Journal of
Water & Climate Change

 Journal of Water and Climate Change Vol 14 No 9, 3385 doi: 10.2166/wcc.2023.377

Development of Upper Euphrates Basin hydro-economic model and hydropower generation optimization

Ayca Aytac[a,*], M. Cihat Tuna[b] and Mustafa Sahin Dogan[c]

[a] Department of Civil Engineering, Dogus University – Dudullu Campus, Istanbul, Turkey
[b] Department of Civil Engineering, Firat University, Elazığ, Turkey
[c] Department of Civil Engineering, Faculty of Engineering, Aksaray University, Aksaray, Turkey
*Corresponding author. E-mail: aaytac@dogus.edu.tr

ABSTRACT

Hydro-economic optimization models are common in hydropower reservoir modeling to aid system operators and planners. In these models, operations are driven by the economic value and constrained by the availability of water. The objective is to either minimize total costs or maximize total benefits. In this study, a hydro-economic optimization model for the integrated reservoir system of the Upper Euphrates Basin, with major tributaries providing water flow to the Euphrates River, is introduced. These model the 10 large-scale reservoirs of the basin with a total installed capacity of 3,255 MW. Water management and hydropower decision-making operations are evaluated with a piecewise linear programming algorithm in monthly time steps using a 45-year historical hydrology between 1971 and 2016. The model aims to maximize hydropower revenue over a long-term time horizon with energy prices varying by month. Reservoir storage and turbine release decisions are optimized for multiple hydropower plants connected in serial or parallel. Hydropower generation, revenue, reservoir storage, capacity ratios and generation reliability results are analyzed. Results show that these hydropower plants generate about 9,481 Gigawatt hour (GWh) of energy with an average turbine capacity use of 36% and obtain a revenue of 620 million $ per year.

Key words: climate change, hydro-economic model, hydropower energy, integrated basin management, the Upper Euphrates Basin

HIGHLIGHTS

- With the Upper Euphrates Basin Hydro-economic Model (FEHEM), a hydro-economic optimization model covering a 45-year period of hydrological datasets was developed.
- With the FEHEM, cost estimates can be developed for adaptation projects to be carried out in the Euphrates Basin water system under future climatic conditions and adaptation strategies that minimize the costs of increased hydrological variability can be developed.

NOTATIONS AND ABBREVIATIONS

AKL	Asagi Kalekoy Dam
BGT	Bagistas Dam
BYH	Beyhan Dam
CALVIN	California Value Integrated Network
DAP	Eastern Anatolia Project
FEHEM	Upper Euphrates Basin Hydro-economic Model
GAP	Southeastern Anatolia Project
GWh	Gigawatt hour
KBN	Keban Dam
KGI	Kigi Dam
MW	Megawatt
MWh	Megawatt hour
M$	Million dollar (revenue)
OZL	Ozluce Dam
PMB	Pembelik Dam
SPI	Standardized Precipitation Index
SYR	Seyrantepe Dam

TTR Tatar Dam
UZN Uzuncayir Dam

1. INTRODUCTION

Global water withdrawals have been increasing rapidly in recent years to sustain rising living standards with ever-increasing energy and food demands (Kummu *et al.* 2010; Mekonnen & Hoekstra 2016; Liu *et al.* 2017). Many basins around the world have experienced widespread water scarcity conditions and associated water management challenges as a manifestation of this situation (Wada *et al.* 2013; Kahil *et al.* 2015; Veldkamp *et al.* 2017). These challenges are expected to become even more critical in the coming years (Hanasaki *et al.* 2013; Kim *et al.* 2016). In addition, the discharge of wastewater degrades water quality, resulting in water that cannot be used for potable water and industrial applications (Panagopoulos & Giannika 2022a, 2022b, 2023). Therefore, policymakers in vulnerable basins need to be able to meet the demands of different sectors. To do so, they need to anticipate how to adapt their management practices to secure future water supply. However, the choice of water management options is often associated with trade-offs across space and time between multiple water-related systems such as food production, energy supply and ecosystem services (Banzhaf 2009; Hurford *et al.* 2014). Appropriate consideration of all these options requires the development of a systematic approach that describes the biophysical and socioeconomic factors that determine the future dynamics of river basins, including the fundamental interactions between water, energy and agricultural systems (Rogers & Fiering 1986; Brown *et al.* 2015; Wada *et al.* 2017).

Hydro-economic models combine water resource engineering and economics, where water allocation is governed by the economic value of water, while operating costs and hydrology influence water allocations (Cai 2008; Harou *et al.* 2009a, 2009b; Booker *et al.* 2012). Hydro-economic models are a mathematical expression of the water demand and allocation relationships of different water-using sectors (e.g. agriculture, industry, municipalities and hydropower generation) and the hydrological relationships in the water system (Bekchanov *et al.* 2015). Hydro-economic models are usually built around a river basin, because there is a strong relationship between water-dependent production and watersheds in terms of environmental systems (Keller & Keller 1995; Keller *et al.* 1996; Ringler *et al.* 2004).

Hydropower is an important renewable energy source in the Euphrates basin. Hydropower plants in the Upper Euphrates Basin Hydro-economic Model (FEHEM) are from large water storage or run-of-river plants. Hydropower plants with storage are advantageous because they add flexibility to water resources operations. This is because these plants store water at times when the demand for water is low and the supply is high. At times of high demand for water, stored water is released and power is generated to meet water and energy demands. Due to these characteristics, hydropower plants with large storage capacities can better adapt to changing climatic conditions with their operational flexibility. Since unit energy prices are key economic factors for hydropower decisions, hydro-economic models are suitable tools for representing hydropower planning and management decisions.

Despite hydro-economic models' importance in more efficient water allocation and hydropower decision-making, this study is the first attempt to develop an integrated hydro-economic optimization model for the Upper Euphrates Basin with 10 hydropower plants. The aim of this study is to analyze the Upper Euphrates Basin water supply system with different management and decision-making strategies and to contribute to management solutions with engineering alternatives. For this purpose, it has developed an efficient and flexible hydropower operation and planning model using state-of-the-art optimization modeling techniques. The FEHEM is a hydro-economic optimization model for the interconnected water supply system of the Upper Euphrates Basin. The FEHEM represents approximately 8.1% of Turkey's total drainage area. Using 45 years of historical hydrological data to represent hydrologic variability, the model determines the optimum hydropower generation decisions of the modeled reservoirs. Using the developed model, it will be possible to prepare water management plans according to different policies and future climate scenarios to determine adaptation strategies in advance.

The paper is organized as follows: Section 2 describes model development, including governing equations for optimizations, modeled reservoirs and their characteristics. Section 3 presents turbine flow, reservoir storage, and hydropower generation and revenue results. Section 4 presents a discussion of the paper and Section 5 provides concluding remarks.

