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Review Article

WATER RESOURCE SCENARIO IN PUNJAB: CHALLENGES AND TECHNOLOGICAL INTERVENTIONS FOR SUSTAINABLE USE IN AGRICULTURE

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ABSTRACT

Punjab, a state in northwestern India, is a major agricultural hub, recognized for its significant contribution to the nation's foodgrain production, despite its relatively small size. The post-green revolution era ushered in a reliance on intensive crops, primarily through the rice-wheat cropping system, supported by a consistent water supply. However, this monoculture has strained water resources. Recent data reveals a water deficit of 13.06 billion cubic meters (BCM), derived by subtracting the available 53.06 BCM from the demand of 66.12 BCM. Canal water supply has stagnated, resulting in the overuse of groundwater to cover the annual 13.06 BCM water deficit. Consequently, 77% of the state grapples with overexploited groundwater, reaching an overall extraction stage of 164%. To safeguard groundwater resources and maintain stability, this deficit must be reduced to zero by simultaneously curbing demand and enhancing supply. This review article explores water resources' demand and availability in Punjab, while presenting sustainable water-use technologies and strategies. It emphasizes the need for changes in water usage behaviour, a balanced regulatory system with sanctions and incentives, and agronomic interventions to diminish the current water deficit without compromising future groundwater resources.

Keywords: Canal water, Groundwater, Irrigation, North-west India, Water productivity

Water is essential for all forms of life and plays a pivotal role in sustaining ecosystems, human health, agriculture, and industry. India receives approximately 3,880 billion cubic meters (BCM) of precipitation annually, which results in an average annual water resource of 1,999.2 BCM, distributed across more than 20 major rivers and their tributaries (CWC, 2019). However, due to geographical and other constraints, the country's usable surface water is limited to 690 BCM, while the replenishable groundwater resource is estimated at 449 BCM (CGWB, 2023). After accounting for natural discharge, the annual usable groundwater resource is 407 BCM, while annual groundwater extraction for irrigation, domestic, and industrial use amounts to 241 BCM. Currently, India utilizes approximately 710 BCM of its total water potential, with sectoral demands as follows: 557 BCM for agriculture, 56 BCM for domestic use, 43 BCM for industrial purposes, and 54 BCM for other sectors (NITI Aayog, 2021). The growing population, rapid urbanization, industrial expansion, and inefficient irrigation practices are driving an escalating demand for freshwater. Water availability and utilization exhibit significant variability across different river basins in India, with the north-western basins, particularly in Punjab, facing considerably higher stress levels compared to other regions.

Punjab, often referred to as the "granary" of India, has played a critical role in the country's agricultural transformation, particularly during the Green Revolution, owing to its reliable irrigation systems and supportive infrastructure. However, the shift to intensive cropping practices has led to significant adverse impacts on natural resources, including groundwater depletion, crop residue accumulation, pollution, ecological imbalance, and a decline in biodiversity. As Punjab's water resources come under increasing stress, it becomes essential to assess groundwater availability, bridge the growing supply-demand gap, and implement effective water management strategies. These issues have been widely discussed in various research papers, reports, and forums (Parihar *et al.*, 1993; Agarwal *et al.*, 2009; Rodell *et al.*, 2009). This review paper offers a comprehensive, updated analysis of these challenges. Punjab spans 5.033 million hectares and is divided into three major regions: *Majha* (situated between the Beas and Ravi rivers), *Doaba* (located between the Satluj and Beas rivers), and *Malwa* (lying between the Satluj and Ghaggar rivers) (Fig. 1). The state consists of 23 districts and has a population of approximately 31.8 million, with more than 62% of its population residing in rural areas. The climate of Punjab is influenced by the proximity of the Himalayas to the north and the Thar

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Fig. 1. **Location, administrative boundaries, cultural zones and major rivers of Punjab**

desert to the southwest, giving rise to three distinct agro-climatic zones. Rainfall in the state varies from heavy precipitation in the foothills to relatively scarce rainfall in other areas. The alluvial soils of Punjab are particularly suitable for agriculture. Major crops include wheat, rice, cotton, sugarcane, maize, berseem, and pulses, with the rice-wheat and cotton-wheat systems being the dominant cropping patterns. Punjab has embraced intensive cropping practices, with about 82% of the state's land area under cultivation. This has led to an impressive 99% irrigation coverage and a cropping intensity of 189.8%. The state also exhibits high fertilizer usage, averaging 256 kg/ha/year, and has undergone extensive mechanization, with approximately 4,70,000 tractors and 1.53 million tubewells in operation, all supported by a robust electricity infrastructure and power subsidies.

Estimation of available water resources

A comprehensive assessment of water resources is crucial for effective allocation and sustainable development. In Punjab, water for consumptive uses is derived from four primary sources: (i) rainfall, (ii) canal water from dams and rivers, (iii) groundwater, and (iv) recycled water. These sources are intricately interconnected within the hydrological cycle. Rainfall serves as the initial source, where water either infiltrates the soil or runs off into surface water bodies. A portion of the infiltrated water is retained in the upper soil layers, addressing immediate crop water requirements, while the remainder replenishes the groundwater reserves (Parihar *et al.*, 1993). Groundwater levels are further replenished by seepage from the canal network and dams, as well as return flows from irrigated fields utilizing both canal water and tube wells. The current status of these water resources in Punjab is discussed below:

Rainfall

Based on an analysis of rainfall variation from 2005 to 2018, Punjab can be categorized into three distinct zones: the North-East/Shivalik foothill/*Kandi* zone, the Central zone, and the South-western zone, covering areas of 1.07 million hectares, 1.75 million hectares, and 2.22 million hectares, respectively. The annual average rainfall in these zones is 823 mm, 590 mm, and 323 mm, respectively. Monsoon rainfall constitutes the largest proportion of the total annual rainfall in Punjab, contributing approximately 78.3%, while pre-monsoon, post-monsoon, and winter rainfall account for 8.3%, 5.5%, and 8%, respectively. Notably, the North zone experiences higher rainfall intensity during the pre-monsoon and post-monsoon periods compared to the South zone. From the base period of 1951-2000 to 2005-2018, there has been a notable decrease in average annual rainfall across the state, with a reduction from 635.9 mm to 521.8 mm. Most years since 2000 have experienced below-normal monsoon rainfall, with nine of these years showing a deficit greater than 20% (Fig. 2). Based on the state's geographic area and the average annual rainfall observed from 2005 to 2018, the total annual rainwater availability is estimated at 26.3 billion cubic meters (BCM). Of this, approximately 22% (5.8 BCM) contributes to groundwater recharge, 20% (5.3 BCM) is lost as surface runoff, while the remaining portion is accounted for by evapotranspiration (ET) losses.

