Allocation of surface and subsurface water resources to competing uses under climate changing conditions: a case study in Halkidiki, Greece

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ABSTRACT

The present study describes an integrated modeling framework for surface and groundwater resources planning, management and allocation. The study area includes four groundwater systems of Halkidiki Prefecture in Northern Greece, all facing serious water quality and/or quantity issues, especially during the summer period due to intensive agricultural activity and tourism. Within all four systems, the water demand is met exclusively by groundwater resources. Initially, a supply–demand model is applied under different climate conditions to assess groundwater resource availability. Then a certain quantity of surface water is considered available, due to the potential (future) construction and operation of two reservoirs within the study area and an optimal water allocation model using linear programming is developed. The combined use and allocation of surface and subsurface water under climate changing conditions is also being studied by investigating three additional scenarios in which either every one of the two reservoirs operates solely or both reservoirs operate together. The model was applied using Water and Evaluation Planning (WEAP) software, while the climate data were abstracted from Regional Climate Model REGCM3_10 km and ERA-Interim reanalysis data bases. Finally, the results of unmet demand, water supply coverage and reservoir storage were evaluated as water management action efficiency indicators.

Key words | climate change, combined surface and groundwater use, integrated modelling, optimal water management, water allocation, WEAP

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INTRODUCTION

Water is necessary for life and socioeconomic development of a country and basic support to all human and eco-environmental systems. However, rapid population growth, urbanization, industrial development and increased agricultural activity have led to overexploitation and pollution of surface and groundwater resources in numerous places worldwide.

Agriculture, especially, contributes greatly to groundwater exploitation, leads to a decrease in piezometric level of the aquifers and increases the risk of water quality deterioration due to the extensive use of fertilizers and pesticides (nitrate contamination). The worst problem is faced in coastal areas, where intensive water abstraction for farming also results to sea water intrusion and salinization of soils.

The basic characteristic in these areas is that the highest water demand is presented during summer due to higher domestic use and irrigation consumption, leading to critical conditions in groundwater resources. Additionally, coastal areas face the environmental impact of tourism, as tourists do not belong to the permanent population and have different habits of water consumption. Their number exhibits significant seasonal and annual variability and the

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combination of tourist activity with the water demand of the permanent population and rural activities leads to overexploitation of water reserves, with high impact on coastal aquifers (Kent *et al.* 2002).

Integrated water resources management in the coastal areas of Greece is assumed to be a difficult task due to the following reasons: (a) semi-arid environment; (b) very high tourist activity, leading to an uncontrolled increase in urban water demand during summer; (c) a combination of high evapotranspiration and low precipitation during the summer growing season, leading to high water consumption for irrigation; and (d) lack of collective irrigation networks infrastructure, which leads to deficit control of rural water consumption. A representative region which presents all previously mentioned characteristics is the region of Halkidiki Peninsula in Northern Greece (Demertzi *et al.* 2013).

The aim of this study is to employ the Water and Evaluation Planning (WEAP) model in order to address the future challenges and limitations and to perform risk assessment of the influence of tourism and agriculture under climate change on the conjunctive operation of local groundwater systems and two reservoirs of dams which are still in the design phase. The study focuses on optimal water resources management aiming at mitigating groundwater overexploitation.

METHODS

Study area

Area, topography, climate, water issues

In the present study, four groundwater systems in the Prefecture of Halkidiki, Northern Greece are studied and presented in Figure 1: Epanomi-Moudania (684.58 km^2), Kassandra (343.60 km^2), Sithonia (406.44 km^2) and Ormilia (40.2 km^2). The topography of Epanomi-Moudania, Ormilia and the north part of Kassandra is characterized as flat and partially hilly-mountainous (low to moderate slopes). The relief in the southern part of Kassandra is mountainous, with highest altitude 339 m, while the topography in Sithonia is intense with many almost parallel gullies, which are arranged on either side of the watershed area (Veranis & Xatzikirkou 2010).

The climate conditions are described as semi-arid Mediterranean, where climate follows a transition (BSk → CSa → CSb) from the lowlands near the shoreline to the upland mountainous areas (Peel *et al.* 2007).

All four systems proved to be in a bad water quality and/or quantity status, as groundwater faces salinity and nitrate pollution issues in Epanomi-Moudania and Ormilia while in Kassandra and Sithonia saline water intrusion in the

Figure 1 | Groundwater systems of the study area.

aquifers during the summer period makes the water non-potable (Veranis & Xatzikirkou 2010).

Reservoirs

Halkidiki region faces many difficulties in covering its current and future water needs due to the currently used low water reserves. The economy of the region is based mainly on agriculture and tourism, leading to an intense competition between the respective water users and creating also significant political constraints for decision making on issues that concern water management (Katirtzidou & Latinopoulos 2016). These problems, as well as the lack of proper technical standards for the implementation of optimal water resources management, were taken into consideration by regional authorities and decision makers and for that reason two research projects were assigned on the design and construction of two dams so that their reservoirs would increase the region's water reserves by capturing the surface runoff of the two hydrologic basins of the Havrias and Olynthios Rivers (Karamouzis *et al.* 2008a, 2008b).

