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A Multi-Objective Optimization Framework for Water Resources Allocation Considering Stakeholder Input †

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Abstract: Water resources and water-related sectors are increasingly affected by multiple challenges such as climate change and extreme events, issues of ageing infrastructure, natural and qualitative water scarcity, recession, wars, population movements, increased energy and resource demand, etc. In an attempt to balance different goals of water allocation under different constraints, we present a multi-objective optimization model. The model considers various water supply sources (groundwater, surface water, desalinated water, treated wastewater) and water uses (domestic, agricultural, industrial). Water demand, availability, quality parameters, costs, and stakeholder input for the prioritization of the different goals set are synthesized through Goal Programming.

Keywords: water resources management; multi-objective optimization; Goal Programming; conceptual model; stakeholder input; water supply; water scarcity; multi-sectoral water demand

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1. Introduction

Water resources and several water-related sectors such as energy, fuels, industry, agriculture, and the economy are increasingly affected by the evident impacts of climate change on environmental resources and extreme events, issues caused by the ageing and mismanagement of existing infrastructure, natural and qualitative water scarcity, and recent changes such as recession, wars, population movements, increased energy and resource demand, and COVID-19. Such a compound of factors affects water allocation, as increasing usage must be met with limited and deteriorating resources and with the maximum efficiency to cope with the increased costs [1,2]. This often creates competition and conflicts among the different users, enhancing mismanagement in terms of water allocation [3]. This problem has been considered through the lens of optimization, maximizing or minimizing predefined goals such as water production, costs, deficits, profits from water-related activities, etc. [4]. Multi-objective optimization techniques have proved useful in assessing the trade-offs among different goals, coupling surface and groundwater sources for various usages [5]. Several studies thus far have accounted for the costs and/or water quality requirements [6]; however, fewer examples exist of applications considering all these parameters together, particularly studies making use of an open source code, thus making the models replicable [7], and studies which allow a direct input from the relevant stakeholders [8]. This study aims to provide a holistic and replicable model accounting for all the above parameters for optimal water allocation. We combine different water supply sources, various water usages, the respective supply costs and water quality requirements, and exploit the capabilities of Goal Programming (GP) to incorporate the input of stakeholders regarding the prioritization of the different goals set. The significance of this work lies in the detailed modeling description that allows its replication and application in different cases and study areas facing similar problems.

2. Conceptual and Mathematical Description of the Model

A multi-objective optimization model was developed which is applicable to any timespan, from a monthly to annual time step and more. GP was used to build this model, as it is a powerful and flexible technique allowing consideration of multiple objectives as well as the possibility to involve stakeholders [9]. The general GP structure is based on linear programing where we set the decision variable(s), specify our desirable goals, define the potential deviations from these goals, and the parameters involved. Each goal can have its own constraints; alternatively, a set of common constraints can be used, depending on the problem at hand.

In this case, the decision variable $Q_{s,u}$ represents the volume of water [m^3/year] from source s allocated to user u. The index s refers to the different water supply sources (groundwater, surface water, desalinated water, treated wastewater = TWW), and u refers to the different water uses (domestic, agricultural, industrial, and hydropower generation). Two deviation variables are introduced for the goals:

- DWD_u: deficit in water demand for user u [m^3/year].
- EWA_s: exceedance (above renewable level) of water extraction of source s [m^3/year].

The parameters of the model are the following:

- WD_u: volume of water demanded by user u [m^3/year].
- WA_s: volume of water availability (renewable resources) of source s [m^3/year].
- $\delta_{s,u}$: binary parameter equal to one if it is feasible to allocate water from source s to user u, and zero otherwise.
- $WQ_{s,q}$: concentration of substance q in water from source s [g/m^3].
- $AQ_{u,q}$: threshold of maximum allowable concentration of substance q to meet quality requirements for user u [g/m^3]. Each user u can have its own mix of quality parameters (e.g., dissolved solids, phosphorous, nitrogen, etc.).
- $cost_s$: unitary water extraction cost of source s [$\$/m^3$].
- Budget: budget allocated for water provision [$/year].

