# Optimising the water we eat—rethinking policy to enhance productive and sustainable use of water in agri-food systems across scales

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**Sustainable and resilient food systems depend on sustainable and resilient water management. Resilience is characterised by overlapping decision spaces and scales and interdependencies among water users and competing sectors. Increasing water scarcity, due to climate change and other environmental and societal changes, makes putting caps on the consumption of water resources indispensable. Implementation requires an understanding of different domains, actors, and their objectives, and drivers and barriers to transformational change. We suggest a scale-specific approach, in which agricultural water use is embedded in a larger systems approach (including natural and human systems). This approach is the basis for policy coherence and the design of effective incentive schemes to change agricultural water use behaviour and, therefore, optimise the water we eat.**

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## No food and nutrition security without sustainable water management

Over 2 billion people live in places with high water stress;[1] this number will continue to increase in the coming decades due to climate change, population growth, urbanisation, industrial demands, changing diets, and the drive to increase agricultural production. With agriculture being responsible for about 70% of global water withdrawals and more than 80% of withdrawals in agrarian economies,[2] business as usual will not be feasible in the future. A combination of ineffective policies and the absence of coordinated approaches across actors and scales are major barriers to systemic change in agricultural water use. This situation, combined with often insufficient monitoring and water accounting systems exacerbates the global water scarcity challenge[3] and hinders the achievement of Sustainable Development Goal (SDG) target 6.4 to improve water use efficiency across all sectors.

Many call for a great food transformation that includes a global shift to healthy diets produced by a sustainable food system.[4] Otherwise, food and nutrition security for the expected population of almost 10 billion people in 2050 cannot be achieved. Innovations across food systems are critical.[5] Agricultural production needs to increase sustainably and to minimise environmental impacts such as resource depletion (eg, land, soil, water, and phosphorous) and pollution. This is essential for achieving several of the SDGs (beyond target 6.4), the Paris Climate Agreement, and to stop the devastating loss of biodiversity and ecosystem services. Sustainable water management plays a vital role in these processes[1,6] and can also facilitate the achievement of other development objectives (eg, climate-resilient growth or job creation).[7,8]

Water is not only essential in agricultural production itself but also needed along the entire food chain, ie, preproduction (eg, generation of farm inputs like fertiliser, seeds, and energy), postproduction (eg, transport and distribution), food preparation and consumption (eg, washing and cooking) and waste and disposal (eg, logistics and pollution). Therefore, the whole food system is an important driver of water use and increasing system efficiency can be achieved through various actions in different sub-components. For instance, reducing waste also reduces the overall water footprint.[9] Also, in contrast to other food production inputs (eg, seeds and agrochemicals), water resources cannot be bought at a market, water is expensive to transport, and water resource availability affects the environment and society. Furthermore, there are many competing water demands by different sectors (eg, energy, industry, domestic, municipal, environment, and disaster management) within and across river basins. Therefore, proper management of local water resources and recognition of the opportunity costs of poor water management is indispensable for sustainability and for minimising conflict. Unsustainable use (eg, overabstraction of groundwater) might provide food production gains in the short term but be detrimental in the long term and limit opportunities for future generations.

Notably, only 20% of the total cultivated area worldwide is irrigated.[10] Food production in Africa, for example, depends predominantly on rain-fed agriculture practised by 500 million smallholders. Only about 6% of the cultivated area in Africa is irrigated.[11] However, irrigation potential using renewable groundwater in Africa could range up to $105\cdot3\times10^6$ hectares corresponding to 48·6% of cropland,[12] which could considerably increase food security and help manage risks related to increasingly unreliable rainfall due to climate change. Furthermore, sustainable irrigation development could benefit 113–369 million rural people and generate net revenues of US$ 14–22 billion per year in sub-Saharan Africa.[13]

With the number of undernourished, food insecure people on the rise,[2] unfortunately exacerbated by the COVID-19 pandemic,[14,15] and rapidly degrading land and water resources, there is a clear urgency to act now. Although the world has managed so far with a diffuse and decentralised approach to agricultural water management (often locally unsustainable),[16] the multitude of changing pressures on water use and supply means that this approach will no longer be adequate. Continuing with current unsustainable water management is too costly for people, the economy, and the environment.[17] This is a globally recognised issue (as evidenced for example by preparation of the UN Food Systems Summit)[1,4,6,15] and calls for significant investments, including ways to increase farmers' productivity and income.[18] Many solutions for more sustainable agricultural production have been suggested,[19–21] but with little change in water management practices at a larger scale.[3,22] This begs the questions of how transformative change can be achieved, how proposed solutions can be more effective and lead to action on the ground, and how change at scale can be facilitated.