The operation of the two reservoirs aims to serve: (a) the urban (municipal) water requirements and (b) additional irrigation water requirements in order to reduce the impacts of over-pumping through pumping wells, saltwater intrusion and groundwater salinization. The Olynthios and Havrias hydrologic basins cover 252 km^2 and 472 km^2, respectively, both dams are designed to be rockfill, with a clay core and a lateral spillway, and the height of the dam and the volume of storage for Havrias are 76 m and 36.55 Mm^3, respectively, while for Olynthios they are 73 m and 22.84 Mm^3, respectively (Karamouzis *et al.* 2008a, 2008b).

WEAP model

The WEAP model operates on the basic principle of water balance and on a monthly and annual basis. It is designed to show an integrated aspect of a water system (both in its current state and in predicted future scenarios) and has the ability to perform simulations even with limited data (Sieber & Purkey 2005; Yates *et al* 2005a, 2005b). The model was applied using different scenarios which concern the operation or not of one or both the (now under design) reservoirs during the study period 2015–2050 (i.e. the reservoirs estimated lifetime). Four scenarios were applied and are schematically presented in Figure 2:

- Scenario 1 (Groundwater only): Current water regime. Each groundwater system covers exclusively its municipal water and irrigation needs.
- Scenario 2 (Groundwater and dams): Operation of Havrias and Olynthios reservoirs. Havrias reservoir supplies Kassandra, Sithonia and Ormilia (urban needs) and covers part of the irrigation needs of Ormilia. Olynthios reservoir supplies Epanomi-Moudania (urban needs).
- Scenario 3 (Havrias only): Operation of Havrias reservoir only, that supplies Epanomi-Moudania, Kassandra, Sithonia and Ormilia (urban needs) and covers part of the irrigation needs of Ormilia.
- Scenario 4 (Olynthios only): Olynthios reservoir supplies Epanomi-Moudania, Kassandra, Sithonia and Ormilia (urban needs).

In scenarios 2, 3 and 4, groundwater resources are used for irrigation purposes and are available to cover supplementarily the municipal needs. The simulations were performed in a monthly step with no return flows, while first and secondary priority of water supply were assigned in the model to urban and rural demand sites, respectively. The water supplied by the reservoirs is preferred to meet municipal and tourist water needs, due to poor groundwater quality (salinization and nitrate pollution phenomena) and because water purification plants are planned to be constructed (along with the reservoirs) in order to provide high water quality. On the other hand, groundwater is preferred for agriculture due to high crop consumption quantity (reservoirs are insufficient to cover the projected rural needs) and lower supply cost.

Water supply (surface and groundwater)

The aim of the present study is to investigate the percentage of urban and irrigation water demand that is not covered in the case of establishing groundwater protection measures. Hence, within the model, it is assumed that the groundwater

