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Managing irrigation under increasing water scarcity

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Abstract

With rising physical and economic scarcity of water, increasing or sustaining agricultural production while limiting or reducing consumptive water use is an urgent challenge. This article examines the case of four countries—India, China, western United States, and Israel—where there is a long history of irrigated agriculture with significant public and private investments, to identify key themes for managing irrigation under increasing physical and economic water scarcity. The focus of irrigation management has expanded from investing in irrigation infrastructure to reforming institutions; strengthening policies pertaining to irrigation prices and rights; using incentives to reward reductions in irrigation application; and improving irrigation efficiency. However, this may not be sufficient to reduce consumptive use of water in agriculture. Reducing freshwater use in agriculture will require cost-effective harnessing of other water sources through processes such as desalination and wastewater reuse, which may be difficult to implement in most geographies. Changes to policies in other sectors will likely be needed, especially in food procurement and land-use, which require balancing water security with food security, and supporting potential losses in livelihoods and incomes from such changes. Finally, reductions in agricultural water use in a country will likely have implications for water use in other countries, through imports.

KEYWORDS
China, India, irrigation, Israel, United States, water scarcity

JEL CLASSIFICATION
Q01, Q15, Q16, Q56

1 | INTRODUCTION

Globally, irrigation accounts for 70% of withdrawals from freshwater surface and subsurface sources (Zhang et al., 2022). With rising physical and economic scarcity of water, increasing or sustaining agricultural production while limiting or reducing consumptive water use is an urgent challenge for countries. This article examines the case of four countries that share a long history of irrigated agriculture with significant public and private investments, to identify key themes in managing water as scarcity increases.

India's groundwater resources are rapidly depleting, especially in the northwest (Rodell et al., 2009). While the focus has switched from augmenting supply to managing demand, a long history of non-regulation of abstraction coupled with subsidies for pumping (Shah et al., 2012; World Bank, 2010) makes punitive and

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payment-based approaches infeasible to implement; the focus is instead on positive incentives such as payments to farmers to reduce groundwater extraction (Fishman et al., 2016; Mitra et al., 2022) or to switch to water-saving cultivation practices for staples. These approaches are likely insufficient to address the seemingly unstoppable problem of groundwater drawdown. Given India's political system, creating nested approaches at different government levels, strengthening legal frameworks, adopting prices and punitive measures, incubating community-based local management approaches, and routine monitoring to adaptively learn from successes and failure will be needed to rationalize both surface and groundwater use in agriculture. Crop procurement policies that encourage the production of water-intensive wheat and rice need to be reconsidered, and livelihood transitions to move away from wheat-rice systems need to be supported.

While the share of water use in agriculture in China has declined, pressure on groundwater has substantially increased, especially in the North China Plains, which has been accompanied by a decline in groundwater tables (Wang, Jiang, et al., 2020). China is focusing on demand-side management using both regulatory and market-based instruments, under a nested approach of water management at different government levels (Wang et al., 2005; Wang, Jiang, et al., 2020; Wang, Zhu, et al., 2020). There is increasing recognition that these efforts may not be sufficient to reduce domestic water use in agriculture; and this may require China to reconsider its goals of self-sufficiency in food production. This will have implications for water use beyond China's territorial boundaries.

The western United States presents a case where water rights have been extensively used for management, with diversity in the manner such rights are allocated, implemented, used and regulated (Burness & Quirk, 1979). While this has allowed demand management solutions to be tailored to local conditions, it has also created perverse incentives. Appropriative water rights make it difficult to shift water use away from agriculture; while doctrines of beneficial use and private property penalize conservation efforts (Collins, 2015). This makes it difficult to reduce water use in agriculture. The doctrine of beneficial use needs to be expanded to explicitly include water for the environment.

