Journal of
Water & Climate Change

 Journal of Water and Climate Change Vol 15 No 8, 3689 doi: 10.2166/wcc.2024.014

Integrated water operations under climate change: Uluova Micro Basin example

Kürşat Şekerci [a],*, Muhammed Cihat Tuna [b] and Mustafa Sahin Dogan [c]

[a] Department of Civil Engineering, Bingol University, Bingol, Turkey
[b] Department of Civil Engineering, Firat University, Elazig, Turkey
[c] Department of Civil Engineering, Aksaray University, Aksaray, Turkey
*Corresponding author. E-mail: ksekerci@bingol.edu.tr

KŞ, 0000-0001-9096-4644; MCT, 0000-0001-9005-1968; MŞD, 0000-0002-3378-9955

ABSTRACT

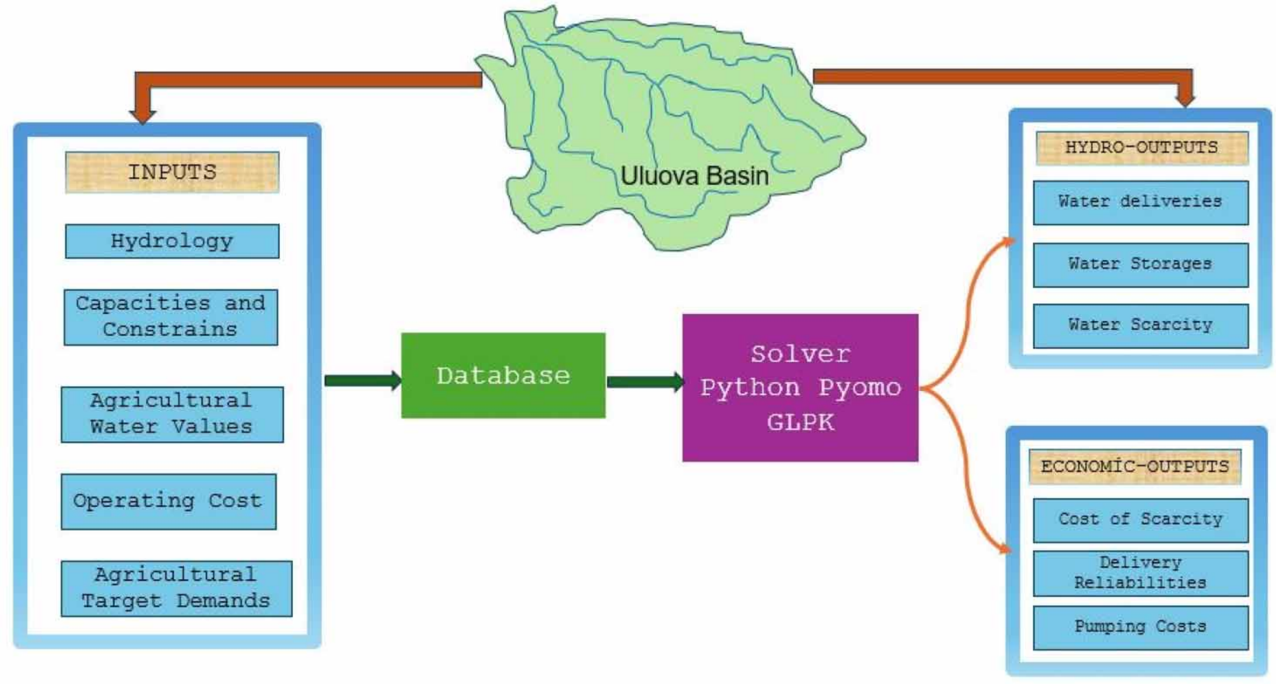
This study examines the impact of climate change on the Uluova Micro Basin, Turkey, employing an optimization model named ULUHEM across various water management and climate scenarios. With ULUHEM, the effects of different climate impact scenarios on agricultural water allocations, pumping costs, water scarcity, and scarcity costs were analyzed. The primary objective of this study is to identify gaps in demand within the current water supply infrastructure due to global warming and to develop adaptation strategies for basinwide water management operations. The research also emphasizes the importance of creating a basin-based hydroeconomic model that includes other surface water resources with a sustainable management approach to address the impact of climate change. In summary, the impacts of climate change on surface waters and groundwater in the Uluova Micro Basin include changes in water availability, water scarcity, and associated costs, and these have implications for agricultural water allocations and overall water management in the region. The study found that drier climate periods lead to reduced surface and groundwater input to farmland, resulting in increased water scarcity and scarcity costs. Conversely, periods characterized by wetter climates yield contrasting outcomes, alleviating water scarcity and its corresponding costs.

Key words: basin management, climate change, ULUHEM, water resources

HIGHLIGHTS

- Effects of climate change on agricultural irrigation.
- Basin-based integrated surface and groundwater management.
- Management of water resources with a hydroeconomic optimization model.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Besides challenges posed by population growth, increasing demands for food and energy, urbanization, and industrialization, freshwater resources face mounting pressure due to climatic conditions and rising global temperature (Vörösmarty *et al.* 2000; Rosegrant *et al.* 2002; Molden & De Fraiture 2010). Increasing water scarcity and decreasing water availability caused by climate change could potentially have adverse impacts on the sustainability of economic activities and overall growth (Gohar *et al.* 2019). Climate change affects surface water and groundwater in various aspects, including changes in temperature, precipitation, water flows, and the amount of water recharge to the groundwater resources (Hatchett & McEvoy 2017). Sarker (2022) conducted a comprehensive study on the consequences of climatic effects on water resources.

Protecting the sustainability of natural resource access, notably water, carries significant global implications (Grey & Sadoff 2007). It is estimated that there will be long-term and significant changes in the flow sizes and timing of reservoir flows in the near future in regions with a Mediterranean climate, including Turkey, attributed to the impacts of global warming and climate change. Climate change drives rising temperatures, a shift from snowfall to rainfall, particularly evident in winter, and altered timing of snowmelt. These effects, which are already visible today, will become even more evident in the near future (National Water Plan 2019). Agricultural water withdrawal globally constituted 62.6% of total water withdrawal on average from 2003 to 2021, highlighting the sector's significant reliance on groundwater. As access to water will become more difficult with the impact of climate change, agricultural activities are expected to be negatively affected (Zhai *et al.* 2022). Management of water resources, which are under the threat of global warming and climate change, is a very important issue in terms of the sustainability of resources. It is also anticipated that the basin-based management approach will indirectly contribute to vital issues such as the international water policy of countries, socio-economic development of the country, water supply, and food security. It is clear that this situation will affect society not only in terms of water resources but also in a wide variety of areas, from the economy to social life (National Water Plan 2019). Pittock *et al.* (2016) emphasized in their study that the storage capacity of groundwater aquifers needs to be increased to mitigate the impacts of climate change. Baccour *et al.* (2021) stated that the pressure on water resources caused by climate change can significantly affect the sustainability of surface and groundwater reservoirs by managing them together with water use models. In other studies, it has been reported that climate change and the overdraft of groundwater resources, especially in dry and semi-dry regions, lead to serious water scarcity and land degradation (Greve *et al.* 2018; Dasgupta 2021). WMO (World Meteorological Organization) (2021) stated that climate change has caused not only environmental disasters in Europe in the last 50 years, but also serious economic losses due to the decrease in surface and groundwater resources resulting from climatic water stress. Baccour *et al.* (2022) stated that more efficient and sustainable adaptation policies should be created in order to manage water stress arising from surface and groundwater use.