2. MATERIALS AND METHODS

2.1. Model development

Hydrological and economic data are used in hydro-economic optimization models. Generally, hydrological datasets consist of reservoir and tributary flows, and evaporation rate and infiltration and gains due to groundwater interaction. In addition, reservoir, canal and water treatment plant capacities, hydropower turbine capacity and agricultural, urban, industrial and, if available, environmental water demand constitute the model inputs. Economic data consist of sectoral supply-demand functions, unit operating costs and unit energy prices (Dogan 2015). The main model outputs are reservoir water storage and diversions, agricultural and urban water allocations, and energy production.

The FEHEM is a deterministic hydro-economic optimization model of the hydropower reservoir system of the Upper Euphrates Basin. The FEHEM is an adaptation of the California Value Integrated Network (CALVIN) model to the Upper Euphrates Basin. CALVIN is a hydro and economic optimization model for California's interconnected water supply system (Draper *et al.* 2003).

The FEHEM supports the quantitative understanding of the integrated water distribution and economic system of Turkey's largest installed capacity power dams in the Upper Euphrates Basin. Initially, 10 selected large surface reservoirs in the Upper Euphrates Basin are modeled with the FEHEM. With further development, the model can represent all groundwater reservoirs of the basin, mega agricultural irrigation projects such as Southeastern Anatolia Project (GAP) and Eastern Anatolia Project (DAP), water demand areas and urban needs.

With the FEHEM, a database consisting of 45 years of historical hydrological and meteorological data of the basin was first created. Following the creation of the database, the network flow model was developed using Pyomo, a high-level optimization modeling language in Python (Hart *et al.* 2017).

The FEHEM network representation in Figure 1 depicts 10 modeled large-scale reservoirs in the Upper Euphrates Basin. Each of the elements shown in different geometric shapes and colors in the diagram is a nodal point indicating a separate reservoir and a connection point. Connections between two different nodes represent links. Flow directions are also shown with arrows.

2.2. Hydrologic inputs and reservoir characteristics

Hydropower plants operate depending on the availability of water. The reservoir in the flows is therefore important for modeling. In the deterministic case, streamflow observations upstream of rim reservoirs (called rim inflows) are used directly as model inputs. The reservoir inflows represent hydrological variability over a modeling period. Some simulation models use historical hydrology to represent this variability, while others use hydrological predictions. Planning models such as the

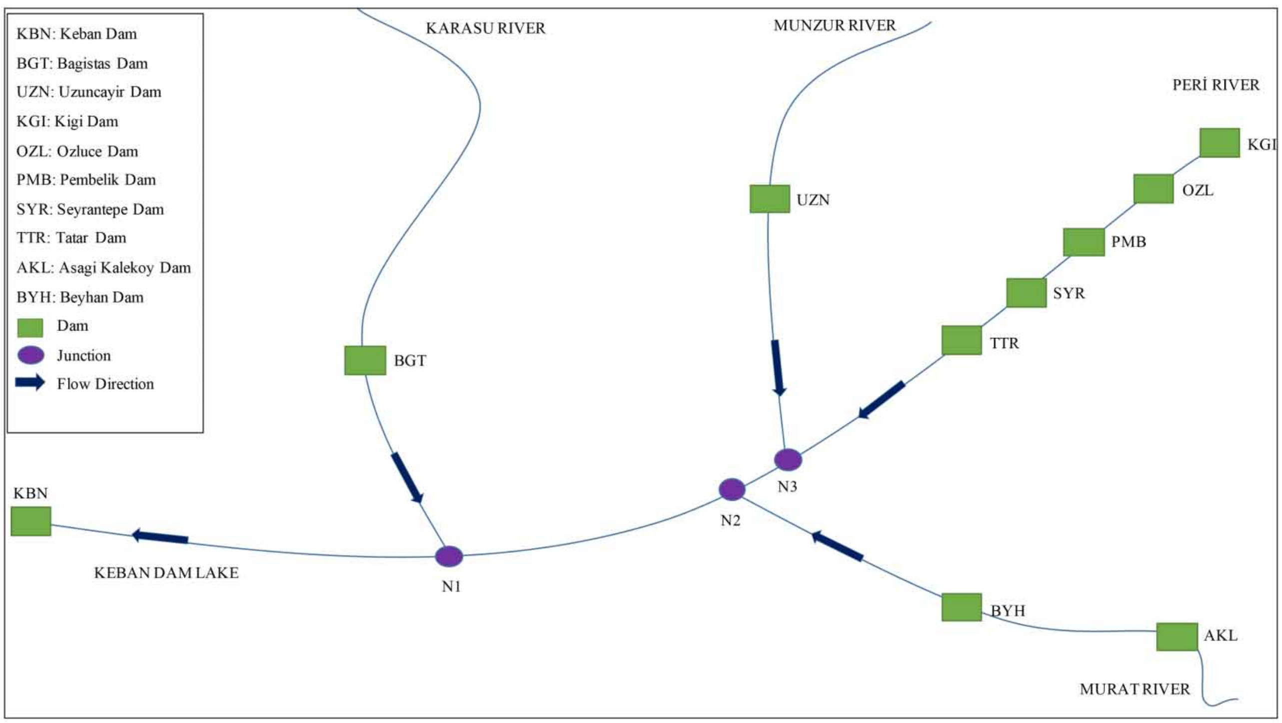

Figure 1 | FEHEM network representation.

FEHEM use long-term historical hydrology and operational models usually use short-term future forecasts. The model can be run at various time step lengths – hourly, daily, weekly, monthly and yearly, depending on data availability – and historical hydrology or future forecasts can be used as reservoir inputs. Table 1 shows the modeled hydropower plants and their characteristics such as storage and release capacity and dead volume storage. The value for overall efficiency η of 0.90 is assumed for all plants.

The FEHEM includes historical hydrological data for 45 years between 1971 and 2016 in the main tributaries of the Karasu River, Munzur River, Peri Suyu and Murat River, where the largest dams of the Upper Euphrates Basin are located. FEHEM hydrology data include runoff, precipitation, temperature and evaporation. Net evaporation rates and evaporation losses for reservoirs were also calculated in FEHEM hydrology. Reservoir inflows in wet and dry seasons are given in Figure 2.

2.3. Penalties

For a facility with a large storage capacity, the water head varies depending on the reservoir levels. As storage increases, the height of the drop increases and as storage decreases, the height of the drop decreases. Depending on the topography of a reservoir site, there is a nonlinear relationship between water storage capacity, elevation and energy storage. Figure 3 shows the polynomial relationship between storage and head for all FEHEM reservoirs. The gross head is the difference between the reservoir height and the tailwater: $H = H_{\text{reservoir}} - H_{\text{tailwater}}$.