## Food production system responses, bottlenecks, and limitations

In response to water scarcity, a wide variety of agricultural water management interventions have been used. The aim is usually to produce more output (eg, biomass, crop yield) for the same or reduced input at the field level. These interventions include biophysical and technical solutions to increase water use efficiency that are based on, for instance, innovations in breeding, biotechnology, irrigation, agronomic practices, and better infrastructure (eg, water storage). Economic instruments (eg, water pricing, and subsidies) and measures to improve water governance (eg, water user associations, policies, and legal framework) are also crucial to improve water use.

Interventions that increase water use efficiency in agricultural production usually have multiple objectives apart from managing water scarcity—for example, to raise farm-level income, alleviate poverty, contribute to economic growth, reduce labour costs, reduce environmental impacts, or support water reallocation from agriculture to other sectors including the environment.[19,23,24] Some of these objectives might be complementary whereas others might be at odds and require tradeoffs that are often not well understood or managed. For example, raising farmer incomes might be in conflict and have significant tradeoffs with preserving sustainable water consumption limits at the basin or aquifer scales.[25,26] Furthermore, related actions are often implemented by a different set of actors and not always in a well coordinated effort.

A review of over 240 interventions to improve water use in agriculture, showed that "higher irrigation efficiency typically contributes to intensification of water scarcity through increased water consumption in the agricultural process".[27] This situation is a result of farmers using so-called saved water for expanding the irrigated area, increasing the cropping intensity, or growing more water-intensive crops.[25,28] Perry and colleagues[29] concluded from a global review that water savings from high-technology irrigation are inconclusive, but that these interventions are often associated with an overall increase in water consumption (although the original objective often was the opposite) and relatively constant water productivity.[29] Hence, the intention to save water at the farm or field level for other users or uses often does not come through at larger scales. Determining the impact of local measures at a larger scale and potential opportunities for reallocation to other sectors requires an in-depth understanding of the broader hydrological context and respective water accounts across users and scales.[30]

Grafton and colleagues[30] defined this phenomenon as the irrigation efficiency paradox, ie, that water saved from water use efficiency measures at the local scale (eg, field and irrigation system) does not lead to reduced consumption at larger scale (eg, basin). This is analogous to the well known Jevons paradox in economics, which states that technological progress increases the efficiency with which a resource is used while the rate of consumption of that resource simultaneously rises due to increasing demand.

To manage this so-called rebound effect,[31] effective regulatory instruments with continuous monitoring of related system parameters and enforcement of regulations are necessary.[32–34] Particularly in the case of collective action problems such as groundwater management.[26,35] Unfortunately, in practice, regulatory frameworks such as permits for water abstractions have had only limited success in many areas, particularly in lower income countries.[36–40] The reasons for this situation are manifold. Given the substantial investments by governments, donors, and multilateral development banks to improve water use in agriculture (through agronomic practices, establishment and modernisation of irrigation systems, and etc), it is paramount to understand the reasons behind these observations and learn from experiences to guide policy making and future investments.

## Disentangling agricultural water management across scales

The characteristics of agricultural water management vary across scales (table 1). Different forces drive water fluxes for different purposes. They change from the dominance of biophysical parameters at the very local scale to an increased impact of human activities (farming activities and infrastructure) at the farm and irrigation system scale. At the large scale (catchment or basin or even country and regional scales), spatial hydro-climatic variability, upstream and downstream interdependencies, and the impacts of other water-using sectors become increasingly important.

At different scales, different academic disciplines develop their methods to address agricultural water management challenges (table 1). They range from predominantly breeding and biotechnology sciences at the crop scale to agronomic techniques and irrigation engineering at the scale of the farm and irrigation

