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# Transforming Agricultural Water Management for Healthy People and Planet: Thinking Beyond Water

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## ABSTRACT

This paper develops the concept of *Thinking Beyond Water*, a transdisciplinary paradigm that reframes agricultural water management (AWM) as a systems catalyst for planetary health, equity, justice and resilience. Moving beyond conventional irrigation-centric models, we reimagine AWM through integrative frameworks such as the planetary boundaries, the doughnut economy and just transitions. We examine the limits of efficiency metrics and highlight trade-offs between equity and resource allocation and ecological externalities of infrastructure and technology-led approaches. We argue that AWM decisions can reinforce exclusion, ecological degradation and policy fragmentation when they are not assessed against planetary health criteria. *Thinking beyond water* does not replace nexus, systems or resilience approaches; it connects them to explicit planetary thresholds, justice criteria and governance. We set out three propositions: a systemic appraisal matrix that distinguishes threshold criteria that cannot be traded off against productivity from criteria that are scored and weighted; a mapping of financing instruments to the barriers they address and the safeguards they require; and a staged process for reorienting National irrigation plans. Ultimately, we propose that water must be seen not as an isolated input–output for agriculture but as a systems connector linking hydrological integrity, human and ecosystem health and human dignity across scales.

## RESUME

Cet article élabore le concept de «Perceptions au-delà de l'eau», un paradigme transdisciplinaire qui redéfinit la gestion agricole de l'eau (AWM) en tant qu'un catalyseur de systèmes pour la santé, l'équité, la justice et la résilience de la planète. En allant au-delà des modèles conventionnels centrés sur l'irrigation, nous réimaginons l'AWM à travers des cadres d'intégration tels que les limites planétaires, l'économie du donut et les transitions justes. Nous examinons les limites des indicateurs d'efficacité, mettons en évidence les compromis entre l'équité et l'allocation des ressources, ainsi que les externalités écologiques des approches axées sur les infrastructures et les technologies. Nous soutenons que les décisions relatives à l'AWM peuvent renforcer l'exclusion,

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la dégradation écologique et la fragmentation des politiques lorsqu'elles ne sont pas évaluées par rapport aux critères de santé planétaire. La perspective au-delà de l'eau ne remplace pas les approches fondées sur les liens, les systèmes ou la résilience; elle les relie à des seuils planétaires explicites, à des critères de justice et à une gouvernance. Nous mettons en place trois propositions: une matrice d'évaluation systémique qui distingue les critères de seuil qui ne peuvent pas être négociés au détriment de la productivité des critères qui sont notés et pondérés; Une cartographie des instruments de financement en fonction des obstacles qu'ils éliminent et les garanties qu'ils requièrent; et un processus progressif pour réorienter les plans nationaux d'irrigation. En fin de compte, nous proposons que l'eau ne soit pas considérée comme un intrant-une production uniquement pour l'agriculture, mais comme un élément de système reliant l'intégrité hydrologique, la santé humaine et celle des écosystèmes, ainsi que la dignité humaine à travers les échelles.

## 1 | Introduction

Agricultural water management (AWM) has traditionally been water-centric; however, research and development are promoting an evolution from water-centric approaches (Smith et al. 2023) to nexus thinking, which aims to address the complexities of AWM (Smith et al. 2024). Integrating nexus thinking into AWM framing (Smith et al. 2024) represents a critical turning point in embracing other sustainability dimensions, such as equity, social justice, governance and planetary health, encompassing both human and ecosystem health. Thus, *thinking beyond water* is no longer a must but rather a need to ensure systematic foresight, social and ecological justice and planetary health. Where these interdependencies are not reflected in planning and appraisal, isolated efficiency metrics fail to capture the complex and dynamic interconnectedness among natural resources, human well-being, and environmental well-being. Thus, the *thinking beyond water* paradigm is timely, as it seeks to embed social foundations within planetary boundaries for a safe and just operating space in the Anthropocene.

The conceptual framing around the nexus and AWM has facilitated a complex-thinking approach that promotes a deeper understanding of multiscale feedback loops and trade-offs. However, despite such progress, global water problems persist. That progress is substantial and extends well beyond the nexus. Integrated water resources management, socio-hydrology, systems dynamics, resilience thinking, multicriteria and composite indicator frameworks, and participatory and polycentric governance have each expanded the repertoire available to AWM. In several countries, these approaches are already embedded in National water planning. The persistence of water problems is therefore not evidence of an absence of integrated thinking. It reflects the uneven institutionalisation of that thinking and the fragmentation among biophysical limits, equity objectives, financing arrangements and operational decision-making. Water scarcity, degradation and intersectoral conflicts intensify as localised freshwater demands increase. An estimated 55% of the global population experiences clean water scarcity at least 1 month a year (Jones et al. 2024). Currently, 200 million people in sub-Saharan Africa alone face water scarcity due to low quantity and poor quality (Jones et al. 2024). Climate change and anthropological factors such as population growth, rapid urbanisation, industrialisation, agricultural expansion, land degradation, agrochemical usage, deforestation and air and soil quality (Zhang et al. 2021) further compound degradation and depletion (Petrov et al. 2023). Additionally, policy responses have long lagged behind these complex interdependencies and often resort

to legacy decision-making that promotes siloed thinking (Vorley and J. Nelles 2020; Allen and Mau 2025), pushing the world into the state of water “bankruptcy” (Madani 2026a). This means that many river basins and human-water systems around the world are already in a “water crisis” stage, where many baseline natural conditions are no longer restorable, calling for major transformative changes in governance models to prevent further irreparable damages (Madani 2026b).

Given the persistent global water crisis and policy laggards, there is an urgent need to *think beyond water* and embrace the nexus for sustainable development. *Thinking beyond water* is not only transformative (de Loë and Patterson 2017) but also an evolutionary approach that acknowledges water as a system connector and as a means through which justice (Sultana 2018), resilience and planetary health can be addressed. *Thinking beyond water* provides a framing through which AWM decisions can be assessed against ecological justice, intergenerational equity and planetary health criteria (Stevis 2000; Grafton et al. 2019). From a food production perspective, *thinking beyond water* entails a shift from the utilitarian approach of more-crop-per-drop metrics (Taguta et al. 2022) to holistic approaches that seek to answer questions such as: Whose water security is prioritised? What ecosystems are sacrificed for irrigated productivity? How are hydrological thresholds accounted for in support of food security? Answering these critical questions is key to developing relational support systems (Uhlenbrook et al. 2022) that effectively link people, landscapes, institutions and ideologies, thus bridging anticipatory, multiscale and pluralistic indigenous knowledge systems; ecological thresholds; and regenerative land–water relationships. Similarly, *thinking beyond water* reframes AWM as a domain in which water-mediated systemic risks can be identified and acted upon.

This paper forms part three of the conceptual AWM trilogy, which seeks to drive the foundational discourse on innovation and technology for AWM (Smith et al. 2023) and to apply the nexus approach to embracing the complexities in AWM (Smith et al. 2024). The progression across the three papers is deliberate: The first addressed technology and innovation, the second the complexity of nexus interactions and this third paper adds explicit ecological thresholds, explicit justice criteria and the institutional and financial architecture through which both can enter AWM decisions. This paper extends that work by specifying how ecological thresholds and justice criteria can be incorporated into AWM appraisal, financing and planning. The paper is structured into six sections. Section 2 conceptually repositions AWM within planetary

health and justice frameworks, and Section 3 examines how established systems, nexus and participatory methods can be more systematically linked to justice criteria and ecological thresholds. Section 4 elevates AWM from a sectoral intervention to a systems catalyst for transformation across multiple levels through co-creation, data democratisation and justice-centred transitions. Section 5 sets out the appraisal, financing and planning mechanisms through which these criteria enter investment decisions. Section 6 consolidates key recommendations for realigning AWM with planetary boundaries and social equity imperatives.

## 2 | Beyond the Drop: Reframing AWM

AWM has been regarded as pivotal and central to solving socio-economic, socio-ecological and environmental challenges, thereby tackling poverty (Gundogdu 2020; Smith et al. 2024). However, a critical analysis would reveal the trade-offs involved in assessing systems' potential to alleviate poverty from a water-centric perspective. Water-centric metrics alone are limited in their capability to appraise system performance. While useful for field and irrigation scheme scales (Uhlenbrook et al. 2022), water productivity (WP) fails to capture the broader systemic trade-offs, ecological impacts and social justice concerns (Molden et al. 2010; Grafton et al. 2018). As water-related pressures escalate, driven by climate change, population growth and competing sectoral demands, there is a need for a more holistic,

transformative and justice-oriented approach to addressing these challenges. This section proposes a reframing of AWM that *thinks beyond water*, both conceptually and operationally, advancing a systems approach that centres resilience, equity and planetary health (Figure 1).

