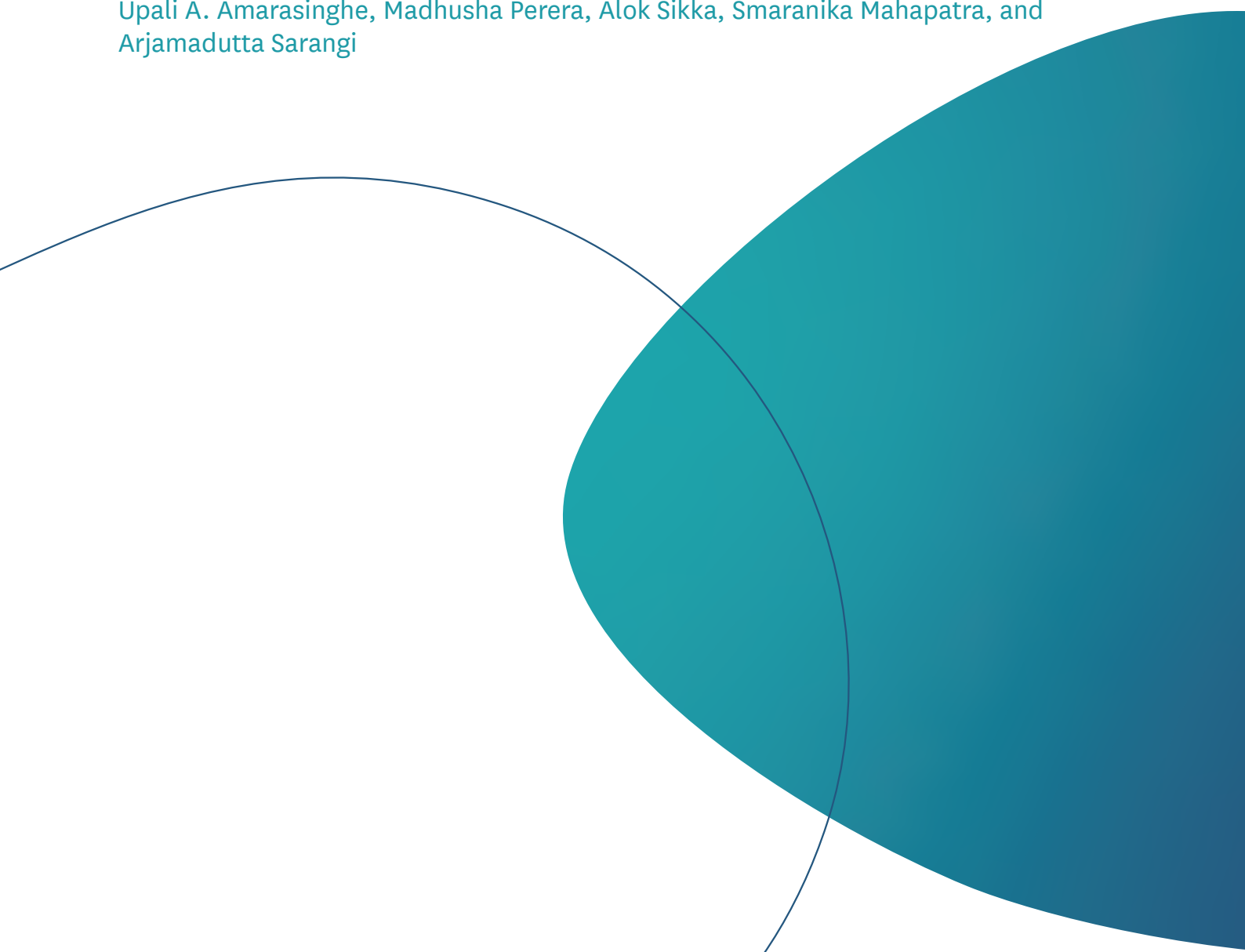


Research Report

Managing Water Productivity, Groundwater Stress, and Nexus Trade-Offs in the Ganga River Basin, India

Upali A. Amarasinghe, Madhusha Perera, Alok Sikka, Smaranika Mahapatra, and
Arjamadutta Sarangi



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IWMI Research Report 190

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Contents

Acronyms and Abbreviations	vi
Summary	vii
Introduction	1
Ganga River Basin – A Brief	3
Methodology and Data	4
Water Productivity	4
Nutritional Water Productivity	5
Nutritional Surplus/Deficit	5
Energy Use	5
Unsustainable Groundwater Use	5
Unraveling the Nexus	5
Data and Analysis	6
Results	7
GWCWU in the GRB	7
Groundwater Overexploitation	8
Water Productivity Variations	11
Addressing WFEE Nexus Externalities	18
GWCWU Reduction Scenarios (GW1-GW3)	18
Increasing Rainwater-Use Efficiency (RWUE)	21
Increasing Surface Water-Use Efficiency with a reduced Surface Water Allocation Scenario	22
Yield Gap Reduction Scenarios	23
Crop Diversification Scenarios	27
Discussion	30
References	32
Annex	37

Acronyms and Abbreviations

CGWB	Central Ground Water Board
CWR	Crop water requirement
CWU	Consumptive water use
DES	Directorate of Economics and Statistics
ETa	Actual evapotranspiration
ETp	Potential evapotranspiration
EWP	Economic water productivity
GIA	Gross irrigated area
GCA	Gross cropped area
GRB	Ganga River Basin
GWCWU	Groundwater consumptive water use
IMD	Indian Meteorological Department
IWMI	International Water Management Institute
MSP	Minimum support price
NIA	Net irrigated area
NGWIA	Net groundwater irrigated area
NWP	Nutritional water productivity
PDS	Public distribution system
PWP	Physical water productivity
RWUE	Rainwater-use efficiency
TCWU	Total consumptive water use
WFEE	Water-food-energy-environment
WP	Water productivity
WUE	Water-use efficiency

Summary

The Ganga River Basin (GRB) is South Asia's major water-food-energy-environment (WFEE) nexus hotspot. This paper explores the current status, challenges, and solutions to unravel the water and food dimensions of the nexus in the Indian section of the GRB. In the western section of the GRB, including Haryana, Uttar Pradesh, and Rajasthan, subsidized energy, especially free electricity, has boosted groundwater irrigation and food production while contributing to a high environmental footprint. In the eastern section of the GRB, including Bihar, Jharkhand, Chhattisgarh, and West Bengal, inadequate energy supply prevents the exploitation of abundant groundwater to increase production.

Currently, 130 out of 237 districts, mostly in the western part of the GRB, play a significant role, directly on the water and food aspects and indirectly on the energy and environmental aspects of the WFEE in the Basin. Of these, 81 districts have severe groundwater overexploitation, with the ratio exceeding 90% (the proportion of groundwater consumptive water use [GWCWU] or evapotranspiration of crops from groundwater irrigation relative to extractable groundwater resources). Furthermore, 10 districts are classified as overexploited, 19 as critical, and 20 as semi-critical, with exploitation ratios exceeding 75%, 60%, and 45%, respectively. Most of the remaining 107 riparian districts maintain safe levels of groundwater use.

The production of macronutrients such as carbohydrates, proteins, and fat from food crops in the Basin significantly exceeds the nutritional needs of the local population. Rice, wheat, and sugarcane, which makes up 88% of the GRB's GWCWU, account for production surpluses of 32%, 74%, and 408% of the total consumption, respectively. Most surpluses from the overexploited to critical districts are from unsustainable groundwater use. However, they meet the food security and nutritional requirements of

people outside the basin via the public distribution system (PDS). These overexploited districts must implement immediate, calculated, and effective measures to reduce GWCWU, especially for rice, wheat, and sugarcane, to avoid further aggravating the WFEE nexus while increasing production to meet some of the PDS requirements of the population outside the Basin. Additionally, semi-critical districts should adopt strategies to prevent unsustainable groundwater practices.

In districts with overexploited groundwater, improving rainfall use efficiency, i.e., greater use of green water, or improving surface irrigation water use efficiency with reallocated surface water withdrawals can reduce some groundwater withdrawals, thereby reducing GWCWU and the energy required for pumping. However, mitigating the food and income losses from reduced GWCWU requires enhancing physical water productivity (PWP in kg/m³) and economic water productivity (EWP in USD/m³). Reducing the yield gap between current and potential maximum yields and diversifying to include high-value, low-water-consuming crops offer opportunities to reduce production and income losses, thereby boosting both PWP and EWP.

All other districts have significant potential to increase production, PWP, and EWP by narrowing yield gaps and diversifying crops. Safe districts with adequate regulation can exploit groundwater further within sustainable limits to enhance crop yields and overall production, thus compensating for production losses in overexploited districts. Without these interventions, much of the 1.32 million km² area of the GRB—especially in the western, northwestern, and southwestern regions—may increase groundwater exploitation, energy use, and environmental footprint in the WFEE nexus. Additionally, climate change could push the GRB, which is already grappling with WFEE issues, toward a critical tipping point.

Managing Water Productivity, Groundwater Stress, and Nexus Trade-Offs in the Ganga River Basin, India

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Introduction

The Ganga River Basin (GRB) is a crucial hotspot in South Asia's water-food-energy-environment (WFEE) nexus (Scott et al. 2009; UN-Water 2024). In the western GRB, the WFEE nexus is characterized by significant crop production surpluses and high consumption of groundwater and energy. This intense resource use led to energy shortages with profound economic and environmental consequences (Mukherjee et al. 2015; CGWB 2022). In contrast, the central and eastern plains of the GRB have limited potential for large surface water storage. Insufficient energy access to pump the abundant groundwater restricts agricultural productivity and hampers economic growth in these areas (Mukherjee 2007). The eastern GRB faces high poverty levels and low economic development (Amarasinghe et al. 2016).

Unrelenting groundwater pumping threatens future food security in India. Freshwater scarcity is a growing concern in the Ganga Delta (Murshed and Kaluarachchi 2018). Climate change is expected to intensify the WFEE nexus by increasing water supply variability and elevating demand (Link et al. 2016). Groundwater depletion is notably more severe during droughts (Dangar and Mishra 2021). Addressing the WFEE nexus in the context of escalating climate impacts on water, land, and the environment is essential for ensuring water, food, and income security. This encompasses managing food availability, stabilizing food prices, supporting farm income, and providing labor income, all of which are vital for climate resilience in the GRB.

Understanding the WFEE nexus in agriculture requires a holistic approach underpinned by reliable data (FAO 2014; Cai et al. 2018; Carmona et al. 2019; UN-Water 2024). The key to this approach is metrics related to water, food, nutrition, and energy productivity:

- **Water and energy use:** Measuring consumptive water use (evapotranspiration of crops), groundwater extraction, and energy use for irrigation reveals the total water and energy consumed in agricultural production. Comparing these metrics with the available resources highlights the extent of the crisis and identifies critical hotspot locations for timely action; and
- **Nutritional footprint:** Assessing the nutritional content of food produced, such as calories, proteins, and fat, and comparing it with dietary needs helps pinpoint food

insecurity hotspots. This comparison provides insights into how well agricultural production meets nutritional requirements.

Such information is crucial for designing effective interventions, including improving productivity, diversifying crops, and optimizing trade strategies. These steps are essential to address the WFEE nexus and evaluate the associated social, economic, and environmental trade-offs.

The Ganges River originates from the Gangotri Glacier at altitudes ranging from 4,000 to 7,000 m. It flows for approximately 2,000 km before merging with the Brahmaputra and Meghna rivers in the east. The river basin covers 1.32 million hectares (Mha), with 79% of this area lying within Union Territory Delhi and 10 Indian states—Bihar, Chhattisgarh, Haryana, Himachal Pradesh, Jharkhand, Madhya Pradesh, Rajasthan, Uttarakhand, Uttar Pradesh, and West Bengal. The remaining basin area is distributed across Nepal (14%), Bangladesh (4%), and China (3%). The Indian region of the GRB is further divided into 18 major sub-basins (Figure 1).

Studies have been done to develop and apply metrics related to water, food, nutrition, and energy productivity in the GRB (Cai et al. 2010; Sharma et al. 2018). Sharma et al. (2018) examined the spatial and temporal variations in water productivity (WP) for major crops across districts up to 2010. They provided the variation in WP for a few main crops across the administrative boundaries and emphasized using water withdrawals to define WP. However, this study uses only crop consumptive water use (CWU) (or evapotranspiration) to avoid double-counting in irrigation withdrawals at a large spatial scale. It provides updated data on WP for several crops and cropping patterns at the district and sub-basin levels, covering the last two decades (1999-2020). Districts are the primary administrative units, while sub-basins are the basic hydrological units for the analysis. Also, the study discusses options for unraveling the WFEE nexus in the GRB.

Focusing on basin-level assessments is essential to understand water scarcity and explore the potential trade-offs in enhancing water productivity. In addition to evaluating WP indicators, the study explores strategies to address the WFEE nexus gains by improving water productivity and reducing the water footprint.

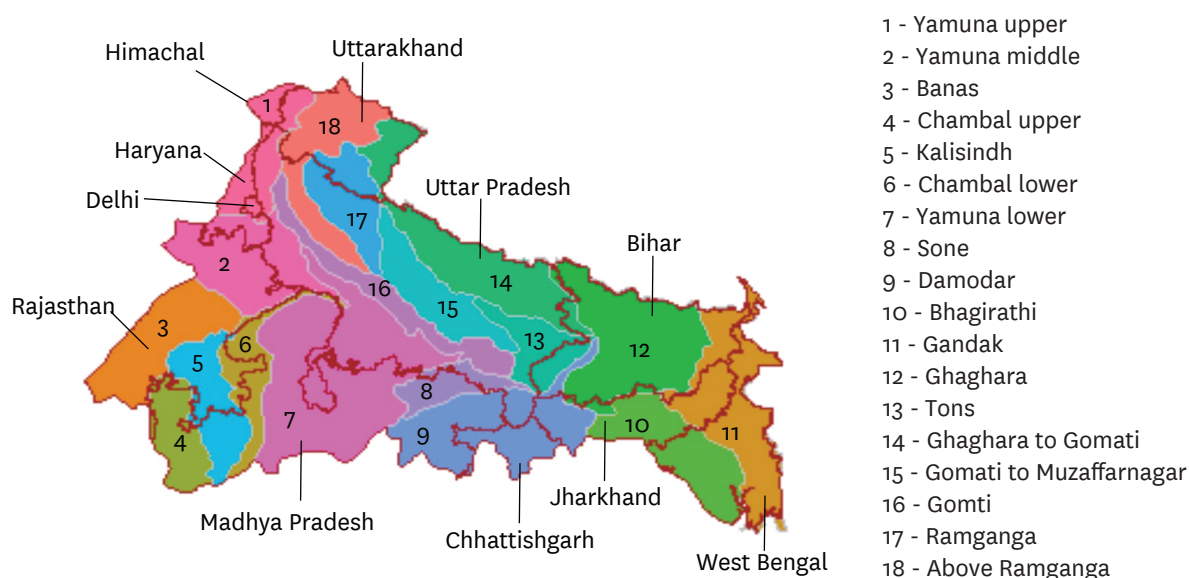


Figure 1. The GRB with its administrative and sub-basin boundaries.

Source: CGWB 2022.

The following four key metrics—physical, economic, nutritional, and energy water productivity—are crucial for analyzing the WFE nexus (Molden 1997; Molden et al. 2003; Renault and Wallender 2000; SIWI and IWMI 2004).

- Physical water productivity (PWP):** This measures the quantity of production per unit of water used, where ‘water use’ refers to CWU or evapotranspiration in crop production. Expressed in kg/m^3 , PWP is a performance indicator for agricultural output. Some assessments use total water withdrawals for irrigation to evaluate PWP. This can sometimes underestimate performance on a larger spatial scale because it does not account for water reuse from return flows, which can be significant. At the same time, using evapotranspiration could overestimate PWP as some non-process losses are not accounted for in crop CWU. Many irrigation systems recycle water multiple times, meaning the total CWU within a system can come close to the total water supply (Amarasinghe et al. 2021a).
- Economic water productivity (EWP):** This metric, expressed as the value per cubic meter of CWU, measures the monetary value of output relative to the amount of water used or depleted. It provides insights into the financial benefits of crop production under scarcity conditions. However, its limitation is that it does not account for production costs, thus failing to reflect the net value of output. To address this shortcoming, a cost curve integrating EWP with the net value of production can be used. This approach helps evaluate the trade-offs involved in crop or agricultural diversification (Amarasinghe et al. 2021b).
- Nutritional water productivity (NWP):** This indicates the nutritional content of crops produced per unit of water consumed, expressed in nutrients per cubic meter. It is calculated by multiplying PWP (kg/m^3) by the nutrient content of the crops produced (e.g., calories, proteins, fat). Besides these primary nutrients, other dimensions of NWP, such as calcium, vitamins, and sodium, are also crucial for assessing health implications (Chibarabada et al. 2017), which this study does not address. Comparing the total nutritional supply from crops with dietary needs helps identify nutritional deficiencies and highlights virtual flows of nutrients at different scales.
- Energy water productivity:** This indicates the unit of energy used for each unit of groundwater pumped for agricultural purposes.

Rice-wheat is the dominant cropping system in the GRB, covering approximately 26 Mha as of 2020. Other cropping systems include rice-rice (2 Mha), maize-wheat (3 Mha), and cotton-wheat (1.5 Mha). Sugarcane, which also occupies a substantial area (3 Mha), demands considerable water resources (MOA 2024). Additionally, milk production is a vital component of the agriculture sector, contributing significantly to the agricultural GDP of the GRB states of Punjab, Haryana, and Uttar Pradesh. In milk production, direct water use includes drinking water for livestock, while indirect water use encompasses the water embedded in green fodder, dry fodder, and concentrates. The water footprint of main crop products includes the water used in producing dry fodder and concentrates.

Water consumption and land productivity vary in rainfed and irrigated crops. In irrigated systems, reliable groundwater availability typically enhances productivity. Comparing PWP across rainfed, canal, and groundwater irrigation systems reveals the trade-offs associated with different water use patterns. Similarly, examining economic water productivity and marginal productivity provides insights into the financial trade-offs of various cropping and water use strategies.

This study aims to assess the spatial and temporal trends in water consumption, water and nutritional productivity in agricultural production, and dietary patterns. It focuses explicitly on the water and food dimensions of the nexus. The energy and environmental components are only partially addressed. They are implicitly considered, as changes in groundwater-irrigated areas and total groundwater withdrawals influence both energy and ecological footprints. A

comprehensive assessment of these components is necessary to understand their interconnectedness and potential solutions fully.

This study examines the temporal and spatial variations in water productivity across districts, states, and sub-basins in the Indian portion of the GRB. It evaluates the role of groundwater in WP, groundwater in CWU, and its subsequent impact on the water-food nexus. It also explores strategies for addressing the challenges for nexus gains.

The following sections provide an overview of the socio-economic and crop production variations within the GRB, followed by an outline of the methodology and data used in the analysis, the variations in WP and CWU within the GRB, and a discussion of the implications of these variations on the WFEE nexus. It finally proposes strategies for addressing the associated challenges.

Ganga River Basin – A Brief

The GRB's Indian region has a high population density, population growth, and income poverty. The GRB's population increased by 14% between 2011 and 2020 (Annex, Table A1). Projections indicate another 47.5% increase in population between 2020 and 2051. Uttar Pradesh, Bihar, and West Bengal with more than 199 million, 104 million, and 91 million people, respectively in 2011, have the highest share of current and projected population and lie entirely in the GRB. The basin is one of South Asia's most severe multidimensional poverty hotspots (Amarasinghe et al. 2016). Multidimensional poverty is a composite measure of inadequate health, education, and standard of living (Alkire and Santos 2010; NITI Aayog 2023). In the GRB, Bihar, Jharkhand, and Uttar Pradesh had the highest Multidimensional Poverty Index (MPI) in 2020, of about 34%, 29%, and 24% of their total population, respectively.

Food grains, including cereals and pulses, account for a large part of the GRB's daily nutritional intake (calories and proteins/person). In 2019/2020, rice, wheat, pulses, and milk provided 79% of the total calorie supply. The main reason for the high food grain consumption was the large population, especially those with low incomes who could not afford to diversify their diets. However, changing income and consumption patterns may decrease the total food grain demand per person (Amarasinghe et al. 2007). As a result, the total demand (for food, feed, seed, etc.) will increase slowly. The projected annual food grain demand between 2000 and 2025 is 1.49% and between

2025 and 2050 it is 1.04%, compared to the growth of 1.99% between 1990 and 2010 (NITI Aayog 2024).

