Multi-criteria decision making methods to address water allocation problems: A systematic review

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Supplementary material (Table S1)

49 published papers between 2000-2019 and indexed by four literature databases (Web of Science, Science Direct, Scopus, and Google scholar) were reviewed. The application of MCDM methods to solve water allocation problems under different water-problem based classification (water shortage, water use management, water quality, ecosystem/environment management, flood management, combined water problems) is presented in table format. It contains the summary of each reviewed paper (problem gap motivated, objectives, criteria, decision techniques used).
| Author  | Problem/ motivation                                                                 | Objectives                                                                 | Criteria/indicator                                                                                      | MCDM     | Decision-Making Techniques                        |
|---------|------------------------------------------------------------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|----------|-------------------------------------------------|
| [1]     | water shortage (water supply-demand mismatch)                                      | maximize the total economic benefit of the entire area                     | optimal quotas for (community, ecological, and economic use); population, territorial area;             | MODM     | dynamic model                                    |
| [2]     | declining in the availability of groundwater reservoirs (issue of sustainability)  | maximizing recharge, maximizing biodiversity, maximizing short term economic gains, maximizing food security, maintaining zero abstraction for public water supply | quantitative indicators (environment (climate, land uses, land management, water allocations), river gauge or river reach), economic and social (policies)) | MODM     | Model (DSS)Innovative modeling approaches        |
| [3]     | water planning problem (incisive supply-demand contradiction, ecosystem deterioration) | maximization of total net return from water supply system                   | water-availability, water-demand in the sectors, water demand by ecosystem, water- security            | MODM     | IQP                                             |
| [4]     | allocation of water problem among competing uses                                   | maximize the net present value of water from allocating it between competing uses | drought status, the current weather, weather correlation, and current storage, controls (environmental release and irrigation allocation) | MODM     | dynamic programming                              |
| [5]     | water allocation complexity problem among stakeholders                             | maximize water resources supply profits of each riparian stakeholder        | water balance, environmental demand, and usage                                                       | MODM     | MIP                                             |
| [6]     | imbalance water uses by human and ecosystems                                      | minimization of water index; maximization of habitat index                 | water and habitat indices                                                                             | MODM     | weighted sum method                              |
| [7]     | water supply shortage for agriculture and industry                                  | minimize industry and agriculture water shortages                           | storage volumes, time step, agricultural water supply, industrial water supply                        | MODM     | NSGAII                                          |
| [8]     | reservoir water allocation problem                                                 | minimizing unmet demands, minimizing the deviation to the full storage, minimizing the water productivity losses function, minimize | hydraulic (storage bound in the surface water sources, flow capacities of transmission links from sources to demand sites in any time period) and storage continuity requirements | MODM     | GA (OPTIWAM: Optimizing Irrigation Water Management) |
| Problem Description                                                                 | Objective                                                                 | Constraints                                                                                                                                                                                                 | Method           |
|-----------------------------------------------------------------------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Reservoir infiltration and deep percolation and water withdrawal from the aquifers, minimizing the unit cost of water over the management area throughout the study period. | Minimize the unit cost of water over the management area.                   | - Supply, demand, environmental water requirement.                                                                                                                                                           | MODM, MIP        |
| Water shortage problem (unmet demands)                                             | Maximize the total net profits of users                                    | - Output quantity of the water for each region is less than 20%; water must meet the demand.                                                                                                                | MODM, GA         |
| Water allocation shortage problem                                                  | Economic objective (minimize cost); Transfer objectives (minimize water deficit); Environmental objectives (maximizing environmental benefits) | - Water volume between transfer rivers, economic objective (minimize cost); transfer objectives (minimize water deficit); environmental objectives (maximizing environmental benefits) | MODM, interactive two-stage fuzzy stochastic programming (ITFSP) |
| Limited water resources                                                            | Maximize agricultural system benefits                                      | Irrigation benefit, economic penalty, water available and irrigation quota.                                                                                                                                  | MODM, rule-based |
| Severe water shortages in the region                                               | Minimize water abandonment, maximize available water quantity             | (1) although the cost of sewage treatment is high, the sewage must be treated and used preferentially to protect the environment; (2) diversion water should be used in preference to local water; (3) underground water is divided into three portions for use | MODM, GA         |
| Water shortage                                                                     | Minimize the water shortage for the whole watershed and balance the water shortage in different districts | Economic (output, profits, gross national product, and gross living product); social (social stability, quality of life, employment and education); environment (minimizing water quality loss caused by water pollution, maximizing water environment benefits, maintaining the ecosystem balance and improving the ecological system) | MODM             |
| Water shortage or scarcity                                                         | Maximizing domestic water use equality, maximizing agricultural water use equality, minimizing industrial water use benefits equality | Water availability, ecological water requirements, water demand.                                                                                                                                              | MODM, GA, compromise programming |
| Limited water availability (unmet demands)                                         | Minimizing industry water shortage, minimizing agriculture water shortage, minimizing water spillage, maximizing ecological satisfaction, minimize the initial water storage at the beginning of period t, ending water storage at the end of period t, inflow, water imported, water supply, water spillage, evaporation loss, | - Initial water storage at the beginning of period t, ending water storage at the end of period t, inflow, water imported, water supply, water spillage, evaporation loss, | MODM, ε-NSGA II  |
| Author | Problem/ motivation | Objectives | Criteria/indicator | MCDM | Decision Making Techniques |
|--------|---------------------|------------|-------------------|------|---------------------------|
| [16]   | water scarcity and poor management | evaluating water resource management strategies | maximum storage, minimum storage, and maximum water transfer capacity in period t, water balance, net profit, and full cost of water | MADM | MAUT, AHP, ELECTRE, TOPSIS |
| [17]   | long periods of water shortages | to balance water supply-demand strategies | implementation cost (min), response time (min), social benefit (max), demand reduction (max), viability (min), water supply (max) | MADM and MODM | PROMETHEE V (out ranking), ILP |
| [18]   | severe water shortage | enhancing water-use efficiency, development of alternative water sources and improvement in effective water management | technical (water-supply potential, systemic energy efficiency), economic (economic feasibility), environmental (climate-related stability) | MADM | weight |
| [19]   | water shortage, demand allocation | maximize hydropower output (generation), maximize water supply reliability | reservoir water storage, water demand, reservoir water inflow | MODM | (NSGA-II) |