| | Crop | Field | Farm | Irrigation system | Catchment or basin | Region or country |
|---|---|---|---|---|---|---|
| Scale (indicative)* | $<10^0$ m² | $10^2$–$10^4$ m² | $10^4$–$10^6$ m² | $10^6$–$10^7$ m² | $10^7$–$10^{10}$ m² | $>10^{10}$ m² |
| Typical parameters defining water use | Weather, bio-chemo-physical parameters, and vertical water fluxes | Weather, vertical fluxes, and forces for lateral redistribution of water; labour needs, energy access, agricultural practices | Vertical and lateral water fluxes, and agricultural practices; connection to infrastructure (ie, water and energy); farm income; household needs | Hydro-climate, irrigation and drainage infrastructure (ie, type and condition); water governance | Hydro-climatic variability in basin; upstream and downstream interdependencies; type and demands of all water-using sectors; environmental requirements | Economic performance of different water-using sectors; development policies; water and food security parameters |
| Main academic disciplines | Plant sciences; biotechnology; soil sciences; ecology | Agronomy, agricultural and irrigation engineering; soil sciences; ecology | Agronomy, agricultural and irrigation engineering, ecology, hydrology, and hydrogeology, micro-economics; various social sciences | Irrigation engineering, hydrology, water resources management, economics and social sciences | Hydrology and water resources management including social sciences and economics | Political sciences and economics; sociology; behavioural sciences and law; water resources management; environmental sciences; agricultural sciences |
| Examples of interventions to improve water use | Breeding; genetic modification; agro-ecological methods; cross-pollination | Improved seeds; agronomic practices and techniques (soil and water conservation, deep tillage, zero tillage, mulching, on-site irrigation, etc); agrochemical inputs; cropping intensity; crop rotation and crop selection | Agronomic practices, soil and water conservation; precision farming, expansion of cultivated land, and increased land productivity; responding to market needs (crop choice) and managing inputs | Optimising irrigation scheduling, water conveyance, and application methods; governance of irrigation schemes (eg, rules, tenure, dispute resolution, etc) | Optimising allocations across water-using subsectors; water pricing, energy availability and pricing (subsidies), water use restrictions (caps), and integrated management of water storage and access to markets | Laws and policies related to water, agriculture, energy, and environment; good agricultural practices; establishment of water markets, incentives (eg, tax, subsidies for inputs, charges, and guaranteed prices for produce); trade policies |

Water resources management includes inputs from natural and social sciences and engineering. *The scales can vary substantially in different regions; for instance, larger fields and farms are common in high-income compared with low-income and middle-income countries. Smallholder farmers usually have less than $2\times10^4$ m².

*Table 1:* **Characteristics of agricultural water management at different scales**

scheme. Water resources management methods that include water allocation policies and economic instruments (eg, pricing, water markets, and subsidies) applied to crops, farming inputs, and infrastructure are applied at larger scales but impact lower levels (nested scale approach). Laws and policies related to the agricultural sector as well as other water-using sectors (eg, energy, mining, forestry, industry, tourism, and environment), international markets, and trade policies, all impact agricultural water management at the country and regional level. Notably, policies across the agricultural, energy, and water sectors can create perverse incentives at the farm level affecting water resources at large scales (eg, electricity subsidies for irrigation can lead to unsustainable water use). Therefore, tackling the intricacies of agricultural water management requires a multi-disciplinary and multi-scale approach to understanding tradeoffs and impacts of specific interventions and to identifying cross-sectoral synergies.

This multiplicity of disciplines and scales involved leads to inconsistencies in the terminology and can cause confusion and misconceptions for policy makers and decision makers and even trigger conflicts.[41] For example, the distinction between water use (ie, abstraction or withdrawal) and water consumption (amount of water that is depleted and no longer available in the reference system) is critical to understanding the effects of various interventions to managing water resource across scales.[3]

Optimising water use is frequently not the primary objective for many actors. Farmers, water user associations, basin managers, private sector (eg, provider of inputs or services) or public sector representatives from different levels (eg, local, province, state, and federal) and sectors (eg, agriculture, energy, environment, trade, economy, and finance) might have different objectives (table 2). These objectives range from optimising yields, farm incomes, or local food availability to environmental objectives (eg, limit resource depletion and environmental integrity) and economic policies set at national level (eg, stimulate growth, job creation, and trade). As such, a wide range of interventions might be applied at different scales (table 1) and some might be related only indirectly to agricultural water management. However, government policies impacting the import and export of certain crops, rural social protection and development programmes, or environmental conservation interventions can have major impacts on water resources.

