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ADBI Working Paper Series

AGRICULTURE WATER MANAGEMENT, FOOD SECURITY, AND SUSTAINABLE AGRICULTURE IN THE PEOPLE'S REPUBLIC OF CHINA AND INDIA UNDER CLIMATE CHANGE

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Abstract

Water shortage is one of the major environmental challenges in emerging Asian economies such as India and the People's Republic of China (PRC), presenting significant threats to livelihood and food security in coming decades. The growing population, increasing demand for food, rapid urbanization, and climate-induced water stress will make water an increasingly scarce and critical resource in these nations. Agriculture, as the largest water-consuming sector, accounts for 64% of water use in the PRC and 80% in India. Understanding both the demand and supply sides of water management in agriculture is crucial to addressing future water and food security in these countries. While there are significant differences between the PRC and India in agricultural water management, both countries have predominantly focused on supply-side measures, emphasizing sustainable production practices such as "more crop per drop". To manage agricultural water resources effectively and ensure long-term sustainability, it is essential to adopt a broader perspective that integrates a comprehensive food system and natural resource management approach. This holistic view will help in developing strategies that balance both the supply and demand sides of water management, addressing the complex challenges of water scarcity in India and the PRC.

Keywords: agricultural water management, food security, sustainable agriculture, India, People's Republic of China

JEL Classification: Q25, Q50

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1. INTRODUCTION

Over the last few decades, the agricultural sector in Asia has experienced remarkable growth driven by the green revolution and increased productivity, particularly in the People's Republic of China (PRC) and India. Following fundamental policy reforms in 1978, agricultural growth surged in the PRC (Lin, 1990, 1992). Similarly, India has grown significantly in the past five decades (Birthal et al. 2014). Despite the PRC's substantial increase in agricultural outputs and its ability to meet the rapid growth of food demand domestically (Huang et al. 2020), it is projected that fulfilling future food demand (between 2020 and 2050) will pose greater environmental challenges (Zhao et al. 2008, 2021). This is especially true for the increasing demand for livestock products, which will require more pasture land and water resources either within the PRC or from countries exporting livestock products to the PRC (Zhao et al. 2021). Additionally, by 2032, the PRC's irrigation water requirement is expected to reach 249 billion m³ if the current food consumption pattern continues (He et al. 2021). These projections have profound implications for agricultural water management and achieving several Sustainable Development Goals (SDGs) in the PRC and other economies. From 1950 to 2017, India's food grain production increased from a mere 50 million tons to 275 million tons, making the country not only self-sufficient but a net exporter of food grains (Kumar and Sharma 2020). Significant growth in the livestock sector has also been observed in India over the last four decades (Government of India 2022). Between 2014 and 2020, the livestock sector grew at a compound annual growth rate (CAGR) of 8.15%, the contribution of livestock in the total agriculture and allied sector global value added (GVA) (at constant prices) increasing from 24.32% to 29.35% during the same period (Government of India 2022).

On the positive side, the increase in agricultural production has improved food security and livelihood, contributing to overall economic growth. On the negative side, the colossal increase in agricultural output has adversely impacted natural resources, particularly land, forests, and water, leading to environmental degradation and challenges for future food production systems. This study focuses on the issue of increased water use in the agriculture sector and its implications for future food security in these two emerging economies of Asia. Examining the agricultural growth over the past decades, a vastly different food security situation emerges between these two largest nations of Asia (Dalin et al. 2015; Saha, Marwaha, and Dwivedi 2019). While the PRC achieved remarkable success in food security in the 20th century compared to India, sustaining this success in the future is projected to be more challenging due to increased competition for land and water resources (Finnin 2016: Liu and Zhou 2021). Conversely, India still has the option to harness its natural resources to achieve future food security (Finnin 2016). However, the overexploitation of groundwater for agricultural irrigation, accelerated by subsidized irrigation, already indicates sustainability challenges in meeting food security goals in India (Devineni, Perveen, and Lall 2022). Additionally, higher population growth will constrain the availability of water required for the agricultural sector in India. United Nations (UN) estimates show that India's population will surpass the PRC's by 2024 and is expected to reach 1.68 billion by the 2050s (Our World in Data 2022).

