Innovation brief

Water Productivity Atlas for addressing the water–energy–food–ecosystems nexus

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November 2024

Introduction

Climate change exacerbates challenges related to the water–energy–food–ecosystems (WEFE) nexus, particularly in regions like South Asia, which is already a major hotspot for these interrelated issues. In countries such as India, water and energy security are strained by the high energy demand for pumping groundwater to meet agricultural needs. For example, 85 percent of water withdrawals in India are for agriculture, with over 60 percent of that coming from groundwater (authors estimate). The energy required to extract this water is so significant that it hampers growth in other sectors. Immediate, transformative actions in water and energy management within agriculture are necessary to mitigate the impacts of climate change and meet Sustainable Development Goals (SDGs) such as SDG1 (No Poverty), SDG2 (Zero Hunger), and SDG6 (Clean Water and Sanitation).

Addressing the challenges of water and energy security for agriculture requires a comprehensive approach. Reliable estimates on the interconnectedness of food, nutrition, water, energy, and the environment are critical for informed policymaking and designing interventions. The CGIAR Initiative on NEXUS Gains aims to enhance this knowledge base by focusing on key indicators such as water, nutrition, energy productivity, and water and environmental footprints of crop production. Understanding the WEFE nexus through these indicators can provide valuable insight into the current crisis and help address other emerging issues as climate-related disasters become more frequent.

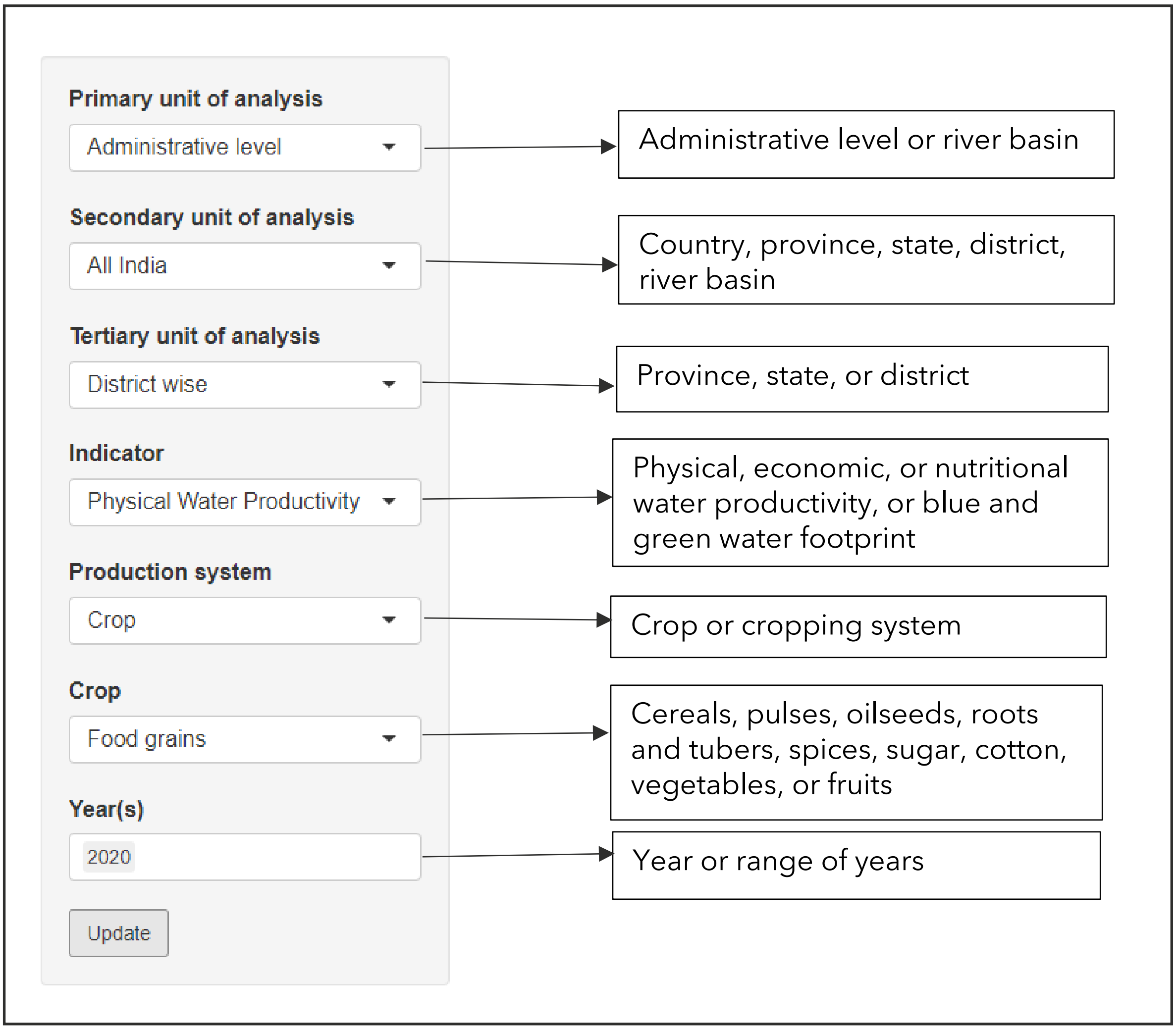
Aggregate productivity and footprint indicators for large regions, such as a whole country or the Indo-Gangetic Plain, are insufficient for understanding the nuances of the WEFE nexus. Indicators' spatial and temporal dynamics must be considered for a clearer understanding. This recognition led to the development of the Water Productivity Atlas, an online tool that visualizes variations in water productivity and water footprint (WFP) indicators. Users can explore spatial variations over time or compare productivity changes between different periods. The tool enables exploratory, scenario-based, and statistical analysis to identify the root causes of WEFE nexus issues and the actions required to address them.

Design of the Water Productivity Atlas

The Atlas is an interactive dashboard created using R-Shiny. It has five main panels: *Home*, *Trends, Comparisons, Scenarios,* and *Nexus*. The *Home* panel gives a brief introduction to the other four panels. The *Trends* and *Comparisons* panels provide dropdown menus (Figure 1) to select spatial units at different scales (e.g., primary: country, secondary: state, tertiary: district) and indicators (physical, economic, or nutritional water productivity, or blue or green WFP). Users can also select a crop or cropping system, such as rice-wheat, rice-rice, or maize-wheat, and time period(s) for analyzing spatial and temporal variation.

In *Trends*, users can compare the spatial variation of indicators at one or two time periods. In *Comparisons*, users can compare variations of two crops or across two spatial units. The *Scenarios* panel facilitates scenario development to assess possible implications for the WEFE nexus of different consumption or development scenarios at the district level, such as improving crop productivity or crop diversification. The *Nexus* panel shows summary indicators such as the spatial variation of nutritional surplus in terms of calories, proteins, and fat, or groundwater depletion as a percentage of extractable resources.

Figure 1. Dropdown menu for *Trends* and *Comparisons* panels of the Water Productivity Atlas



Source: Authors

The Water Productivity Atlas of India

The Water Productivity Atlas of India has options for selecting administrative levels of the whole country, 32 states, 596 districts, or 19 major river basins. It has water productivity and footprint indicators of about 30 crops, including total food grain, cereals (total, rice, wheat, maize, jowar/sorghum, ragi, barley, bajra, and other cereals), and pulses (gram, arhar/pigeon pea, and other pulses). Additionally, the Water Productivity Atlas of India has information on oilseeds (groundnut, soybean, sesame, sunflower, and mustard), fruits (apple, banana, grape, mango, pome fruit, citrus fruit, papaya, and other fruits), vegetables (onion, chili, and other vegetables), roots and tubers (potato, sweet potato, and tapioca), spices (ginger, turmeric, and dry chili), sugar, cotton, fodder, and tobacco. Figures 2–5 show screenshots of the *Trends*, *Comparisons*, *Scenarios*, and *Nexus* panels.