Understanding what drives behaviours of actors with diverse social and cultural norms at different scales (table 2) is an important step for effective policy making. Breeders that focus on individual plant productivity enhancements must meet the needs of their customers (eg, farmers, cooperatives) to be successful. Farmers look for ways to maximise income or provide food security for their immediate households. Their investment (bundled) innovations such as new seeds, agrochemicals, or

| | Crop | Field | Farm | Irrigation system | Catchment or basin | Region or country |
|---|---|---|---|---|---|---|
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| Main actors | Farmers, breeders, and private sector (plants and seeds) | Farmers and private sector (inputs and outputs), NGOs, and CSOs | Farmers, extension services, private sector, NGOs, and CSOs | Farmers, WUA, local irrigation departments, public–private partnerships, and private sector (inputs and outputs) | Basin management authority, local government, cities or municipalities, NGOs, and CSOs | Governments and line ministries; policy makers for environment, agriculture, and water; regional trade unions; development partners (DFI, donors, etc); private sector |
| Typical objectives or actors | Conversion of inputs (eg, water, energy, and materials); optimise biomass production and harvestable yield; climate resilience | Optimising yields; reduction of cost and labour | Optimising economic returns for a farm; optimising multiple water use (irrigation, WASH, and livestock) | Optimising irrigation system performance in terms of command area; serving members of the scheme | Optimising overall water use; balancing water allocation to agriculture and other sectors (eg, environmental requirements); preventing water-related conflicts | Achieving food security or self-sufficiency at national scale; macro-economic and environmental sustainability; implementation of trade objectives; political stability |
| Typical drivers for change of water use | Development of new seeds; climate, pest and disease resiliency; input efficiency (reduced cost) | Change of inputs (fertiliser, pesticides, fuel, and labor); market value of selected crops; GAP certification | Access to inputs, market prices, and increased farm income; access to and affordability of infrastructure (eg, irrigation and machinery) | Increase revenue; access to improved infrastructure; reliable water supply; establishment of WUA; equitable sharing of costs and benefits; subsidies and taxes | Possibility to reduce conflicts across sectors and actors; de-risking business for private sector; meeting environmental standards | Thriving private sector (eg, agriculture); increased employment; increased public income (tax, trade, and reduced subsidies); sufficient goods and services for all people; environmental integrity; honouring transboundary agreements; achieving SDGs |
| Typical barriers to change of water use | Poor soil fertility, seeds, climate, and water availability; pests and diseases | Poor biophysical conditions; lack of access to inputs, knowledge, capital, and labour; beliefs, customs, and habits; perverse incentives through policies | Lack of knowledge and capital; internal competition between resources and users (eg, gendered preferences); lack of access to markets and extension services; land tenure uncertainty | Inadequate infrastructure and capacity for operation and maintenance; internal inequity and conflicts; poor extension services (lack of knowledge and skills); poor market access; price fluctuation; limited private sector investment | Poor governance within basin, competing demands for limited resources and lack of synergistic and integrated sectoral approaches; administrative bottlenecks | Lack of policies and incoherence; lack of resources and capacity; conflicts over shared land and water resources (eg, transboundary); barriers for accessing international markets |

CSO=civil society organisation. DFI=development finance institutes. GAP=good agricultural practices. NGO=non-governmental organisation. SDG=Sustainable Development Goal. WASH=water, sanitation, and hygiene. WUA=water user association.

***Table 2:* Disentangling actors, objectives, drivers, and barriers for change in agricultural water management across scales**

technology (including high-technology irrigation systems) will depend on their investment capabilities, financing possibilities, risk preferences, the maturity of the supplier market, and its enabling environment. Catchment water resources managers, driven by long-term water and environmental sustainability concerns, will look for ways to enforce environmental standards or to reduce conflicts between sectors and water users. National governments aim, for example, to meet their economic (including trade), food security, and environmental objectives, support the private sector, and honour international agreements. Ethical dimensions including gender equality and social inclusion cut across scales.

Barriers to achieving these objectives also vary across scales (table 2). Poor and further degrading environmental conditions provide major obstacles to change towards better agricultural water management at every level. The same applies to inadequate infrastructure (including monitoring, planning, and management), lack of skills and capacity (human and institutional), and poor governance of water, land, and other environmental resources. Furthermore, an actor achieving their objective in one scale can work against another actor within the same or another scale. Overcoming these barriers needs integrated approaches, and multi-scale and multi-actor thinking based on a good understanding of scale-dependency and interdependencies of nested systems. In the same vein, Zhu and colleagues[42] advocate the application of systems analysis in agricultural water management that adequately considers the inter-relationships between human and natural systems.

