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Minimizing trade-offs for sustainable irrigation

A more comprehensive understanding of the role of irrigation in coupled natural–human systems is needed to minimize the negative consequences for climate, ecosystems and public health.

Sonali Shukla McDermid, Rezaul Mahmood, Michael J. Hayes, Jesse E. Bell and Zoe Lieberman

Nearly 40% of global food production is reliant on irrigation, which directly aids crop growth and minimizes the effects of weather and climate variability. However, copious water use for irrigation is depleting many water supplies and increasing pollution levels. Furthermore, extensive irrigation is modifying local and regional climate and environmental conditions, with implications for both humans and natural ecosystems. New and cross-disciplinary approaches to irrigation research and decision-making are needed to better understand and predict irrigation–environment–public health interactions, particularly to quantify the trade-offs and benefits of irrigation under global environmental change.

Environmental and climatic impacts

Irrigation is an important driver of regional environmental change. Irrigation now accounts for over 70% of global freshwater withdrawals[1] and intensifying use over the past century has compromised the availability and quality of many water supplies, especially groundwater. The resulting widespread redistribution of surface fresh water, particularly via dams and diversions, has produced a range of ecological impacts at local and regional scales. The resulting fragmented rivers and streams have degraded or even eliminated aquatic habitats and species, and/or disrupted finely tuned biological cycles[2]. These changes also impact inland commercial fisheries, jeopardizing human livelihood. Among the most striking examples was the state-sanctioned draining of the Aral Sea for irrigated agriculture, resulting in its near 90% loss by 2014[3].

Irrigation applications to the field can further disrupt ecosystem processes. Irrigation drainage laden with agricultural chemicals has functionally degraded downstream wetlands[4] across North America and other industrialized agricultural areas. Nitrate leaching, a stubborn problem in industrialized agricultural zones, is exacerbated by extensive irrigation. Such nutrient losses substantially alter biogeochemical cycling and lead to seasonal hypoxia in coastal and riverine areas[5]. Growing commercial agricultural development along river basins shared by critical protected areas, such as the Okavango River Basin[6], may heighten the risks of these impacts to wildlife. Current irrigation practices have also resulted in enhanced soil salinization and bioaccumulation of environmental toxins, such as mercury and arsenic[7]. These impacts also pose substantial risks to human health.

Even the presence and timing of irrigation water can result in unanticipated ecosystem impacts. For example, human regulation of rivers and modern irrigation application methods (for example, centre pivot systems) have partly enabled the westward expansion of white-tailed deer across northern North America. This poses potential challenges to woodland regeneration and increases competition pressure on other native fauna[8].

Furthermore, an increasing body of observational and modelling studies has revealed how irrigation can alter regional climates (Box 1). Irrigation applications increase soil moisture to satisfy crop water demand. As a result, many extensively irrigated areas have displayed clear increases in evapotranspiration, latent heat fluxes and moist enthalpy[9]. These changes cool the land surface and can reduce diurnal temperature ranges and seasonal mean temperatures[10]. Across major agricultural regions, such as the US High Plains, California's Central Valley and the Indo-Gangetic Basin, irrigation-induced cooling can limit the maximum growing season temperatures, and alleviate heat extremes and anthropogenic warming trends[11].

Irrigation may also impact both local moisture recycling and remote precipitation via interactions with larger-scale atmospheric circulation[12], and alter surface and underground runoff, contributing to changes in erosion processes, sediment transport and water-table height. These myriad impacts and interactions motivate including irrigation in simulations of current and future climate change[13].

Emerging public health impacts

Another emerging concern is that extensive irrigation may lead to unanticipated and adverse public health outcomes. Intensive agricultural practices can result in the over-application of agricultural chemicals (for example, pesticides, herbicides and fertilizers). These chemicals have been linked to numerous negative health outcomes, including cancers and chronic health conditions. As irrigation development opens up new areas to intensive agriculture, more people may be exposed to these health concerns.