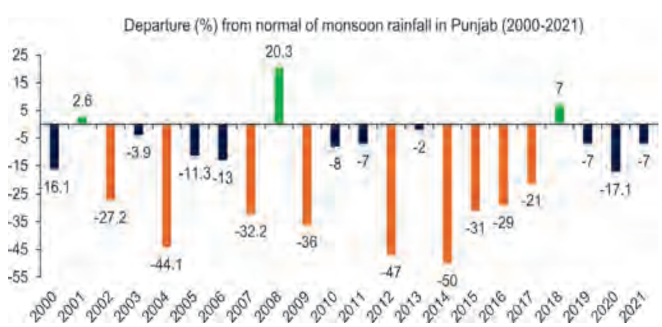

Fig. 2. **Rainfall variation during monsoon season in Punjab**

Canal water resources

In Punjab, canal water is primarily sourced from three major dams: the Bhakra Dam, the Pong Dam, and the Ranjit Sagar Dam (RSD), all located in the north-east region. The Bhakra Dam, constructed between 1948 and 1963, is one of the tallest gravity dams in the world and is fed by the Satluj River. The Pong Dam, operational since 1974, serves multiple purposes, including power generation and irrigation, and is supplied by the Beas River. The RSD, also known as the Thein Dam, began operations in 2000 and receives water from the Ravi River. Surface water in Punjab is primarily replenished by Himalayan rainfall, snowmelt, and precipitation from the surrounding catchment areas. The perennial rivers that flow through the state carry an estimated 42.4 billion cubic meters (BCM) of water annually, with Punjab's allocation under existing agreements set at 14.8 BCM per year.

Punjab, the name derived from the Persian words *Punj* (five) and *Aab* (water), was historically defined by its five rivers, which were part of the Indus Basin until 1947. Following the partition of India in that year, a dispute emerged between India and Pakistan over the sharing of water from the Indus River Basin. The upper reaches of the main Indus River and its tributaries are situated in India, while the lower reaches lie in Pakistan. The Indus Water Treaty, signed in 1960, resolved these water-sharing conflicts by allocating specific river systems to each country. Under the terms of the treaty, India gained access to the Ravi, Beas, and Sutlej rivers-the three eastern rivers-while Pakistan retained rights to the Jhelum, Chenab, and Indus rivers. As a result, India's share constitutes just 20% of the total annual flow of the Indus River system, amounting to 34.3 million acre-feet (MAF), whereas Pakistan's share is significantly larger, totalling 136 MAF.

India has efficiently utilized its allocated water from the eastern rivers, such as the Beas and Sutlej, by constructing a network of dams and diversion projects. The Indira Gandhi Nahar Project (IGNP), which includes the Indira Gandhi Feeder and Main Canal, has played a transformative role in converting arid regions into productive agricultural lands. However, escalating water demand, depleting groundwater reserves, and the creation of new states have fuelled ongoing disputes over river water distribution. Although the sharing of water from the Sutlej River between Punjab, Haryana, and Rajasthan is without dispute, the allocation of Ravi-Beas river waters to multiple states is governed by complex agreements. Currently, Punjab's canal irrigation network spans a total of 14,500 km, comprising systems such as the Upper Bari Doab Canal (UBDC), Bist Doab Canal, Sirhind Canal, Bhakra Main Line (BML), Ferozepur Feeder/Sirhind Feeder, Eastern Canal, Makhu Canal, Shahnehar Canal, and the *Kandi* Canal. Initially, Punjab's river water entitlements were determined based on average river inflows between 1921 and 1960. However, the availability of river water has significantly declined in recent decades. For instance, the surplus water from the Ravi-Beas rivers has dropped by 22%, from 17.17 million acre-feet (MAF) to 13.38 MAF, based on flow data from 1981 to 2013. Similarly, water availability from the Sutlej has reduced from 13.78 MAF (1921-1960) to 11.39 MAF (1981-2018) (Pannu, 2018). This decline in river water inflows can be attributed to factors such as reduced rainfall in the catchment areas, climate change, and increased water consumption by hilly states. Following the Green Revolution, farmers, seeking more reliable irrigation sources, increasingly turned to tube-wells as the canal system became less dependable. The widespread availability of cheap, subsidized electricity further accelerated groundwater extraction, leading to a shift in irrigation practices. Consequently, the area irrigated by canals in Punjab declined from 58% in 1960-61 to 28% in 2021-22, while the area irrigated by tube-wells surged from 41% to 72% during the same period (Statistical Abstract of Punjab, 2021; Statistics of Punjab Agriculture, 2023-24).

Groundwater resources

The vast Indo-Gangetic Plains, a geologically significant foredeep depression formed as a result of the Himalayan uplift, serve as a critical repository for groundwater resources. The region's aquifers are primarily classified as both confined and unconfined (CGWB, 2018). In Punjab, the predominant source of groundwater is the shallow alluvial aquifer, which flows in a west-southwest direction across the Indo-Gangetic Plain. In some southwestern areas, however, the freshwater aquifers are thinner and are influenced by brackish or saline water (CGWB, 2014). Groundwater levels in the region vary considerably, ranging from near-surface levels to depths of approximately 60 meters below ground level. Deeper groundwater levels are typically observed in the northeastern Kandi Belt, while waterlogging issues are more prevalent in certain southwestern districts. In other regions, the water table typically ranges from 3 to 40 meters below ground level, exhibiting a southwestward slope. The use of shallow tubewells for irrigation in Punjab results in an annual groundwater draft ranging from 0.27 to 2.59 hectare-meters (electric) and 0.21 to 2.3 hectare-meters (diesel), supporting the irrigation of approximately 1 to 3 hectares of land per well (CGWB, 2022b).

Punjab's groundwater resources encompass both replenishable and in-storage components. The annual extractable groundwater has been recently estimated at 16.98 BCM (CGWB, 2023). In contrast, the assessment