## Changing water use behaviour of actors

Preventing over-abstraction of water resources through increases in use efficiency is very difficult and often leads to contradictory outcomes. Nevertheless, if a shift to more efficient irrigation technology is accompanied by strict limits and control of pumping for irrigation, it can help to arrest further increase in water consumption—seen for instance, in Nebraska, USA,[32,33] and the Guadalquivir basins in Spain.[34]

Single approaches that focus on registering and licensing of water abstractions have rarely been successful in areas with many (mainly agricultural) users of different sizes[38] and where the capacity for monitoring and enforcement of regulations is limited. Issues that can jeopardise licensing systems include not knowing the sustainable abstraction rates due to hydrological complexity and scarcity of data, the high administrative burden (particularly with many small users), and ineffective sanctions. Power games around resource access and control and competing political and bureaucratic interests are common.[36] Cases of fraud, bribery, and corruption have also been observed.[43] van Koppen and Schreiner[44] concluded that "permit systems widen inequalities and their implementation is logistically impossible" based on an analysis of five sub-Saharan African countries. This situation is attributed to the colonial roots of the system, which over-ride customary water rights regimes and marginalise smallholders that do not have permits, because they are too expensive or too complicated to receive, and de jure criminalise users without a permit.

The success of command and control systems with imposed fees, restrictions, and sanctions (disincentives) is limited, changing water use behaviour through different benefit sharing and incentives is often more promising.[38,45] Understanding actors, their objectives, motives, and drivers for change (table 2) and the enabling environment allows policy makers to design the right incentives to support sustainable water use. This approach goes well beyond the conventional remedy to simply increase irrigation service fees. Although many have argued for greater use of water pricing instruments to reduce use, multiple studies have shown that irrigation water demand is quite inelastic.[46] That is, water prices would have to increase substantially before considerably reducing water demands, thereby adversely impacting farmer incomes. Thus, other instruments to impact water use could include pricing of energy for pumping and distribution, electricity connection fees, finance models (including risk management), incentive schemes that restrict or ban water-intensive crops, and the support for reuse of wastewater. Providing access to (international) markets and subsidies (to farming inputs and produce) can also be effective. The private sector can play a key role, if enabled, to support implementation; effective partnerships with the public sector can be the catalyst for change.

A good example of inter-related policies is the use of energy subsidies and motorised pumps in India that have led to the over-extraction of groundwater.[47–49] The fear of near-zero marginal costs of solar pumping and further decline of groundwater tables has resulted in a new approach where solar pumps are connected to the electrical grid and farmers can sell the solar energy that is not needed to power the irrigation system (known as solar power as a remunerative crop). Reducing groundwater overuse depends on setting an appropriate electricity feed-in-tariff.[48] This tariff must be high enough to dis-incentivise groundwater over-pumping, but not too high to discourage crop production and jeopardise food security. A comprehensive analysis of impacts in different regions worldwide is ongoing.

## Policy implications and recommendations

Given the central role of food production, not only for food security and nutrition but also for poverty reduction, climate-resilient economic growth, and job creation, policy makers have a hugely important challenge in determining how best to use water within sustainable limits. This daunting task is getting increasingly difficult due to rising water scarcity levels and simultaneously growing water demand in many locations around the world. Understanding processes, actors, drivers, and barriers at different scales of agricultural water management (tables 1, 2) and their interdependencies in nested scales matters. Interventions are likely to impact multiple scales and several sectors (intentional or otherwise) and, therefore, policy objectives, practical solutions, and implementation need to be based on a coherent policy framework that supports these water, energy, food, and environmental security objectives. This task is, however, not easy because of overlapping decision scales, competing policy objectives, and often poorly understood synergies and tradeoffs. Therefore, a high degree of integrated thinking and coordination across various sectors and scales is required. These are both technical and political challenges.

We draw attention to the following key policy implications. First, agricultural water management needs to be designed and implemented within a wider systems approach including natural systems and human systems,[42] taking a changing climate into account. Policy measures and interventions (eg, water allocation and re-allocation, land use decisions or implementation of incentives) impact and interact, and are influenced by processes and dynamics at different scales. Not recognising this complex situation, or lack of understanding of interactions of the natural systems (eg, evaporation and surface–groundwater interlinkages) with the human systems (eg, food, energy, and social systems), can lead to unintended consequences and failing or suboptimal water management. In practice this is a major challenge, requiring the coordination and collaboration of a wider set of actors than is typical in the policy making process; however, the long-term benefits are sure to exceed the short-term costs of this integration.