The Objective Function (Equation (1)) minimizes the deficits in water demand for users and the exceedances of water extraction from the sources:

$$\min z = \sum_u \alpha_u DWD_u + \sum_s \beta_s EWA_s \tag{1}$$

The parameters α_u, β_s penalize the deviation from the water demand and water extraction goals, respectively. Goal 1, water demand (Equation (2)): water supply must be at least sufficient to satisfy the water demand of the users:

$$\sum_s Q_{s,u} \geq WD_u - DWD_u \quad \forall u \tag{2}$$

Goal 2, water supply (Equation (3)): water supply must not exceed renewable water volumes for each type of source:

$$\sum_u Q_{s,u} \leq WA_s + EWA_s \quad \forall s \tag{3}$$

Water quality constraint (Equation (4)): the water volume mix supplied to each user must have the concentration of the harmful substances below their maximum allowable thresholds for that user:

$$\sum_s WQ_{s,q} Q_{s,u} \leq AQ_{u,q} \left(\sum_s Q_{s,u} \right) \quad \forall u, q \tag{4}$$

Budget constraint (Equation (5)): the budget for water extraction must not be exceeded:

$$\sum_s \left[cost_s \left(\sum_u Q_{s,u} \right) \right] \leq \text{Budget} \tag{5}$$

Feasibility constraint (Equation (6)): if certain variables $Q_{s,u}$ are unfeasible due to practical reasons, the following restriction controls which variables are available for the model:

$$Q_{s,u} \leq \delta_{s,u} M \ \ \forall s, u \tag{6}$$

where the value of M would be a very large constant, as, for example, shown in Equation (7).

$$M = \sum_s \sum_u Q_{s,u} \tag{7}$$

The model presented in Equations (1)–(6) finds an optimal balance between the two goals, i.e., having deficits on the demand of water by the different users and incurring in over extractions of the sources. Additionally, the model ensures that the water quality thresholds by substance, as needed by each user, are met and the cost of water extraction is within the allocated budget. The parameters α_u, β_s express the 'cost' for the decision-makers of having deficit on each user and overexploitation of each water source. The conceptual model is also described in Figure 1.

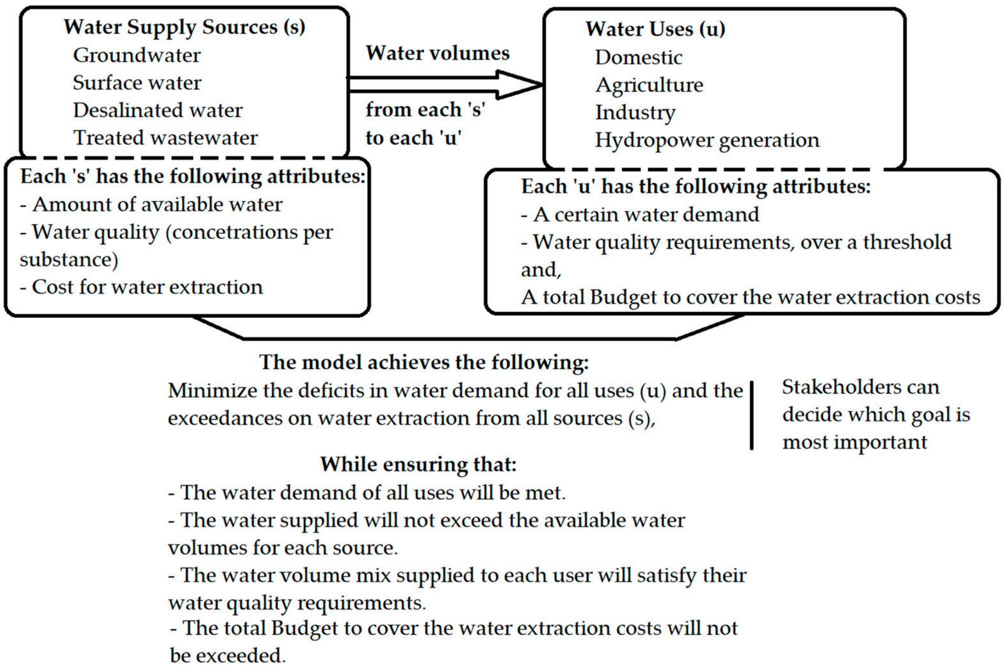

Figure 1. The conceptual diagram representing the proposed model.

The coverage of the various water demands from the supply sources need to be done in a way that will also enhance the water allocation efficiency. While the model ensures that the deficits for users and supply sources will be minimized, it is up to the decision-makers to increase the efficiency of the coverage of the water demand. For example, they could promote more water re-use, or usage of renewable surface water, while using less groundwater and reducing the costly operation of the desalination plants to produce drinking water or reducing the hydropower production to reduce its environmental impact in terms of carbon emissions. The preferences among different supply sources could be inserted in the Objective Function, with different coefficients per source promoting or penalizing its extraction; this, however, would make the model result more complex to interpret.

