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Integrating equity and justice principles in water resources modeling and management

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1. Introduction

Water resources management (WRM) models have traditionally distributing water based on system capacities, economic efficiency, and demand (Loucks and Van Beek 2017). However, these efficiency-oriented models often fail to address water distribution inequities (Savenije and Van Der Zaag 2002, Hanemann 2005, Garrick *et al* 2020). As challenges around water scarcity and distribution inequity intensify, the need for models integrating justice principles to ensure fair and equitable resource allocation is evident.

Ideas of morality have long been central to human thought, shaping essential debates about equity and justice in modern political philosophy. Prominent philosophers like John Rawls and Amartya Sen have significantly contributed to these discussions, offering influential frameworks for understanding these concepts (Rawls 1958, Sen 2008). They argue for the inseparability of justice and fairness, that individuals should have not only equal opportunities (justice) but also equal chances to utilize those opportunities (fairness). Equity is thus achieved when justice and fairness are consistently applied to all.

Justice considerations in WRM broadly encompass distributive justice, focusing on fair resource allocation, and procedural justice, emphasizing transparency in decision-making. Water resources equity may concern distribution between upstream and downstream states in a transboundary basin (Zeitoun *et al* 2014, Yalew *et al* 2021), rights and access to clean water in communities (Syme *et al* 1999) or governance issues addressing multi-sectoral water demands, such as irrigation water demands in the agriculture sector (Gross 2014, Neal *et al* 2014).

Distributive justice addresses the questions of 'what' (what to distribute), 'to whom' (to whom to distribute), and 'how' (how to distribute) of allocation of common pool resources. This aligns with the principle of 'equitable and reasonable use' of water resources outlined in the United Nations Watercourses Convention (United Nations 1997). It is also reflected in the United Nations Sustainable Development Goal 6 (SDG6), which aims to 'Ensure access to water and sanitation for all' (United Nations 2015). Despite some attempts to incorporate equity aspects in water resources assessments (Dore *et al* 2012), a significant gap remains in effectively integrating justice principles into WRM models. Addressing these challenges requires the operationalization of specific fairness and justice principles within WRM models. By incorporating insights from socio-economic and philosophical theories, such as welfare economics and Rawlsian justice, into water resource assessments, hydro-economic models could be significantly improved to deliver operational and policy alternatives that balance efficiency and equity.

2. Conventional models and their limitations

Conventional water resources allocation models are typically grounded in utilitarian principles, focusing on allocations that maximize hydrological or economic efficiency, such as total output or economic returns. These models often rely on demand forecasting, supply management, and economic valuation, prioritizing efficiency in sectors such as agriculture (irrigation) and hydropower. However, such economic or efficiency-driven approach can overlook equity, resulting in allocations that, while efficient, may perpetuate or exacerbate inequalities among water users. For example, models prioritizing water allocation based on the highest economic return per cubic meter may favor commercial agricultural operations over smallholders, which might contribute less to macroeconomic outputs but are vital for local food security and community livelihoods.

Consider a hypothetical WRM case with three irrigation schemes (A, B, and C) drawing water from a shared river basin (table 1). An irrigation scheme is a specific water management system, such as a network of canals, ditches, or pumps, to supply water to agricultural fields. Scheme A, operated by a commercial farmer, has the highest crop production and water productivity, and requires 6.25 Mm^3 of water per season. Scheme B, run by smallholder farmers, covers a large area and with lower water productivity, needing 9 Mm^3 of water per season. Scheme C, managed by two commercial farmers, has moderate productivity, demanding 3.4 Mm^3 of water per season. In a typical conventional/utilitarian allocation model, Scheme A would likely be favored for its efficiency (using efficiency metrics (e) and (f) in table 1), followed by Scheme C, while Scheme B would receive less consideration despite its higher demand and support for many smallholders.