Second, multiple policy instruments are needed to achieve multiple objectives of agricultural water management, for instance, to conserve water resources, to make water allocations available for other uses, or to increase agricultural production or farmers' incomes. Some objectives might be complementary and have co-benefits (eg, increase agricultural production and farmers' incomes), while others might be in conflict (eg, increase agricultural production and conservation of water resources). Inevitable tradeoffs will need to be understood, quantified, and managed, which will involve political choices. Tradeoffs will be made across different water users and sectors (including the environment) and different scales (eg, change of farm water use can impact groundwater recharge and water availability for downstream users). Therefore, every policy objective should have at least one policy instrument[50] that needs to be embedded in a coherent, broad policy framework. There is normally no single, simple, solution to such complicated problems, and certain policy objectives can preclude the achievement of others. For example, Ahmad and colleagues[25] showed for Punjab in Pakistan that the objectives of farmers (improve income and livelihood security) can contradict wider basin-wide sustainability objectives. Technologies to increase water use efficiency at the field scale did not result in water-saving at larger scales. The increased crop water productivity made water use more profitable and increased water demand and, consequently, increased groundwater depletion as a result of the expansion of cropping areas.

Third, understanding the state of water resources and its uses requires detailed monitoring and assessment. Water accounts, ie, the stocks, flows, and uses of water throughout the system, and their variability in space and time have to be developed to enable well informed planning and management, and to increase transparency in decision making.[51] This process requires reversal of the declining trend of monitoring and considerable upscaling of investments in monitoring systems at multiple scales.[52] Modern Earth observation methods (remote sensing of precipitation, evaporation, biomass, etc) supported by big data approaches (eg, internet of things, citizen science, and artificial intelligence) can complement traditional ground-based monitoring networks.[53] This is especially critical in the context of climate change and other changes leading to increasing water scarcity (non-stationarity of time series).[54] Integrated modelling combining biophysical and human systems models[55] can support future dynamic assessments of water accounts, resource availability and uses, and the effect of interventions across scales. However, uncertainties remain high, particularly at finer scales due to data availability and model uncertainties. Assessment of the hydrological system under current and future conditions to provide as complete a picture as possible and minimise uncertainties will support the design and implementation of policies and technical interventions that will be more effective.

Finally, sustainable water consumption caps (instead of limits on withdrawal rates) need to be set, monitored, and enforced. Sustainable boundaries for resource use cannot be exceeded. As water management decisions are made at different scales but actions are implemented locally, these caps need to be defined locally, informed by a basin-wide water accounting,[56] and result from a consultative process.[26] Allocations and reallocations, if water was not used consumptively and water quality allows reuse, across various water-using sectors (including the environment) should be regularly revisited and adapted as necessary (eg, change of water demand and availability) to support whole system performance and sustainability. In the end, necessary changes in water use behaviours should be facilitated through a delicate balance of a regulatory system with sanctions and incentives and sharing of benefits that drive behaviours of the actors. The latter is often more promising if well designed, and if implemented considering multiple sectors, scale dependencies, and local circumstances.

The stakes are high and, no doubt, accelerated action is needed. Policy makers will have to make difficult choices about how to manage increasing resource deficits and set priorities. Consideration of the policy implications discussed here will help ensure that water management decisions are made in an informed manner, and that we optimise the water we eat.

## Contributors

SU conceptualised and made a first draft of the manuscript based on discussions with the coauthors. All authors contributed ideas, reviewed, and edited the manuscript.

## Declaration of interests

We declare no competing interests.

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## References

1 UN. Sustainable Development Goal 6: synthesis report 2018 on water and sanitation. New York, NY: United Nations, 2018.

2 Rossi A, Biancalani R, Chocholata L. Change in water-use efficiency over time (SDG indicator 6.4.1): analysis and interpretation of preliminary results in key regions and countries. Rome: Food and Agriculture Organization of the United Nations, 2019.

3 Yu W, Uhlenbrook S, von Gnechten R, van der Bliek J. Can water productivity improvements save us from global water scarcity? White paper 1. Rome: Food and Agriculture Organization of the United Nations, 2021.

4 Willett W, Rockström J, Loken B, et al. Food in the Anthropocene: the EAT-*Lancet* Commission on healthy diets from sustainable food systems. *Lancet* 2019; **393:** 447–92.

5 Herrero M, Thornton PK, Mason-D'Croz D, et al. Articulating the effect of food systems innovation on the Sustainable Development Goals. *Lancet Planet Health* 2021; **5:** e50–62.

6 Smith DM, Matthews JH, Bharati L, et al. Adaptation's thirst: accelerating the convergence of water and climate action. Background paper prepared for the 2019 report of the Global Commission on Adaptation. Rotterdam: Global Center on Adaptation, 2019.

7 UNESCO. UN-Water. United Nations world water development report 2020: water and climate change. Paris: United Nations Educational, Scientific and Cultural Organization, 2020.