Finally, Israel presents a case where both regulation and market-based instruments have been deployed from the inception of agriculture in the country towards maintaining high irrigation efficiency for high-value agriculture. Wastewater use in agriculture has increased and has replaced freshwater, thus augmenting supplies without increasing pressure on freshwater (Tal, 2017); while desalination boosts drinking water supplies (Teschner et al., 2013). However, Israel is a food importer, which impacts water use outside its territorial boundaries, and its successes may not be easily replicable.

The experiences from these four countries suggest that sustaining agricultural production while reducing freshwater consumption requires going beyond regulatory and market-based incentives that improve irrigation efficiency. Choices pertaining to domestic production of crops might secure a country's freshwater sources but could have implications for water use beyond the territorial boundaries of a country. Technological innovations that augment supply are going to be important, but these must be appropriate to local socioeconomic and ecological conditions, and a major gap exists in this space.

2 | INDIA: A SEEMINGLY UNSTOPPABLE PROBLEM OF GROUNDWATER DEPLETION

India is the world's largest user of groundwater, the bulk of it being used for irrigation and tapped through privately-installed wells (Mishra et al., 2018). While surface water projects were the focus of state investments in the mid-20th century, borewell drilling technology has led to a revolution in recent decades, to the point where India's groundwater resources are depleting, especially in the north and west (Asoka et al., 2017), and increasingly in the southern peninsula. Well drilling, motor pumps and energy (electricity especially) have historically been heavily subsidized for agricultural use in most Indian states, with pumps rarely metered and drilling rarely regulated (Shah et al., 2012; World Bank, 2010). Coupled with government procurement policies for water-intensive staples such as rice and wheat that encourage its production, this has resulted in groundwater decline (Badiani & Jessoe, 2019; Shah et al., 2012).

Most attempts to regulate groundwater abstraction in India have focused on regulating the energy needed to pump it, mainly by restricting supply and quality to farmers either through rationing electricity supply or by changing subsidies on diesel (Shah et al., 2008). In an agricultural landscape characterized by millions of smallholder farmers, regulating groundwater either through regulatory methods that cap quantities or through metering and pricing of water and electricity has been regarded as challenging to implement from a political, implementation and equity perspective (Bajaj et al., 2021; Dubash, 2007; Ghose et al., 2018; Ryan & Sudarshan, 2022; Sidhu et al., 2020). Consequently, groundwater suffers from the usual problems of open-access resources.

Private groundwater "development" was encouraged so that farmers not served by public surface water schemes might gain access to irrigation, which has been argued as being equity improving (Mukherji, 2020). However, as groundwater declines, borewells run dry, and access becomes limited to those who can afford to drill frequently and deeper; dynamically, access to groundwater will likely be inequitable, even as the costs of abstracting it increase for all farmers (Dubash, 2002).

Recognizing this problem, federal and state governments are increasingly experimenting with positive solutions or "carrots" to incentivize reductions in water abstraction—rewarding desirable behaviors rather than penalizing undesirable ones. Given the significant energy subsidy burden of the government (Badiani et al., 2012; Bassi, 2018); this approach is desirable for the state and farmers. For example, farmers in Punjab and Gujarat have been given entitlements of electricity for an agricultural season, with the utility purchasing unused units (rebates) to encourage reductions in pumping groundwater. While such a program did not reduce groundwater pumping in Gujarat (Fishman et al., 2016), it was successful in doing so in Punjab (Mitra et al., 2022). Among other factors, the success and failure of such programs will depend on whether pump owners are also selling irrigation services to farmers who do not own wells, a practice that is fairly widespread in many states in India (Balasubramanya & Buisson, 2022; Saleth, 2004).