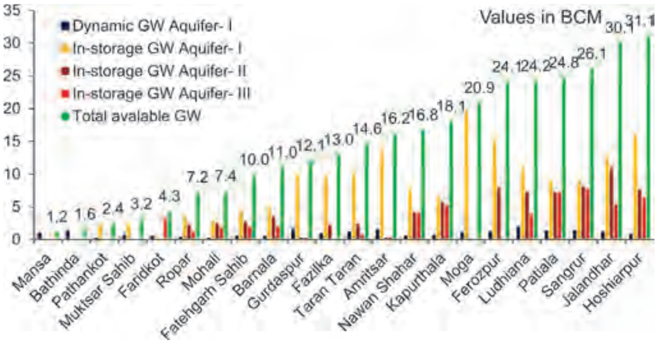

Fig. 3. District-wise variability in available groundwater resources in Punjab (upto 300 m depth); Depths of aquifer-I, II and II are 0 to 100, 100-200 and 200-300 m, respectively; figures excluding saline water (adapted from CGWB report, 2018)

for the period 2012-2016 estimated it at 21.58 BCM, sourced from various contributors: rainfall (6.88 BCM), canal seepage (4.0 BCM), return seepage from surface irrigation (3.10 BCM), return seepage from groundwater irrigation (7.58 BCM), and dam seepage (0.02 BCM) (CGWB, 2018). While dynamic resources are considered for sustainable use, static resources are primarily relied upon during emergencies or for drinking water purposes. Accessibility to groundwater diminishes with depth; 57.3% of groundwater is accessible within 100 meters in unconfined aquifer-I (Table 1). Both availability and water quality exhibit considerable spatial variation across districts. Some areas have water accessible only up to a depth of 100 meters, while others extend to 200 meters. The southwestern region, in particular, faces issues of brackish or saline water (Fig. 3). Groundwater quality ranges from good in the northern and northeastern regions to poor in the southern and southwestern parts of the state. Approximately 42% of Punjab, especially the southwestern districts of Muktsar, Bathinda, Ferozepur, Mansa, and Faridkot, is characterized by groundwater with high salt concentrations, resulting in saline (chlorides and sulfates of sodium) or sodic (carbonates and bicarbonates of sodium) conditions. In certain areas, the presence of toxic elements such as fluoride and boron further complicates water quality. Nitrate levels in groundwater samples range from 0 mg/L to 775 mg/L, with approximately 22.4% of the samples exceeding the permissible limit of 45 mg/L set by the Bureau of Indian Standards (BIS) for drinking water (CGWB, 2022a; CGWB, 2022b).

Recycled water

The water available from various sewerage treatment plants (STPs) operating in the state and water entering back to canal system from thermal plants is estimated to be 1.26 BCM per annum. As per the available data, the installation capacity of STPs in Punjab is 1781 MLD (million liters per day), and the current operational capacity is 1601 MLD, providing 587 MCM of available water (https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1779799). This represents approximately 22% of the current industrial and domestic water demand. The availability of recycled water is expected to increase in the future as more STPs become operational. Punjab Government aims to achieve operational capacity of 2,600 MLD for irrigation purposes to save the depleting groundwater.

Estimation of present water demand

The demand for water is rising rapidly due to ongoing population growth, urbanization, and industrialization. The agricultural sector, which accounts for the largest share (94.8%) of total water demand, is of paramount importance in the context of water resource measurement, management, and supply regulation.

Agricultural sector

Punjab has a large proportion of its geographical area dedicated to cultivation, with a net sown area of 4.124 million hectares, which constitutes about 82% of the total geographical area of the state. The estimation of evapotranspiration (ET)-based water demand revealed that *kharif* crops, particularly rice, account for the majority of water demand. Considering the food-

Table 1. Total groundwater resources of Punjab state upto 300 m depth (adapted CGWB report, 2018)

(i) In-storage (static) groundwater resources				
S. No.	Aquifer no.	Type	Depth (m)	Available groundwater (BCM)
1	Aquifer-I	Unconfined	Upto 100	171.53
2	Aquifer-II	Semi-confined	100-200	75.83
3	Aquifer-III	Confined	200-300	51.58
Total in-storage (static) groundwater resources				299.12
(ii) Total annual replenishable/dynamic groundwater resources				21.58*
Total groundwater resources upto 300 m				320.72

* The value has been revised to 16.98 BCM in report by CGWB 2023; additional potential resources in water logged and shallow water level areas-0.09 BCM, Groundwater resources in poor quality (saline water) areas-9.043 BCM

water-energy nexus, the total water demand of crops needs to be considered, taking into account factors such as percolation rates of alluvial soils. For example, ET of rice is about 65 cm but due to higher percolation rates of alluvial soils its average total irrigation demand is 120-160 cm. In contrast, the estimated ET of sugarcane - a long duration crop is about 135 cm whereas its irrigation water demand is approximately 90 cm because its grand growth period coincides with the monsoon rains. Irrigation demand is linked to energy requirements, while evapotranspiration (ET) demand accounts for the decline in groundwater levels (Arora 2023). It has been reported that rice had the highest drainage component (67%), while onion had the lowest (6.1%), following the order rice > citrus > maize > wheat > cotton > mustard > sugarcane > chickpea (Jalota and Arora, 2002; Jalota and Gill, 2003; Jalota *et al.,* 2021). ET values and the area under field crops, vegetable, and fruit crops in different districts were used to calculate total irrigation demand. In Punjab, the south zone has the highest irrigation water demand, accounting for approximately 47.7% of the state's total water demand (Fig.4), attributed to its larger area and hot, dry climatic conditions. The central and north zones contribute about 37.5% and 14.8% of the total irrigation water demand, respectively. Among the districts, Sangrur has the highest estimated irrigation water demand, followed by Ludhiana and Patiala, while Pathankot, Ropar, and Mohali, which are relatively smaller districts located in the north zone, have the lowest demand (Fig.4).

Domestic needs (Rural + urban)

About 62% of the state's total population resides in rural areas, while urban population has been growing due to industrialization, rural-urban migration, and migration from other states in search of opportunities.

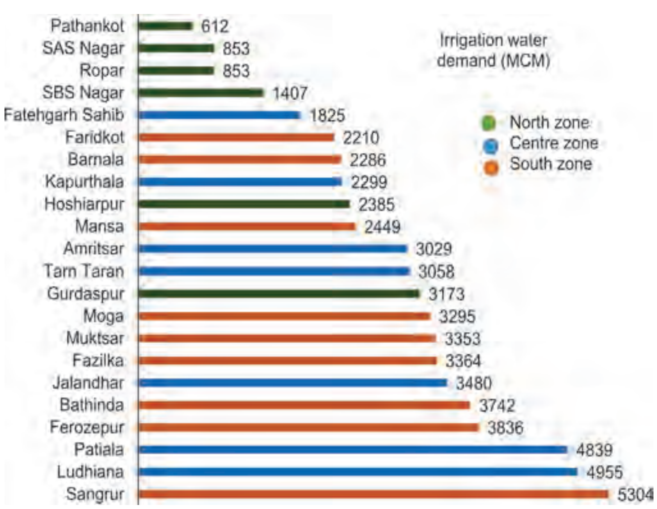

Fig. 4. Share of different districts in total annual irrigation water demand of the state

The urban population proportion has increased from 24% in 1971 to 37% in 2011, leading to variations in expected domestic water consumption across districts (Statistical Abstracts of Punjab, 2021). The total demand for water used in urban and rural domestic consumption is estimated to be 2.41 BCM.

Industrial, thermal and livestock sectors' demand

An aggregated demand of 1.13 BCM is estimated for water used by industries, thermal plants, and livestock. However, more precise measurements of industrial water usage would provide a clearer estimate.