Irrigation may also impact public health through the rising prevalence of high heat indexes (a measure of combined heat and humidity), which disproportionately impact the elderly, very young, underserved communities and people engaged in strenuous outdoor labour[14]. Irrigation can substantially raise local and regional humidity levels and, consequently, dew point temperatures. Even small increases in dew point temperature can inhibit perspiration, leading to fatigue, cramps, lower productivity and, in severe cases, heat stroke[14]. Irrigation-induced extremes may already be impacting human populations in key agricultural regions (Box 1). Observational analyses and climate modelling show increases in moist heat stress over several regions of extensively irrigated farmland that could impact millions of people[15,16].

Managing irrigation trade-offs and benefits

Irrigation aids in food production and buffering crop yields against weather variability. In addition, modern irrigation can locally and regionally attenuate dry heat extremes wrought by climate change and modulate anthropogenic warming trends[13], albeit for a limited time. In these ways, irrigation may appear to serve as a purposeful climate adaptation strategy.

Despite these benefits, the current extent and intensity of irrigation also incurs regional public health, climate and ecological trade-offs that undermine its potential climate adaptation benefits (Fig. 1). There also remain impacts with ambiguous consequences, process-level uncertainties, and limits in our understanding of the full role of irrigation in natural and human

Box 1 | The impacts of irrigation in India

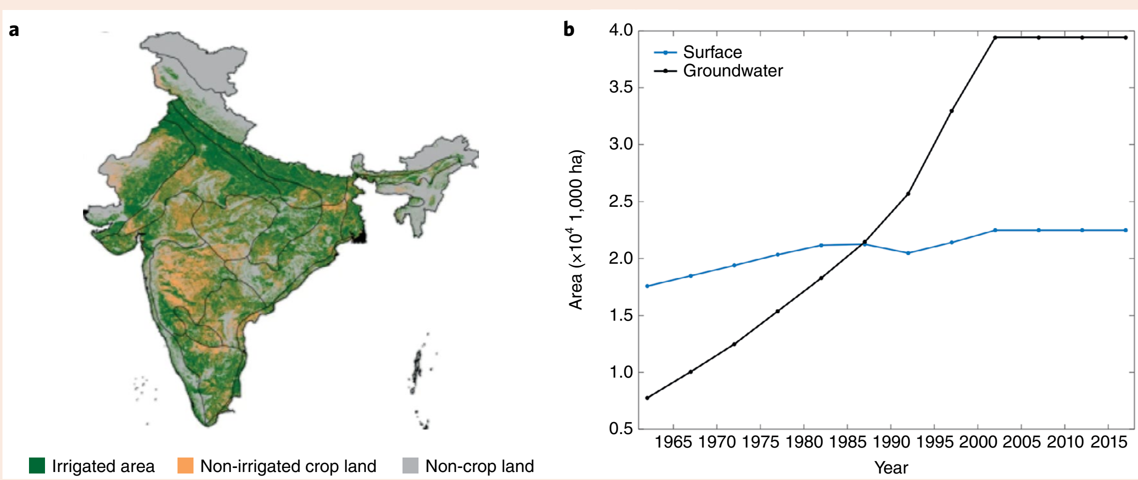
Following from twentieth century Green Revolution trends, India's total current agricultural water withdrawals probably exceed 680 billion cubic metres per year[25] and Indian farmlands are now among the most extensively irrigated (Box 1). Groundwater accounts for ~60% of total irrigated areas using ~230 billion cubic metres per year[26]. While irrigation supports many Indian agricultural systems, rice–wheat systems across the Indo-Gangetic Basin are particularly high in irrigation demand.

This copious water use has resulted in depletion of regional groundwater resources, which are some of the most endangered in the world[27]. In addition, water use for irrigation, particularly groundwater, has resulted in both degraded water quality and soil salinization[28], which could impact food security by way of both production and utilization. In eastern Indian regions, irrigation water laden with arsenic can further contaminate crops and lead to deleterious human health outcomes[29].