Currently, the PRC and India account for almost 60.4% of the total population in Asia (2.85 billion out of 4.72 billion) (Our World in Data 2022). Over the last 2.5 decades, the average GDP growth rates were 8.6% and 4.5% for the PRC and India, respectively (FAO et al. 2020). Moreover, agricultural water use in these two giant economies accounts for 64% (the PRC) and 87% (India) of their total water use (Global Water Partnership 2013). Consequently, water use in agriculture and its management in these

two nations are of global concern. Water and food insecurity could threaten global food security and global peace.

2. WATER USE EFFICIENCY IN CROP AND LIVESTOCK PRODUCTION

Irrigated agriculture consumes almost 70% of all freshwater withdrawals globally. As such, agricultural water use and its efficiency are major concerns when addressing the challenges of freshwater scarcity (Fishman et al. 2015). The issue is particularly relevant for the two most populous and economically emerging countries in Asia—India and the PRC. In the PRC, irrigated lands occupy 51% of the country's cultivated land, producing almost 75% of its grain and above 90% of its economic crops (Wang and Wu 2018). However, due to the increase in industrial and domestic water demand, the share of agricultural water in total water use in the PRC declined from 88% to 62% between 1978 and 2017 (Wang et al. 2020).

According to the Economic Survey 2021–2022, irrigated lands occupy about 49% of the total net sown area in India. Of the total irrigated area, almost 60% is under groundwater irrigation, the remaining 40% under canal irrigation (Government of India 2022). Agricultural water use currently accounts for about 80% of total water use in India (Government of India 2022; Sharma et al. 2018). However, canal and groundwater irrigation efficiencies are low in India. The overall efficiency of canal irrigation is 30%–65%, while it is around 65%–75% for groundwater irrigation (Sharma et al. 2018).

	Internal Renewable Freshwater Resources (cubic meters per person per year)			Annual Freshwater	Water	
Country	2002	2014	Change (%)	Withdrawals, BCM	Productivity in 2014*	
PRC	2,141	1,999	(-)6.8	604	14	
India	1,326	1,103	(-)16.8	648	3	

Table 1: Freshwater Resources and Water Productivity in India and the PRC

BMC = billion cubic meters.

Source: FAO AQUASTAT, and Sharma et al. (2018).

Another critical issue is the large production of rice—one of the largest waterconsuming crops globally—in India and the PRC (Sharma et al. 2018). In 2014–15, the PRC and India, despite facing increasing water scarcity, were together responsible for almost 50% of global rice production. Moreover, there is a significant misalignment of cropping patterns and spatial water distribution in both countries. Northeastern PRC produces almost 10% of the country's total rice production, and northwestern India (including Punjab and Haryana) contributes about 15% of India's total rice production. These regions in both countries have been identified as water-stressed regions (OECD 2017). Therefore, aligning cropping patterns with spatial water distribution is crucial for future agricultural water management and food security.

	Area	Production	Vield	Production Share
Country	(million ha)	(million tons)	(tons/ha)	(%)
PRC	30.3	207	6.8	27.9
India	43.9	157	3.6	21.2
World	163	741	4.6	100

Table 2: Rice Production and Productivity in the PRC
and India vs. Global Production in 2014

Livestock production, including the production of livestock feed and livestock drinking water, consumes a significant amount of water. From 1971 to 2012, global livestock water use increased globally from 145 km³ per year to 270 km³ per year (Leng and Hall 2021). The proportion of drinking water for livestock has remained relatively stable, with livestock feed production alone accounting for about 41% of total water use globally (Heinke et al. 2020). Livestock water productivity (protein produced per m³ of water) varies greatly across livestock types, climatic zones, regions, and production systems. Additionally, the water issue related to livestock is highly variable spatially. Leng and Hall (2021) found that in some regions, such as eastern PRC and northern India, livestock are a major cause of unsustainable water use. An increase in the production of water-intensive animal products will result in a sharp rise in water consumption in the agricultural sector.

India exported a significant amount of virtual water through the export of rice, maize, and buffalo meat from 2006 to 2016 (SreeVidhya and Elango 2019). The virtual water content in rice (2,850 m³/ton) and maize (1937 m³/ton) is much lower than in buffalo meat (16,482 m³/ton); therefore, increasing the export of buffalo meat may significantly contribute to future water scarcity (Chapagain and Hoekstra 2004).