### Water use management based problem

| Author | Problem/ motivation | Objectives | Criteria/indicator | MCDM | Decision Making Techniques |
|--------|---------------------|------------|-------------------|------|---------------------------|
| [20]   | water resources planning policies problem | minimize (evaporative/spill loss; hydropower deficit; fisheries deficit; agricultural deficit, flow alteration); maximize (land availability) | evaporation rate, hydropower production, agriculture production, fish production, land area, water flow | MODM | epsilon Dominance Non-dominated Sorted Genetic Algorithm-II (e-NSGAII) |
| [21]   | water resource management problem | supply-demand equilibrium, drought mitigation, and economic efficiency | domestic water supply, industrial water supply, agricultural water supply, environmental water supply; benefit-cost ratio, net benefit, economic risk; maximum drought duration and severity, drought loss | MODM | TOPSIS |
| [22]   | water use efficiency problem | maximum economic benefit and minimize water shortage | surface water supply, groundwater supply, minimum water requirement level, maximum water requirement level | MODM | fuzzy programming; (TLFWM (two-level linear fractional water management)) and stochastic two-level linear fractional chance-constrained water management |
| Study | Problem Description | Methodology | Water Quality and Quantity Indices | Hydrological Indices | Economic Benefits | Tropical Agriculture and Food Security | Environmental and Ecological Benefits |
|-------|---------------------|-------------|-----------------------------------|---------------------|------------------|-----------------------------|----------------------------------|
| [23]  | need for culture-based fisheries (CBFs), a form of extensive aquaculture to select a suitable reservoir (non-perennial reservoirs) for culture-based fisheries | reservoir productivity, catchment characteristics, and socio-economic factors | diversity of water authorities, autonomy of water users, data accessibility and sharing, GDP output per unit water, ratio of industrial water to agricultural water, utilization rate in canal system, wastewater recycling rate, water resources per capita, water amount per unit area, percentage of forest cover, integrated water qualification rate, sewage treatment rate, percentage of ecological water utilization, urbanization rate, per capita GDP | | | |
| [24]  | technical water allocation problem to assess the harmoniousness of water resources allocation | | reservoir storage, reservoir water level, turbine release, power output, release outflow, penalty | | | |
| [25]  | water demand for power generation and ecological benefits balance problem maximize power generation and minimize ecological flow shortage | | water availability, Irrigation demand fulfillment, environmental flow fulfillment, storage continuity, end storage, storage target fulfillment, turbine flow, turbine capacity, release capacity, storage capacity, production capacity, power supply, power deficit, | | | |
| [26]  | water stresses and food scarcity minimize power deficit, maintenance of water availability for irrigation to support food self-sufficiency, reduction in flood risk, maintenance of environmental flows, and maximization of power export | | | | | |
| [27]  | water management problems maximize net revenue, minimize variable costs, minimize groundwater pumping | | available water, cultivated area, environmental flow, groundwater pumping, cropping areas | | | |
| [28]  | water management or reservoir operation management problem minimization of deviation to develop an optimal reservoir operational programming (to calculate ecological water demands under steady and pulse states; construction of the proposed IMOOM considering ecological water demands under multiple hydrologic runoff guarantee rates, setting the | | discharge flow quantity, canal flow volume, diversion pipe flow, economic benefits of Danjiangkou and the Taocha Canal headwork, flood control, water supply, power generation, ecological water demand | | | |
| Author | Problem/ motivation | Objectives | Criteria/indicator | MCDM | Decision Making Techniques |
|--------|---------------------|------------|-------------------|------|---------------------------|
| [29]   | prioritization of tradeoffs in water allocation problem | maximum of core ecosystem service function values as the operational target | water extracted for irrigation, net benefits to irrigation, average spring terrestrial vegetation encroachment into the river channel, maximum spring terrestrial vegetation encroachment into river channel, water allocation to suppress terrestrial vegetation encroachment | MODM | NSGA-II, CP |
| [30]   | water allocation problem | to prioritize water allocation options that trade-off socio-economic and hydro-ecological benefits in rivers without direct interaction with decision-makers (i.e. tradeoffs prioritizing tradeoffs that favored either irrigation or hydro-ecological condition) | to keep the storage of the six key reservoirs between their dead storage and capacity | MODM | eNSGAII, NSGAII, OMOPSO, MOEAs, GDE, SPEA, SMPSO |