### 2.1 | Complementing WP With Resource Justice

While WP remains a valuable measure of technical efficiency, it does not capture the distributional and governance aspects of water use, thereby limiting its usefulness for understanding the “water for all” concept. Also, despite efforts to apply nexus approaches to untangle AWM complexities, critics have argued that excluding governance and health dimensions from the nexus framework limits its ability to capture on-the-ground realities. These limitations justify reframing the need to *think beyond water*. This is not to suggest that multidimensional assessment is absent from AWM. Composite indicators spanning technical, economic, social and environmental dimensions have been developed and applied at a range of scales, including in irrigation system appraisal (Taguta et al. 2022). Despite the presence of such indicators, there remains an incorporation gap regarding distributional justice, ecological thresholds and accountability in the appraisal frameworks that govern investment decisions. Evidence (Lankford and Scott 2023) suggests that, under the paracommons phenomenon, farm productivity, as measured by WP, might be high; however, it has different ecological and

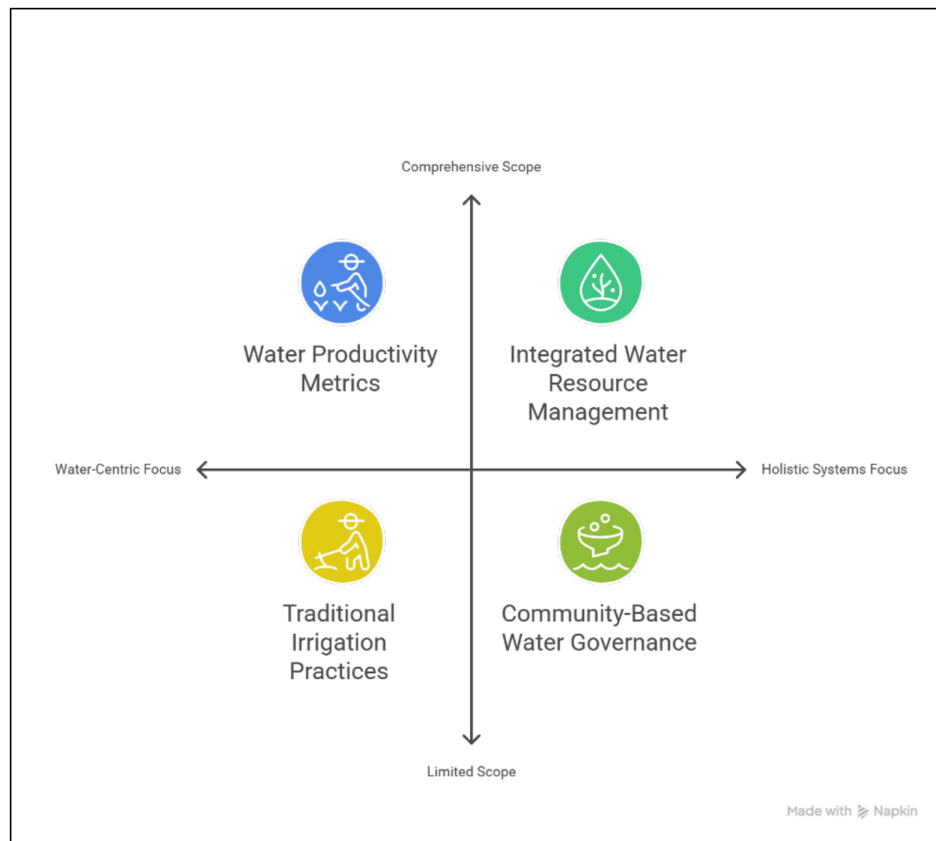


**FIGURE 1** | Holistic and comprehensive scopes versus limited scopes that push ecological limits whilst promoting siloed approaches. Evolving AWM paradigms, positioning strategies by scope and systems orientation. The quadrant framework maps four dominant paradigms in agricultural water management (AWM) along two axes, namely systemic comprehensiveness (vertical) and focus orientation (horizontal). It illustrates the strategic positioning of AWM approaches based on their breadth of engagement and alignment with integrated systems thinking.

human health impacts for downstream users (Allan et al. 2019; Lankford and Scott 2023; Lankford and McCartney 2024). Thus, WP inherently fails to answer two critical questions: Whose productivity is being enhanced? and at what social and ecological cost(s)? These trade-offs are one of many that WP fails to capture. Other social and ecological penalties incurred by high WP include the following: (i) farmer displacement, for example, in Sardar Sarovar Dam on the Narmada River in India, the large dam construction caused displacement without adequate resettlement (Hasanain et al. 2012; Scudder 2012); (ii) downstream ecosystem degradation; and (iii) undermining customary water rights<sup>1</sup> point in case intensified use of groundwater fuelled conflict among rich and resource constrained farmers. The conflict disrupted reciprocal arrangements for shared water points. Given these unintended consequences, there is a need to embed resource justice within AWM, which considers access, agency and accountability in the allocation and governance of water (Sultana 2018). A resource justice lens expands the frame of reference from “how much” water is used to “who decides” and “who benefits” from water use efficiency. In operational terms, this can be expressed through indicators that are already collectable at scheme level: the distribution of command area and delivered volume by gender, tenure status and age; reliability of delivery to tail-end relative to head-end users; the proportion of affected user categories holding decision rights in scheme governance; formal recognition of customary rights within allocation registers; downstream environmental flow compliance; and the affordability of irrigation technology and service charges to the lowest income quartile of participating households. Responses to these questions inform the redesign of AWM systems to include recognition of historical and gender inequalities, empowerment of local water governance and inclusion of Indigenous knowledge systems (Zwarteveen and Boelens 2017).

## 2.2 | Complementing Irrigation Efficiency With System Resilience

Taguta et al. (2022) conducted an appraisal of irrigation system transition using holistic water-energy-food (WEF) nexus indicators. The assessment went beyond orthodox efficiency metrics, such as conveyance efficiency (the ratio of water delivered to water diverted) and application efficiency (the ratio of water stored in the root zone to water applied). Key findings revealed that across different agro-ecological regions, drip irrigation outperformed other irrigation types, followed by sprinkler irrigation, and then furrow irrigation. Despite providing the best performing metrics, drip irrigation occupies a mere 5% of irrigated agricultural land, followed by sprinkler (20%) and surface (75%), which have relatively low WEF nexus performance (Al-Agele et al. 2021; Taguta et al. 2022). Reality on the ground suggests that sub-Saharan Africa's smallholder irrigation is predominantly flood irrigation, which has low efficiencies, and in cases where access is available, farmers adopt drip irrigation, which still relies on orthodox appraisal metrics which assess physical water losses at the field or scheme level; they fail to reflect system-wide outcomes or actual water savings at river basin scale. Several studies have shown that a drip irrigation system helps smallholder farmers conserve water and nutrients and reduces evaporation when properly set up. The efficiency paradox has been observed across a range of irrigation contexts,

including in the Global South, because water-saving technologies or infrastructure modernisation reduce nonbeneficial losses locally (e.g., percolation, runoff) but enable the expansion of irrigated areas, intensification of cropping patterns or shifts to high-value, water-intensive crops, thereby increasing total water consumption (Dirwai et al. 2024).

Resilience-oriented outcomes complement efficiency by anchoring AWM in adaptive capacity and reducing nonbeneficial losses (Folke et al. 2010). From a planetary boundaries perspective, resilience-oriented outcomes facilitate the inclusion of justice considerations into Earth system thresholds (Rockström et al. 2023). Practical AWM approaches can be used to fundamentally redesign AWM objectives and practices. Practices such as flexible water allocation under uncertainty promote a shift from rigid volumetric entitlements based on legacy flows to probabilistic, adaptive management approaches that accommodate variability in precipitation, river flows and groundwater recharge. Operationalising this would entail the following: (i) establishing tiered allocation structures linked to weather and climate information services (WCIS) that take into consideration base plus variable volumes for ensuring water adequacy for crop development (Mabhaudhi et al. 2025), ecosystem services and multiple use systems (MUS) (van Koppen et al. 2006); (ii) integrating early warning systems for anticipatory decision-making under extreme weather events; and (iii) embedding environmental flow thresholds to protect ecosystems during low-flow periods (Poff et al. 2010; Richter et al. 2012).

Nature-based solutions (Nbs) also play a critical role in enhancing water resilience (Thomas et al. 2024). AWM at the crop scale is a function of soil-water-plant interactions, which, if perfectly managed, can minimise external water demands. Agro-ecological and conservation agriculture practices, such as mulching, intercropping, zero tillage and contour bunding, enhance soil organic matter, infiltration capacity and water-holding capacity (Tittonell 2014). Adopting these practices enhances green WP, which is essential for farmers who rely on rainfall for crop production. Moreover, agronomic interventions such as integrating cover crops and agroforestry into irrigated areas potentially buffer hydrological extremes by regulating microclimates through controlled evapotranspiration losses (Lin 2011; Altieri et al. 2015).

