SUPPLEMENTAL MATERIALS

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Review of Decision Support Systems and Allocation Models for Integrated Water Resources Management Focusing on Joint Water Quantity-Quality

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Table S1. Allocation models and Decision Support Systems, classified according to the major challenge/IWRM concepts.

IWRM CONCEPTS				MODEL						
ECONOMIC OPTIMIZATION	**EQUALITY**	**SUSTAINABILITY**	**SOCIAL WELFARE/ECONOMIC ASSESSMENT**	**WATER QUANTITY-QUALITY**	**ORIENT/ STRUC (See note 1)**	**DODS APPROACHES MAIN CHARACTERISTICS**	**QUALITY MODEL**	**DSS NAME**	**LOCATION**	**REFERENCE**
Conflict resolution, transboundary management and sustainability										
Maximize the total net benefit of water use in any year using a hybrid genetic algorithm and linear programming (GA-LP)	Provides for temporal equality (water use benefits are nondecreasing in all years) and spatial equality (equitable access to water supply in different locations)	Flow release for environmental and ecological use are modeled	-	The major state variables of the yearly model include water storage, water salinity, soil moisture and soil salinity	PEDC/ L+D		No specific name	-	Syr Darya River Basin, Central Asia	(Cai et al. 2002)
Maximize the annual net profits from water uses in different sectors	-	Environmental requirements for controlling saltwater intrusion are included as flow restrictions	-	-	PEDC/ N+D		-	-	Dong Nai River Basin, Vietnam	(Ringler et al. 2006)
-	-	-	-	**The model assesses the effects of global climate and land use changes by long-term availability and quality of water bodies**	**DODS/ N+D**	**An integrated regional model was developed as a model cascade of nine submodels covering large scale hydrology, groundwater flow, water demand, agricultural production, point and non-point pollution and chemical as well as biological water quality. Tests and calibration to indicate that the model can be used for application and integration**	**QUAL2K**	**MOSDEW**	**Germany, West Africa, and Central Asia basins**	(Gaiser et al. 2008)
Maximize the net benefits, considering domestic and industrial supply, hydropower generation and fertirrigation	-	-	-	Pollution level restrictions as Government-mandated and to limit eutrophication in reservoirs (estimated from BOD)	PEDC/ N+D		Streeter–Phelps	-	Pirapama River Basin, Brazil	(Alcoforado de Moraes et al. 2010)
-	-	-	-	**Integrated modeling of water quantity (SIMGES module) and quality (GESCAL module)**	**DODS/ N+S**	**Integration of quality and quantity to provide calibration and validation of the biochemical reaction coefficients, sedimentation rates and sediment oxygen demand to serve as a basis for future studies on quantitative or qualitative interventions in the basin**	**GESCAL module**	**AQUATOOL**	**Araguari River Basin, Brazil**	(Salla et al. 2014)
-	**Priority given to water supply from dams for drinking water purposes**	**Ecological constraints are expressed as monthly needs of water levels and lake salinity**	**The 'socio-economic' criteria cluster includes satisfaction rates in meeting the water demand for drinking, irrigation, and fishing purposes**	**-**	**DBRS/ N+D**		**-**	**SDSS**	**Ichkeul Catchment, Tunisia**	(Chakroun et al. 2015)