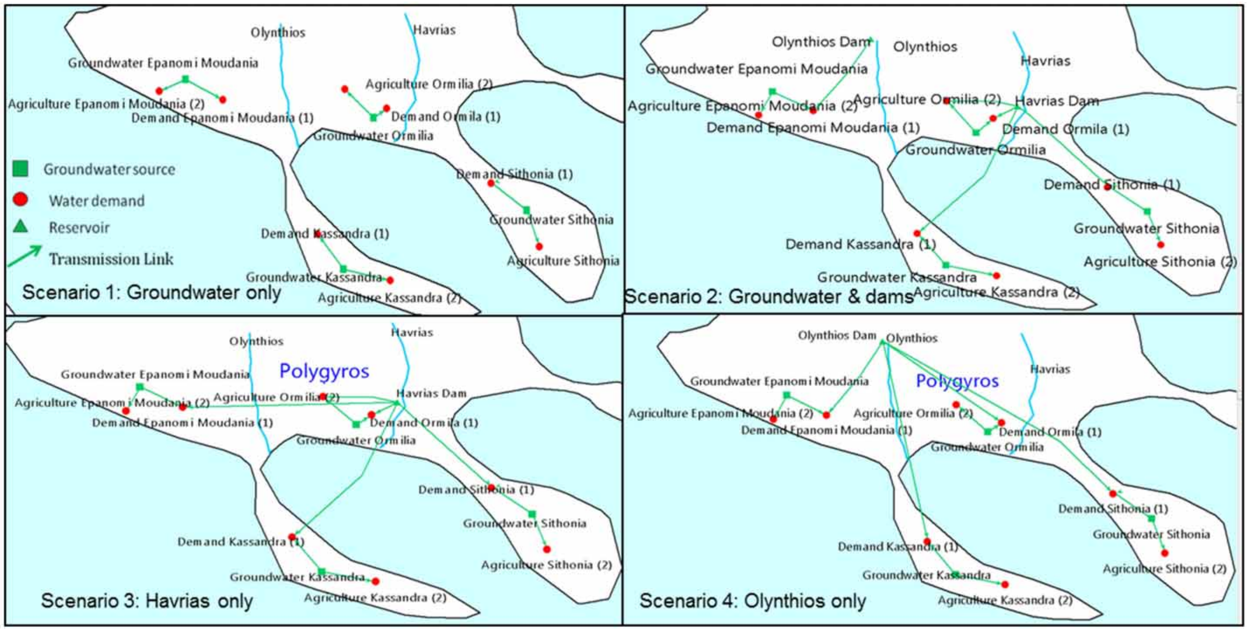


Figure 2 | Schematic depiction of the WEAP model scenarios.

initial storage (at the beginning of the simulation) is equal to the annual renewable groundwater reserves, meaning that abstraction from non-renewable reserves are not allowed.

Due to the absence of notable surface resources in Kassandra and Sithonia and the negligible infows from Olynthios and Havrias rivers to the aquifers in Epanomi-Moudania and Ormilia, respectively, it is assumed within the model that the only water resource for all four systems is precipitation inflow.

The mean annual inflows to each groundwater system for a normal year were calculated using both the Santoro method (Santoro 1970) and the annual renewable groundwater reserves equation (Veranis & Xatzikirkou 2010). In order to convert the annual inflows into monthly water recharge values of the aquifer the mean monthly ERA-Interim precipitation data were used. The reservoir inflows were calculated using the Thornthwaite and Mather model (McCabe & Markstrom 2007) for the Havrias and Olynthios catchments, while evaporation from the water surface of the reservoirs was estimated using the DeBruin equation (DeBruin 1978). The annual groundwater and reservoirs inflows for every year of the study period were determined according to water year method.

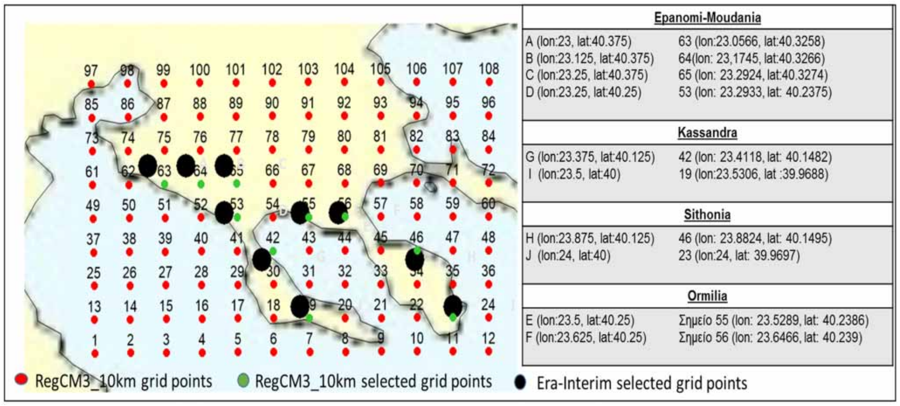
Water year method

Water year drought classes

The climatic conditions were built according to WEAP's 'water year method', using as a base the precipitation data which were incorporated in the model. According to this method, the historic annual inflow rates are divided into five drought classes (very dry, dry, normal, wet and very wet), where the mean monthly inflows of each drought class are calculated in order to describe the respective climatic conditions. The drought classes are empirically defined using percentiles of the annual total precipitation data time series (very dry: minimum value-10th percentile; dry: 11th–30th percentile; normal: 31st–70th percentile; wet: 71st–90th percentile; very wet: 91st percentile–maximum value).

Data evaluation

Precipitation data of the updated very high resolution model RegCM3_10 km were used for the definition of water year drought class of the study period 2015–2050. RegCM3 was built upon the NCAR-Pennsylvania State University (PSU) Mesoscale Model version 4 (MM4) in the late 1980s



Epanomi-Moudania	
A (lon:23, lat:40.375)	63 (lon:23.0566, lat:40.3258)
B (lon:23.125, lat:40.375)	64(lon: 23,1745, lat:40.3266)
C (lon:23.25, lat:40.375)	65 (lon: 23.2924, lat:40.3274)
D (lon:23.25, lat:40.25)	53 (lon: 23.2933, lat: 40.2375)
Kassandra	
G (lon:23.375, lat:40.125)	42 (lon: 23.4118, lat: 40.1482)
I (lon:23.5, lat:40)	19 (lon:23.5306, lat :39.9688)
Sithonia	
H (lon:23.875, lat:40.125)	46 (lon: 23.8824, lat: 40.1495)
J (lon:24, lat:40)	23 (lon:24, lat: 39.9697)
Ormilia	
E (lon:23.5, lat:40.25)	Σημείο 55 (lon: 23.5289, lat: 40.2386)
F (lon:23.625, lat:40.25)	Σημείο 56 (lon: 23.6466, lat: 40.239)

Figure 3 | Coordinates of REGCM3 and Era-Interim selected points (WGS 84 Web Mercator).