Hydroeconomic models integrate hydrological, engineering, environmental, and economic aspects of regional water resources systems into a cohesive framework. The idea is to operationalize economic concepts by incorporating them into the heart of water resources management models. These models have emerged as indispensable tools for facilitating integrated water resources management, offering solution-driven approaches to enhance efficiency and transparency in water use. The aim is to look at a system in a new way to investigate promising water management plans and policy insights (Harou *et al.* 2009). In integrated water resources management models, groundwater and surface water connections can be evaluated in a broader context through basin management. In other words, a basin-centric approach is necessary, beyond the aquifer, with a perspective that addresses intersectoral issues related to the economy, energy, climate, agriculture, and environment (UNEP 2008). Zhang & Guo (2016) emphasized the management of agricultural water resources with the economic optimization method in their studies. Several researchers have explored the impacts of climate change on basin hydrology across various regions under diverse real and potential scenarios (Albek *et al.* 2004; Fujihara *et al.* 2008; Önol *et al.* 2009; Türkeş 2012; Okkan & Fıstıkoglu 2014; Türkeş 2014; Kale *et al.* 2016; Turan 2018). In their study, Dogan *et al.* (2019) investigated historical hot-dry climate conditions in the California Central Valley basin to investigate the impact of climate change on groundwater with a hydroeconomic management model. Hydrological scenarios were carried out to determine the effects of climate change on water resources and to determine the optimal use of resources (Zaman *et al.* 2016; Farjad *et al.* 2017; Morid *et al.* 2019). Sarker *et al.* (2019) have carried out a number of studies to understand the weakness of river networks under external factors with an optimization approach. In another study, Sarker (2021) worked on a model that investigated the physical properties of river networks under different climatic conditions. Singhal *et al.* (2024) carried out a number of studies on stream flows and sediment formations in river basins using climatic parameters with the Soil and Water Assessment Tool (SWAT) simulation model. Gao *et al.* (2022), with the optimization approach in their studies, focused on the potential deterioration of dams at critical node points in the river network.

This study focuses on the management of groundwater and surface agricultural water resources, specifically investigating water deliveries, pumping costs, water shortages, and scarcity costs under various climatic scenarios. A hydroeconomic model was developed for the Uluova basin, located within Turkey's Euphrates and comprising significant agricultural areas. The Uluova basin and its groundwater aquifer have been used for years as the most important and easily accessible resource for agricultural activities. For this reason, we built a basin-based hydroeconomic model Uluova hydroeconomic (ULUHEM) that includes surface water and groundwater resources to study and eliminate groundwater overdraft for sustainable water management. Through our modeling efforts, we aim to identify potential demand gaps in the current water supply system within the Uluova Micro Basin due to global warming and propose adaptation strategies for basin-oriented water management operations. Six different climate impact scenarios were examined, apart from the historical period (Scenario 1), altering inflows of water resources feeding both surface and groundwater reservoirs in response to climatic changes.

1.1. Study area and management scenarios

Uluova Basin, which has fertile alluvial soils, consists of an area of approximately 35,000 ha. The plain has an irrigable area of approximately 25,000 ha. In plant production activities in Uluova, grain production is carried out in dry conditions, industrial and forage crop production is carried out in irrigated conditions, and vineyard and garden production is carried out in regions where ecological conditions are suitable. In regions where crop production is carried out, agricultural enterprises are medium and small-scale, but they are mostly family enterprises. Since the Uluova Basin has alluvial soils, commercial agriculture can be carried out. Agricultural production of field crops such as barley, wheat, orchard, sugar beet, potatoes, corn, clover, and strawberries is carried out in the plain. Various vegetables and fruits are produced in vineyard and garden agriculture. Figure 1 shows the groundwater and surface water reservoirs used in agricultural irrigation activities in the Uluova basin. As water sources, there are groundwater aquifers and surface water sources that cover the entire plain. There are various water structures for agricultural irrigation purposes in Uluova. These are the Eyup Baglari pumped irrigation station, whose source is the Keban Dam Lake, the Tadım Reservoir, which is the Hos Stream, the Dedeyolu Reservoir, which is the Kumardı River, and finally the Gökçe Reservoir, which is the Uluova River.

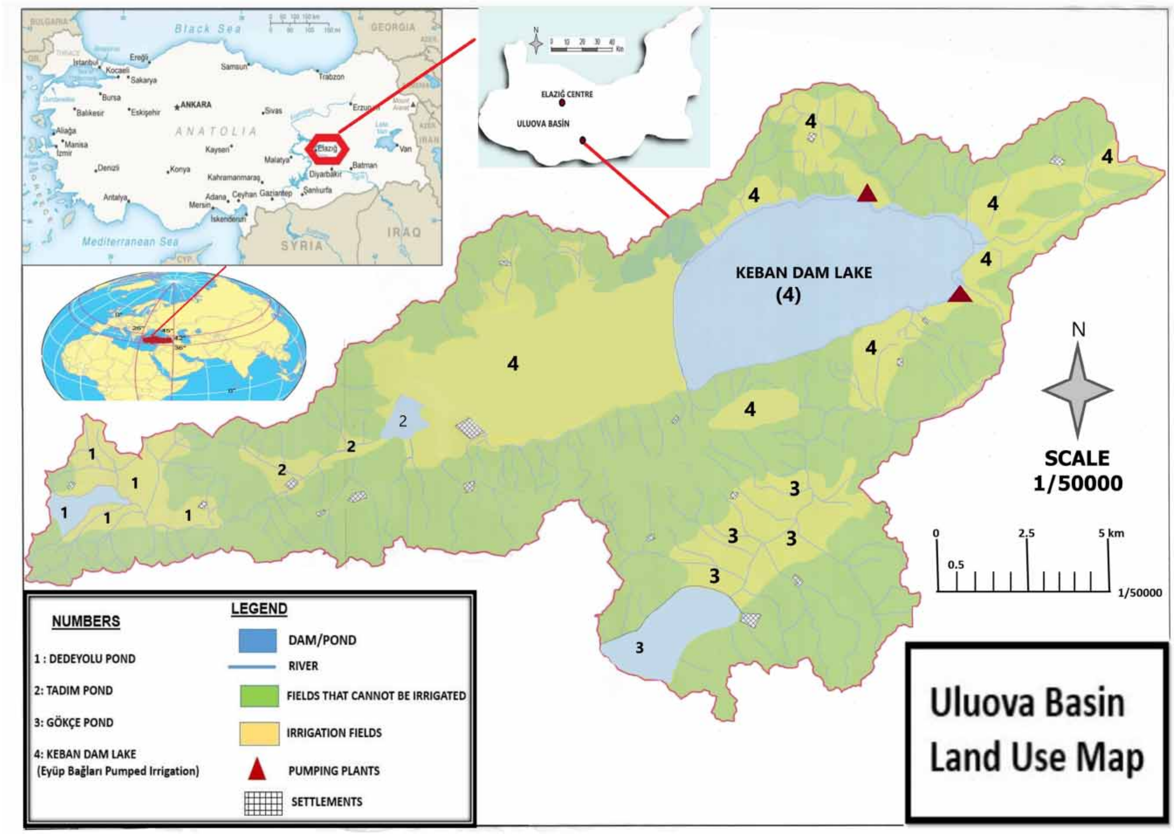


Figure 1 | Working area, irrigation fields, and reservoirs.