Figure 2. *Trends* panel of the Water Productivity Atlas of India

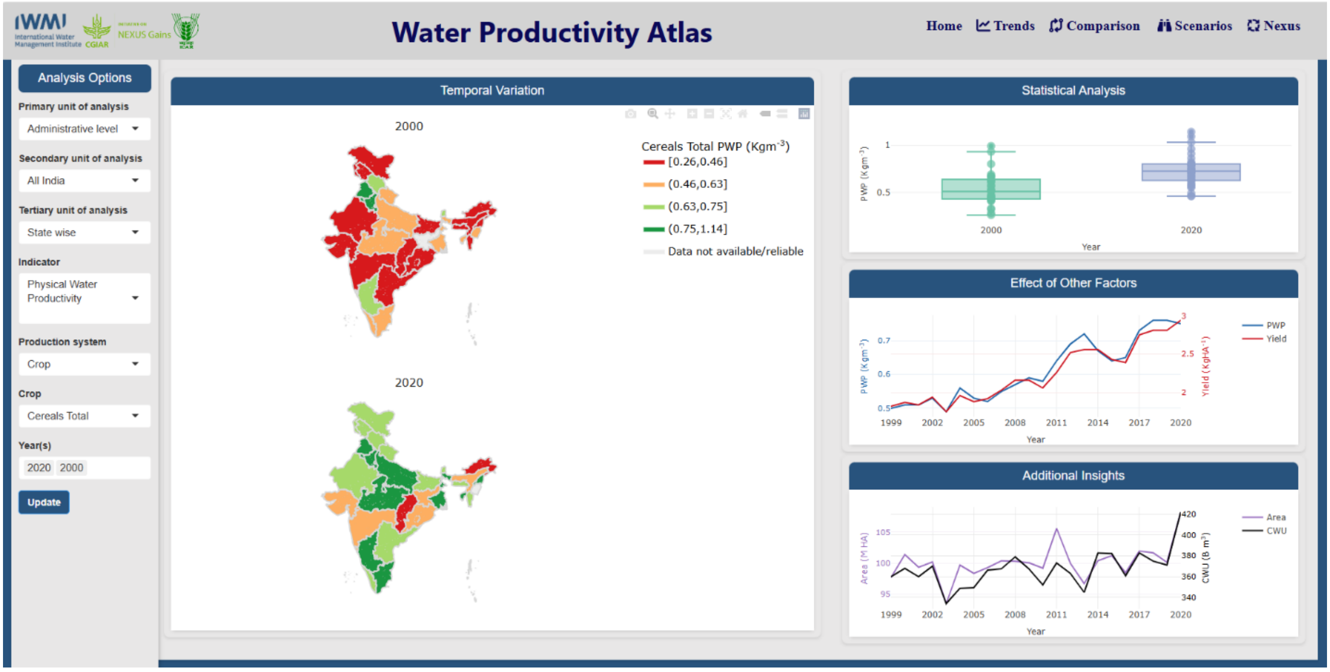
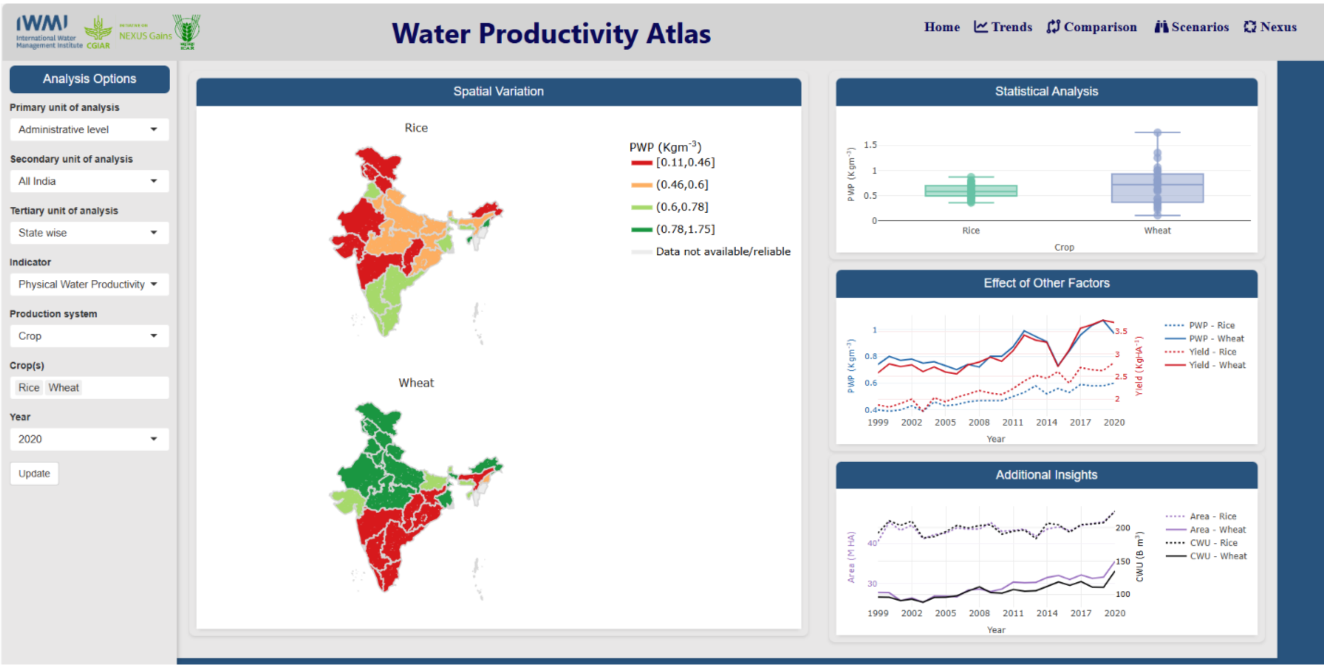