The model presented here was coded in Python, as it is an open-source programming language that can handle complex and computationally demanding optimization problems. The code is available (see Supplementary Materials) to enhance replicability and allow any necessary modifications to the model.

3. Stakeholder Input

In the previous section where the model was described, it was mentioned that the objectives of the model can be prioritized based on the weights assigned (α and β). GP attempts to minimize this set of deviations from multiple pre-specified (desirable) goals which are introduced simultaneously in the Objective Function. These weights can be assigned on a custom scale, usually a 0–1 scale, and the rationale is to assign higher weights to those goals that are considered more important. Thus, the model will 'penalize' the deviations from these goals, so that lower order goals are considered only after higher order goals.

The weights can be assigned by the analyst (modeler) to test the model and the sensitivity of the various decisions, and, ultimately, a group of stakeholders will define them. This is particularly important and it is the necessary condition to integrate the modeling technology into the social and political components of the planning and management process. Table 1 includes some stakeholder groups that would have a direct or indirect interest in participating in such a process of weighing the different goals.

Table 1. Potential stakeholders that could be involved in the proposed modeling process, with a general description of their role.

Stakeholder Group A: Representatives from the central Government. This group refers to representatives from the Ministry of Environment, the Environmental Protection Agencies (EPA), General Water Directorate, Agency of Land Reclamation Works, or relevant bodies of climate, energy, agriculture, etc., depending on the management structure of each country. These stakeholders operate at a higher-level, providing more general guidelines (e.g., River Basin Management Plans), so they can be key for connecting their more general guidelines to the actual decisions at a smaller scale.
Stakeholder Group B: Representatives from the regional-scale authorities, such as regional governments, the Prefecture, State or Municipal Division level agencies depending on the country. They are often responsible for implementation of the higher-level guidelines at the regional scale and for tracking the progress, so it will be useful to stay connected with all other stakeholder groups.
Stakeholder Group C: Local authorities, industry stakeholders, agricultural co-operations relating to water and agricultural management, organizations of land reclamation, urban regulators, and representatives of municipal institutions. Continuous dialogue with stakeholder groups A and B will help seek the proper expertise and skills and consider the broader picture of the goals discussed, in order to apply any measure with the maximum efficiency. Non-Governmental Organizations (NGOs) can be a part of this group, or a separate one, depending on the connection with the other stakeholders and, often, on the alignment of their environmental policies.
Stakeholder Group D: Experts and experienced professionals; start-ups and technology experts; researchers and academics. These will play the role of the solution holders in theoretical and practical terms, and will also provide feasibility considerations with respect to the application of the different decisions discussed.

It might be challenging to sit together with relevant stakeholders and explain, test, and finalize such models, as stakeholders usually do not accept implementation of modeling within their planning process; however, the ability to appreciate the trade-offs among different objectives is often appealing [3,10]. This is expected to be an element that will draw the attention of stakeholders and decision-makers in the future, as the management of the water sector becomes more challenging: the discovery of the effect of alternative assumptions and goal prioritization through collective workshops and discussions. In many cases, such exercises have helped create a common or shared understanding among stakeholders of the systems they are managing. Involving stakeholders in the model-building process provides them with a sense of ownership, a much better understanding of what the models can do, what answers they can and cannot provide, the assumptions used, the reasoning behind them, and their possible impacts; therefore, it could clarify ways to reduce any uncertainties [11].

Moreover, stakeholder participation in modeling exercises, where they can see models as a tool that they will be able to benefit from, creates also discussions that lead toward a better understanding of everyone's interests and concerns.

4. Concluding Remarks

In this study, a model for optimal water allocation was developed, considering multiple goals regarding water demand, water availability, water quality requirements, and costs. Among the advantages of the model presented here are (i) the parsimony of its formulation, which captures the relevant features of water resource allocation all the while remaining clear, simple, and easy to interpret; (ii) the low data requirements, which makes it easy to implement; and (iii) its versatility to be extended or enriched with study-specific requirements. For example, the model can be coupled with hydrological models to estimate water supply available per source along with its quality and water demand per use, while including additional economic modeling to account for the relevant costs.