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Maximize the net monetary benefits from agriculture, residential and non-residential uses	Price elasticities of water demand were selected to reflect the demographic composition of the population	-	-	-	PEDC/ N+S		-	-	Santa Cruz River Basin, USA/Mexico	(Ghosh et al. 2017)
-	-	Environmental flow requirement is equal to 0.8 times the groundwater	-	-	DBRS/ N+S		-	-	Neshanic River Basin, USA	(Giri et al. 2018)
Minimize the total abatement cost for firms subject to the total abatement target, considering four policy options in cost-effectiveness analysis	-	-	-	Defined shadow prices with respect to a pollutant as the marginal cost of abatement for BOD	PEDC/ N+D		Mike ECO Lab	-	Kelani River, Sri Lanka	(Gunawardena et al. 2018)
Balance water supply and demand based on the objective of maximizing economic benefits from water use.	-	In-stream uses include flows for hydropower generation, fish production, wetlands, and navigation and minimum flows for the maintenance of the river ecology and control of saltwater intrusion into the Mekong Delta.	-	-	PEDC/ N+D		-	-	Mekong River Basin, China, Myanmar, Laos, Thailand, Cambodia, and Vietnam.	(Ringler et al. 2004)
Maximize all stakeholders' profits considering different numbers of dams	The results suggest migration of the proposed dam sides from well-developed downstream areas of the Basin to the upstream provinces where population is in less economically advantageous situation	The model considers reliability of environmental water supply as a priority	-	-	PEDC/ L+D		-	-	Sefidrud River Basin, Iran	(Roozbahani et al. 2020)
-	-	There are strong constraints on groundwater utilization for refilling and restoring groundwater ecologically and as gradually as possible and preservation of the ecological flow of the rivers	Priorities of water allocation are constructed from low to high according to their socioeconomic development and importance to regions and sectors	-	PHDC/ N+D		-	-	Wei River Basin and Han River Basin, China	(Ma et al. 2021)
-	-	-	**The SDSS assesses the Water Use Efficiency, indicating income and the number of jobs generated per volume of water used**	-	**PHDC/ N+D**		-	**HEAL** - See note 2	**Four interlinked river basins in Northeast of Brazil**	(Alcoforado de Moraes et al. 2021)

<u>Conjunctive use of groundwater and surface water</u>

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-	-	-	-	MODSIMQ and QUAL2E convergence satisfying water rights priorities and attempting to maintain minimum water quality requirements	DODS/ N+D	An iterative procedure based on the Frank-Wolfe nonlinear programming algorithm links MODSIMQ and the water quality models to assure convergence with solutions satisfying water right priorities, while attempting to maintain minimum water quality requirements	QUAL2E	-	Arkansas River Basin, EUA	(Dai and Labadie 2001)
-	-	**Scenarios consider the length of the area where the changes to land-use policies would be introduced; intensity of change in land-use patterns; intensity of the urbanization changes over the considered area.**	-	-	**DBRS/ L+D**		-	**Web-based DSS prototype**	**Ganges River, India and Bangladesh**	(Salewicz and Nakayama 2004)
-	-	**Environmental flows and diversions from each valley are not allowed to increase above what they were at 1993/94 level of development**	-	-	**DODS/ L+D**	**Two case studies covering major urban and rural water supply systems illustrate REALM's capabilities in the use of stochastically generated data in water supply planning and management, modeling of environmental flows, and assessing security of supply issues**	**-**	**REALM**	**The Goulburn and the Melbourne Water Supply System, Australia**	(Perera et al. 2005)
To maximize net benefits from farming activities in each year.	-	-	Hired labor dedicated per type of crop under different scenarios	-	PEDC/ N+D		-	-	São Francisco River Basin, Brazil	(Maneta et al. 2009)
Maximize expected net economic benefit considering agriculture, urban water conservation, costs of groundwater pumping, artificial recharge, and water transfers	-	-	-	-	PEDC/ N+D		-	-	Semiarid region with a Mediterranean climate	(Zhu et al. 2015)
Maximize the net present value	Constraints on urban water supply protected in all scenarios by policy requirements	The sustainable policy considered under climate change scenarios avoids water stock depletion and protects minimum river flow	-	-	PEDC/ N+S		-	-	Jucar River Basin, Spain	(Kahil et al. 2016)
-	-	The carbon footprint associated with each treatment system referred to as the global warming potential is considered as an environmental cost	Minimize the overall economic and environmental cost of the water treatment and distribution system	The water quality of each source is considered when choosing the treatment technology, as well as the cost of transport to the WTP	PHDC/ N+D		No specific name	-	Theoretical region	(Abdulbaki et al. 2017)