Cereals and Livestock	2011–12	2012–13	2013–14	2014–15	2015–16	Total
Rice	20.41	28.92	31.04	34.13	29.68	144.18
Wheat	1.24	10.78	9.2	4.83	1.02	27.07
Maize	7.65	8.27	7.65	5.47	1.25	30.29
Buffalo meat	16.23	17.74	23.93	24.33	23.62	105.85
Total agricultural export	57.67	91.75	87.02	83.04	70.04	398.52

Table 3: Export of Virtual Water for Cereals and Buffalo Meat 2011–2016 in Gm³/y

Source: Adapted from SreeVidhya and Elango (2019).

In the PRC, from 1978 to 2009, per capita consumption of animal products in rural and urban households increased by 225.8% and 126.2%, respectively, indicating a significant shift in the food consumption pattern in the country (Lin et al. 2021; Tian 2013). Since animal product production generally requires a larger quantity of water than crops with equivalent nutritional value (Water Footprint Network n.d.), any increase in animal product demand will intensify water scarcity.

3. IRRIGATION WATER MANAGEMENT IN INDIA AND THE PRC

Water management is more complex than other natural resources, such as land and forests (Cosgrove and Loucks 2015; Young and Haveman 1985). Ambiguous property rights, involvement of multiple stakeholders, and externalities to downstream users associated with the upstream irrigation water use add to this complexity (Ahmed and Araral 2019; Asprilla-Echeverria 2021; FAO 2019; Randall 1981). In some countries, such as India, the failure of the public sector irrigation system has led to a situation where the majority of farmers rely on groundwater for irrigation, creating new complexities in agricultural water management (Shah, Giordano, and Wang 2004). In India, the number of mechanized wells and tube wells rose from less than a million in 1960 to an estimated 19 million in 2000, resulting in groundwater table depletion (Shah 2007). Groundwater management is linked to complex hydrological attributes, climate change, and multiple social and institutional patterns (Asprilla-Echeverria 2021). Therefore, agricultural water management should address both supply-side management (e.g., infrastructure provision such as aquifer recharge, deepening of water wells, construction of new boreholes) and demand-side management, including sociopolitical and governance systems affecting water use in agriculture. It also connects groundwater irrigation with the common property resource management issue.

Water management for irrigation differs significantly between the PRC and India. In India, water resource management falls under the jurisdiction of states and union territories. In a democratic setting, effective water management is complex due to the decentralized power structure and varying political situations at different levels of government. This has led to significant variations in irrigation water governance and pricing across the Indian states. State policies and political situations influence irrigation water governance, pricing, subsidies, and revenue collection. Despite differences across states, revenue collection from irrigation water has generally been low due to low water prices, lack of periodic revision, inadequate institutional regulation/governance, and politics governing water and agriculture (Chaudhuri and Roy 2019; Parween, Kumari, and Singh 2020). Additionally, India has a much lower surface water storage capacity (about 190 m³ per capita) compared to the PRC (about 2,486 m³ per capita) (Global Water Partnership 2013). Thus, India is more vulnerable to climate change and its associated threats, such as melting glaciers, unpredictable rainfall patterns, and changes in river flows (Biemans et al. 2019; Moors and Stoffel 2013).

Supply-side management may be easier than demand-side management of irrigation water in India, making the agricultural water crisis more of an issue of governance (Kulkarni, Shah, and Vijay Shankar 2015; Mollinga 2010; Narain 2000). In the PRC, the nation-state fully owns the land, water, and other natural resources, giving the government full authority to manage water resources in agriculture and other economic sectors. Almost 74 million hectares of agricultural land in the PRC are irrigated, making water management in agriculture a critical issue (Yang et al. 2022; Yao, Zhao, and Xu 2017). Given the role of agricultural water management in national food security and economic growth, the PRC's irrigation management has evolved significantly over time.