| [31]   | sustainable water resource management problem | to prioritize water allocation options that trade-off socio-economic and hydro-ecological benefits in rivers without direct interaction with decision-makers (i.e. tradeoffs prioritizing tradeoffs that favored either irrigation or hydro-ecological condition) | to keep the storage of the six key reservoirs between their dead storage and capacity | MODM | eNSGAII, NSGAII, OMOPSO, MOEAs, GDE, SPEA, SMPSO |
| [32]   | saltwater intrusion into aquifer | maximize net benefits by optimize water allocation schemes over the planning horizon | water availability, water demand by vegetation, Water demand by sectors, target water delivery, penalties, | MODM | (MFSP) multi-stage fuzzy stochastic programming |
| [33]   | water pollution problem | maximization of the extracted volume of freshwater from the aquifer, maximization of the contaminant mass removal; minimization of the total cost of a remediation system | penalty and hydraulic head threshold | MODM | LP and heuristic optimization (differential evolution, DE) |
| [34]   | integrated wastewater management system problem | minimization of the CSO volume(combined sewer overflows); minimization of ecological impacts, and minimization of volume discharged, and also minimization of | discharged hydraulic load, amount of ammonia, nitrate concentration, energy or total operation costs | MODM | Fuzzy programming |
|        |                     |            |                   |      |                       |
| Author | Problem/ motivation | Objectives | Criteria/indicator | MCDM | Decision Making Techniques |
|--------|---------------------|------------|-------------------|------|---------------------------|
| [35]   | marine pollution problem in coastal zones | suitable site selection of industrial wastewater discharge in coastal regions | consistency with marine function zone and marine law, marine dilution conditions, ecological risk, engineering risk and project cost, engineering cost | MADM | AHP |
| [36]   | poor quality of water problem | minimize allocation of monitoring sites, maximized detection of pollutant areas, maximize population protection benefit areas, maximize river hydrological category benefits | contaminant concentration at all nodes of the study area should not violate the standard at the end of the bioremediation period, hydraulic head lower and upper bound, injection and extraction flow rates should be less than the well injection or extraction capacity | MODM | Multi-Objective Artificial Bee Colony-based optimization approach (MOABC) |
| [37]   | groundwater contamination problem | minimize cost, sum of contaminant concentrations that violate standard and contaminant plume fragmentation | water remaining in the reservoirs, reservoir level and discharge | MODM | NSGA-II |
| [38]   | water-quality problem (phosphorous export to downstream areas) | maximizing hydropower energy production from a network of reservoirs, minimizing the total phosphorous discharge | water supply, demand of water use sectors, regional wastewater treatment capacity, regional wastewater reuse capacity, total emissions of water pollutants, water environment carrying capacity, engineering for carrying capacity improvement | MODM | NSGA-II |
| [39]   | water resources allocation strategies and emission control problem | maximize total system benefit in the river basin (Water utilization benefits, water shortage penalty, water supply cost, wastewater treatment cost, environmental capacity improvement cost) | MODM | ITSP (inexact two-stage stochastic programming model) |
| [40]   | wetland ecosystem protection problem | maximize ecological or ecosystem health; maximize economic returns | water volume; water use; water balance between water release and the water level; water level | MODM | GA,Fuzzy |
| [41]   | decline in fish habitat protection(ecosystem disturbance) | maximizing river habitat suitability for fish survival, maximizing the hydropower production | minimum flow requirement level, habitat conditions of the river stretch, energy production needs | MODM | NSGA II, e-constraint methods |
| Author | Problem/ motivation | Objectives | Criteria/indicator | MCDM | Decision Making Techniques |
|--------|---------------------|------------|-------------------|------|---------------------------|
| [42]   | economic and environmental benefits balance problem | minimizes the impact on the environment, maximizes the utility function of income | land availability, forest area, soil property, minimum agricultural area size, minimum residential area size, land slope, minimum recreational area size, minimum water-body area, total phosphorous assimilative capacity | MODM | multi-objective game-theory model (MOGM), constraint |
| [43]   | environmental concerns (high salinity load increment) | maximize the outflow; minimize salinity load, maximize water allocations to the agricultural fields | water demand of the agricultural water user, streamflow downstream of the withdrawal point of agricultural water user, minimum environmental flow | MODM | GA; surrogate worth trade-off (SWT) method |
| [44]   | environment problems | maximizing the comprehensive benefits (environmental, ecological, social and economic) | minimum ecological flow, maintain minimum water quality standards, flood control, | MODM | (FS-DDDP) Feasible search discrete differential dynamic programming |