The coefficients in Equation (1) (θ, α, β, γ and c) represent the polynomial parameters used by the model. Observed storage and elevation data were obtained from the State Hydraulic Works (DSI). The parameters i and t are specific for each power plant:

$$H = \theta_i S^4 + \alpha_i S^3 + \beta_i S^2 + \gamma_i S + c_i \quad (1)$$

Using the polynomial parameters θ, α, β, γ and c, the drop height H is calculated as a function of storage. The polynomial parameters for each reservoir are shown in Figure 3.

In the FEHEM, water scarcity costs are represented by piecewise linear functions for hydropower water demand. The objective is to minimize costs resulting from not generating hydropower. These cost curves are the inverse of hydropower revenue curves as a function of storage and turbine release. Figure 4 shows a surface plot with penalty curves for the reservoir of a variable head power plant. This graph shows the variation of penalties according to storage drop and turbine water amounts. As can be seen in the figure, the penalty value reaches the lowest value when there is maximum flow and storage, and the penalty reaches the highest value at the lowest storage and flow. The slopes of this graph in the x and y directions are used in the model matrix to obtain hydropower outputs.

Hydropower generation is modeled with penalty curves in the FEHEM, but power capacity use, energy production and revenue are calculated in a separate post-processor. A hydropower processor takes storage and release data from the

Table 1 | FEHEM plant characteristics and parameters

Reservoir	Storage (hm^3)	Minimum storage (hm^3)	Energy benefit (GWh)
BGT	250	115	503
UZN	308	123	322
KGI	528	153	450
OZL	1,120	391	413
PMB	358	136	405
SYR	23	6.4	207
TTR	300	100	421
AKL	517	233	1,193
BYH	591	191	1,294
KBN	29,475	17,074	6,600

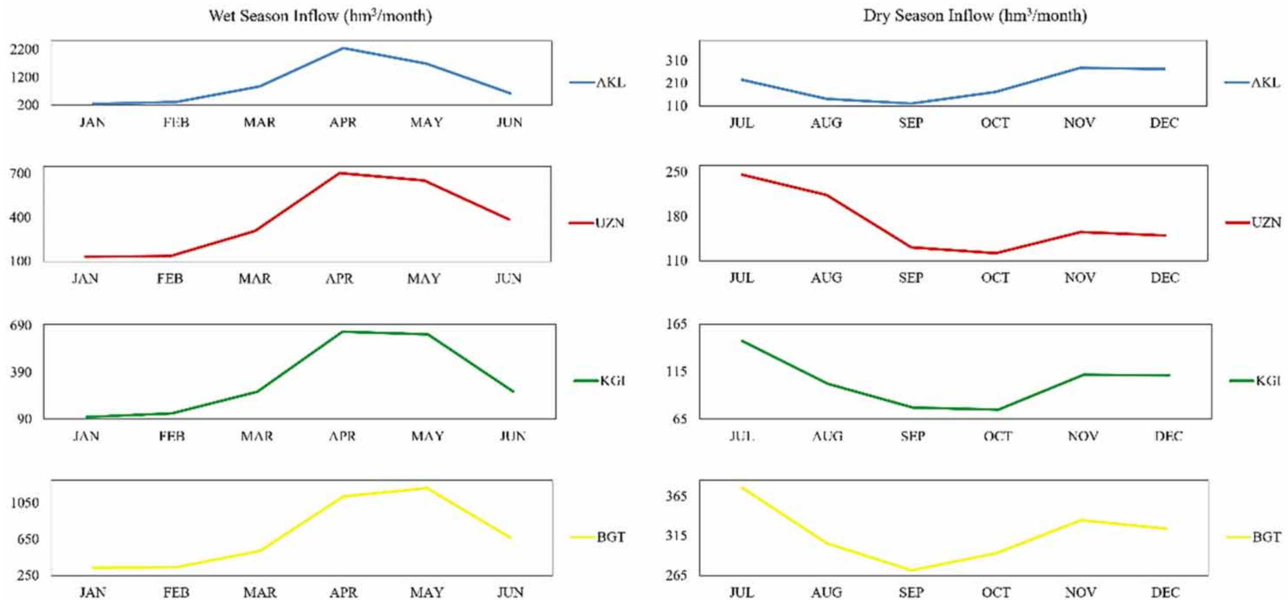

Figure 2 | Flows entering the reservoirs in wet and dry seasons.

FEHEM output file and provides time-series data for each FEHEM plant, such as power capacity, total monthly and annual energy production and revenue, amount of water spilled and total turbine capacity used.

2.4. Generalized network flow

Network flow optimization models allocate water that is transported in the network and are commonly used in transportation, transmission and water resources modeling (Draper *et al.* 2003, 2004; Bazaraa *et al.* 2010; Dogan *et al.* 2018). A typical hydropower network contains nodes and links, where nodes indicate power plants and links indicate streams, channels or pipelines. The overall representation of the hydropower network flow representation includes the objective function to be minimized (Equation (2)).

The objective function:

$$\min_{X} z = \sum_{i} \sum_{j} \sum_{k} c_{ijk} X_{ijk} \tag{2}$$

In Equation (2), z represents the cumulative cost. For each link, the index i represents the start node and the index j represents the end node. In the piecewise linear programming technique, k represents each linear segment. These parts are the result of the linearization of nonlinear functions. c represents the linear unit cost. In this equation, the independent variable is X and represents the flow from node i to node j. All functions used in the model must be concave in maximization problems or convex in minimization problems to guarantee the global optimum outcome (maximum or minimum). Equation (2) can be explained simply as minimizing the total cost by multiplying the unit cost by the flow rate.

The objective function is subject to three constraints:

$$X_{ijk} \le u_{ijk}, \;\; \forall (i, j, k) \in A \tag{3}$$

$$X_{ijk} \ge l_{ijk}, \;\; \forall (i, j, k) \in A \tag{4}$$

$$\sum_{i} \sum_{k} X_{jik} - \sum_{i} \sum_{k} a_{ijk} X_{ijk} = 0, \quad \forall j \in N \tag{5}$$

where indices (i, j) represent the origin and terminal nodes in time and space. A denotes the link matrix and N the matrix of nodes.