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-	Urban water shortage penalty function	Flow targets for coastal estuaries are evaluated to maintain the environmental integrity of the estuarine ecosystems	Investigate the trade-offs, incorporating the economic value of water in urban and agricultural sectors and economic damages due to urban flooding while also accounting for water supply to sustain fragile ecosystems	-	PHDC/ L+D		-	-	South Florida, USA	(Mirchi et al. 2018)
-	**-**	**Environmental flow, future emission scenarios: HadCM3 climatic model was used under the emission scenarios**	**-**	**-**	**DODS/ L+D**	**Evaluation of the indices of environmental and agricultural sustainability using performance criteria influenced by climate change and water management strategies for the Zarrinehrud and Siminehrud River basins using WEAP21**	**-**	**WEAP21**	**Urmia Lake Basin, Iran**	(Ahmadaali et al. 2018)
-	-	Sustainability scenarios for groundwater exploration	Economic trade-offs between limiting groundwater overdraft and sub-basin specific costs as well as maps of water availability shadow prices are presented. The optimizer minimized total monetary costs within the whole Haihe River basin over an eight-year planning period.	The authors evaluated the water availability shadow prices under water quality targets	PHDC/ L+D		No specific name	-	Haihe River Basin, China	(Martinsen et al. 2019)
-	-	The model considers sustainability parameters, such as volumetric reliability, time-based reliability, resilience and vulnerability.	-	-	PHDC/ L+D	-	-	-	Zayandehrud River Basin, Iran	(Chakraei et al. 2021)
<u>Institutions, water markets and pricing</u>										
Maximize economic benefit from irrigated agricultural, industrial, municipal, and hydroelectric demand sites	-	-	-	-	PEDC/ N+D		-	-	The Brantas River Basin, Indonesia	(Rodgers et al. 2003)
-	**-**	**Priority to meet in-stream flow demands first and then irrigation requirements**	**-**	**Replicated the altered flow regime of the watershed and estimating the hydropower production and associated water temperatures**	**DODS/ L+D**	**The bio-physical and socioeconomic components of two tributaries of the Sacramento River were used to illustrate how a new hydrologic sub-module in WEAP21 can be used in conjunction with an imbedded water allocation algorithm to simulate the hydrologic response of the watersheds and aid in evaluating freshwater ecosystem service trade-offs under alternative scenarios**	**Quality Module WEAP21**	**WEAP21**	**Sacramento River Basin, USA**	(Yates et al. 2005)

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-	-	The flow that leaves the reservoir is counted in the MODSIM water allocations but not for allocation availability within the system, in order to maintain the ecological balance.	The model simulates how water users behave and make market decisions considering water costs and availability; model also estimates the economic and operational impacts of alternative policies	-	DODS/ L+D	The model simulates how water users conserve and select supplies and make water exchange and market decisions in response to water costs and availability. Model provides estimates of economic and operational impacts of alternative policies for the Friant-Kern system	-	-	California's Friant-Kern	(Marques et al. 2006)
-	Analysis of an equality measure	The instream flow requirement, is considered the single largest user of surface water, which is a statutory requirement by law, intended to maintain riparian ecosystem health	Compare different scenarios to evaluate the effect of a water tax on distribution and potential economic and environmental impacts	-	DBRS/ L+D		-	-	South Africa	(van Heerden et al. 2008)
Optimize the total economic benefits subject to constraints of equality, sustainability, hydrology, and institutions	Human consumption prioritized	Willingness to pay was measured as the maximum price that could be charged to visitors of the basin's recreation facilities	-	-	PEDC/ N+D		-	-	Rio Grande, USA	(Ward and Pulido-Velázquez 2008)
-	-	Sustainability index integrates results of several performance criteria considering reliability (time and volume), vulnerability, resilience, and maximum deficit	-	-	DODS/ N+D	The objective of this research was to estimate the maximum volume of water available for the environmental flows without affecting human and international water requirements, and without increasing flood risk	-	-	Rio Grande, USA	(Sandoval-Solis and McKinney 2014)
-	-	The implementation of minimum environmental flows investigated as a water policy intervention	Analyzed the impact on farm labor employment for the whole study region	-	DODS/ L+D	Provides an integrated economic-hydrologic modeling framework that captures the socio-economic and environmental effects of various policy initiatives and climate variability	-	-	Middle Guadiana River Basin, Spain	(Blanco-Gutiérrez et al. 2013)
-	-	-	Employed a multi-regional input-output model to calculate water footprint and virtual water flows through tracing the whole regional and national supply chain	-	DBRS / L+D		-	-	Haihe River Basin, China	(White et al. 2015)
Maximize the regional economic benefits at each time step. The water trading model (on GAMS software) tracks pair-wise water market transactions between water users	-	Comparison of the summary descriptive statistics for each of the trading scenarios, showing how trading affects the overall habitat availability in the studied reach	-	-	PEDC/ N+S		-	-	Nar River Basin, England	(Garbe and Beevers 2017)
Maximize economic benefit, expressed by the direct benefit of water supply and minimum pollutant discharge	Social benefit was considered to meet human demand	Environmental benefit function is measured by the minimum discharge of important pollutants in the water receiving area	-	-	PEDC/ N+S		-	-	Malian River Basin, China	(Gao et al. 2019)