Another resilience-oriented approach entails integrating ecosystem services into irrigation planning. Such planning recognises the role of regulating and supporting ecosystem services such as groundwater recharge via managed aquifer recharge (MAR) systems, buffering flood peaks through restored wetlands, and upstream sediment retention practices. Adopting a multifunctional landscape systems thinking approach intentionally accounts for hydrological connectivity and ecological feedbacks, thus designing and planning for irrigation beyond the command area to the river basin as the primary planning unit. The multifunctional landscapes approach also promotes low-cost natural infrastructure such as check-dams that can be used for irrigation investment planning, thus availing water beyond the wet seasons (Ozment et al. 2015). Overall, evaluating efficiency gains alongside resilience and river basin scale outcomes supports the building of adaptive capacity and systems level sustainability for vulnerable and exposed groups.

### 2.3 | Beyond SDG 6: Linking AWM to the Doughnut Economy and Planetary Boundaries

Sustainable Development Goal 6 (SDG 6), particularly Target 6.4, aims to substantially increase water use efficiency across all sectors and ensure sustainable water withdrawals to reduce water scarcity. While this target represents an important recognition of water's finite nature, its dominant efficiency oriented framing risks reinforcing narrow, technocratic approaches to AWM (UN-Water 2021). As already alluded to, when pursued in isolation, efficiency metrics fail to capture broader systemic risks such as ecological degradation, social inequity or inter-generational injustice (Grafton et al. 2018). For AWM to be sustainable, it must extend beyond SDG 6's volumetric framing and integrate with holistic frameworks that acknowledge the planetary boundaries framework (Rockström et al. 2009) and doughnut economic models (Raworth 2017). There is an urgent need to reframe AWM within nature's safe operating space; failure to do so could destabilise hydrological cycles, promote ecosystem degradation and catalyse salinisation, wetland loss and groundwater depletion, pushing systems into a state of "water bankruptcy" (Madani 2026b). To address these challenges, AWM must operate within the planetary boundaries. Operating within planetary boundaries is not a directive that a National irrigation agency can act on directly; it requires translation through a defined chain. The global freshwater boundary is expressed as a river basin scale environmental flow requirement (EFR) that sets an allocation ceiling for the reach, thereby constraining the

abstraction permitted under individual irrigation entitlements and is verified through monitoring. The equivalent chain for groundwater runs from recharge estimation to a sustainable yield limit, to seasonal abstraction allocations, to metered verification. Section 5.1 specifies where in the investment cycle these translated thresholds enter the decision. This systematic and pragmatic shift requires redefining metrics and operationalising indicators such as EFR, which is a percentage of total annual river flow maintained for ecosystem functions, groundwater recharge rates versus abstraction rates, particularly in overdrawn aquifers (e.g., North China Plain, Ogallala and Indo-Gangetic River Basin) and blue water footprint per tonne of output, disaggregated by crop and region.

Reframing AWM to align with planetary boundaries is one piece of the puzzle. Embedding contextual social indicators is critical and foundational in the reframing process. Harmonising the complex relationship between planetary boundaries and critical socio-economic dynamics is a positive step towards planetary health. Complementary frameworks such as the doughnut economy model (Raworth 2017) help clearly define the safe and just space in which humanity can thrive (Figure 2). At the centre of the doughnut are holistic critical human needs that form the basis for social foundations. These critical human needs are a priority as they define a lack of deprivation, meaning all human beings are empowered with the rights and resources needed to provide a social foundation for leading lives of dignity, opportunity and fulfilment (Raworth 2012; Raworth 2017). The

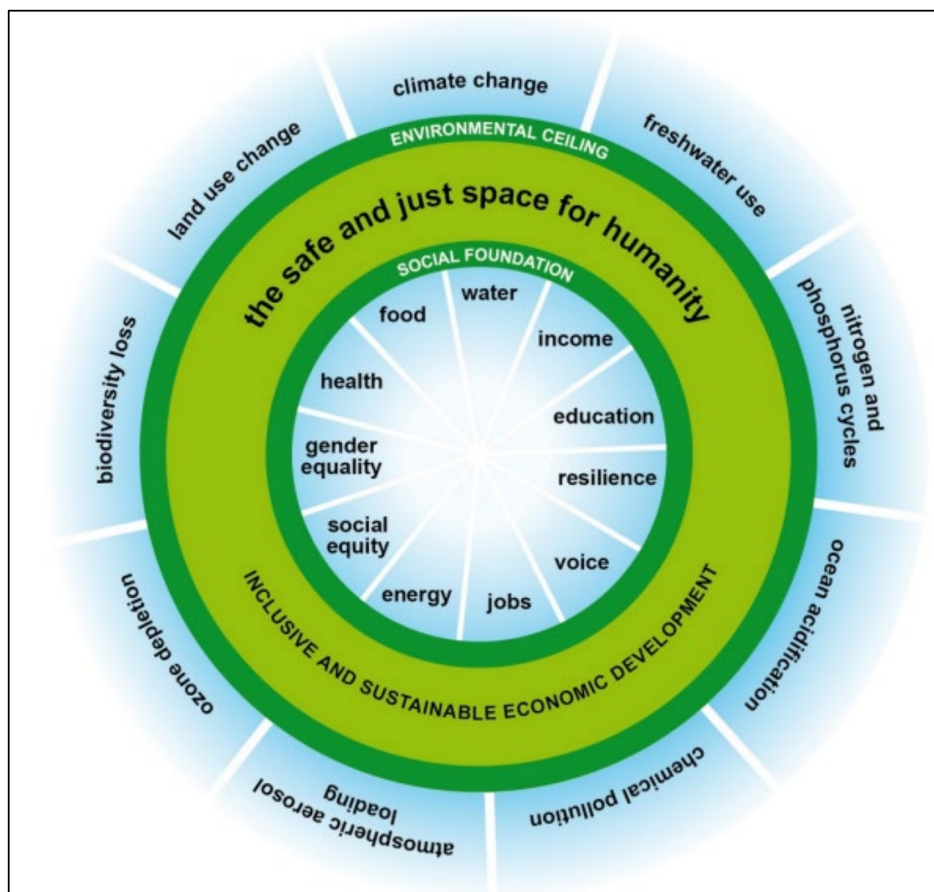


**FIGURE 2** | The doughnut model complements the planetary boundaries framework to create a safe and just space for humanity to thrive. The model incorporates social justice and equity as an integral pillar of sustainability. Source: Raworth (2017).

outer ring represents the planetary boundaries that should not be crossed in pursuit of attaining human dignity, opportunity and fulfilment (Rockström et al. 2009; O'Neill et al. 2018). The complex nature of achieving this goal is well-documented, and evidence indicates that at the national level, countries overshoot ecological ceilings by between 32%–55% and 50%–66%, depending on the indicator, while the number of countries achieving social thresholds increased for five social indicators (in particular life expectancy and educational enrolment) and decreased for two indicators, particularly social support and equality (Fanning et al. 2022).

The primary goal of the SDGs is to eradicate poverty, ensuring that all people live a life free from deprivation. However, eradicating poverty is a double-edged sword that requires a middle ground or “soft spot” between top-down and bottom-up approaches. This safe and just space for humanity is complex because social and planetary boundaries are interdependent. Aggressive top-down approaches, that is, policies aimed at pushing humanity within the planetary boundaries, risk pushing people further below the social foundation, and vice versa (Raworth 2012). Thus, *thinking beyond water* within AWM is critical to ensure that people remain within acceptable planetary boundary limits. This is possible through coherent policies that promote justice and equity without compromising environmental integrity. In AWM terms, this means ensuring the following:

- equitable access to irrigation water for women, smallholders, marginal lands;
- food and nutrition security via inclusive irrigation coverage;
- secure land and water rights for marginalised and vulnerable groups; and
- affordability of irrigation technologies such as solar pumps and drip kits

Failing to uphold these foundations risks further reinforcing social exclusion, even while appearing efficient. Where solar irrigation is deployed without attention to equitable access and to the governance arrangements coordinating it, expansion can reproduce existing gender- and wealth-based inequalities in who obtains and benefits from the technology (Lefore et al. 2021). Despite smallholder farmers' increased access to irrigation hardware and technologies, uncoordinated and fragmented policies on tariffs, recharge limits and land tenure persist around communally owned lands. This consequently led to inequity and unregulated expansion (Hartung and Pluschke 2018).

Repositioning AWM into flexible and contextual frameworks, such as the doughnut economy and planetary boundaries, represents a revolutionary and evolutionary lens of viewing and conceptualising sustainability in the Anthropocene (Rockström et al. 2009; Raworth 2012; Raworth 2017; Rockström et al. 2023). It represents a bold transition towards system-wide approaches that account for the ecological ceilings we must not exceed and the social foundations we must not neglect. This repositioning entails rethinking water not as a resource to be allocated efficiently but as a systems connector linking hydrological integrity, ecosystem resilience, social justice, and intergenerational equity.