Overall, State's water demand is projected to increase due to population growth, socio-economic development, and climate change. Consequently, the total water demand is projected to increase from the current 66 BCM to 70 BCM by 2030 and 72 BCM by 2050 (Kukal and Sidhu, 2022).

Estimation of water balance

Water budgeting is crucial for understanding water shortages and groundwater depletion, enabling informed decisions on water allocation, distribution, management, and conservation. Based on earlier estimates, the annual water resources and their utilization can be summarized as follows - water demand: 66.12 BCM (Domestic and urban use: 2.41 BCM, Industrial: 1.13 BCM, Agricultural: 62.58 BCM); water availability: 53.06 BCM (rainfall: 26.3 BCM, canals/dams: 14.8 BCM, STPs: 1.26 BCM, return flow: 10.7 BCM); water deficit/gap: 13.06 BCM (Table 2).

The availability of canal water has remained relatively static, with some decline due to reduced river flow and decreased carrying capacity of the canal network system. The return seepage from groundwater irrigation (7.58 BCM) from areas irrigated by tube-wells, seepage from surface water irrigation (3.10 BCM) from areas irrigated by canals, and seepage from dams (0.02 BCM) contribute to the available groundwater return flow of 10.7 BCM. The actual annual water deficit of 13.06 BCM is met through the over-exploitation/ overdraft of groundwater. Out of the excessive water use of 13.06 BCM, 5.10 BCM accounts for drawdown water, leading to an average annual decline in the groundwater table (averaging about 0.7 meters per year), while 7.96 BCM is the calculated value of water extracted from deep groundwater aquifers, contributing to the slow rate of groundwater depletion despite higher annual extraction volumes. To compensate for the 13.06 BCM water deficit, an average annual drop of 1.7 meters in the phreatic aquifer can be expected by considering the total geographic area and specific yield (15%). However, measured groundwater level data shows an actual average decline of approximately

Table 2. Annual water balance of Punjab (billion cubic meters, BCM)

Water availability		
1	Total rainfall (average rainfall of 522 mm from 2005-18)*	26.30
2	Canal water (from 3 dams)	14.80
3	Treated water	1.26
4	Return flow (irrigation recirculated water, canal + tubewells; infiltered rainwater not included)	10.70
Total		**53.06**
Water demand		
1	Agricultural sector (irrigation-based demand)	62.58
2	Domestic (rural + urban)	2.41
3	Industrial + Thermal	0.95
4	Livestock	0.15
Total		**66.12**
Deficit/Gap**		13.06
1	Drawdown groundwater (deficit of 4 years average)	5.10
2	Deep groundwater aquifer contributions***	7.96

Adapted from State Irrigation Plan, 2017 and M/s Mekorot report, *-Average values fluctuate based on the selected timeframe; **-Precise estimates can vary with the availability of accurate data in the future; ***-Calculated value based on assuming all other values to be correct and explaining the slow rate of groundwater depletion despite greater volume of annual extracted water.

0.7 meters per year. These conflicting values suggest the presence of an additional water inflow. A conceptual model assumes that water from the upper Shiwalik hills infiltrates into the deep aquifers of the *Bhabhar* zone and flows as deep groundwater southwards. The higher elevation of the *Bhabhar* zone possibly creates a relatively high-pressure head in these sub-aquifers, causing the water to flow upward from deep to shallow sub-aquifers, partially compensating for the groundwater level decline resulting from excessive pumping. This highlights the unsustainability of the current groundwater extraction regime, emphasizing the need to determine the aquifer's sustainable yield.

Urgent need of groundwater resource management

Changes in groundwater level from 1984 to 2021 reveal long-term fluctuations across the state (Fig 5). While water levels have risen in the northern, north-eastern, and southwestern regions, a widespread decline is evident in southern, south-eastern, and central areas. The most significant drops are observed in districts such as Sangrur, Barnala, Patiala, and Malerkotla, closely linked to higher rice-wheat productivity and water use in these regions. Groundwater extraction in Punjab exceeds the annual recharge from rainwater and seepage, leading to overexploitation of resources. Recent estimates from central groundwater board shows that annual groundwater extraction is 27.80 BCM, with irrigation accounting for 26.39 BCM and domestic/industrial use for 1.42 BCM (CGWB 2023). The district with the highest groundwater extraction is Ludhiana (3.17 BCM) while the lowest is Muktsar (0.20 BCM). The net groundwater availability for future irrigation is negligible in over-exploited blocks but amounts to 1.82 BCM in safe, semi-critical, critical, and waterlogged areas.

Out of 153 assessment units, 114 blocks and 3 urban areas are over-exploited, covering 76.5% of the state's area. Three blocks are classified as critical (1.96%), 13 blocks are semi-critical (8.5%), and only 20 blocks fall into the safe category (13.07%) (Fig. 5). Among the over-exploited units, 62 have groundwater extraction exceeding 200%, including 17 units where extraction is over 300%, indicating a significant imbalance between withdrawals and recharge (CGWB, 2022b). The number of over-exploited blocks has risen from 53-73 during 1984-1999 to 103-117 during 2004-2023, while the number of safe blocks has remained relatively stable. However, among the safe blocks, only 9, located near three major dams in the sub-mountainous regions, can be considered truly safe. In contrast, groundwater in the remaining 11 blocks in the southwestern districts is of poor quality and unsuitable for use. In Faridkot, Muktsar, Malout, Lambi, Abohar, and Gidderbaha blocks, approximately 84,800 hectares of arable land suffer from waterlogging. About 25% of this area is located along the Rajasthan Feeder and Sirhind Feeder, where poor groundwater quality exacerbates soil salinity issues. Continuous canal seepage worsens the situation, gradually increasing soil salinity and making the land less viable for farming. Overall, the groundwater situation in Punjab is a growing concern.

Groundwater overdraft in Punjab is directly linked to the growing number of tubewells. Unlike canal