The increasing demand for non-food grain products exceeds population growth by several percentage points. The demand for milk will increase by 50%, and for fruits and vegetables by 7% and 19%, respectively by 2050. The water demand to meet food demand will grow by 42%. Groundwater will contribute to most of this increased demand. Hence, energy demand will increase significantly with continued high groundwater use (Kholod et al. 2021).

Rice and wheat occupy 61% of the cropped area in the GRB (Annex, Table A1). In the western region, rice-wheat in the *kharif* (June-September) and *rabi* (November-March) seasons is the dominant cropping system. In the eastern region, rice-rice and rice-wheat are the dominant cropping systems. Food grains, including cereals and pulses, constitute 59% of the cropped area.

A significant impact of groundwater overexploitation is the decline in the water table, observed across various parts of the GRB (Janardhanan et al. 2023). Water tables in states like Haryana and in western Uttar Pradesh have dropped by several meters over the past few decades, making it increasingly difficult and expensive for farmers to access groundwater (Sangawan 2023). This decline has led to the drying up of wells, reduced water availability for irrigation, and increased energy costs as farmers are forced to pump water from greater depths.

Another consequence is the deterioration in water quality. Overpumping can cause the leaching of contaminants such as arsenic and fluoride into the groundwater. In many areas of the GRB, particularly in the Gangetic Plains, arsenic contamination has become a severe public health issue, affecting millions of people who rely on groundwater for drinking (Chakraborty et al. 2018).

Groundwater depletion has significant ecological impacts too. The depletion of aquifers affects the base flow of rivers, threatening aquatic ecosystems' health (Ahmed et al. 2014). Many rivers and wetlands in the GRB depend on groundwater to maintain flow during the dry season. As groundwater levels drop, these ecosystems risk drying

up, leading to a loss of biodiversity and the degradation of habitats.

Groundwater depletion also has profound social and economic consequences. In regions where agriculture relies heavily on groundwater, declining water levels threaten the livelihoods of millions of smallholder farmers (Srivastava et al. 2017; Zaveri et al. 2016). As the groundwater table declines, becomes more expensive to access and its quality worsens, agricultural productivity and production can decrease, reducing income and food security (Bhattarai et al. 2021). This can exacerbate poverty and short-term migration from rural to urban areas (Zaveri et al. 2020)

Methodology and Data

This study focuses on assessing variations in WP and total consumptive water use (TCWU) to address the WFEE nexus in the GRB. First, the different indicators of WP, including PWP, economic WP (EWP), and nutritional WP (NWP) are defined. NWP includes calories, proteins, and fat. The nutritional content in crop production represents the food component in the nexus.

Water Productivity

The PWP of crops, cropping, or agricultural systems is the production per total crop consumptive use (CWU), i.e., kg/m³. The EWP is the value per total CWU, i.e., \$/m³.

$$PWP = \frac{\text{Crop production}}{\text{Total CWU}} \quad (1)$$

$$EWP = \frac{\text{Value of crop production}}{\text{Total CWU}} \quad (2)$$

The total CWU, or the total crop water requirement (CWR) of a crop is the sum of the actual evapotranspiration (ETA) of four growth periods -- initial, development, middle, and late stage. For crop j:

$$CWR_j = \sum_{k=1}^4 C_{jk} \times \sum_{months1} ETp_{jkl} \times n_{jkl} \quad (3)$$

Where, for crop j, C_{jk} is the crop coefficient of the kth growth period, and n_{jkl} and ETp_{jkl} are the number of days and daily potential evapotranspiration (mm/day) of the lth month in the kth growth period.

$$EFRF_{kl} = \begin{cases} RF_{kl} \times (125 - 0.2 RF_{kl}) / 125 & \text{if } RF_{kl} < 250 \text{ mm} \\ 125 + 0.1 \times RF_{kl} & \text{if } RF_{kl} > 250 \text{ mm} \end{cases} \quad (7)$$

Ideally, we need to introduce a deficit irrigation factor d_k for irrigated crops for the kth growth period to estimate actual evapotranspiration (equation 4). The deficit irrigation factor is important in severe water-scarce areas, where crops rarely meet the entire irrigation requirement. However, this factor is not available for any region. Therefore, we assumed no deficit irrigation in this analysis, i.e., $d_k=1$, or that the irrigation supply meets the full irrigation requirement.

$$CWU_j = CWR_j = \sum_{k=1}^4 C_{jk} \times d_k \sum_{months1} ETp_{jkl} \times n_{jkl} \quad (4)$$

For rainfed crops, the CWU is the minimum of CWR and the effective rainfall at the root zone, i.e., for crop j,

$$CWU_j^{RF} = \min \{CWR_j, EFRF_j\} \quad (5)$$

Where the effective rainfall EFRFj is

$$EFRF_j = \sum_{k=1}^4 \sum_{months1} \frac{n_{jkl}}{N_{kl}} EFRF_{jkl} \quad (6)$$

Where: EFRFjkl is the effective rainfall and N_{kl} is the number of days of the lth month of the kth growing period. The effective rainfall for the lth month of the kth growth period, estimated from the United States Geological Service (USGS) method, is:

The analysis includes estimating the CWU of the green fodder used for livestock production. The CWU of concentrate feed (cereals, oilseed cakes, etc.) and dry fodder (rice and wheat straw) are already accounted for in primary crop production.

Nutritional Water Productivity

The nutritional water productivity (NWP) of crops is the nutritional content available per cubic meter of water consumed to produce the crop. It is the product of PWP and the nutrition content in each kilogram of crop product, i.e., for the i th nutrition component:

$$NWP_i = PWP \times NC_i \quad (8)$$

Where, NC_i , the conversion ratio (nutritional unit/kg), is the nutrition content in a unit of crop or livestock products. The conversion ratios of crops to calories, proteins, and fat using the estimates provided in the Indian food composition tables (Longvah et al. 2017) have been used.

Nutritional Surplus/Deficit

Nutritional surplus or deficit refers to the difference between nutritional supply and consumption. Nutrition supply is calculated by multiplying the nutritional conversion factor by annual food production. Similarly, nutrition consumption is determined by multiplying the nutritional conversion factor by annual food consumption.

Energy Use

The energy use contributing to the nexus, which this paper does not address directly, includes the energy consumed for pumping groundwater for crop production. Total energy consumption depends on the volume of water abstracted, dynamic head (average depth to groundwater table + average drawdown + frictional head loss), energy source (electricity, diesel, solar), and pump efficiency. These factors are useful for understanding the dynamics of energy needs for pumping in groundwater-depleting areas and the implications of subsidized energy supply for groundwater abstraction.

Unsustainable Groundwater Use

We define the groundwater exploitation ratio as the ratio of groundwater consumptive water use (GWCWU) to extractable resources to assess unsustainable groundwater use. The GWCWU of a district is estimated as the product of the total irrigation CWU and the ratio of the district's net groundwater irrigated area to net irrigated area (NIA). The net groundwater irrigated area includes areas with deep and shallow tubewells for extracting groundwater.

The Central Ground Water Board (CGWB) of India uses the ratio of groundwater extraction (withdrawals) to extractable resources, known as the groundwater extraction ratio, to classify districts based on the sustainability of groundwater use (CGWB 2022). According to this classification, districts with extraction ratios above 100% are labeled as overexploited, those between 90% and 100% as critical, those between 70% and 90% as semi-critical, and those below 70% as practicing safe groundwater withdrawals.

However, this classification has limitations for assessing sustainable groundwater use. Groundwater extraction or withdrawals can include substantial reuse of water already withdrawn for the same or different purposes. As a result, the reported groundwater extraction at higher spatial scales, such as districts or river basins, often exceeds the actual GWCWU. Therefore, the ratio of groundwater extractions to extractable resources might be a misleading indicator of unsustainable water use, particularly in water-scarce areas. To address this issue, this study employed the groundwater exploitation ratio as a more accurate measure of unsustainable groundwater use. This approach helps better capture the true extent of groundwater dependency and stress in different regions. The reduced exploitation ratio addresses groundwater depletion, while reduced exploitation and extraction ratios address unsustainable groundwater depletion and high energy use.

Following the CGWB nomenclature, this study classified districts with a groundwater exploitation ratio of over 90% as highly overexploited, those between 75% and 90% as overexploited, those between 60% and 75% as critical, those between 45% and 60% as semi-critical, and those below 45% as safe. To compare with the CGWB classification, assuming a groundwater irrigation efficiency of approximately 65%, exploitation ratios above 90%, 75%, 60%, and 40% have extraction ratios above 138%, 115%, 92%, and 69%, respectively.

Unraveling the Nexus

Pathways to unravel the nexus' externalities on water and food were explored by developing groundwater use, crop and food production, and available nutritional supply scenarios. The energy and environmental footprints are implicitly addressed in changes in cropping patterns and groundwater irrigated areas. GWCWU was calculated at the district level, and is a product of irrigation CWU and the percentage of groundwater irrigated area. The following scenarios of GWCWU were developed:

1. A reduction in GWCWU to bring GWCWU to a sustainable level (i.e. below extractable resources), and assessing the impacts on crop area, production, and nutritional supply.

2. A reduction in crop production and nutritional supply with reduced GWCWU and yield gap.
3. A reduction in GWCWU and area under increased efficiency of rainfall use.
4. A reduction in surface water withdrawals, but an increase in surface irrigation efficiencies to increase surface irrigation CWU, thereby reducing groundwater CWU.
5. A reduction in GWCWU, area, production, nutritional supply, and value of production under various GWCWU scenarios.
6. Scenarios of crop diversification which can mitigate the losses of value of production under decreased GWCWU and area scenarios.

Data and Analysis

The analysis was conducted using Microsoft Excel software and was based on the data collected for the Water Productivity Atlas (Amarasinghe et al. 2024). Time series data between 1999 and 2020; published by the Directorate of Economics and Statistics (DES) of the Ministry of Agriculture (MOA 2024) (available at <https://data.desagri.gov.in/website/crops-apy-report-web>). The analysis used the following district-level land use and crop production (area and yield) statistics:

1. The cultivated and irrigated area of seasonal crops that include cereals (rice, wheat, maize, sorghum [jowar], pearl millet [bajra], finger millet [ragi], barley, and other coarse cereals); pulses (pigeonpea [arhar], chickpea [gram], black gram [urad]); oilseeds (groundnut, soyabean, mustard/rapeseed, and sesame seed); potato, onions, other seasonal vegetables, chili; and annual crops such as sugarcane, cotton, spices (ginger, turmeric); fruits (banana, mango, papaya, grapes, and apple); and fodder from the DES database. These crops comprise most of the GRB cropped area (95%). Only annual production data was available for some seasonal crops. To estimate sugarcane production, the study used the conversion ratio of sugarcane to sugar yield as 11%.
2. Net and gross irrigated area (GIA) under canals, tanks, open wells, tubewells, and other sources from land use patterns from the DES database.
3. Monthly rainfall (Indian Meteorological Department [IMD]).
4. ETp (potential evapotranspiration) (district-level estimates from the monthly ETp grids at 0.5° resolution) are available at the Climate Research Unit of University of East Anglia (<https://crudata.uea.ac.uk/cru/data/hrg/>, Harris et al. 2020).
5. Crop coefficient and crop growth periods from the FAO Irrigation and Drainage Paper No 56 (Allen et al. 1998).
6. Extractable/dynamic groundwater resources from India's CGWB (CGWB 2022).
7. Per capita food consumption data from National Sample Survey reports (NSSO 2025).
8. Nutritional conversion ratios from food composition tables published by the National Institute of Nutrition (Longvah et al. 2017).

The inconsistent reporting and missing data on seasonal cropped and irrigated areas and production for some years in the DES crop production database were corrected by comparing them with the trends available for years when data were reliable. Missing data were presented as the average of two years before and after the missing year.

Results

GWCWU in the GRB

The GRB's GWCWU increased by 43% between 2000 and 2020 (Figure 2[A]). With this increase, groundwater, surface water, and rainfall CWU were 34%, 12%, and 54% of the total CWU, respectively. The groundwater exploitation ratio of the basin reached about 66% of the extractable resources in 2019-

2020, indicating that groundwater exploitation in the basin surpassed the critical exploitation level.

However, groundwater exploitation varies significantly within the basin. Most groundwater overexploited districts are in the northwestern, southwestern, and northern parts of the GRB (Figure 2[B]).

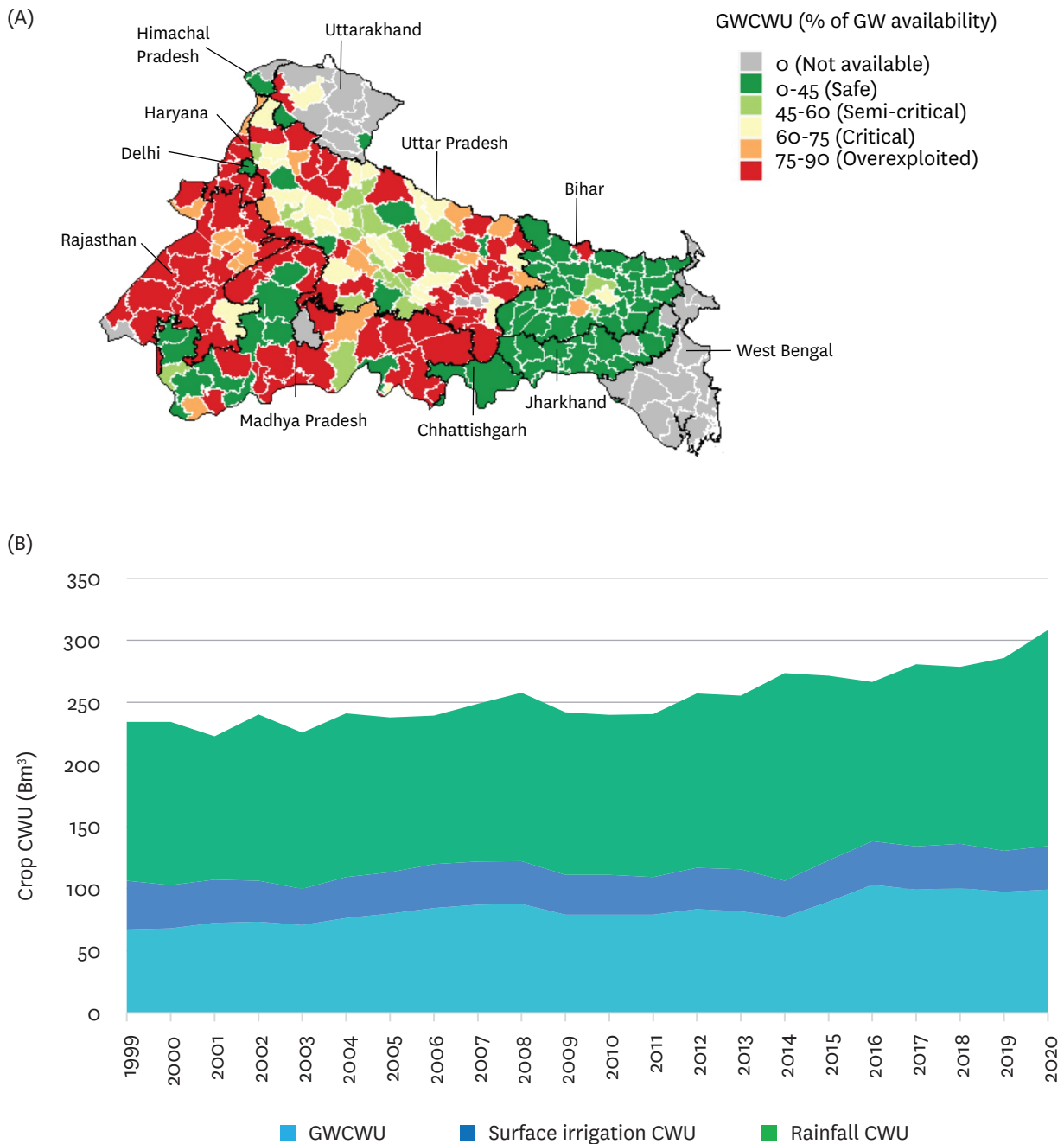


Figure 2. (A) GWCWU of crop production as a percentage of the total resources in the GRB; (B) Groundwater irrigation, surface irrigation, and rainfall CWU trends in crop production in the GRB.

Source: Authors' estimation based on the data collected for the Water Productivity Atlas.

Groundwater Overexploitation

There is severe groundwater overexploitation in 91 districts (~38%) in the GRB, with 80 districts (34%) that are highly overexploited (group 1) and 11 (4%) that are overexploited

(group 2) (Table 1). Groups 3 and 4, with 19 and 20 districts, respectively, have critical and semi-critical groundwater use. About a third (75) of the districts have safe groundwater use (group 5).

Table 1. Distribution of districts across states falling under various groundwater exploitation classes.

GWCWU (% of groundwater availability)	State											Total
	Bihar	Chhattisgarh	Haryana	Himachal Pradesh	Delhi	Jharkhand	Madhya Pradesh	Rajasthan	Uttar Pradesh	Uttarakhand	West Bengal	
Group 1 (highly overexploited)	1	0	11	0	0	0	22	19	26	1	0	80
Group 2 (overexploited)	1	0	2	0	0	0	2	0	6	0	0	11
Group 3 (critical)	1	0	0	0	0	0	1	0	16	1	0	19
Group 4 (semi-critical)	2	0	0	0	0	0	3	0	15	0	0	20
Group 5 (safe)	32	4	1	2	1	19	9	0	5	2	0	75
Group 6 (not available)	0	0	0	2	0	0	0	1	2	9	18	32
GRB	37	4	14	4	1	19	37	20	70	13	18	237

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

The most overexploited districts are in Haryana, Madhya Pradesh, Rajasthan, and Uttar Pradesh. Most districts in Bihar and Jharkhand, which lie entirely in the GRB, have safe groundwater use. Only three districts in Bihar are in the critical to highly overexploited categories. In contrast, 90% of the districts in Uttar Pradesh, which also lie entirely inside the GRB, have critical to highly overexploited groundwater resources. Group 6 mainly includes West Bengal's districts; data on their groundwater irrigated area was unavailable for this analysis. However, the CGWB groundwater resources use assessment report (CGWB 2022) shows only one overexploited district in West Bengal.

Across states, the groundwater exploitation ratios in Haryana, Rajasthan, and Uttar Pradesh in the GRB exceed 90% (Figure 3[A]). In fact, the exploitation ratio in Haryana and Rajasthan is more than 100%. Although some districts in Haryana and Uttar Pradesh are not currently highly overexploited (Figure 2[B]), their overall groundwater depletion ratios exceed

extractable groundwater resources by more than 90%. As a result, these states are categorized as highly overexploited (Figures 3[A] and [B]). The riparian region of Madhya Pradesh in the GRB has more than 85% exploitation ratio. Bihar, Jharkhand, and part of Chhattisgarh in the eastern region have an exploitation ratio below 25%.

Groundwater is the source of irrigation in over 70% of the NIA in most CWU groups (Table 2). Unsustainable groundwater use contributes substantially to crop production and nutritional supply in the GRB. Across sub-basins, upper and middle Ganga sub-basins have exploited groundwater resources. Specifically, the eight sub-basins – Yamuna upper, Yamuna middle, Chambal upper, Chambal lower, Banas, Kalisindh, Ramganga, and Above Ramganga have severely overexploited groundwater resources. Four sub-basins -- Yamuna lower, Ghaghara to Gomati, Gomati to Muzaffarnagar, and Gomati have overexploited groundwater resources (Figure 3[B], see Figure 1 for sub-basin names).