*Thinking beyond water* entails repurposing AWM as a lever for integrated socio-ecological transformation, grounded in inclusive governance, spatial and temporal hydrological limits, and a redistributive ethic that privileges long-term resilience over short-term gains. *Thinking beyond water* represents a shift from incremental gains towards transformative change achieved through multiscale coordination, participatory planning and embedded accountability mechanisms. This shift is oriented towards water futures that remain within ecological limits while supporting social foundations. Realising this reorientation requires examining how established analytical approaches can be linked more systematically to these criteria, a topic addressed in the following section.

### 3 | Building on Systems and Nexus Advances: Externalities, Trade-Offs and Plural Knowledge

Sections 1 and 2 have argued for a conceptual reorientation of AWM towards equity, resilience and sustainability; however, translating this vision into practice remains constrained by the uneven institutionalisation of existing approaches and their incomplete linkage to distributional and ecological criteria. Substantial advances in nexus thinking, systems dynamics, integrated assessment and participatory governance have already extended AWM well beyond volumetric efficiency. Their application, however, remains uneven across contexts, and their systematic linkage to criteria for distributive justice and explicit ecological thresholds remains incomplete. This section examines three areas in which that linkage can be strengthened. Specifically, we draw on established systems based approaches to mapping externalities, tools for modelling trade-offs and feedback loops and participatory diagnostics for marginalised water users. These are established methods; this paper proposes their consistent application under explicit justice and threshold criteria, recasting AWM as a dynamic, relational and contested domain that demands integrated, justice oriented approaches.

#### 3.1 | Systems Mapping of AWM Externalities

Cross-scale externalities are well-documented in the AWM literature. Still, they are inconsistently reflected in scheme level planning and appraisal, particularly when water savings at one scale lead to overuse or inequity at another. Established systems-mapping tools, including causal loop diagrams (CLDs) and Bayesian belief networks, provide a structured approach to visualising and interrogating these interactions. For example, efficiency gains at the field level may result in rebound effects, enabling expansion of irrigated area and exacerbating groundwater depletion at river basin scale (Grafton et al. 2018; Apostolaki et al. 2019; Lankford and Scott 2023). Similarly, infrastructure-focused schemes frequently exclude informal irrigation actors, reinforcing institutional blind spots even in polycentric water governance (Bruns 2017). Systems mapping reveals reinforcing and balancing loops that shape these dynamics, including those related to pricing, land tenure and political economy. Incorporating spatialized systems models that account for evapotranspiration, land use and ecosystem service flows is vital to building a more integrated *thinking beyond water* AWM framework (Stermann 2002; Jakeman et al. 2006).

### 3.2 | Integrating Established Trade-Off and Feedback Approaches Within *Thinking Beyond Water*

Agricultural water (AW) use is embedded in larger systems, including the nested and diverse agro-eco-systems comprising natural and human systems (Mutiro et al. 2017; Uhlenbrook et al. 2022; Smith et al. 2024). Also, agriculture and AW are multiscalar concepts and problems of the WEF nexus (Hamidov et al. 2022). It is expected that AWM interventions should generate multidimensional trade-offs between upstream and downstream users, short-term gains and long-term ecosystem health or equity and efficiency. These multiscalar, cross-sectoral dynamic trade-offs are not captured by the single-criterion appraisal that remains common at the point of investment approval. Trade-off matrices and multicriteria decision analysis (MCDA) approaches are increasingly used to evaluate scenarios across ecological, economic and social performance metrics (Nouri et al. 2019; Okura et al. 2022). For example, prioritising water for high-value export crops may boost gross domestic product (GDP) but reduce local food security or exacerbate gender disparities in access to water. Feedback loops further complicate these trade-offs. Declining groundwater tables, for instance, drive rising energy use for pumping, which contributes to both economic costs and emissions (Qiu et al. 2018; Singh et al. 2021; Koushki et al. 2024). Integrating agent-based models, systems dynamics modelling and resilience metrics allows for more robust planning under uncertainty, making explicit the pathways through which AWM either reinforces or mitigates systemic vulnerability. These approaches are not new to AWM. Systems dynamics, MCDA and agent-based modelling have been applied extensively, including within nexus frameworks, and their treatment of feedback loops and intersectoral trade-offs is well-developed. The contribution proposed here is not methodological novelty but the consistent application of these tools under explicit justice criteria, published ecological thresholds and participatory decision rules.

### 3.3 | Stakeholder Narratives From Underrepresented Communities

*Thinking beyond water* requires reframing AWM not just as a technical or ecological challenge but as a pluralistic governance issue that must integrate lived experiences, power asymmetries and social histories (Beaumont and Nicholls 2008; Brown et al. 2015; Murphy 2024). Participatory diagnostics such as citizen observatories, participatory rural appraisal (PRA) or narrative-based modelling are vital tools for eliciting local perspectives, particularly those of marginalised groups (Cornwall 2008). In many regions, resource-constrained informal irrigation actors, such as women farmers, pastoralists, youth and people with disabilities, are not visible in National water registries but are essential to achieving water security outcomes (van Koppen 1998). Their exclusion often results in inappropriate infrastructure designs or enforcement regimes. By embedding situated knowledge into the design and monitoring of AWM, co-production fosters not only local legitimacy but also greater adaptability and learning in the face of climatic and institutional uncertainty (Lemos and Morehouse 2005; Chambers 2007).

Together, these theoretical and empirical advancements underscore the imperative to reconceptualise AWM as a complex, adaptive system shaped by feedbacks, trade-offs and socio-political asymmetries that conventional approaches often fail to capture (Figure 3). Systems mapping of externalities exposes the hidden consequences of narrowly framed sectoral/siloed interventions. At the same time, trade-off models underscore the need for deliberative, multicriteria planning that considers competing objectives across time and space. Crucially, integrating inclusive narratives and participatory diagnostics ensures that the lived realities of marginalised water users, often absent from data and decision spaces, are embedded into both problem framing and solution design.

This consolidation (Figure 3) of systems science, modelling and co-produced knowledge provides the conceptual scaffolding for *thinking beyond water*. On this basis, AWM can be treated as a relational entry point through which equity, resilience and ecological limits enter water-related decisions. Section 4 examines the governance, knowledge and transition conditions on which that depends. Where these diagnostics enter the decision process is specified in Section 5.3:

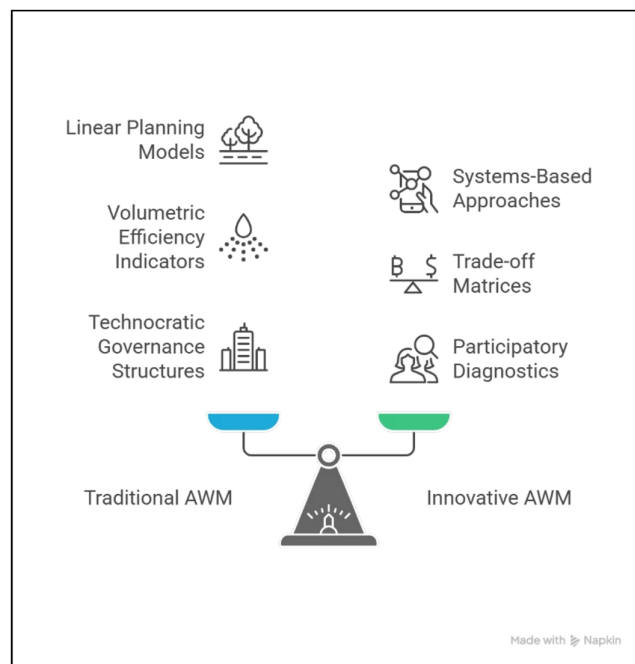


**FIGURE 3** | Reframing agricultural water management: from traditional paradigms to systems innovation Traditional AWM is typified by linear planning models, volumetric efficiency indicators and technocratic governance structures, reflecting a technocentric and infrastructure heavy approach focused primarily on maximising water use efficiency at the plot or scheme level. While historically effective in structured irrigation contexts, such models often overlook broader system dynamics, socio-institutional complexity and environmental trade-offs. Innovative AWM embraces a systems-based approach, integrating multiscalar trade-off matrices and participatory diagnostics to navigate better the interlinkages among water, ecosystems, energy, food production and equity. This shift reflects a growing recognition of AWM as a systems catalyst rather than a sectoral intervention, one that requires tools to support co-design, resilience building and sustainable water futures.

stakeholder identification and problem framing at step one, negotiation of criterion weights at step three and monitoring accountability at step six.

#### 4 | AWM as a Systems Catalyst: Multiscalar and Transdisciplinary Approaches for Practice-Oriented System Change

*Thinking beyond water* treats AWM as a domain that operates across multiple spatial, temporal and disciplinary scales. From the microbial dynamics of soil moisture regimes to the geopolitics of virtual water trade, AWM both shapes and is shaped by interactions spanning ecology, technology, finance and social foundations, including equity. This section examines three conditions under which those interactions can be reflected in practice rather than only in analysis: governance arrangements that distribute decision rights among the actors affected (Section 4.1); knowledge and data systems accessible to, and maintained by, the users who generate them (Section 4.2); and transition measures specifying who bears the costs of change and who is protected from them (Section 4.3). Figure 4 sets out how these elements relate. Biophysical intelligence provides the empirical basis for spatial targeting and risk assessment; institutional innovation determines whether that evidence reaches decisions, and just transition principles govern how the

resulting benefits and costs are distributed. None of the three is sufficient alone, and the practical difficulty in AWM lies less in any one of them than in sustaining all three together.

