case of Pinios. *Agricultural Water Management* **139**, 31–42.

Panagopoulos, Y., Makropoulos, C., Kossida, M. & Mimikou, M. 2014b Optimal implementation of irrigation practices: cost-effective desertification action plan for the Pinios Basin. *Journal of Water Resources Planning and Management* **140** (10) doi: http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000428.

Pfeiffer, L. & Lin, C.-Y. 2014 Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence. *Journal of Environmental Economics and Management* **67** (2), 189–208.

Psomas, A. 2012 *Water Resources Management in Pinios River Basin Under Climate and Socio-Economic Change Using the WEAP21 Software (in Greek)*. Postgraduate Thesis, IPPS Water Resources Science & Technology, National Technical University of Athens, Athens, Greece.

Psomas, A., Panagopoulos, Y., Konsta, D. & Mimikou, M. 2016 Designing water efficiency measures in a catchment in Greece using WEAP and SWAT models. Special Issue: International Conference on Efficient & Sustainable Water Systems Management toward Worth Living Development, 2nd EWaS 2016. *Procedia Engineering* **162**, 269–276.

Riepl, D. 2013 *Knowledge-Based Decision Support for Integrated Water Resources Management with an Application for Wadi Shueib, Jordan*. PhD Dissertation, Fakultät für Bauingenieur-, Geo- und Umweltwissenschaften, Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany.

Sieber, J. & Purkey, D. 2015 *WEAP – Water Evaluation And Planning System: User Guide for WEAP 2015*. Stockholm Environment Institute – US Center, Somerville, MA, USA.

SSW (Special Secretariat for Water) 2014a *River Basin Management Plan of the River Basin District of Thessaly (GR08)*. Ministry of Environment, Energy and Climate Change, Athens, Greece.

SSW (Special Secretariat for Water) 2014b *Interim Implementation Progress Report of the Programme of Measures of the River Basin Management Plan of the River Basin District of Thessaly (GR 008) (in Greek)*. Ministry of Environment, Energy and Climate Change, Athens, Greece.

Stefanidis, K., Panagopoulos, Y., Psomas, A. & Mimikou, M. 2016 Assessment of the natural flow regime in a Mediterranean river impacted from irrigated agriculture. *Science of the Total Environment* **573**, 1492–1502.

Tsoukalas, I. & Makropoulos, C. 2013 Hydrosystem optimization with the use of Evolutionary Algorithms: The case of Nestos River. In: *13th International Conference on Environmental Science and Technology (CEST2013)*, 5–7 September, Athens, Greece.

Uncles, R. J., Stephens, J. A. & Harris, C. 2013 Towards predicting the influence of freshwater abstractions on the hydrodynamics and sediment transport of a small, strongly tidal estuary: The Devonshire Avon, special issue: managing estuarine sediments. *Ocean & Coastal Management* **79**, 83–96.

van Meijgaard, E., van Ulft, L. H., van de Berg, W. J., Bosveld, F. C., van den Hurk, B. J. J. M., Lenderink, G. & Siebesma, A. P. 2008 *The KNMI Regional Atmospheric Climate Model RACMO Version 2.1*. Technical Report 302, Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands.

WFD CIS 2015 *Guidance Document No 31: Ecological Flows in the Implementation of the Water Framework Directive*. Technical Report – 2015–086, Office for Official Publications of the European Communities, Luxembourg.

White, P. W. (ed.) 2003 *Part IV: Physical Processes (CY23R4), IFS Documentation Cycle CY23r4*. European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK.

Yang, T., Zhang, Q., Chen, Y. D., Tao, X., Xu, C. & Chen, X. 2008 A spatial assessment of hydrologic alteration caused by dam construction in the middle and lower Yellow River, China. *Hydrological Processes* **22**, 3829–3843.

Yates, D., Sieber, J., Purkey, D. & Huber-Lee, A. 2005 WEAP21 – A demand-, priority-, and preference-driven water planning model, part 1: model characteristics. *Water International* **30** (4), 487–500.

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