Before the 1980s, the Chinese government administered the irrigation system. Under this system, collective ownership arrangements at the village committee level were responsible for agricultural water management (Wang et al. 2020). Such an arrangement under collective ownership reduced incentives to invest in new irrigation infrastructure and discouraged the maintenance of existing systems, preventing water use efficiency. This situation necessitates a change in irrigation management in the PRC. With the introduction of de-collectivization and fiscal reforms in the late 1970s and early 1980s, many villages were left without access to investment funds for irrigation management, including the cost of replacing tube wells. In 1988, the PRC issued its first Water Law, increasing government investment in water

infrastructure and initiating reforms in irrigation management (Li, Beresford, and Song 2011; Yu 2011).

The first Water Law of 1988 brought fundamental changes to the PRC's water resource governance by applying market-based instruments in water management (Li, Beresford and Song 2011). By using economic instruments such as licensing of water use rights and levying charges for possessing these rights, the government addressed the demand side of water management. This shift marked a major paradigm change, as water was previously considered an open-access natural resource, government policy focusing on supply-side measures such as irrigation infrastructure investment and maintenance (Li, Beresford and Song 2011; Wang et al. 2020; Yu 2011). However, in the absence of proper institutional settings, these market-based solutions did not yield the desired effects on water resource management, often due to government failure at the local level (Li, Beresford, and Song 2011).

From the mid-1990s, the PRC's traditional top-down approach to irrigation water governance gradually shifted to a bottom-up approach, transferring many rights and responsibilities to water user associations (WUA) (Ricart et al. 2019; Wang and Wu 2018). The WUA is an organization in which local farmers form a board with their representatives to manage the village irrigation system. After the revision of the 1988 Water Law in 2002, the number of WUAs in the PRC increased massively (Wang and Wu 2018).

The 2002 revision of the Water Law addressed many of the issues by emphasizing integrated water resources management (IWRM) and water conservation over supplyside solutions. The revised Water Law followed the concept of water rights to manage water across multiple economic sectors, developing a transparent, rules-based system for allocating water within and across sectors. This was a crucial step in managing irrigation water, given the increasing competition for water use between agriculture and other economic sectors, particularly industry, in the PRC (Calow, Howarth, and Wang 2009). Two major policy shifts in the PRC's irrigation water management can be observed: the decentralized irrigation governance from 2003, with the transfer of irrigation management to WUAs (Zhou 2013) and the promotion of formal monitors—a leader to enforce rules and collect information about potential issues from irrigators (Ricart et al. 2019). Overall, the PRC has shown new evidence for how state control and marketization can be complementary in irrigation water management, highlighting the importance of understanding the roles of the state and the market in irrigation water governance (Jiang et al. 2020).

4. GLOBAL AGRICULTURAL TRADE AND VIRTUAL WATER

The demand and supply sides of agricultural water management have become critical issues in both India and the PRC due to increasing water requirements to ensure the food security of large populations, changing food consumption patterns, competing water uses from other economic sectors, declining water resources, and the impacts of climate change. In this context, virtual water associated with global agricultural trade has emerged as a key concern for sustainable use of water resource use and future food security at both regional and national levels (Goswami and Nishad 2015; Graham et al. 2020; Nishad and Kumar 2021; Rosa et al. 2019; Wu et al. 2019, 2022). Virtual water is particularly important in countries with limited water resources compared to demand. For example, India has only 3.83% of the global freshwater resources but must feed a population of over 1.3 billion. Similarly, the PRC has

only 6% of the global freshwater resources but needs to feed more than 1.3 billion people. In such a situation, virtual water trade and its composition require careful consideration in agricultural water management plans (Goswami and Nishad 2015). Furthermore, India and the PRC are among the world's leading consumers of virtual water (Chen et al. 2012).

Globally, India is a major virtual water exporting nation, exporting around 32 billion m³ of water (about 1.6% of the total available water), accounting for almost 24% of the total global virtual water export (Nishad and Kumar 2021). India's virtual water export is much higher than its import (Goswami and Nishad 2015). If this trend continues, the large virtual water export through trade of agricultural products may pose an irreversible risk to India's water resources (Graham et al. 2020; Wu et al. 2022). Brindha (2017) analyzed India's virtual water trade through crop and livestock product exports over 28 years (1986 to 2013) and found that the average virtual water import was 32.6 billion m³ per year. As a water-scarce country, India needs to consider exporting less water-intensive crops in future agricultural policies to ensure sustainable water management (Brindha 2017).