Different climate scenarios cause different hydrological flows. A drier climate scenario results in smaller inflows, and a wetter climate scenario results in larger inflows. In this section, six different climatic scenarios, apart from the base case (Scenario 1), were examined by changing the inflows of water resources feeding the surface and groundwater reservoirs (other numerical parameters are the same), as given in Table 1.

Table 1 | Climatic management scenarios

Scenario	Description	Implementation	Importance
Scenario 1	Operations with historical	Historical (1991–2011) long-term water operations for the entire Uluova Basin for 20 years.	Historical base case operation
Scenario 2	Somewhat dry	A situation in which the flows entering the reservoirs for a hot and dry climate decrease by −10% (less dry) compared to the historical period.	10% drier than historical period
Scenario 3	Dry	A situation in which the flows entering the reservoirs for a hot and dry climate decrease by −20% (dry) compared to the historical period.	20% drier than historical period
Scenario 4	Very dry	A situation in which the flows entering the reservoirs for a hot and dry climate decrease by −30% (extremely dry) compared to the historical period.	30% drier than historical period
Scenario 5	Somewhat wet	For a wet climate, the inflows into reservoirs increase by +10% compared to the historical period.	10% wetter than historical period
Scenario 6	Wet	For a wet climate, the inflows into reservoirs increase by +20% compared to the historical period.	20% wetter than historical period
Scenario 7	Very wet	For a wet climate, the inflows into reservoirs increase by +30% compared to the historical period.	30% wetter than historical period

2. ULUHEM MODEL

Mathematically, ULUHEM is a network-flow reservoir optimization model. Within the scope of the model, the physical water allocation and distribution system is represented by nodes, and links connecting these nodes and their parameters. Links are defined by $(i, j, k) \in A$. Where 'i' is the initial node, 'j' is the final node, and 'k' is a piecewise component used to represent linear penalty (or cost) curves with a convex piecewise description. The 'k' component creates multiple links from the initial node 'i' to the terminal node 'j' (Şekerci 2023).

Each link has the following parameters:

Loss factor 'a', unit cost 'c', lower bound 'l', and upper bound (or capacity) 'u'.

The objective function (Dogan *et al.* 2018):

$$\max_X z = \sum_i \sum_j \sum_k c_{ijk} X_{ijk} \tag{1}$$

The objective function in Equation (1) is a sum over all links (i, j, k) and represents the total cost of the flow transported in the network. Equations (2)–(4) represent the lower bound, upper bound, and mass balance constraints, respectively.

$$X_{ijk} \leq u_{ijk}, \ \forall (i, j, k) \in A \tag{2}$$

$$X_{ijk} \geq l_{ijk}, \ \forall (i, j, k) \in A \tag{3}$$

$$\sum_i X_{jik} - \sum_i a_{ijk} X_{ijk} = 0, \ \forall j \in N \tag{4}$$

The ULUHEM model uses historical hydrological data from 1991 to 2001 to represent hydrological variability. The model was developed using the Python-based Pyomo platform. Pyomo is a high-level optimization modeling language written in Python programming language. This platform uses the GNU Linear Programming Kit (GLPK) solver (Dogan *et al.* 2018).

Operating costs include pumping, treatment, and facility expenses incurred during the transportation of water. Since water quality costs (treatment) for urban users can be represented as operating costs, operating costs vary because the incoming water quality varies depending on the primary source (whether it comes from a groundwater or surface source). In the created model, the hydrological data of the water resources used and planned to be used in the future for Uluova agricultural irrigation demand areas and Elazığ province urban drinking water demands, as well as the capacity and unit costs of structures such as groundwater and surface reservoirs, pumping facilities, drinking and wastewater treatment facilities fed by these water resources. It consists of parameters such as the loss coefficient (loss during the transmission of water). This study focuses only on the agricultural management scenarios and outputs of the Uluova model. Figure 2 shows the flow chart and legend of the ULUHEM model.

3. RESULTS

Six different climatic impact scenarios were examined, apart from the historical period (Scenario 1), by changing the inflow of surface and groundwater reservoirs, while keeping other numerical parameters constant. The results presented in this section show the interaction of agricultural water allocations, pumping costs, water scarcity (from groundwater and surface water sources), and scarcity costs for each of the six different management scenarios. These results are compared with Scenario 1, involving water operations in the historical period.

3.1. Uluova basin historical period agricultural water operations and reservoir storage

Figure 3 shows the monthly average storage changes of agricultural water reservoirs in Uluova for all years. It can be said that groundwater reservoir storage is higher. The reason for this may be that users prefer surface water in the first place and turn to groundwater reservoirs in times of water scarcity. It can be said that the storage amount in both groundwater and surface reservoirs increased significantly as of January and decreased depending on water usage at the end of May and the beginning of June. The monthly average storages of Keban Dam, one of the agricultural water resources, are not given in the figure. Since very little water can be taken from Keban Dam, which is a very large capacity water source compared to other