Recent studies (Doorn *et al* 2021, Jafino *et al* 2021, Yalew *et al* 2021), emphasize the need to incorporate distributive justice into WRM to ensure equitable allocation across sectors and generations. Integrating these principles involves applying moral frameworks that offer diverse perspectives on water allocation, enabling models to generate equity-informed policy and operational alternatives. While the optimal approach depends on specific policy and operational objectives, models should present and assess equity-focused resource allocation strategies. By integrating concepts such as egalitarianism (Dworkin 2002), utilitarianism (Mill 2016), the capability approach (Nussbaum 2007, Sen 2008), and proportional justice (Konow 2001), water resource models can be designed to provide managers and policymakers better analytical insights into both the efficiency and equity aspects of water resource allocation. Water resource models can be designed to provide managers and policymakers improved analytical insights into the efficiency and equity of water resource allocation.

3. Operationalizing distributive justice

This perspective explores applying selected distributive justice principles to water allocation, focusing on Utilitarian, Strict Egalitarian, Proportional Justice, Capability Approach, and sufficientarian principles. These principles offer distinct perspective for distributing water among water users based on various criteria and metrics. The primary equation we used across these principles is the generic weighted proportional allocation equation (Nguyen and Vojnovic 2011) as shown in equation (1),

$$Q_i = \frac{C_i}{\sum_{i=1}^{3} C_i} * \text{AW} \qquad (1)$$

where,

Q_i = water allocated to irrigation scheme i

C_i = value of criteria C for irrigation scheme i

AW = Available water

The utilitarian approach, often incorporated in conventional water allocation methods, aims on maximize overall utility, such as output or productivity. We demonstrate here a variant called 'Weighted Utilitarianism' (Heinen *et al* 2015, Argenziano and Gilboa 2017), which allocates water using efficiency metrics like 'Total Crop Production' and 'Water Productivity' to maximize crop production per unit of water (see equation (2) in supplementary material).

The egalitarian principle, which views fairness and equality as 'equal' distribution irrespective of individual requirements or consideration of individual outputs (see equation (3) in supplementary material). This principle is often quantified as a Gini coefficient and has been effectively applied in some water allocation case studies (Hu *et al* 2016).

The capability approach, theorized by philosopher Martha Nussbaum (2011) and economist Sen (2008), emphasizes the specific potential of entities—in this case irrigation schemes—to achieve valuable outcomes. Capabilities refer to the real opportunities that people have reason to value (Sen 2001). 'Capability factors' may include various variables identified as essential criteria specific to each case, which can be incorporated into a unified distribution equation, as exemplified by Van der Zaag *et al* (2002). In the context of the previous irrigation schemes, each can be evaluated differently based on their potential to provide real opportunities. Schemes A and C excel in total crop production and water productivity, demonstrating efficient resource utilization. In contrast, Scheme B, although less efficient, provides employment for a large group of smallholder farmers, highlighting its potential for social impact. These important factors are considered in this allocation principle (see equation (5) in the supplementary material).

The sufficientarian principle ensures a minimum resource standard for all before further distribution. In our example, each scheme receives enough water to meet basic needs, with any surplus distributed by other principles, like maximizing productivity (see equation (6) in supplementary material).

With a total water demand of 18.65 Mm^3 per season for the three hypothetical irrigation schemes detailed in table 1, and an available supply of only

Table 1. Attributes of three hypothetical irrigation schemes.

(a) Irrigation scheme	(b) Number of farmers	(c) Number of employees	(d) Total water demand (Mm^3)	(e) Total crop production (ton)	(f) Water productivity (ton m^{-3})
A	1	80	6.25	5000	0.0008
B	1000	1000	9	4500	0.0005
C	2	40	3.4	2000	0.0006