##### 4.1 | Co-Creation and Governance

Shifting from consultative irrigation to co-produced water futures reframes AWM as a systems catalyst, facilitating a transformation from top-down decision-making to dynamic, polycentric co-creation. Irrigation governance often operates through formal institutions, such as irrigation management committees or line ministries that may not engage with informal actors and customary water users, particularly in pluralistic legal systems. The *thinking beyond water* paradigm emphasises governance as an emergent property of relational, iterative and context specific processes involving multiple stakeholders, including farmers, extension agents, local leaders, river basin authorities and private sector actors. Transdisciplinary co-design platforms, such as water dialogues, for example, WaterNET, scenario planning workshops, such as the University of KwaZulu-Natal and its strategic partners organised WEF nexus winter schools, and actor network mapping can be used to surface conflicting goals on productivity versus ecosystem health and mediate trade-offs among users with differentiated access to power, voice and knowledge (Pahl-Wostl 2009). Importantly,

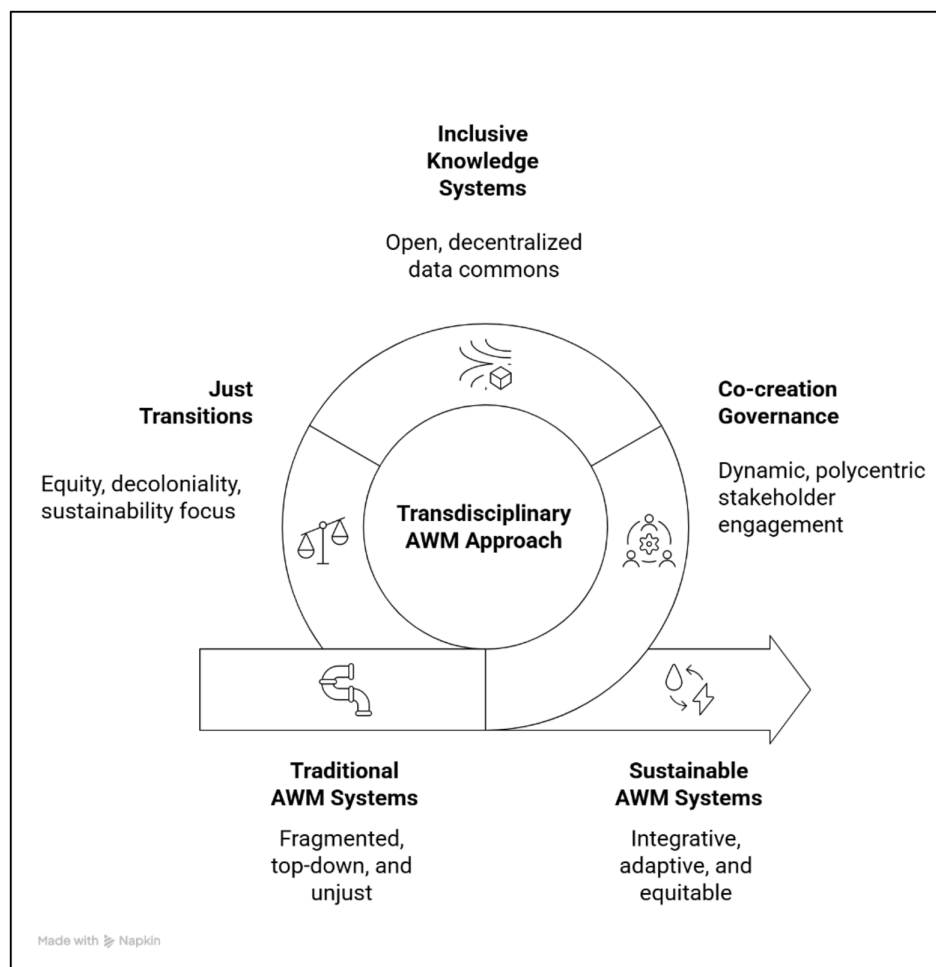


**FIGURE 4** | Towards integrated agricultural water management: linking biophysical intelligence, institutional innovation and just transitions.

effective co-creation requires attention to social power dynamics (Chambers 2007; Beaumont and Nicholls 2008; Brown et al. 2015; de Loë and Patterson 2017). For instance, women and tenant farmers are frequently excluded from water users associations, despite being principal water users in many contexts. Operationalising this requires three specifications that are frequently left implicit: which body convenes the process and at what planning scale; which participants hold decision rights as distinct from advisory voice; and what procedure applies where participants disagree, since consensus requirements can entrench the position of incumbent users (Meinzen-Dick et al. 2002). External partnerships and hybrid institutions are equally critical because they can facilitate knowledge brokering, link local practices to National policies and build trust in contested landscapes. This co-creation approach establishes AWM as a tool for governing the commons, one that requires collective stewardship, iterative learning and multilevel accountability.

## 4.2 | Knowledge Systems and Data Commons

To effectively reframe AWM and link it to safe operating environments for planetary health, we need to shift from data silos to inclusive intelligence for water justice. Effective decision-making is hinged on the quality, accessibility and integration (Stephenson et al. 2017) of data across hydrological, agronomic, social and economic domains (Stephenson et al. 2017; MacDonald 2025). However, many data ecosystems remain fragmented, proprietary or mismatched with on-the-ground decision needs. The shift towards *thinking beyond water* requires a shift towards open, decentralised and inclusive knowledge systems. This implies a transition from traditional expert-driven paradigms to commons-based information architectures, anchored in transparency, reciprocity and local empowerment (Buytaert et al. 2014; Fritz et al. 2019).

Innovations in citizen science (Buytaert et al. 2014; Fritz et al. 2019; Loghmani-Khouzani et al. 2024), mobile sensing and real-time feedback mechanisms are rapidly changing how irrigation data are generated and used. Initiatives such as Akvo Flow (Lama and Khatri 2014), WaterWatch (Dyer et al. 2014) and the Trans-African Hydro-Meteorological Observatory (TAHMO) (van de Giesen et al. 2009; van de Giesen et al. 2013) have demonstrated the value of combining local knowledge with sensor based hydrometeorological data for adaptive irrigation planning. However, such tools must be designed for interoperability, contextual relevance and digital inclusivity, especially given the gendered digital divide and literacy constraints in many rural areas (Wyche and Steinfield 2016; Anadozie et al. 2022). Emerging technologies such as AI and remote sensing (e.g., soil moisture modelling and evapotranspiration estimates from Sentinel-2 and MODIS) offer significant potential. However, the technologies must be aligned with locally defined priorities, transparent algorithmic governance and feedback-informed learning cycles.

Building robust, open access data commons for AWM involves investing in interoperable GIS platforms, National irrigation observatories, FAIR (Findable, Accessible, Interoperable, Reusable), data protocols (Dumontier and Wesley 2018; Inau

et al. 2021) and cross-sectoral learning networks. These commons must be governed not only by technical standards but also by ethical norms that uphold equity, inclusivity and data sovereignty, especially for indigenous and marginal communities. Four questions determine whether such commons persist beyond project funding: who owns the data, who hosts and maintains the platform, who finances that maintenance once establishment funding ends and who may access which level of data. Answering them requires a named custodian institution, a minimum data specification agreed with the users who generate it, interoperability standards and access rules that distinguish open aggregate data from information identifying individual users or holdings. In short, the future of AWM data systems is not just digital; it is relational, distributed and justice oriented.

## 4.3 | AWM and Just Transitions

Linking irrigation futures with equity, decoloniality and sustainability is equally important for accelerating the deployment of AWM technologies, including solar irrigation and micro-irrigation systems, as well as climate smart infrastructure. These technologies offer promise for boosting resilience under climate stress. Deliberate social equity designs are needed to prevent existing injustices. The “just transition” lens challenges us to align technological transformation in AWM with broader goals of inclusion, fairness and historical redress. This means paying attention to who gains, who loses and who decides—questions that are often sidelined in water planning.

Irrigation schemes frequently displace indigenous and pastoralist communities, marginalising women's water rights (van Koppen 1998), or impose extractive cost-recovery models that are incompatible with local livelihoods (Easter and Liu 2005; Cortignani et al. 2018). In many cases, elite capture of irrigation benefits reflects deep rooted legacies of colonial land–water regimes (e.g., Zimbabwe, India, Egypt). AWM as a catalyst for just transitions thus demands redistributive water policies, land tenure reform, gender responsive financing and participatory regulatory frameworks (Schlosberg 2007; Newell and Mulvaney 2013). These mechanisms need to be embedded within National climate strategies and aligned with frameworks such as the Global Goal on Adaptation of the United Nations Framework Convention on Climate Change (UNFCCC) or the Comprehensive Africa Agriculture Development Programme (CAADP) of the African Union. At the operational level, transitions in AWM involve the following:

- subsidising low-carbon irrigation access for poor households;
- ensuring secure customary land and water rights;
- embedding environmental justice metrics in water allocation decisions;
- enabling alternative governance forms like water cooperatives and user-owned service models.