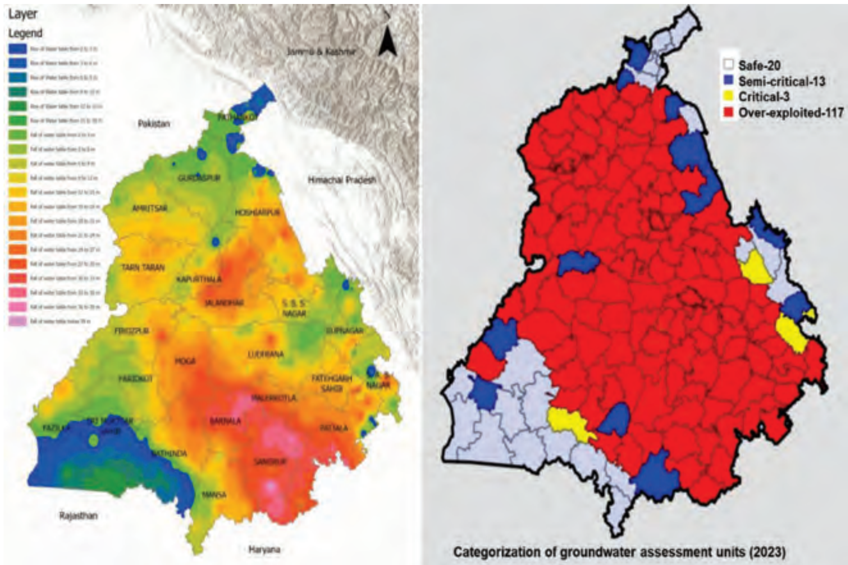

Fig. 5. Changes in water table depth over the years (L) and stages of groundwater development of different blocks in 2023 (R) (source: CGWB 2022b, CGWB 2023)

irrigation, which has a long history, the widespread use of tubewells for irrigation in Punjab emerged as a result of individual farmers' initiative and enterprise (Sekhon, 2023). The adoption of tubewell irrigation was particularly driven by farmers in the northern and central parts of the state. The number of tubewells has risen dramatically over the years, from 1.92 lakh in 1970-71 to 15.29 lakh at present (Fig. 6). This extensive extraction of groundwater has caused a continuous decline in the water table. As a result, farmers have had to drill deeper wells and replace centrifugal pumps with submersible pumps, which consume more energy. This increased reliance on energy has led to a surge in electricity consumption within the agriculture sector, along with rising subsidies and cultivation costs. From 2000-01 to 2021-22, electricity consumption in agriculture grew from 5.53 billion units to 12.49 billion units (kilowatt-hours), with a corresponding increase in subsidies from Rs. 1,659 crores to Rs. 7,059 crores (Statistics of Punjab Agriculture, 2023-24). The availability of free or heavily subsidized electricity has significantly contributed to the unchecked extraction of groundwater. To ensure the sustainable use of water and energy in agriculture, it is essential to reduce water demand while increasing water availability, which would help address the current deficit of 13.06 BCM. Achieving the long-term goal of saving over 20 BCM annually is realistic, especially considering the need to replenish depleted groundwater reserves and allocate water to support natural ecosystems.

Measures to enhance water availability

Rainfall in Punjab's north-east (*kandi*) region is relatively high, with approximately 40% contributing

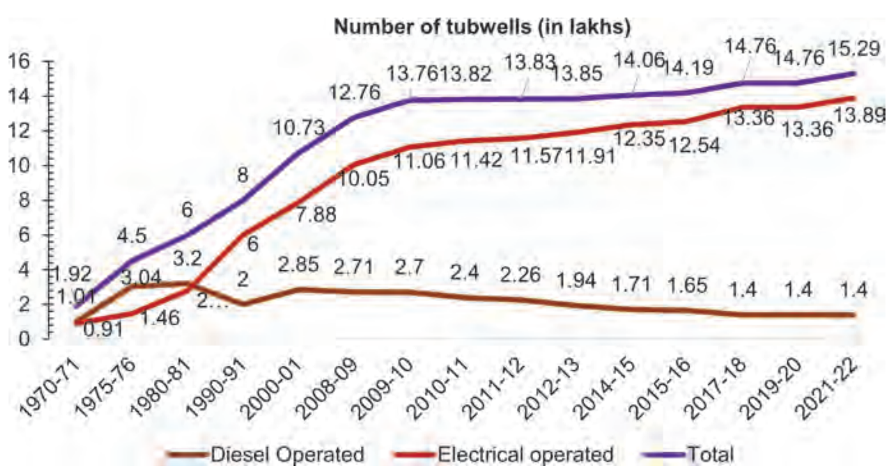

Fig. 6. Increase in tubewell density from 1970 to 2022 (Statistics of Punjab Agriculture, 2023-24)

to runoff. Implementing *in-situ* water conservation measures, along with constructing check dams and water harvesting structures, can help capture this rainwater and promote groundwater recharge. However, the availability of source water for artificial recharge in Punjab is insufficient compared to the recharge needed, as outlined in the 'Master Plan for Artificial Recharge to Groundwater in India' (CGWB, 2021). Around 4.56 million hectares of the state's area are suitable for artificial recharge, with a sub-surface storage potential of 86.8 BCM. To fill this storage capacity, approximately 115.4 BCM of water is required, while the available non-committed surface water amounts to just 1.2 BCM. To make use of the surplus runoff, various techniques such as check dams, recharge shafts, and injection wells can be employed. Additionally, farm ponds can help recharge runoff from agricultural fields, and rooftop rainwater harvesting can be implemented in urban areas. The estimated cost for artificial recharge projects in Punjab is around Rs. 6,774 crores, with Rs. 5,120 crores allocated for rural areas and Rs. 1,654 crores for urban areas (CGWB, 2021).

Over 90% of rainwater in urban areas, approximately 3 BCM per year, ends up in drains and rivers (Kukal and Mann, 2022). Rooftop rainwater harvesting has significant potential for groundwater recharge and can be used for non-drinking domestic purposes (CWC, 2019). Additionally, grass paver tiles can facilitate the rapid percolation of rainwater into the ground. The Central Ground Water Board (CGWB) recommends implementing rooftop rainwater harvesting in government buildings, institutions, and in 5.5 million homes with roof areas of 200 sq. m for artificial recharge. With normal rainfall and a system efficiency of 70%, this initiative could capture up to 52.5 MCM of rainwater annually to augment groundwater resources. The estimated cost for installing rooftop rainwater harvesting systems in a building with a 200 sq. m roof and paved areas, within a cluster of 4 to 6 houses, is approximately Rs. 30,000 (CGWB, 2021).

Wastewater from domestic and industrial sources can be treated in sewage treatment plants (STPs) or effluent treatment plants (ETPs) to augment water supplies for non-food crops and landscaping. Punjab has the potential to treat over 2 billion liters of wastewater per day (Arora, 2023). Rejuvenating village ponds can enhance groundwater recharge while providing water and nutrients for crops (Toor *et al.*, 2011). To optimize water use, the canal water supply can be rationalized to prioritize the central region, while increasing the adoption of drip irrigation in the southwestern areas to recharge groundwater and prevent waterlogging. Additionally, creating new reservoirs can help store surplus river water during monsoons and floods, thereby improving the overall water supply. These measures will require both time and investment, highlighting the urgent need for the development, demonstration, and large-scale implementation of water conservation strategies.

Improved technologies to reduce water demand

Field-scale interventions to reduce irrigation water requirements are essential for minimizing the water deficit. Rice accounts for over 80% of water usage during the *kharif* season, making it a key target for crop diversification efforts. Despite recommendations to replace rice with alternative crops, the area under rice cultivation continues to expand due to its higher profitability. Therefore, the immediate focus should be on implementing water-saving technologies within the existing rice-wheat cropping systems, while also developing a comprehensive crop diversification policy.