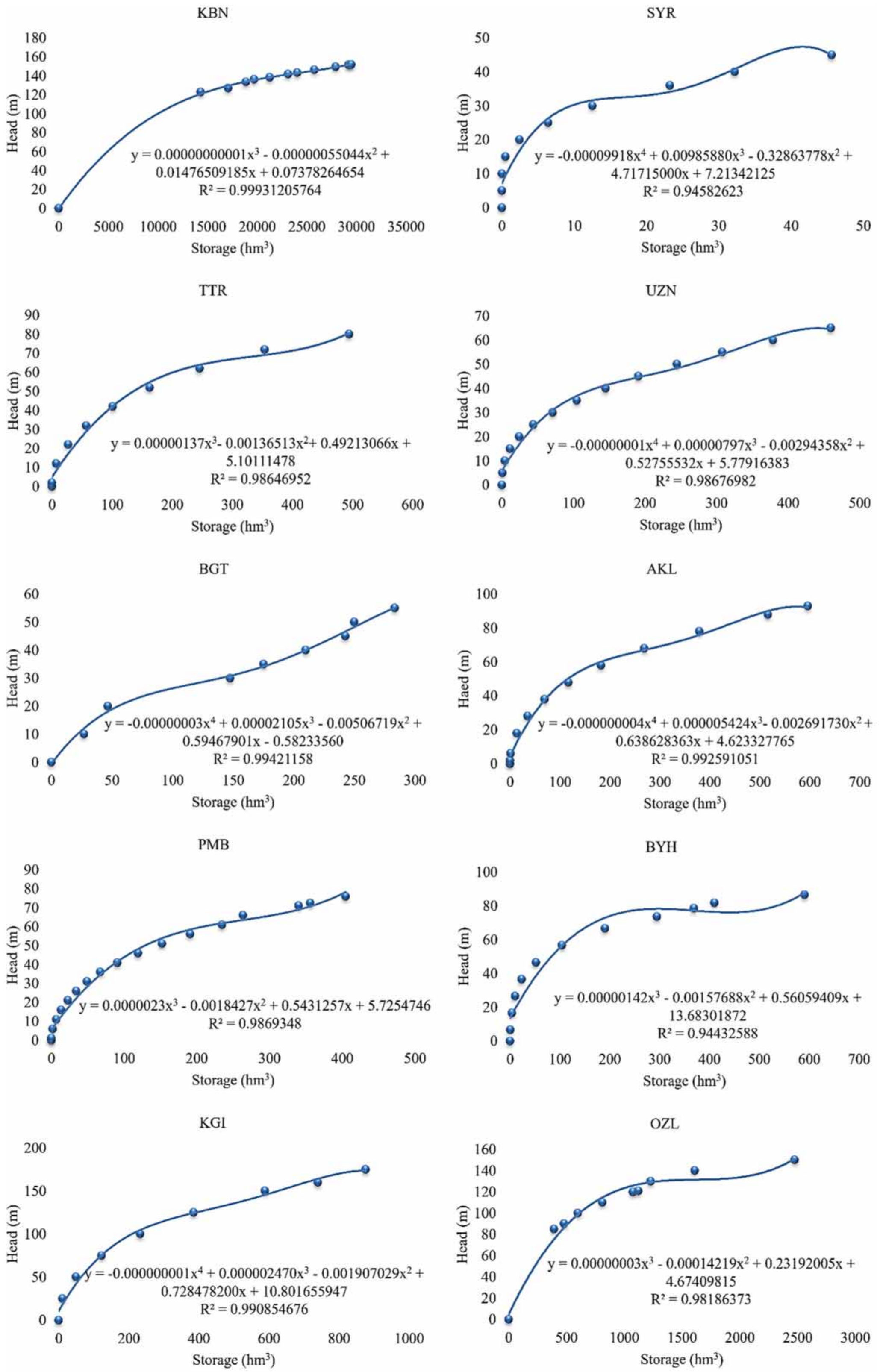

Figure 3 | Storage-head relationship of modeled reservoirs.

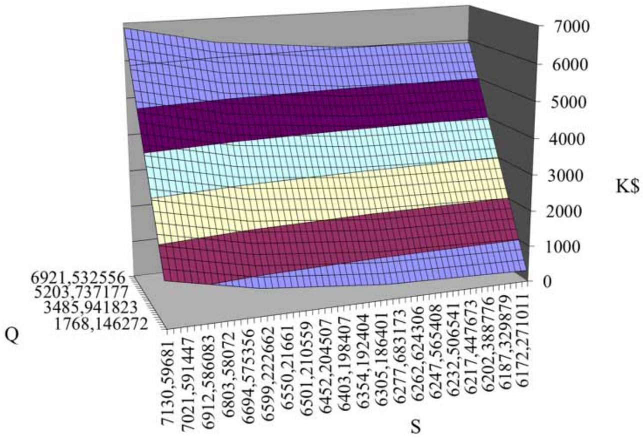

Figure 4 | Surface graph for the reservoir BYH.

Equation (2) is subject to the mathematical function of three constraints. The first limiter represents the lower current limit (l) for each connection (Equation (3)). The lower limit value is zero unless otherwise specified. This lower limit can also be used to represent minimum flow requirements for environmental purposes. The second limiting function (Equation (4)) represents the upper flow limit (u) and its value is plus infinity unless otherwise specified. This function can also be used to represent the flow-carrying capacity for reservoirs, canals and turbines. The last limiter (Equation (5)) represents the mass balance. For each connection, the incoming flow must be equal to the outgoing flow. In this function, a is used to represent loss factors such as evaporation. In all functions, the independent variable is X, which represents the flow carried in the links. All other parameters (c, l, u and a) are fixed. These four parameters are predefined for all links in the system. The default value of c and the unit benefit (or cost) are zero. However, this c value can take a positive or negative value in connections that require benefit or cost.

The objective of the FEHEM is to minimize costs and maximize benefits. All these objectives are expressed mathematically in Equation (2). Equations (2), (3), and (5) are defined in the format that Pyomo uses. The Pyomo model solves the optimization problem through preloaded solvers (such as GLPK), and the results are organized and analyzed as time series through postprocessors.

3. RESULTS

3.1. Turbine flows

Water stored in reservoirs is released via turbines to generate hydropower when demand and energy prices are high. The FEHEM reservoirs are mostly snowmelt-fed reservoirs, where snowmelt runoff often peaks around April and May. Therefore, peak turbine flows occur in April and May in large reservoirs (Keban Dam (KBN), Asagi Kalekoy Dam (AKL), Beyhan Dam (BYH), Bagistas Dam (BGT), and Uzuncayir Dam (UZN)), as shown in Figure 5. Some reservoirs, such as Tatar Dam (TTR), Seyrantepe Dam (SYR), Pembelik Dam (PMB) and Ozluce Dam (OZL), are located downstream of the rim reservoir of Kigi Dam (KGI) and their peak turbine discharge occurs around May and June.

3.2. Storage

Reservoir storage increases when release is less than the reservoir inflow in the wet season and storage decreases in dry seasons with greater releases to generate energy. With monthly varying energy prices, the FEHEM tends to store more water in months when the unit price of energy is low. Reservoirs usually approach maximum levels with rainfall and melting snow in winter and spring. It is used for irrigation in summer and dry times to meet urban water demands and to generate hydropower. As a result of this use, the reservoir water level is lowered.