A distinction should be drawn between measures within the mandate of AWM institutions—water allocation rules, scheme governance arrangements, tariff and subsidy design,

irrigation investment priorities and technology support—and those requiring coordination with other sectors, including land tenure reform, social protection, energy pricing, trade and employment policy. The first can be pursued through the appraisal and planning processes set out in Section 5; the second requires AWM institutions to act as one participant among several. Conflating the two overstates what water agencies can deliver and obscures where responsibility for delivery actually lies.

This orientation is especially critical in dryland and postcolonial contexts, where irrigation development has historically reflected extractive approaches rather than regenerative justice. Attention to justice in AWM supports outcomes in which water contributes to both equity and productivity. Realising these transitions depends on the institutional and financial arrangements through which AWM investments are appraised, financed and monitored, which the following section examines.

Biophysical intelligence emphasises leveraging high-resolution data on water availability, soil health and agro-ecological variability to inform adaptive irrigation practices. This includes digital diagnostics such as remote sensing, IoT, crop-water modelling and groundwater monitoring. This forms the empirical foundation for spatial targeting and risk mitigation. Institutional Innovation, on the other hand, calls for rethinking governance, finance and policy arrangements to align with decentralised, inclusive and adaptive water management. Key shifts include blended finance, incentive-aligned delivery models, co-investment mechanisms and regulatory agility that enables scalability and sustainability. Just transitions embed principles of equity, inclusion and social justice in water planning. It promotes participatory approaches, local capacity-building and mechanisms to address historical disparities in water access and climate vulnerability, especially for women, youth and marginalised communities.

## 5 | Implications for Policy, Innovation and Financing

The preceding sections have argued that AWM needs to be assessed against ecological limits and questions of equity alongside more conventional measures of productivity and efficiency. The critical binder is the mechanism by which these considerations are incorporated into actual investment and planning decisions. Multicriteria analysis, systems modelling, composite indicators and participatory methods are already well-established and, in some contexts, routinely applied. The difficulty is that their use remains uneven, particularly at the points where irrigation investments are appraised, financed and approved. The practical challenge, therefore, is not simply to introduce more methods but to strengthen the connection between available evidence and the institutions that make decisions. This section considers three areas where such a shift could be made: how irrigation investments are appraised, how different financing instruments are matched to the problems they are intended to solve and how National Irrigation Plans (NIP) can progressively incorporate ecological, social and institutional considerations.

### 5.1 | Redefining Value: From Cost–Benefit to Systemic Appraisal

Narrow, engineering-centric metrics such as infrastructure cost per hectare irrigated, or benefit–cost ratios based solely on yield increases, and water savings dominate cost–benefit analysis (CBA) in AWM (Helming et al. 2013; McCarthy et al. 2023). These measures remain useful, but they provide only a partial account of whether an investment is desirable. This limitation has long been recognised. True cost accounting, natural capital approaches, MCDA and WEF nexus indicators have all been used to broaden irrigation assessment, including in Southern Africa (The Economics of Ecosystems and Biodiversity (TEEB) 2018; Taguta et al. 2022). The more important question, therefore, is not whether these methods exist, but whether they are used in ways that meaningfully influence investment decisions. In practice, such assessments are often undertaken as part of research projects or after implementation, rather than being incorporated into appraisal processes from the beginning. Even when multidimensional assessments are conducted ex ante, the use of aggregate scores can mask important trade-offs. A project may, for example, receive a favourable overall score because of strong projected productivity, despite poor environmental or distributional outcomes that could create significant risks.

A more robust approach is to distinguish between factors that can be weighed against one another and those that should be treated as minimum requirements. Water abstraction beyond an agreed sustainable limit, for instance, should not be justified simply because a project is expected to generate strong economic returns. Similar minimum conditions could apply to EFRs, affordability and agreed standards for participation and equitable access. Table 1 presents one way in which this type of appraisal could be organised. It is not intended to prescribe universal thresholds. Appropriate limits for environmental flows, groundwater abstraction, affordability and equity will depend on local conditions and need to be determined through National, river basin level or scheme level processes. The matrix aims to ensure that these issues are explicitly considered during appraisal and that they have a clear bearing on the eventual investment decision.

The level of appraisal should nevertheless be proportionate to the scale and risk of the investment. A large public irrigation scheme can expect to undergo a detailed assessment across hydrological, ecological, social and financial dimensions. Applying the same requirement to every small, dispersed irrigation investment would quickly become impractical. A simpler screening process is more appropriate for smaller investments, with fuller assessment undertaken at the programme level.

The institutional location of the assessment is equally important. River basin authorities are generally better placed to establish and monitor hydrological and ecological thresholds, while irrigation agencies are responsible for the design and performance of investments. The intention is not to create another parallel assessment process but to link the information already generated by these institutions more directly to approval and subsequent monitoring.

**TABLE 1** | A systemic appraisal matrix for AWM investment decisions, distinguishing screened (threshold) criteria from scored (weighted) criteria.

| Appraisal dimension      | Indicator                                                                                                              | Reference threshold                                                                             | Data source                                                      | Scale               | Decision rule              |
|--------------------------|------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|------------------------------------------------------------------|---------------------|----------------------------|
| Water sustainability     | Ratio of abstraction to renewable supply attributable to the scheme                                                    | At or below the published sustainable yield for the aquifer or allocation ceiling for the reach | Piezometric monitoring; recharge estimation; abstraction records | Aquifer/river basin | Screen                     |
| Ecological integrity     | Proportion of time environmental flow requirements are met downstream of abstraction                                   | River basin or regulatory EFR standard                                                          | Gauging records; hydrological model                              | Reach/river basin   | Screen                     |
| Distributional equity    | Share of command area and of delivered volume accruing to women, tenant farmers, youth and customary users             | Agreed minimum floor, set nationally or at scheme level                                         | Scheme registers; household survey                               | Scheme              | Screen (floor), then score |
| Procedural inclusion     | Proportion of affected user categories holding decision rights in the scheme governance body                           | Defined participation standard                                                                  | Governance records; membership rolls                             | Scheme/river basin  | Screen                     |
| Affordability            | Tariff and repayment obligation as a proportion of net farm income for the lowest quartile of participating households | Affordability ceiling set at appraisal                                                          | Financial model; farm budget survey                              | Household/scheme    | Screen                     |
| Water productivity       | Physical and economic water productivity per unit of water consumed                                                    | Context specific benchmark                                                                      | Scheme records; remote sensing evapotranspiration estimates      | Field/scheme        | Score                      |
| Resilience               | Reliability of supply under a defined dry-year scenario                                                                | Scenario reliability threshold                                                                  | Hydrological scenario modelling                                  | Scheme/river basin  | Score                      |
| Livelihood and nutrition | Change in net household income; dietary diversity among participating households                                       | No decline against baseline                                                                     | Baseline and panel survey                                        | Household           | Score                      |
| Energy and emissions     | Emissions intensity per unit of output, inclusive of pumping energy                                                    | Declining trajectory against baseline                                                           | Energy consumption records; emission factors                     | Scheme              | Score                      |
| Fiscal sustainability    | Net present value, inclusive of full operation and maintenance provision                                               | Financing criterion of the approving authority                                                  | Financial model                                                  | Project             | Score                      |

## 5.2 | Financing Change: From Infrastructure to Institutional Capital

AWM investments have historically been heavily skewed towards grey infrastructure, such as dams, canals and pumps, reflecting a 20th century logic of hydraulic mission and yield maximisation. While infrastructure remains vital, there exist challenges in failure to adequately finance the institutions, regulatory capacity, adaptive governance and services required to make it work (Horst 1998; Horst 1999). This is a critical blind spot, particularly in climate vulnerable regions where social capital and institutional flexibility often determine long-term water resilience. In many Sub-Saharan African contexts, underfunded water users associations, ill-equipped extension services (Dirwai et al. 2024) and poorly enforced water rights laws undermine the very performance of irrigation hardware (Boelens 2009; Meinzen-Dick 2014).