This model can be tested under different management strategies or future scenarios (e.g., climate change) by altering certain parameters. For example, various interventions to make water use more efficient, and thus reduce water demand, can be considered for each use u. Water storage infrastructure can be considered to increase water supply; consideration of other supply sources and/or uses are also possible.

Sensitivity and uncertainty analyses are included in our future plans, for example considering: water demand for agricultural water use (the others are more inelastic), depending on management scenarios; water availability from surface water (SW) and groundwater (GW), depending on temperature and precipitation variations (considering also climate change scenarios); costs depending on monetary considerations, or accounting for the full cost of water; and finally, different weights of importance (α, β) for the different goals.

Given the current and future complex challenges of the water sector, solutions and approaches need to be supported by science and integrated. The model presented here, with the opportunities that it offers, can be a good example for such future applications: it is replicable, it can be tailored to similar problems, it allows the input of stakeholders in the model-building process, and it can assist the relevant stakeholders in reaching a common or 'shared' vision of at least how the systems they manage (as represented by the model) work. Finally, such exercises can also be useful for education purposes, for building an understanding of the functions and the interconnectedness of water systems.

Supplementary Materials: The following supporting information can be downloaded at: https://github.com/jorge-antares/water_allocation_model, including the Python script (accessed on 5 February 2023).

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References

1. Greve, P.; Kahil, T.; Mochizuki, J.; Schinko, T.; Satoh, Y.; Burek, P.; Fischer, G.; Tramberend, S.; Burtscher, R.; Langan, S.; et al. Global Assessment of Water Challenges under Uncertainty in Water Scarcity Projections. *Nat. Sustain.* **2018**, *1*, 486–494. [CrossRef]
2. Souza da Silva, G.N.; de Moraes, M.M.G.A. Economic Water Management Decisions: Trade-Offs between Conflicting Objectives in the Sub-Middle Region of the São Francisco Watershed. *Reg. Environ. Chang.* **2018**, *18*, 1957–1967. [CrossRef]
3. Alamanos, A.; Koundouri, P.; Papadaki, L.; Pliakou, T.; Toli, E. Water for Tomorrow: A Living Lab on the Creation of the Science-Policy-Stakeholder Interface. *Water* **2022**, *14*, 2879. [CrossRef]
4. Alamanos, A.; Xenarios, S.; Mylopoulos, N.; Stålnacke, P. Integrated Water Resources Management in Agro-Economy Using Linear Programming: The Case of Lake Karla Basin, Greece. *Eur. Water* **2017**, *60*, 41–47.
5. Naghdi, S.; Bozorg-Haddad, O.; Khorsandi, M.; Chu, X. Multi-Objective Optimization for Allocation of Surface Water and Groundwater Resources. *Sci. Total Environ.* **2021**, *776*, 146026. [CrossRef]
6. Majedi, H.; Fathian, H.; Nikbakht-Shahbazi, A.; Zohrabi, N.; Hassani, F. Multi-Objective Optimization of Integrated Surface and Groundwater Resources Under the Clean Development Mechanism. *Water Resour. Manag.* **2021**, *35*, 2685–2704. [CrossRef]
7. Garcia, J.A.; Alamanos, A. Integrated Modeling Approaches for Sustainable Agri-Economic Growth and Environmental Improvement: Examples from Greece, Canada and Ireland. *Land* **2022**, *11*, 1548. [CrossRef]
8. Tarebari, H.; Javid, A.H.; Mirbagheri, S.A.; Fahmi, H. Multi-Objective Surface Water Resource Management Considering Conflict Resolution and Utility Function Optimization. *Water Resour. Manag.* **2018**, *32*, 4487–4509. [CrossRef]
9. Charnes, A.; Cooper, W.W. *Management Models and Industrial Applications of Linear Programming*; John Wiley: New York, NY, USA, 1961; Volumes 1–2.
10. Rojas, R.; Castilla-Rho, J.; Bennison, G.; Bridgart, R.; Prats, C.; Claro, E. Participatory and Integrated Modeling under Contentious Water Use in Semiarid Basins. *Hydrology* **2022**, *9*, 49. [CrossRef]
11. Loucks, D.P.; van Beek, E. *Water Resource Systems Planning and Management: An Introduction to Methods, Models, and Applications*; Springer Nature: Berlin, Germany, 2017; ISBN 978-3-319-44234-1.