Storage in FEHEM reservoirs generally reaches its maximum value in May–June and its minimum value in September–October (Figure 6). Storage differences are less in spring and summer and more in winter. Storage variations across months are higher in plants with large storage capacities, such as KBN and OZL, and lower small plants are usually located

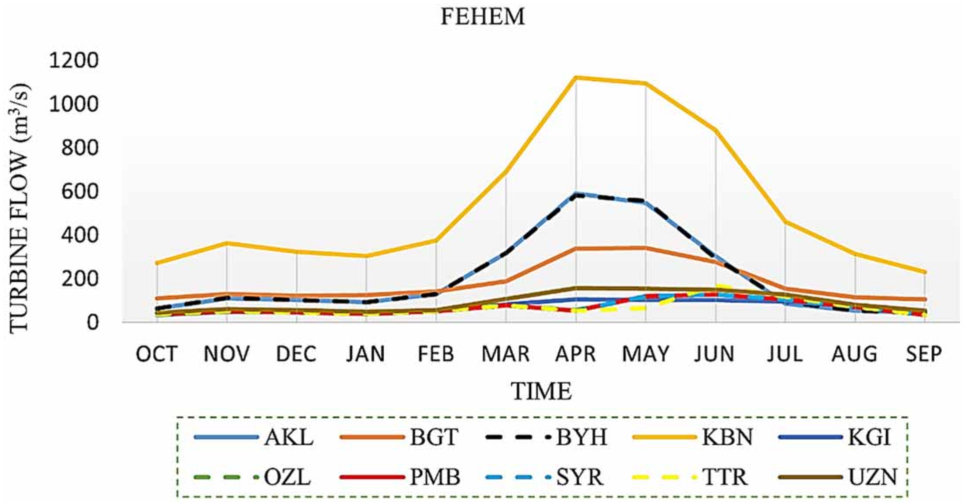

Figure 5 | FEHEM reservoirs monthly turbine discharge.

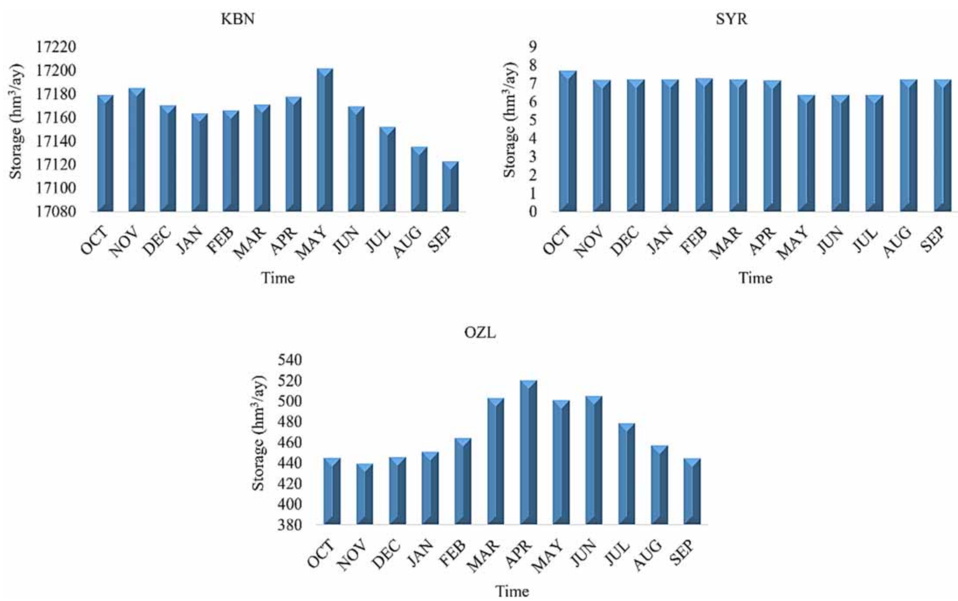

Figure 6 | KBN–SYR–OZL dams monthly storage graphs.

downstream of large plants, such as SYR. The FEHEM generally opts for water storage as there is no economic benefit to spill. Spills are penalized, so the model avoids spilling unless it is inevitable.

3.3. Energy revenue

The average monthly electricity generation-income comparison for FEHEM reservoirs is presented in the graphs in Figure 7. In general, monthly hydropower generation and revenue patterns do not differ significantly as power is generated in months with higher energy prices, resulting in higher hydropower revenue, depending on water availability and storage limitations. Generation and revenue in reservoirs have a similar monthly trend, fluctuating higher in the summer and lower during the rest of the year. However, hydropower generation revenue, whose prices vary by month, is higher in the spring months when average energy prices are lower due to increased water availability in these months. As the generation is high in spring,

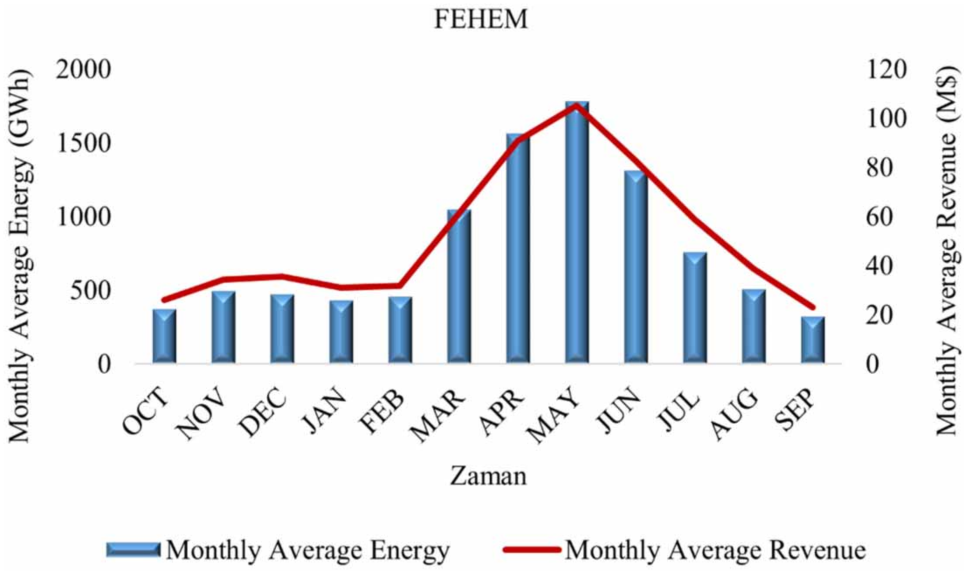

Figure 7 | FEHEM monthly average energy generation and revenue.

income is also high. However, since the unit price is low, the production curves are lower than the energy bars in terms of production and income. The other months also have low hydropower generation and revenue with declining flows.

Water year types for the Upper Euphrates Basin are prepared according to the Standardized Precipitation Index (SPI). The total energy produced according to this analysis provides the expected electricity generation values for different water year types, ranging from wet, dry, normal, heavy wet and severe dry. Figure 8 shows the yearly changes in the SPI and annual total energies of the reservoirs in the FEHEM. As precipitation increases over the years, hydropower production increases. However, there is no sudden drop in hydropower generation with decreasing rainfall. This can be explained by the presence of dams with large storage capacity. In general, total annual energy production in reservoirs with large storage capacity does not decline significantly. However, it can be said that energy production increases in direct proportion in years with high rainfall. As the SPI rises in successive years, hydropower generation increases.