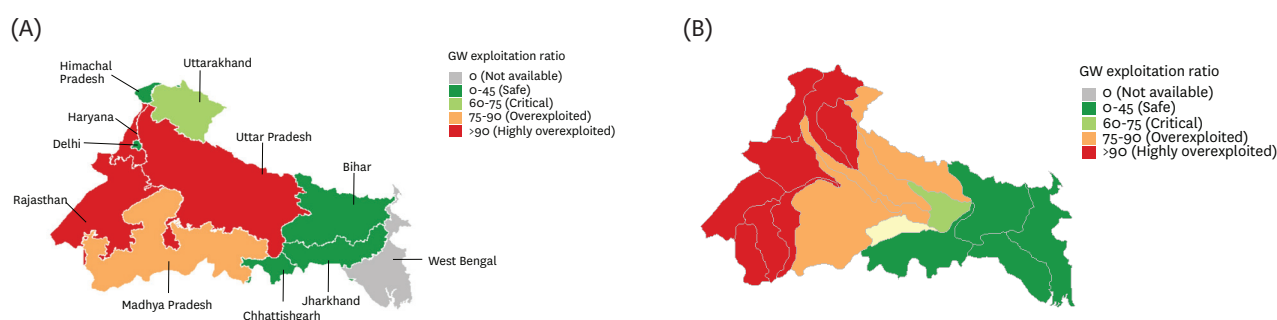


Figure 3. Groundwater exploitation ratio of (A) states and (B) sub-basins.

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

Irrigation is available for about half the cultivated areas in the GRB (Table 2, column 4). However, groundwater is the prominent source of irrigation, accounting for 79% of the total irrigated area. A similar variation exists for all

groups, except in Group 5, where groundwater irrigation is available only for about 60% of the gross irrigated area (Table 2, column 3).

Table 2. Groundwater irrigated areas and nutritional surpluses in water use groups.

Groundwater CWU (% of groundwater availability)	Districts	NGWIA (% of NIA) ¹	GIA (% of GCA) ²	Nutritional surplus/deficit of all crops (%) ³			Nutritional surplus/deficits of rice, wheat, and sugarcane (%) ³		
				Number	%	%	Calorie	Proteins	Fat
Group 1 (highly overexploited)	80	85	52	305	338	313	197	199	202
Group 2 (overexploited)	11	72	48	357	418	92	266	267	269
Group 3 (critical)	19	84	48	232	270	101	168	167	167
Group 4 (semi-critical)	20	76	52	276	325	145	186	193	200
Group 5 (safe)	75	60	40	111	132	67	92	94	96
Group 6 (NA ⁴)	32	NA	NA	146	155	112	131	122	107
GRB	237	79	49	210	244	159	151	155	158

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

Notes:

¹ NGWIA is the net groundwater irrigated area and NIA is the net irrigated area.

² GIA is the gross irrigated area and GCA is the gross cropped area.

³ Nutritional surplus/deficit is the ratio of nutrition (calories, proteins, and fat) available from production and the nutritional intake from food consumed.

⁴ NA denotes data for groundwater irrigated area is not available for districts in West Bengal.

The nutritional surplus/deficit ratio is the ratio of nutrition (carbohydrates, proteins, and fat) available in the production to the nutritional intake in the food consumed. The GRB has substantial nutritional surpluses of energy (in calories), proteins, and fat from the crops produced. The calorie supply of total food crops produced in the overexploited districts is more than 300% of the calorie intake from food consumed by the population (Table 2, column 5), which in critical and semi-critical groups exceeds 200%. Similar surpluses are available in proteins and fat (Table 2, columns 6 and 7). Most GRB districts in Haryana, Uttar Pradesh, Madhya Pradesh, and Rajasthan

belong to the first four groups. However, group 5, with safe GWCWU, has low nutritional surpluses. Most of these districts are in the eastern GRB in Bihar, Jharkhand, and Chhattisgarh.

The nutritional supply of all crops includes nutritional supply from both food and feed crops (Table 2). The feed crops include maize, sorghum, pearl millet, etc. Since the nutritional consumption or food intake from animal products is not accounted for in this analysis, the nutritional surpluses of all crops do not show the real impacts of groundwater overexploitation.

Rice, wheat, and sugarcane account for most of the groundwater depletion in the GRB, contributing to about 87% of the groundwater CWU (Table 3). These three crops constitute 59% of the cropped area but

82% of the irrigated area. They also account for 72% of the GRB's total CWU but, most importantly, about 90% of the total irrigation and groundwater CWUs (Table 3).

Table 3. Area and total CWU of rice, wheat, and sugarcane in the GRB.

Factors	Rice	Wheat	Sugarcane	All crops ¹	Rice + wheat + sugarcane (% of all crops)
Cropped area (Mha)	16.7	20.4	2.8	67.9	59
Irrigated area (Mha)	11.3	19.9	2.6	43.2	82
Total CWU (Bm ³)	79.1	75.2	41.0	276.8	72
Total irrigation CWU (Bm ³)	17.2	67.0	28.9	129.5	90
Groundwater CWU (Bm ³)	9.8	51.0	24.8	98.7	87
Group 1 (highly overexploited)	4.2	29.5	21.3	64.3	85
Group 2 (overexploited)	0.6	2.6	0.7	4.5	87
Group 3 (critical)	2.0	7.7	0.6	11.2	92
Group 4 (semi-critical)	1.1	5.9	1.2	9.1	90
Group 5 (safe)	1.8	5.3	1.2	9.7	86
Group 6 (NA)	NA ²	NA	NA	NA	NA

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

Notes: ¹ All crops include rice, wheat, sugarcane, and other major coarse cereals, pulses, oilseeds, roots and tubers, spices and condiments, fruits and vegetables, cotton, and fodder.

² NA denotes not available.

Table 3 illustrates that groundwater is a critical resource for food production throughout the GRB. For example, the three crops account for 85% of the total groundwater CWU in the highly overexploited group. A similar use pattern exists in the safe group, where the three crops still account for 86% of the groundwater CWU.

- Contrary to common belief, GWCWU from rice (about 10% of total GWCWU [*kharif* rice - 9.6%, *rabi* rice - 0.4%]) is much lower than that of *rabi* wheat (52%) and annual sugarcane (25% throughout the year). Further analysis shows that of the total CWU of 79.1 Bm³ of rice, groundwater and surface water irrigation CWUs constitute only 9.8 Bm³ and 7.4 Bm³, respectively. The rainfall CWU of rice is 61.9 Bm³. This is because 89% of the rice cultivated area is in the *kharif* season (Annex, Table A2), where rainfall is substantially higher than the potential evapotranspiration. In fact, the significantly higher rainfall CWU of rice (78% of the total), primarily during the *kharif* season, indicates that groundwater was used mainly as supplemental irrigation in critical periods of crop growth.
- In contrast, groundwater was crucial in sustaining wheat and sugarcane crops during the *rabi* season. It is important to note that although the *rabi* rice cropped areas contributed to a small percentage of the total GWCWU, the crop would not have survived without irrigation because

the total irrigation requirement per unit area is substantially higher than that of the wheat crop. Furthermore, irrigation was a critical input that contributed to higher rice yield growth than in sugarcane. Also, the fact that groundwater contributed to 13% of the rice CWU shows that effective rainfall significantly contributed to rice production. This is understandable given that 89% of the GRB's rice production is in the *kharif* season when the southwest monsoon in June-July provides water to the root zone for crop growth.

- The contribution of rice to total groundwater depletion is even smaller – 7% in group 1 and 13% in group 2, compared to wheat with 46% and 58%, and sugarcane with 33% and 15% (Table 3). As mentioned above, the reason for these differences is that rice is mainly grown in the *kharif* season, when effective rainfall or green water contribution is substantial. Wheat is a *rabi* season crop with most of its CWU from irrigation, mainly from groundwater. Sugarcane is an annual crop, with a large part of the CWU outside the *kharif* season from irrigation. Most group 1 and 2 districts are mainly in the western GRB (Annex, Table A3), with high water demand during the *rabi* season. In contrast, groups 4 to 6 are in the eastern and central regions with a higher effective rainfall contribution.
- Substantial food production and nutritional surpluses in the GRB are from unsustainable

groundwater use. The 110 districts in the first three groups account for 88% of the groundwater CWU, of which rice, wheat, and sugarcane account for 78% (Annex, Table A3). The highly overexploited group alone accounts for 63% of the GWCWU.

- Of the 110 districts critical to overexploited groundwater use, 48 are in Uttar Pradesh, 25 in Madhya Pradesh, 19 in Rajasthan, 13 in Haryana, 3 in Bihar, and 2 in Uttarakhand. The contributions of these districts to sugarcane GWCWU are 40% in Uttar Pradesh, 30% in Madhya Pradesh, 15% in Haryana, 13% in Rajasthan, and less than 1% in Bihar and Uttarakhand (Annex, Table A3).

High groundwater exploitation leading to water scarcity and unsustainable use is a critical issue in the first three groups of districts. Therefore, any strategy to reduce GWCWU in these critical and overexploited areas must address water use in rice, wheat, and sugarcane cultivation. To mitigate the impacts of reducing GWCWU on crop production and income, the districts should focus on improving physical and economic water productivity—achieving greater crop yield and value per water unit—for all crops, especially rice, wheat, and sugarcane. In contrast, 82 districts in groups 4 and 5, and potentially many in group 6 (primarily in West Bengal), have the potential to increase groundwater use further to enhance crop production and nutritional supply within the basin, with adequate regulations for not reaching unsustainable groundwater use.

Both anthropogenic and natural factors contribute to groundwater overexploitation in the Ganges. Anthropogenically, the large groundwater irrigated areas of wheat, sugarcane, and rice contributed most to groundwater overexploitation, especially during the *rabi* and summer seasons. The production and production surpluses of these crops contributed to the livelihood security of rural farmers in the GRB and to food security in food-deficit areas within and outside the GRB.

The natural factors include monsoon rainfall between June and September that contributes to much of the groundwater recharge in the GRB. The highest irrigation needs are in the *rabi* and summer seasons, which receive very little rainfall. Farmers withdraw groundwater when rainfall or surface water supply is insufficient to meet crop water requirements. However, much of the groundwater is recharged from monsoon rainfall and is not adequate to meet the huge irrigation demand and growing water needs of the domestic and industrial sectors. In years with low rainfall, which are expected to occur more frequently with climate change, groundwater depletion is more pronounced. Moreover, in areas with shallow aquifers, the capacity for groundwater recharge is low.

Before discussing how potential WP improvements can address the nexus, energy use for and cost of groundwater

extraction, and spatial and temporal variation of WP and CWU in rice, wheat, sugarcane, and major crop categories are examined. The energy used for groundwater abstraction depends on many factors. However, on average, 1 kWh is used for pumping 1 m³ of groundwater (Rajan and Ghosh 2019). The energy requirement is much higher in the western region and can be as high as 3 kWh/m³ of groundwater extracted. At the average rate of 1 kWh/m³ and with 60% irrigation application efficiency, the GRB may have used 165 billion kWh of energy/year to meet the GWCWU requirement in 2018-2020, and the overexploited groups contributed to about 70% of the total energy used.

The cost of groundwater extraction varies from USD 0–5/MWh in the western region due to highly subsidized or free electricity supply (Shah et al. 2018). In the eastern region, which mainly has diesel-powered pumps, the cost of groundwater extraction is USD 355/MWh. Gulati et al. (2019) reported that the average cost of groundwater extraction in Uttar Pradesh is INR 0.64/m³ with electricity subsidy and INR 1.09/m³ without electricity subsidy (USD 1 = INR 80). The comparable costs in Bihar are INR 0.93/m³ and INR 1.26/m³ and in Rajasthan INR 2.21/m³ and INR 3.27/m³, respectively. The pumping cost with diesel pumps is INR 1.90/m³ in Uttar Pradesh and INR 2.08/m³ in Bihar. The output per unit of energy use (INR/kWh) in Bihar, West Bengal, and Assam is higher than in highly overexploited states in western India (Rajan and Ghosh 2019). States with the highest groundwater-extracted districts have lower output per unit of energy use, although they contribute to higher crop yields, food production, and surpluses. These studies show that with subsidized or free electricity supply, farmers do not feel the cost of groundwater abstraction and are contributing to strengthening the WFEE nexus.

Water Productivity Variations

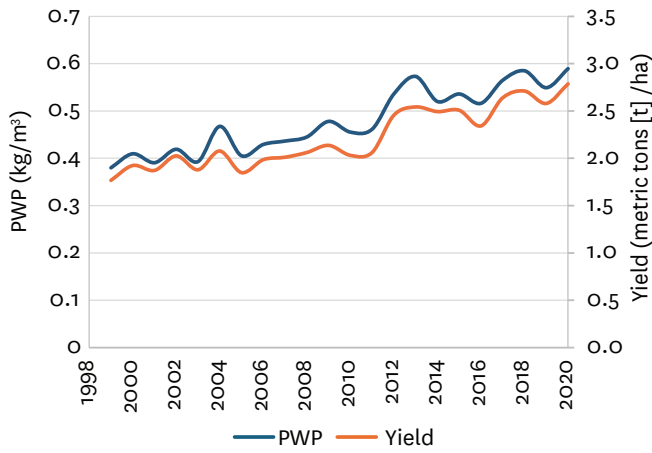
Rice, Wheat, and Sugarcane PWP, EWP, and NWP

This section explores the temporal and spatial variations in PWP and yields of rice, wheat, and sugar. These three crops contribute to about 90% of the irrigation CWU of all crops. Figures 4A.1 to 4A.3 show the trends in yield and PWP and Figures 4B.1 to 4B.3 show the trends in irrigated and rainfed areas contributing to PWP and yield trends of rice, wheat, and sugarcane. Figures 4C.1 to 4C.3 and 4D.1 to 4D.3 show the spatial variations in PWP and yield, respectively.

Temporally, the yield increases in rice, wheat, and sugarcane (~58%, 45%, and 42%, respectively) were the primary drivers of PWP growth (~58%, 42%, and 37%, respectively) (Figures 4A.1 to 4A.3). The discussion on rice in this section focuses on the *khariif* season, as it accounts for 95% of the rice-cropped area in the GRB.

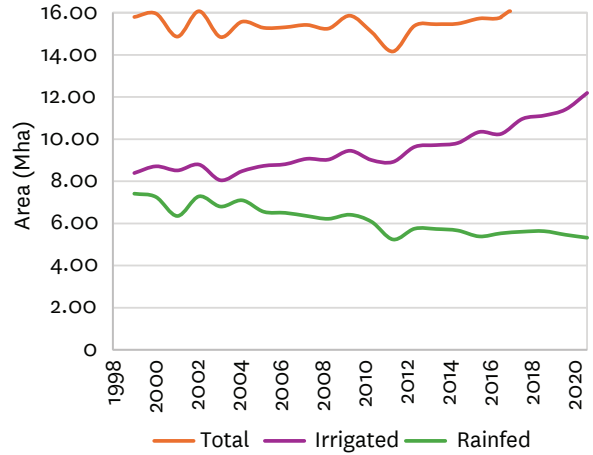
4A. Temporal variation in yield and PWP

4A.1 Rice

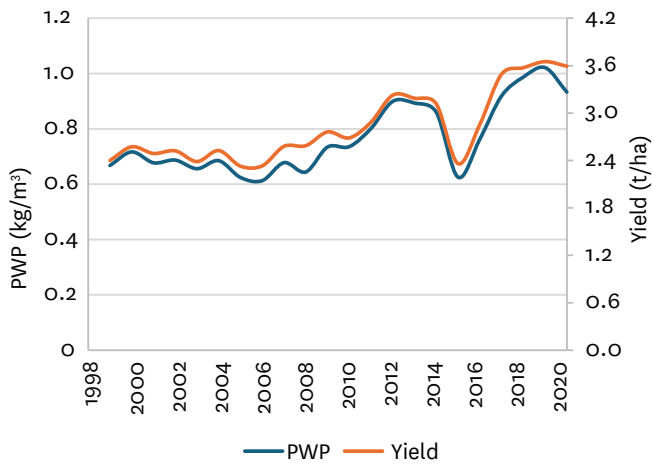


4B. Temporal variation in total, irrigated and rainfed areas

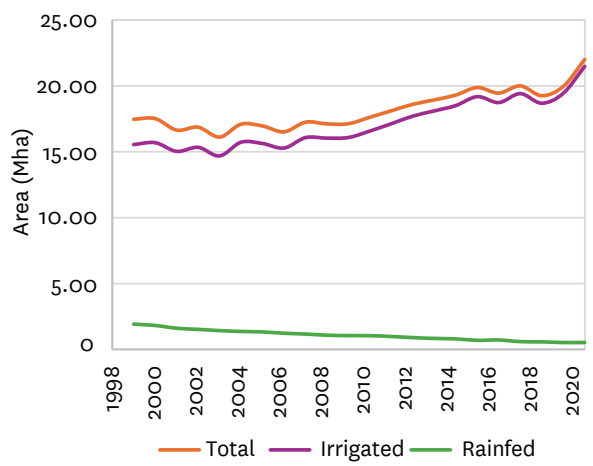
4B.1 Rice



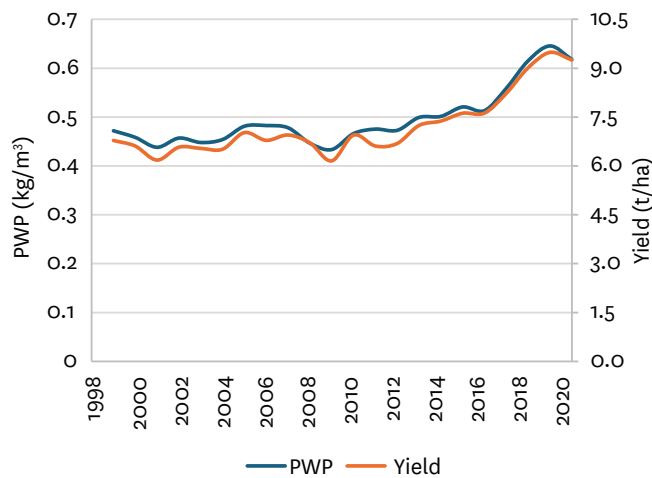
4A.2. Wheat



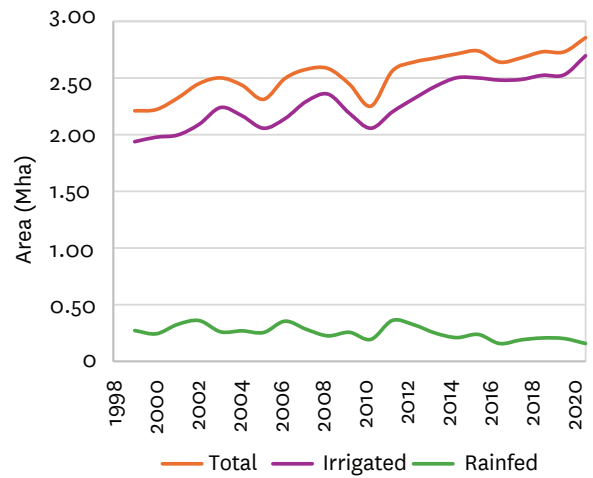
4B.2. Wheat



4A.3. Sugarcane

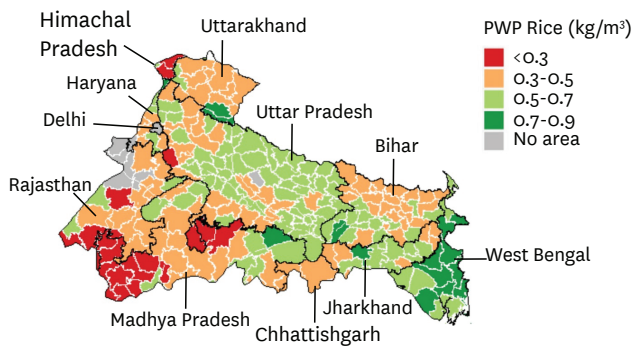


4B.3. Sugarcane



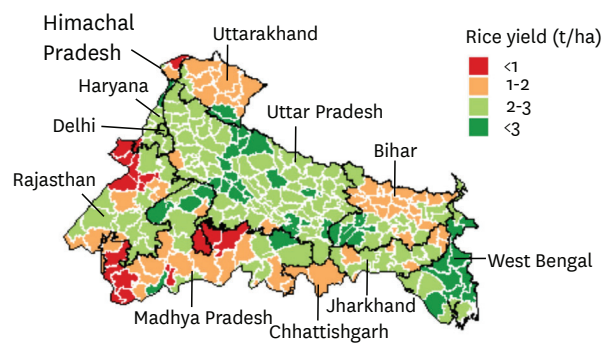
4C. Spatial variation in PWP

4C.1 Rice PWP

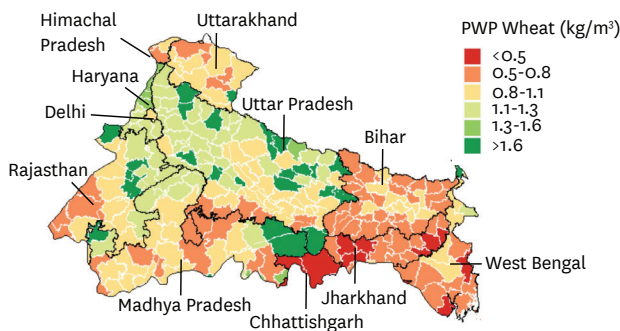


4D. Spatial variation in yield

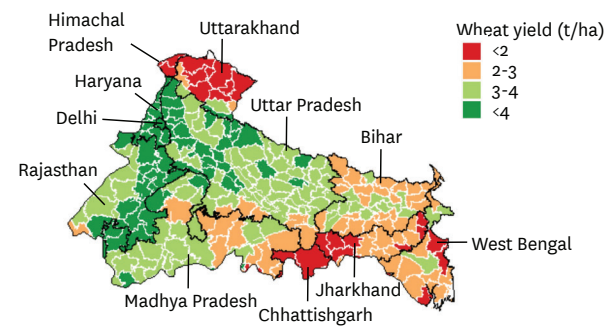
4D.1. Rice yield



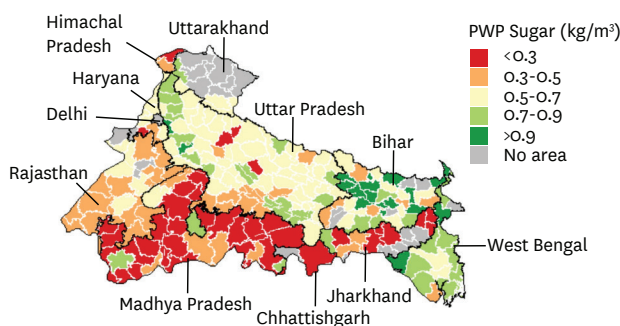
4C.2 Wheat



4D.2. Wheat



4C.3. Sugar



4D.3. Sugar

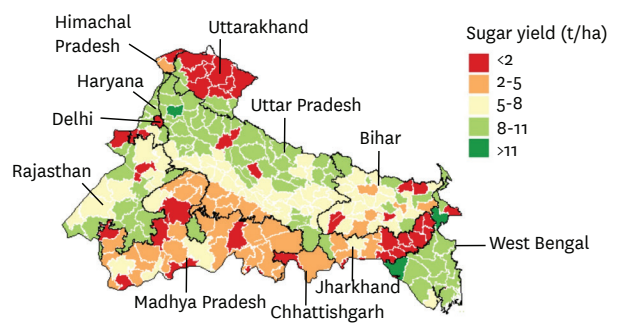


Figure 4. Temporal variation in (A) yield and PWP, and (B) total, irrigated and rainfed areas; and spatial variation in (C) PWP, and (D) yield of rice, wheat and sugarcane.

