



# Integrated Water Management Approach for Adaptation to Climate Change in Highly Water Stressed Basins

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## Abstract

Adaptation aims at increasing the resilience of natural and human systems to current and future impacts of climate change. The main objective of the current research is to introduce an innovative methodological framework which can effectively assess adaptation measures in basins with severe water deficits by coupling hydrology, climate change and management scenarios, leading to accurate decision making. In this paper, both supply and demand adaptation measures were proposed in line with various regional, national and European policies in order to improve the severe water problem of the Mygdonia basin. The overexploitation of the surface water systems (Lakes Koronia and Volvi) and groundwater resources of the Mygdonia basin during the previous decades, along with the projected decrease of the future water availability, due to climate change, accentuate the need for concerted action towards adaption to climate change. The measures include the increase of a stream diversion towards Lake Koronia, the increase of the embankment elevation at the outfall point of Lake Volvi, the restructuring of crops and their combinations. The measures were examined in terms of their sustainability and effectiveness in the short-term (2020–2050) and long-term (2050–2080) future periods under the most reliable climatic model. The results indicate that the application of demand management measures is more efficient compared to supply oriented solutions for addressing the future water deficit of the Mygdonia water system. The combination of crop restructuring and the decrease of agricultural land proved to be the most efficient and sustainable solution.

**Keywords** Adaptation measures · Water resources management · Climate change · Lake Koronia · Lake Volvi · Mygdonia basin

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## 1 Introduction

Freshwater resources are among the systems that are particularly vulnerable to climate change (IPCC 2014). Major economic activities related to many sectors and systems depend on water resources availability, so that changes both in the hydrological processes and water quality due to climate change will have significant impacts.

Timely analysis of the characteristics of climate change and their relationship to the development model of a country allows the protection of productive sectors, facilitates the identification and development of new sectors that compensate for those affected and highlights the importance of national but also of regional development planning. The involvement of human activity in predictive models has not yet been refined to the extent that fully reliable results can be produced (Majkut 2017).

Climate change is another major water stress factor in many areas contributing both to the quantitative and qualitative degradation of fresh water resources. Climate change adaptation measures, a prominence management option, to reduce vulnerability and enhance resilience in different sectors, should take the form of preventive action or ex-post reaction and involve both physical and human systems. Extended literature have been dedicated to addressing adaptation to future climatic conditions given the uncertainty related to climate projections (Dessai et al. 2009; Swart et al. 2009), including water resources (Connell-Buck et al. 2011; Hanak and Lund 2012; Iglesias et al. 2013).

Global water demand is expected to continue to increase at a similar rate until 2050, accounting for an increase of 20 to 30% above the current level of water use (Burek et al. 2016). Agriculture's share of total water use is likely to fall in comparison with other sectors, but it will remain the largest user overall over the coming decades, in terms of both water withdrawal and water consumption (WWAP 2019).

Given the reduced water availability due to climate change demand management which controls uses and promotes water conservation is mainly the answer to water shortage problems compared to supply management (Kolokytha et al. 2017).

In the case of the agricultural sector, major changes should respond to the reduction of water needs by restructuring of crops. Therefore, an adaptation water management plan in this case should answer critical questions such as: what infrastructure works are required to replenish the water potential, what kind of crops are needed to respond to the new climatic conditions, what will be the effect on the reduction in the production of agricultural products, but also what will be the occupation of those who are away from agriculture.

The main objective of the current research is to introduce an innovative methodological framework which can effectively assess adaptation measures in basins with severe water deficits by coupling, hydrology, climate change and management scenarios leading to accurate decision making. The framework is examined and tested in the Mygdonia basin.

In the Mygdonia basin, the irrational agricultural activity, which accounts for 95% of the water demand (Babori et al. 2016) has resulted in the quantitative degradation of both the surface and groundwater resources while the projections of the future water availability in the basin prioritize the urgent need for adaptation measures in order to confront the water deficit of Mygdonia basin (Malamataris et al. (2019). The research on water management measures in the Mygdonia basin is still very limited in the literature focusing mainly on the restoration of the sub-catchment of Lake Koronia (Zalidis et al. 2004; Manakou et al. 2013) Regionalized climate change impacts on water and agriculture have never before been taken into account in the area.

Two water supply management scenarios and three water demand management scenarios are proposed and examined in the current study to confront the severe water deficit of the system under the most suitable climate scenario.

The paper is structured as follows: Section 2.1 explains the methodology and the modeling framework, then the characteristics of the Mygdonia basin are described in section 2.2. Model integration and management scenarios, strategies and results are presented in 2.3. In section 3 results are presented and discussed. Section 4 summarizes the conclusions.

## 2 Materials and Methods

### 2.1 Methodology

An integrated methodological approach was developed and implemented which combined and linked a series of models so that the output of one model is used as input for the next.

More specifically:

- A series of GCMs-RCMs were collected and utilized which simulate and study the impact of climate change in the area.
- The outputs of these climatic models were introduced as input to a set of hydrological models (conjunctive use of groundwater and surface water resources) whose combined development simulated the natural operation of the basin under the most representative climate scenario.
- And last, the output of the above was introduced as input to a system of water management options in order to assess a series of alternative adaptation scenarios and strategies as responses to climate change and severe water shortages of the basin.

The methodology is depicted in Fig. 1.

This paper gives specific emphasis on the formulation of water management adaptation scenarios and investigates whether demand or supply policies can provide effective and

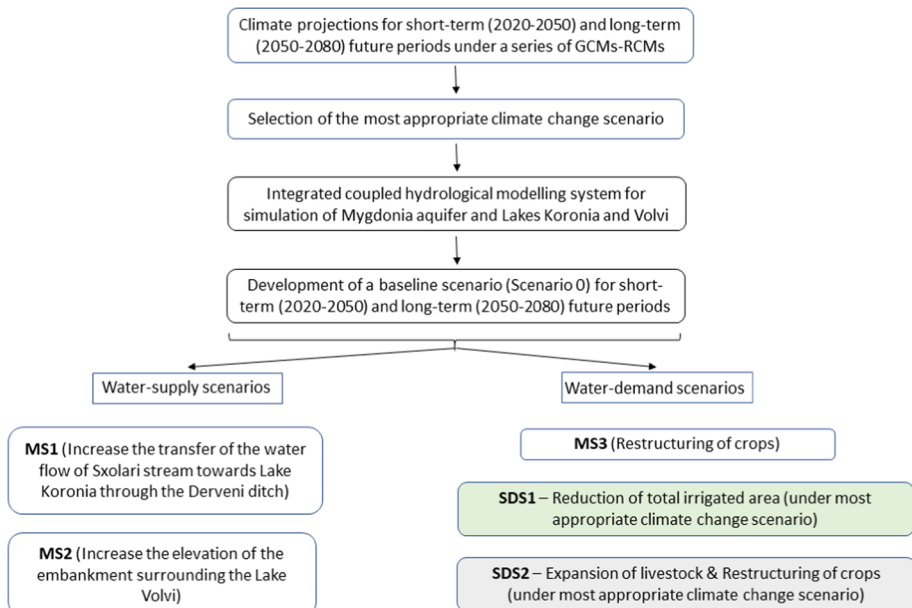


Fig. 1 Methodology roadmap

efficient solutions to highly water stressed basins. It, further, identifies the kind of measures which can reverse the negative water balance. The selection of scenarios is in line with local, national and European policies. Then, the combination of the most efficient water scenarios led to the proposal of Sustainable Development Strategies for the sustainable development of the area. The effectiveness of the proposed measures is evaluated against a base line scenario (scenario 0 -no measures) for the future periods 2020–2050 and 2050–2080. The methodology is tested in the agricultural Mygdonia water basin.

## 2.2 The Mygdonia Basin

Mygdonia basin is located in Northern Greece, 32 km eastern of the city of Thessaloniki, which is the second largest and most populated city of Greece. A wide part of the Mygdonia basin constitutes a Ramsar wetland of international importance, a Special Protection Area. The hydrographic network of the Mygdonia basin is depicted in Fig. 2. Lake Koronia had been overflowing to Lake Volvi through the Derveni ditch and Lake Volvi had been overflowing to the Strymonikos gulf through the Richios stream during the wet periods until the 1970s.

During the last decades, surface water and groundwater of the Mygdonia basin have undergone a severe quantitative and qualitative degradation as a result of intensive agricultural and industrial activities. In particular, the water depth of Lake Koronia has continuously decreased since 1970 resulting to the total depletion of the lake in the summer of 2008. Lake Volvi has exhibited a smaller reduction of its depth because of its almost three times larger maximum stored water volume. Furthermore, the limited groundwater recharge and the unsustainable pumping for fulfilling agricultural and industrial water needs have caused a drawdown of the Mygdonia groundwater table. Climate change will add further pressure on the already stressed water system and will pose additional challenges for the irrigation sector.