The impacts of irrigation in India may extend beyond the surface environment to the regional climate system, that is, the South Asian summer monsoon. Recent work has shown that irrigation can cool the surface by way of increased latent heat fluxes[30], and alter regional thermal and moisture gradients to delay and weaken the seasonal monsoon circulation[30]. This in turn can lead to remote effects, such as reduced monsoonal precipitation across peninsular India[19], upon which a majority of Indian farmers rely. Furthermore, higher atmospheric water vapour resulting from irrigation may increase moist heat stress across India and amplify risks to human health, particularly outdoor and agricultural labourers[15].

Rising population and water demand across sectors, increased regional hydroclimate variability and change, and even socio-political tensions all contribute to increasing pressure on Indian (and South Asian) water supplies for irrigation[31]. Recently, India has considered large-scale diversions of regional river systems, both transnationally and within national borders, to meet irrigation and other water demands. However, such strategies could both amplify socio-political disputes and/or create further negative ecological externalities. In contrast, strategies such as meeting agricultural demand with lower-volume irrigation systems and management (for example, alternate wetting and drying in rice-based farming systems)[28] and possibly crop switching[23] may help to conserve precious regional water resources while also delivering other environmental and public health co-benefits, such as crop and human nutrition diversification.

Novel planning approaches for future, sustainable water use have been recently explored for the South Asian region, including India. For example, the Integrated Solutions for Water, Energy, and Land (ISWEL)[31] approaches engage both experts and national stakeholders (from multiple South Asian states) at the nexus of food, energy and water priority areas to co-develop research scenario activities exploring a range of regionally tailored water solutions. Such cross-disciplinary, stakeholder-driven approaches will be crucial to advancing water conservation goals while reconciling water needs, particularly for irrigation, in an era of rapid global change.



Irrigation in India. a, Irrigated area in India in 2015. **b**, Area (1,000 ha) equipped for surface irrigation (blue) and groundwater irrigation (black) from 1961 to present. Data obtained for five-year averages from the Food and Agriculture Organization (FAO) Aquastat. The plateau in groundwater-serviced area starting around 2000 onwards represents five-year values carried forward ('imputed') from FAO Aquastat. Panel **a** adapted with permission from ref. [32] under a Creative Commons licence (https://creativecommons.org/licenses/by/4.0/).

systems. We therefore urge caution in considering all irrigation strategies as a sure means of long-term climate change adaptation[13]. Furthermore, current irrigation strategies may be unsustainable in many regions, as water resources are over-exploited and/or natural water cycling processes are diminished in both complexity and quality[17]. Irrigation for purposes other than meeting crop water demand may put additional pressure on regional water resources, thereby compromising their capacity to serve future agricultural needs. Incentivizing irrigation for climate change adaptation may also further amplify water resource scarcity and inequities: those with more means, either technically or by policy, may feel pressure to intensify irrigation water use.

There is, nevertheless, an urgent need to manage simultaneous objectives

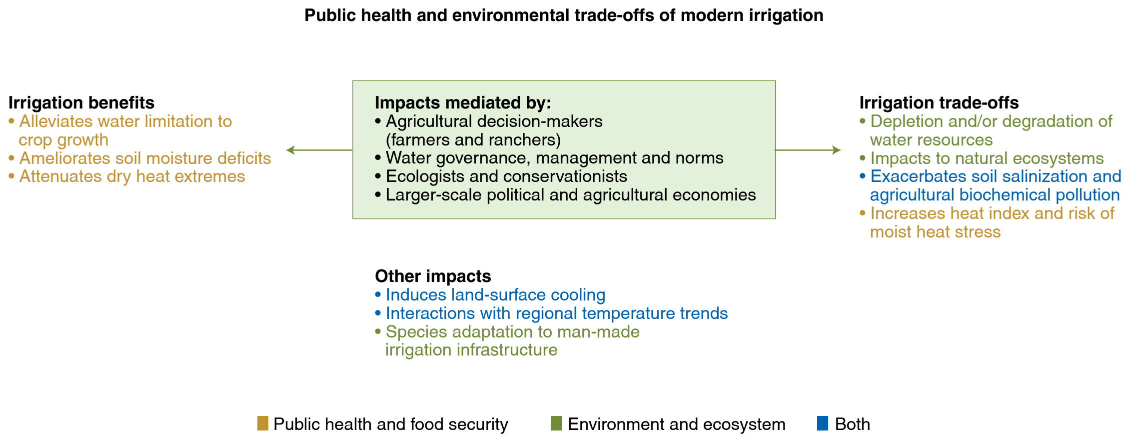


Fig. 1 | Environmental and public health trade-offs of modern irrigation. The trade-offs and benefits of irrigation across public health and food security (gold), environment and ecosystems (including climate; green), and both dimensions (blue).