Agronomic interventions

Rice cultivation in Punjab has expanded to 3.17 million hectares, covering 75% of the cultivated area and requiring 140-160 cm of irrigation water, often exceeding this amount in lighter soils (Humphreys *et al.*, 2010; Dhanda *et al.*, 2022). Short- and medium-duration rice cultivars require less water, offer higher yields, and allow for timely wheat sowing (Brar *et al.*, 2018; 2021). In contrast, long-duration varieties demand 15-20% more water and additional pesticides, which reduces profitability (Khanna *et al.*, 2021). Despite the higher costs, farmers continue to prioritize grain yield. However, short- and medium-duration varieties like PR 126 and PR 131 provide better net returns than long-duration varieties like Pusa 44, even without the benefit of free electricity. These varieties also simplify straw management and enable timely sowing of *rabi* crops. Moreover, the timing of transplanting is critical for both water conservation and maximizing yield. To address these challenges, the Punjab Government enacted the *Punjab Preservation of Subsoil Water Act, 2009* (revised in 2018), which restricts early nursery preparation and transplanting to reduce groundwater extraction during periods of high evaporative demand, while taking advantage of later rainfall (Sidhu *et al.*, 2020). Delaying transplanting significantly reduces water usage, with a potential annual saving of 2.4 BCM by shifting the transplanting date from June 10 to June 25 (Table 3). A study by Brar *et al.* (2012) found that delaying paddy transplanting from June 15 to July 5 resulted in a 22.3% reduction in irrigation water use. In conclusion, late transplanting with short-duration rice varieties not only results in higher net returns but also contributes to substantial water savings.

The Alternate Wetting and Drying (AWD) technique for rice irrigation conserves water without compromising yield. Studies have shown that there is no significant

Table 3. Irrigation water saving through shifting in dates of paddy transplanting

Sr. No.	Shifting in dates of paddy transplanting	Saving in irrigation water (m^3/ha)	Total water saving potential (BCM)*
1	10 June to 15 June	400	1.1
2	15 June to 20 June	300	0.8
3	20 June to 25 June	200	0.5
4	Total water saving by shifting from 10 June to 20 June		1.9
5	Total water saving by shifting from 10 June to 25 June		2.4

*Area under paddy cultivation in Punjab-2.74 mha (2020-21)

impact on rice grain yield when using continuous ponding or scheduled irrigation at 1, 2, or 3 days after infiltration of ponded water (DAIPW). However, the conventional practice of continuous ponding requires 5.9%, 15.2%, and 23.5% more water compared to the AWD approach at 1, 2, and 3 DAIPW, respectively (Brar *et al.*, 2017). Recent studies further indicate that water savings increase progressively, from 19.1% to 24.5%, when transplanting is delayed from June 15 to July 5 and irrigation is scheduled at 3 DAIPW, compared to continuous ponding.

Medium to heavy-textured soils are ideal for direct seeding of rice, offering water savings of 10-15% (Kumar *et al.*, 2018) and increasing groundwater recharge by 10-12% (Gulati *et al.*, 2022). Direct seeding eliminates the need for puddling and nursery preparation, reducing water losses and leading to significant savings in fuel, water, and labour (Pathak *et al.*, 2011). The extent of water savings depends on factors such as climate, variety, crop duration, soil type, and the expertise of growers. For instance, direct seeding of PR 126 with irrigation scheduled at 4 DAIPW saved 42.8 cm of irrigation water, improving both apparent crop water productivity and total crop water productivity by 43% and 30.2%, respectively, without reducing yield compared to the puddled transplanting of PR 124 with irrigation at 2 DAIPW (Brar *et al.*, 2021). Furrow irrigation in raised beds is another alternative to flood irrigation, enhancing water productivity for both rice and wheat (Sandhu *et al.*, 2012; Kaur *et al.*, 2024). Bed planting ensures efficient use of water and fertilizers, while also reducing weed emergence. This method is particularly beneficial in medium to heavy-textured and waterlogged soils. Field studies have shown that rice residue mulching in wheat reduces water requirements by conserving soil moisture and decreasing evaporation (Balwinder-Singh *et al.*, 2016), while maintaining or even increasing grain yield (Chakraborty *et al.*, 2008; Sidhu *et al.*, 2007). For example, heavy rice straw mulch (9 t/ha), combined with irrigation equivalent to 6.5 cm at 30% soil moisture depletion, led to higher wheat yields and saved one irrigation compared to conventional sowing and flooding practices (Mandal *et al.*, 2022). Straw mulching also promotes rainwater infiltration, boosting crop growth and yield. This strategy has proven effective for various crops, including potato (Brar *et al.*, 2019), turmeric (Kaur and Brar, 2016), spring maize (Singh *et al.*, 2015; Kaur and Arora, 2019), and summer moong (Kaur *et al.*, 2021). Additionally, residue mulching helps lower soil temperatures in spring, benefiting crops like maize.

Crop diversification

Crop diversification is crucial for sustaining natural resources, particularly groundwater, in Punjab. However, government efforts to encourage farmers to shift from rice to less water-intensive crops have faced challenges due to policies that favour rice cultivation. These include free or subsidized irrigation power, guaranteed minimum support prices, and assured crop procurement. Promising alternatives to rice are *Basmati* rice, cotton, maize, and sugarcane (Dhillon et al., 2021). *Basmati* rice, with its delayed planting and lower nutrient requirements, has a milder ecological impact compared to non-*Basmati* rice due to its growth phase coinciding with the rainy season. Cotton, which offers higher profitability than maize, ranks just below paddy in net returns among *kharif* crops. Additionally, its economic water productivity is approximately 2.5 times greater than that of paddy. To make cotton cultivation more profitable than paddy in the future, setting fair prices for water and electricity could be key. However, interspersed paddy and cotton cultivation in the cotton belt should be discouraged by implementing a crop planning policy that promotes judicious water use and reduces excessive humidity, which favours pests and insects. In cases of price instability, market interventions by the Cotton Corporation of India should be considered to set benchmark prices for cotton, thus helping to minimize losses to farmers.

Sugarcane is a promising crop for diversifying the rice-wheat monoculture, offering resilience to both waterlogging and drought. Its irrigation water requirement is lower than its evapotranspiration (ET) demand, thanks to higher effective rainfall during the crop's critical growth period. To support economically viable sugar mills, expanding the area under sugarcane is essential. Key interventions to boost sugarcane acreage include ensuring timely payments to farmers, upgrading and expanding old mills, establishing bio-ethanol distilleries, setting up power co-generation units, and incentivizing entrepreneurs to acquire planters and harvesters for custom hiring.