Blended finance is defined as the strategic use of public or philanthropic capital to mobilise private sector investment (Pereira 2017; Attridge and Engen 2019; Anshori et al. 2023). Blended finance offers a promising approach to redressing this imbalance. To unlock its full potential in AWM, blended finance must go beyond infrastructure derisking to support the “soft systems” that underpin sustainability. Targeted funding in participatory planning processes, performance based subsidies for inclusive governance and community led monitoring frameworks can catalyse soft skills training for sustainability. Mechanisms such as Irrigation-as-a-Service (IaaS), PAYGO solar irrigation (Lefore et al. 2021) and results based climate adaptation financing (e.g., performance frameworks of the Green Climate Fund [GCF]) demonstrate scalable models that combine technological diffusion with social safeguards. Moreover, innovative investment instruments such as impact bonds, resilience scorecard linked disbursements and ecosystem service payments (e.g., upstream river basin protection for downstream water reliability) need to be prioritised. Rigorous safeguards and co-designed governance arrangements must accompany these to prevent elite capture (Food and Agriculture Organisation of the United Nations (FAO) and the International Fund for Agricultural Development (IFAD) 2022). The success of blended finance hinges on rethinking value beyond return on investment (ROI) to include return on resilience, return on equity and return on planetary stability. Table 2 links common financing instruments to the barriers they are intended to address and, importantly, to some of the risks that accompany their use.

The larger point is that not every component of a functioning irrigation system can or should be made commercially bankable. Regulatory capacity, extension, participatory planning, monitoring and the routine functioning of water users institutions often generate broad public benefits without producing a direct revenue stream. They will therefore continue to require public expenditure. Blended finance can complement this public investment. It can help spread the upfront cost of technologies, reduce selected risks or link financing to clearly defined outcomes. It cannot substitute for the recurrent financing needed to maintain institutions. This distinction matters because otherwise an emphasis on innovative finance may shift attention away from the less visible institutional expenditure on which irrigation performance ultimately depends.

## 5.3 | Planning for Transformation: Reorienting NIP for Systems Resilience

NIP remain important instruments for coordinating public investment in AW infrastructure. Their utility differs across regions and countries. Some already incorporate environmental flow provisions, water allocation limits, participatory planning and broader resilience objectives. In other contexts, particularly where irrigation expansion remains a central development objective, planning continues to be strongly organised around infrastructure, hectares developed, water supplied and capital cost. Therefore, we argue that the existing NIPs should not be replaced but that they should progressively incorporate ecological limits, distributional considerations, institutional capacity and mechanisms for adaptation alongside conventional engineering and economic objectives (FAO 2021).

Reorientation requires a comprehensive assessment of the irrigation system and the wider water context within which it operates, led by the National irrigation agency in conjunction with the relevant river basin authority and published as a diagnostic baseline. This assessment needs to cover available water, current abstraction, existing infrastructure and its condition, institutional responsibilities and financing arrangements, as well as the distribution of access to irrigation water. Importantly, the diagnosis needs to extend beyond formal registers to identify customary, informal and otherwise poorly represented users. Where formal registers are treated as the sole representation of the irrigation system, existing inequalities may be reproduced because some users remain invisible in both planning and investment decisions.

The ecological and social conditions within which irrigation development can proceed should then be defined explicitly. River basin institutions are generally best placed to establish hydrological limits, such as EFRs, groundwater abstraction ceilings and sustainable allocation levels, while National irrigation and agricultural authorities define objectives related to food production, affordability, equitable access and livelihood outcomes. These thresholds and objectives would have to be part of project screening and appraisal before financial commitments are made. This also implies that the thresholds and the evidence used to establish them are published rather than retained as internal technical parameters. A threshold that exists in policy but has no consequence for an investment decision does little to alter planning practice.

River basin institutions, working with the irrigation agency, need to convene to develop planning options with farmers, water users associations, traditional authorities, private operators and relevant government agencies. These actors may pursue different objectives and experience very different costs and benefits from irrigation development. Engaging them before preferred options are fixed allows these differences to shape the alternatives under consideration rather than merely being recorded after decisions have been made. This stage is also the point at which the relative importance assigned to scored appraisal criteria can be discussed and negotiated rather than determined administratively. The resulting option set should therefore document not only the alternatives considered but also the agreed weighting of appraisal criteria and any substantive

**TABLE 2** | Financing instruments for AWM, the barriers they address and associated safeguards.

| <b>Instrument</b>                                          | <b>Barrier addressed</b>                                                   | <b>Actors</b>                                                                  | <b>What it funds</b>                                                                | <b>Required safeguard</b>                                                                       | <b>Characteristic failure mode</b>                                                         |
|------------------------------------------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| Concessional blending and first-loss guarantees            | Perceived risk deters commercial capital from smallholder irrigation       | Development finance institution; treasury; commercial lender; service provider | Capital cost; risk cover                                                            | Additionality test; distributional screen on beneficiary profile                                | Subsidising investment that would have proceeded regardless, capture by larger landholders |
| Asset finance and PAYGO for solar irrigation               | Upfront cost exceeds household liquidity                                   | Equipment supplier; microfinance institution; farmer                           | Pump and system cost spread across the productive life of the asset                 | Transparent pricing; repossession rules; abstraction conditionality where aquifers are stressed | Household debt distress; unregulated expansion of groundwater abstraction                  |
| Irrigation-as-a-Service                                    | Operation, maintenance and spare parts capability gap                      | Service provider; water users association; farmers; regulator                  | Service delivery and maintenance under contract                                     | Service-level agreement; tariff oversight; handover and exit provisions                         | Provider monopoly; tariff escalation; loss of local capability                             |
| Results-based and outcome-linked disbursement              | Weak incentives to deliver nonhardware outcomes                            | Donor or treasury; implementing agency; independent verifier                   | Verified outcomes such as supply reliability, equity of delivery and EFR compliance | Independent verification; indicator review to detect gaming                                     | Measurable proxies displace outcomes that are harder to measure                            |
| Payments for ecosystem services and river basin investment | Upstream land use imposes uncompensated downstream costs                   | Downstream water users, upstream land users, river basin authority             | Upstream land management practice                                                   | Tenure security as a precondition; monitoring; anticapture provisions                           | Payments accrue to titled landholders while informal users bear costs                      |
| Recurrent public financing of institutional capital        | Chronic underfunding of associations, extension, regulation and monitoring | Treasury; ministry; river basin authority                                      | Staffing, training, monitoring systems, participatory processes                     | Ring-fenced budget line; published expenditure tracking                                         | First expenditure category cut under fiscal stress                                         |
| Impact bonds and resilience-linked disbursement            | Long payback horizon on resilience outcomes                                | Outcome funder; investor; implementing agency; evaluator                       | Outcome payments against agreed resilience metrics                                  | Clear attribution; independent evaluation                                                       | Transaction costs disproportionate to scheme size                                          |

areas of disagreement. Participation in this sense is not consultation for its own sake; it improves the evidence available to planners and makes visible whose priorities, risks and trade-offs are reflected in the eventual plan.

The resulting options need to be assessed using hydrological and economic analysis alongside ecological, distributional, affordability, resilience and institutional criteria. The systemic appraisal proposed in Table 1 provides one possible structure for doing this. Established approaches such as MCDA and systems modelling are useful at this stage because they allow competing objectives to be considered together while preserving those ecological and social conditions that should not be treated as fully compensable. The distinction between screened and scored criteria is particularly important. A proposal that exceeds an agreed abstraction limit, for example, should not become acceptable simply because it generates high economic returns. The purpose is not to introduce another analytical layer but to ensure that information already generated through hydrological, social and economic assessment is recorded in the documentation on which investment approval is based, including the outcome of each screened criterion.

Financing would have to follow appraisal rather than determining the plan in advance. Different constraints require different financing responses. Capital intensive infrastructure may warrant public investment, concessional finance or blended instruments, while constraints in technology access and service delivery may be addressed through asset finance or service-based models. Institutional functions such as regulation, extension, monitoring, water users organisation and participatory planning, however, often generate public benefits without a direct revenue stream and therefore require recurrent public financing. A credible NIP needs to consequently distinguish between capital expenditure and the continuing institutional expenditure required to sustain the performance of that capital, while also identifying the agency accountable for financing and delivering each component. This is important because securing funds for infrastructure without adequately financing operation, monitoring, extension or governance may transfer the constraint from construction to implementation.

Indicators used during appraisal should continue to be monitored once investments have been implemented, particularly those relating to abstraction, environmental flows, affordability, reliability and the distribution of benefits. Monitoring has limited value if threshold breaches merely generate additional reporting. NIPs should therefore specify in advance the conditions under which allocations, operating rules, financing arrangements or future investment priorities will be reviewed, along with the frequency of monitoring and the office responsible for initiating the review. Such predefined triggers create a feedback mechanism through which plans can respond to changing hydrological conditions, institutional performance and emerging evidence rather than remaining fixed for the duration of a planning cycle.

These steps are unlikely to be implemented uniformly or immediately. Institutional responsibilities for agriculture, water, land and the environment are often distributed across agencies that do not necessarily plan or budget together. Technical and financial capacity also varies considerably across countries

and river basins. Hydrological and socio-economic data may be incomplete, abstraction may remain poorly measured and the transaction costs of participation can fall disproportionately on users with the least time and resources. Existing water rights may favour incumbent users and be politically difficult to renegotiate, while political and budget cycles are often substantially shorter than the periods over which resilience and ecological benefits become visible. These constraints do not invalidate the approach, but they determine both the pace and the form of implementation, making wholesale institutional redesign unrealistic in many settings.