**Flood based problems**

| Author | Problem/ motivation | Objectives | Criteria/indicator | MCDM | Decision Making Techniques |
|--------|---------------------|------------|-------------------|------|---------------------------|
| [45]   | decision-making problem of flood operation in a multi-reservoir system | minimizing the maximum flood release value from a reservoir and minimizing the maximum water level in the upstream reservoir; maximizing hydropower generation and maximizing flood control benefits; minimizing peak flow at a downstream flood control point and minimizing maximum water level in the upstream reservoir | Outflow limitation, water level limitation, water continuity in reservoir, water continuity amid reservoirs, start and end water level | MODM | multi-objective best compromise decision model (MoBCDM), FAHP, segmentation and averaging (Seg/Ave), differential evolution (DE) algorithm |

**Combined water problems**

| Author | Problem/ motivation | Objectives | Criteria/indicator | MCDM | Decision Making Techniques |
|--------|---------------------|------------|-------------------|------|---------------------------|
| [46]   | limited water quantity and quality | prioritization of water management strategies | cost; driving force (population and population density), impact (urban area ratio, groundwater withdrawal, slope of watershed, ratio of covered stream length, state and pressure (DPSIR framework (Driving force-Pressure-State-Impact Response))) | MADM | ELECTRE II, AVF (simple additive weighting method) |
| Author | Problem/ motivation | Objectives | Criteria/indicator | Decision Making Techniques |
|--------|---------------------|------------|-------------------|---------------------------|
| [47]   | water supply limitation and water pollution problem | maximize economic growth, water utilization, and water environment benefits | water quantity, water quality, water pollutants, water supply-demand balance, water environmental carrying capacity | MODM LP |
| [48]   | water quantity and quality management problem | allocating wastewater and urban runoff to agricultural lands and groundwater recharge | groundwater controlling, cost, environmental water right, keeping surface and groundwater quality, water supply | MADM Fuzzy(modified fuzzy social choice (MFSC)) |

**Water shortage and flood based problems**

| Author | Problem/ motivation | Objectives | Criteria/indicator | Decision Making Techniques |
|--------|---------------------|------------|-------------------|---------------------------|
| [49]   | water is insufficient; water availability is variable in space and time, spatiotemporal discrepancy in demand | minimize all costs caused by unmet demands as well as by floods in river segments; to optimally meet water demands, | regulate mass balance water flow between locations; capacity (reservoir and river segment);continuity | MODM LP |
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