8 World Water Assessment Programme. The United Nations world water development report 2016: water and jobs. Paris: United Nations Educational, Scientific and Cultural Organization, 2016.

9 Hoekstra AY. The water footprint of modern consumer society. London: Routledge, 2020.

10 Food and Agriculture Organization. Ending poverty and hunger by investing in agriculture and rural areas. Rome: Food and Agriculture Organization of the United Nations, 2017.

11 You L, Ringler C, Wood-Sichra U, et al. What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. *Food Policy* 2011; **36:** 770–82.

12 Altchenko Y, Villholth KG. Mapping irrigation potential from renewable groundwater in Africa – a quantitative hydrological approach. *Hydrol Earth Syst Sci* 2015; **19:** 1055–67.

13 Xie H, You L, Wielgosz B, Ringler C. Estimating the potential for expanding smallholder irrigation in sub-Saharan Africa. *Agric Water Manage* 2014; **131:** 183–93.

14 Fore HH, Dongyu Q, Beasley DM, Ghebreyesus TA. Child malnutrition and COVID-19: the time to act is now. *Lancet* 2020; **396:** 517–18.

15 UN. The impact of COVID-19 on food security and nutrition. Policy brief. New York, NY: United Nations, 2020.

16 Chatterjee P. Agricultural reform in India: farmers versus the state. *Lancet Planet Health* 2021; **5:** e187–89.

17 Sadoff CW, Borgomeo E, Uhlenbrook S. Rethinking water for SDG 6. *Nat Sustain* 2020; **3:** 346–47.

18 Jat ML, Chakraborty D, Ladha JK, et al. Conservation agriculture for sustainable intensification in South Asia. *Nat Sustain* 2020; **3:** 336–43.

19 Giordano M, Turral H, Scheierling SM, Treguer DO, McCornick PG. Beyond "more crop per drop": evolving thinking on agricultural water productivity. IWMI Research Report 169. Colombo: International Water Management Institute, 2017.

20 World Water Assessment Programme. UN-Water. The United Nations world water development report 2018: nature-based solutions for water. Paris: United Nations Educational, Scientific and Cultural Organization, 2018.

21 Jia F, Hubbard M, Zhang T, Chen L. Water stewardship in agricultural supply chains. *J Clean Prod* 2019; **235:** 1170–88.

22 Food and Agriculture Organization. Productivity and efficiency measurement in agriculture: literature review and gaps analysis. Rome: Food and Agriculture Organization of the United Nations, 2017.

23 Molden D, Oweis T, Steduto P, Bindraban P, Hanjra MA, Kijne J. Improving agricultural water productivity: between optimism and caution. *Agric Water Manage* 2010; **97:** 528–35.

24 Lankford B, Closas A, Dalton J, et al. A scale-based framework to understand the promises, pitfalls and paradoxes of irrigation efficiency to meet major water challenges. *Glob Environ Change* 2020; **65:** 102182.

25 Ahmad MD, Turral H, Masih I, Giordano M, Zubair M. Water saving technologies: myths and realities revealed in Pakistan's rice-wheat systems. IWMI Research Report 108. Colombo: International Water Management Institute, 2007.

26 Drysdale KM, Hendricks NP. Adaptation to an irrigation water restriction imposed through local governance. *J Environ Econ Manage* 2018; **91:** 150–65.

27 Pérez-Blanco CD, Hrast-Essenfelder A, Perry C. Irrigation technology and water conservation: a review of the theory and evidence. *Rev Environ Econ Policy* 2020; **14:** 216–39.

28 Scott CA, Vicuña S, Blanco-Gutiérrez I, Meza F, Varela-Ortega C. Irrigation efficiency and water-policy implications for river basin resilience. *Hydrol Earth Syst Sci* 2014; **18:** 1339–48.

29 Perry C, Steduto P, Karajeh F. Does improved irrigation technology save water? A review of the evidence. Discussion paper on irrigation and sustainable water resources management in the near east and north Africa. Cairo: Food and Agriculture Organization of the United Nations, 2017.

30 Grafton RQ, Williams J, Perry CJ, et al. The paradox of irrigation efficiency. *Science* 2018; **361:** 748–50.

31 Wheeler SA, Carmody E, Grafton RQ, Kingsford RT, Zuo A. The rebound effect on water extraction from subsidising irrigation infrastructure in Australia. *Resour Conserv Recycling* 2020; **159:** 104755.