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

Note: Sugarcane yield is sugar equivalent yield (1 kg sugar = 0.11 kg of sugarcane).

- Irrigation was the key factor driving area growth in rice, wheat, and sugarcane crops. While rainfed wheat and sugarcane areas decreased by 70% and 33% between 2000 and 2020, respectively (Figures 4B.2 and 4B.3), the total cropped areas of wheat and sugarcane increased by 19% and 23%, respectively, during the same period. The total rainfed area of rice decreased by 1.69 Mha, while the total cropped area increased by 1.06 Mha. This shows that irrigation, sourced mainly from

- groundwater, helped compensate for the water deficit in previously rainfed areas and also helped add new areas under the two crops.
- The marginally lower growth in PWP indicates that while reliable water supply through irrigation generally facilitates more efficient management of other inputs, leading to higher yield growth, irrigation supply also contributed to increasing CWU of all crops. Much of the focus was on achieving higher yields rather than on decreasing irrigation CWU.

Spatially, a substantial variation in PWP (Figures 4C.1 to 4C.3) and yield (Figures 4D.1 to 4D.3) remains.

- The average PWP of rice was 0.58 kg/m³ but varied from 0.04 kg/m³ to 0.88 kg/m³ across districts. All except 22 districts in Rajasthan, Madhya Pradesh, and Himachal Pradesh have more than 1,000 ha of rice-cropped area. Across states, West Bengal and Haryana have the largest PWP (~0.63 kg/m³ and 0.61 kg/m³, respectively), followed by Uttar Pradesh, Uttarakhand, Bihar, and Madhya Pradesh (~0.55 kg/m³). Rajasthan has the lowest PWP (~0.41 kg/m³).
- The average PWP of wheat was 0.98 kg/m³ and varied from 0.25 kg/m³ to 1.86 kg/m³ across districts. Across states, the highest PWP was in Haryana (1.40 kg/m³), followed by Uttar Pradesh (1.05 kg/m³), Rajasthan, West Bengal, Uttarakhand, and Madhya Pradesh (~0.90 kg/m³), and Bihar (0.75 kg/m³).
- The average PWP of sugar was 0.63 kg/m³ and varied from 0.09 kg/m³ to 1.90 kg/m³.

Unlike rice and wheat, only a few districts lead in sugarcane production. In the GRB, only 87 districts have more than 1,000 ha under sugarcane, of which 57 are in Uttar Pradesh and 11 are in Bihar. These districts account for 96% of total sugarcane production.

Seasonally, the *rabi* season has higher PWP and EWP, primarily due to irrigation, particularly groundwater irrigation. However, the *kharif* season registered higher PWP and EWP growth (Table 4). The share of the *kharif* season irrigated area increased from 38% to 44%, which in absolute terms was about 3.71 Mha, compared to 0.22 Mha in the *rabi* season. Assured supplemental irrigation, mainly through groundwater, helped increase *kharif* rice yield by 54%, compared to 45% in the *rabi* season.

Most *rabi* season rice areas (called *boro* rice) receive irrigation. The share of irrigation to the total *rabi* season rice area increased from 89% to 97%. The *rabi* season rice yield of 3.51 t/ha is 34% higher than the *kharif* rice yield.

Table 4. Physical, economic, and nutritional WP of cereals¹.

Water productivity	1999-2001	2018-2020	Growth (%)
PWP - Total	0.51	0.74	44
PWP (<i>kharif</i>)	0.36	0.53	50
PWP (<i>rabi</i>)	0.71	0.98	38
EWP (USD/m ³)	0.22	0.31	41
EWP (<i>kharif</i>)	0.21	0.29	37
EWP (<i>rabi</i>)	0.24	0.34	49
NWPC ² (1,000 Kcal/m ³)	1.48	2.23	50
NWPP ² (gm/m ³)	38.12	57.82	52
NWPF ² (gm/m ³)	6.78	10.45	54

Source: Authors' estimates.

Notes: ¹ Cereals include rice, wheat, maize, pearl millet, finger millet, barley, and other coarse cereals.

² NWPC, NWPP, and NWPF are the nutritional water productivity of calories, proteins, and fat, respectively.

Cereals, Pulses, and Oilseeds PWP

Temporal variation in PWP, yield, irrigated and rainfed areas of cereals and pulses in the GRB are shown in Figures 5A.1, 5A.2, 5B.1, and 5B.2, respectively. Spatial variations in PWP and yield of cereals and pulses across districts and sub-basins are shown in Figures 5A.3, 5A.4, 5B.3, and 5B.4.

Cereals' PWP growth (~52%) was marginally lower than yield growth (~54%) (Figure 5A.1). This is primarily due to the low growth in total and irrigated area (Figure 5A.2), and hence total and irrigation CWU (Figure 5). The latter was due to lower additional irrigation CWU requirement, with increased irrigated cereal area (~28%) replacing much of the decreased rainfed cereal area (~24%). Also, much of the irrigation CWU growth was in the *kharif* season cereals, especially rice.

The average cereal PWP in 2018-20 was 0.74 kg/m³. It varied from 0.16 kg/m³ to 1.05 kg/m³ across districts (Figure 5A.3), and 0.64 kg/m³ to 0.91 kg/m³ across sub-basins (Figure 5A.4).

Variation in PWP across states (Table 5) revealed the following:

- The cereal PWP varied from 0.45 kg/m³ to 0.95 kg/m³. The highest is in Haryana (0.95 kg/m³), followed by Delhi (0.88 kg/m³), Uttar Pradesh, Madhya Pradesh, and Rajasthan (about 0.83 kg/m³). The eastern region states—Chhattisgarh, Jharkhand, and Bihar—have lower PWP (< 0.69 kg/m³). Rice and wheat are the major cereals, comprising 88% of the area.

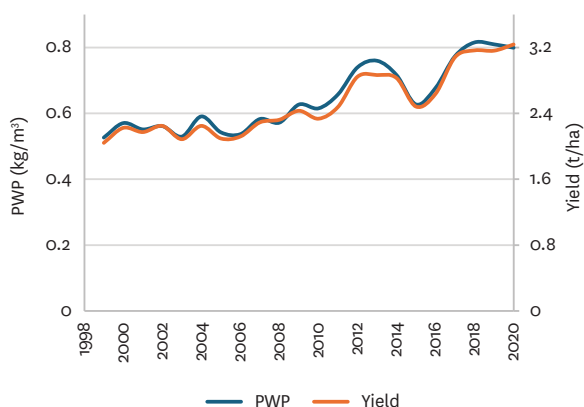
- The highest rice PWP is in West Bengal (0.70 kg/m³), followed by Bihar, Jharkhand, Uttar Pradesh, Haryana, and Uttarakhand (0.52 kg/m³ to 0.57 kg/m³). West Bengal and Bihar have substantial areas under irrigated rice in *rabi* and the summer season, and substantially higher yield and PWP.
- The highest wheat PWP is in Haryana (1.31 kg/m³), followed by Uttar Pradesh (1.05 kg/m³). Wheat PWP is between 0.85 kg/m³ and 0.99 kg/m³ in West Bengal, Delhi, Rajasthan, Madhya Pradesh, and Uttarakhand. The eastern GRB states of Bihar, Jharkhand, and Chhattisgarh, and Himachal Pradesh in the Western GRB have relatively lower wheat PWP.

Maize and pearl millet are the other major cereals, comprising 12% of the cereal area. Maize for animal feed accounts for 45% of total maize production and 60% of the total cereals feed. In 2020, the feed share of cereals was 6%, while that of pulses was 13% (FAO 2023).

The average PWP of maize and pearl millet are 1.09 kg/m³ and 0.88 kg/m³, respectively. Maize PWP varies from 2.28 kg/m³ in West Bengal, 2.22 kg/m³ in Delhi, and 1.60 kg/m³ in Bihar to below 0.92 kg/m³ in all other states. In pearl millet, Delhi, Madhya Pradesh, and Uttar Pradesh have a PWP higher than 1.0 kg/m³, followed by Haryana with 0.89 kg/m³.

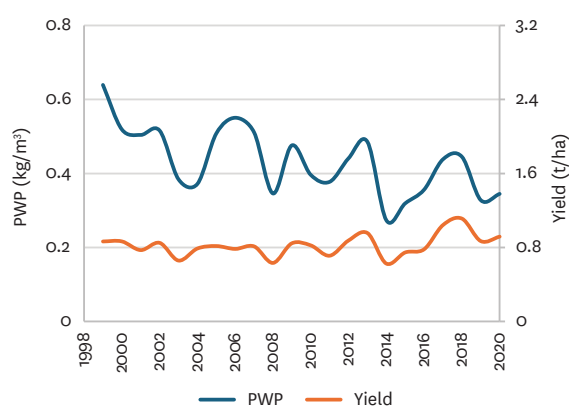
5A. Cereals

5A.1. Temporal variation in PWP and yield

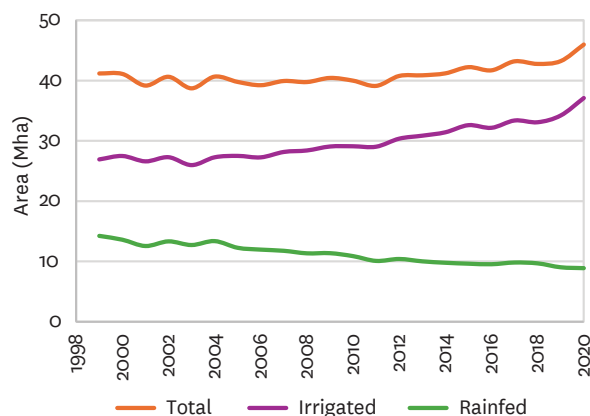


5B. Pulses

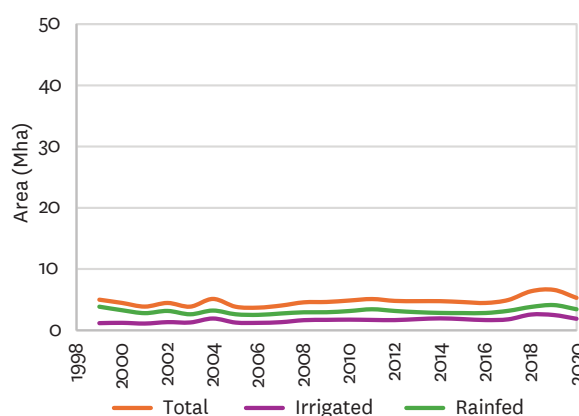
5B.1. Temporal variation in PWP and yield



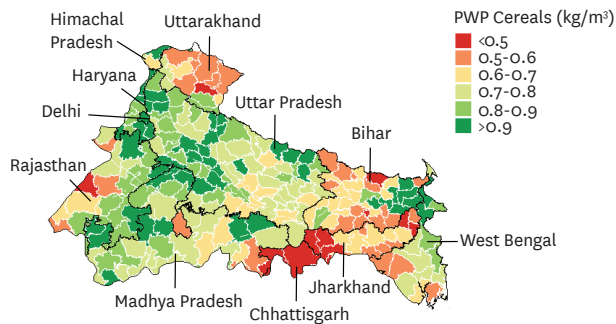
5A.2. Irrigated and rainfed area



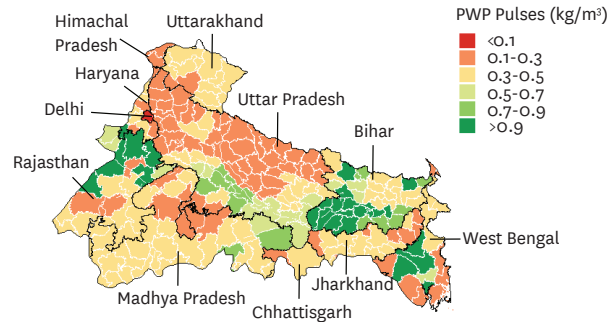
5B.2 Irrigated and rainfed area



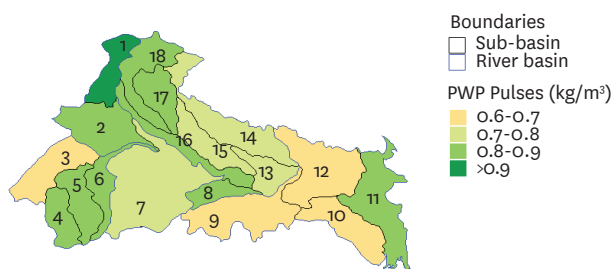
5A.3. Spatial variation across districts



5B.3. Spatial variation across districts



5A.4. Spatial variation across sub-basins



5B.4. Spatial variation across sub-basins

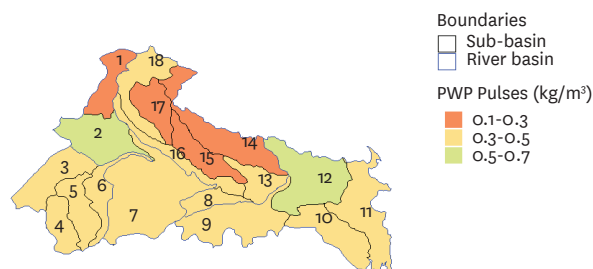


Figure 5. Temporal variation in PWP, yield, and irrigated and rainfed areas in (A) cereals, and (B) pulses; and spatial variation in PWP across districts and sub-basins in (A) cereals, and (B) pulses.

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

Pulses comprise about 7.5 Mha, only 14% of the grain-cropped areas. The main pulses are *kharif* pigeonpea, black lentil, and *rabi* chickpea. The area and yield trends and PWP variations in pulses across districts and sub-basins (Figure 5B.1-5B.4) are entirely different from those of cereals. The irrigated pulse area increased by more than 100% since 1999 (mainly chickpea), but the total pulse area increased by only 53%. Only half of the chickpea area is currently irrigated, but its yield increased by 48% in the last two decades with increased irrigation coverage. However, with only a 36% share of irrigation in the total area, the average pulse yield has increased by only 5% over the last two decades.

The increase in total CWU in pulses is more than the rate of yield increase, resulting in a decrease in PWP. The average PWP of pulses is 0.35 kg/m³, less than half that of cereals. However, the average EWP (USD 0.28/m³) is almost equal to that of cereals due to the high EWP of the *rabi* chickpea crop, which is about USD 0.56/m³ and is significantly more than the EWP of wheat at about USD 0.27/m³.

Oilseeds are grown on 12 Mha. Of this total, *kharif* soybean and *rabi* rapeseed/mustard are the main oilseed crops. The average PWP of oilseeds is 0.41 kg/m³. Due to the high EWP of rapeseed/mustard, the EWP is similar to that of pulses.

Rice-wheat is the dominant *kharif-rabi* cropping system in the GRB, followed by maize-wheat and rice-rice (Annex, Table A2). The rice-wheat system accounts for 68% and 69% of the total cereal area and production, respectively. The rice-rice and maize-wheat systems account for 10% and 4% of the area and 10% and 5% of cereal production, respectively. All three systems had substantial PWP increases, primarily due to crop productivity increases. However, the maize-wheat system has the most considerable PWP growth due to the higher yield growth of (*rabi*/winter) maize, followed by rice-wheat and rice-rice systems. Maize yield and PWP growth increased by 120% and 112%, respectively.

Table 5. The PWP, EWP, and NWP of cereals, pulses, and oilseeds in riparian states.