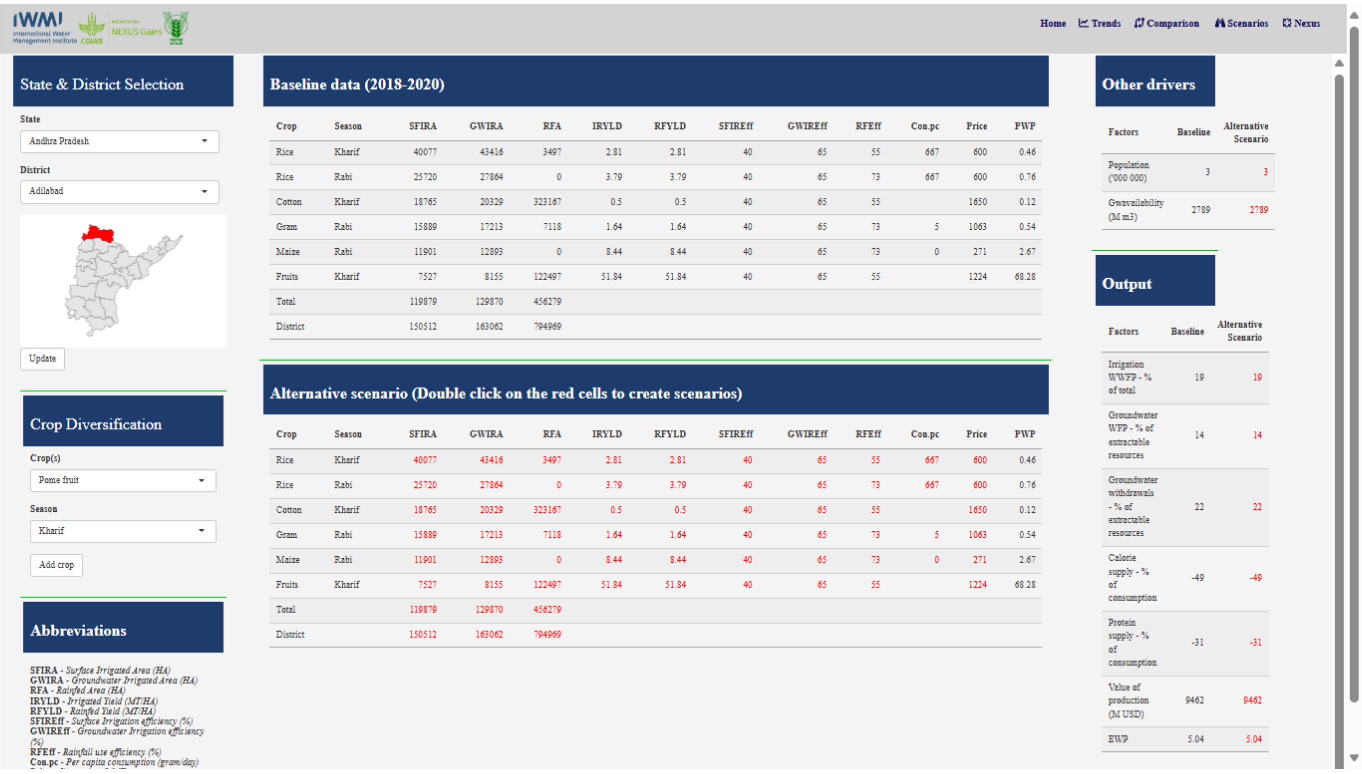
Figure 3. *Comparisons* panel of the Water Productivity Atlas of India



Figures 2 and 3 illustrate the four main visualization components of the *Trends* and *Comparisons* panels. First, users can explore spatial variations of a selected indicator through an interactive map. If indicator values are unavailable, the map displays “Data not available/reliable.” The map highlights variations within the chosen unit of analysis. Second, the statistical summary section includes a boxplot showing the distribution of estimated values, which aids in identifying outliers and assessing skewness. The third and fourth charts present trends in the drivers of the selected indicator. When a user selects any water productivity indicator, these plots illustrate yield, area, and consumptive water use (CWU) changes over time, reflecting secondary unit trends. Additionally, users can view data at district, river basin, and sub-river basin levels across the country.

The *Scenarios* panel is a central feature of this atlas, allowing users to create potential future crop production scenarios by adjusting key drivers and analyzing projected outcomes of nutritional surpluses and deficits with respect to demand and groundwater extraction with respect to extractable resources. This panel uses average values for the base year (2018–2020) and includes four tables. The first table displays data on area, yield, price, per capita consumption, and physical water productivity (PWP) for the crops with the largest irrigated areas. By default, the second table mirrors the values in the first table, but these values can be modified based on user-defined assumptions. Users can edit values by double-clicking on the red-text cells. Tables with orange-colored headings are designated for scenario creation, where values can be altered to explore various outcomes. The output table shows both baseline values and results generated by the scenario, enabling users to compare and evaluate the impact of changes in the selected drivers. This panel supports users in assessing the impact of crop diversification on the WEFE nexus.

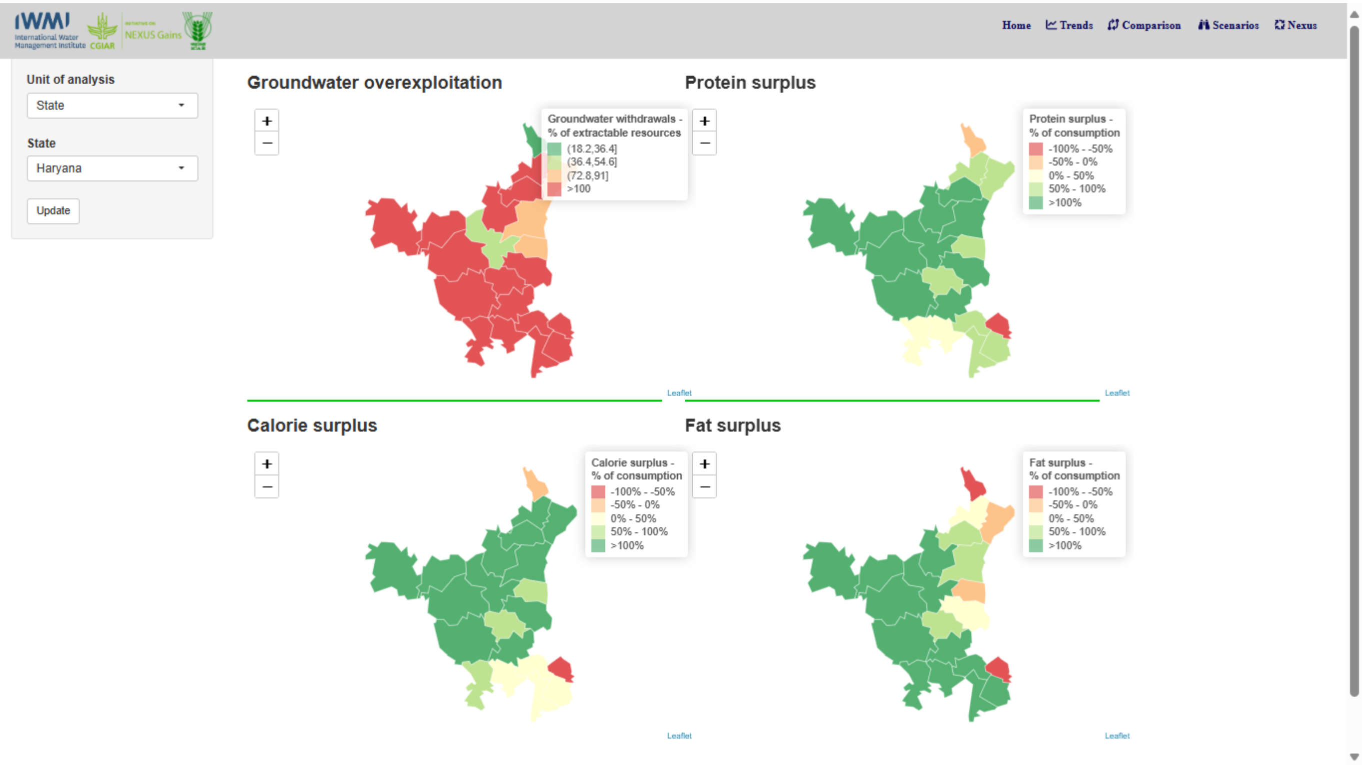
Figure 4. *Scenarios* panel of the Water Productivity Atlas of India



The *Nexus* panel shows spatial variation of the groundwater consumptive water use of all crops as a percentage of extractable groundwater resources estimated by the Central Ground Water Board and the nutritional (calories, protein, and fat) surplus or deficit as a percentage of consumption at the district level. This allows users to identify nutritionally deficient and groundwater over-exploited districts.