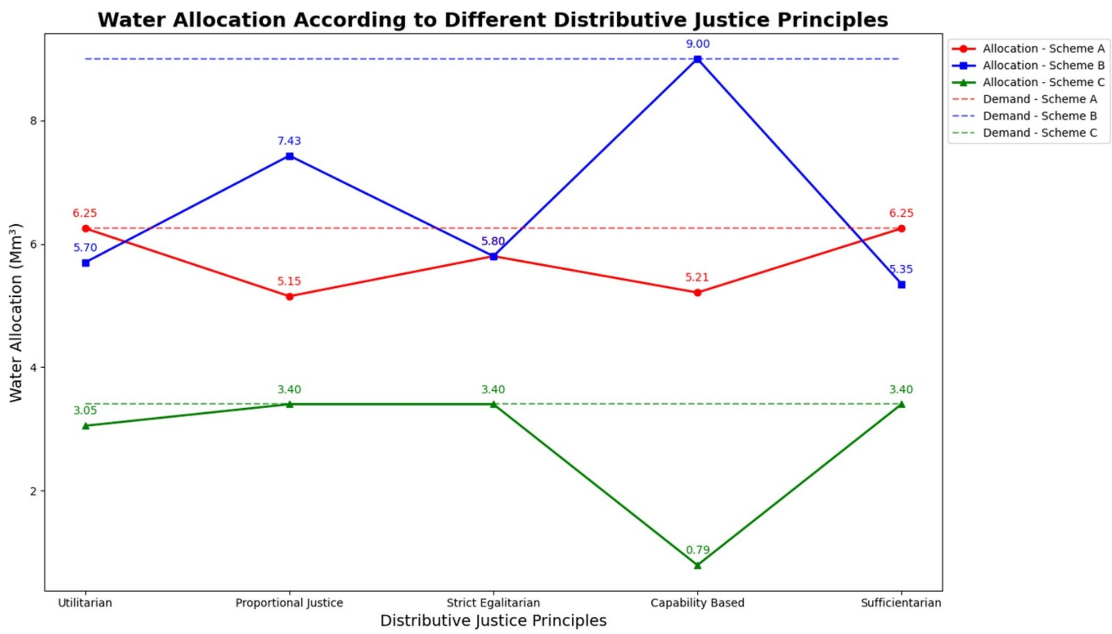

Figure 1. Water allocation based on different equity perspectives. The figure shows water allocation for irrigation schemes (A)–(C) under the various distributive justice principles. Markers indicate the allocation for each scheme under each principle, with solid lines connecting allocations across principles. Dashed lines represent each scheme's water demand, enabling direct comparison. Excess water was redistributed to other schemes according to the equity principles. Detailed calculations and methodology are in the supplementary material.

15 Mm^3 per season, a condition of water scarcity arises. Figure 1 illustrates how the limited water supply is allocated according to the various justice principles discussed earlier.

As shown in figure 1, the utilitarian principle favours the more efficient schemes, such as Scheme A and, to some extent, Scheme B. In contrast, the capability approach and proportional justice principles prioritize Scheme B in this specific example. The strict egalitarian, proportional justice, and sufficientarian principles tend to favour schemes with lower water demands, like Scheme C, since their water needs are more likely to be met when available water is distributed equally or when a minimum threshold is allocated to all schemes.

4. Example applications in India

Water management and allocation in India offer rich examples of how different principles of equity are embedded in policy and practices in varied scenarios, illustrating how abstract ideas of distributive justice are practically applied. The utilitarian perspective is evident in groundwater management, where government programs subsidize private irrigation infrastructure to maximize total production. Given the limited budgets of these programs, decisions need to be made on what type of infrastructure would be subsidized and who would be eligible to receive subsidies within the target region. When the focus of the program is to maximize total production, this is seen in the targeting of 'progressive' farmers, i.e. farmers who are at the frontier of irrigation practice, and have the capability to maximize production from the given subsidy to new technology such as private farm-ponds, micro-irrigation kits, and pipeline sets. These investments allow the selected irrigators to shift to high-value irrigated crops such as orchards. On the other hand, when the program focus is on the most vulnerable farmers (e.g. in a program on climate resilient agriculture), then it would prioritize the rain-fed farmers within the same geography and subsidize investments (e.g. shallow wells) that enable protective irrigation during dry spells, and not necessarily productive irrigation, which would align with the sufficientarian principle (Prasad *et al* 2023).