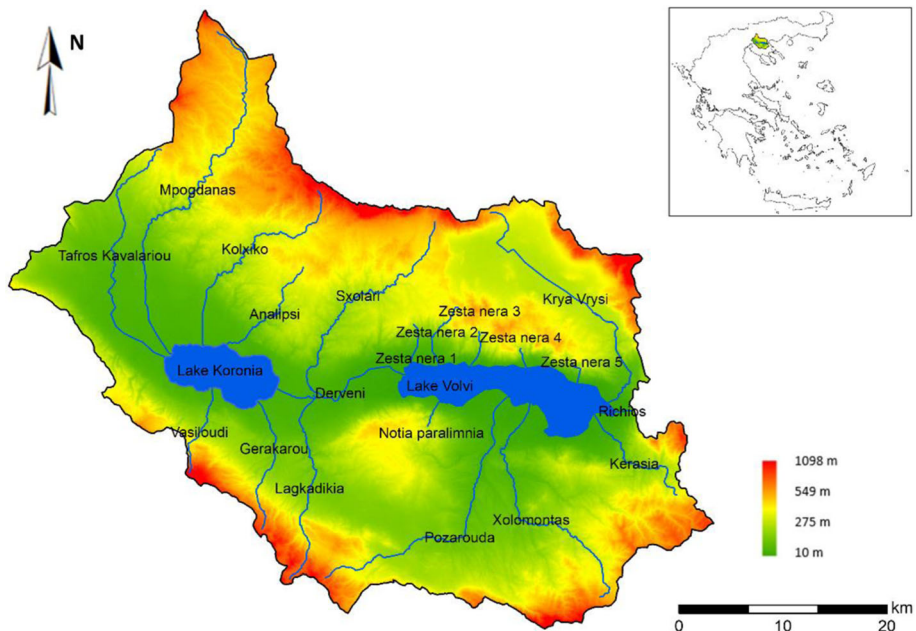


Fig. 2 The hydrographic network of the Mygdonia basin

The environmental problems of the Mygdonia basin were initially recognized in 1995 when an incident of mass fish deaths occurred in Lake Koronia. The environmental collapse of Lake Koronia resulted in the drafting of the “Master Plan for the restoration of Lake Koronia” in 1998. The Master Plan focused on large-scale infrastructural works including a water transfer scheme from the River Aliakmon, which flows in a neighboring catchment and is partly exploited for the water supply of the city of Thessaloniki. Several of the proposed technical works in the Master Plan were met with objections from the central administration and international institutions since they were hard engineering solutions resulting in significant environmental impacts on the area, as they were harming the Ramsar protected ecosystem and were altering the hydrodynamics of the water systems. In 2004, a “Revised Restoration Plan of Lake Koronia” was carried out reviewing the Master Plan and proposing “softer” water management measures. The Master Plan and the Revised Plan are so far the only official documents proposing water management measures for the restoration of the water in Mygdonia basin. (Zalidis et al. 2004).

## 2.3 Model Simulation and Integration

Climatic projections in a water basin derived from several GCMs-RCMs where the Bias Correction Quantile Mapping (BCQM) method, in R software was applied to correct the biased raw climatic data (Gudmundsson 2016). The exponential tendency to an asymptote transformation function was used to fit the quantile-quantile relation of observed and modelled data.

### 2.3.1 Simulation of the Surface Water Balance

The UTHBAL model (Loukas et al. 2007) was used for the simulation of the surface hydrological processes. The model requires time series of precipitation, temperature, potential evapotranspiration and measured discharge, and it produces time series of actual snow water equivalent, actual evapotranspiration, actual soil moisture, total surface runoff and groundwater recharge. Calibration is made by monthly measured discharge while validation by using the rest measured discharge values.

### 2.3.2 Simulation of the Groundwater Balance and the Lakes-Aquifer Interaction

The MIKE SHE model (Danish Hydraulic Institute 2017c) was used for the simulation of groundwater flow along with the MIKE HYDRO River model (Danish Hydraulic Institute 2017b) which was utilized for the simulation of water exchange between the lakes and the aquifer. The groundwater recharge and discharge to lakes timeseries are imported to MIKE SHE and MIKE HYDRO River models along with monthly time series of precipitation and evaporation of the lakes, pumping from the lakes, pumping from groundwater and return flows of the pumped water for irrigation use. The MIKE SHE and MIKE HYDRO River models are calibrated and validated using hydraulic head observations and the water exchange volumes between the under study aquifer and the neighbouring aquifer.

### 2.3.3 Simulation of the Lakes Water Balance

The lakes - aquifer water exchange volumes as calculated in previous step along with precipitation, evaporation and pumping from the lakes were imported into the MIKE HYDRO

Basin (Danish Hydraulic Institute 2017a) model which calculates the water balance of the lakes.

**Reference Period 1970–2000:** For the historical reference period 1970–2000, the average annual rainfall in Mygdonia catchment was calculated at  $1017.05 \text{ hm}^3/\text{year}$  using the Thiessen polygon method modified by the precipitation gradient method, and the average annual evapotranspiration was calculated at  $860.82 \text{ hm}^3/\text{year}$  using the Thornthwaite method. The recharge to groundwater was calculated at  $154.18 \text{ hm}^3/\text{year}$  and the average surface runoff at  $31.82 \text{ hm}^3/\text{year}$  using the UTHBAL model.

The average annual discharge of each stream is presented in Fig. 3. The period from 2000 to 2020 was not taken into consideration due to the unavailability of measured meteorological data; in particular, the meteorological stations located in the study area were shut down at the end of 2000, after the completion of the Master Plan for the rehabilitation of Lake Koronia.

The abstractions from the Mygdonia aquifer for agricultural, industrial, livestock, tourist and household use were estimated at  $164.94 \text{ hm}^3/\text{year}$ ,  $7.33 \text{ hm}^3/\text{year}$ ,  $1.86 \text{ hm}^3/\text{year}$ ,  $0.02 \text{ hm}^3/\text{year}$  and  $6.40 \text{ hm}^3/\text{year}$ , respectively (Exarchou Nikolopoulos Bensasson S.A. (ENM) et al. 2007; Greek Ministry of Environment Energy and Climate Change 2013). The total water amount of abstractions, the recharge to groundwater as well as geometrical (upper level and lower level) and hydraulic (horizontal hydraulic conductivity, vertical hydraulic conductivity, specific yield and storage coefficient) groundwater parameters were then imported into the MIKE SHE and MIKE HYDRO River models.

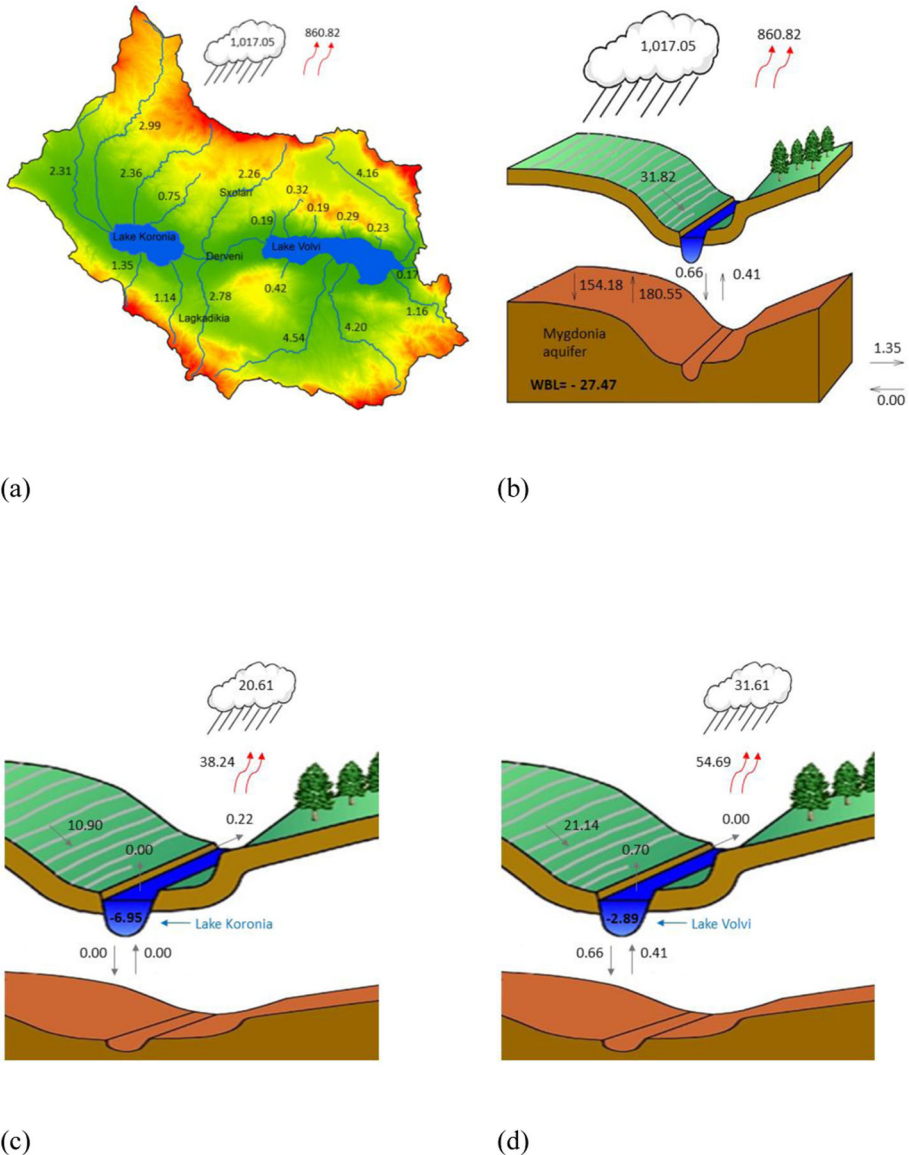
The Mygdonia basin aquifer was considered as an endorheic basin in hydrogeological terms, apart from a small region in the area of the Richios stream (Veranis 2010). The coupled use of the MIKE SHE and MIKE HYDRO River models estimated the flow from the Mygdonia basin aquifer to the lakes at  $0.41 \text{ hm}^3/\text{year}$ , the flow from the lakes to Mygdonia basin aquifer at  $0.66 \text{ hm}^3/\text{year}$ , the outflow to the neighbouring groundwater aquifer at  $1.35 \text{ hm}^3/\text{year}$  and also that there is no inflow from the neighbouring aquifer (Malamataris et al. 2019). The average annual water balance of the Mygdonia basin aquifer was estimated at  $-27.47 \text{ hm}^3/\text{year}$  (Fig. 3b).