(Dickinson *et al.* 1989; Giorgi & Bates 1989), and its dynamical component is a compressible, finite-difference model with hydrostatic balance and vertical σ-coordinates (Giorgi *et al.* 1993).

In order to assess the reliability of the model, a comparison was performed between REGCM3 annual total precipitation data and ERA-Interim reanalysis data for the period 1980–2014 for each one of the groundwater systems. ERA-Interim is a global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Precipitation data from ERA-Interim represents 3-h averages, and in order to avoid the initial spin-up the 3-hourly forcing surface fluxes it corresponds to the 09–21 h forecast interval from initial conditions at 00 and 12 UTC. Monthly means were computed from the original 3-hourly model output at T255 resolution (Balsamo *et al.* 2010).

As presented in Figure 3, 10 Era-Interim grid points (A, B,…,J) were selected (four in Epanomi-Moudania and two in Kassandra, Sithonia and Ormilia, respectively) and each precipitation value was compared annually with the corresponding value of the REGCM3 grid points (63,64,65,53,55,56,42,46,19,23) with the nearest latitude and longitude. The mean annual precipitation (MAP) for both time series and every groundwater system within the period 1980–2014 is presented in Figure 4.

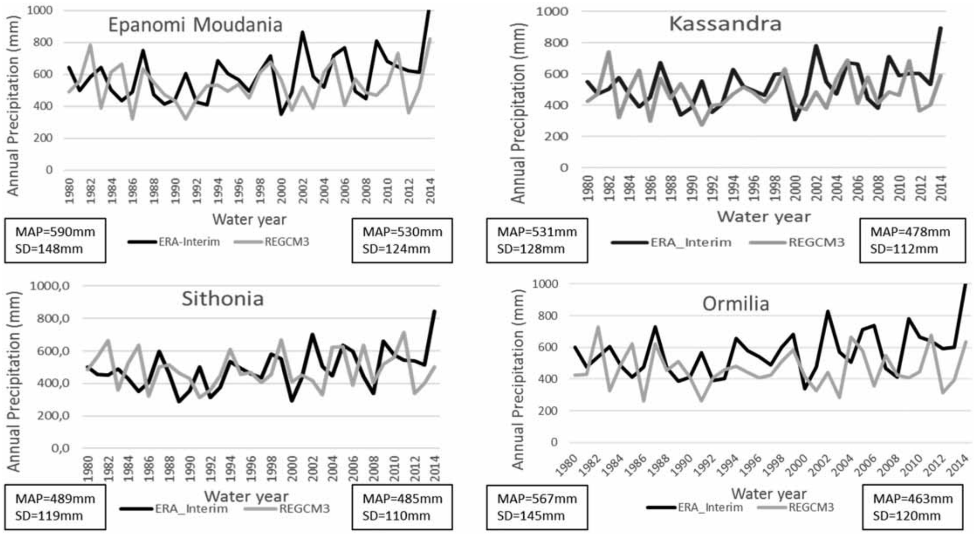


Figure 4 | MAP for every water system according to Era-Interim database and REGCM3 model (period 1980–2015).

The evaluation results show that, in the case of Epanomi-Moudania and Kassandra groundwater systems, the MAP is underestimated by 10% in average, in Ormilia this underestimation reaches 18%, while Sithonia's groundwater system shows a satisfying performance (underestimation 1%). The standard deviations (SD) of REGCM3 and ERA-Interim time series for all four study areas show agreement with non-statistically significant differences, according to the t-test used.

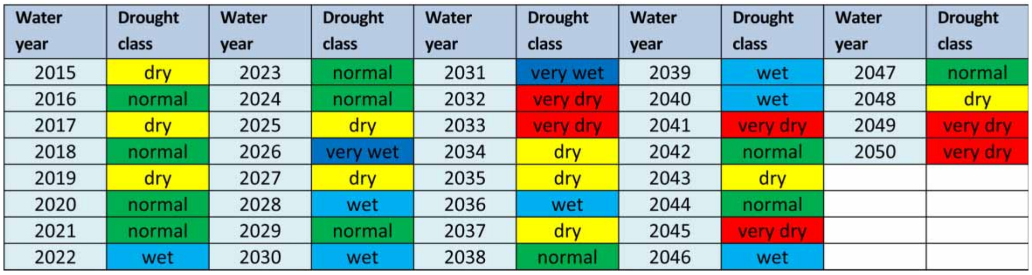
Additionally, WEAP water year coefficients (Table 1), that specify how much more or less water flows into the system in a specific year relative to a normal water year, were calculated, for the ERA-Interim data (1980–2014) and the REGCM3 time series for both the comparison period 1980–2014 and study period 2015–2050, comparing the median precipitation value of each drought class with the median of the whole time-series.