The *Nexus* panel displays the spatial variation in groundwater consumptive water use for all crops as a percentage of extractable groundwater resources, based on Central Ground Water Board estimates, along with the nutritional surplus or deficit as a percentage of district-level consumption. This enables users to identify tertiary units with nutritional deficiencies and groundwater over-exploitation.

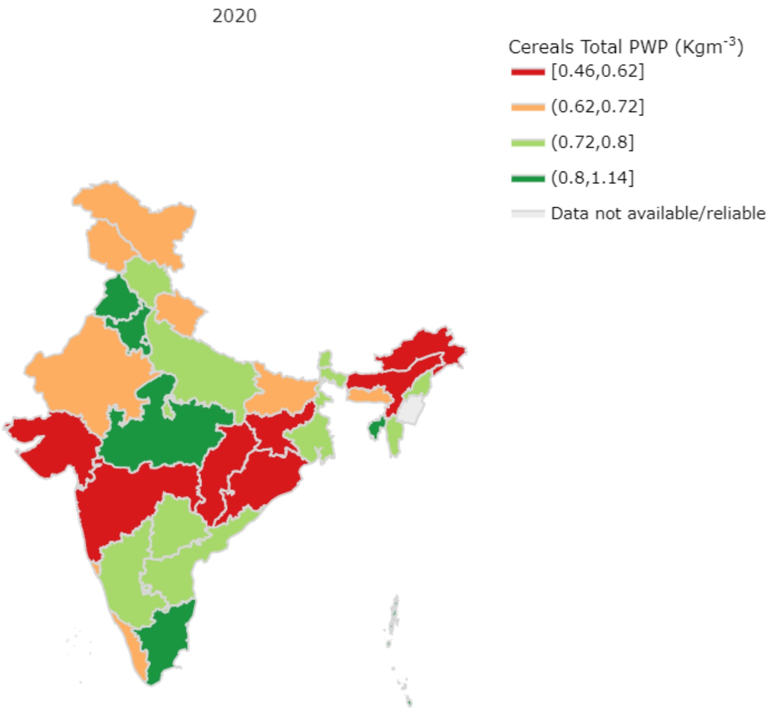
Figure 5. *Nexus* panel of the Water Productivity Atlas of India



Use cases

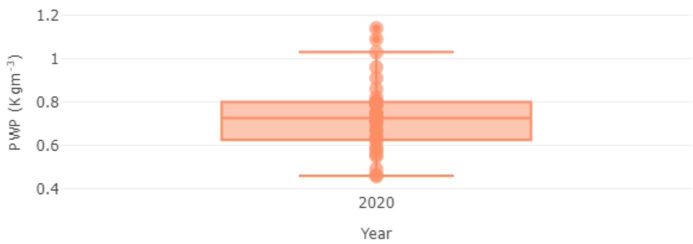
Use case 1: Physical water productivity (PWP) variation of cereals across states in India

Spatial variation of cereal PWP across states in India

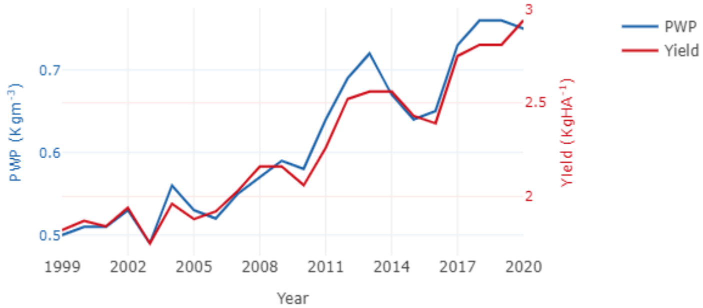


The average PWP for Indian grains is 0.76 kg/m³, with state-level values ranging from 0.46 to 1.14 kg/m³. Yield growth in India has had a positive and significant impact on PWP growth. While there is no clear trend in area and CWU, both have shown an upward trend since 2014, with a notable increase in 2019–2020.

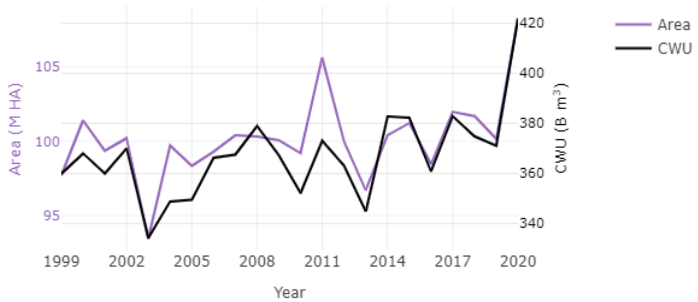
Statistical summary



Trends of PWP and yield

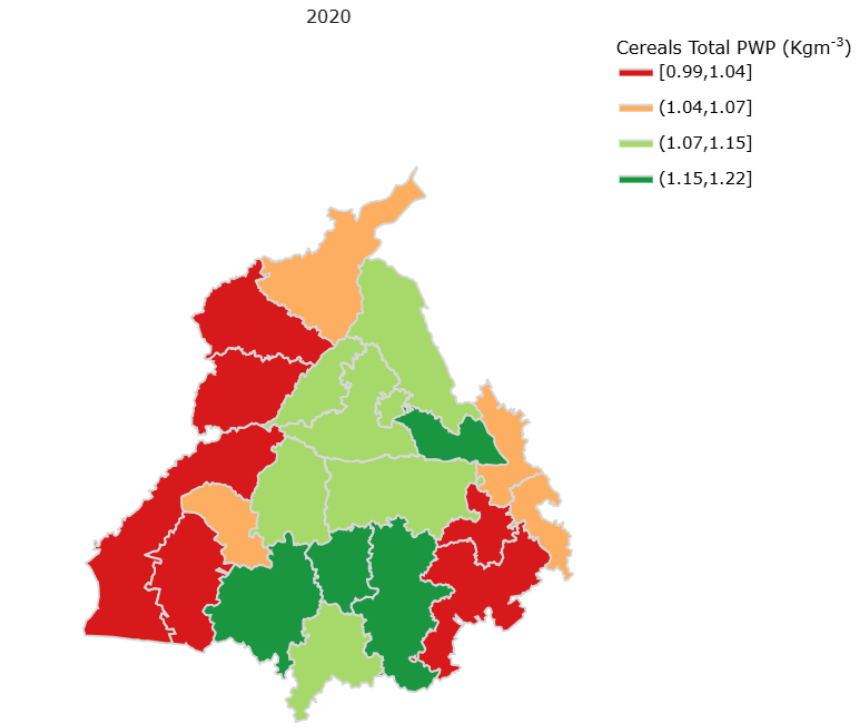


Trends of area and consumptive water use (CWU)



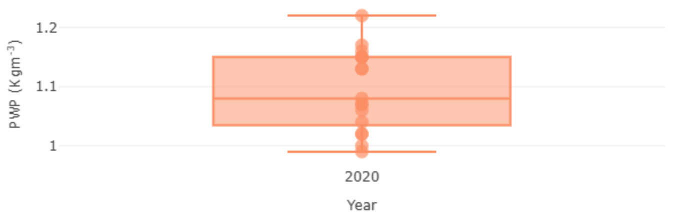
Use Case 2: Physical water productivity (PWP) variation of cereals across districts in Punjab

Spatial variation of cereal PWP across districts in Punjab



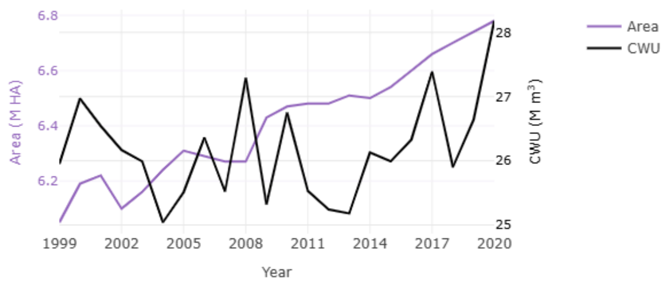
Punjab's average cereals PWP, at 1.09 kg/m³, is the highest among all Indian states, though it varies across districts. The national average cereals PWP for 2018–2020 was lower than the lowest district-level PWP in Punjab.