As for Lake Koronia, the average direct precipitation was estimated at  $20.61 \text{ hm}^3/\text{year}$  using the modified Thiessen polygon method, the evaporation at  $38.24 \text{ hm}^3/\text{year}$  using a mathematical equation of fourth grade between temperature and evaporation between temperature and evaporation of the study area and the runoff from the watershed was estimated at  $10.90 \text{ hm}^3/\text{year}$ . There is no pumping from Lake Koronia and no water flow interaction between the Lake Koronia and the Mygdonia basin aquifer. The overflow of the Lake Koronia to the Lake Volvi was estimated at  $0.22 \text{ hm}^3/\text{year}$  and the average water balance of the Lake Koronia at  $-6.95 \text{ hm}^3/\text{year}$  using the MIKE HYDRO Basin model Fig. 3c.

Regarding Lake Volvi, the average direct precipitation was estimated at  $31.61 \text{ hm}^3/\text{year}$  using the modified Thiessen polygon method, the evaporation at  $54.69 \text{ hm}^3/\text{year}$  using a mathematical equation of fourth grade between temperature and evaporation, the runoff inflows at  $21.14 \text{ hm}^3/\text{year}$ , the pumping from the lake at  $0.70 \text{ hm}^3/\text{year}$ , the outflow to the



aquifer at  $0.66 \text{ hm}^3/\text{year}$  and the inflow from the aquifer at  $0.41 \text{ hm}^3/\text{year}$ . There is no overflow from Lake Volvi to the Richios stream and the average water balance of the Lake Volvi was estimated at  $-2.89 \text{ hm}^3/\text{year}$  using the MIKE HYDRO Basin model Fig. 3d.

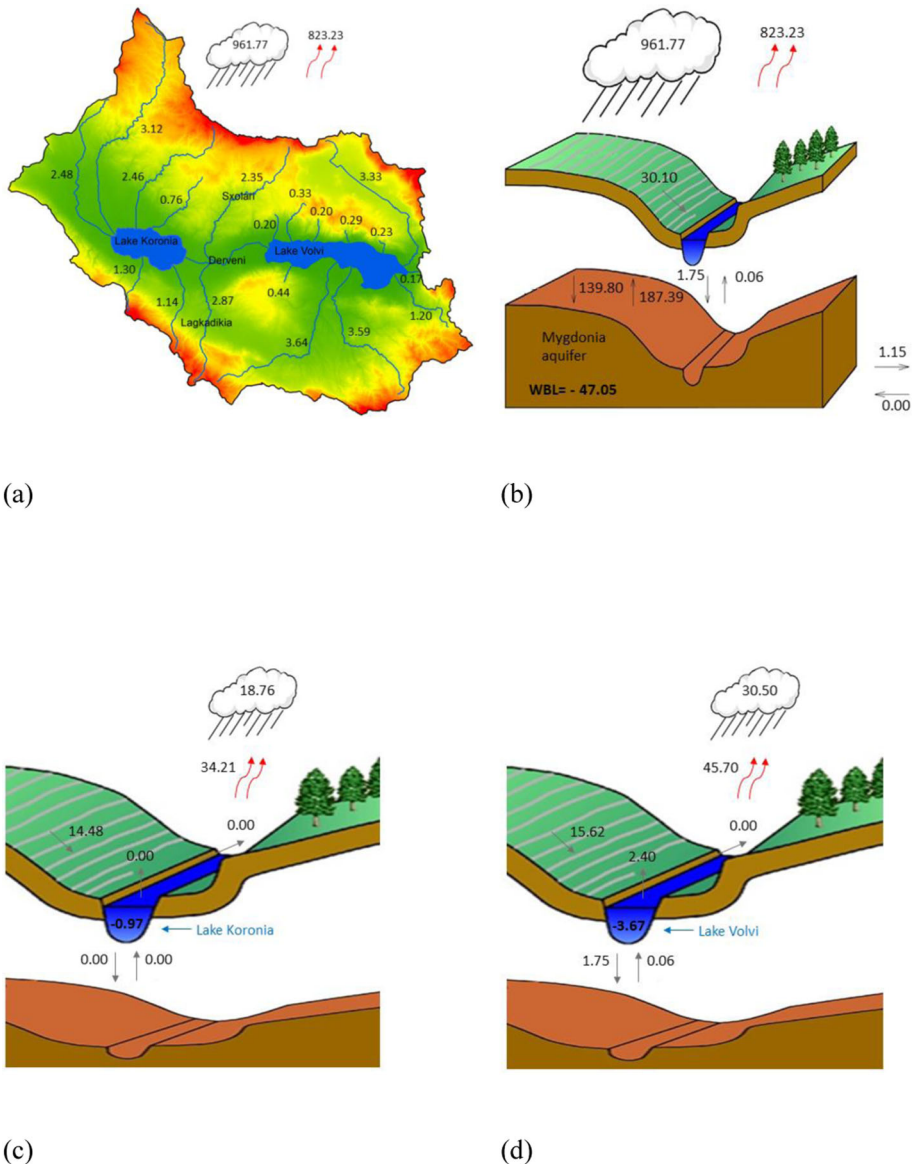


**Fig. 3** **a** Average annual runoff of each stream ( $\text{hm}^3$ ), **b** Average annual surface water – groundwater balance parameters ( $\text{hm}^3$ ), **c** Average annual Lake's Koronia water balance parameters ( $\text{hm}^3$ ) and **d** Average annual Lake's Volvi water balance parameters ( $\text{hm}^3$ ) for the reference period 1970–2000

### 2.3.4 SMHIRCA Climate Model 2020–2050

### 2.3.5 SMHIRCA Climate Model 2050–2080

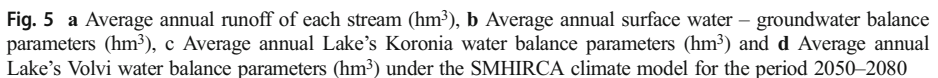
The estimation of the future water availability (hydrology) in the Mygdonia basin until 2100 was performed using the climatic projections of the SMHIRCA climate model (Figs. 4 and 5) since the precipitation and temperature data of this model are found to be closer to the



**Fig. 4** **a** Average annual runoff of each stream (hm<sup>3</sup>), **b** Average annual surface water – groundwater balance parameters (hm<sup>3</sup>), **c** Average annual Lake's Koronia water balance parameters (hm<sup>3</sup>) and **d** Average annual Lake's Volvi water balance parameters (hm<sup>3</sup>) under the SMHIRCA climate model for the period 2020–2050



Precipitation is projected to decrease from 518.69 mm/year in the 1970–2000 period to 490.44 mm/year (−5.45%) in 2020–2050, to 425.40 mm/year (−17.99%) in 2050–2080. As for the temperature, it is projected to increase from 13.27 °C in 1970–2000 to 14.54 °C (+1.27 °C) in 2020–2050, to 15.50 °C (+2.23 °C) in 2050–2080 period (Table 1).



**Table 1** Historical data and future climatic projections.

	Precipitation (mm/year)			Temperature (°C)				
	Observations	SMHIRCA	MPL-M-REMO	METO-HC_HadRM3Q0	Observations	SMHIRCA	MPL-M-REMO	METO-HC_HadRM3Q0
Observations (1970–2000)	518.69				13.27			
Raw climatic data (1970–2000)		575.03	354.20	644.60		13.24	15.07	13.96
Downscaled climatic data (1970–2000)		517.95	516.74	516.14		13.26	13.29	13.28
Climatic projections (2020–2050)		490.44	494.78	525.66		14.54	14.46	14.93
Climatic projections (2050–2080)		425.40	425.48	467.47		15.50	15.74	16.09

Climate modeling results predict that the rising temperatures (+1.27 – +2.23) and the decreasing precipitation levels (–5.45–17.99%) will likely translate into increased water requirements for farming activities and thus further deteriorate the already disturbed water balance of the system.