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Maximize the economic values of agricultural and urban water use statewide. Optimization solved using HEC-PRM. Water is valued by the economic principle	-	Environmental objectives are represented by a series of minimum flow constraints on selected river locations and minimum flows to major wetlands	-	-	PEDC/ L+D		-	-	California's major water supply system, USA	(Draper et al. 2003)
Maximize current benefits through release decisions and expected benefits from future operations, which are represented by the recursively calculated benefit-to-go function	-	-	-	-	PEDC/ L+D		-	-	Euphrates River Basin in Turkey and Syria	(Tilmant et al. 2008)
In-stream and off-stream intersectoral allocation and use										
-	-	**The objectives addressed are more operational than planning and may include flood control, power plant scheduling, irrigation management, and environmental flow regulation**	-	-	**DODS/ N+D**	**The Nile DSS modules can express the response of the Nile system in terms of river flow, water supply, food production, and energy generation**	-	**NILE DSS**	**Atankwidi River Basin, West Africa**	(Georgakakos 2007)
-	-	Recreational and environmental uses are considered	Evaluates the physical and economic outcomes from alternative water allocation policies	-	DODS/ L+D	Evaluation of a range of complex operating rules water managers may apply based on a combination of water balance with a linear optimization algorithm with user-defined penalties to impose constraints and preferential water use	-	-	Musi Sub-Basin, India	(George et al. 2011)
-	-	**Annual demand growth and environmental flows considered**	-	-	**DBRS/ N+D**		-	**IRAS-2010**	**Thames River Basin, England**	(Matrosov et al. 2011)
Minimize the immediate cost arising from water allocation, water curtailment and pollution treatment	-	-	-	Hydropower revenue was maximized while the DO concentration, computed from the BOD, was used as water quality constraint	PEDC/ L+D		Numerical Method - Streeter–Phelps	-	Ziya River Basin, China	(Davidsen et al. 2015)
-	Municipal demand considered first priority; other demands as second priority (present policy).	Water Resources Sustainability Index is used to summarize the performance criteria results and to facilitate comparison among trade-offs	-	-	DODS/ L+D	Because the Zayandehrud model is a planning model and not a hydrologic model (rainfall-runoff model), an Adaptive Network-based Fuzzy Inference System (ANFIS) is used to generate synthetic natural flows considering temperature and precipitation as inputs	-	-	Zayandehrud River Basin, Iran	(Safavi et al. 2015)

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Maximize the sum of irrigation benefits, energy production and environmental benefit	-	Economic benefits of environmental flows are considered with and without irrigation modernization under different levels of water supply.	-	-	PEDC/ N+D		-	-	Aral Sea Basin, Central Asian	(Bekchanov et al. 2015)
Maximize the net system benefit (i.e., municipal, agricultural, industrial, and ecological incomes)	-	-	-	Formulation of water resources allocation and water quality management with trading-mechanism (WAQT) model	PEDC/ L+D		No specific name	-	Kaidu-Kongque River Basin, China	(Zeng et al. 2016)
-	Gini coefficient used to optimize water allocation equality in agricultural, domestic, and industrial sectors	-	Development of a multi-objective model involving water allocation equality and economic efficiency risk controlto help water managers mitigate these problems	-	PHDC/ N+S		-	-	Qujiang River Basin, China	(Hu et al. 2016)
-	-	-	Allocation of water resources to maximize the number of jobs created in industrial and agricultural sectors	-	PHDC/ N+D		-	-	Iran’s central desert	(Habibi Davijani et al. 2016)
Maximize the gross margins of all production sectors	**-**	**The objective function in the SEWEM considers benefits from environmental flows**	**-**	**-**	**PEDC/ L+D**		**-**	**SEWEM**	**Aral Sea Basin, Central Asian**	(Bekchanov and Lamers 2016)
-	-	Consideration of CO2 emission restrictions	Trade-offs among economic objectives, resources constraints and environmental protection are effectively quantified	-	PHDC/ L+D		-	-	Generic	(Zhang and Vesselinov 2017)
Maximize the economic benefit of electricity production, minimizing the scarcity cost for irrigation sites, small farmers, and human consumption	Human consumption prioritized in one scenario.	Ecological flow as constraint. The restriction of variations in the water level also serves to increase the stability and maintenance of reservoir ecosystems	-	-	PEDC/ N+D		-	See note 2	São Francisco River Basin, Brazil	(Souza da Silva and Alcoforado de Moraes 2018)
-	**Satisfaction of social demands (e.g. municipal use and power generation) prioritized under water stress condition**	**Model outputs include recreational reservoir uses, and environmental flows, among others**	**Based on the water use values modeled, socio-economic outputs are calculated, contributing to the Integrated Basin Water Sustainability Index (IBWSI)**	**-**	**DBRS/ L+D**		**-**	**BRIM**	**Bow River Basin, Canada**	(Wang et al. 2019)
-	-	The deviation between the river flow and the ecological water demand is minimized	-	-	PHDC/ L+D		-	-	Fuhe River Basin, China	(Yan et al. 2020)