At the same time, federal and state governments are also exploring how solar irrigation, which is being promoted to reduce the carbon footprint of agriculture, can be implemented to provide incentives to farmers to reduce groundwater pumping (Bassi, 2018). Since one of the challenges of switching farmers from fossil fuel to solar energy is that the marginal cost of pumping with solar is zero, connecting solar pumps to grids and paying farmers for generating electricity and evacuating it into the grid is viewed as a way to incentivize desirable behaviors (Kumar et al., 2011; Shah et al., 2014). This is being pursued in solar irrigation programs in several Indian states, including Karnataka, Gujarat, Maharashtra and Rajasthan. However, such incentives may not lead to reductions in groundwater abstraction, as farmers could generate electricity without reducing pumping, especially when tariffs offered are modest. A preliminary analysis of such a scheme in Karnataka found no reductions in groundwater abstraction, even though pump owners sold electricity to the grid (Durga et al., 2021). Given the costs of connecting pumps to grids, reducing groundwater overdraft through tariffs offered to electric units evacuated from grid-connected pumps may not be economically feasible, as Jadhav et al. (2020) found in Maharashtra. Positive incentives may have a role to play, but it is unlikely to solve the seemingly unstoppable problem of groundwater depletion by itself.

Over the longer term, holistic policy approaches are needed, and identifying them will likely need a reexamination of the institutional dimensions of groundwater (and water as a whole) in the Indian context. A multi-layered integrated water resource regulatory system is needed that builds upon participatory democracy in its smallest administrative unit, and representative but transparent and accountable democracy at larger scales (Task Group on Water Policy, 2019). It is necessary that such a system manages both surface and groundwater, as the two are part of the same hydrological system (Srinivasan & Lele, 2017). Water allocation (quotas) would come from the top (river basin scale); and lower-level allocations within these quotas and day-to-day management and monitoring would be implemented at the milli-watershed, municipal ward and village scales. To ensure equity, such irrigation allocations may need to be delinked from land ownership and be based instead on per capita needs, to accommodate the landless who rent land (Joy & Paranjape, 2004).

Finally, agricultural procurement policies for water-intensive crops such as rice, wheat and sugarcane that guarantee a price to farmers will need to be reconsidered to reduce both surface and groundwater use in agriculture (Devineni et al., 2022; Mukherjee et al., 2018). Such changes are likely to have livelihood and income implications for many farmers, who will need to be supported through such transitions (Baviskar & Levien, 2021; Ceballos et al., 2021). Expanding the cultivation of less water-intensive staples such as millets will likely need extension and procurement support, coupled with campaigns that encourage dietary changes to increase demand for these crops.

3 | CHINA:FROM DEMAND-SIDE MANAGEMENT TO RETHINKING FOOD SECURITY GOALS

While the share of water withdrawals for agriculture in total water withdrawals has declined from 97% in 1949 to 62% in 2020 (Wang, Jiang, et al., 2020), agriculture has started relying more heavily on groundwater since the 1980s, as competition over surface water has increased. Around 83% of all wells were private in 2004, and the share fell to 62% in 2016 due to an increase in public wells (Wang, Zhu, et al., 2020). As groundwater-based irrigation has expanded, groundwater levels have declined. This is especially the case in the North China Plain, where the share of groundwater irrigated lands increased from 1% in 1950 to 67% in 2015 (Wang, Zhu, et al., 2020); accompanied by 34% villages experiencing a groundwater decline of more than 1.5 m annually, and 31% experiencing a decline of between .25 and 1.5 m and between 2005 and 2015.

China has moved from supply-side management to demand-side management; with a focus on regulating

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total use and increasing water use efficiency (Wang, Jiang, et al., 2020). Surface water institutions have been transformed into water user associations (WUAs), sometimes with contracted management; by 2016, almost 80% of villages had WUAs (Wang, Jiang, et al., 2020). In some villages, water managers have been provided with incentives, where they can earn higher incomes by reducing water applications; these initially incentivized reductions in applications which have since slowed down (from 40% in 2000s to 20% in 2011; Wang et al., 2005, 2014).