### 3 Results and Discussion

In this section, water supply (MS1,MS2) and demand management scenarios (MS3) and strategies (SDS1,SDS2) are analysed and examined in terms of their effectiveness and sustainability to respond to climate change and to water deficits.

#### 3.1 Management Scenario 1 (MS1): Enhancement of the Water Potential of Lake Koronia by Increasing the Transfer of the Water Flow of Sxolari Stream towards Lake Koronia through the Derveni Ditch

Sxolari and Lagkadikia streams normally mouthing into Derveni ditch outflowing to Lake Volvi. The Revised Restoration Plan of Lake Koronia proposed a transfer of the 15% of the water flow of Sxolari stream and the total water flow of Lagkadikia stream to Lake Koronia through the Derveni ditch.

The Plan also proposed a hydraulic modification of the Derveni ditch in order to operate in a reversible way along with the decrease of the elevation of the ditch at the area of the outflow of Lake Koronia to the ditch from +73.00 m a.s.l. (above sea level) to +72.00 m a.s.l. (Greek Ministry of Environment, Energy and Climate Change 2012) (Fig. 6).

The Derveni ditch operates in a bidirectional way, meaning that it transfers the water flow of Sxolari diversion and Lagkadikia stream to Lake Koronia and also transfers the overflow of Lake Koronia to Lake Volvi. In particular, in case the Sluice Gate 1 (SG1) is opened and the Sluice Gate 2 (SG2) is closed, the water flow of Sxolari diversion and Lagkadikia stream is transferred to Lake Koronia. In case the Lake Koronia reaches the water level of +72.00 m a.s.l., both SGs will be opened in order for the Lake Koronia to overflow to Lake Volvi through the Derveni ditch. The measures aimed at increasing the water level of Lake

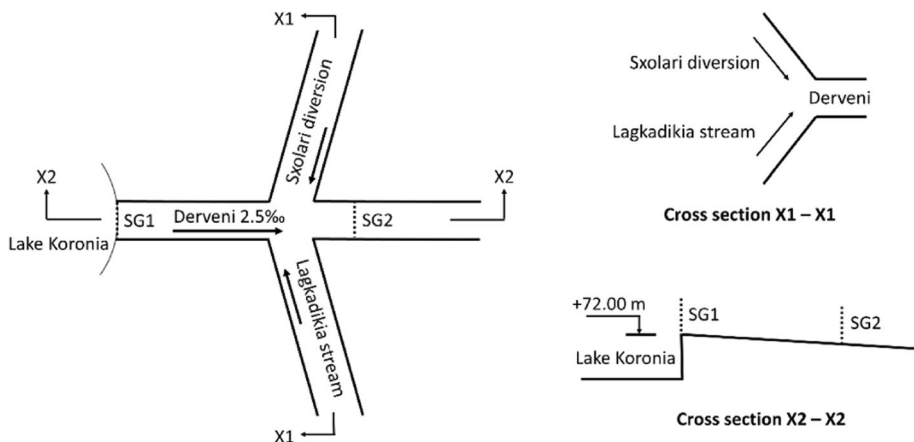


Fig. 6 Bidirectional operation of the Derveni ditch

Koronia to +72.00 m a.s.l. within a period of 6 to 7 years (Zalidis et al. 2004) resulting in the overflow of Lake Koronia to the Derveni ditch, reducing the concentration of pollutants in Lake Koronia. Afterwards, the total water flow of both streams is proposed to outflow to Lake Volvi through the Derveni ditch as before the technical interventions.

In MS1, the water flow of Sxolari stream towards Lake Koronia is proposed to increase from 15% (no-action scenario) to 20% (MS1i), 40% (MS1ii) and 60% (MS1iii).

The selection of the maximum rate of increase of the Sxolari stream water flow transfer towards Lake Koronia is based on the requirement to maintain the ecological flow of the Sxolari stream. The Tennant method (Tennant 1976) constitutes the most widespread method for estimating ecological flow of rivers (Georgalas and Mamasis 2015).

In addition, it is proposed that the structural works be constructed in the area of current stream diversion in order to minimize the required construction works, as well as to avoid changing the hydrological conditions of the upper part of the Sxolari stream. Moreover, it is recommended that the structural works be carried out from early March till the end of July in order not to reduce the reproductive capacity of the protected birds (March to April) in the surrounding area (Omikron LLC 2005).

The MIKE HYDRO Basin model was used for the water balance simulation of the Lakes Koronia and Volvi under all the water flow transfer scenarios towards Lake Koronia. The detailed description of the model setup in case of Mygdonia basin is presented in Malamataris et al. (2019). The inflows and outflows of Lakes Koronia and Volvi under the MS1i-iii are presented in Table 2 and depicted in Fig. 7 for the periods 2020–2050 and 2050–2080.

An increase of inflows and outflows from Lake Koronia is projected under MS1i-iii compared to the no-action scenario. This is attributed to the increase of water flow transfer to Lake Koronia and the increase of evaporation losses from the surface area of the lake, respectively. These changes are predicted to result in the water balance improvement of Lake Koronia for the 2020–2050 period. On the other hand, the water balance of the lake is projected to deteriorate during the 2050–2080 period since the increase of outflows is projected to be higher than the increase of inflows which is attributed to the wider surface area of Lake Koronia in 2050 under MS1i-iii in comparison to the no-action scenario. In particular, the surface area of Lake Koronia in 2050 is projected at 18.70 km<sup>2</sup> under the no-action scenario and at 18.84 km<sup>2</sup>, 19.11 km<sup>2</sup> and 19.39 km<sup>2</sup> under the MS1i, MS1ii and MS1iii scenarios, respectively.

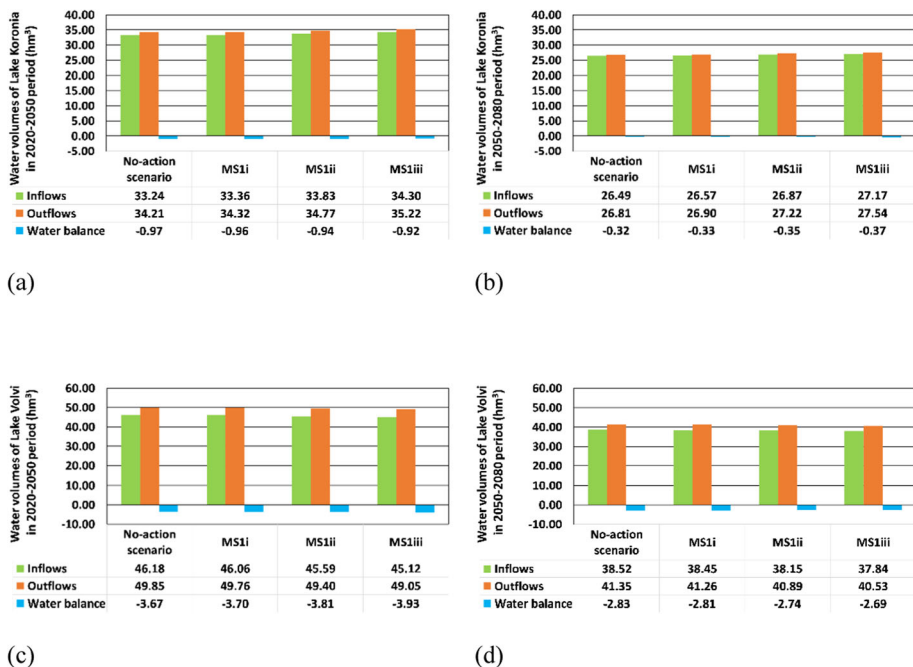
The no-action scenario results in the decrease of runoff to Lake Koronia and the decrease of evaporation from the surface area of the lake. Under MS1i-iii, Lake Volvi will exhibit a decrease of inflows and outflows compared to the no-action scenario. The above changes will then result in the deterioration of Lake Volvi's water balance in the 2020–2050 period, while onwards the water balance of the lake is projected to slightly improve since the decrease of outflows is projected to be higher than the decrease of inflows, due to the smaller surface area of Lake Volvi in 2050 under MS1i-iii in comparison to the no-action scenario. In particular, the surface area of Lake Volvi in 2050 is projected at 31.50 km<sup>2</sup> under the no-action scenario and at 31.41 km<sup>2</sup>, 31.10 km<sup>2</sup> and 30.79 km<sup>2</sup> under the MS1i, MS1ii and MS1iii scenarios, respectively.