	Bihar	Chhattisgarh	Haryana	Himachal Pradesh	Delhi	Jharkhand	Madhya Pradesh	Rajasthan	Uttar Pradesh	Uttarakhand	West Bengal	Basin
PWP (kg/m³)												
Cereals	0.69	0.45	0.95	0.68	0.88	0.54	0.81	0.84	0.81	0.67	0.75	0.78
-Rice	0.52	0.42	0.56	0.26	0.54	0.53	0.54	0.45	0.55	0.57	0.70	0.58
-Wheat	0.74	0.35	1.31	0.56	0.99	0.52	0.90	0.99	1.05	0.90	0.85	0.97
-Maize	1.60	0.87	0.72	0.92	2.22	0.61	0.67	0.60	0.63	0.61	2.28	0.97
-Pearl millet	0.57	0.16	0.89	0.41	1.64	0.31	1.03	0.80	1.00	0	0.20	0.89
Pulses	0.28	0.14	0.69	0.07	0	0.29	0.36	0.35	0.35	0.12	0.40	0.35
-Pigeonpea	0.54	0.11	0.25	0.20	0	0.31	0.33	0.33	0.34	0.34	0	0.33
-Chickpea	2.31	0.87	1.50	0.92	0	1.23	0.63	0.81	1.57	0.48	2.25	0.73
Oilseeds	0.72	0.41	1.15	0.46	1.44	0.42	0.28	0.56	0.75	0.44	0.81	0.41
-Rapeseed/ mustard	0.85	0.79	1.15	0.47	1.44	1.24	1.01	0.88	0.94	0.78	0.66	0.89
EWP (USD/m³)												
Cereals	0.28	0.24	0.36	0.22	0.29	0.28	0.26	0.21	0.30	0.28	0.42	0.31
-Rice	0.31	0.25	0.33	0.16	0.32	0.31	0.32	0.27	0.33	0.34	0.42	0.35
-Wheat	0.20	0.10	0.35	0.15	0.27	0.14	0.24	0.27	0.28	0.24	0.23	0.26
-Maize	0.43	0.23	0.19	0.25	0.58	0.16	0.18	0.17	0.17	0.17	0.61	0.26
-Pearl millet	0.19	0.08	0.29	0.13	0.53	0.12	0.33	0.26	0.33	0	0.07	0.29
Pulses	0.25	0.40	0.99	0.73	0	0.20	0.34	0.38	0.30	0.24	0.40	0.28
-Pigeonpea	0.18	0.05	0.08	0.07	0	0.10	0.14	0.11	0.12	0.11	0	0.12
-Chickpea	2.44	0.93	1.65	0.98	0	1.32	0.64	0.88	1.69	0.53	2.38	0.76
Oilseeds	0.46	0.11	0.70	0.36	2.76	0.34	0.16	0.35	0.49	0.27	0.54	0.28
-Rapeseed/ mustard	0.53	0.49	0.71	0.29	2.76	0.78	0.62	0.54	0.58	0.48	0.41	0.55
NWP-Calories (1,000 kcal/m³)												
Cereals	0.28	0.24	0.36	0.22	0.29	0.28	0.26	0.21	0.30	0.28	0.42	0.31
-Rice	0.31	0.25	0.33	0.16	0.32	0.31	0.32	0.27	0.33	0.34	0.42	0.35
-Wheat	0.20	0.10	0.35	0.15	0.27	0.14	0.24	0.27	0.28	0.24	0.23	0.26
-Maize	0.43	0.23	0.19	0.25	0.58	0.16	0.18	0.17	0.17	0.17	0.61	0.26
-Pearl millet	0.19	0.08	0.29	0.13	0.53	0.12	0.33	0.26	0.33	0	0.07	0.29
Pulses	0.25	0.40	0.99	0.73	0	0.20	0.34	0.38	0.30	0.24	0.40	0.28
-Pigeonpea	0.18	0.05	0.08	0.07	0	0.10	0.14	0.11	0.12	0.11	0	0.12
-Chickpea	2.44	0.93	1.65	0.98	0	1.32	0.64	0.88	1.69	0.53	2.38	0.76
Oilseeds	0.46	0.11	0.70	0.36	2.76	0.34	0.16	0.35	0.49	0.27	0.54	0.28
-Rapeseed/ mustard	0.53	0.49	0.71	0.29	2.76	0.78	0.62	0.54	0.58	0.48	0.41	0.55
NWP-Proteins (proteins/m³)												
Cereals	0.28	0.24	0.36	0.22	0.29	0.28	0.26	0.21	0.30	0.28	0.42	0.31
-Rice	0.31	0.25	0.33	0.16	0.32	0.31	0.32	0.27	0.33	0.34	0.42	0.35
-Wheat	0.20	0.10	0.35	0.15	0.27	0.14	0.24	0.27	0.28	0.24	0.23	0.26
-Maize	0.43	0.23	0.19	0.25	0.58	0.16	0.18	0.17	0.17	0.17	0.61	0.26
-Pearl millet	0.19	0.08	0.29	0.13	0.53	0.12	0.33	0.26	0.33	0	0.07	0.29
Pulses	0.25	0.40	0.99	0.73	0	0.20	0.34	0.38	0.30	0.24	0.40	0.28
-Pigeonpea	0.18	0.05	0.08	0.07	0	0.10	0.14	0.11	0.12	0.11	0	0.12
-Chickpea	2.44	0.93	1.65	0.98	0	1.32	0.64	0.88	1.69	0.53	2.38	0.76
Oilseeds	0.46	0.11	0.70	0.36	2.76	0.34	0.16	0.35	0.49	0.27	0.54	0.28
-Rapeseed/ mustard	0.53	0.49	0.71	0.29	2.76	0.78	0.62	0.54	0.58	0.48	0.41	0.55

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

Addressing WFEE Nexus Externalities

As shown earlier, the GWCWU in many districts, particularly in overexploited and critical groups, significantly exceeds extractable resources. In these areas, reducing GWCWU is essential to address unsustainable groundwater use. This will require reducing groundwater-irrigated areas, or increasing surface irrigation, or rainfall CWU. Reducing groundwater irrigated areas will reduce food production and nutritional supply. Replacing a part of groundwater CWU with surface water irrigation or rainfall CWU may or may not change yield, and hence production. The extent of these impacts and potential mitigation strategies using a scenario-based approach are explored below.

GWCWU Reduction Scenarios (GW1-GW3)

Three scenarios assess the impact of reducing GWCWU on food and nutritional surpluses/deficits. These scenarios include reducing the GWCWU as a percentage of extractable groundwater resources to 90%, 75%, and 60%.

1. **The GW1 scenario** reduces the GWCWU of those districts exceeding 90% of the extractable resources to 90%. It considers the highly overexploited 80 districts in group 1 (Figure 2[B]).
2. **The GW2 scenario** reduces the GWCWU to 75% of the extractable resources, which includes the 80

group 1 districts and 11 group 2 districts. It considers the 91 severely overexploited and overexploited districts.

3. **The GW3 scenario** reduces the GWCWU to 60% of the extractable resources, which includes districts in groups 1, 2, and 3. It considers 110 highly overexploited to critical districts.

Since this study focuses on addressing groundwater overexploitation, the scenario analysis only considered the districts in groups 1 to 3 that mainly require reducing GWCWU to address the WFEE nexus. Furthermore, only rice, wheat, and sugarcane were taken into account for the analysis, as they contribute to most of the GWCWU. In each scenario, it was assumed that the GWCWU reductions from rice, wheat, and sugarcane are proportional to the share of total GWCWU of the three crops, which in 2018-2020 for the GRB were 10%, 52%, and 25%, respectively. In the highly overexploited group, these shares for rice, wheat, and sugarcane were 6.5%, 46%, and 33%, respectively.

Table 6 shows the implications of GW1 to GW3 scenarios on total GWCWU, groundwater-irrigated area, production, and nutritional supply (calorie, protein, and fat) of rice, wheat, and sugarcane. In Table 6, GRB values are for the whole area, showing that the groundwater GWCWU of highly overexploited to critical areas (groups 1 to 3) is about 75% of the groundwater irrigated area.

Table 6. Total groundwater irrigated area and GWCWU reduction in rice, wheat, and sugarcane under three GWCWU reduction scenarios.

Groundwater area, CWU, and calorie supply	GWCWU scenario	Group 1 (GWCWU>0.9)	Group 2 (GWCWU>0.75)	Group 3 (GWCWU>0.6)	GRB ³
GWCWU (Million m ³)	Baseline	55,079	3,707	10,244	85,276
	GW1 (<0.90) ¹	39.3	0	0	25.4
	GW2 (<0.75) ¹	48.1	4.3	0	31.3
	GW3 (<0.60) ¹	56.9	12.3	4.6	37.8
Groundwater irrigated area (1,000 ha)	Baseline	13,248	1,231	3,806	24,303
	GW1 (<0.90) ¹	25.2	0	0	14.0
	GW2 (<0.75) ¹	32.3	3.9	0	18.2
	GW3 (<0.60) ¹	39.5	11.1	4.2	23.2
Rice production (Million t)	Baseline	9.30	1.70	5.43	45.9
	GW1 (<0.90) ¹	3.7	0	0	0.7
	GW2 (<0.75) ¹	5.3	0.9	0	1.1
	GW3 (<0.60) ¹	7.0	3.3	1.1	1.7
Wheat production (Million t)	Baseline	38.58	3.90	10.25	73.3
	GW1 (<0.90) ¹	20.3	0	0	10.7
	GW2 (<0.75) ¹	27.3	3.3	0	14.5
	GW3 (<0.60) ¹	34.3	9.7	4.7	19.2
Sugarcane production (sugar equivalent) (Million t)	Baseline	20.83	0.59	0.57	25.6
	GW1 (<0.90) ¹	59.2	0	0	48.1
	GW2 (<0.75) ¹	68.4	1.9	0	55.6
	GW3 (<0.60) ¹	77.6	7.9	0.8	63.2
Calorie surplus/ deficit ² (%)	Baseline	174	149	79	72
	GW1 (<0.90)	91	149	79	47
	GW2 (<0.75)	72	142	79	42
	GW3 (<0.60)	53	129	73	35
Protein surplus/ deficit ² (%)	Baseline	111	145	85	54
	GW1 (<0.90)	72	145	85	42
	GW2 (<0.75)	59	137	85	37
	GW3 (<0.60)	46	124	78	32
Fat surplus/ deficit ² (%)	Baseline	117	149	86	59
	GW1 (<0.90)	74	149	86	44
	GW2 (<0.75)	60	141	86	39
	GW3 (<0.60)	46	127	78	32

Source: Authors' estimates.

Notes: ¹ GW1, GW2, and GW3 scenario values are the percentage reduction from the baseline values.

² Surplus/deficit (+/-) as a percentage of the baseline values.

³ Surplus/deficit for the GRB is for the whole region under the three GW scenarios.

- **GW1** needs to reduce the GWCWU in group 1 by 39.3% and groundwater irrigated area by 25.2%. This scenario reduces rice, wheat, and sugarcane production of group 1 by 3.7%, 20.3%, and 59.2%, and of the GRB by 0.7%, 10.7%, and 48.1%, respectively. As a result, the calorie, protein, and fat surpluses of the GRB decrease by 25%, 12%, and 15% of the baseline supplies, respectively
- **GW2** needs to reduce the GWCWU in groups 1 and 2 by 48.1% and 4.3%, respectively, and as a result, groundwater-irrigated areas need to be reduced by 32.3% and 3.9%, respectively. This scenario reduces GRB's rice, wheat, and sugarcane production by 1.1%, 14.5%, and 55.6%, respectively. Group 1 districts share much of these reductions.
- **GW3** needs to reduce GWCWU in the GRB by 37.8%, and groundwater irrigated area by 23.2%. This scenario reduces the GRB's rice, wheat, and sugarcane production by 1.7%, 19.2%, and 63.2%, respectively. This will reduce calorie, protein, and fat supply by 35%, 32%, and 32%, respectively.

This scenario analysis shows that although a substantial reduction in groundwater irrigated areas is required to meet sustainable groundwater use targets, the nutritional (calories, proteins, and fat) surpluses under GW1 to GW3 in the three groups and of the GRB still exceed the demand. For example, the GW1 scenario generates a calorie surplus of 91% of the demand in group 1. Even under the most desirable scenario of GW3, groups 1 to 3 have calorie, protein, and fat surpluses of 53%, 46%, and 46% of the baseline supply, respectively.

The production losses under GW1 to GW3 will reduce farmers' incomes and production surpluses available for the public distribution system (PDS) or other welfare schemes for the poor. Therefore, these scenarios may only be realistic if they accompany other measures to compensate for the direct benefit losses to farmers and indirect production losses to the local economy. While currently food surplus areas meet the consumption demand of food deficit areas and the demand for PDS, reduced production is likely to disrupt the backward and forward linkages associated with the agricultural economy in the food surplus areas. For example, in the Bhakra irrigation system in northwestern India, every dollar of crop production generates USD 0.90 more in indirect benefits downstream or from backward and forward linkages (Bhatia et al. 2007). These indirect benefit losses need to be considered before any reduction in crop-irrigated areas.

The options for mitigating the area, production, and value losses under reduced GWCWU include:

1. **Augmenting surface irrigation supply:** Given the physical, economic, and environmental constraints in developing surface water storage structures in the GRB (Sadoff et al. 2013), it is assumed that large-scale surface irrigation augmentation is not possible, at least in the short term. However, planned surface water projects such as linking the Ken and Bethwa rivers and other water transfers in the river linking project (Amarasinghe et al. 2010) could alleviate groundwater depletion in many regions.
2. **Increasing the efficiency of rainfall use:** This is possible by increasing the soil's water-holding capacity through soil conservation, mulching, etc., providing better climate information, and following irrigation practices (FAO 2014). Rainfall use efficiency may also be enhanced by raising the bund height around paddy fields to a minimum of 10–15 cm to retain most of the rain within the fields. The construction of farm ponds and tanks at suitable locations can aid in critical water needs and thus the need for groundwater irrigation.
3. **Increasing water-use efficiency (WUE):** This study focuses only on GWCWU. However, with low WUE (the ratio of CWU to withdrawals), groundwater withdrawals could be much higher. For example, with 60% WUE, the total groundwater withdrawals of groups 1 and 2 could be 97 Bm³ more than the CWU. With increased WUE, the non-process evaporation of this withdrawal can be reduced along with the large amount of energy used for pumping. Piped irrigation, drip irrigation, and other non-water related interventions such as direct benefit transfer of an electricity subsidy in Punjab can reduce withdrawals and increase WUE.
4. **Increasing surface irrigation efficiency:** This is a popular intervention suggested in Indian irrigated agriculture that is expected to save water for other uses, including a reduction in groundwater withdrawals. However, as Perry and Steduto (2017) argue, without a reduction in allocation, infrastructure solutions to increase surface irrigation efficiency may not lead to real water saving at basin scale, and in fact, may increase groundwater depletion. Therefore, reducing surface irrigation allocation combined with advanced irrigation technology and infrastructure can increase surface irrigation efficiency and save water. These savings can reduce groundwater withdrawals.
5. **Augmenting groundwater recharge:** In large parts of the GRB, there is surplus surface water supply that may be used for augmenting groundwater recharge through check dams, sub-surface dykes, retrofitting abandoned wells, and constructing percolation tanks. IWMI has demonstrated the technology of underground taming of floods for irrigation (Pavelic 2020; Pavelic et al. 2021) and re-energizing the Ganges Water Machine (Amarasinghe et al. 2016; Surinaidu et al. 2016). These can be adopted on a scale to augment groundwater supplies.

6. **Increasing PWP:** This is possible by increasing crop yield with reduced GWCWU. As discussed before, increased crop yields have contributed to much of the PWP growth in the last two decades. There is a significant gap between current and potential yields in the GRB and the potential to reduce the yield gap (Debnath et al. 2021; Islam et al. 2024). Reducing the yield gap would mean increasing the average yield through both water and non-water inputs and improving practices targeted for different regions of the GRB (Sharma et al. 2016). Reduced GWCWU and increased yield will significantly increase PWP.
7. **Increasing EWP:** As shown in the GW1-GW3 scenarios, groups 1 and 3 continue to have substantial production losses even under reduced GWCWU scenarios. Therefore, another option for districts with unsustainable groundwater use is to reduce irrigated areas and diversify cropping patterns with high-value crops (fruits and vegetables, milk production, pulses and oilseeds) to increase EWP and farm income.
8. **Adoption of drip irrigation:** Drip irrigation in sugarcane areas can increase yields and PWP while reducing water withdrawal (Gulati and Mohan 2018).

Increasing Rainwater-Use Efficiency (RWUE)

Increasing RWUE (or effective rainfall use) could also reduce the irrigation CWU requirement in irrigated areas. At present, effective rainfall at the root zone in kharif rice (June to September), rabi wheat (November to March), and sugarcane (annual crop) are 82%, 10%, and 40%, respectively, of the total CWU requirement of each crop. As rainfall is substantially higher than ETp in much of the kharif season (Figure 6), kharif rice has a significantly higher RWUE. Wheat has lower RWUE due to virtually no rain during the rabi season. Much of the effective rainfall use in sugarcane is also during the kharif season. Table 7 shows the potential impacts of reducing GWCWU on groundwater-irrigated areas under two alternative RWUE scenarios:

- **RWUE1 scenario:** 10% increase in rainfall CWU.
- **RWUE2 scenario:** 20% increase in rainfall CWU.

With increased rainwater-use efficiency, there is a slight reduction in GWCWU and groundwater-irrigated areas. For example, with 10% RWUE, additional reductions under GW1 in group 1 are 2.6% (38.8% to 36.2%) of GWCWU and 2.3% (25.0% to 22.7%) of groundwater irrigated area. Under GW3 in group 1, additional GWCWU and irrigated area reductions are 3.0% (56.6% to 53.6%) and 3.2% (39.8% to 36.6%), respectively. With a 20% increase in rainwater-use efficiency, the additional reduction in GWCWU and groundwater-irrigated area under GW3 are 5.4% (56.6% to 51.2%) and 4.9% (39.8% to 34.9%), respectively.

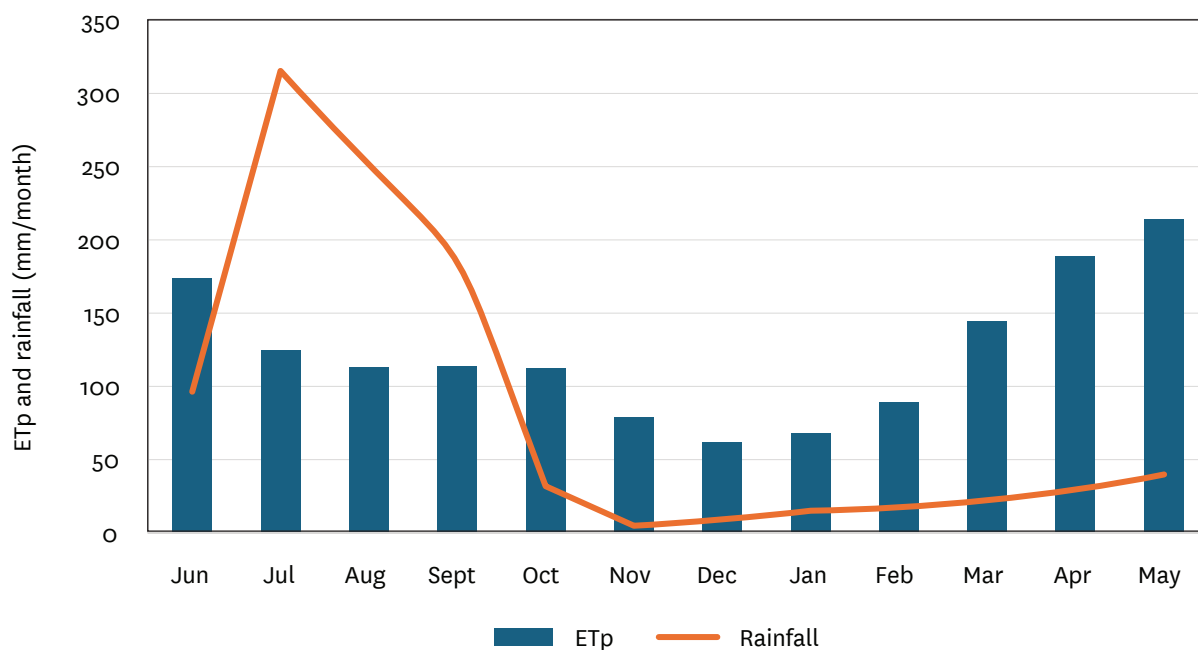


Figure 6. Monthly Evapotranspiration and effective rainfall in the GRB.

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

Table 7. Groundwater irrigated area and GWCWU reduction under increased rainfall-use efficiency.

Rainfall use efficiency scenario	Groundwater area and CWU	GWCWU scenario	Reduction from baseline value (%)			
			Group 1 (GWCWU>0.9)	Group 2 (GWCWU>0.75)	Group 3 (GWCWU>0.6)	GRB
Baseline (no increase in RWUE)	GWCWU	GW1	38.8	0	0	24.9
		GE2	47.7	3.9	0	30.8
		GW3	56.6	12.1	4.5	37.4
	Area	GW1	25.0	0	0	13.6
		GW2	32.4	3.5	0	17.8
		GW3	39.8	10.7	4.1	22.8
RWUE1 (10% increase in rainfall CWU)	GWCWU	GW1	36.2	0	0	23.2
		GW2	44.9	2.5	0	28.9
		GW3	53.6	9.5	3.2	35.2
	Area	GW1	22.7	0	0	12.3
		GW2	29.6	2.2	0	16.2
		GW3	36.6	7.8	2.6	20.7
RWUE2 (20% increase in rainfall CWU)	GWCWU	GW1	34.1	0	0	21.9
		GW2	42.5	1.9	0	27.4
		GW3	51.2	7.8	2.4	33.5
	Area	GW1	21.3	0	0	11.6
		GW2	28.0	1.6	0	15.3
		GW3	34.9	6.6	1.9	19.6

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

The main reason for these minor changes is that the potential evapotranspiration is significantly lower than rainfall in the *kharif* season (June to September) and significantly higher in the *rabi* season (November to March) (Figure 6). In the *rabi* season, rainfall must be higher to increase effective rainfall use significantly. The RWUE-GW scenarios show that the potential for increased effective rainwater use to reduce GWCWU requirements is low; hence, the mitigating area and production losses are small in the GRB.