China is aiming to increase irrigation prices, but there are challenges. Since demand for irrigation is inelastic, raising water prices is likely in conflict with the goal of raising farmer incomes (Q. S. Huang et al., 2010). Water is often not metered, making it challenging to implement volumetric pricing; consequently, water fees are often collected by area, which is often not closely related to actual water use behaviors. An "increase price and provide subsidy" scheme was piloted in Hebei Province, where farmers were levied higher prices but were refunded post-harvest. Groundwater irrigation prices was raised and collected based on electricity use. The increased irrigation fees were retained by water managers and refunded to farmers post-harvest according to land area. This policy led to a reduction in groundwater applications for wheat by 30%, but implementation costs were high and a government subsidy of 30% of irrigation fees was needed, making it fiscally difficult to scale and sustain such an approach (Wang et al., 2016).

Since the early 2000s, China has been working to set up a water rights system and piloting water trades. Trade between regions and transfers between the agricultural and industrial sectors, which are coordinated by local governments, has been observed in pilot efforts (Wang, Jiang, et al., 2020). Promoting water trade between small individual irrigators has been difficult, as farmers were often unaware that they had rights that could be traded (-). When water rights were granted to farmers in the form of a water certificate, implementation and monitoring costs have been high.

To increase irrigation efficiency, the government has launched a large program for upgrading, renovating, and investing in water-saving technologies in large- and middle-scale irrigation districts over the past two decades. Between 2000 and 2017, the share of irrigated land adopting water savings technologies increased from 31% to 50%, mostly in the form of canal lining and underground pipes; drip and sprinkler adoption has been low (Wang, Jiang, et al., 2020). While Q. Huang et al. (2017) found that such technologies reduced crop water use and improved the productivity of water, such technologies may not always reduce water application as acreage might expand for profit maximizers, or more profitable water-intensive crops could be cultivated (Huffaker & Whittlesey, 1995; Ward & Pulido-Velazquez, 2008).

Seasonal following is also being considered. This was first piloted in Hebei province, and currently, 13 provinces plan to pilot this approach (Deng et al., 2021). Farmers are incentivized to change cropping pattern from winter wheat and summer maize to summer maize alone; and are paid to keep their fields fallow in the winter. The Hebei pilot reduced wheat cropping area, and achieved 84% of the water application reduction target; however, sustaining such a scheme is fiscally expensive as few farmers are able to find off-farm work and payments will have to be continuously provided.

Despite these efforts, more will need to be done to reduce water applications in agriculture. China has relaxed its goal of food security through domestic production (except for major grains), and this is likely to ease pressure on domestic water sources, but will have consequences for water resources abroad, as those food items are imported instead.

4 | WESTERN UNITED STATES:WATER RIGHTS FOR THE ENVIRONMENT NEED TO BE STRENGTHENED

In the western US, surface water rights tend to follow the prior appropriation doctrine ("first in time, first in right")—senior users may use their full allocation before junior users (Dellapenna, 2011). Most senior users are farmers. As populations in the western US have expanded, municipalities have had to purchase water rights for domestic and other uses, including water-right claims of Native American communities, from senior users (Schaible & Aillery, 2012).

This system of surface water rights makes it challenging to reduce water use in agriculture. During a shortage, higher value water uses (drinking water, hospitals) will be curtailed (due to their juniority), while lower value agricultural uses (hay, alfalfa) receive their full allocation (Sax et al., 2006). Since rights related to "water for the environment" have been recognized recently (junior rights), these also have to come as transfers from senior right holders; most such transfers have been on short-term arrangements, rather than permanent long-term ones (Scarborough & Lund, 2007). "Water rights for the environment" are among the first to lose access during scarcity, due to their "juniority" (Garrick et al., 2011).

Groundwater rights in the western US are mostly correlative, which means that regulations are written to treat categories of water users equally (Babbitt et al., 2018). In cases where water use restrictions are necessary, these are generally applied equally across all users.

However, both surface and groundwater rights are subject to the beneficial use doctrine ("use it or lose it"), where a water right may be revoked when it has not been used for an extended period, to disincentivize speculative and monopolistic behaviors (Anderson & Kraft, 2012). Beneficial use is a large impediment to incentivizing reductions in water in agricultural use as the doctrine effectively penalizes successful conservation efforts (Williams, 1983).