for agricultural productivity, ecological rehabilitation, water conservation and public health, particularly in the face of global environmental change. Irrigation decision-makers require technological, management and governance options, alongside enhanced data collection and monitoring efforts, that can help facilitate these multi-fold goals. Site-specific examples of improved irrigation management can serve as important models, while global and regional modelling of water conservation potentials can help establish thresholds and test scenarios for assessing benefits and trade-offs. For example, in California, responsible irrigation management could provide adequate crop production while fostering habitat for animal populations under drier climate conditions or where natural wetland ecosystems have been lost[18]. Idealized irrigation–climate model experiments for the Indo-Gangetic Basin demonstrate how stronger water-use regulations, and subsequent gains in crop water-use efficiency, can minimize irrigation-induced changes in precipitation and humidity[19].

Globally, idealized model-based assessments indicate that, when regionally tailored for changing climate conditions, a combination of both centralized and locally-distributed irrigation projects have the potential to sustainably feed a growing population, even under more extreme global temperature increases[20]. The widespread adoption of more efficient irrigation systems alone could substantially reduce irrigation consumption while maintaining food supplies and natural environmental flows[21].

Where irrigation is reliant on groundwater stores, withdrawals should not exceed recharge rates, which should be rigorously mapped and quantified for appropriate decision-making and cropping system design[22]. Furthermore, incentivizing potential shifts towards less water-demanding crops could further reduce irrigation demand while diversifying human nutrient supplies[23]. Overall, water-conserving irrigation practices and alternative cropping systems could weight the public health impacts of irrigation towards food security benefits while minimizing other trade-offs.

Cross-sectoral approaches to sustainable irrigation development

Enabling these potential irrigation benefits, and reducing deleterious impacts, requires that we rigorously quantify the total available water resources regionally, respect natural ecosystem needs, re-evaluate the human demand for water, bracket potential trade-offs between productivity, the environment, and public health, and devise solutions that integrate concerns of social equity[24]. To accomplish this, three (at least) general areas of scientific and stakeholder engagement must be developed.

First, improving quantification of irrigation's agricultural, ecological/environmental and public health trade-offs requires coordinated research initiatives that integrate these disciplinary perspectives. Fostering such cross-disciplinary enquiry could fall within the purview of established, related research initiatives. For example, the Daugherty Water for Food Global Institute at the University of Nebraska — whose mission is to have positive, lasting and substantial food security impacts with less pressure on scarce water resources — recently expanded their focus to include issues related to water, climate and health. Similar cross-disciplinary research missions and mandates will provide unique opportunities to incorporate public health research in understanding potential outcomes of climate change adaptation strategies.

Second, such research initiatives should necessarily engage the array of non-academic stakeholders relevant to irrigation management, inclusive of growers, managers, planners and policymakers, to inform key priority areas. Engaging diverse stakeholder perspectives in cross-disciplinary irrigation research could further result in the creation and comparison of local-to-regional irrigation water-use scenarios representing varying degrees of ambition and social, economic and political feasibility (Box 1).

Third, the governance and management of irrigation resources must further engage the public health community for more comprehensive treatment and prioritization of the benefits and trade-offs of irrigation. While our understanding of the health consequences of climate change is improving, it is also important to understand health impacts arising from climate change adaptation strategies. Bringing public health policymakers and practitioners to the table will allow for enhanced monitoring of health issues, more holistic decision-making, and increased awareness and education for improved public dialogue about outcomes and solutions.

These scientific and stakeholder avenues of engagement are a critical first step in better characterizing the benefits and trade-offs of irrigation regionally and globally, which will be crucial to securing sustainable irrigation resources both now and in the future. ❐

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Competing interests

The authors declare no competing interests.