REGCM3 (1980–2014) data show 1% less precipitation (in comparison with ERA-Interim) during a very dry year compared to a normal one and 3%, 8%, 4% more during a dry, wet and very wet year, respectively. Even though it should be taken under consideration, the coefficient differences are not particularly important, proving that the selection of the REGCM3 dynamical regional model provides satisfactory present-day projections and also reliable future climate change scenarios, over the study area. According to REGCM3, (2015–2050) precipitation data show 2%, 8%, 6%, 5% less precipitation (in comparison with (1980–2014) data) during a very dry, dry, wet and very wet year, respectively, compared to a normal one. As the calculated average precipitation value of the study area between the comparison and study period is almost the same, climate is expected to be drier. The water year sequence as projected by REGCM3 model for the study period and inserted in 'WEAP hydrology data' is presented in Table 2.

Table 1 | WEAP water year coefficients

Drought class	ERA-Interim (1980–2014)	REGCM3 (1980–2014)	REGCM3 (2015–2050)
Very dry	0.67	0.66	0.64
Dry	0.83	0.86	0.78
Normal	1.00	1.00	1.00
Wet	1.17	1.25	1.19
Very wet	1.42	1.46	1.41

Table 2 | Water year sequence (2015–2050)-REGCM3 model



Water year	Drought class	Water year	Drought class	Water year	Drought class	Water year	Drought class	Water year	Drought class
2015	dry	2023	normal	2031	very wet	2039	wet	2047	normal
2016	normal	2024	normal	2032	very dry	2040	wet	2048	dry
2017	dry	2025	dry	2033	very dry	2041	very dry	2049	very dry
2018	normal	2026	very wet	2034	dry	2042	normal	2050	very dry
2019	dry	2027	dry	2035	dry	2043	dry		
2020	normal	2028	wet	2036	wet	2044	normal		
2021	normal	2029	normal	2037	dry	2045	very dry		
2022	wet	2030	wet	2038	normal	2046	wet		

Water demand

Halkidiki is one of the most touristic sites in Greece, as a population increase of approximately 700% is usually recorded during the summer season (May–September) in the coastal settlements. In order to take into account the seasonal fluctuation of urban demand, the population was divided into three categories: permanent population, seasonal population (owners of summer houses-water consumers inhabiting the area from May to September) and tourists (visiting the area during the touristic period of June to August). Data regarding permanent, seasonal and tourist population, as well as the average daily water consumption per inhabitant, were determined by considering local records and are presented in Table 3. The monthly water demand for urban sites was determined by multiplying the population by the varying per capita water consumption and is presented in Figure 5 (Katirtzidou & Latinopoulos 2016).

Table 3 | Urban and rural water demand data

Urban water demand data				**Rural water demand data**	
Population					
Area	**Permanent population**	**Seasonal population**	**Tourists**	**Total irrigated area (km^2)**	**Mean crop water consumption (10^6 m^3/km^2)**
Epanomi-Moudania	33,500	115,500	152,100	118.57	0.57
Kassandra	15,457	69,000	140,400	56.72	0.50
Sithonia	13,101	30,500	70,700	25.32	0.50
Ormilia	4,282	8,768	11,500	20.00	0.57
Water consumption (ltr/cap/day)				**Monthly share of annual demand**	
Month	**Permanent population**	**Seasonal population**	**Tourists**	**Monthly variation (%)**	
Jan.	200	0	0	0	
Feb.	200	0	0	0	
Mar.	200	0	0	0	
Apr.	200	0	0	0	
May	250	250	0	11	
Jun.	250	250	300	20	
Jul.	300	300	300	30	
Aug.	300	300	300	28	
Sep.	250	250	0	11	
Oct.	200	0	0	0	
Nov.	200	0	0	0	
Dec.	200	0	0	0	