Increasing Surface Water-Use Efficiency with a Reduced Surface Water Allocation Scenario

The third scenario assumes a reallocation of surface water withdrawals to reduce groundwater CWU. This requires a significant increase in surface irrigation efficiency to meet surface irrigation CWU with reduced allocation. It is assumed that the current level of surface irrigation efficiency at the district level is 50% (the often-quoted figures for farm-level application efficiency are between 35% and 40%). This study assumed a slightly higher figure at the district level to account for water reuse at a larger spatial scale. It also assumed that with new technology

and infrastructure, surface irrigation efficiency at the district scale can be increased to 70% so that surface irrigation supply after reallocation can meet the existing CWU requirement in the surface irrigated area. The water savings with revised surface allocation can reduce groundwater CWU in the GRB by 11%, and the number of severely groundwater-exploited districts by about 50% (Table 8).

The surface water reallocation scenario reduced the number of districts with groundwater overexploitation. Although the number of districts with severe groundwater exploitation fell under this scenario, most of these districts now fall in the overexploited, critical, or semi-critical use categories of groundwater use. The number of districts in the overexploited to semi-critical categories increased from 50 to 69. Among the states with severe groundwater depletion, Madhya Pradesh saw a significant reduction in the number of districts from 22 in the baseline scenario to only 4 districts (now classified as severely overexploited), and 6 districts moved to a safer level of exploitation. In contrast, 3 districts in Uttar Pradesh moved out of the highly overexploited category while the number of districts in the safe category increased from 5 to 14 (Table 8).

Table 8. Number of districts in the groundwater depletion categories under baseline and a surface water reallocation scenario.

Groundwater CWU (% of groundwater availability)	Baseline status (2018-2020)					Surface water reallocation scenario				
	Haryana	Madhya Pradesh	Rajasthan	Uttar Pradesh	Total ¹	Haryana	Madhya Pradesh	Rajasthan	Uttar Pradesh	Total ¹
Group 1 (highly overexploited)	11	22	19	26	80	5	4	9	23	42
Group 2 (overexploited)	2	2	0	6	11	3	7	3	3	17
Group 3 (critical)	0	1	0	16	19	1	8	3	13	27
Group 4 (semi-critical)	0	3	0	15	20	4	3	2	15	25
Group 5 (safe)	1	9	0	5	75	1	15	2	14	94
Group 6 (not available)	0	0	1	2	32	0	0	1	2	32
GRB	14	37	20	70	237	14	37	20	70	237

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

Note: ¹ Total includes districts of other riparian states of the GRB.

Overall, the combination of reduced surface water supply and higher surface irrigation efficiency moved 19 districts to the safe groundwater use category. Still, many districts are in the highly to critical groundwater exploitation category. This indicates that while water reallocation and increased efficiency in surface irrigation have some potential for reducing groundwater overexploitation in some districts, they are insufficient to address groundwater depletion in the entire GRB.

Yield Gap Reduction Scenarios

The fourth set of scenarios assesses the requirement of GWCWU reduction under a reduced yield gap, which is the difference between a district's average yield and the current production frontier yield at the CWU interval to which the district's TCWU belongs. Overall, a substantial yield gap exists at all CWU levels for rice, wheat, and sugarcane (Figure 7). The red dots in Figures 7(A)-(C) show the maximum yield attained in the crops in the GRB at various intervals of TCWU.

The dotted line is the quadratic regression fitted to maximum yield at the midpoint of each TCWU interval. The green line shows the current maximum yield of all districts in India. Some districts have already attained a higher yield than those in the maximum yield curve. So, the attainable yield frontier could be even higher than these maximum yield curves. These figures also show the potential for reducing yield gap within the GRB's current production frontier. The potential is higher when estimating the yield gap with the yield frontier of all districts.

Wheat and rice have significant gaps between actual and current maximum yield (Annex, Table A4). The average rice yield gap is highest in the 400-500 mm CWU range. Significant yield gaps exist in the states of Bihar, Chhattisgarh, Madhya Pradesh, Jharkhand, and Uttarakhand with substantial rainfed cropped areas. Haryana and Uttar Pradesh have lower yield gaps. The average yield gap in wheat is relatively higher in all CWU ranges, especially in the eastern and southern states. Haryana has the lowest yield gap.

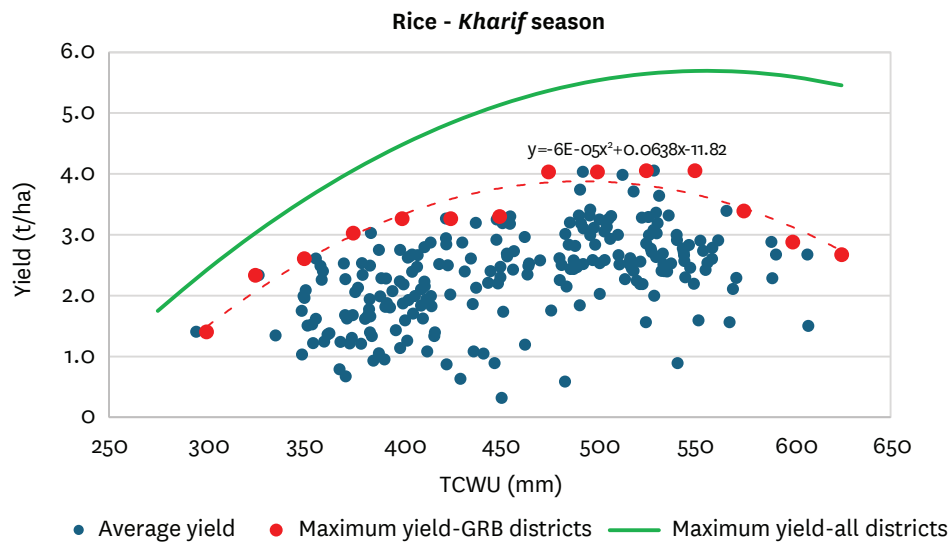


Figure 7A. Rice

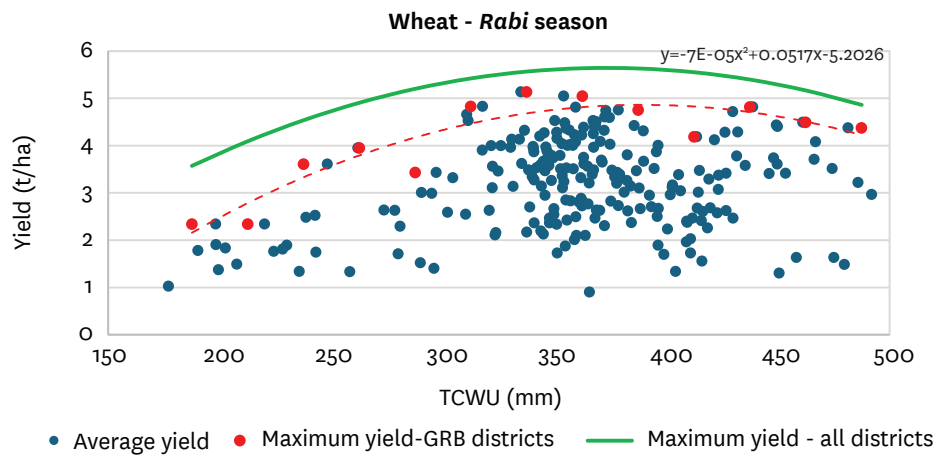


Figure 7B. Wheat

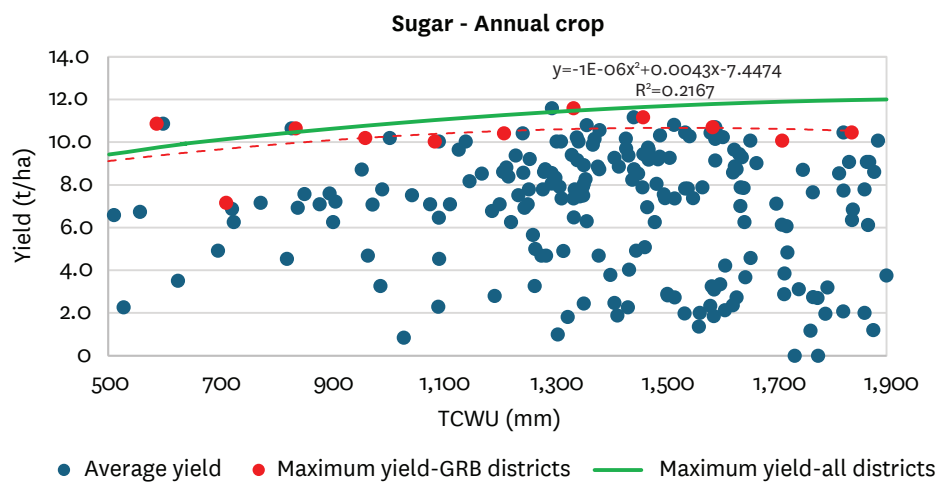


Figure 7C. Sugarcane¹

Figure 7. Average and maximum rice, wheat, and sugarcane (sugar equivalent) yields in the GRB and all Indian districts.

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

Note: ¹Sugar equivalent yield. The red line shows the 2nd order polynomial trend of Max-yield-GRB districts.

The potential for reducing yield gaps implies that the GRB can reduce groundwater CWU and irrigated area and still offset some reduction in crop production and nutritional value. The next set of scenarios assesses the extent to which yield gap reduction can mitigate the effects on crop production losses and the nutritional value of those losses with reduced GWCWU.

Tables 9A–9G assess the aggregate impacts of four yield gap reduction scenarios (Y1 to Y4) that range from 0% (no reduction) to 25%, 50%, and 75%, but with no increase in rainfall CWU. They show the aggregate impacts on crop production and the nutritional surpluses and deficits in rice, wheat, and sugar, and change in value of production from the baseline under three GWCWU reduction scenarios (GW1 – up to 90%, GW2 – up to 75%, and GW3 – up to 60%).

Table 9A assesses the changes in the aggregate production of rice under the four yield gap reduction scenarios. It reveals the following:

- With no yield gap reduction (Y1), rice production in group 1 under the GW1 GWCWU reduction scenario decreased by 0.3 t, or 3% from the baseline production of 9.3 t. Under the GW2 and GW3 GWCWU reduction scenarios, rice production in group 1 decreased by 0.5 t and 0.7 t, or 5% and 8%, respectively, from the baseline production. At the GRB level, the largest loss is under GW3, which is less than 2% (=0.8/45.9) of the total baseline production of the GRB.
- A 25% reduction in yield gap (Y2) can wipe out the production losses in group 1 under GW1 and GW2 but not under GW3. However, it can wipe out the production losses of GRB under all three groundwater CWU reduction scenarios (GW1–GW3). Rice production surpluses in the GRB increased under GW1, GW2, and GW3 by 2.8 t, 2.6 t, and 2.3 t, respectively.
- Yield gap reduction scenarios (Y3 and Y4) of 50% and 75% can generate some production surpluses in groups 1 to 3, but substantial production surpluses at the GRB level. This is because of the high yield gaps that exist in the districts in groups 4–6.

Tables 9B and 9C assess the production losses in wheat and sugar, respectively under the yield gap reduction scenarios.

- The wheat production losses in the GRB under GW1–GW3 scenarios are significant, with a 0% reduction in yield gaps (Table 9[B]). None of the yield gap reduction scenarios (Y2–Y4) can eliminate the production losses in group 1. However, yield gap reduction under Y2–Y3 can wipe out production losses in groups 2 and 3. Overall, yield gap reduction scenarios Y3 and Y4 can eliminate the wheat production losses in the GRB.
- In the case of sugarcane (sugar equivalent sugarcane production), production deficits

exist even with a 75% reduction in yield gap (Table 9C). This is because most of the sugarcane production is in the group 1 districts with severe groundwater overexploitation.

Tables 9D–9F show the ratio of calorie supply, protein supply, and fat supply to consumption under baseline conditions under the four yield gap reduction scenarios and three GWCWU reduction scenarios.

- In group 1, reduced GWCWU (GW1 to GW3) and no reduced yield gap (Y1) scenarios still have substantial food and nutritional production surpluses, although they are below the baseline ratios.
- Moreover, any yield gap reduction scenarios (Y2–Y4) would not offset the reduced calorie, protein, and fat surpluses associated with reduced GWCWU in group 1. For example, even a 75% yield gap reduction (Y4) scenario is insufficient to offset the production surplus losses under GW1 which has the lowest reduction of GWCWU.
- In group 2, a 25% yield gap reduction is sufficient to offset the nutritional losses under the GW3 scenario of GWCWU reduction. In group 3, the 25% yield gap reduction is sufficient to meet the production losses under GW3.
- Groups 4 to 6 (not shown in these tables) districts have safe groundwater exploitation now, and require no reduction in GWCWU; hence, any yield gap reduction would only contribute to increasing the production and nutritional surpluses of these groups and in the GRB.
- Overall, a 50% yield gap reduction can offset most of the reduced nutritional surpluses with reduced GWCWU in the GRB.

Table 9G shows the value of production of the three crops under GWCWU reduction (GW1–GW3) and yield gap reduction (Y1–Y4) scenarios, in which:

- Group 1 experiences the most reduction in the value of production under any yield gap reduction scenario. The GW3 and Y1 scenarios lead to a 41% reduction in the value of production in group 1, while the GW3 and Y4 scenarios reduce the value of production by about 25%.
- Even a 25% reduced yield gap (Y2) can overcome the value losses under GWCWU reduction in groups 2 and 3.

The scenarios in Tables 9A to 9G show that group 1 districts face major production, nutritional, and production value losses with GWCWU reduction. The reduced yield gaps are insufficient to offset the production and production value losses affecting some people's livelihoods and income security. Therefore, additional measures are necessary, such as crop diversification and increasing WUE, to reduce the value of production losses in districts in this group.

Table 9. Aggregate impacts of four yield gap reduction scenarios (Y1-Y4).**(A) Change in rice production (in t).**

GWCWU group	Baseline (t)	Yield gap reduction (Y1-Y4) and GWCWU (GW1-GW3) reduction scenarios											
		Y1			Y2			Y3			Y4		
		GW1	GW2	GW3	GW1	GW2	GW3	GW1	GW2	GW3	GW1	GW2	GW3
1	9.3	-0.3	-0.5	-0.7	0.2	0.1	-0.1	0.8	0.6	0.4	1.3	1.2	1.0
2	1.7	0	0	-0.1	0.1	0.1	0	0.2	0.2	0.1	0.3	0.3	0.2
3	5.4	0	0	-0.1	0.3	0.3	0.2	0.6	0.6	0.5	0.8	0.8	0.8
GRB	45.9	-0.3	-0.5	-0.8	2.8	2.6	2.3	5.8	5.6	5.4	9.1	8.9	8.6

(B) Change in wheat production (in t).

GWCWU group	Baseline (t)	Yield gap reduction (Y1-Y4) and GWCWU (GW1-GW3) reduction scenarios											
		Y1			Y2			Y3			Y4		
		GW1	GW2	GW3	GW1	GW2	GW3	GW1	GW2	GW3	GW1	GW2	GW3
1	38.6	-7.8	-10.5	-13.2	-4.5	-7.5	-10.5	-1.2	-4.5	-7.8	2.1	-1.5	-5.1
2	3.9	0	-0.1	-0.4	0.5	0.4	0.1	1.1	0.9	0.6	1.6	1.4	1.1
3	10.2	0	0	-0.5	1.3	1.3	0.8	2.6	2.6	2.0	3.9	3.9	3.2
GRB	73.3	-7.8	-10.6	-14.1	0.5	-2.6	-6.4	8.9	5.5	1.3	17.3	13.5	8.9

(C) Change in sugarcane¹ production (in t).

GWCWU group	Baseline (t)	Yield gap reduction (Y1-Y4) and GWCWU (GW1-GW3) reduction scenarios											
		Y1			Y2			Y3			Y4		
		GW1	GW2	GW3	GW1	GW2	GW3	GW1	GW2	GW3	GW1	GW2	GW3
1	20.8	-12.3	-14.2	-16.2	-11.7	-13.7	-15.7	-11.1	-13.2	-15.3	-10.5	-12.7	-14.9
2	0.6	0	0	0	0.1	0.1	0	0.1	0.1	0.1	0.2	0.2	0.1
3	0.6	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
GRB	25.6	-12.3	-14.3	-16.2	-11.1	-13.1	-15.2	-9.9	-12.0	-14.1	-8.6	-10.8	-13.0

Source: Author's estimation.

Note: ¹ Sugar equivalent sugarcane production.

(D) The ratio of calorie supply to consumption of rice, wheat, and sugar.

GWCWU group	Baseline (ratio)	Yield gap reduction (Y1-Y4) and GWCWU (GW1-GW3) reduction scenarios											
		Y1			Y2			Y3			Y4		
		GW1	GW2	GW3	GW1	GW2	GW3	GW1	GW2	GW3	GW1	GW2	GW3
1	2.8	2.0	1.8	1.6	2.1	1.9	1.7	2.3	2.1	1.9	2.5	2.2	2.0
2	2.3	2.3	2.3	2.1	2.6	2.5	2.3	2.8	2.7	2.5	3.0	2.9	2.7
3	1.7	1.7	1.7	1.7	1.9	1.9	1.8	2.1	2.1	2.0	2.2	2.2	2.2
GRB	1.7	1.5	1.4	1.4	1.6	1.6	1.5	1.8	1.7	1.6	1.9	1.8	1.7

(E) The ratio of protein supply to consumption of rice, wheat, and sugar.

GWCWU group	Baseline (ratio)	Yield gap reduction (Y1-Y4) and GWCWU (GW1-GW3) reduction scenarios											
		Y1			Y2			Y3			Y4		
		GW1	GS2	GW3	GW1	GS2	GW3	GW1	GS2	GW3	GW1	GS2	GW3
1	2.1	1.8	1.6	1.5	2.0	1.8	1.7	2.1	2.0	1.8	2.3	2.1	2.0
2	2.3	2.3	2.2	2.1	2.6	2.5	2.3	2.8	2.7	2.5	3.1	2.9	2.7
3	1.8	1.8	1.8	1.7	2.0	2.0	1.9	2.2	2.2	2.1	2.4	2.4	2.3
GRB	1.5	1.4	1.4	1.3	1.6	1.5	1.5	1.7	1.7	1.6	1.9	1.8	1.8

(F) The ratio of fat supply to consumption of rice, wheat, and sugar.

GWCWU group	Baseline (ratio)	Yield gap reduction (Y1-Y4) and GWCWU (GW1-GW3) reduction scenarios											
		Y1			Y2			Y3			Y4		
		GW1	GS2	GW3	GW1	GS2	GW3	GW1	GS2	GW3	GW1	GS2	GW3
1	1.2	1.0	0.9	0.8	1.0	1.0	0.9	1.1	1.1	1.0	1.2	1.1	1.0
2	0.9	0.9	0.9	0.8	1.0	1.0	0.9	1.1	1.1	1.0	1.2	1.2	1.1
3	0.8	0.8	0.8	0.7	0.9	0.9	0.8	0.9	0.9	0.9	1.0	1.0	1.0
GRB	0.9	0.8	0.8	0.7	0.9	0.9	0.8	1.0	1.0	0.9	1.1	1.0	1.0

(G) Change in value of production from the baseline.

GWCWU group	Baseline ¹ (ratio)	Yield gap reduction (Y1-Y4) and GWCWU (GW1-GW3) reduction scenarios											
		Y1			Y2			Y3			Y4		
		GW1	GS2	GW3	GW1	GS2	GW3	GW1	GS2	GW3	GW1	GS2	GW3
1	1.00	0.72	0.66	0.59	0.78	0.71	0.64	0.83	0.76	0.69	0.88	0.81	0.73
2	1.00	1.00	0.97	0.92	1.08	1.05	0.99	1.16	1.13	1.06	1.24	1.20	1.14
3	1.00	1.00	1.00	0.97	1.09	1.09	1.06	1.17	1.17	1.14	1.26	1.26	1.22
GRB	1.00	0.89	0.86	0.83	0.96	0.93	0.90	1.04	1.01	0.97	1.11	1.08	1.04

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

Note: ¹The value of production under the baseline is considered as 1. Columns 3 to 14 show the ratio of the value of production to that under the baseline scenario.