Another major issue is that India is the second largest producer of rice. Rice production increased from 50 million tons in 1961 to 172 million tons in 2018, with India exporting about 17 million tons of rice in 2018 (Nishad and Kumar 2021). Given that rice is a very water-intensive crop with a global average virtual water content (VWC) of 2.414 m³ per ton, large-scale rice exports from India, a country with a water stress index of 0.967, can lead to unsustainable water use (Wu et al. 2022). India may also need to reconsider exporting other cereals such as maize, which, though a less water-intensive crop than rice, has a VWC of 2,537 m³ per ton in India, much higher than the global average of 1,222 m³ per ton (Wu et al. 2022). The main reason for India being a net exporter of virtual water is its large exports of low value-added and high water-intensive agricultural products in exchange for high value-added finished products such as electronics, household appliances, and transport equipment (Wu et al. 2019). This issue is also significant in the interstate trade of cereals in India, as groundwater reserves in major cereal-producing states are rapidly declining. Nearly 41% of total cereals traded within Indian states are produced in states with over-exploited groundwater reserves and 21% in states with critically depleting groundwater reserves, indicating a need for substantial change in production patterns to ensure sustainable water management in agriculture and sustainable food security (Harris et al. 2020; Katyaini, Barua, and Duarte 2020).

In the PRC, increasing water scarcity has made virtual water a key aspect of national water management. This is crucial because the demand for water in agricultural and other sectors is rising rapidly. The virtual water trade is influenced by socioeconomic, market, and climate factors. The progressive liberalization of food markets in the PRC has made virtual water trade a key strategy for water resources management and food security (Liu, Zehnder, and Yang 2007; Rosa et al. 2019). However, the PRC needs to reconsider the spatial distribution of water, as the current trade structure is not favorable in terms of water resource distribution and use efficiency (Guan and Hubacek 2007). For instance, the water-scarce northern PRC exports almost 5% of its total available freshwater resources through virtual water (Guan and Hubacek 2007). Rapid economic development and trade globalization have put enormous stress on the PRC's water resources. The spatial mismatch of water resource availability and major food-producing regions has raised several questions regarding the sustainability of agriculture and water resource management (Guan and Hubacek 2007; Xin, Wang,

and Xing 2022; Zhang et al. 2020). Understanding interprovincial virtual water flow is crucial to ensure sustainable water resource management and agricultural sustainability. It is estimated that the annual virtual water flow embedded in interprovincial grain trade from North to South PRC was almost 73.46 billion m³ in 2012 (An et al. 2021). If this trend continues, it will severely affect future agricultural production and water scarcity in northern PRC, indicating a need to increase water use efficiency, re-adjust grain production regions, and restructure agricultural production and trade structure (An et al. 2021).

Another crucial issue is that over the past two decades the PRC has shifted from being a net virtual water exporter to a net importer at the regional level (Qian et al. 2019; Wei et al. 2022). Between 1995 and 2009, the PRC was a net exporter of virtual water, closely associated with globalization (Tian et al. 2018). However, with the inception of Belt and Road Initiatives (BRI) in 2013, crop trade between PRC and BRI countries has increased massively, gradually changing the PRC to a net importer of virtual water (Wei et al. 2022; Xia et al. 2022). The trade of crops influences water availability and use through virtual water, affecting agriculture water demand, supply, and management at the national and regional levels. In this context, green virtual water content can be one of the major factors influencing the virtual water trade between the PRC and other BRI countries (Wei et al. 2022). Examining the virtual water trade associated with agricultural trade between the PRC and BRI countries during 2000–2016, Qian et al. (2019) found that southeastern Asia and southern Asia are the leading net virtual water exporters to the PRC, while eastern Asia is a net importer.

The water footprint of a crop depends on agricultural practices, water use efficiency, and local climatic conditions. Generally, producing a crop in an arid region requires more virtual water than in wet or semi-arid regions (Nishad and Kumar 2021). Analyzing data from 2003 to 2010, the virtual water content of the grain crops varied significantly between northern (1,293 m³ per ton) and southern PRC (942 m³ per ton), while the national average was 1,117 m³ per ton (Fu et al. 2018). Other estimates show that the national average virtual water content of wheat, maize, and rice was 1,071 m³ per ton, 830 m³ per ton, and 1,294 m³ per ton, respectively (Sun et al. 2013). The PRC's net import of virtual water through agricultural products trade increased from 44 billion m³ per year in 2003 to 178 billion m³ per year in 2010 (Fu et al. 2018). However, this large increase in agricultural imports has negatively affected the self-sufficiency status of domestic agricultural production.