The above analysis reveals that even with a 60% transfer of the water flow of Sxolari stream to Lake Koronia, the water balance of the lake is projected to remain negative for the short-term (2020–2050) (Fig. 7a) long-term (2050–2080) (Fig. 7b) future periods. Further, the collateral effect of the MS1i-iii scenarios is the deterioration of the water balance of Lake Volvi in 2020–2050 period projected at −3.70 hm<sup>3</sup>/year, −3.81 hm<sup>3</sup>/year and −3.93 hm<sup>3</sup>/year

**Table 2** Average annual water balance parameters of the Lakes Koronia and Volvi for the 2020–2050 and 2050–2080 periods under the no-action scenario and MS1i–iii

	No-action scenario	MSi	MSii	MSiii
Inflows to the Lake Koronia (2020–2050) (hm <sup>3</sup> /year)				
Direct precipitation	18.76	18.76	18.76	18.76
Runoff from the watershed	14.48	14.60	15.07	15.54
Inflow from the groundwater aquifer	0.00	0.00	0.00	0.00
Outflows from the Lake Koronia (2020–2050) (hm <sup>3</sup> /year)				
Evaporation	34.21	34.32	34.77	35.22
Pumping from the lake	0.00	0.00	0.00	0.00
Outflow to the groundwater aquifer	0.00	0.00	0.00	0.00
Overflow to the Derveni stream	0.00	0.00	0.00	0.00
Water balance of the Lake Koronia (2020–2050) (hm <sup>3</sup> /year)	−0.97	−0.96	−0.94	−0.92
Inflows to the Lake Koronia (2050–2080) (hm <sup>3</sup> /year)				
Direct precipitation	15.89	15.89	15.89	15.89
Runoff from the watershed	10.60	10.68	10.98	11.28
Inflow from the groundwater aquifer	0.00	0.00	0.00	0.00
Outflows from the Lake Koronia (2050–2080) (hm <sup>3</sup> /year)				
Evaporation	26.81	26.90	27.22	27.54
Pumping from the lake	0.00	0.00	0.00	0.00
Outflow to the groundwater aquifer	0.00	0.00	0.00	0.00
Overflow to the Derveni stream	0.00	0.00	0.00	0.00
Water balance of the Lake Koronia (2050–2080) (hm <sup>3</sup> /year)	−0.32	−0.33	−0.35	−0.37
Inflows to the Lake Volvi (2020–2050) (hm <sup>3</sup> /year)				
Direct precipitation	30.50	30.50	30.50	30.50
Runoff from the watershed	15.62	15.50	15.03	14.56
Inflow from the groundwater aquifer	0.06	0.06	0.06	0.06
Inflow from the Derveni stream	0.00	0.00	0.00	0.00
Outflows from the Lake Volvi (2020–2050) (hm <sup>3</sup> /year)				
Evaporation	45.70	45.61	45.25	44.90
Pumping from the lake	2.40	2.40	2.40	2.40
Outflow to the groundwater aquifer	1.75	1.75	1.75	1.75
Overflow to the Richios stream	0.00	0.00	0.00	0.00
Water balance of the Lake Volvi (2020–2050) (hm <sup>3</sup> /year)	−3.67	−3.70	−3.81	−3.93
Inflows to the Lake Volvi (2050–2080) (hm <sup>3</sup> /year)				
Direct precipitation	25.58	25.58	25.58	25.58
Runoff from the watershed	12.94	12.87	12.57	12.26
Inflow from the groundwater aquifer	0.00	0.00	0.00	0.00
Inflow from the Derveni stream	0.00	0.00	0.00	0.00
Outflows from the Lake Volvi (2050–2080) (hm <sup>3</sup> /year)				
Evaporation	36.19	36.10	35.73	35.37
Pumping from the lake	2.40	2.40	2.40	2.40
Outflow to the groundwater aquifer	2.76	2.76	2.76	2.76
Overflow to the Richios stream	0.00	0.00	0.00	0.00
Water balance of the Lake Volvi (2050–2080) (hm <sup>3</sup> /year)	−2.83	−2.81	−2.74	−2.69

under the MS1i, MS1ii and MS1iii, respectively (Fig. 7c) while the water balance of the Lake Volvi is also projected to be negative in 2050–2080 period (Fig. 7d). Thus, MS1 is a non-sustainable solution since measures taken to enhance the water potential of the one water system will cause negative.



**Fig. 7** Inflows, outflows and water balance of **a** the Lake Koronia in 2020–2050 period, **b** the Lake Koronia in 2050–2080 period, **c** the Lake Volvi in 2020–2050 period, **d** the Lake Volvi in 2050–2080 period

### 3.2 Management Scenario 2 (MS2): Reduction of the Overflow of Lake Volvi by Increasing the Elevation of the Embankment Surrounding the Lake

The MS2 was proposed in the Revised Plan in order to mitigate the negative hydrological collateral effects of the transfer of 15% of the Sxolari stream water flow to Lake Koronia on the water balance of Lake Volvi. However, the MS2 has not been constructed to date because of the decrease of the water level of Lake Volvi according to the Directorate of Technical Works of the Region of Central Macedonia 2017 resulting to the non-overflow of Lake Volvi to the Richios stream. The scenario of elevating the crowning of the perimeter embankment of Lake Volvi (MS2) has as its main objective to help maintain and / or raise the level of Volvi Lake. This scenario cannot fulfill its objective.

### 3.3 Management Scenario 3 (MS3): Restructuring of Crops

MS3 refers to the restructuring of the agricultural crops in the Mygdonia basin with the aim of reducing the agricultural water demand but also promote crops which sustain the farmers' income.

Table 3 present data provided by the Greek Ministry of Environment, Energy and Climate Change (2013) as well as from the Regional Administration of Central Macedonia. The net farm income provided by each crop was collected from the Greek Ministerial Circular 1077/2014.



**Table 3** Crops and land data in the study area (2020–2050, 2050–2080)

Scenario 0–2020–2050				Scenario 02050–2080		
Crops	Area (km <sup>2</sup> )	Irrigation water needs (hm <sup>3</sup> /y)	NetFarm Income (€/y)	Area (km <sup>2</sup> )	Irrigation water needs (hm <sup>3</sup> /y)	Net Farm Income (€/y)
Cereals	619,60	0,00	13,984,372,00	619,60	0,00	13,984,372,00
Animal feed	112,94	7,14	3,782,360,60	112,94	7,95	3,782,360,60
Alfalfa	96,91	79,89	7,616,156,90	96,91	86,19	7,616,156,90
Maize	94,89	63,27	4,570,851,30	94,89	68,45	4,570,851,30
Sunflower	26,09	5,13	788,700,70	26,09	5,24	788,700,70
Vegetables	23,71	9,55	9,293,134,50	23,71	10,35	9,293,134,50
Legumes	10,26	3,52	329,756,40	10,26	3,88	329,756,40
Eastern tobacco	5,94	1,91	1,319,036,40	5,94	2,09	1,319,036,40
Tomatoes	4,40	1,75	2,846,140,00	4,40	1,90	2,846,140,00
Olive trees	3,50	1,07	142,835,00	3,50	1,21	142,835,00
Cotton	3,09	1,65	144,457,50	3,09	1,80	144,457,50
Sugar beet	2,62	1,57	138,021,60	2,62	1,73	138,021,60
Potatoes	2,49	0,95	385,551,60	2,49	1,04	385,551,60
Beans	0,75	0,23	83,602,50	0,75	0,25	83,602,50
Tobacco	0,74	0,28	152,181,00	0,29	0,30	152,181,00
Vineyards	0,65	0,18	90,077,00	0,65	0,20	90,077,00
Fruit trees	0,39	0,12	59,896,98	0,39	0,14	59,896,98
Fig trees	0,38	0,13	42,959,00	0,38	0,14	42,959,00
Sorghum	0,13	0,04	2947,10	0,05	0,04	2947,10
Summary	1009,48	178,38	45773038,08	774,67	192,91	45773038,08

Maize and alfalfa are the highest water intensive crops in the study area providing high net income to the farmers. On the contrary, the low water intensive crops, such as cereals and animal feed, were found to provide low farm income. The current annual total net farm income in the whole Mygdonia basin is estimated at 45,773,037.90 euros.

According to López-Bellido et al. (2014), energy crops development in European agriculture used for the second-generation biofuel production is the key to preserving the environment and food security. The second-generation biofuel production is projected to significantly increase in the near future in compliance with the European energy policies both in Europe and Greece. Nine energy crops, namely cardoon, reed, miscanthus, pseudoacacia, eucalyptus, switchgrass, *Jatropha curcas*, white willow and poplar were examined in terms of the suitable climate and soil conditions, the irrigation requirements, the harvest period and the net income of the farmers. It was found that cardoon is the most suitable, in terms of climatic and environmental conditions, to be cultivated in the Mygdonia basin. In particular, cardoon is a rainfed crop with a high resistance to the Mediterranean climate, also providing high net farm income; at about 76,533.33 €/km<sup>2</sup>/year.