A major challenge in reducing water use in agriculture is data on actual water use. There is significant variability in the percentage of wells metered; thus, measurement errors are pervasive when considering agricultural water use data at a field level. From an economic perspective, even if measurement errors are mean zero, Jensen's equality implies that mean-zero measurement error translates to a positive welfare loss that is increasing in the standard deviation of the error (Foster et al., 2020). If a binding regulatory reduction on agricultural water use at the field level were implemented in the presence of measurement errors in monitoring, this could lead to large welfare losses; making it harder to reallocate water towards the environment (Grantham & Viers, 2014).

In some states, large datasets on field-level agricultural water use are available to download directly from the internet, allowing researchers to perform a variety of econometric and data mining exercises to find correlations that are interesting and publishable. This access to data does not require interacting with the people who collected it, which runs the risk of researchers not being adequately aware of the context and local conditions. From a policy research perspective, a shift to context-light analysis carries the risk of misinterpreting results, especially when local rules and regulations are concerned, where there is often a difference between how policies are written and how they are actually implemented on the ground (Garrick et al., 2011). One of the important challenges for furthering evidence-driven agricultural water policy in the United States is the need for researchers to treat data and context as complements and to invest time to develop institutional connections at the same time as working to improve analytical capacity.

Finally, the doctrine of beneficial use needs to be expanded more robustly to explicitly include the environment as a "beneficial use," so that water can be reallocated for environmental amenities, especially in overallocated basins (Garrick et al., 2011; Grafton et al., 2010).

5 | ISRAEL: PARTNERSHIP BETWEEN STATE, PRIVATE SECTOR AND FARMERS FOSTERS INNOVATION

Since the 1980s, overall agricultural water use in Israel has not increased, but agricultural production has continued to grow rapidly, with a seven-fold increase in the output of crops per unit of water (Kislev, 2013). This is due to a couple of factors. Agriculture is highly productive, and micro-irrigation technologies that were developed in the country are almost ubiquitous (Raveh & Ben-Gal, 2016; Yasuor et al., 2020). A substantial and growing portion of the water used for irrigation is treated wastewater, which has been gradually replacing freshwater as the main source of irrigation since the 1970s (Aharoni & Cikurel, 2006). Agriculture consumes a little more than half of all water used in Israel, and of that, more than 60% is recycled, brackish or captured from floods (Lipchin & Pennycock, 2015), one of the highest rates in the world. Several factors have enabled Israeli irrigation to achieve these successes.

First, the public agricultural research and development (R&D) system has actively worked with private sector companies and with farmers since the early days of the state, bolstered by an energetic public extension system (that has been partially privatized in recent years); this public-private R&D ecosystem is often credited for much of the innovation in Israeli agriculture over the years (Tal, 2021). Israeli agriculture has evolved towards high-value and highly profitable horticultural production, which supports investments in technologies that have substantial costs. Low-value cereal crops are seldom irrigated at all in Israel.

Second, all water resources have been publicly owned by the state since 1959; water management is centralized; and the government is able to regulate all water use, including in agriculture (Ellis et al., 2022; Gelpe, 2010). All water use is metered, and quotas and prices for extraction and use are enforced and adjusted to reflect cost of supply and scarcity values of both freshwater and wastewater (Slater et al., 2020). Third, the high population density of the country results in water use in the urban and industrial sectors to be similar in magnitude to agricultural usage, enabling treated wastewater to form a large fraction of the supply of water for agriculture (Friedler et al., 2006).

Whether the success of Israel can be replicated in or transferred to other countries, especially low-and middle-income ones (LMICS), is difficult to answer. In LMICs, agriculture occupies a much larger share of overall water demand, and urban and agricultural areas are geographically distant, making it expensive to transport treated wastewater and limiting its ability to replace freshwater. Israel's micro-irrigations systems are likely to be expensive, and unsuitable, for smallholder farmers in LMICs; contextually appropriate technologies would need to have lower costs, even if performance was somewhat reduced. Without enforcing withdrawal restrictions or pricing irrigation water, it is unlikely that irrigation-efficiency improving technologies will be adopted. Finally, the role of the Israeli state in fostering an environment of innovation between the public and private sector and with farmers cannot be emphasized enough.