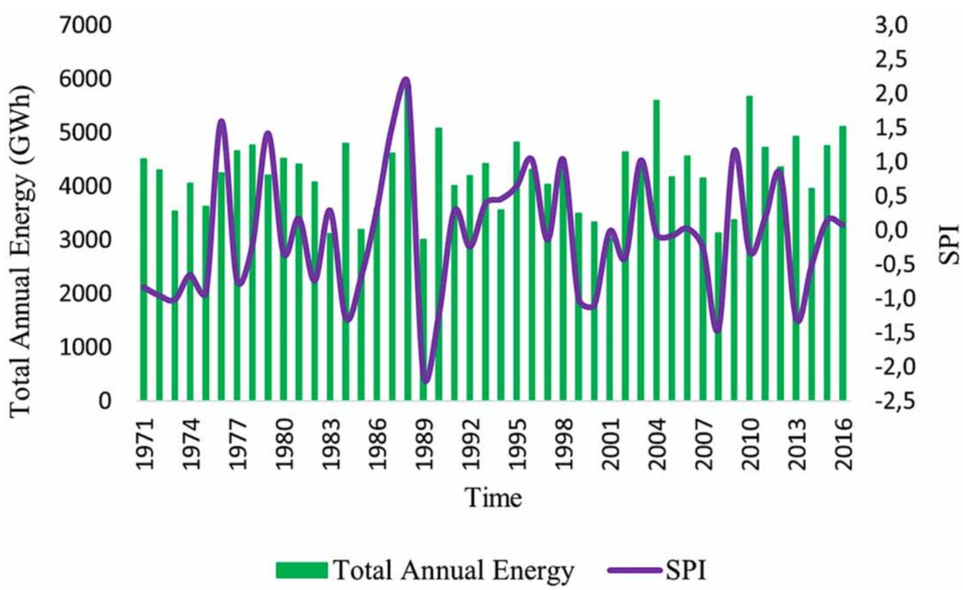

Figure 8 | Year-based change in the SPI and total annual energy in the FEHEM.

3.4. Turbine capacity use

Figure 9 shows the relationship between the monthly average energy revenue from the BYH and the turbine capacity over the 45-year period, depending on the turbine capacity, drop height and monthly changing energy prices. The nonlinear trend curve shows diminishing marginal benefits in percentage terms. Most of the revenue from changes in turbine capacity and hydropower generation is concentrated between 20 and 80% capacity utilization.

3.5. Capacity factor

In the evaluation of the model outputs, the capacity factor, which is one of the determining parameters in the comparison of hydropower plants, was utilized. The capacity factor can be expressed as the ratio of the maximum energy that a power plant produces to the actual generation in that year. In the FEHEM, the capacity factor is obtained by taking the total annual energy production values as the model output and assuming that the relevant power plant operates at full capacity 80% of the time in that year. Capacity factors were obtained by proportioning these two production values. Calculations were made with the assumption that the power plant does not operate 20% of the time. Downtimes represent maintenance, breakdowns, etc. Figure 10 shows the capacity factors of the reservoirs in the FEHEM.

Figure 11 shows the generation reliability of FEHEM hydropower plants in integrated hydropower and water supply operations. The generation reliability curve of power plants with high installed capacity has steeper slopes. The high slope of the reliability curve implies that these power plants may experience a sudden decrease in electricity generation across months. The reliability of energy production in these power plants is lower than in other power plants.

The hydropower facilities in the Upper Euphrates Basin are located on the main tributaries of the Euphrates River. The system is complex as it consists of reservoirs with large sizes and different characteristics. The annual average results obtained from the modeled dams are summarized in Table 2. The largest plant, KBN, generates an annual average energy of 5,239 Gigawatt hour (GWh) energy/year, with a revenue of 343 million$ per year, utilizing a turbine capacity of about 55%. Overall, the FEHEM plants generate about 9,481 GWh of energy with an average turbine capacity use of 36% and obtain a revenue of 620 million $ per year.

4. DISCUSSION

Water resources system models use different time scales, ranging from hourly to annual. To maximize revenue, the models assume that a hydropower plant with reservoir storage preferably allocates hydropower releases to peak price times when energy demand and prices are highest. The developed model presents the combination of hydrological differences and electricity price changes in the operations of the long-term FEHEM using a monthly time step over a 45-year hydrological period.

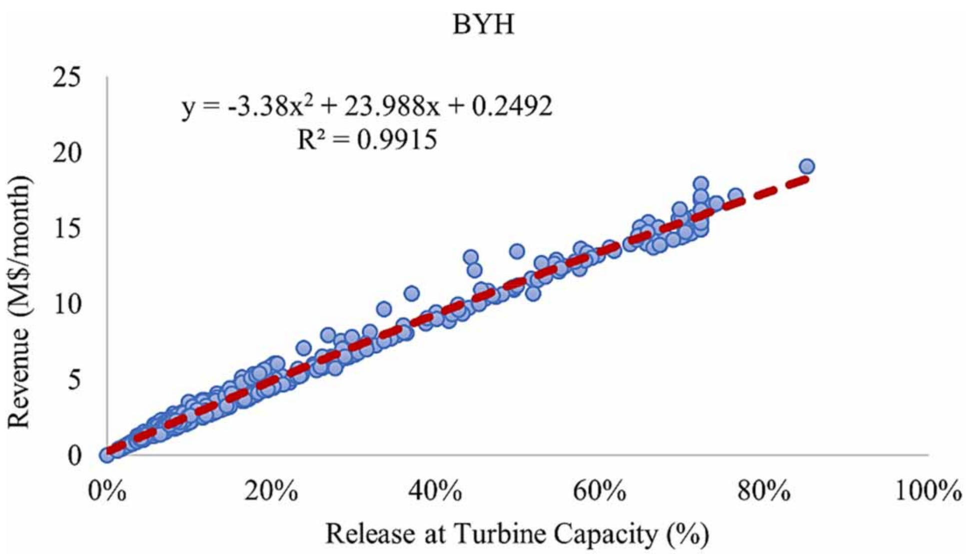

Figure 9 | Monthly average revenue curve of BYH with turbine capacity use.