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Use of objective function to maximize total economic benefit and the total expected benefit in time	-	-	-	-	PEDC/ N+S		-	-	São Marcos River Basin, Brazil	(Bof et al. 2021)
Land-use management: floods and water quality										
	Management objectives include equitable distribution of good water quality throughout the river basin and over time	**Minimum in-stream flows and target storage levels in the reservoirs are considered**		**Assessment of a water quality index, spatial uniformity of water quality and temporal uniformity of water quality.**	**DBRS/ L+D**		**Modified QUAL2E-UNCAS**	**Modified MODSIM and QUAL2E-UNCAS**	**Piracicaba River Basin, Brazil**	(Azevedo et al. 2000)
-	-	-	-	**Presentation of GIBSI DSS. The water quality model is built around QUAL2E**	**DBRS/ L+D**		**QUAL2E**	**GIBSI**	**Chaudière River Basin, Canada**	(Rousseau et al. 2000)
-	-	**Multiple-criteria decision analysis - Developed with chart comparing the economic x environmental x social aspects**	**Depending on the changes in state of water resources, positive or negative consequences for society may occur. These consequences are identified and evaluated to describe impacts by means of evaluation indices.**	**Case studies on restoring river quality, reducing nitrate concentrations in groundwater and combating saltwater intrusion and subsidence**	**DBRS/ N+D**		**MULINO Quality Module**	**MULINO DSS - mDSS**	**Dyle, Belgium; Caia, Portugal; Vahlui, Romania; Bure and Yare, England; Vela and Cavallino Catchments, Italy**	(Mysiak et al. 2005)
-	-	Environmental demand of river is estimated according to the special water quality target of river. A minimum flow is required to maintain the riverine ecosystem under a prescribed condition	-	Calculated water deficits before and after a reservoir implantation project; water quality after implementing improvement measures in the basin	DBRS/ N+D		No specific name	-	Jiaojiang River Basin, China	(Zhang et al. 2010)
-	-	-	-	A water quantity and quality joint operation model (QCmode) and genetic algorithm coupled with SWAT to optimize the operation of dams and floodgates	PHDC/ N+S		SWAT quality modules (CREAMS, QUAL2E, WASP)	-	Wenyu River Basin, China	(Zhang et al. 2011)