Crop Diversification Scenarios

Since rice, wheat, and sugarcane take up most of the groundwater irrigated area and CWU, the objective of the crop diversification scenario is to identify crops that offset the value losses under reduced GWCWU and yield gap scenarios. Although the western GRB has high GWCWU and PWP, it has low to moderate EWP because it grows low-value crops, partly because of assured minimum support prices (Figure 8). This reveals the immense scope for increasing production value with lower GWCWU by diversifying into high-value crops.

Estimates of a few indicators – water use per unit area and water productivity – including PWP and EWP that aid

these diversification choices are shown in Annex, Table A5. The GWCWU of sugarcane is more than 11,000 m³/ha, one of the highest for all crops. Wheat requires about one-third of sugarcane's GWCWU. The other dominant crop, *khariif* rice, requires only about one-third of the GWCWU of the wheat crop. However, *rabi* rice, which constitutes only a small area, requires higher GWCWU and withdrawals. In GWCWU terms, maize, pearl millet, black gram, groundnut, and sesame seed with irrigation CWUs of less than 1,000 m³/ha are potential *khariif* season crops. In value terms, sorghum, chilli, mustard, potato, onion, ginger, turmeric, and vegetables are potential crops to replace low-value seasonal or annual crops.

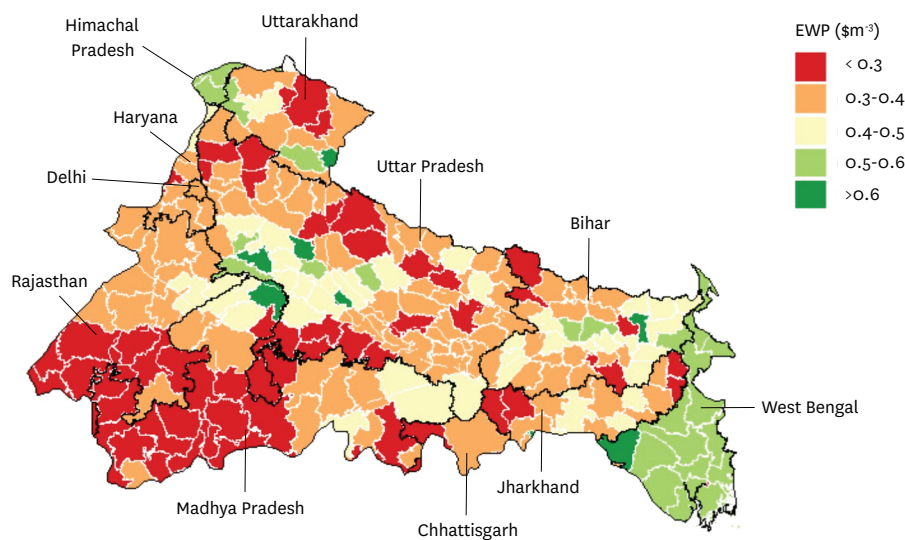


Figure 8. The economic water productivity of all crops.

Source: Authors' estimates based on the data collected for the Water Productivity Atlas.

Many other water- and non-water-related factors besides CWU and production value factors matter in crop diversification. These include water availability, weather, climate variability, soils, input availability, market access, minimum support price, income generation, and profitability, many of which were not available for this analysis. Therefore, crops with relatively high EWP and low groundwater CWU were used to illustrate the potential for crop diversification to address the WFEE nexus and value losses.

Table 10 shows a few alternative crop diversification choices for rice, wheat, and sugarcane under GW3-Y4 scenarios in group 1. The GW3-Y4 scenario has reduced GWCWU to 60% of the extractable resources and 75% of the yield gaps. The alternative scenarios assume two diversified cropping patterns:

1. Scenario 1 (SCE 1) is the GW3-Y4 scenario.
2. Scenarios SCE 1a to 1c replace the reduced rice, wheat, and sugar areas in SCE 1 with maize, pearl millet (bajra), soybeans, and vegetables in the *kharif* season and gram, mustard, and vegetables in the *rabi* season.
3. Scenario 2 (SCE 2) shows a slight variation from SCE 1, emphasizing the importance of wheat for food security in the basin. Wheat has the highest GWCWU in the GRB, yet it serves other important uses. Milk production is a major agricultural activity and a source of protein supply for people. Wheat straw is a major by-product of livestock feed. Most importantly, unlike rice, wheat can be produced at scale in the

northern regions with suitable climatic conditions in the *rabi* season to meet the national consumption demand. So, SCE 2 assumes no reduction in wheat area but no sugarcane area.

4. SCE 2a and 2b replace a part of the reduced rice and sugarcane areas in SCE 2 with maize, finger millet, gram, mustard, and vegetables in the *kharif* and *rabi* seasons.

The alternative scenarios SCE 1a to SCE 1c and SCE 2a to SCE 2b have substantially decreased GWCWU from the baseline but increased GWCWU from GW3- Y4.

- SCE 1a-1c and SCE 2a-2b variations have more GWCWU than in SCE 1 but are still below the baseline GWCWU.
- SCE 2 has a slightly higher GWCWU than SCE 1, but it is still below the extractable resources.
- All alternative scenarios show more output value than the baseline and SCE 1. SCE 1a-1c and SCE 2a-2b record more production value than the baseline and SCE 1 and completely wipe out the production deficit in the SCE 1 scenario.
- The calorie supply from the alternative cropping patterns is less than that from the baseline but more than in the SCE 1 scenario.

The selected cropping patterns show that it is possible to replace rice, wheat, and sugarcane areas with other crops to manage the WFEE nexus. Some cropping patterns can drastically reduce GWCWU and increase production value, but with some calorie supply losses. However, overall calorie supply levels are still substantially more than the consumption demand.

Table 10. WP, EWP, and CWU of crops in the GRB from 2018 to 2020.

Crop	Season	Groundwater irrigation CWU ² (m ³ /ha)	Value (USD/ha)	EWP ² (USD/m ³)	Cropping patterns scenarios (Mha)																	
					7	8	9	10	11	12	13	14	Baseline (2018-2020)	SCE 1 ³ (GW3-Y4)	SCE 1a	SCE 1b	SCE 1c	SCE 2	SCE 2a	SCE 2b		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	Baseline (2018-2020)	SCE 1 ³ (GW3-Y4)	SCE 1a	SCE 1b	SCE 1c	SCE 2	SCE 2a	SCE 2b	
1	Rice	1,488	1,556	598	1.05	2.80	1.43	1.43	1.43	1.43	1.43	1.43	1.43	2.80	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
2	Wheat	3,468	1,022	269	0.29	8.49	4.32	4.33	4.33	4.33	8.49	8.49	8.49	8.49	4.32	4.33	4.33	4.33	8.49	8.49	8.49	8.49
3	Sugarcane	11,368	3,275	336	0.29	1.87	0.95	0.95	0.95	0.95	0	0	0	1.87	0.95	0.95	0.95	0.95	0	0	0	0
4	Maize	636	591	275	0.93																	
5	Pearl millet ¹	886	591	327	0.67																	
6	Gram	2,760	1,471	1,043	0.53																	
7	Soyabean	1,117	513	5,56	0.46																	
8	Mustard	1,922	1,047	1,043	0.54																	
9	Vegetables	1,729	12,474	798	7.21																	
10	Vegetables	3,335	14,255	799	4.27																	
11	Total area (Mha)					13.2	6.7	12.1	12.1	13.2	9.9	14.1	16.0	13.2	6.7	12.1	12.1	13.2	9.9	14.1	16.0	
12	Total GWCWU (Bm ³)					54.9	28.0	37.8	38.1	39.3	31.6	37.2	39.2	54.9	28.0	37.8	38.1	39.3	31.6	37.2	39.2	
13	- % of extractable resources					118%	60%	81%	82%	84%	68%	80%	84%	118%	60%	81%	82%	84%	68%	80%	84%	84%
14	Value of production (billion USD)					22.96	10.9	30.7	30.7	31.5	12.4	28.5	28.8	22.96	10.9	30.7	30.7	31.5	12.4	28.5	28.8	28.8
15	- % of baseline value						0.47	1.34	1.34	1.36	0.54	1.24	1.25		0.47	1.34	1.34	1.36	0.54	1.24	1.25	
16	Calorie supply (billion Kcal)					194,115	98,857	133,874	132,633	136,259	116,963	142,806	158,894	194,115	98,857	133,874	132,633	136,259	116,963	142,806	142,806	158,894
17	- % of baseline supply						0.51	0.69	0.68	0.70	0.60	0.74	0.82		0.51	0.69	0.68	0.70	0.60	0.74	0.82	
18	- % of consumption ⁴					2.254	1.15	1.55	1.54	1.58	1.36	1.66	1.85	2.254	1.15	1.55	1.54	1.58	1.36	1.66	1.85	

Source: Author's estimates

Notes:

¹ Irrigation CWU (m³/ha) for maize is generally higher than that for pearl millet. However, due to the spatial variations in irrigated and groundwater-irrigated areas of maize and pearl millet, the groundwater CWU of pearl millet is higher than that of maize at the GRB level.

² CWU and EWP are production and value per total CWU.

³ SCE stands for scenarios.

⁴ Calorie consumption in group 1 districts in 2018-2020 was 86,107 billion Kcal.

Discussion

There is ample evidence that water productivity addresses water, food, and environmental security (Molden et al. 2003; Brauman et al. 2013; Kumar et al. 2014; Kang et al. 2017; Zheng et al. 2018). It has a greater role in enhancing climate resilience under water-scarce conditions and increased climate variability (Amarasinghe et al. 2021). However, there is little evidence to understand the role of WP in unraveling the WFEE nexus, which some major food-producing regions are currently facing. Given the contribution of groundwater irrigation to agricultural water and energy use, both PWP and EWP have a role in unraveling the WFEE nexus in the Indian part of the GRB, one of the world's major nexus hotspots.

Groundwater is an overexploited resource in many districts in the GRB, where there is a substantial food production surplus to ensure food and livelihood security within and outside the region. A large part of this surplus depends on unsustainable groundwater use. Pumping from deep aquifers requires substantial energy, contributing to greenhouse gas emissions. To reduce this overexploitation, groundwater withdrawals and CWU must decrease significantly from present levels.

In irrigation alone, GWCWU exceeds 90% of the extractable resources in 81 districts, mainly in the western riparian states of Haryana, Uttar Pradesh, Madhya Pradesh, and Rajasthan of the GRB. These districts mine groundwater from deep aquifers, as their process and non-process consumptive water use for all sectors is significantly more than the available resources for extraction. Energy requirement increases with groundwater abstraction from deeper aquifers, which require higher horsepower electric motors (generally 10-15 hp submersible pumps compared to 5.0-7.5 hp centrifugal pumps for shallow depths). Without drastic measures, these districts get entangled deeper and deeper in the nexus year after year.

Reducing GWCWU requires reducing groundwater irrigated areas and/or groundwater withdrawal for irrigation. However, reducing cropped areas is a highly sensitive issue primarily due to the impacts on the income and livelihood of farmers. Therefore, most groundwater reduction-related interventions consider reducing groundwater withdrawals. For example, the direct benefit transfer of electricity in Punjab, known as the *Paani Bachao Paisa Kamao* scheme (Gulati and Saraswat 2021), changing from transplanting to direct sowing and wet and dry irrigation, will mainly reduce withdrawals. This, in turn, reduces some evaporation from non-process depletion. Moreover, a large reduction in withdrawals can reduce substantial energy consumption. However, this is only part of the WFEE nexus; the most important groundwater overexploitation and depletion will remain the same.

The difficulty of untangling the nexus in the GRB is that groundwater meets the irrigation requirements of the

three major crops (rice, wheat and sugarcane), which not only have an increasing demand for food needs in and outside the GRB but also have guaranteed minimum support prices (MSP) for production. The MSP and free/highly subsidized electricity for pumping encourage more groundwater irrigation to grow these water-guzzling crops in overexploited regions (Sahu and Pradhan 2024). Therefore, the three crops make up a substantial share of the groundwater irrigated area (82%), which has expanded by 1% annually in the past decade.

However, this trend is hydrologically and economically untenable, as much of the production surpluses of crops depend on unsustainable groundwater use. For example, the demand for rice and wheat in food consumption in GRB is 79 million t. About 60 Bm³ groundwater CWU is required to fulfil this demand, in addition to available surface irrigation and rainfall supply. This groundwater requirement is within the extractable resources of 149 Bm³. So, most groundwater use beyond unsustainable limits is currently exported as virtual water to food deficit areas within the country or as exports to other countries. This is the paradox of the food and energy policy that demands immediate attention.

Many solutions are proposed to reduce unsustainable water use in the GRB. These include alternate wet-and-dry irrigation, direct seeded rice, high-tech irrigation, use of sprinklers and drip irrigation, underground pipe irrigation, etc. (van Opstal et al. 2021). These solutions can reduce non-process and non-beneficial evaporation, but real savings in CWU could be smaller (Perry and Steduto 2017). These are not lasting solutions to the large process depletion of groundwater that exceeds extractable resources. Without a substantial reduction in GWCWU in agriculture, the nexus will remain and perhaps increase within the basin, especially in the districts that produce large surpluses in food production.

The proposed water transfers between river basins under the National River Linking Project (<https://nwda.gov.in/content/innerpage/overview.php>), the Ken and Bethwa river link being implemented now, and the proposed transfers from Nepal, Upper Ganga, and Yamuna rivers may contribute to reducing groundwater depletion in many districts. However, many of these inter-basin transfers are very contentious and may not be implemented in the short term to address the groundwater overexploitation issues in the GRB (Shah and Amarasinghe 2016).

The analysis in this paper illustrates that all the districts in the GRB must take measures to correct the existing nexus. To reduce the GWCWU to a sustainable extraction level, many districts must reduce groundwater-irrigated sugarcane, rice, and wheat areas. This measure will reduce production and the income it generates. However, alternative measures can mitigate the production and

value losses. Districts with low groundwater use should augment irrigation supply to increase crop productivity and area, and hence production, to meet the reduced food production surpluses in the highly overexploited districts. For example, increasing groundwater application by 100-200 mm in the safe groundwater use districts (exploitation ratio <40%) can maintain sustainable groundwater use while increasing rice, wheat, and sugar yields by 1 t/ha to 3 t/ha.

Increasing PWP is one solution to mitigate production losses. This can be done by reducing the yield gap, which is significant for rice, wheat, and sugarcane, even at the current level of attainable productivity. The current productivity frontier of the GRB, especially in the eastern and southern parts, is substantially lower than that at the national level. So there is significant scope to reduce the yield gap and mitigate production losses with reduced area. The yield gap analysis in this paper shows that a 75% reduction in the yield gap of rice, wheat, and sugarcane can offset production losses in many districts with reduced GWCWU and area. In 81 districts, increased production is insufficient to offset the value losses from reduced area.

Increasing EWP is the solution for districts that cannot offset the value losses with reduced cropped area. These districts can replace the reduced rice, wheat, and sugarcane areas with low water-consuming and high-value crops to reduce water use and increase production value. The crop diversification scenarios developed with maize, pearl millet, gram, vegetables, and fruits show substantially higher production value than the baseline condition in 2018-2020 and groundwater depletion below the extractable limits. To start with, 'hotspot' districts with the highest overexploitation of groundwater (>100% of the 'extractable limit' may be encouraged/facilitated/or even incentivized to transition a part of the land holdings to high-value, low-water use cropping systems.

Increasing WUE can reduce GWCWU by reducing non-beneficial evaporation and energy use for pumping groundwater. All the districts can benefit from increased WUE. Highly efficient irrigation methods such as drip, sprinkler, or underground pipes can increase crop yields and production too.

A limitation of this paper is that it explicitly analyzed only two dimensions of the nexus. It did not evaluate the energy and environmental footprints, sources, and impacts within the nexus, although the energy component is implicitly addressed through GWCWU reduction. A large reduction in GWCWU and withdrawals is assumed to require less energy than the present. However, this aspect requires in-depth analysis given the increasing trend of using deep tubewells in the western parts of the GRB. Moreover, more studies are required on promoting solar irrigation, which reduces electricity and diesel use for pumping, has a smaller carbon footprint, and can

benefit farmers by connecting to the grid. These solutions have already been demonstrated on a pilot scale in some states in India (Shah and Rai 2021). Solar irrigation programs could be implemented at scale to address the energy and environmental components of the nexus (Shah et al. 2018). Moreover, livestock production, especially milk production, needs to be included to assess the overall influence of agricultural production in the nexus (Amarasinghe et al. 2010). Further research on these topics will complement the solutions proposed to address the WFEE nexus.

This study shows that to achieve WFEE nexus gains, the following policy measures are required in the GRB:

- a) Gradual reduction in groundwater irrigated area/or groundwater use for rice, wheat, and sugarcane in the 110 overexploited and critical districts (Annex, Table A3) so that the overall production within the basin meets the consumption demand or has a slight surplus for exports until the deficit areas increase their production to meet the consumption demand.
- b) Districts with less than 60% groundwater exploitation may be encouraged to intensify their cropping systems vertically by improving rainfall water-use efficiency, augmenting groundwater recharge, underground taming of floods for irrigation, improving seed, fertilizer, and agronomic practices, and providing access to affordable energy (both electricity and solar power). Improved production in these districts will lead to positive nexus gains and be a win-win proposition for the GRB and beyond.
- c) Increase the PWP of rice, wheat, and sugarcane. Introduce a national and state-level program to increase the land productivity of these three crops by at least reducing existing yield gaps within a district or going beyond current yield frontiers outside the district. Benchmarking land productivity and determinants should help propel this initiative. Yield increase has contributed to much of the PWP increase in most crops during the last two decades. A substantial increase in PWP itself could solve the nexus in many districts.
- d) In districts with a major WFEE nexus issue, replace parts of rice, wheat, and sugarcane areas with crops that reduce the GWCWU in a time-targeted program to ensure hydrological and energy sustainability. Also, identify crops with higher EWP for diversification. The yield gap analysis should be widened to capture potential PWP increase in other crops.

The need for these actions is well-known in policy management. The analysis in this paper shows where these actions need priority. Specifically, it shows to what extent PWP and EWP increases can help unravel the water and food components of the nexus.

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Annex

Table A1. Socio-economic indicators, nutritional intake, and cropped area in the riparian states in the GRB.

Indicators	Bihar	Chhattisgarh	Delhi	Himachal Pradesh	Jharkhand	Madhya Pradesh	Rajasthan	Uttar Pradesh	Uttarakhand	Water Bengal	GRB	India
Area (% of total) ¹	2.9	4.1	0.1	1.7	2.4	9.4	10.4	7.3	1.6	2.7	43.9	100.0
Total population in 2011 (in millions) ²	104.1	25.6	16.8	6.9	33.0	73.9	68.6	199.8	10.1	91.3	654.0	1,210.9
Estimated population in 2051 (in millions) ³	121.3	29.2	20.2	7.4	38.1	83.8	78.3	227.9	11.3	97.7	744.3	1,380.0
Projected population in 2051 (in millions)	190.5	36.2	27.7	9.1	54.5	116.0	124.7	363.9	15.0	119.2	1,098.8	1,823.5
Rural population (% of the total in 2011) ⁴	88.7	76.8	2.5	90.0	76.0	71.0	75.1	77.7	69.8	68.1	0.7	68.7
Agri. population (% of the total in 2011)	24.5	35.6	0.4	32.6	25.0	30.3	27.1	19.5	19.7	16.8	22.6	21.7
Income poverty (% of population) ⁵	0.42	0.41		0.11	0.46	0.37	0.19	0.33	0.41	0.29	NA7	0.28
Multidimensional poverty (% of population)	0.27	0.13	0.02	0.03	0.20	0.17	0.14	0.18	0.08	0.10	NA	0.12
Primary school enrolment of female (% of total female) ⁵	48.2	48.8	47.1	47.6	48.2	47.9	47.2	47.7	46.8	48.8	47.8	47.9
Maternal mortality/100,000 live births ⁶	118.0	137.0	97.0	55.0	56.0	173.0	113.0	167.0	103.0	103.0	NA	97.0
Stunting (% of children <5 years) ⁷	42.9	34.6	30.9	30.8	39.6	35.7	31.8	39.7	27.0	33.8	34.0	35.1
HDI ⁸	0.57	0.61	0.73	0.7	0.59	0.6	0.64	0.59	0.67	0.62		0.63
Agriculture GDP (% of the total)	4.5	2.0	0.2	1.0	2.2	9.5	6.5	13.7	0.8	7.3	51.7	
Nutritional intake in 2009-2010												
• Calories (kcal/person/day)	2,013	1,971	1,536	2,372	1,902	1,929	2,115	2,059	2,043	1,835	1,989	1,959
• Proteins (grams/person/day)	56	47	45	69	50	57	64	60	57	47	56	53
• Fat (grams/person/day)	34	31	51	63	32	42	59	41	50	33	45	41
Composition (Kcal/person/daily)												
• Rice	736	1,235	155	488	894	263	42	455	517	1,049	540	831
• Wheat	664	185	572	739	431	919	1,025	455	663	1,049	699	373
• Pulses	80	98	77	171	79	97	57	96	107	56	91	89
• Milk	135	56	280	345	100	169	336	186	252	77	214	163

Cropped area (Mha)													
• Rice	3.20	4.10	0	0.10	1.30	2.60	0.20	6.70	0.30	5.50	17.48	46.20	
• Wheat	2.10	0.10	0	0.30	0.10	7.70	3.20	10.20	0.30	0.10	20.41	32.79	
• Maize	0.70	0.10	0	0.30	0.30	1.40	0.90	0.70	0	0.30	2.62	9.46	
• Sorghum	0	0	0	0	0.00	0.10	0.60	0.20	0	0	0.56	5.36	
• Other cereals	0	0	0	0	0.00	0.40	5.10	1.20	0.10	0	2.93	9.04	
• Cereals	6.00	4.30	0	0.70	1.70	12.20	10.00	19.00	0.70	5.90	44.00	102.85	
• Pulses	0.10	0.50	0	0	0.30	5.00	2.60	1.20	0	0.10	7.00	17.01	
• Oilseeds	0.10	0	0	0	0.50	12.50	5.20	0.80	0	0.70	4.49	34.37	

Sources: Crop area estimates are authors' estimates derived from district-level data collected for the Indian Water Productivity Atlas; data on population (GOI 2011); population projections (GOI 2020); income and multidimensional poverty (Amarasinghe et al. 2016); and food consumption patterns (FAO 2023).