Statistical summary



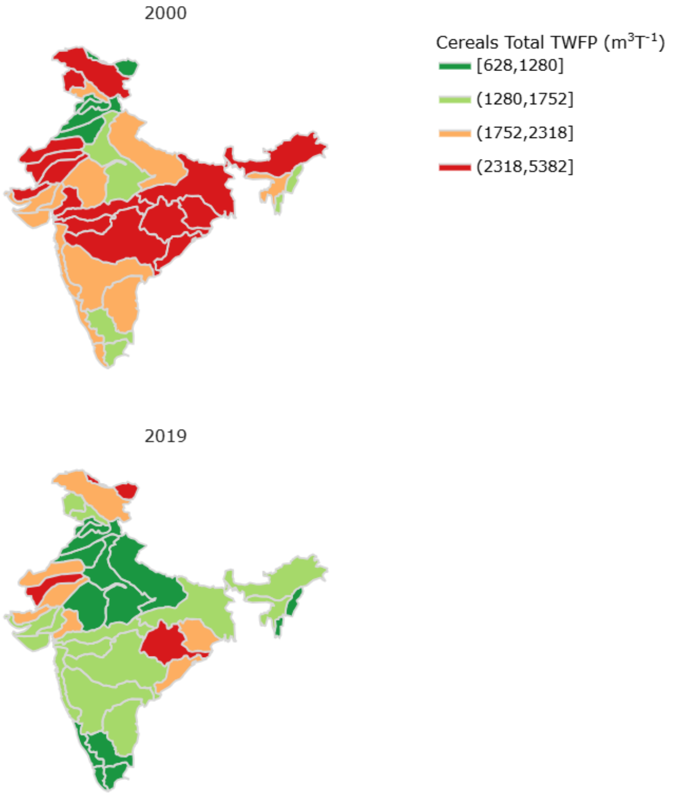
Trends of PWP and yield

Trends of area and consumptive water use (CWU)



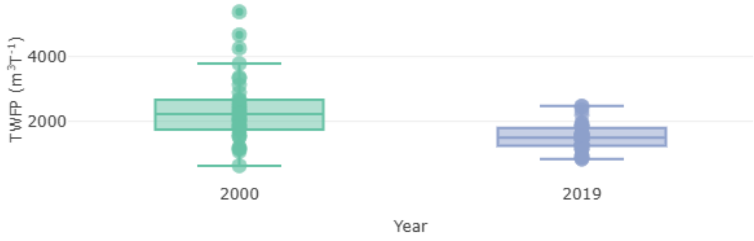
Use case 3: Change in water footprint (WFP) of cereals across Indian river basins from 2000 to 2019

Spatial and temporal variation of cereal WFP

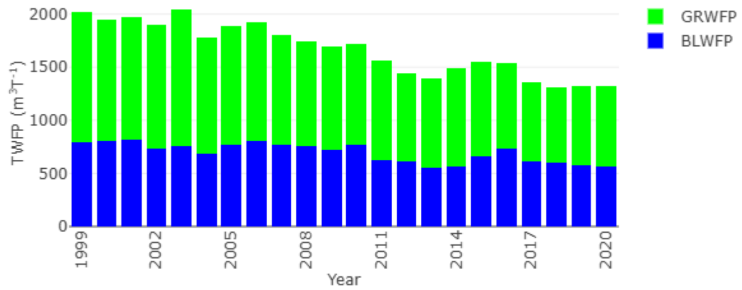


The figure above shows changes in total cereal WFP at the river basin level between 2000 and 2019, as selected from the *Trends* panel. Cereal WFP declined significantly over this period, driven primarily by two factors: an increase in irrigated area and a reduction in rainfed cereal area, along with an increase in average yield. The yield improvements, mainly due to expanded irrigation and enhanced crop varieties, contributed to reductions in both blue and green WFP.

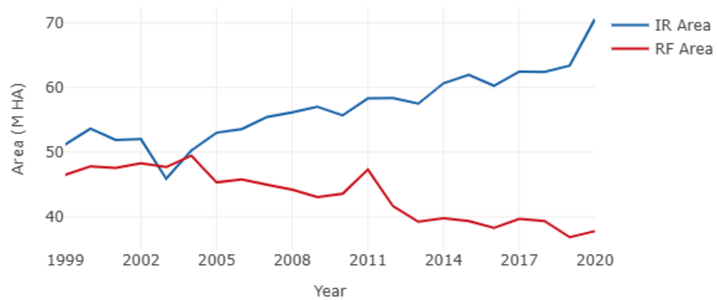
Statistical summary



Trends of blue and green WFP

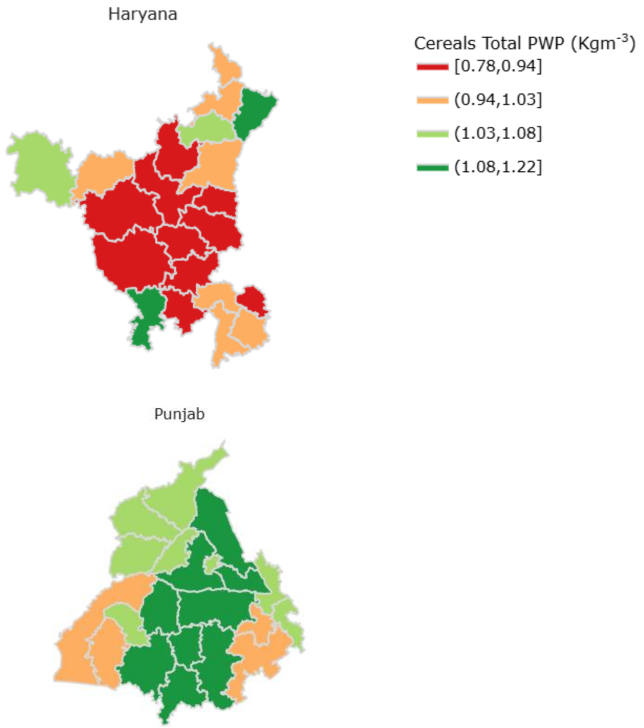


Trends of irrigated and rainfed area



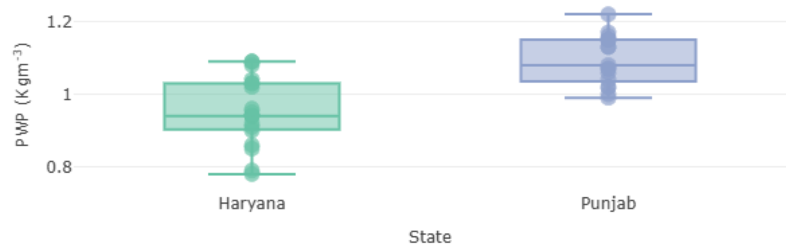
Use case 4: Differences in rice physical water productivity (PWP) between Punjab and Haryana