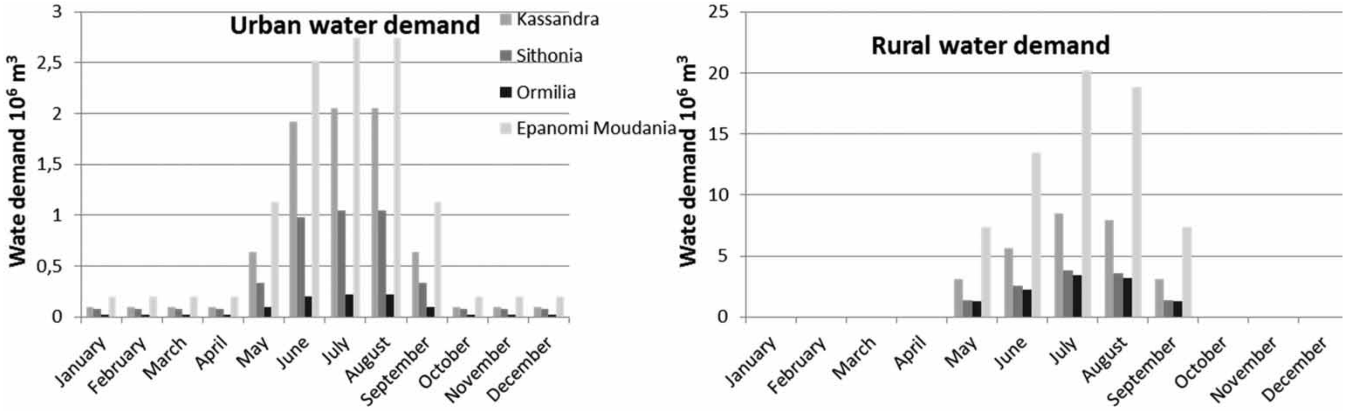


Figure 5 | Monthly urban water needs (left) and rural water needs (right).

The total irrigated area of each system, the mean irrigation water consumption per km^2, estimated using the Penman-Monteith method (Allen *et al.* 1998) using regional crop coefficients (Veranis & Xatzikirkou 2010) and the monthly variation of the agricultural demand is also presented in Table 3. More than 70% of the studied regions is covered by olives, while the rest consists of cereals, cotton, vegetables, and fruit and nut trees. Both urban and rural water demands are assumed to remain stable during the study period, as the population and agricultural area are considered constant.

RESULTS AND DISCUSSION

Demand coverage

The unmet demand of all water demand sites is investigated in each scenario and studied on an annual and monthly base. Urban water needs are completely covered in every groundwater system, all scenarios and all years of the study period regardless of the corresponding year's drought class. In scenario 1, the unmet demand for agriculture of Epanomi-Moudania is $5.1 \times 10^6\,m^3$ and $26.8 \times 10^6\,m^3$ in the years 2049 and 2050, respectively, as according to REGCM3 model, there is a trend for consecutive dry and very dry years after 2043, where 2048 is a dry and 2049–2050 are very dry years, leading to the depletion of renewable reserves of Epanomi-Moudania groundwater system at the end of the first half of the 21st century (Katirtzidou & Latinopoulos 2016).

The highest unmet demand values are observed in Ormilia and presented in Figure 6, where groundwater resources are unable to cover properly the agricultural needs during the whole study period in scenarios 1 and 4. Specifically the unmet demand percentage is 24–32% during very wet years, 33–44% during wet years and reaches 50%, 62% and 68% during normal, dry and very dry years, respectively. In fact, this percentage is covered by non-renewable reserves, leading to groundwater depletion. In the case of constructing both reservoirs (scenario 2), the agricultural need is completely covered, except for the case of consecutive dry and very dry years, while if only Havrias reservoir is constructed (scenario 3), the demand is not met during all dry and very dry years of the study period (despite of water year sequence) up to 55% and 67%, respectively. The unmet agricultural demand basically refers to the summer period, as the