5. CONCLUSION AND FUTURE DIRECTIONS

In both the PRC and India, the agriculture sector uses the largest share of water. As both countries face water scarcity, there is a need to reconsider agricultural water management to ensure food security and sustain agriculture under changing climate scenarios. Over the last four decades, crop production and livestock production and consumption have massively increased in the PRC and India. Both countries have applied several measures to increase water use efficiency in agriculture, but at different levels. The PRC has managed to enhance its irrigation water demand through technological improvements and improved crop water productivity, while India has focused more on using groundwater resources. Compared to India, the PRC has also recently considered virtual water trade more cautiously.

Given this context, these nations need to consider the following issues carefully to manage the future challenges of water use in agriculture better.

- (i) Technological improvements. More research on enhancing irrigation water use efficiency and scaling up water-saving agricultural technologies is essential (Li et al. 2016; Meena et al. 2019; Sandhu et al. 2019). Recent research in the PRC shows that irrigation water productivity is influenced more by agronomic practice factors than by climate factors (Li et al. 2016). Research in northwest PRC indicates that agronomic practices, including irrigation, fertilization, agricultural film, and agricultural pesticide, contributed 20.6%, 32.8%, 42.3%, and 11.1%, respectively, to the increase of irrigation water productivity (IWP), while the contribution of climatic factors like daily mean temperature and solar radiation, were, respectively, 0.9% and 0.9%. Similarly, in India, Sandhu et al. (2019) showed that agronomic practices such as drip irrigation with residue retention increased irrigation water productivity by 259% in maize and 66% in wheat compared to furrow irrigation.
- (ii) Better selection of crops. The selection of crops is crucial for water resource management in agriculture as crop types significantly differ in their water use efficiency (WUE). A meta-analysis by Mbava et al. (2020) showed that cereals produce, on average, 2.37 kg of dry grain per cubic meter (m-3) of water, followed by oilseeds (0.69 kg m-3), fiber crops (0.45 kg m-3), and legumes (0.42 kg m-3). Amongst cereals, maize (3.78 kg m-3) and sorghum (2.52 kg m-3) were more water-use efficient than wheat (1.02 kg m-3), barley (1.21 kg m-3), and millet (0.47 kg m-3). Overall, maize was the most water-use efficient crop under well-watered conditions (9.90 kg m-3), but sorghum was the most efficient under dry conditions (5.99 kg m-3). The WUE of crops increased from desert to tropical through sub-tropical climate (Mbava et al. 2020).
- (iii) Enhancing institutional/governance aspects of water management. Strengthening the institutional and governance frameworks surrounding water management is critical. Effective water governance involves setting up policies and regulations that ensure equitable and sustainable water use, monitoring compliance, and fostering stakeholder participation.
- (iv) Considering the spatial distribution of water and agricultural land. In designing an agricultural water management plan, it is important to consider the spatial distribution of water and agriculture land. In the PRC, the gap between supply and water demand is widening. The mismatch between the distribution of agricultural land and water resources exacerbates this challenge. For instance, northern PRC, which has 60% of arable land and 80% of grassland, only possesses 20% of the country's water resources. Ignoring this disparity will threaten future agricultural production in the PRC.
- (v) Acknowledging the role of global agricultural trade. Producing more in the water-abundant region and using virtual water concepts in regional and global agricultural trade, especially in water-intensive products, is essential. Virtual water trade can help manage water resources more sustainably by allowing water-scarce regions to import water-intensive products from water-rich regions.
- (vi) Sustainable consumption. Water policies often focus more on sustainable production than on sustainable consumption (Hoekstra 2014). Reducing the consumption of animal products can significantly reduce future water scarcity. Water management in agriculture needs to be viewed from a food system approach rather than a production approach alone.

By addressing these key areas, the PRC and India can develop more sustainable agricultural water management practices, ensuring long-term food security and resilience to climate change.

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