Punjab's agro-climatic conditions are also well-suited for turmeric cultivation, which is relatively pest-resistant and responds well to organic inputs like manure. Although turmeric is a long-duration crop (requiring 215-240 days), it has a high-water demand (~115 cm), which can be reduced to 79 cm with drip irrigation (Kaur and Brar, 2016). Combining drip irrigation with straw mulching can further conserve water. To boost turmeric production across the state, it is important to support its cultivation through the establishment of processing facilities, collective marketing initiatives, and knowledge-sharing platforms for farmers.

Triple cropping systems, such as *Basmati-wheat-summer moong* and *rice-potato-spring maize*, can provide equivalent or even higher economic returns than the traditional *rice-wheat* cycle but lead to increased total water requirements. Spring crops like maize, sunflower, moong, and mentha, grown during the hot, dry season, demand substantial irrigation. The shift towards high-water-demand crops that replace wheat while retaining rice in the *rice-wheat* cycle is concerning. While rice-based triple cropping systems are more profitable, they are unsustainable due to their excessive water usage. Successful diversification away from paddy depends on supportive policies, access to lucrative markets, and the adoption of mechanization (Vatta *et al.*, 2022). Transitioning from *rice-wheat* to high-value crops like fruits and vegetables requires innovative policies, price compensation, and incentives to encourage diversification. Potential savings from reduced power subsidies could help offset the transition costs (Bhogal and Vatta, 2021).

Irrigation water management interventions

Laser levelling improves irrigation efficiency and crop establishment by reducing irrigation needs and optimizing input resource usage. Efficient water management focuses on retaining water within the crop's root zone, which can be achieved by dividing fields into appropriately sized plots-typically 8 plots per acre for heavy soils and 16 plots per acre for light soils. Conventional surface flood irrigation often results in significant water losses. Adopting an underground pipeline system (UGPS) for water delivery enhances irrigation efficiency and extends the area available for cultivation with low maintenance costs. The adoption of UGPS has been shown to increase rice yields by 2.98%, save 17.9% of water, and result in an average monetary saving of Rs. 1093 per hectare (Singh *et al.*, 2022). Furthermore, integrating micro-irrigation systems with UGPS refines water use precision. Converting open canals into piped water supply systems can also significantly reduce water losses, particularly in regions experiencing waterlogging and brackish groundwater.

Precision irrigation techniques

Precise irrigation scheduling using tensiometers at a soil depth of 15-20 cm (150±20 cm soil matric tension) can save 25-30% of water in rice cultivation (Kukal *et al.*, 2005). An automated Alternate Wetting and Drying (AWD) system, piloted through participatory trials in Punjab, employed ultrasonic sensors and Internet of Things (IoT) tools to monitor water levels. This system resulted in a 4-6% increase in grain yield, 17% water savings, and additional benefits (Brar *et al.*, 2020). Drip irrigation (both surface and sub-surface) offers several advantages, including significant water savings, increased irrigation efficiency, reduced runoff, improved crop yields, and better nutrient utilization (Brar *et al.*, 2022). These systems also enable fertigation, further enhancing nutrient use efficiency (Fan *et al.*, 2016), saving net energy consumption (Dhillon *et al.*, 2018), and reducing carbon footprints (Chen *et al.*, 2020). The integration of moisture sensors, communication technologies, and artificial intelligence (AI) can further improve water use efficiency, reduce labour requirements, and lower production costs (Bwambale *et al.*, 2022; Sidhu *et al.*, 2021; Anjaly *et al.*, 2024). Once predominantly used in horticulture, drip irrigation systems are now being applied to cereal crops such as maize, sunflower, and mentha. This shift has led to significant water savings (15-60%), increased productivity, and a 20% reduction in nutrient use (Sahoo *et al.*, 2018; Sharma *et al.*, 2021).

Sub-surface drip irrigation (SSDI) is a precise water-saving technique that delivers water below the soil surface, resulting in significant water savings and improved productivity. In the *maize-wheat-summer moong* cropping system, SSDI saves about 29% of water, while in sugarcane and *cotton-wheat* systems, the savings are 43% and 45%, respectively. Additionally, SSDI leads to a 20% reduction in nutrient use (Brar and Sindhu, 2019; Singh *et al.*, 2022). When applied under no-tillage conditions, SSDI offers 11-30% higher net returns in rice-wheat cropping systems compared to conventional practices (Sidhu *et al.*, 2019). SSDI also has a longer lifespan (10-15 years) compared to surface drip irrigation (SDI), helping to reduce annual costs (Ayar *et al.*, 2015). The use of a tractor-operated SSDI layering machine for installation further reduces input costs through mechanization. SSDI is particularly valuable in addressing future water challenges in north-west India, where groundwater levels are declining. It also provides benefits such as mitigating heat stress for wheat during ripening and improving rainwater utilization for *kharif* crops.

Groundwater scenario under improved supply and demand management – way forward

Improved supply and demand management in the state is expected to have a significant positive impact on groundwater. Better supply management can increase the availability of surface water, which can be used for groundwater recharge, thus enhancing aquifer replenishment and overall groundwater availability. On the other hand, improved demand management can promote water-efficient farming practices, which would reduce reliance on groundwater, lower pumping needs, decrease energy consumption, and slow down groundwater depletion. Theoretically, shifting approximately 1.3 million hectares from paddy cultivation to low-water crops could eliminate the water deficit. However, practical constraints such as comparable returns, marketing policies, and seepage rates limit the potential reduction in water usage. To address this irrigation-related water deficit, the State Irrigation Plan (2017) estimates an annual shortfall of 9.0 BCM, based on crop water demand (using evapotranspiration, or ET) and non-agricultural water use (Arora, 2019).

Ensuring sustainable agriculture requires a balanced shift from paddy cultivation to low-water crops, along with the adoption of water-saving practices (Arora *et al.*, 2008). Arora (2019) estimated that shifting 1.0 million hectares of rice area to crops like *basmati* rice, *kharif* maize, and pulses could save 2 BCM of evapotranspiration (ET), provided there is assured pricing and procurement. In blocks where water extraction exceeds recharge by more than three times, paddy cultivation should be gradually phased out. These areas should transition to alternative crops, with compensation for farmers to ensure they receive higher returns than from paddy cultivation. Blocks with similarly high-water extraction rates should be addressed in subsequent phases.

Shifting the paddy transplanting date by ten days across 2 million hectares and using short-duration varieties (SDVs) could save an estimated 2 BCM of evapotranspiration (ET). To achieve this, the cultivation of long-duration paddy varieties should be entirely prohibited in the state. Greater emphasis should be placed on research to develop SDVs that require less water. The adoption of SDVs, combined with strict enforcement of late-June to early-July transplanting dates under the *Punjab Preservation of Sub-Soil Water Act, 2009* will lead to substantial water savings. Additionally, implementing straw mulching in wide-row crops and retaining residue in wheat fields for part of the area could reduce ET by an estimated 1.5 BCM.