Spatial variation of rice PWP

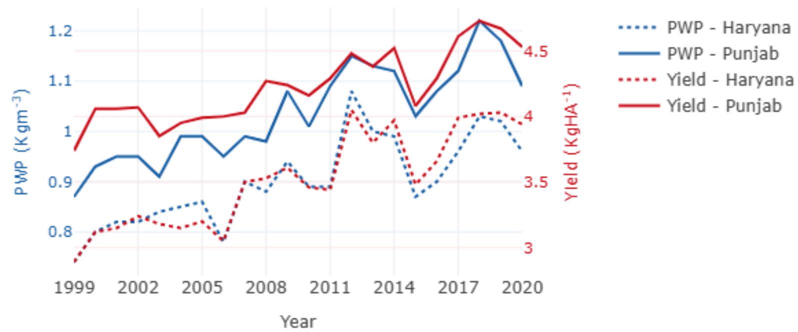


The figure above compares cereal PWP between Haryana and Punjab in 2020, using the *Comparisons* panel. While Haryana's cereal PWP is higher than the national average, many of its districts have substantially lower PWP than those in Punjab. From 2000 to 2019, both the average PWP and yield have increased in Punjab and Haryana, but Punjab has consistently maintained significantly higher PWP and yield over the decades.

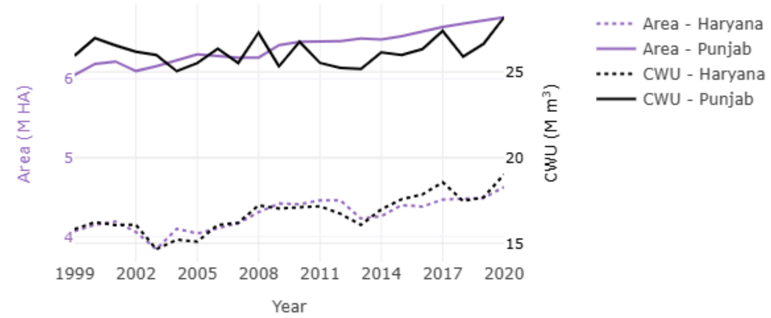
Statistical summary



Trends of PWP and yield

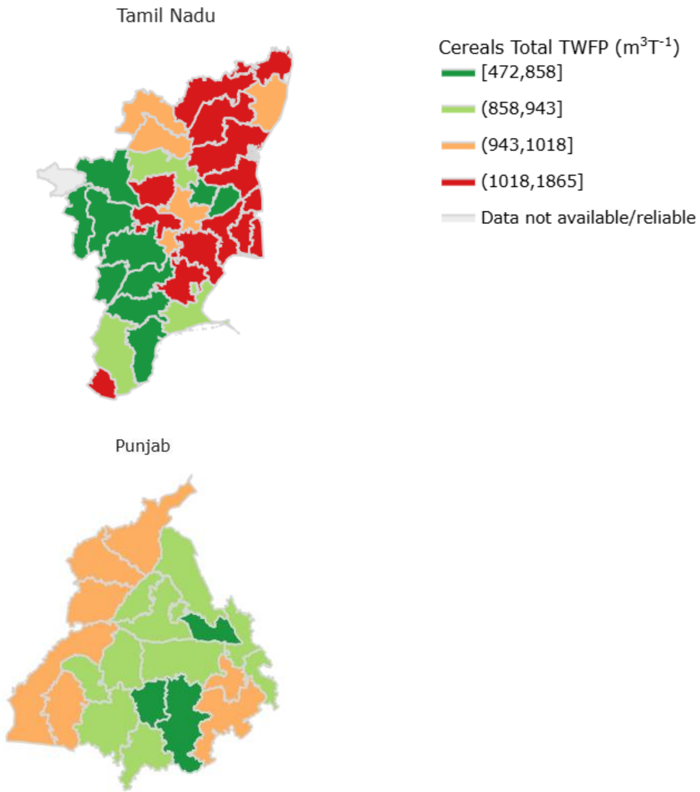


Trends of area and consumptive water use (CWU)



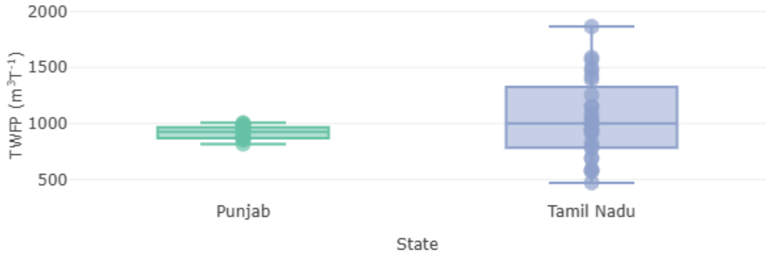
Use case 5: Differences in rice cereal water footprint (WFP) between Punjab and Tamil Nadu

Spatial variation of cereal WFP

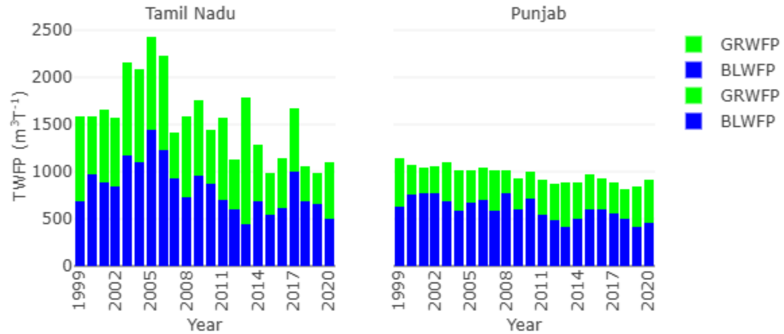


The figure above compares the total cereal WFP between Tamil Nadu and Punjab in 2020, using the *Comparisons* panel. In many districts of Tamil Nadu, both the cereal WFP and its variability are substantially higher than those in Punjab. This greater variability in Tamil Nadu's WFP is largely due to its rice-rice cropping system, whereas Punjab's cropping pattern is dominated by the rice-wheat system.

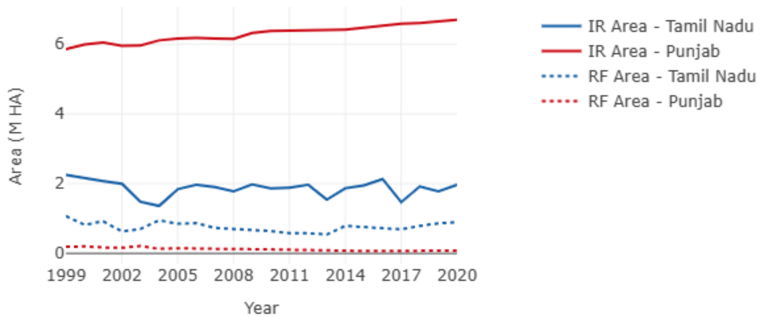
Statistical summary



Trends of blue and green WFP

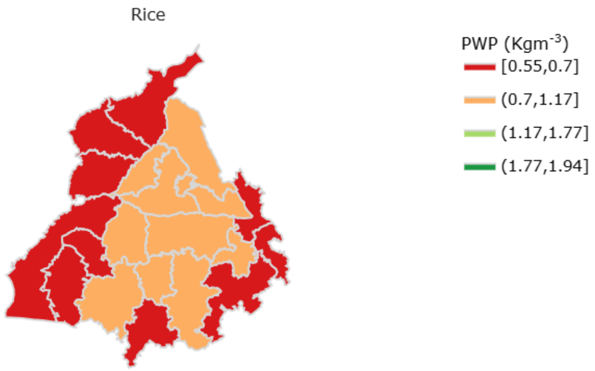


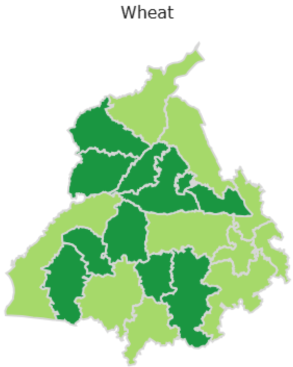
Trends of irrigated and rainfed area



Use case 6: Differences between rice and wheat physical water productivity (PWP) in Punjab