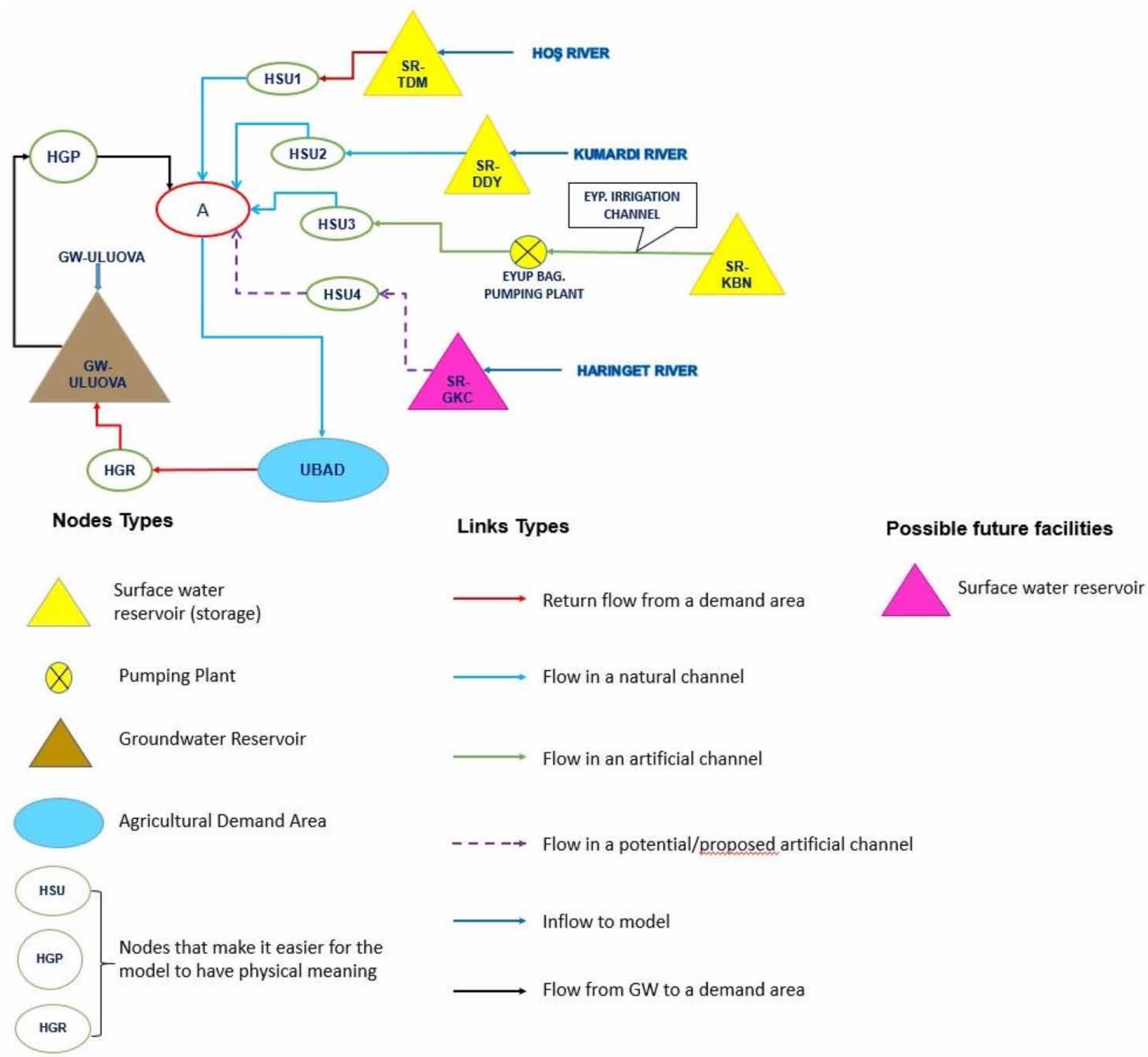


Figure 2 | ULUHEM model schematic.

agricultural reservoirs, with Eyup Baglari pumped irrigation compared to its capacity, the monthly average storage value almost does not change.

Figure 4 shows the change in the annual total amount of water drawn from surface-groundwater reservoirs to the Uluova agricultural area. It can be said that the groundwater (GW) reservoir alone meets almost half of the agricultural water withdrawal. There are two reasons for this. The first is that groundwater is less costly for agricultural users. The second reason is the insufficient capacity of surface water resources that do not have pumping costs and the high pumping cost of Eyup Baglari surface irrigation, which has sufficient capacity.

3.2. Uluova basin agricultural water operations according to different management scenarios

Figure 5 shows the annual water deliveries and water shortages from surface and groundwater to the agricultural area by comparing six different climatic impact scenarios with the historical period represented in the ULUHEM Model (Scenario 1). Figure 5 shows the annual average groundwater pumping, surface water flow, return flow to the groundwater reservoir (by

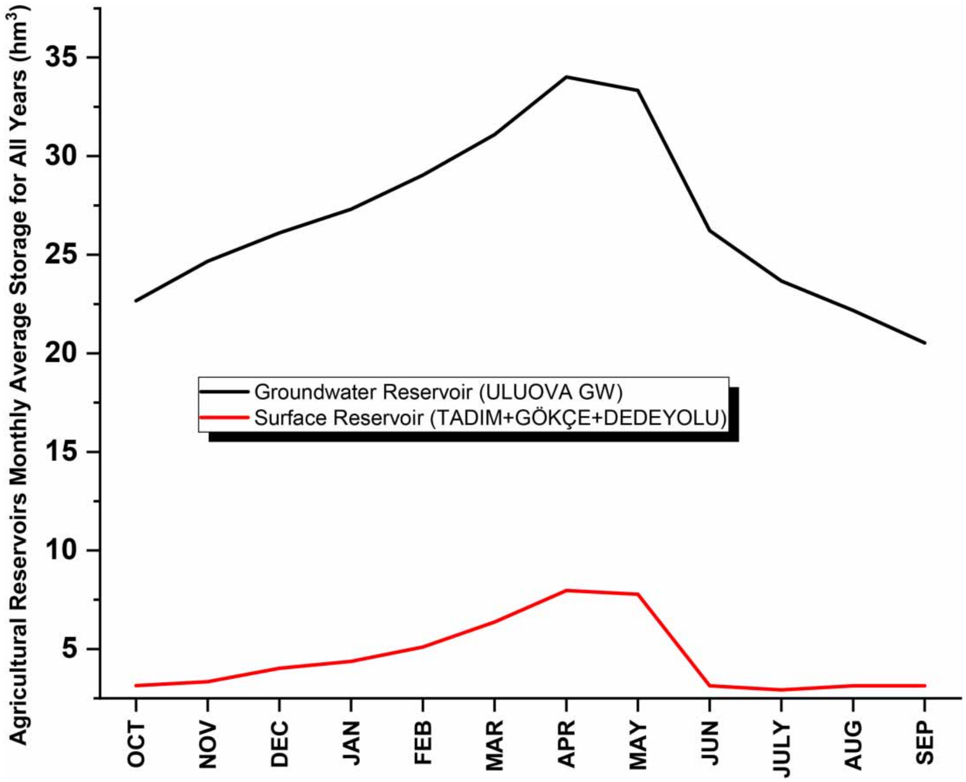


Figure 3 | Monthly storage of agricultural reservoirs.

infiltration), and water scarcity changes in the Uluova agricultural area under different climatic change scenarios. The expression hm^3/year in the ordinate axis refers to the water deliveries that take place annually on average on the basis of hm^3. According to the historical period (Scenario 1), it can be said that agricultural water scarcity increases in dry climate scenarios and decreases in wet climate scenarios. It can be said that the water scarcity that occurs especially in the lowest dry climate scenario (Scenario 4) is almost the same as the base case.