### 3.4 Sustainable Development Strategy 1 (SDS1): Reduction of the Total Irrigated Agricultural Area

The SDS1 proposes the reduction of the irrigated agricultural land in the Mygdonia basin by following the EU CAP directions and the national Rural Development Program of Greece 2014–2020, according to which the fallow land measure is applied to at least 30% of the irrigated area, while in the set aside land all types of agricultural activity are prohibited.

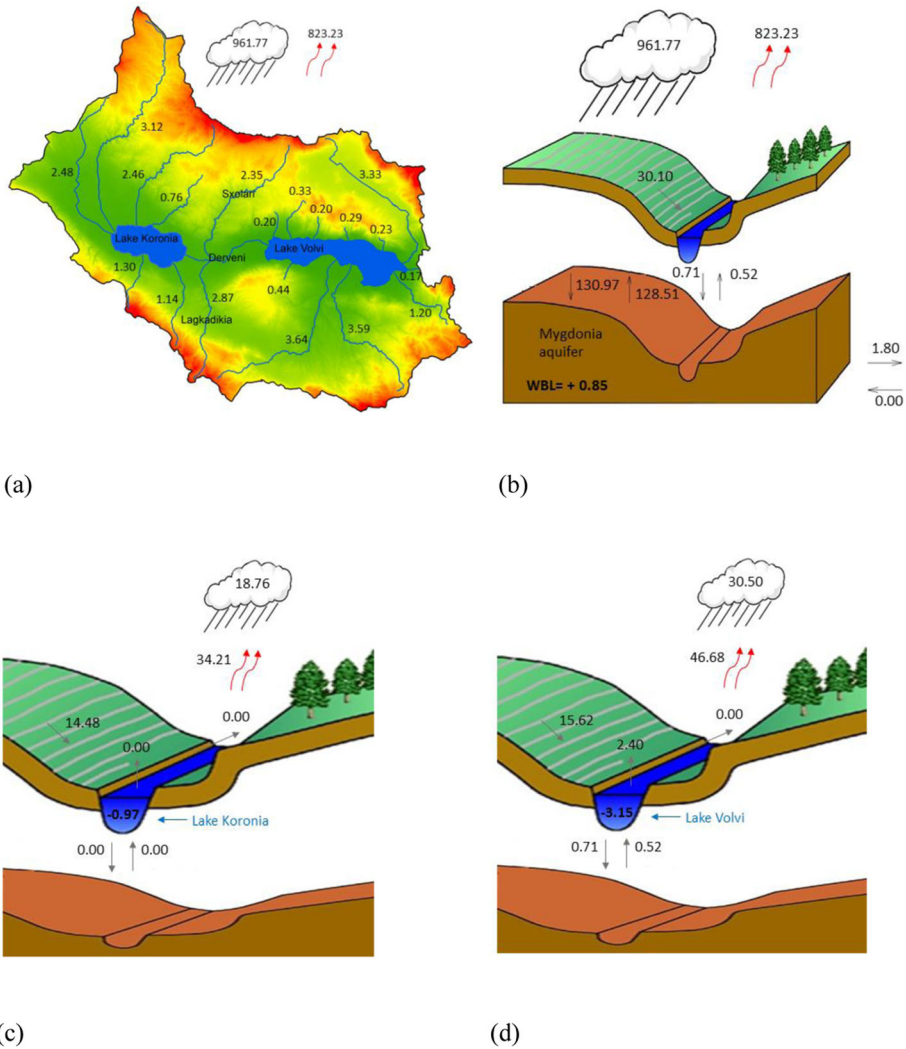
In particular, the fallow land measure is applied to all kinds of irrigated crops with the exception of tree plantations and vineyards, which are multiannual crops. Following a trial and error method it was found that the minimum percentage of the irrigated land of the Mygdonia basin that should be set aside in order to achieve a water surplus of Mygdonia basin aquifer is 33% and 61% for the 2020–2050 and 2050–2080 periods, respectively. Within the framework of the proposed SDS1 (Table 4), the irrigation water demand is projected to decrease from 178.38 hm<sup>3</sup>/year to 119.50 hm<sup>3</sup>/year in the 2020–2050 period and from 192.91 hm<sup>3</sup>/year to 75.38 hm<sup>3</sup>/year in the 2050–2080 period. The water balance under the SDS1 is presented in Figs. 8 and 9 for the 2020–2050 and 2050–2080 periods, respectively. Application of the SDS1 results in the water balance for the aquifer of +0.85 hm<sup>3</sup>/year and +0.20 hm<sup>3</sup>/year respectively for the two future periods.

### 3.5 Sustainable Development Strategy 2 (SDS2): Expansion of the Livestock Sector and Restructuring of Crops

The SDS2 refers to the increase of the livestock sector in the Mygdonia basin by 20% following directions by the Management Body of Lakes Koronia and Volvi. Livestock feed cultivated area, i.e. the alfalfa and the animal feed crops, is proposed to decrease as a means of reducing the total agricultural water needs in the study area. The maximum acceptable

**Table 4** Crop area under SDS1 for 2020–2050 and 2050–2080

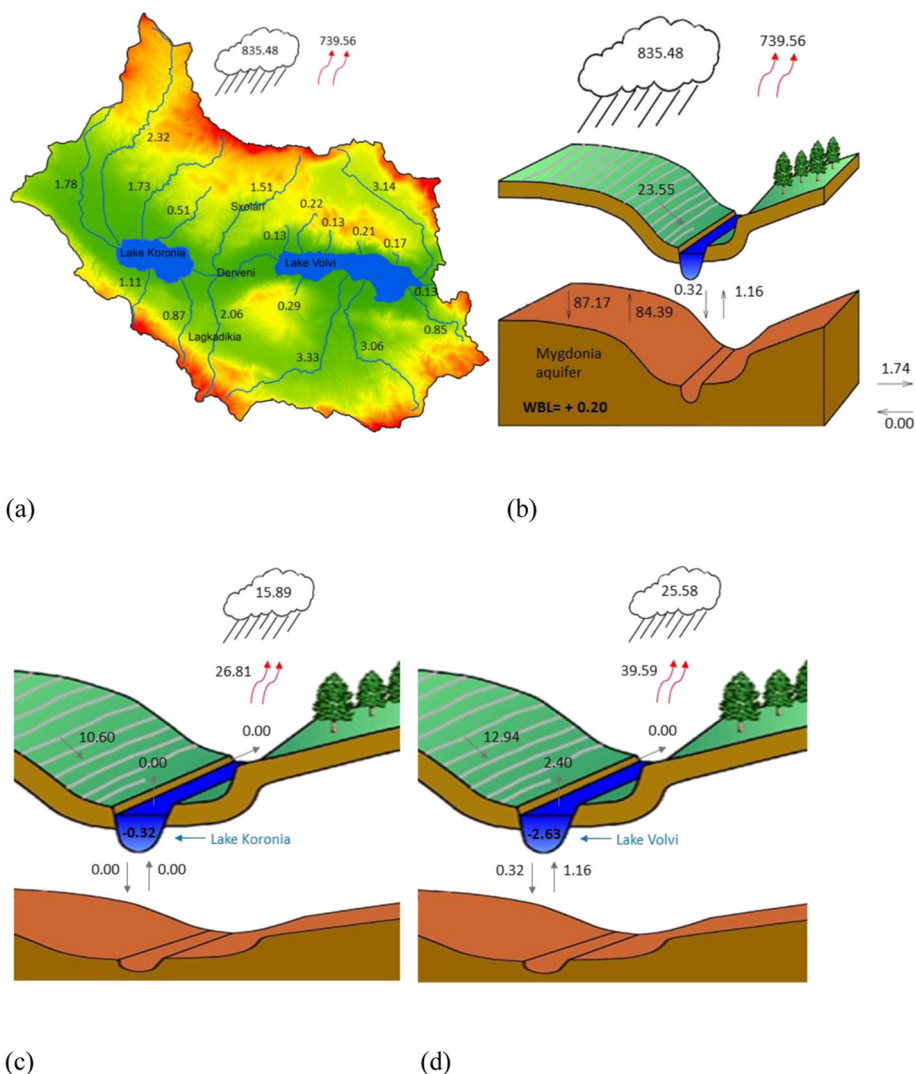
SDS1–2020–2050				SDS1 2050–2080			
Crops	Area (km <sup>2</sup> )	Irrigation water needs (hm <sup>3</sup> /year)	NetFarm Income (€/year)	Area (km <sup>2</sup> )	Irrigation water needs (hm <sup>3</sup> /year)	Net Farm Income (€/year)	
Cereals	619,60	0,00	13,984,372,00	619,60	0,00	13,984,372,00	
Animal feed	75,67	4,75	2,534,188,30	44,05	3,04	1,475,234,50	
Alfalfa	64,93	53,37	5,102,848,70	37,80	33,33	2,970,702,00	
Maize	63,58	42,26	3,062,648,60	37,01	26,46	1,782,771,70	
Sunflower	17,48	3,41	528,420,40	10,18	2,01	307,741,40	
Vegetables	15,89	6,36	6,228,085,50	9,25	3,97	3,625,537,50	
Legumes	6,87	2,34	220,801,80	4,00	1,48	128,560,00	
Eastern tobacco	3,98	1,26	883,798,80	2,32	0,79	515,179,20	
Tomatoes	2,95	1,15	1,908,207,50	1,72	0,71	1,112,582,00	
Olive trees	3,50	1,07	142,835,00	3,50	1,21	142,835,00	
Cotton	2,07	1,09	96,772,50	1,20	0,68	56,100,00	
Sugar beet	1,76	1,03	92,716,80	1,02	0,64	53,733,60	
Potatoes	1,67	0,62	258,582,80	0,97	0,38	150,194,80	
Beans	0,50	0,15	55,735,00	0,29	0,09	32,326,30	
Tobacco	0,49	0,18	100,768,50	0,29	0,11	59,638,50	
Vineyards	0,65	0,18	90,077,00	0,65	0,20	90,077,00	
Fruit trees	0,39	0,12	59,896,98	0,39	0,14	59,896,98	
Fig trees	0,38	0,13	42,959,00	0,38	0,14	42,959,00	
Sorghum	0,08	0,02	1813,60	0,05	0,01	1133,50	
Summary	882,44	119,50	35,395,528,78	774,67	75,38	26,591,574,98	