Spatial variation of rice and wheat PWP

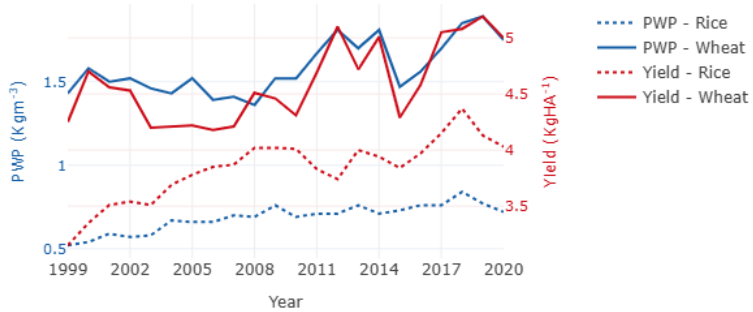




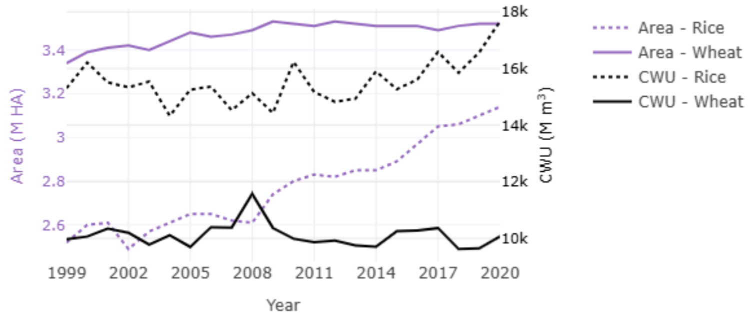
The figure above compares the rice and wheat PWP in Punjab, using the *Comparisons* panel. The wheat PWP is twice that of rice. These crops in Punjab are grown in different seasons, with wheat in the Rabi season. Wheat has a significantly higher yield and lower CWU, while rice has a lower yield and PWP but a higher CWU.

Statistical summary

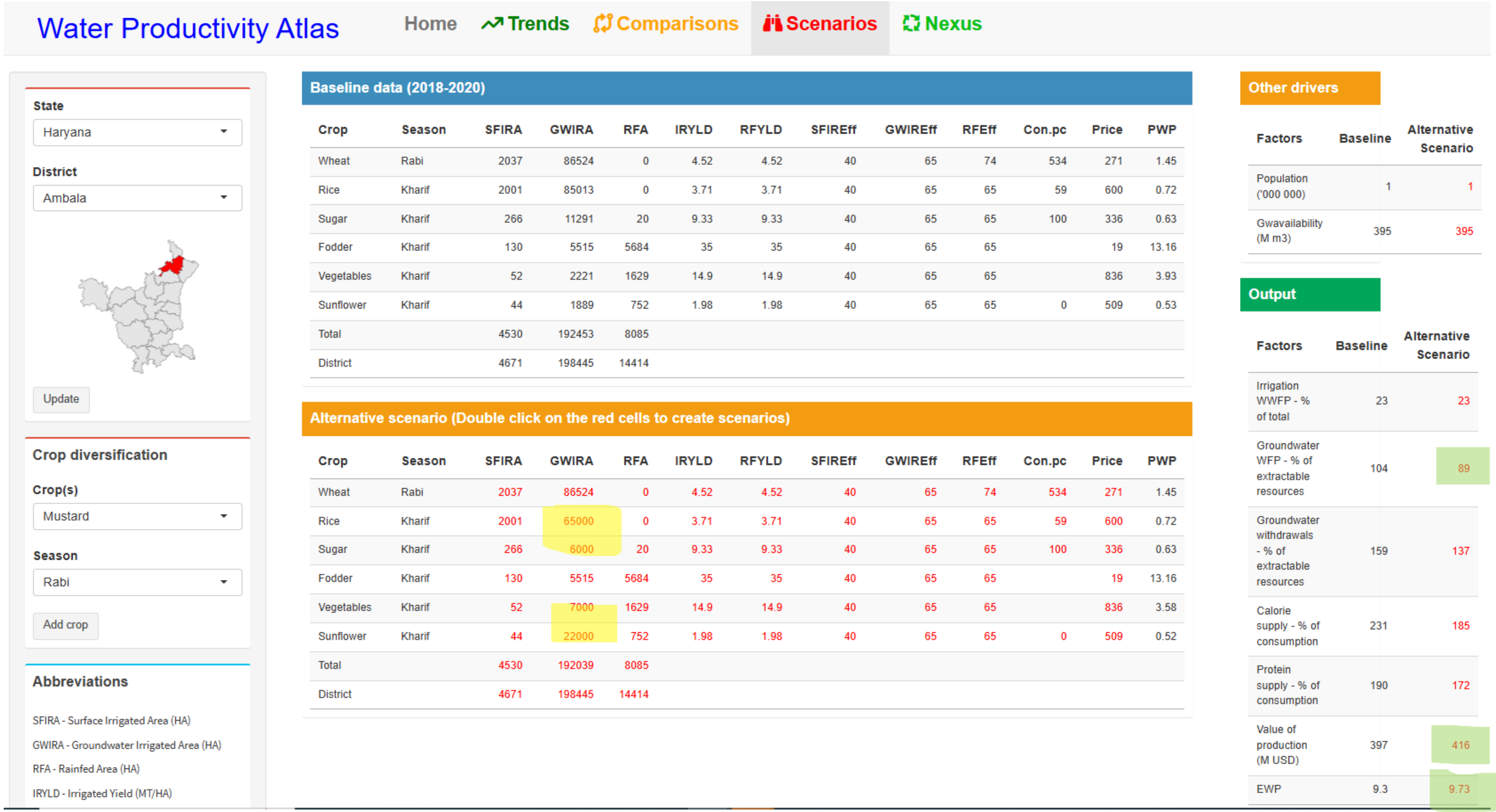
Trends of PWP and yield



Trends of area and consumptive water use (CWU)



Use case 7: Creating scenarios for addressing the water-energy-food-ecosystems (WEFE) nexus in Ambala District, Haryana



Baseline data (2018-2020)