Table 2 compares six different climatic impact scenarios with the historical period in the ULUHEM model and expresses the annual water allocations from surface and groundwater to the agricultural area, pumping costs, water shortages, scarcity costs, and flows that return to the groundwater aquifer through infiltration as a result of irrigation. While the annual water scarcity of the Uluova Micro Basin was approximately 92.27 million m^3 in the historical period, the cost of scarcity resulting from the loss of agricultural production due to water deficiency is approximately 53.6 million dollars annually. The cost of pumping from groundwater and surface reservoirs to irrigate agricultural areas is a total of $1.87 million per year.

The results of the scenarios created under climate change are as follows:

In Scenario 2, which is one of the dry climate scenarios, the total annual water shortage is 95.23 hm^3, the resulting scarcity cost due to loss of production is $55.3 million, and the cost of pumping water from surface and groundwater reservoirs to the agricultural area is $1.82 million.

In Scenario 3, the total annual water shortage is 98.92 hm^3, the cost of the resulting shortage due to loss of production is $57.44 million, and the cost of pumping water from surface and groundwater reservoirs to the agricultural area is $1.76 million.

In Scenario 4, the total annual water shortage is 102.50 hm^3, the cost of the resulting shortage due to loss of production is $59.52 million, and the cost of pumping water from surface and groundwater reservoirs to the agricultural area is $1.70 million.

In Scenario 5, which is one of the wet climate scenarios, the total annual water shortage was 91.08 hm^3, the cost of the resulting shortage due to production loss was 52.89 million dollars, and the cost of pumping water from surface and groundwater reservoirs to the agricultural area was $1.67 million.

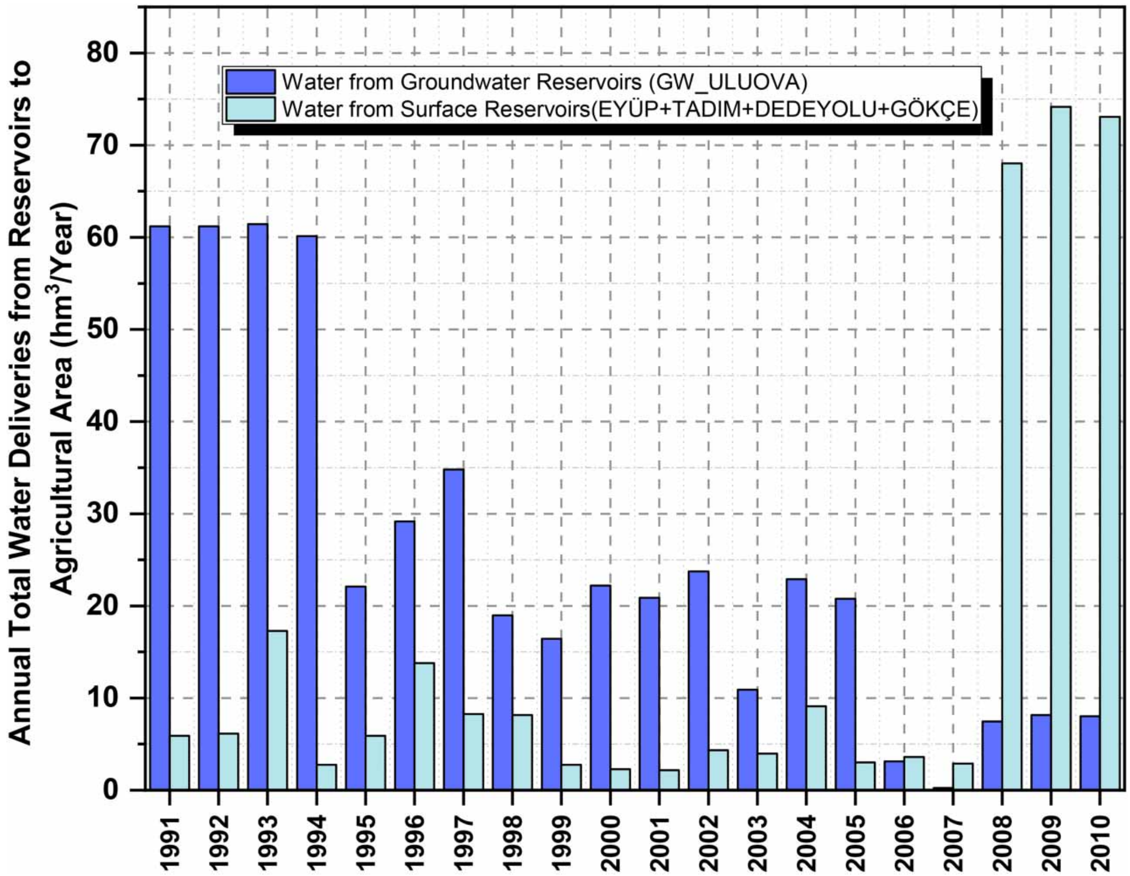


Figure 4 | Total annual surface-groundwater deliveries for Uluova agricultural irrigation.

In Scenario 6, the total annual water shortage was 89.80 hm^3, the cost of the resulting shortage due to production loss was 52.15 million dollars, and the cost of pumping water from surface and groundwater reservoirs to the agricultural area was 1.68 million dollars.

Finally, in Scenario 7, the total annual water shortage was 86.64 hm^3, the cost of the resulting shortage due to production loss was 50.31 million dollars, and the cost of pumping water from surface and groundwater reservoirs to the agricultural area was 1.72 million dollars.

3.3. Share of surface and groundwater in the Uluova Basin according to different management scenarios

Figure 6 shows the percentage distribution of the annual total water pumping and surface water of the total water portfolio coming to the agricultural area according to climate-indexed scenarios. In the historical period, 49.79% of the water used in Uluova agricultural demand was provided by groundwater, and 50.21% was provided by surface sources. In the basic case, approximately half of the water entering the agricultural area is via groundwater pumping. The reason why the percentage of groundwater pumping in agricultural use is high is that not enough water can be taken from surface water resources due to high pumping costs. In addition, agricultural users can obtain water more easily from water wells in their areas of activity. In Scenarios 23, and 4, as the degree of climatic drought increases, the amount of water realized from both the surface and groundwater reservoirs decreases compared to the historical case. However, since the water pumping decreases proportionately more than the surface water pumping in these three scenarios compared to the base case, the percentage of the water coming from the water pumping decreases as the severity of the drought increases, while the value of the percentage of the water coming from the surface reservoir increases. In wet climate conditions, the inlet flow rates to groundwater and surface reservoirs increase. Accordingly, agricultural users tend to further increase the pumping of groundwater instead of Eyup Baglari, which has high-cost surface water. This means that, compared to the base case, as the severity (percentage) of