32 Mekonnen M, Neale C, Ray C. Nebraska water productivity report. Nebraska: Robert B Daugherty Water for Food Global Institute, University of Nebraska, 2019.

33 Mekonnen MM, Hoekstra AY, Neale CMU, Ray C, Yang HS. Water productivity benchmarks: the case of maize and soybean in Nebraska. *Agric Water Manage* 2020; **234:** 106122.

34 Borrego-Marin MM, Berbel J. Cost-benefit analysis of irrigation modernization in Guadalquivir river basin. *Agric Water Manage* 2019; **212:** 416–23.

35 Perez-Quesada G, Hendricks NP. Lessons from local governance and collective action efforts to manage irrigation withdrawals in Kansas. *Agric Water Manage* 2021; **247:** 106736.

36 Mukherji A. Political ecology of groundwater: the contrasting case of water-abundant west Bengal and water-scarce Gujarat, India. *Hydrogeol J* 2006; **14:** 392–406.

37 Hoogesteger J, Wester P. Regulating groundwater use: the challenges of policy implementation in Guanajuato, Central Mexico. *Environ Sci Policy* 2017; **77:** 107–13.

38 Molle F, Closas A. Groundwater licensing and its challenges. *Hydrogeol J* 2020; **28:** 1961–74.

39 Molle F, Closas A. Comanagement of groundwater: a review. *WIREs Water* 2020; **7:** e1394.

40 Schreiner B, van Koppen B. Hybrid water rights systems for pro-poor water governance in Africa. *Water* 2020; **12:** 155.

41 Balasubramanya S, Stifel D. Water, agriculture & poverty in an era of climate change: why do we know so little? *Food Policy* 2020; **93:** 101905.

42 Zhu T, Ringler C, Rosegrant MW. Viewing agricultural water management through a systems analysis lens. *Water Resour Res* 2019; **55:** 1778–91.

43 Molle F, Closas A. Why is state-centered groundwater governance largely ineffective? A review. *WIREs Water* 2020; **7:** e1395.

44 van Koppen B, Schreiner B. A hybrid approach to decolonize formal water law in Africa. IWMI Research Report 173. Colombo: International Water Management Institute, 2018.

45 Shah T, Giordano M, Mukherji A. Political economy of the energy-groundwater nexus in India: exploring issues and assessing policy options. *Hydrogeol J* 2012; **20:** 995–1006.

46 Easter KW, Liu Y. Cost recovery and water pricing for irrigation and drainage projects. Agriculture and Rural Development Discussion Paper 26. Washington, DC: World Bank, 2005.

47 Verma S, Kashyap D, Shah T, Crettaz M, Sikka A. Solar irrigation for agriculture resilience (SoLAR): a new SDC-IWMI regional partnership. SDC-IWMI Discussion Paper. Anand: IWMI-Tata Water Policy Program, 2018.

48 Shah T, Durga N, Verma S, Rathod R. Solar power as remunerative crop. IWMI-Tata Water Policy Research Highlight 10. Gujarat: IWMI-Tata Water Policy Program, 2016.

49 Gupta E. The impact of solar water pumps on energy-water-food nexus: evidence from Rajasthan, India. *Energy Policy* 2019; **129:** 598–609.

50 Tinbergen J. Economic policy: principles and design. Amsterdam: North-Holland Publishing Company, 1956.

51 Karimi P, Bastiaanssen WGM, Molden D, Cheema MJM. Basin-wide water accounting based on remote sensing data: an application for the Indus Basin. *Hydrol Earth Syst Sci* 2013; **17:** 2473–86.

52 World Bank. Assessment of the state of hydrological services in developing countries. Washington, DC: Global Facility for Disaster Reduction and Recovery, World Bank, 2018.

53 Cudennec C, Lins H, Uhlenbrook S, Arheimer B. Towards FAIR and SQUARE hydrological data. *Hydrol Sci J* 2020; **65:** 681–82.

54 Milly PCD, Betancourt J, Falkenmark M, et al. Climate change. Stationarity is dead: whither water management? *Science* 2008; **319:** 573–74.

55 Wada Y, Flörke M, Hanasaki N, et al. Modeling global water use for the 21st century: the Water Futures and Solutions (WFaS) initiative and its approaches. *Geosci Model Dev* 2016; **9:** 175–222.

56 O'Donnell EL, Garrick DE, Horne AC. Reallocation through irrigation modernization: the 'once-in-a-hundred-year' opportunity of the North-South Pipeline, Australia. *Water Secur* 2019; **6:** 100028.