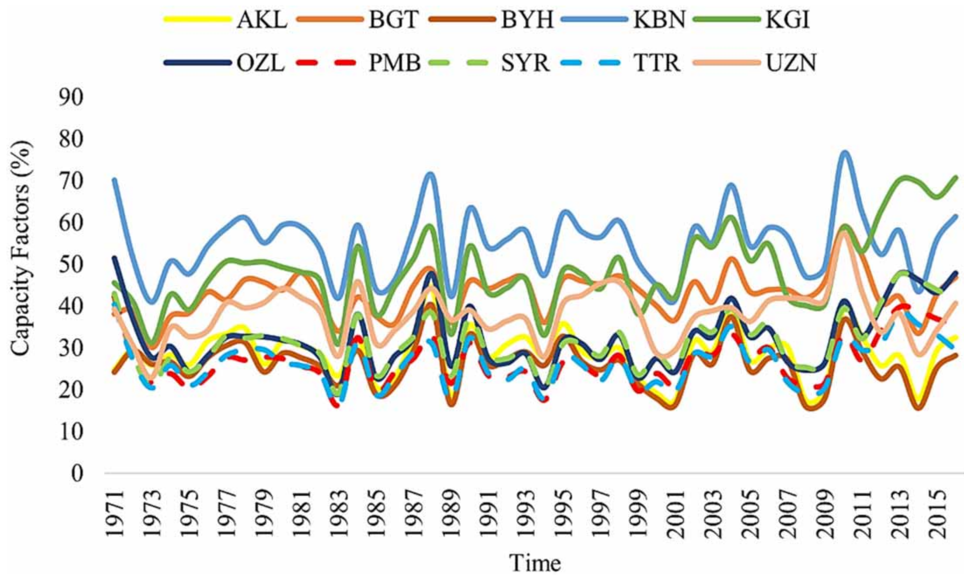

Figure 10 | Capacity factors of FEHEM reservoirs.

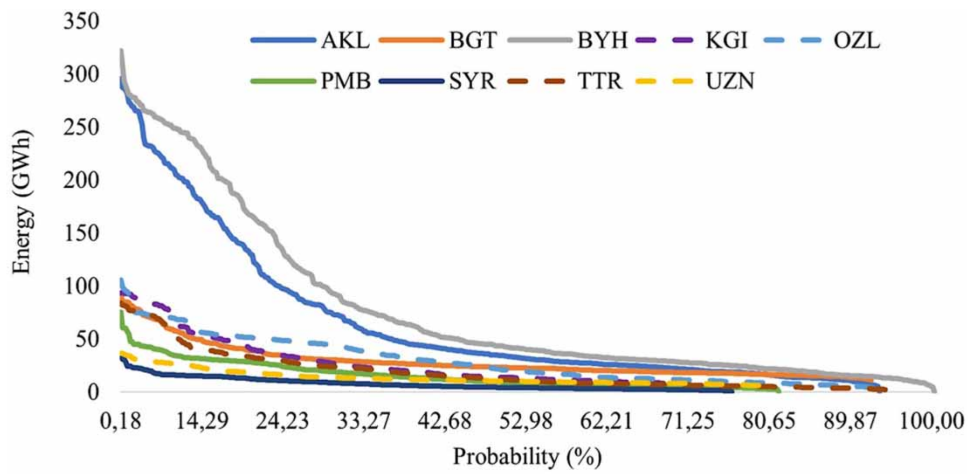

Figure 11 | Production reliability of FEHEM hydropower plants.

According to the model outputs, the lowest storage was realized in energy stages with series-connected reservoirs. The model shows such a trend because it focuses on energy generation in a series of successive dams. With monthly variable prices, the FEHEM tends to store more water in months when the unit price of energy is low. The model generally chooses to store water as there is no economic benefit to spill. The FEHEM stored an average of 23.43×10^6 hm^3 of water per year in reservoir storage operations. In some years, this value reaches 27.13×10^6 hm^3, while there are also years when it drops as low as 12.33×10^6 hm^3. Spills are penalized to minimize the energy cost in the model. The model spills only if a plant's reservoir capacity is full and inflows exceed the turbine release capacity. When the FEHEM was operated for a period of 45 years, according to the model outputs, there was no spill from the Keban reservoir. However, in reality, the Keban reservoir spilled three times in 1985, 2004 and 2019. Therefore, the model gains by converting spill, which is an economic loss, into production with its optimized decisions.

Limitations are inherent to all models. Piecewise linearization of nonlinear hydropower curves sacrifices some accuracy. Moreover, the model uses perfect hydrologic foresight, knows all hydrologic events, such as floods and droughts, and prepares for them in advance. Perfect foresight results in somewhat optimistic storage and release decisions.

Table 2 | FEHEM annual average hydropower generation and revenue

Reservoir	Name	Installed capacity (MW)	Annual average energy (GWh/year)	Annual average revenue (M$/year)	Annual average capacity factor (%)	Annual average storage (hm^3/year)
BGT	Bagistas	141	429	28	43	172
UZN	Uzuncayir	82	219	15	38	204
KGI	Kigi	138	555	38	49	311
OZL	Ozluce	170	396	27	33	471
PMB	Pembelik	127	245	17	27	155
SYR	Seyrantepe	57	123	8	32	7
TTR	Tatar	128	235	16	26	136
AKL	Asagi Kaleköy	500	999	63	29	304
BYH	Beyhan	582	1,041	66	26	227
KBN	Keban	1,330	5,239	343	55	17,166
Total		3,255	9,481	620	36	19,154

5. CONCLUSIONS

Hydro-economic models provide engineering solutions to large-scale water management planning and policy problems. Models simulate likely scenarios to help decision-makers and stakeholders. They also offer an optimization opportunity to increase the benefit under various operating conditions. For this purpose, 10 large dams in the Upper Euphrates Basin with an installed capacity of about 3,255 Megawatt (MW) were modeled with a hydro-economic optimization model for hydropower operations, called the FEHEM. The current model uses 45 years of monthly historical data between 1971 and 2016 to represent hydrologic variability. The modeled plants generated about 9,481 GWh of energy and contributed to the economy with a revenue of 620 million $ per year. In further development, the FEHEM will be expanded to include more reservoirs. As more hydrologic observations become available, its hydrological time horizon will be extended. In addition, agricultural and urban demands and groundwater basins can be added for a better-integrated water system representation.

AUTHORS CONTRIBUTIONS

A.A. and M.C.T. analyzed the data and wrote the paper. M.S.D. performed research conceptualization and methodology, supervised the work, and reviewed and edited the manuscript.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Banzhaf, H. S. 2009 Objective or multi-objective? Two historically competing visions for benefit-cost analysis. *Land Economics* **85** (1), 3–23. https://doi.org/10.3368/le.85.1.3.

Bazaraa, M. S., Jarvis, J. J. & Sherali, H. D. 2010 *Linear Programming and Network Flows*, 4th edn. John Wiley & Sons, Inc., Hoboken, New Jersey.

Bekchanov, M., Sood, A. & Jeuland, M. 2015 Review of hydro-economic models to address river basin management problems: Structure, applications and research gaps. *International Water Management Institute (IWMI)* **167**. https://doi.org/10.5337/2015.218.

Booker, J. F., Howitt, R. E., Michelsen, A. M. & Young, R. A. 2012 Economics and the modeling of water resources and policies. *Natural Resource Modeling* **25** (1), 168–218. https://doi.org/10.1111/j.1939-7445.2011.00105.x.