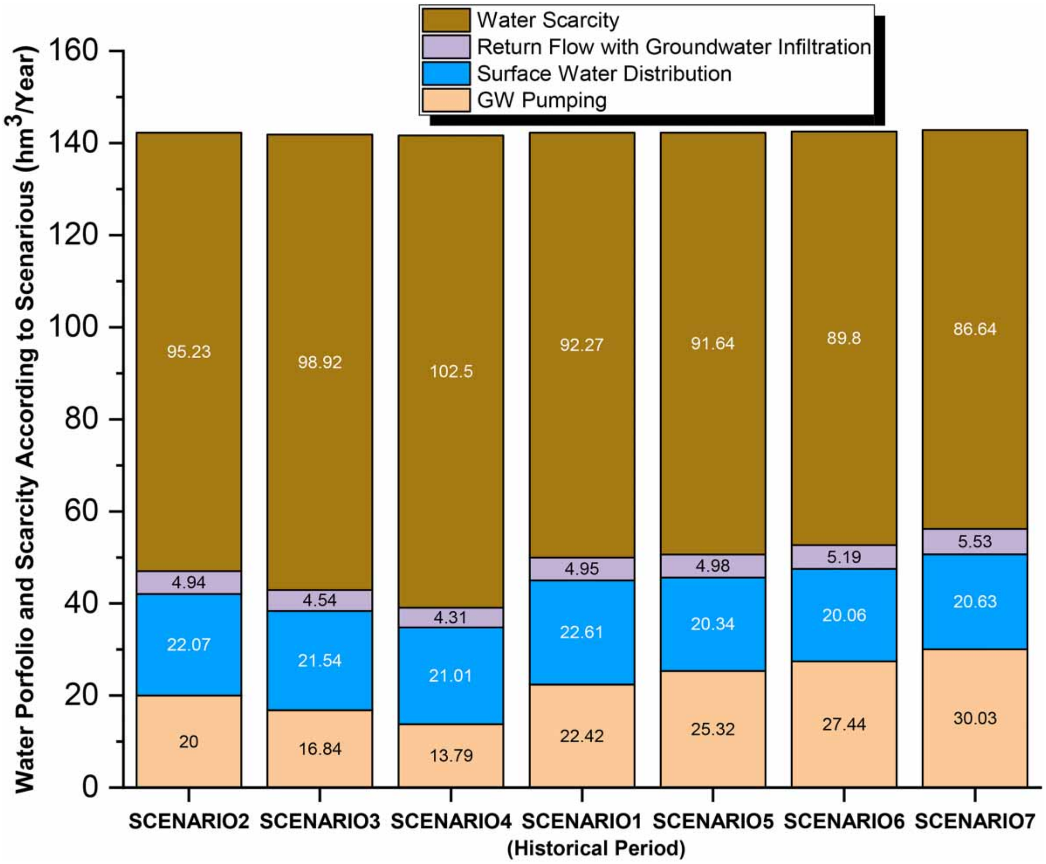


Figure 5 | Water portfolios formed according to historical periods and climate scenarios.

Table 2 | Different climatic management scenarios

Climatic situation	Scenarios	Groundwater pumping (hm^3/year)	Surface water distribution (hm^3/year)	Infiltration returning to the groundwater (hm^3/year)	Water scarcity hm^3/year	Total pumping cost (GW + SW) million $/year	Scarcity cost
Somewhat dry	Scenario 2	20	22.07	4.94	95.23	1.82	55.30
Dry	Scenario 3	16.84	21.54	4.54	98.92	1.76	57.44
Very dry	Scenario 4	13.79	21.01	4.31	102.5	1.70	59.52
Historical	Scenario 1	22.42	22.61	4.95	92.27	1.87	53.58
Somewhat wet	Scenario 5	25.32	20.34	4.98	91.08	1.67	52.89
Wet	Scenario 6	27.44	20.06	5.19	89.8	1.68	52.15
Very wet	Scenario 7	30.03	20.63	5.53	86.64	1.72	50.31

climatic wetness increases in Scenarios 5, 6, and 7, the percentage of water pumping from the groundwater reservoir increases while the percentage of water drawn from the surface reservoir decreases. The expression hm^3/year in the ordinate axis refers to the water deliveries that take place annually on average on the basis of hm^3.

4. DISCUSSION

In this section, similar studies and results of our study conducted by other researchers are discussed. Tian *et al.* (2018) emphasized in their studies that agricultural sustainability will be possible with the efficient use of water resources. They emphasized