Grassroots initiatives also operationalize equity in water distribution. The Pani Panchayat (water council) initiative that started in late 1970s in the Maharashtra state developed minor irrigation group schemes where water was distributed based on agreed principles. Accordingly, each family was given an entitlement enough to irrigate 0.5 acre per head with an upper ceiling of 2.5 acres per household (Deahpande and Reddy 1990). This entitlement was not linked to land ownership. Landless agricultural laborers also received the same entitlement, which would be transferred along with the laborer to the landowner who employed the laborer. Water intensive crops such as sugarcane, paddy and banana were not to be cultivated within this agreement. This community-led approach to equity aligns with the strict egalitarian perspective of equity where each is allocated exactly the same entitlement. This same principle is also currently being replicated in Sangli district of Maharashtra where a pilot project is ongoing to distribute water from the Tembhu lift irrigation in a way that meets an entitlement of 5000 cubic meter of water per household per year, including entitlements for landless laborers (Vohra 2022).

The World Bank's Andhra Pradesh Drought Adaptation Initiative illustrates operationalization of the sufficientarian perspective in irrigation water distribution (Reddy *et al* 2014). Here, groundwater collectives are formed between borewell owning and non-borewell owning farmers, and the existing borewells within the group are pooled amongst all farmers (borewell owners and non-owners) using a pipe network so that all can have access to groundwater for irrigation. This is made possible through a binding legal agreement that no new borewells will be dug by any farmer of the collective for the next ten years, in order to prevent competitive borewell drilling. It is agreed that the first priority is to assure protective irrigation for all farmers within the group to overcome long dry spells during the main Kharif (rainfed) season. Hence, there is entitlement of protective irrigation during Kharif season to all plots within the designated area regardless of ownership of borewells (Ravindra and Raina 2012). Beyond this, the borewell owning farmers are free to irrigate a second crop or to trade water with others within the group, for which no regulations are in place. This idea of assuring a basic minimum amount of water to all aligns again with the perspective of the sufficientarian principle. These examples from India highlight how different equity principles—utilitarian, egalitarian, and sufficientarian—can be applied in real-world water management scenarios.

These examples highlight how some of the distributive justice principles discussed earlier are applied in real-world water management cases. Conventional WRM models rarely enable decision-makers in such cases to evaluate the operational and policy implications of water allocation based on various equity perspectives. By integrating diverse equity principles, models can provide a comprehensive understanding of trade-offs and outcomes, enabling policymakers to balance efficiency and fairness in sustainable water management.

5. Implications

The previous examples demonstrate that integrating equity principles into water resource allocation offers alternative distribution perspectives often missing from conventional models. This underscores the need for models that assess water allocation through diverse equity and efficiency lenses, offering valuable policy insights for improved management. However, integrating justice perspectives introduces complexity, requiring social metrics alongside hydrological variables.

While our focus here was on operationalizing distributive justice, it is crucial to recognize the equally important role of procedural justice, which emphasizes the need for inclusive and participatory procedures in water distribution decision-making. Advancing WRM requires models that incorporate diverse equity perspectives and facilitate procedural justice considerations through a collaborative, consensus-based methodologies on deciding who gets what during water allocation. Modelers and developers are therefore tasked with quantifying and incorporating aspects of fairness and justice, traditionally explored by philosophers and ethicists. This change requires policymakers and water management agencies to adopt new approaches that prioritize equity.

Translating abstract concepts of justice and fairness into measurable criteria is challenging. This perspective adds to the evolving discourse by providing a rationale for reforming conventional water allocation models and offering practical examples for doing so. It introduces a framework for applying distributive justice equations in water resources modeling, essential for balancing efficiency and equity. Although equity considerations may not always be fully quantifiable, the approaches discussed outline steps for robust water resource assessment and modeling. These steps address the evolving needs of policy and decision-making, ensuring that models are not only efficient but also ethically defensible. Achieving this requires collaboration among hydrologists, economists, ethicists, and stakeholders to develop models reflecting shared values for sustainable water management.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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