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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 resources 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

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 of ageing and mismanaged infrastructure, natural and qualitative water scarcity, and recent changes such as recession, wars, population movements, increased energy and resources demand, COVID-19. This affects water allocation, as increasing uses must be met with limited and deteriorating resources, with the maximum efficiency to cope with the increased costs [1,2]. This often creates competition and conflicts among the different users, that enhance mismanagement in terms of water allocation [3]. This problem has been seen 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 been useful for assessing the trade-offs among different goals, coupling surface and groundwater sources for various uses [5]. There are studies that consider the respective costs or water quality requirements [6]; however, there are fewer applications considering all these parameters together, in an open source code making the models replicable [7], and also allowing 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 uses, 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 modelling description that allows its replication and application in different cases and study areas facing similar problems.

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2. Conceptual and Mathematical Description of the Model

A multi-objective optimization model has been developed, applicable for any timespan at a monthly, annual or other time step. GP was used to build this model, as it is a powerful and flexible technique allowing the consideration of multiple objectives and 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, or a set of common constraints can be used, depending upon the problem.

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) in water extraction from 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) on 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 the 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 on source s [\$/m^3].
- Budget: budget allocated for the water provision [\$/year].

The Objective Function (Equation (1)) minimizes the deficits in water demand for users and the exceedances on 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:

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

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

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

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:

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

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:

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

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 on 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 on each water source. The conceptual model is also described in Figure 1.

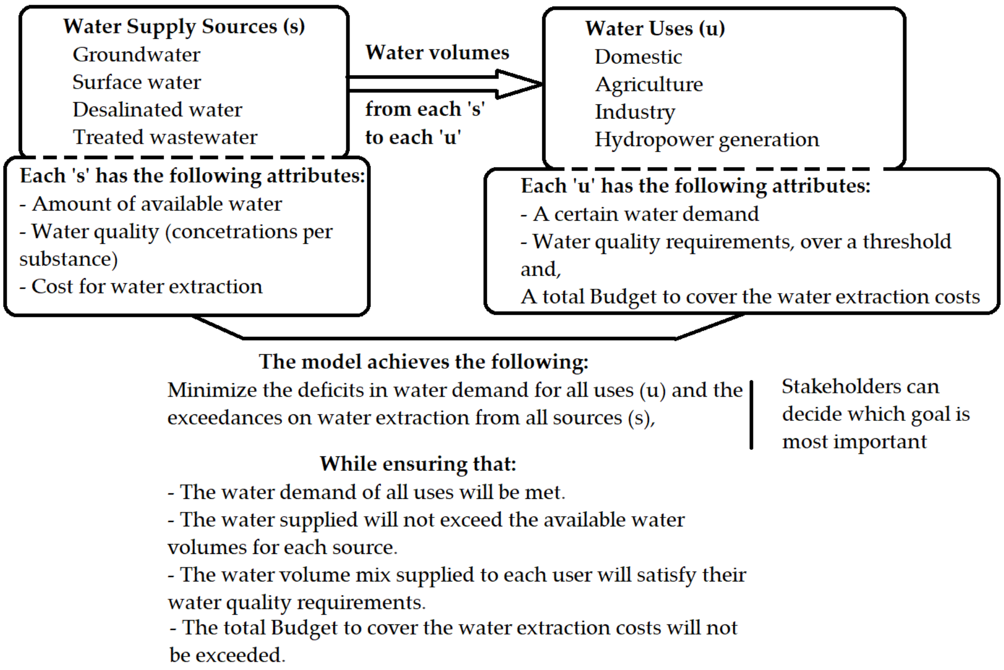

Figure 1. The conceptual diagram representing the proposed model.

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 using 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 coefficients per source that would promote or penalize its extraction, but that would make the model's result more complex to interpret.

The model presented has been coded in Python, because it is an open source programming language that can handle complex and computationally demanding optimization problems. The code will be made available to enhance the replicability and any necessary modifications of 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 put 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 from the analyst (modeler) for testing the model, and the sensitivity on 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 modelling 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 weighting the different goals.

Table 1. Potential stakeholders that could be involved in the proposed modelling 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 each country's management structure. These stakeholders operate in a higher-level of 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 in the smaller scale.
Stakeholder Group B: Representative 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 to implement the higher-level guidelines in the regional scale, and 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 on water and agricultural management, Organizations of Land Reclamation, Urban regulators and representative from the municipal level. Continuous dialogue with the stakeholder groups A and B will help seeking the proper expertise and skills, and considering the broader picture of the goals discussed, in order to apply any measure with the maximum efficiency. Non-Governmental Organizations (NGOs) can be part of this group, or a separate one, depending on the connection with the other stakeholders, and often the alignment of their environmental policies.
Stakeholder Group D: Experts and experienced professionals; Start-ups and technology experts; Researchers and academics. These will have the role of the solution-holders in theoretical and practical terms, and will also bring feasibility considerations for the application of the different decisions discussed.

It might be challenging to sit together with relevant stakeholders and explain, test, and finalize such models, because they usually do not accept modelling to their planning processes; however, the ability to see 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, where the management of the water sector is becoming more challenging: to discover the effect of alternative assumptions and goals' prioritization, through collective workshops and discussions. In many cases, such exercises have helped stakeholders to create a common or shared understanding, among them and for the systems they are managing. Involving stakeholders in model-building process gives them a sense of ownership, a much better understanding of what the models can do, what answers they can provide and what they cannot, the assumptions used, the reasoning behind them, their impacts and thus could clarify ways to reduce any uncertainties [11].

Moreover, stakeholder participation on the occasion of a modelling exercise (seeing it as a tool that they will be able to advice), 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 the parsimony of its formulation, that captures the relevant features of water resource allocation while being clear, simple, and easy to interpret; the low data requirements needed, which makes it easy to implement; and its versatility to be extend 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, the water demand per use, and include additional economic modelling 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 the water demand can be considered for each use u. The consideration of water storage infrastructure can be considered to increase water supply, or the consideration of other supply sources and 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 SW and GW, depending on temperature and precipitation variations (considering also climate change scenarios); costs depending on their monetary consideration, 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, the solutions and the approaches need to be science-supported and integrated. The model presented with the capabilities it provides, can be a good example for such future applications: It is replicable, can be tailored for similar problems, allows the input of stakeholders in the model-building process and can assist the relevant stakeholders to reach a common or 'shared' vision of at least how the systems they manage (as represented by the model) work. Finally, such exercises can be also useful for education purposes, for building an understanding of the functions and the interconnections 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.

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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. https://doi.org/10.1038/s41893-018-0134-9.
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. https://doi.org/10.1007/s10113-018-1319-5.
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. https://doi.org/10.3390/w14182879.
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. https://doi.org/10.1016/j.scitotenv.2021.146026.
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. https://doi.org/10.1007/s11269-021-02860-0.
7. Garcia, J.A.; Alamanos, A. Integrated Modelling Approaches for Sustainable Agri-Economic Growth and Environmental Improvement: Examples from Greece, Canada and Ireland. *Land* **2022**, *11*, 1548. https://doi.org/10.3390/land11091548.
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. https://doi.org/10.1007/s11269-018-2051-0.
9. Charnes, A.; Cooper, W.W. *Management Models and Industrial Applications of Linear Programming. Vols. 1 & 2*; John Wiley: New York, NY, USA, 1961.
10. Rojas, R.; Castilla-Rho, J.; Bennison, G.; Bridgart, R.; Prats, C.; Claro, E. Participatory and Integrated Modelling under Contentious Water Use in Semiarid Basins. *Hydrology* **2022**, *9*, 49. https://doi.org/10.3390/hydrology9030049.
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.