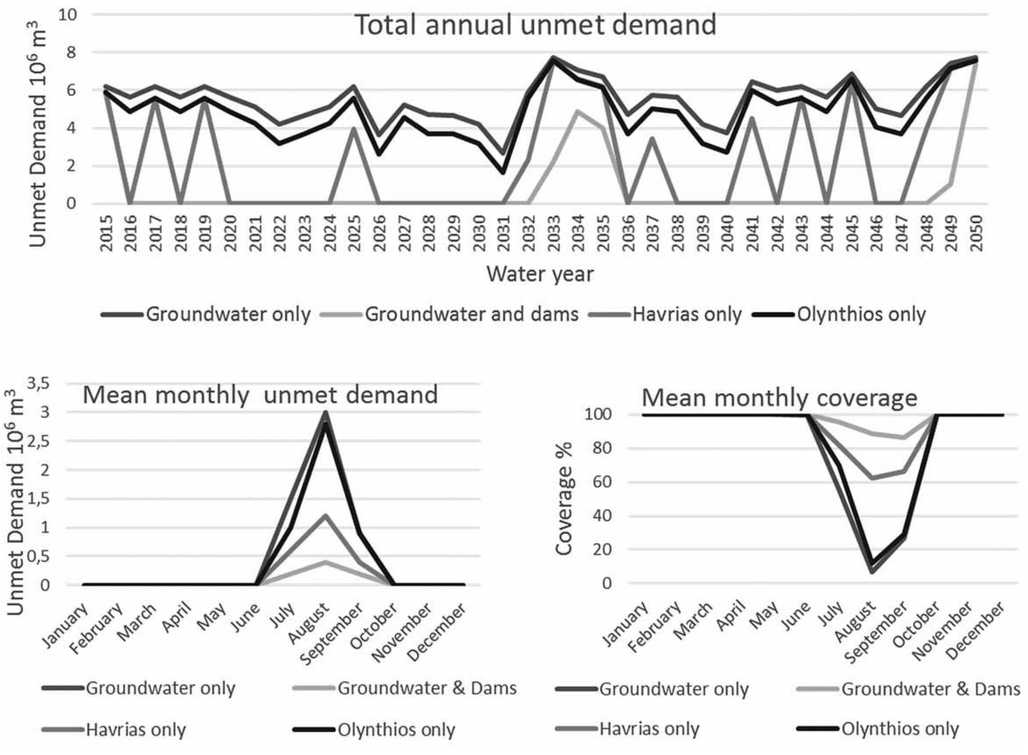


Figure 6 | Total annual, mean monthly unmet demand and mean monthly coverage percentage of Ormilia agricultural water needs in all studied scenarios.

mean monthly coverage reaches 56% in July, only 7% in August and 27% in September in scenario 1. Olynthios reservoir operation (scenario 4) does not significantly improve the coverage results (Jul.: 69.8%, Aug.: 12%, Sep.: 29%). Havrias operation (scenario 3) shows better performance (Jul.: 82%, Aug.: 62%, Sep.: 66%), while the combined operation of both reservoirs manages to satisfy the agricultural water demand by 96% in July, 86% in August and 88% in September.

Combined use of surface and groundwater resources

In the present study, the conjunctive use of surface and groundwater is also investigated and presented in Figure 7. In scenario 2, all urban water demands are covered entirely by the reservoirs, except for 5 years (2033, 2034, 2035, 2049, 2050), where, due to extreme drought conditions, extra water from groundwater aquifers is required, while Ormilia's rural demand is basically covered by groundwater sources and supplementarily by Havrias dam (percentage: very wet: 14–23%, wet: 28–33%, normal: 32–44%, dry: 37–48%, very dry: 43–53% years). In scenario 3, all urban water demands are covered exclusively by Havrias reservoir during normal, wet and very wet years and water from aquifers is needed in all dry and very dry years (percentages: 18–60% and 36–90%, respectively, depending on the water year sequence). Finally, in the case of scenario 4, Olynthios reservoir covers urban water demands only during wet and very wet years and extra groundwater is needed in normal, dry and very dry years (percentages up to 30%, 65% and 90%, respectively).

Reservoir storage

Figure 8 presents the reservoir storage for each scenario and reservoir, every month of the study period. According to scenario 2, Havrias reservoir stored water is depleted during the summer periods of 5 years (2033, 2034, 2035, 2049 and 2050), while in scenario 3, during all dry and very dry years (15 out of 35 years of total operation). Olynthios reservoir stored water is depleted during the summer periods of 3 years (2033, 2034 and 2050), while in scenario 4, during all normal, dry and very dry years (27 out of 35 years of total operation).

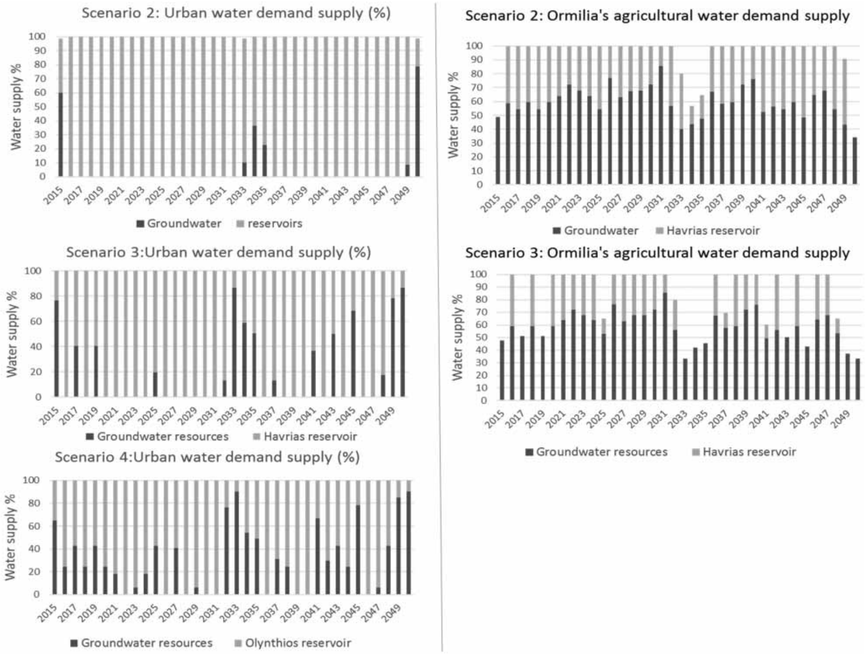


Figure 7 | Water supply percentage from surface and groundwater resources to urban and agricultural needs.