**Fig. 8** **a** Average annual runoff of each stream (hm<sup>3</sup>), **b** Average annual surface water – groundwater balance parameters (hm<sup>3</sup>), **c** Average annual Lake's Koronia water balance parameters (hm<sup>3</sup>) and **d** Average annual Lake's Volvi water balance parameters (hm<sup>3</sup>) under the SDS1 for the period 2020–2050

decrease of the livestock feed area was found to be 75% in order for the required livestock feed amount in the Mygdonia basin to be ensured.

The restructuring of crops consists of the promotion of less water-intensive crops and the promotion of energy crops that are cultivated with the purpose of the second-generation biofuels production. In particular, the promotion of less water-intensive crops is in compliance with the Regional Operational Programme 2014–2020 for Central Macedonia which promotes



**Fig. 9** **a** Average annual runoff of each stream (hm<sup>3</sup>), **b** Average annual surface water – groundwater balance parameters (hm<sup>3</sup>), **c** Average annual Lake's Koronia water balance parameters (hm<sup>3</sup>) and **d** Average annual Lake's Volvi water balance parameters (hm<sup>3</sup>) under the SDS1 for the period 2050–2080

the sustainable use of natural resources, the Revised Restoration Plan of Lake Koronia which supports the promotion of sustainable agricultural activities, the First Revision of the River Basin Management Plan of the Water District of Central Macedonia which promotes water saving measures in agriculture.

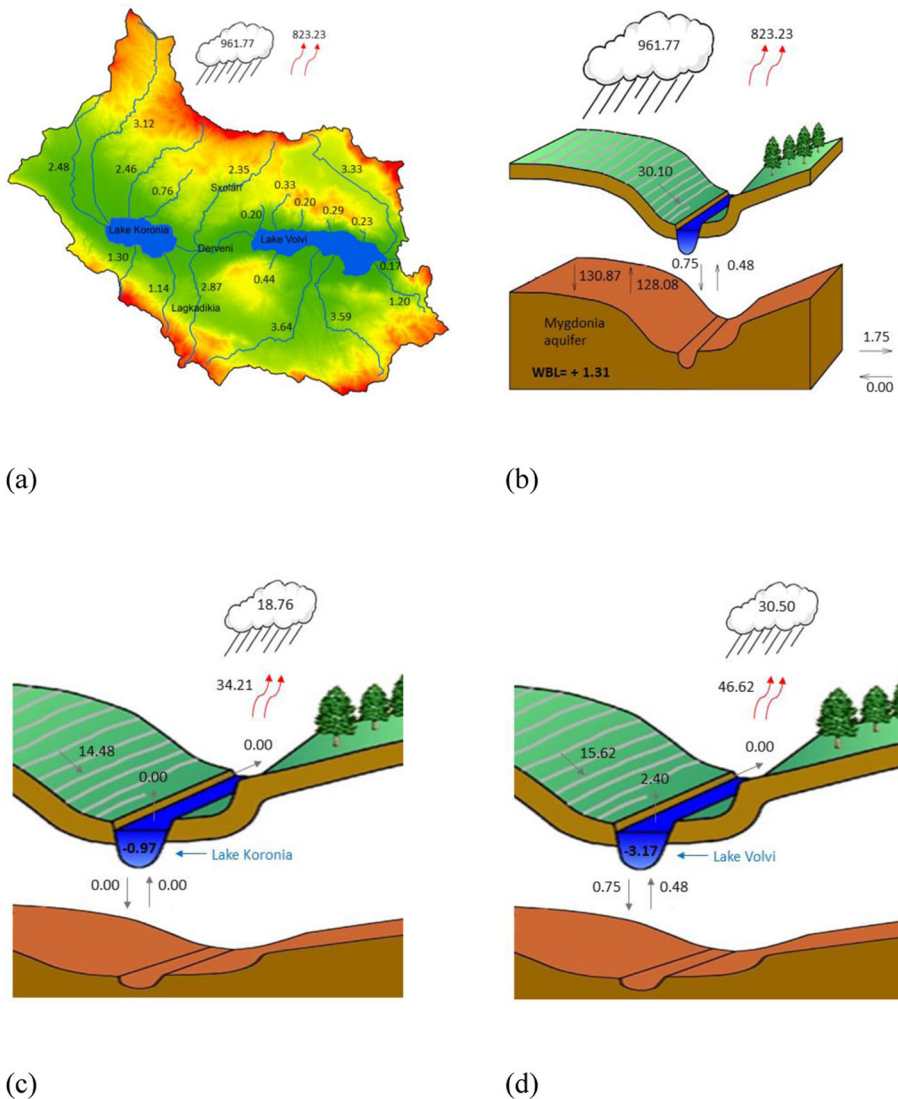
In the 2020–2050 period, the minimum decrease of the livestock feed area was estimated to 62% in order for a water surplus of the Mygdonia basin aquifer to be achieved. In the 2050–2080 period, the decrease of the livestock feed area at 75% would not be adequate to rehabilitate the water deficit of the Mygdonia basin aquifer and so it is proposed to be supplemented by a reduction of the rest water intensive crops in the study area, i.e. maize, tobacco, eastern type tobacco, cotton, sugar beet, sorghum, beans, legumes and potatoes. In both time periods, the reduction of the irrigated area is projected to decrease the total farm income in the Mygdonia basin. Therefore, the decrease of the irrigated area is proposed to be implemented along with a promotion of crops providing high net income capable to sustain farmers. In particular, cardoon, as a high profitable rainfed crop, and cereals, as crops that improve food security, are proposed to be promoted. The area of each crop for 2020–2050 and 2050–2080 is presented in Table 5 respectively.

The future water balance of the Mygdonia basin aquifer and the Lakes Koronia and Volvi under the SDS 2 is presented in Figs. 10 and 11.

Overall, the Mygdonia basin, is a highly water stressed basin which suffers from the impacts of both climate change and human interventions reflected in the constant decrease

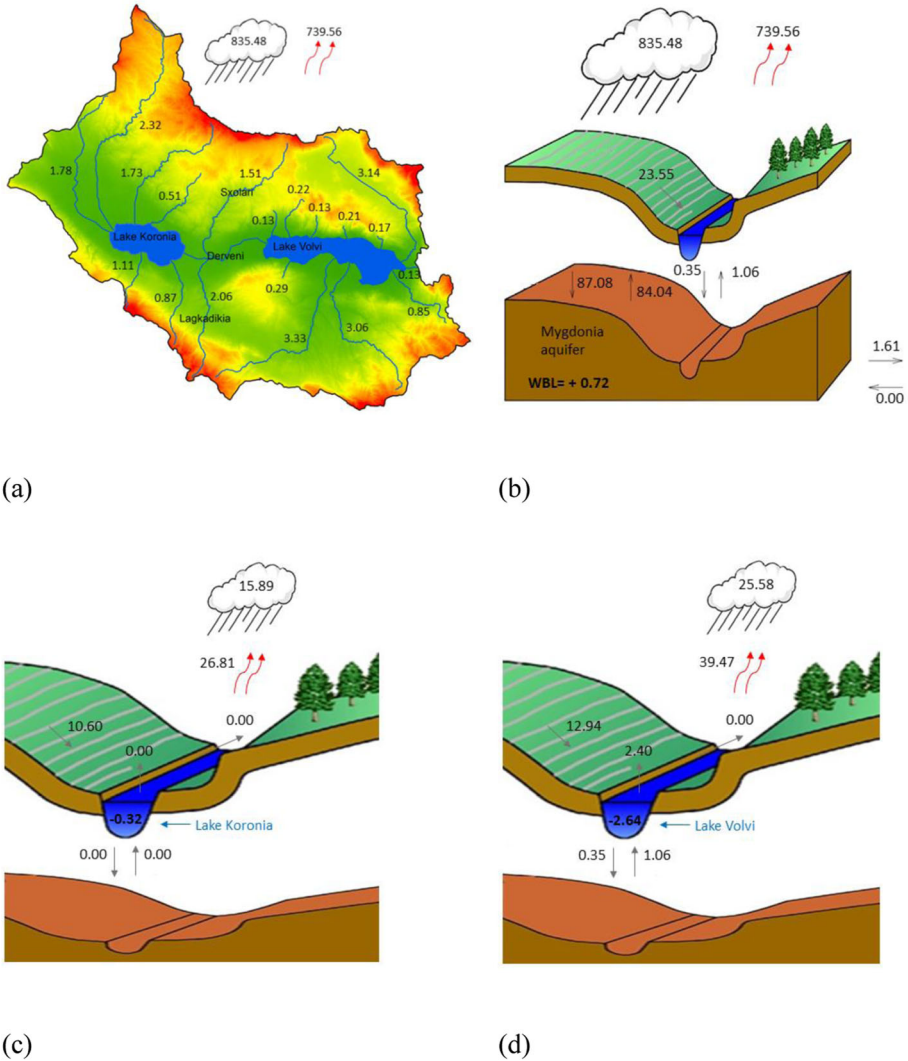
**Table 5** Crop and land data in the Mygdonia basin under the SDS2 for 2020–2050 & 2050–2080