Brown, C., Lund, J., Cai, X., Reed, P., Zagona, E., Ostfeld, A., Hall, J., Characklis, G. W., Yu, W. & Brekke, L. 2015 The future of water resources systems analysis: Toward a scientific framework for sustainable water management. *Water Resources Research* **51**, 6110–6124. https://doi.org/10.1002/2015WR017114.

Cai, X. 2008 Implementation of holistic water resources-economic optimization models for river basin management reflective experiences. *Environmental Modelling & Software* **23** (1), 2–18. https://doi.org/10.1016/j.envsoft.2007.03.005.

Dogan, M. S. 2015 *Integrated Water Operations in California: Hydropower, Overdraft, and Climate Change. Master of Science*, University of California Davis, Office of Graudate Studies.

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

Draper, A. J., Jenkins, M. W., Kirby, K. W., Lund, J. R. & Howitt, R. E. 2003 Economic- engineering optimization for California water management. *Journal of Water Resources Planning and Management* **129** (3), 155–164. http://doi.org/10.1061/(ASCE)0733-9496(2003)129:3(155).

Draper, A. J., Munévar, A., Arora, S. K., Reyes, E., Parker, N. L., Chung, F. I. & Peterson, L. E. 2004 Calsim: Generalized model for reservoir system analysis. *Journal of Water Resources Planning and Management* **130** (6), 480–489. http://doi.org/10.1061/(ASCE)0733-9496(2004)130:6(480).

Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., Kainuma, M., Kanamori, Y., Masui, T., Takahashi., K. & Kanae, S. 2013 A global water scarcity assessment under shared socio-economic pathways – part 2: Water availability and scarcity. *Hydrology and Earth System Sciences* **17** (7), 2393–2413. https://doi.org/10.5194/hess-17-2393-2013.

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.

Hart, W. E., Laird, C. D., Watson, J.-P., Woodru, D. L., Hackebeil, G. A., Nicholson, B. L. & Siirola, J. D. 2017 *Pyomo Optimization Modeling in Python*, Vol. 67. Springer International Publishing, Cham. doi:10.1007/978-3-319-58821-6.

Hurford, A., Huskova, I. & Harou, J. 2014 Using many-objective trade-off analysis to help dams promote economic development, protect the poor and enhance ecological health. *Environmental Science & Policy* **38**, 72–86. https://doi.org/10.1016/j.envsci.2013.10.003.

Kahil, M. T., Dinar, A. & Albiac, J. 2015 Modeling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions. *Journal of Hydrology* **522**, 95–109. https://doi.org/10.1016/j.jhydrol.2014.12.042.

Keller, A. & Keller, J. 1995 *Effective Efficiency: A Water Use Efficiency Concept for Allocating Freshwater Resources, Water Resources and Irrigation Division Discussion Paper 22*. Winrock International, Arlington, VA, USA.

Keller, A., Keller, J. & Seckler, D. 1996 *Integrated Water Resource Systems: Theory and Policy Implications*. International Irrigation Management Institute (IIMI), Colombo, Sri Lanka, p. 18 (IIMI Research Report 3).

Kim, S. H., Hejazi, M., Liu, L., Calvin, K., Clarke, L., Edmonds, J., Kyle, P., Patel, P., Wise, M. & Davies, E. 2016 Balancing global water availability and use at basin scale in an integrated assessment model. *Climatic Change* **136** (2), 217–231. https://doi.org/10.1007/s10584-016-1604-6.

Kummu, M., Ward, P. J., Moel, H. & Varis, O. 2010 Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environmental Research Letters* **5** (3), 034006. https://doi.org/10.1088/1748-9326/5/3/034006.

Liu, J., Yang, H., Gosling, S. N., Kummu, M., Flörke, M., Pfister, S., Hanasaki, N., Wada, Y., Zhang, X., Zheng, C., Alcamo, J. & Oki, T. 2017 Water scarcity assessments in the past, present, and future. *Earth's Future* **5** (6), 545–559. https://doi.org/10.1002/2016EF000518.

Mekonnen, M. & Hoekstra, A. 2016 Four billion people facing severe water scarcity. *Science Advances* **2** (2), e1500323. https://doi.org/10.1126/sciadv.1500323.

Panagopoulos, A. & Giannika, V. 2022a Decarbonized and circular brine management/valorization for water & valuable resource recovery via minimal/zero liquid discharge (MLD/ZLD) strategies. *Journal of Environmental Management* **324**, 116239.

Panagopoulos, A. & Giannika, V. 2022b Comparative techno-economic and environmental analysis of minimal liquid discharge (MLD) and zero liquid discharge (ZLD) desalination systems for seawater brine treatment and valorization. *Sustainable Energy Technologies and Assessments* **53**, 102477.

Panagopoulos, A. & Giannika, V. 2023 Study on the water resources and the opportunities for sustainable desalination & minimal/zero liquid discharge (MLD/ZLD) practices in Greece (Eastern Mediterranean). *Sustainable Water Resources Management* **9** (4), 1–14.

Ringler, C., Von Braun, J. & Rosegrant, M. W. 2004 Water policy analysis for the Mekong River Basin. *Water International* **29** (1), 30–42.

Rogers, P. P. & Fiering, M. B. 1986 Use of systems analysis in water management. *Water Resources Research* **22** (9S), 146S–158S. https://doi.org/10.1029/WR022i09Sp0146S.

Veldkamp, T. I. E., Wada, Y., Aerts, J. C. J. H., Döll, P., Gosling, S. N., Liu, J., Masaki, Y., Oki, T., Ostberg, S., Pokhrel, Y., Satoh, Y., Kim, H. & Ward, P. J. 2017 Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. *Nature Communications* **8**. https://doi.org/10.1038/ncomms15697.

Wada, Y., Van Beek, L. P. H., Wanders, N. & Bierkens, M. F. P. 2013 Human water consumption intensifies hydrological drought worldwide. *Environmental Research Letters* **8** (3), 034036. https://doi.org/10.1088/1748-9326/8/3/034036.

Wada, Y., Bierkens, M. F. P., De Roo, A., Dirmeyer, P. A., Famiglietti, J. S., Hanasaki, N., Konar, M., Liu, J., Schmied, H. M., Oki, T., Pokhrel, Y., Sivapalan, M., Troy, T. J., Van Dijk, A. I. J. M., Van Emmerik, T., Van Huijgevoort, M. H. J., Van Lanen, H. A. J., Vörösmarty, C. J., Wanders, N. & Wheater, H. 2017 Human-water interface in hydrological modelling: Current status and future directions. *Hydrology and Earth System Sciences* **21** (8), 4169–4193. https://doi.org/10.5194/hess-21-4169-2017.

First received 25 June 2023; accepted in revised form 25 August 2023. Available online 12 September 2023