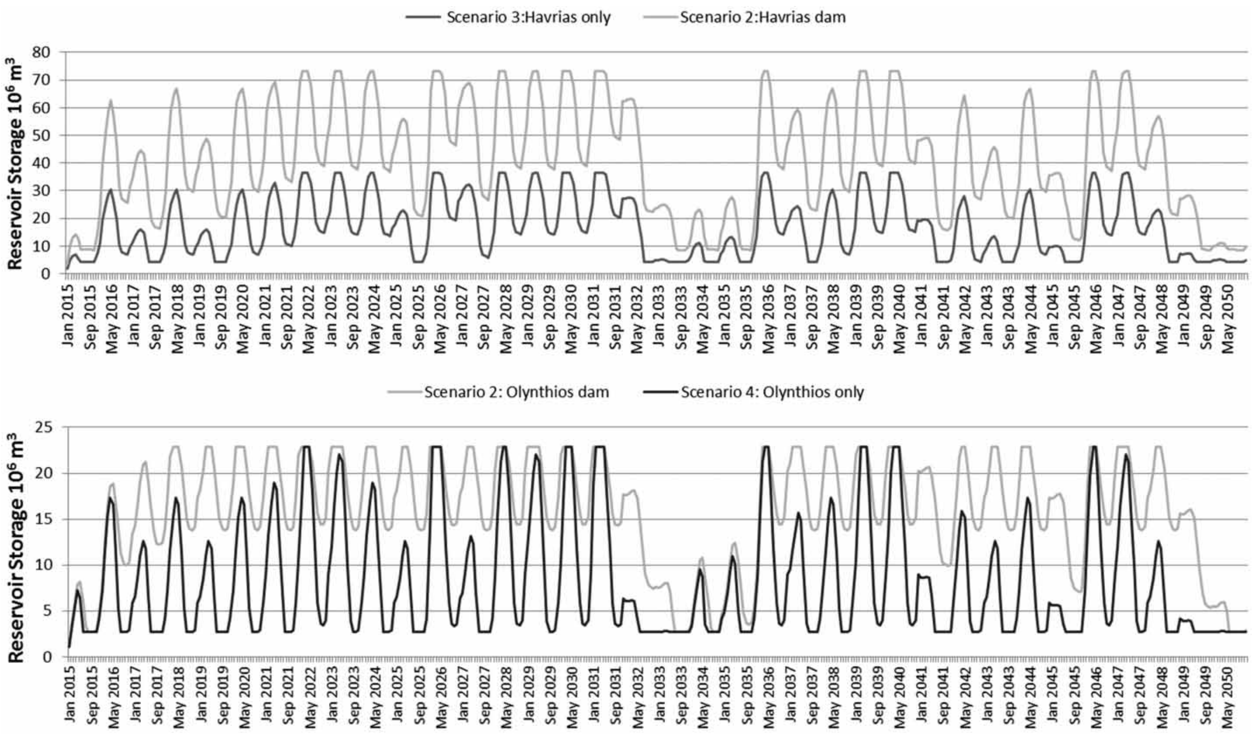


Figure 8 | Storage of Havrias (up) and Olynthios (down) reservoir in scenarios 2, 3 and 4.

CONCLUSIONS

The problems concerning management and allocation of water resources in coastal areas with Mediterranean climate are well known, given the variability of both water supply and demand patterns in space but mostly in time and cannot be solved using only local groundwater, even when sophisticated water allocation methods are employed (Latinopoulos *et al.* 2011). Thus, in the study area, the parallel exploitation of unused surface water resources seems to be an inescapable task.

In the present work, an optimal water management-allocation model was applied, using WEAP software, in order to investigate the combined effects of climate change and tourist-agricultural activities on surface and groundwater reserves in a semi-arid environment.

The application concerned the probable future operation of two reservoirs in Halkidiki Peninsula. According to the obtained results, when reservoirs operate simultaneously urban water demand is basically met (by the reservoirs), while supplementary groundwater is needed only in the case of short-term droughts and agricultural water demand peaks cannot be properly covered only after consecutive dry and/or very dry years. In the case when only Havrias reservoir operates (scenario 3), urban water needs of all demand sites are basically met (by the dam) and extra groundwater is needed during dry and very dry years, while scenario 4 (exclusive operation of Olynthios reservoir) should be rejected due to non-satisfactory results (low coverage percentage).

The model of the present study could be applied in other studies in order to investigate the impact of human activities, climate change and drought on surface and groundwater and assess various environmental policies by estimating the environmental benefits and calculating the cost of each management action.

In conclusion, regional water management and allocation plans concerning the study area should be carefully re-examined, considering economic, environmental, political and social factors before implementing any water action. To this end, a multi-criteria optimization model should be applied.

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