SDS2–2020–2050				SDS2 2050–2080		
Crops	Area (km <sup>2</sup> )	Irrigation water needs (hm <sup>3</sup> /y)	NetFarm Income (€/y)	Area (km <sup>2</sup> )	Irrigation water needs (hm <sup>3</sup> /y)	Net Farm Income (€/y)
Cereals	687,76	0,00	15,522,743,20	724,93	0,00	16,361,670,10
Animal feed	42,92	2,67	1,437,390,80	28,24	1,94	945,757,60
Alfalfa	36,83	30,23	2,894,469,70	24,23	21,33	1,904,235,70
Maize	94,89	63,07	4,570,851,30	45,55	32,56	2,194,143,50
Sunflower	0,00	0,00	0,00	0,00	0,00	0,00
Vegetables	23,71	9,52	9,293,134,50	23,71	10,27	9,293,134,50
Legumes	10,26	3,51	329,756,40	4,92	1,83	158,128,80
Eastern tobacco	5,94	1,90	1,319,036,40	2,85	0,98	632,871,00
Tomatoes	4,40	1,75	2,846,140,00	4,40	1,89	2,846,140,00
Olive trees	3,50	1,07	142,835,00	3,50	1,20	142,835,00
Cotton	3,09	1,65	144,457,50	1,48	0,84	69,190,00
Sugar beet	2,62	1,57	138,021,60	1,26	0,80	66,376,80
Potatoes	2,49	0,94	385,551,60	1,19	0,46	184,259,60
Beans	0,75	0,23	83,602,50	0,36	0,11	40,129,20
Tobacco	0,74	0,28	152,181,00	0,35	0,14	71,977,50
Vineyards	0,65	0,18	90,077,00	0,65	0,20	90,077,00
Fruit trees	0,39	0,12	59,896,98	0,39	0,14	59,896,98
Fig trees	0,38	0,13	42,959,00	0,38	0,14	42,959,00
Sorghum	0,13	0,04	2947,10	0,06	0,02	1360,20
Summary	88,04	0,00	6,737,994,67	141,02	0,00	10,792,730,67



**Fig. 10** a Average annual runoff of each stream (hm<sup>3</sup>), b Average annual surface water – groundwater balance parameters (hm<sup>3</sup>), c Average annual Lake's Koronia water balance parameters (hm<sup>3</sup>) and d Average annual Lake's Volvi water balance parameters (hm<sup>3</sup>) under the SDS2 for the period 2020–2050





**Fig. 11** a Average annual runoff of each stream (hm<sup>3</sup>), b Average annual surface water – groundwater balance parameters (hm<sup>3</sup>), c Average annual Lake's Koronia water balance parameters (hm<sup>3</sup>) and d Average annual Lake's Volvi water balance parameters (hm<sup>3</sup>) under the SDS2 for the period 2050–2080

**Table 6** Water balance of Mygdonia basin for Scenario 0, SDS1, SDS2

Water balance				
Period	Water demand (hm <sup>3</sup> /y)	Groundwater aquifer	Lake Koronia	Lake Volvi
1970–2000	164,94	–27,47 (water deficit)	–6,95 (water deficit)	–2,89 (water deficit)
2020–2050				
SCENARIO 0	178,38	–47,05	–0,97	–3,67
SDS1	119,50 (33%)	+0,85	–0,97	–3,15
SDS2	118,85 (59,5%)	+1,31	–0,97	–3,17
2050–2080				
SCENARIO 0	192,91	–93,58	–0,32	–2,83
SDS1	75,38 (60,9%)	+0,20	–0,32	–2,63
SDS2	74,83 (61,2%)	+0,72	–0,32	–2,64

of its water potential (Table 6). It has become clear, through this study, that water supply scenarios cannot cope with the deterioration of the area, whereas demand management adaptation scenarios proved to be more efficient and sustainable. The cumulative effect of the combination of the crop restructuring (Table 7) and the agricultural land decrease of 66% proved to be the most appropriate sustainable water policy.

**Table 6** Crop restructuring under SDS1 and SDS2

2020–2050				2050–2080	
Crops	Scenario 0 Area (km <sup>2</sup> )	SDS1 % decrease	SDS2 % decrease	SDS1 % decrease	SDS2 % decrease
Cereals	619,60	0,00	11,00	0,00	17,00
Animal feed	112,94	–33,00	–62,00	–61,00	–75,00
Alfalfa	96,91	–33,00	–62,00	–61,00	–75,00
Maize	94,89	–33,00	0,00	–61,00	–52,00
Sunflower	26,09	–33,00	–100,00	–61,00	–100,00
Vegetables	23,71	–33,00	0,00	–61,00	0,00
Legumes	10,26	–33,00	0,00	–61,00	–52,05
Eastern tobacco	5,94	–33,00	0,00	–61,00	–52,02
Tomatoes	4,40	–33,00	0,00	–61,00	0,00
Olive trees	3,50	0,00	0,00	0,00	0,00
Cotton	3,09	–33,00	0,00	–61,00	–52,10
Sugar beet	2,62	–33,00	0,00	–61,00	–51,91
Potatoes	2,49	–33,00	0,00	–61,00	–52,21
Beans	0,75	–33,00	0,00	–61,00	–52,00
Tobacco	0,74	–33,00	0,00	–61,00	–52,70
Vineyards	0,65	0,00	0,00	0,00	0,00
Fruit trees	0,39	0,00	0,00	0,00	0,00
Fig trees	0,38	0,00	0,00	0,00	0,00
Sorghum	0,13	–33,00	0,00	–61,00	–53,85
Cardoon	–		introduced in SDS1		introduced in SDS1
Summary	1009,48	–12,58		–23,26	

## 4 Conclusions

This paper proposed and assessed various water adaptation management scenarios and strategies on a highly water deficit agricultural basin through the use of an integrated approach combining climate model projections, hydro-technical and socio economic data.

Climate change seriously affects all water systems in a river basin. Water supply adaptation scenarios, as water transfer, in agriculture proved to be insufficient to respond to further water shortages due to climate change. This is natural since potential water transfers aimed at enhancing the water quantity in a basin, will also be affected by the decrease of water flows due to climate change.

A basin should be seen as an integral water system and its management should not be limited to the temporary restoration of specific degraded water bodies. Particular attention should be given to limiting and / or eliminating the direct and indirect causes of degradation in the whole system. Tested in the Mygdonia basin, MS1 showed that this scenario is inefficient and at the same time unsustainable. The steady water diversion of the Sxolari stream to Lake Koronia is expected to have a very small positive contribution to the enhancement of the water potential of Lake Koronia and cannot cope with the water deficit of the lake. This happens because the contribution of MS1 in the water balance of the lakes is not sufficient to overcome the negative impact of climate change. At the same time, this measure is expected to further reduce the water potential of Lake Volvi, which in combination with its environmental impact on the area's fauna, make it unsustainable.

MS3 and their combinations (SDS1 and SDS2) depict demand management policies, in terms of reducing the agricultural water demand either through crop restructuring or through the decrease of the cultivated land. Concerning the strategy of reducing the total irrigated land area, it was found that the minimum percentage of irrigated land to be set aside in order to achieve positive surplus for the groundwater aquifers is 33% and 61% for the short 2020–2050 and the long term 2050–2080 period, respectively. In addition, the water balance of Lake Volvi is projected to improve compared to the zero scenario, with the improvement being attributed to the elevation of groundwater aquifers. The elevation contributes to the increase in hydraulic outflow from the underground aquifers to Lake Volvi. On the contrary, it is not expected to improve the water balance of Lake Koronia compared to the zero scenario, due to the impermeable bottom of the lake.

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## Compliance with Ethical Standards

**Conflict of Interest** None.

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