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-	**-**	**Results showed very low impacts of the environmental flows on the reliability supply related to demand**	**-**	**SIMGES (water allocation) and GESCAL (water quality)**	**DODS/ N+D**	**Modeling water quality and management for a very complex water resources system**	**GESCAL module**	**AQUATOOL**	**Jucar River Basin, Spain**	(Paredes-Arquiola et al. 2010)
Maximize economic profit from water supply for irrigation, municipal and industrial water use, and hydroelectric power generation, subject to institutional, physical, and other constraints.	-	-	-	-	PEDC/ N+D		-	-	Maipo River Ban, Chile	(Rosegrant et al. 2000)
-	-	-	-	Blue water, green water flow, green water storage, and nitrate concentration of groundwater recharge were quantified	DODS/ N+D	The calibrated model and results provide information support to the European Water Framework Directive and lay the basis for further assessment of the impact of climate change on water availability and quality	SWAT	-	Europe	(Abbaspour et al. 2015)
-	-	-	-	HEQM simultaneously simulates water related processes at basin scale, including hydrological, soil biogeochemical and water quality processes	PHDC/ N+S		HEQM Module (WQM)	-	Huai River Basin, China	(Zhang et al. 2016)
Maximize economic benefit by applying objective function to find optimal trajectory of allocation	A lower bound constraint is set to ensure coverage of a minimum potable urban demand	-	-	Water permits are allocated over different river reaches subject to water quality targets	PEDC/ N+S		No specific name	-	Sinos River Basin, Brazil	(Dalcin and Fernandes Marques 2020)
Managing for climate change and drought										
-	**-**	**Environmental and policy constraints affect subsurface drainage and minimum instream flow requirements**	**-**	**Basin level drainage flow and salt load estimates (APSIDE) are inserted on DSM2-SJR to obtain a more accurate estimate of water quality by the monitoring station**	**DBRS/ N+D**		**DSM2-SJR/QUAL/ APSIDE**	**Modular Modeling System/Object User Interface**	**San Joaquin River Basin, USA**	(Quinn et al. 2004)

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-	-	-	The economic model represents the farmer's behaviors in terms of crop pattern and water use given climatic and policy conditions	The economic model provides irrigated area, crop yields, regional agricultural income, salt emissions, and the amount of water to be released at the reservoir levels	DODS/ L+D	The hydro-economic model was developed to assess how global change and policy options affect the catchment's water scarcity and the economic implications on the agricultural sector. The model associates physical processes (hydrology) with regulatory and economic processes (agricultural water demand, reservoir operation)	No specific name	-	Galego River Basin, Spain	(Graveline and Recherches 2014)
Maximize the comprehensive benefits of water resources management, according to multiple objectives: social benefit, economic benefit, environmental benefit and under baseline period	Gini indices used to compare the results of water consumption for best and worst scenarios of social objectives and to compare these to the observed values	Ecological water demand to protect aquatic resources in river was based on average flow; the simulation results of ecological water shortages were compared with observed values	-	Total sewage discharge, COD and ammonia–nitrogen were used as pollutant indexes	PEDC/ N+S		No specific name	-	Dongjiang River Basin, China	(Zhou et al. 2015)
-	Environmental requirements and the target supplies for the urban demands must be met in order of priority	Water allocation must meet the flow requirements for maintaining the environmental functions of the river	Minimizes the total annualized cost of the measures to meet urban and agricultural demands and minimum in-stream flow	-	PHDC/ N+D		-	-	Orb River Basin, France	(Girard et al. 2015)
Maximize the net benefit under uncertainty and climate change scenarios	-	-	-	-	PEDC/ N+S		-	-	Heihe River Basin, China	(Li et al. 2016)
Maximize of the annual agricultural benefit using PSO (Particle Swarm Optimization)	-	Uses an environmental link (stream) of minimum water	-	-	PEDC/ N+S		-	-	Karkheh River Basin, Iran	(Fereidoon and Koch 2018)
-	Criteria preferences for short-term and long-term evaluation, including social criteria (reduction of poverty) according to questionnaire applied to experts	The downscaled LARS-WG model outputs used as inputs to the SWAT model to evaluate the effects of climate change on surface-water resources and reservoir inflows, and on surface-water resources and evapotranspiration crop demands downstream of the dam to understand changes in basin uses.	Several experts participated by filling out questionnaires as to their preferences of criteria for short-term and long-term evaluation, including social criteria (job opportunities, migration from village to cities, migration from west to east, hygiene and health, tourism, reduction of poverty)	-	DBRS/ N+D		-	-	Zayandehrud River Basin, Iran	(Safaei et al. 2013)

Notes: 1) DBRS = Descriptive Based on Rules Simulation; DODS = Descriptive Optimization-Driven Simulation; PHDC = Prescriptive Hydrological Decision Criteria; PEDC = Prescriptive Economic Decision Criteria; N+D = Nonlinear+Deterministic; N+S = Nonlinear+Stochastic; L+D = Linear+Deterministic; L+S = Linear+Stochastic.

2) This model is also available in the newest version of the HEAL System (Souza da Silva and Alcoforado de Moraes 2021)