Crop	Season	SFIRA	GWIRA	RFA	IRYLD	RFYLD	SFIREff	GWIREff	RFEff	Con.pc	Price	PWP
Wheat	Rabi	2037	86524	0	4.52	4.52	40	65	74	534	271	1.45
Rice	Kharif	2001	85013	0	3.71	3.71	40	65	65	59	600	0.72
Sugar	Kharif	266	11291	20	9.33	9.33	40	65	65	100	336	0.63
Fodder	Kharif	130	5515	5684	35	35	40	65	65		19	13.16
Vegetables	Kharif	52	2221	1629	14.9	14.9	40	65	65		836	3.93
Sunflower	Kharif	44	1889	752	1.98	1.98	40	65	65	0	509	0.53
Total		4530	192453	8085								
District		4671	198445	14414								

Alternative scenario (Double click on the red cells to create scenarios)

Crop	Season	SFIRA	GWIRA	RFA	IRYLD	RFYLD	SFIREff	GWIREff	RFEff	Con.pc	Price	PWP
Wheat	Rabi	2037	86524	0	4.52	4.52	40	65	74	534	271	1.45
Rice	Kharif	2001	65000	0	3.71	3.71	40	65	65	59	600	0.72
Sugar	Kharif	266	6000	20	9.33	9.33	40	65	65	100	336	0.63
Fodder	Kharif	130	5515	5684	35	35	40	65	65		19	13.16
Vegetables	Kharif	52	7000	1629	14.9	14.9	40	65	65		836	3.58
Sunflower	Kharif	44	22000	752	1.98	1.98	40	65	65	0	509	0.52
Total		4530	192039	8085								
District		4671	198445	14414								

Other drivers

Factors	Baseline	Alternative Scenario
Population ('000 000)	1	1
Gwavailability (M m3)	395	395

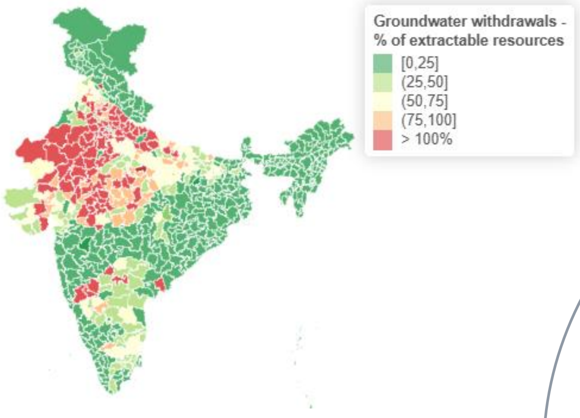
Output

Factors	Baseline	Alternative Scenario
Irrigation WWFP - % of total	23	23
Groundwater WFP - % of extractable resources	104	89
Groundwater withdrawals - % of extractable resources	159	137
Calorie supply - % of consumption	231	185
Protein supply - % of consumption	190	172
Value of production (M USD)	397	416
EWP	9.3	9.73

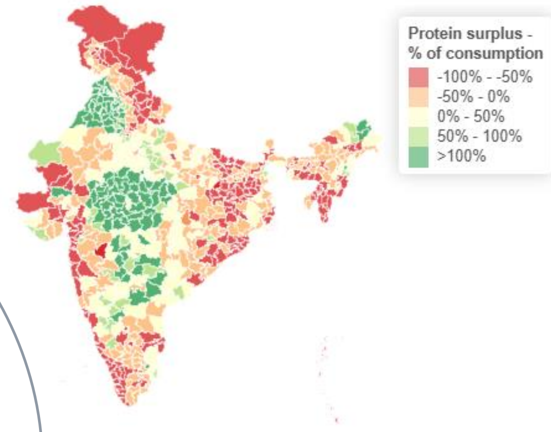
This Scenarios panel examines crop diversification as a strategy to address challenges within the WEFE nexus. In the baseline data from 2018 to 2020, cropping patterns in many regions, including Ambala District, were dominated by water-intensive crops like rice, wheat, and sugarcane. In Ambala, groundwater consumptive water use reached 104% of extractable groundwater resources, indicating unsustainable water use levels. To address this, a diversification scenario was modeled, reducing the area of rice from 85,013 to 65,000 ha and sugarcane from 11,291 to 6,000 ha. Concurrently, the area for less water-intensive crops such as vegetables and sunflowers increased, from 2,221 to 7,000 ha and 1,889 to 22,000 ha respectively. These adjustments reduced the groundwater extraction ratio from 104% to a more sustainable 89%. The shift not only helped in conserving groundwater but also enhanced economic outcomes, with the value of production rising from USD $307 to $416, and economic water productivity increasing from USD $9.3 to $9.73 per m³. Although not explicitly calculated, the substantial reduction in rice and sugarcane cultivation would likely lead to a significant decrease in energy consumption due to reduced groundwater pumping, leading to further benefits within the WEFE nexus.

Use case 8: The water-energy-food-ecosystems (WEFE) nexus in all districts of India

Groundwater overexploitation

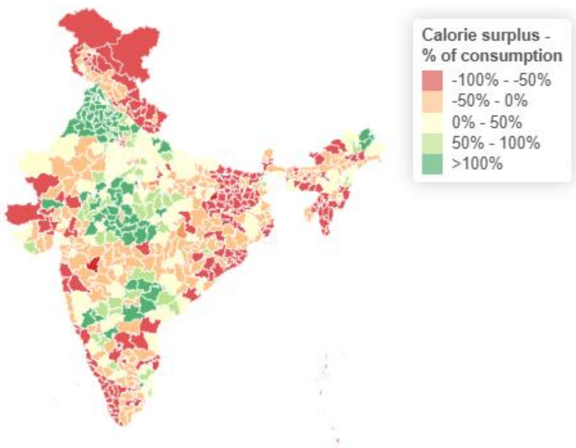


Calorie surplus

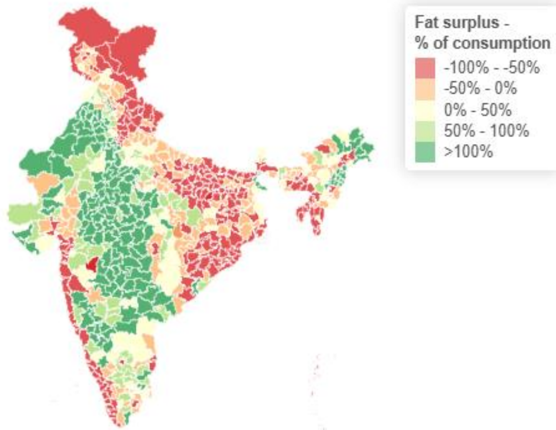


The *Nexus* panel of the Water Productivity Atlas highlights the connection between water resources and food security in India, especially evident in the interplay between groundwater extraction and crop-based nutrition surpluses or deficits. Regions with nutritional surpluses, like many districts in the northwest and some southeastern areas, are also marked by high groundwater extraction ratios. This trend suggests that **the agricultural activities driving food surplus in these areas are heavily reliant on groundwater, intensifying WEFE nexus challenges.**

Protein surplus



Fat surplus



Citation

Amarasinghe, U. A.; Perera, M.; Sikka, A.; Sarangi, A.; Mahapatra, S.; Sharma, R. 2024. *Water Productivity Atlas for addressing the water–energy–food–ecosystems nexus.* Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Initiative on NEXUS Gains. 14p.

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We would like to thank all funders who support this research through their contributions to the CGIAR Trust Fund: www.cgiar.org/funders

We also appreciate the Directorate of Economics and Statistics, Ministry of Agriculture, Indian Meteorology Department, Central Groundwater Board, Climate Research Unit at the University of East Anglia, and Food and Agriculture Organization of the United Nations for providing open, accessible data on their websites for the estimation of indicators of the Water Productivity Atlas.

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