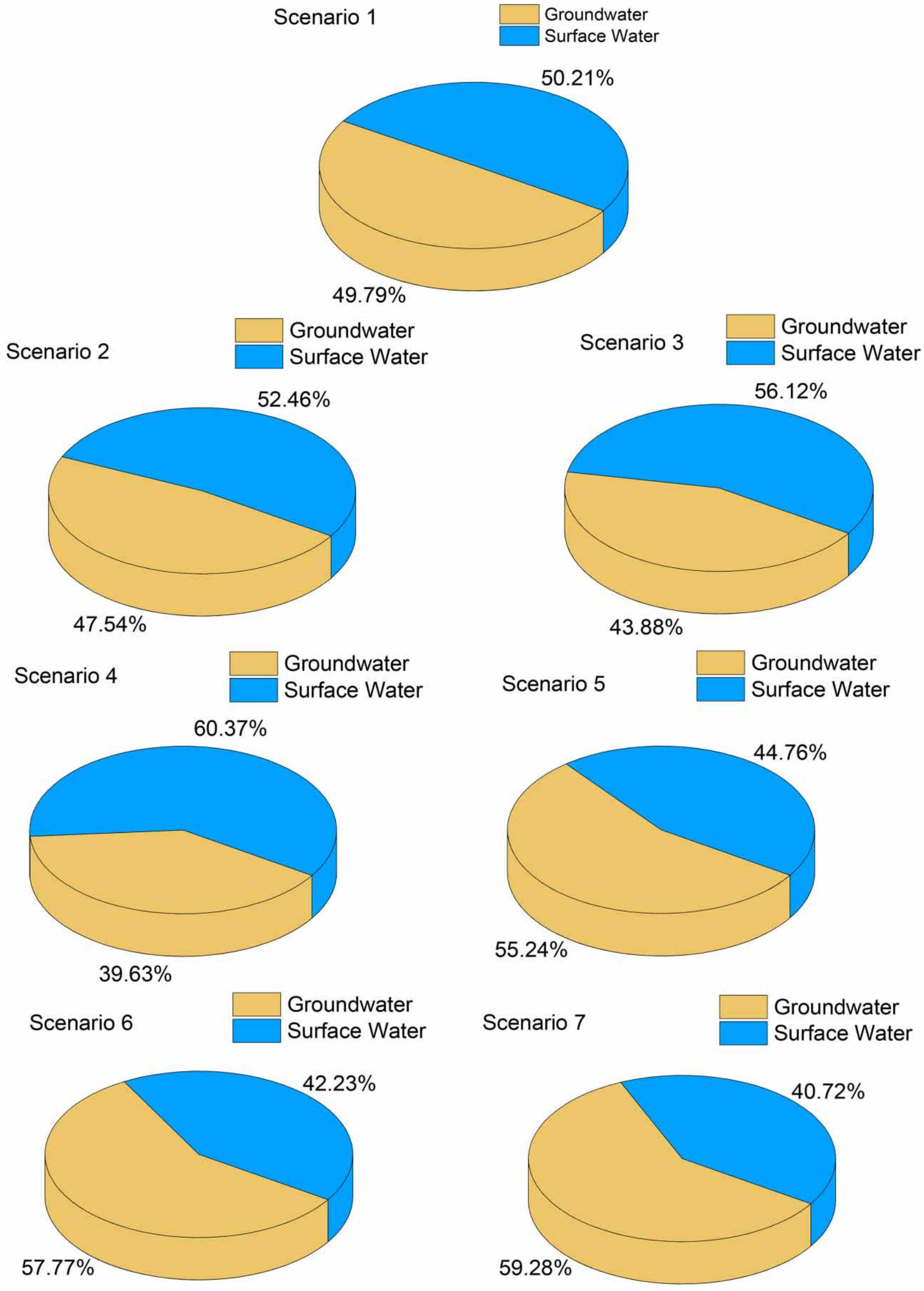


Figure 6 | Water deliveries from groundwater and surface reservoirs according to historical period and climate scenarios (in percentage terms).

the importance of introducing many economic elements for water resources management using the optimization method (Davijani *et al.* 2016).

In other studies, a framework is presented for measuring and solving the negative effects of climate change through local water management decisions based on the basin economy (Auffhammer 2018; Eamen *et al.* 2021). Aytac *et al.* (2024) carried out some studies on water resources management and climate change adaptation strategies with the hydroeconomic model called Upper Euphrates Basin Hydro-economic Model (FEHEM). In their study results, they emphasized the importance of including agricultural and urban demands and groundwater basins into the system for a better-integrated water system representation.

Previous researchers have emphasized the importance of investigating factors such as integrated water management for agricultural sustainability, efficient use of water resources, monitoring the negative effects of climate change, and incorporating economic parameters into water resources management with the optimization method. In this study, the issues whose importance was emphasized and recommended above were discussed with a holistic approach using the optimization method on a basin-based scale. The study attracts attention in terms of containing concrete outputs such as examining the negative effects of climate change mentioned in the literature, economic parameters of water resources management, and integrated use of water resources for agricultural sustainability.

5. CONCLUSION

In this study, six different climatic impact scenarios created by changing the historical period water operations and the inlet currents of water resources feeding surface and groundwater reservoirs under the influence of climate change (other numerical parameters are the same) were compared with the ULUHEM hydroeconomic model.

As the climate dries, surface, and groundwater inflow to agricultural areas is decreasing as a result of the decrease in flows entering reservoirs. Water inflows from the flow (infiltration) returning from the agricultural irrigation area to the groundwater reservoir also decrease as climatic drought increases. In wet climate scenarios, the flow from groundwater pumping to agricultural areas increases. Inflows from surface reservoirs decreased in +10, +20, and +30% (wet climate situations) scenarios as the effect of the wet climate scenario increased, as the water entering the agricultural area through the more cost-effective groundwater pumping increased. Although water inflow from surface reservoirs to the agricultural area decreased in Scenarios 5, 6, and 7 compared to Scenario 1, which is the base case, surface water delivery in Scenario 7, where the climatic precipitation was the highest, increased compared to Scenarios 5 and 6. With the increase in precipitation, the amount of water entering the groundwater reservoir by infiltration during the wet seasons has also increased. Due to water shortages in agricultural areas, scarcity costs increase as the severity (percentage) of the climatic drought scenario increases. In wet climate scenarios, water scarcity and scarcity costs tend to decrease according to the basic situation with the increase in incoming water.

It can be said that the only advantage of dry climate scenarios compared to the historical period is the reduction of pumping costs paid for irrigation. In wet climate scenarios, as the degree of wetness increases (percentage), it has been observed that the water pumping costs of agricultural users have increased compared to the base case, but the total pumping cost has decreased since the water drawn from the surface water, which has a high unit cost, will decrease. As the severity (percentage) of climatic wetness increases, the total pumping cost for agricultural users decreases in wet climate scenarios compared to the base case, as agricultural users will turn to groundwater pumping rather than getting water from Eyup Baglari with high pumping costs.

In the results obtained, it has been seen that the agricultural activities of the plain are directly affected according to different climatic change scenarios. The ULUHEM model represents hydrological events on a 20-year time scale. As better data for the model becomes available, it will be useful to revisit the model.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Albek, M., Öğütveren, Ü. & Albek, E. 2004 Hydrological modeling of Seydi Suyu watershed (Turkey) with HSPF. *Journal of Hydrology* **285**, 260–271. doi:10.1016/j.jhydrol.2003.09.002.

Auffhammer, M. 2018 Quantifying economic damages from climate change. *Journal of Economic Perspectives* **32** (4), 33–52. doi:10.1257/jep.32.4.33.

Aytac, A., Dogan, M. S. & Tuna, M. C. 2024 Energy-based hydro-economic modeling of climate change effects on the Upper Euphrates Basin. *Journal of Water and Climate Change* **15** (2), 733–746. https://doi.org/10.2166/wcc.2024.550.

Baccour, S., Albiac, J., Kahil, T., Esteban, E., Crespo, D. & Dinar, A. 2021 Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain. *Journal of Cleaner Production* **327**, 129459.

Baccour, S., Ward, F. A. & Albiac, J. 2022 Climate adaptation guidance: New roles for hydroeconomic analysis. *Science of the Total Environment* **835**, 155518.

Dasgupta, P. 2021 *The Economics of Biodiversity: The Dasgupta Review*. HM Treasury, London.

Davijani, M. H., Banihabib, M. E., Anvar, A. N. & Hashemi, S. R. 2016 Optimization model for the allocation of water resources based on the maximization of employment in the agriculture and industry sectors. *Journal of Hydrology* **533**, 430–438.

Dogan, M. S., Fefer, M. A., Herman, J. D., Hart, Q. J., Merz, J. R., Medellin-Azuara, J. & Lund, J. R. 2018 An open-source Python implementation of California's hydroeconomic optimization model. *Environmental Modelling & Software* **108**, 8–13. doi:10.1016/j.envsoft.2018.07.002.

Dogan, M. S., Buck, I., Medellin-Azuara, J. & Lund, J. R. 2019 Statewide effects of ending long-term groundwater overdraft in California. *Journal of Water Resources Planning and Management* **145** (9), 04019035.

Eamen, L., Brouwer, R. & Razavi, S. 2021 Integrated modelling to assess the impacts of water stress in a transboundary River Basin: Bridging local-scale water resource operations to a River Basin Economy. *Science of The Total Environment* **800**, 149543.

Farjad, B., Gupta, A., Razavi, S., Faramarzi, M. & Marceau, D. 2017 An integrated modelling system to predict hydrological processes under climate and land-use/cover change scenarios. *Water* **9** (10), 767.

Fujihara, Y., Tanaka, K., Watanabe, T., Nagano, T. & Kojiri, T. 2008 Assessing the impacts of climate change on the water resources of the Seyhan River Basin in Turkey: Use of dynamically downscaled data for hydrologic simulations. *Journal of Hydrology* **353** (1–2), 33–48.