However, it is important to remember that Israel relies on imports to supply most cereals, and consequently imports high levels of virtual water to satisfy its needs (Shtull-Trauring & Bernstein, 2018). Had the country needed to produce its own cereal supply, the manner in which water would have been used in agriculture; and the ability to increase production without increasing freshwater use; might have been different.

The risks of using wastewater in agriculture need to be better managed (Lavee, 2010). Emerging evidence suggests that long-term irrigation with treated wastewater results in degradation of the soil structure (e.g., see Yasuor et al., 2020); crop yields (Tal, 2016); and groundwater quality (e.g., see Shalev et al., 2015). The health risks of consuming vegetables irrigated with treated wastewater are potentially significant, and are an emerging policy concern that needs attention and management (Assouline et al., 2015; Malchi et al., 2014).

Whether Israel's successes are sustainable is debatable. Many of the country's aquifers are falling in quality due to intrusion of seawater and pollution from agricultural and industrial sources; and addressing this will require desalinization of wastewater (Tal, 2016). The Dead Sea continues to shrink, mainly because of diversions from the Jordan river (Yechieli et al., 2016). Internationally, water-sharing agreements may need to be revisited for peace-keeping, given the changes in population and technologies, which will have implications for how Israel continues to invest in technologies and innovation (Talozi et al., 2019).

6 | DISCUSSION

The four cases highlight some key themes in managing irrigation under increasing water scarcity. Quantity restrictions and pricing of irrigation water will need to be undertaken; however, history, institutional capacity and current politics will have a bearing on how successfully this is carried out. On the technology front, field-based technologies such as drip irrigation can form a complement to quantity restrictions and pricing; but water-saving methods of cultivating cereals especially may need to be incentivized for farmers to adopt them. Other technological innovations that augment freshwater supply are needed, but these need to be appropriate to local socioeconomic and ecological conditions, and a major gap exists in this space.

A country might secure its domestic water resources through a change in crop production policy, but this will have global implications. For example, withdrawing minimum support prices on wheat and rice in India would help reduce the over-production of these water-intensive crops and reduce groundwater overdraft, but this will affect the livelihoods of farmers, and the export of these commodities overseas. In contrast, as China's food security policy that emphasized food production sufficiency is relaxed to reduce demand on domestic water sources, the country will import these commodities from other places, thus affecting water use overseas. Israel's ability to feed its population is already dependent on the water resources of countries Israel imports grains from.

Climate change is going to make it more challenging to manage irrigation. For example, higher variability in rainfall and change in quantity of precipitation in Israel implies that demand for irrigation will increase and buffer use will become important. Irrigation will likely retreat in portions of the western United States, and unirrigated part of the eastern US will come under irrigation in the future; institutions and water right regimes in these geographies are currently inadequate for managing agricultural water and will need to be strengthened to protect drinking water rights and water quality. In the case of China, improving the adoption of drip and sprinkler systems, while limiting expansion of cultivated area and changes in crop-choice towards water-intensive crops through schemes such as fallowing have promise, but will require fiscal support from the state, while the off-farm sector is developed. In the case of India, climate change will increase variability in a monsoon-dependent country by impacting glaciers and the flow of rivers in the Indo-Gangetic Plain. A system of centralized allocation of water, with those allocations locally managed, will be needed to respond to this challenge.

Finally, better data on water, especially at the farm level, needs to be collected in India and China; identifying innovative ways to collect data parsimoniously will be particularly important. In the United States, where better data is available, there is a risk of using this data without sufficiently understanding the context and erroneously interpreting results, since researchers are often not engaged with those who collected the data. In Israel, data on water quality needs to be urgently collected, which is an emerging concern in the policy space.

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