Notes: ¹ <https://www.indiaatstat.com/specimen-tables/geographical-data>

² <https://www.census2011.co.in/>

³ <https://statisticstimes.com/demographics/country/india-population.php>

⁴ <https://www.macrotrends.net/countries/IND/india/rural-population>

⁵ <https://www.rbi.org.in/Scripts/AnnualPublications.aspx?head=Handbook-of-Statistics-on-Indian+States>

⁶ <https://censusindia.gov.in/nada/index.php/catalog/44379>

⁷ <https://pib.gov.in/PressReleasePage.aspx?PRID=1806601>

⁸ <https://statisticstimes.com/economy/india/indian-states-gdp.php>

Table A2. Area, yield, and PWP of rice, wheat, and maize crops and rice-wheat, rice-rice, and maize-wheat cropping systems.

Factor	Crop/cropping system	<i>Kharif</i>	<i>Rabi</i>	Summer	Total
Area (Mha)	Rice	15.6	1.2	0.7	17.5
	Wheat	0	20.4	0	20.4
	Maize	1.9	0.4	0.3	2.6
	Rice-wheat	12.3	17.2	0.5	30.0
	Rice-rice	3.1	1.1	0.2	4.4
	Maize-wheat	0.4	1.4	0.1	1.9
Yield (t/ha)	Rice	2.59	3.50	1.80	2.62
	Wheat	0	3.60	0	3.60
	Maize	2.22	7.09	4.98	3.28
	Rice-wheat	2.53	3.54	1.51	3.09
	Rice-rice	2.84	3.62	2.60	3.02
	Maize-wheat	2.77	4.21	3.98	3.89
PWP (kg/m ³)	Rice	0.56	0.95	0.45	0.58
	Wheat	0	0.98	0	0.98
	Maize	0.66	3.54	1.09	0.99
	Rice-wheat	0.55	0.99	0.37	0.77
	Rice-rice	0.64	0.97	0.65	0.71
	Maize-wheat	0.79	1.08	0.83	1.01

Source: Authors' estimates.

Table A3. GWCWU in districts with overexploited, critical, and semi-critical groundwater use.

	State	District	GWCWU					Wheat	Sugarcane
			Group	% of GW availability	Rice <i>kharif</i>	Rice total			
1	Rajasthan	Churu	1	418	0	0	0.008	0	
2	Uttar Pradesh	Baghpat	1	319	15.8	15.8	162.1	871.8	
3	Rajasthan	Chittaurgarh	1	294	1.3	1.3	570.6	17.8	
4	Rajasthan	Jhunjhunun	1	288	0	0	185.0	0	
5	Uttar Pradesh	Ghaziabad	1	245	66.8	66.8	197.2	613.5	
6	Rajasthan	Bharatpur	1	240	2.1	2.1	476.8	0.1	
7	Haryana	Mahendragarh	1	234	0	0	117.4	0	
8	Uttar Pradesh	Muzaffarnagar	1	233	53.4	54.3	278.6	2,063.9	
9	Haryana	Bhiwani	1	215	2.5	2.5	10.1	1.0	
10	Uttar Pradesh	Bijnor	1	206	47.8	48.4	225.7	2,454.3	
11	Rajasthan	Alwar	1	199	0.4	0.4	697.2	0.2	
12	Uttar Pradesh	Badaun	1	195	294.7	295.0	699.4	347.5	
13	Rajasthan	Bhilwara	1	192	0.9	0.9	457.5	0.4	
14	Uttar Pradesh	Meerut	1	186	28.6	28.8	178.7	1,152.7	
15	Uttar Pradesh	Jyotiba Phule Nagar	1	186	41.9	42.0	276.4	1,014.5	
16	Uttar Pradesh	Lakhimpur Kheri	1	186	189.5	198.1	473.2	3,172.8	
17	Rajasthan	Sikar	1	185	0	0	106.12	0.04	
18	Uttar Pradesh	Moradabad	1	170	190.7	192.3	639.1	868.5	
19	Rajasthan	Jhalawar	1	168	5.6	5.6	517.2	0.1	
20	Madhya Pradesh	Ujjain	1	167	0	0	1,154.3	0.2	
21	Haryana	Kurukshetra	1	167	8.4	8.4	9.3	4.4	
22	Rajasthan	Rajsamand	1	163	0	0	93.3	2.6	
23	Madhya Pradesh	Ashoknagar	1	163	2.5	2.5	401.6	3.1	
24	Rajasthan	Bundi	1	163	52.6	52.6	338.9	4.0	
25	Rajasthan	Jaipur	1	153	0	0	418.4	0.6	

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26	Uttar Pradesh	Sitapur	1	151	219.1	219.2	637.0	1,844.5
27	Madhya Pradesh	Dewas	1	151	0.0	0.0	359.5	1.1
28	Uttarakhand	Haridwar	1	149	11.5	11.5	94.5	533.9
29	Rajasthan	Tonk	1	147	0	0	140.8	0.1
30	Madhya Pradesh	Indore	1	146	0	0	497.7	0.3
31	Haryana	Rewari	1	144	6.4	6.4	145.7	0.3
32	Rajasthan	Sawai Madhopur	1	143	3.1	3.1	245.0	0.1
33	Uttar Pradesh	Bareilly	1	142	178.3	179.7	507.7	893.0
34	Uttar Pradesh	Basti	1	141	152.4	152.8	397.3	505.8
35	Uttar Pradesh	Lalitpur	1	140	43.0	43.0	422.6	0.2
36	Haryana	Faridabad	1	139	37.8	37.8	99.1	3.9
37	Haryana	Sonepat	1	138	221.3	221.3	333.9	77.2
38	Uttar Pradesh	Gonda	1	137	127.7	128.3	446.6	908.8
39	Haryana	Gurgaon	1	136	110.0	110.0	614.5	29.3
40	Madhya Pradesh	Sehore	1	129	9.1	9.1	376.3	3.4
41	Rajasthan	Udaipur	1	127	0	0	82.4	0.7
42	Madhya Pradesh	Narsinghpur	1	126	1.7	1.7	18.6	38.1
43	Rajasthan	Baran	1	126	17.6	17.6	475.0	0
44	Uttar Pradesh	Hamirpur	1	122	2.4	2.4	395.1	37.5
45	Rajasthan	Karauli	1	119	0	0	249.1	0.2
46	Madhya Pradesh	Mandsaur	1	118	0	0	583.2	0.1
47	Uttar Pradesh	Farrukhabad	1	117	26.5	26.6	236.0	111.2
48	Uttar Pradesh	Aligarh	1	116	197.3	197.5	648.5	64.8
49	Madhya Pradesh	Rajgarh	1	115	0	0	800.9	0
50	Haryana	Rohtak	1	114	41.3	41.3	78.7	27.8
51	Rajasthan	Dhauipur	1	112	0	0	182.5	0.1
52	Uttar Pradesh	Pilibhit	1	110	109.7	122.8	351.5	650.1
53	Uttar Pradesh	Bulandshahr	1	109	244.9	245.3	587.5	586.0
54	Madhya Pradesh	Shajapur	1	107	0	0	768.0	0.2
55	Madhya Pradesh	Tikamgarh	1	107	0	0	528.4	1.1
56	Haryana	Jhajjar	1	105	72.3	72.3	185.1	15.2
57	Haryana	Ambala	1	104	0	0	0	0
58	Uttar Pradesh	Hardoi	1	104	157.9	158.0	971.6	466.6
59	Uttar Pradesh	Rampur	1	104	108.6	123.3	363.4	225.4
60	Madhya Pradesh	Dhar	1	103	0	0	164.3	4.9
61	Rajasthan	Ajmer	1	103	0	0	104.8	0
62	Madhya Pradesh	Damoh	1	103	1.4	1.4	209.8	0.3
63	Uttar Pradesh	Saharanpur	1	102	68.3	68.4	290.6	966.1
64	Uttar Pradesh	Sultanpur	1	100	216.6	216.7	507.0	85.1
65	Madhya Pradesh	Sagar	1	99	0	0	768.6	2.6
66	Madhya Pradesh	Satna	1	99	62.3	62.3	573.0	2.2
67	Madhya Pradesh	Raisen	1	99	41.3	41.3	296.3	6.2
68	Madhya Pradesh	Katni	1	98	29.5	29.5	182.0	0.7
69	Madhya Pradesh	Neemuch	1	97	0	0	277.9	0.1
70	Madhya Pradesh	Bhopal	1	97	0	0	347.2	0.2
71	Madhya Pradesh	Guna	1	96	0.1	0.1	469.2	4.8
72	Uttar Pradesh	Ambedkar Nagar	1	96	148.6	149.1	357.2	161.9
73	Rajasthan	Kota	1	95	24.6	24.6	307.4	0
74	Madhya Pradesh	Chhatarpur	1	95	0	0	659.1	0.8
75	Madhya Pradesh	Shivpuri	1	93	20.7	21.0	548.2	3.2
76	Bihar	Sitamarhi	1	92	82.0	91.5	279.8	192.8
77	Madhya Pradesh	Ratlam	1	91	0	0	351.2	0
78	Haryana	Panipat	1	91	88.4	88.4	102.1	34.7
79	Uttar Pradesh	Azamgarh	1	91	248.5	248.5	675.1	172.5
80	Uttar Pradesh	Jhansi	1	90	30.7	30.7	475.4	0.8
81	Uttar Pradesh	Mau	2	89	98.5	98.5	255.8	50.2
82	Uttar Pradesh	Auraiya	2	86	135.4	135.5	319.2	6.5
83	Uttar Pradesh	Mahoba	2	86	0	0	171.7	23.8
84	Madhya Pradesh	Jabalpur	2	85	4.8	4.8	41.0	2.1
85	Madhya Pradesh	Vidisha	2	84	0.5	0.5	503.4	0.4

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86	Uttar Pradesh	Banda	2	82	81.7	81.7	449.3	2.9
87	Haryana	Yamuna Nagar	2	82	29.8	29.8	100.9	119.4
88	Uttar Pradesh	Kannauj	2	80	45.7	45.9	219.6	1.4
89	Uttar Pradesh	Balrampur	2	79	34.9	35.1	189.3	421.9
90	Haryana	Karnal	2	76	71.6	71.6	101.7	30.6
91	Bihar	Nalanda	2	75	131.5	131.5	256.6	0.5
92	Uttar Pradesh	Kaushambi	3	75	79.24	79.24	228.56	6.60
93	Uttar Pradesh	Ballia	3	73	131.78	131.87	414.34	40.85
94	Uttar Pradesh	Ghazipur	3	73	153.06	153.07	476.56	34.63
95	Uttar Pradesh	Fatehpur	3	72	123.81	123.88	494.65	80.55
96	Uttar Pradesh	Etah	3	72	82.21	82.23	695.07	76.14
97	Uttar Pradesh	Agra	3	70	17.04	17.04	382.01	1.90
98	Uttar Pradesh	Rae Bareli	3	69	179.50	179.50	547.34	18.60
99	Uttar Pradesh	Jaunpur	3	69	163.28	163.31	562.54	69.40
100	Uttarakhand	Udham Singh Nagar	3	69	53.31	83.17	273.43	117.80
101	Uttar Pradesh	Sant Kabir Nagar	3	69	15.45	15.68	276.37	38.88
102	Uttar Pradesh	Chitrakoot	3	67	18.25	18.25	239.92	1.14
103	Uttar Pradesh	Mathura	3	66	122.49	122.49	590.07	3.89
104	Uttar Pradesh	Allahabad	3	66	295.03	295.14	649.66	2.18
105	Uttar Pradesh	Etawah	3	65	96.75	97.01	272.78	2.21
106	Uttar Pradesh	Siddharth Nagar	3	64	81.50	82.87	435.92	31.27
107	Uttar Pradesh	Pratapgarh	3	63	220.18	220.21	538.55	10.08
108	Uttar Pradesh	Varanasi	3	63	59.01	59.01	201.78	28.37
109	Bihar	Begusarai	3	60	7.67	7.92	206.88	17.38
110	Madhya Pradesh	Rewa	3	60	51.60	51.60	224.10	0.17
111	Uttar Pradesh	Mirzapur	4	60	85.06	85.06	230.48	6.56
112	Uttar Pradesh	Hathras	4	59	48.41	48.93	230.99	1.07
113	Uttar Pradesh	Mainpuri	4	59	94.26	94.29	329.15	2.58
114	Uttar Pradesh	Kushinagar	4	59	92.59	92.60	265.67	514.09
115	Uttar Pradesh	Bahraich	4	58	51.26	51.27	473.27	225.83
116	Uttar Pradesh	Kanpur Dehat	4	56	83.92	83.92	298.59	14.80
117	Uttar Pradesh	Firozabad	4	56	39.62	39.78	271.86	0.83
118	Uttar Pradesh	Unnao	4	55	146.34	146.36	649.38	9.46
119	Bihar	Samastipur	4	53	45.90	66.09	181.14	12.28
120	Uttar Pradesh	Deoria	4	53	130.95	131.15	494.32	67.50
121	Uttar Pradesh	Maharajganj	4	52	1.54	1.67	380.61	140.65
122	Uttar Pradesh	Kanpur	4	52	53.48	53.48	249.98	32.32
123	Uttar Pradesh	Shravasti	4	51	13.29	13.29	182.46	62.16
124	Madhya Pradesh	Morena	4	50	3.73	3.73	200.74	0.98
125	Bihar	Sheikhpura	4	50	23.72	23.72	55.23	0.07
126	Uttar Pradesh	Gautam Buddha Nagar	4	50	79.71	79.71	129.53	8.24
127	Madhya Pradesh	Datia	4	49	14.09	14.09	140.18	29.21
128	Madhya Pradesh	Sheopur	4	46	30.13	30.13	158.80	0.06
129	Uttar Pradesh	Gorakhpur	4	46	77.96	78.51	588.39	23.33
130	Uttar Pradesh	Jalaun	4	46	5.56	5.56	382.27	4.71

Table A4. Yield gaps in rice and wheat (t/ha) in the GRB.

	Total CWU of rice (mm)					Total CWU of wheat (mm)			
	200-300	300-400	400-500	500-600	500-600	200-300	300-400	400-500	500-600
All districts	0.834	1.136	0.610	0.312		2.260	2.069	2.247	
Bihar		1.209	1.580			2.634	2.582		
Chhattisgarh		1.881							3.301
Delhi			0.180					1.041	
Haryana			0.279			0.773	0.629		
Himachal Pradesh		2.157	0.799				3.620	3.646	
Jharkhand	0.535	0.849					3.626	3.304	
Madhya Pradesh	1.509	1.583	1.229					2.256	1.585
Rajasthan	0.843		0.663	0.312			1.496	1.208	
Uttar Pradesh		0.777	0.536					1.652	2.313
Uttarakhand		1.449	1.175	0.850			2.929	3.406	1.758
West Bengal		0.480	0.547			1.656	2.927		

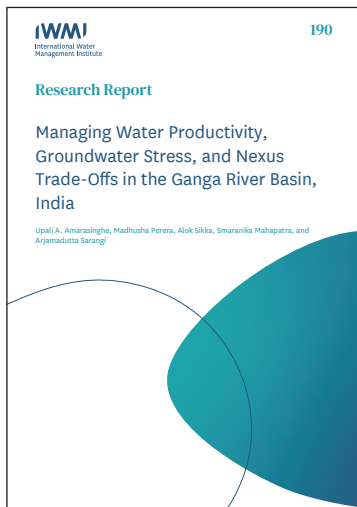
Table A5. PWP, EWP, and other water-related indicators.

Crop	Season	Irrigation supply (m ³ /ha)	PWP (Kg/m ³)	EWP (USD/m ³)	Value/ha (USD/ha)
Rice	<i>Kharif</i>	1,302	0.56	0.34	1,550
Maize	<i>Kharif</i>	490	0.66	0.18	599
Sorghum	<i>Kharif</i>	1,618	0.34	3.72	400
Pearl millet	<i>Kharif</i>	788	0.90	0.29	629
Pigeonpea	<i>Kharif</i>	1,864	0.34	0.12	363
Black gram	<i>Kharif</i>	347	0.19	0.19	598
Groundnut	<i>Kharif</i>	908	0.31	0.33	1,284
Soyabean	<i>Kharif</i>	1,046	0.23	0.12	513
Chili	<i>Kharif</i>	2,525	0.12	0.28	1,287
Sesame seed	<i>Kharif</i>	375	0.12	0.07	216
Onion	<i>Kharif</i>	1,859	6.21	1.39	4,765
Potato	<i>Kharif</i>	1,140	5.85	1.09	4,810
Other vegetables	<i>Kharif</i>	1,589	25.66	2.91	10,101
Rice	<i>Rabi</i>	2,209	0.95	0.57	1,350
Wheat	<i>Rabi</i>	3,371	0.99	0.26	971
Maize	<i>Rabi</i>	1,666	3.48	0.93	1,871
Gram	<i>Rabi</i>	2,714	1.34	0.76	1,469
Mustard	<i>Rabi</i>	1,805	0.98	0.55	950
Chilli	<i>Rabi</i>	2,700	0.12	0.28	2,393
Other vegetables	<i>Rabi</i>	3,136	12.41	7.36	14,833
Sugarcane	Annual	11,172	0.63	0.21	3,109
Ginger	Annual	4,427	0.69	0.95	6,616
Cotton	Annual	3,985	0.08	0.12	788
Fodder	Annual	571	14.23	0.27	662
Turmeric	Annual	4,853	1.26	1.51	13,017
Banana	Annual	11,579	0.55	0.28	3,401
Potato	Annual	1,140	5.85	1.09	4,810
Mango ¹	Annual	0	1.68	1.61	5,439

Source: Authors' estimates.

Note: ¹ Assumed to be not irrigated.

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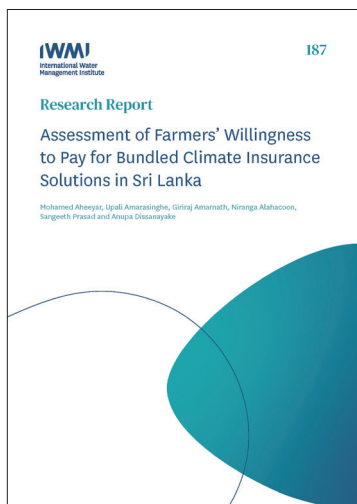
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