Gao, Y., Sarker, S., Sarker, T. & Leta, O. T. 2022 *Environmental Research Communications* **4**, 101001. doi:10.1088/2515-7620/ac9459.

Gohar, A. A., Cashman, A. & Ward, F. A. 2019 Managing food and water security in Small Island states: New evidence from economic modelling of climate stressed groundwater resources. *Journal of Hydrology* **569**, 239–251.

Greve, P., Kahil, T., Mochizuki, J., Schinko, T., Satoh, Y., Burek, P., Fischer, G., Tramberend, S., Burtscher, R., Langan, S. & Wada, Y. 2018 Global assessment of water challenges under uncertainty in water scarcity projections. *Nature Sustainability* **1**, 486–494. https://doi.org/10.1038/s41893-018-0134-9.

Grey, D. & Sadoff, C. W. 2007 Sink or swim? Water security for growth and development. *Water Policy* **9** (6), 545–571.

Harou, J. J., Pulido-Velázquez, M., Rosenberg, D. E., Medellín-Azuara, J., Lund, J. R. & Howitt, R. E. 2009 Hydro-economic models: Concepts, design, applications, and future prospects. *Journal of Hydrology* **375**, 627–643. doi:10.1016/j.jhydrol.2009.06.037.

Hatchett, B. J. & McEvoy, D. J. 2017 Exploring the origins of snow droughts in the Northern Sierra Nevada, California. *Earth Interactions*. https://doi.org/10.1175/EI-D-17-0027.1.EID-17-0027.1.

Kale, S., Ejder, T., Hisar, O. & Mutlu, F. 2016 *İklim değişikliğinin Bakırçay Nehrinin yıllık akışı üzerine etkisi*.

Molden, D. & De Fraiture, C. 2010 Comprehensive assessment of water management in agriculture. *Agricultural Water Management* **97** (4), 493–578.

Morid, R., Shimatani, Y. & Sato, T. 2019 Impact assessment of climate change on environmental flow component and water temperature – Kikuchi River. *Journal of Ecohydraulics* **4** (2), 88–105.

National Water Plan 2019 *T.C. Tarım ve Orman Bakanlığı, Ankara*. Available from: https://www.tarimorman.gov.tr/SYGM/Belgeler/NHYP%20DEN%C4%B0Z/ULUSAL%20SU%20PLANI.pdf (Erişim: 17 Mart 2021).

Okkan, U. & Fistikoglu, O. 2014 Evaluating climate change effects on runoff by statistical downscaling and hydrological model GR2M. *Theoretical and Applied Climatology* **117** (1–2), 343–361.

Onol, B., Unal, Y. S. & Dalfes, H. N. 2009 Modelling impacts of climate change scenario over Turkey. *ITU Journal Series D: Engineering* **8** (5), 169–177.

Pittock, J., Hussey, K., Stone, A., 2016 Groundwater management under global change: Sustaining biodiversity, energy and food supplies. In: *Integrated Groundwater Management* (Jakeman, A. J., Barreteau, O., Hunt, R. J., Rinaudo, J. D. & Ross, A., eds.). Springer, Cham. https://doi.org/10.1007/978-3-319-23576-9_4.

Rosegrant, M. W., Cai, X. & Cline, S. A. 2002 *World Water and Food to 2025: Dealing with*. International Food Policy Research Institute (IFPRI), Washington, DC.

Sarker, S. 2021 *Investigating Topologic and Geometric Properties of Synthetic and Natural River Networks Under Changing Climate. Electronic Theses and Dissertations. 2020-*.965. Available from: https://stars.library.ucf.edu/etd2020/965.

Sarker, S. 2022 Fundamentals of climatology for engineers: Lecture note. *Eng* **3** (4), 573–595. https://doi.org/10.3390/eng3040040.

Sarker, S., Veremyev, A., Boginski, V. & Singh, A. 2019 Critical nodes in river networks. *Scientific Reports* **9**, 11178. https://doi.org/10.1038/s41598-019-47292-4.

Şekerci, K. 2023 *Sustainable Management of Uluova Micro Basin Groundwater*. PhD Thesis, Firat University, Graduate School of Natural and Applied Sciences, Elazığ.

Singhal, A., Jaseem, M., Divya, Sarker, S., Prajapati, P., Singh, A. & Jha, S. K. 2024 Identifying potential locations of hydrologic monitoring stations based on topographical and hydrological information. *Water Resources Management* **38**, 369–384. https://doi.org/10.1007/s11269-023-03675-x.

Tian, H., Lu, C., Pan, S., Yang, J., Miao, R., Ren, W., Yu, Q., Fu, B., Jin, F. F., Lu, Y. & Melillo, J. 2018 Optimizing resource use efficiencies in the food–energy–water nexus for sustainable agriculture: From conceptual model to decision support system. *Current Opinion in Environment Sustainability* **33**, 104–113.

Turan, E. S. 2018 Türkiye'nin iklim değişikliğine bağlı kuraklık durumu. *Doğal Afetler ve Çevre Dergisi* **4** (1), 63–69.

Türkeş, M. 2012 Türkiye'de gözlenen ve öngörülen iklim değişikliği, kuraklık ve çölleşme. *Ankara Üniversitesi Çevrebilimleri Dergisi* **4** (2), 1–32.

Türkeş, M. 2014 Kuraklık Olaylarının İklim Değişikliği ve Çölleşme Açısından Önemi ve Türkiye'deki 2013–2014 Kuraklığının Sinoptik Klimatolojik/Meteorolojik ve Atmosferik Bağlantıları. *Hidropolitik Akademi İklim Değişikliği ve Kuraklık Çalışmaları, Ankara* 1–12.

UNEP 2008 *Vital Water Graphics – An Overview of the State of the World's Fresh and Marine Waters*, 2nd edn. UNEP, Nairobi. ISBN 92-807-2236-0.

Vörösmarty, C. J., Green, P., Salisbury, J. & Lammers, R. B. 2000 Global water resources: Vulnerability from climate change and population growth. *Science* **289** (5477), 284–288.

WMO (World Meteorological Organization) 2021 *2021 State of Climate Services: Water*.

Zaman, M. R., Morid, S. & Delavar, M. 2016 Evaluating climate adaptation strategies on agricultural production in the Siminehrud catchment and inflow into Lake Urmia, Iran using SWAT within an OECD framework. *Agricultural Systems* **147**, 98–110.

Zhai, R., Tao, F., Chen, Y., Dai, H., Liu, Z. & Fu, B. 2022 Future water security in the major basins of China under the 1.5 °C and 2.0 °C global warming scenarios. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2022.157928.

Zhang, D. & Guo, P. 2016 Integrated agriculture water management optimization model for water saving potential analysis. *Agricultural Water Management* **170**, 5–19.

First received 4 January 2024; accepted in revised form 23 July 2024. Available online 7 August 2024