A staged approach is therefore more practical. An initial tier could apply a small set of core screening requirements to new investments, including sustainable water availability, EFRs, affordability and minimum equity and procedural inclusion provisions. Even where detailed social data are not yet available, proposals would have to at least disclose who is expected to receive water and other benefits, which user groups are excluded or underrepresented and who holds formal decision rights. This preserves equity and participation as noncompensatory considerations from the outset rather than postponing them until better data become available. As users register, monitoring systems and governance arrangements improve; these minimum requirements can be strengthened through more disaggregated distributional indicators and clearer participation standards. A later tier can introduce full multicriteria appraisal, adaptive management triggers and outcome linked financing as analytical and institutional capacity develops.

Such sequencing is important because it avoids making institutional sophistication a precondition for reform. The elements that are most consequential and relatively feasible can be introduced first, while more data-intensive and administratively demanding components develop over time. It also allows NIPs to evolve from predominantly investment-oriented plans towards adaptive planning instruments in which engineering performance, ecological sustainability, equity and institutional viability are considered together.

This reorientation does not require abandoning established irrigation planning practice. Rather, it builds on advances already evident in contemporary water and irrigation management and strengthens the links among diagnosis, appraisal, financing, implementation and learning. In this sense, *thinking beyond water* is less a call for an entirely new planning model than for the more systematic institutionalisation of considerations already recognised but often remain disconnected within AWM decision-making.

## 6 | Conclusions and Recommendations

Contemporary AWM already encompasses substantial advances in systems, institutions and nexus. *Thinking beyond water* builds on these by making explicit the links between water decisions, ecological thresholds, distributive justice and the institutional and financial conditions required for implementation. Where appraisal remains anchored primarily in volumetric efficiency, infrastructure expansion and output maximisation, important relationships between water use, ecological limits, the

**TABLE 3** | Recommended operational priorities for implementing *thinking beyond water* in AWM.

| Principle             | Operational action                                                                                                                                                | Lead actor                                                                   | Instrument                                                    | Indicator                                                                                                     | Scale                | Principal constraint                                                                     |
|-----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|----------------------|------------------------------------------------------------------------------------------|
| Ecological thresholds | Screen proposed investments against published abstraction limits and environmental flow requirements before approval                                              | River basin authority with irrigation agency                                 | Screened criteria in Table 1                                  | Proportion of investment approvals with completed threshold screening                                         | River basin          | Thresholds absent, contested or weakly enforced                                          |
| Systemic appraisal    | Apply screened and scored criteria during concept development and formal appraisal, with results recorded in approval documentation                               | Irrigation agency and approving authority                                    | Table 1 appraisal matrix; MCDA with noncompensatory screens   | Share of investment value subjected to systemic appraisal                                                     | Project/scheme       | Analytical capacity and transaction costs                                                |
| Resource justice      | Establish and publish minimum standards for access and participation for women, tenant farmers, youth, customary users and other poorly represented groups        | National irrigation authority with scheme level institutions                 | Equity and participation criteria within investment screening | Distribution of command area and delivered water across user categories                                       | Scheme               | Informal and customary users are absent from formal registers                            |
| Adaptive planning     | Define in advance the conditions under which changes in water availability or performance trigger review of allocations, operating rules or investment priorities | Irrigation agency with river basin authority                                 | Trigger framework embedded within the NIP                     | Proportion of threshold breaches resulting in the prescribed management review                                | River basin/national | Political and planning cycles shorter than resilience horizons                           |
| Financing design      | Match financing instruments to the specific barrier being addressed and specify the corresponding safeguards at the point of selection                            | Responsible ministry with development finance partners and service providers | Instrument mapping in Table 2                                 | Share of financed components with corresponding safeguards documented                                         | Project/national     | Instrument selection driven by available capital rather than the barrier being addressed |
| Institutional capital | Budget recurrent expenditure for regulation, monitoring, extension and water users institutions separately from infrastructure expenditure                        | Treasury and responsible ministry                                            | Dedicated recurrent budget provision                          | Recurrent institutional expenditure relative to infrastructure investment and agreed operational requirements | National/scheme      | Institutional expenditure vulnerable to fiscal cuts                                      |
| Data commons          | Establish clear responsibility for data custodianship, access, interoperability and long-term maintenance                                                         | Designated National or river basin data custodian                            | Data-governance agreement; FAIR data principles               | Proportion of priority AWM datasets under active custodianship with funded maintenance                        | National/river basin | Sustained financing, interoperability and data-sovereignty concerns                      |

distribution of benefits and risks and institutional capacity can remain weakly connected in decision-making.

*Thinking beyond water* consequently positions AWM as a systems connector across water, food, energy, ecosystems, health, finance and governance. Its contribution lies less in proposing new analytical methods than in bringing established approaches into a common decision framework. Ecological thresholds in this framing provide an operational expression, at river basin and aquifer scales, of the planetary boundaries and social foundations discussed in Section 2.3: broader ecological limits are translated into allocation ceilings, EFRs and other thresholds against which specific AWM decisions can be assessed. This requires moving beyond treating equity, resilience and environmental integrity as desirable co-benefits and specifying where they enter the planning process, which institutions are responsible for them, how the costs and benefits of the transition are distributed among water users and how performance is assessed.

The same systems perspective provides an entry point for reconnecting AWM with human health. Water management decisions influence not only agricultural production but also water quality, exposure to contaminated irrigation or wastewater, food and nutrition outcomes, and the integrity of ecosystems on which human well-being depends. These relationships should not be interpreted as implying that AWM determines planetary or human health outcomes on its own. Rather, they show how AW decisions contribute to health-related outcomes within wider food, environmental and socio-economic systems. AWM can thereby contribute to the water-mediated dimensions of water insecurity, ecological degradation and social exclusion, while recognising that the determinants of these conditions extend well beyond the sector.

The operational implication is that change need not begin with wholesale institutional redesign. Section 5 provides practical entry points that leverage existing planning and investment processes. Ecological limits can be incorporated as screening criteria before investment approval; distributional and procedural considerations can be included within appraisal; financing instruments can be matched more deliberately to the barriers they are intended to address; recurrent institutional expenditure can be distinguished from infrastructure finance, and NIP can incorporate explicit feedback mechanisms that link monitoring to management action. Section 5.3 further sets out how these entry points can be sequenced, beginning with a limited set of nonnegotiable screening criteria applied using existing information and extending as registers, monitoring systems and institutional capacity develop. Importantly, minimum equity and procedural inclusion requirements remain part of the initial screening stage, even where more disaggregated indicators can only be introduced later. In this sense, the framework seeks to strengthen the institutionalisation of existing knowledge rather than replace established AWM practice.

Three limitations are important. First, *thinking beyond water* is a conceptual and integrative framework rather than an empirically validated model, and the propositions advanced here have not yet been systematically tested through implementation. Second, its operational form will necessarily vary across hydrological, institutional and political contexts. EFRs, abstraction

limits, affordability criteria and equity thresholds cannot be derived from the framework itself; they must be established through appropriate National, river basin and local processes. Third, many determinants of planetary health, social justice and resilience—including trade, industry, energy, land policy and broader political economic conditions—lie outside the mandate of AWM institutions. The framework, therefore, positions AWM as an entry point for coordinated action rather than as a sufficient mechanism for achieving these outcomes.

The practical implications of the framework are consolidated in Table 3. Rather than presenting recommendations as general imperatives, the table identifies the required action, the institutions responsible, the instrument through which the action can be implemented, an indicator for assessing progress and the principal constraint likely to affect implementation.

These priorities are mutually reinforcing. Ecological thresholds have little effect if they are not linked to investment approval; systemic appraisal is weakened when important users remain absent from the underlying data; financing instruments can create new risks when they are selected without reference to the barrier they are intended to address; adaptive planning depends on monitoring systems that are adequately financed; and infrastructure investment cannot remain productive where institutional capacity is neglected. The value of *thinking beyond water*, therefore, lies in connecting these elements within the same decision architecture rather than treating them as separate dimensions of AWM.

Application of the framework across contrasting irrigation, institutional and hydrological contexts is needed to determine which elements can be readily integrated into existing planning systems, where implementation costs become prohibitive and which combinations of thresholds, appraisal criteria, financing arrangements and institutional structures produce meaningful changes in investment and water management decisions. Comparative application would also help establish how ecological and social thresholds need to be adapted across different contexts and whether the proposed screening and adaptive planning mechanisms influence outcomes in practice. Such testing would allow *thinking beyond water* to evolve from a conceptual framing into an increasingly evidence-based approach for supporting more equitable, resilient and ecologically sustainable AWM.

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### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Endnotes

- <sup>1</sup> The International Water Management Institute (IWMI) drew extensive lessons from MCC Lesotho.

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