Switching 50% of horticultural and wide-row crop areas from flood irrigation to drip irrigation can save an estimated 1.2 BCM of evapotranspiration (ET) annually. A phased approach should be adopted for installing drip irrigation systems to reduce groundwater extraction and cut power subsidies. The initial focus should be on fruits and vegetables, followed by wide-row crops such as sugarcane and cotton. The adoption of sub-surface drip irrigation in the cotton-wheat system, integrated with water storage structures and solar pumps, should be demonstrated and incentivized for individual farmers, particularly in the southwestern districts. Additionally, drip irrigation systems are ideal for integration with lift irrigation from canals or harvested rainwater in the *Kandi* region, especially when powered by solar energy. High-water-demand spring crops, such as maize and sunflower, should be mandated for drip irrigation. To facilitate this transition, a dedicated organization or special purpose vehicle for promoting drip irrigation should be established in the state. A substantial, well-targeted investment is needed to promote drip irrigation, particularly in the southwestern zone. Aligning technological interventions with revised electricity supply schedules and canal water delivery times should be prioritized to support alternative crops, rather than the traditional rice-wheat cycle. Rationalizing canal water supply towards the central region, while expanding drip irrigation in the southwestern region, will allow for groundwater recharge through canal seepage in the central areas and help reduce waterlogging in the southwestern parts. This approach could result in an annual ET saving of 13.0 BCM, based on a drainage-to-ET ratio of 1.5 for rice and 0.1 for other crops. Collectively, these measures can significantly improve water sustainability and agricultural productivity in the state (Fig. 7).

Climate Change and Water Resources: Future Impacts

Climate change presents significant challenges to the sustainability of agriculture, water resources, long-term food security, and livelihoods. While groundwater exhibits resilience to climate variability due to its long residence time in aquifer systems, shallow aquifers, recently recharged, are more sensitive to fluctuations in climate than older, deeper aquifers. Changes in rainfall patterns, frequency, and intensity over time can significantly affect groundwater storage, primarily through variable recharge rates. Recent assessments project that maximum and minimum temperatures in Punjab will rise by 1.1°C to 4.8°C across different regions by mid-century (2040–60) and late-century (2080–95) (Kingra *et al.*, 2024). Additionally, while annual and *kharif* season (June–October) rainfall is expected to increase by 18% to 43%, *rabi* season (October–April)

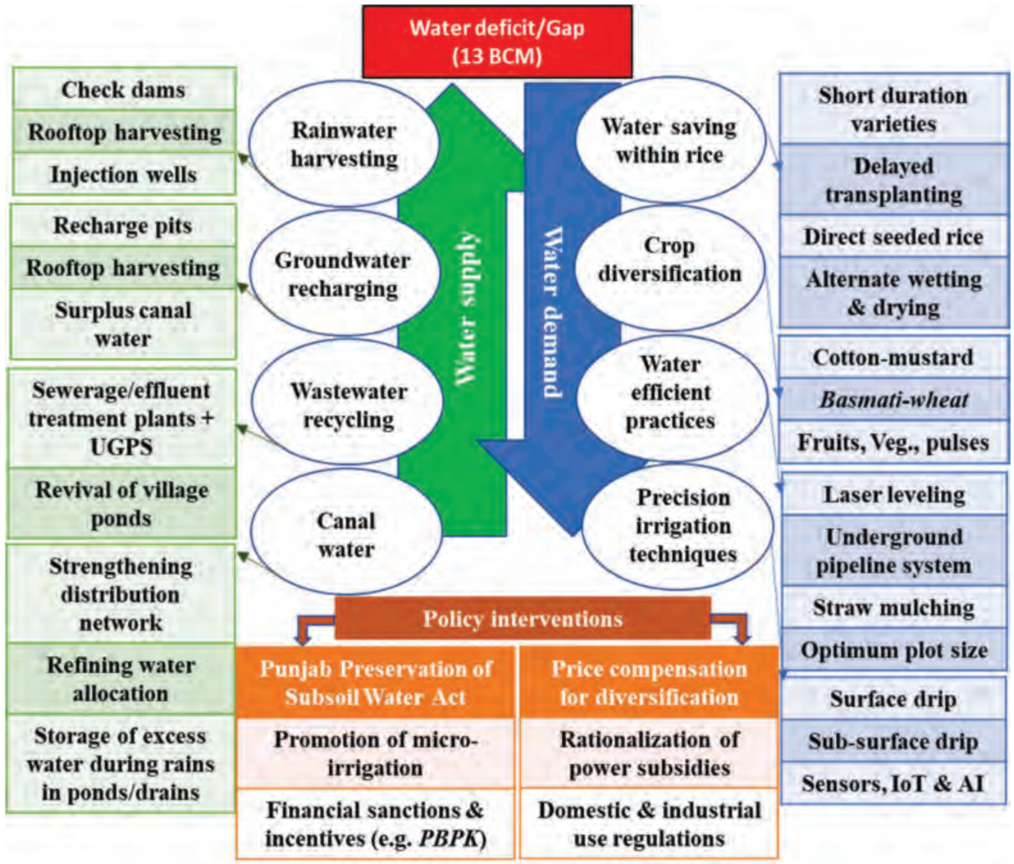

Fig. 7. Interventions to enhance water supply and reduce demand

rainfall is predicted to decrease significantly, with reductions ranging from −8% to −62%. This decline will vary regionally: −27% to −8% in the northeast, −24% to −18% in the central region, and −43% to −62% in the southwest. Rising temperatures and erratic rainfall patterns may create uncertainties in water availability, exposing crops to both heat and water stress, which could reduce productivity. Basin-wise assessments of climate change impacts on surface water resources indicate that variability will result in more intense rainfall over shorter durations, fewer rainy days but higher total precipitation, initial surges in glacial melt runoff followed by declines, increased surface runoff with reduced groundwater recharge, and heightened risks of both floods and droughts (Pathak *et al.*, 2014).

Groundwater responses to rainfall variations from 1901 to 2019 were examined through an empirical relationship between annual rainfall and recharge in Punjab (Krishna *et al.*, 2022). The findings revealed that a 20% reduction in normal rainfall (600 mm) could lead to a 65% decrease in groundwater recharge. This highlights the impacts of climate change on groundwater resources, driven by shifts in precipitation patterns. Water scarcity in agriculture is expected to worsen due to rising demand from non-agricultural sectors, compounded by declining water availability influenced by climate change. The state's total water demand is projected to increase from the current 66 BCM to 70 BCM by 2030, and to 72 BCM by 2050 (Kukal and Sidhu, 2022). This increase in demand is expected to reduce the share of water available for agriculture by 10-15% over the next two decades. In conclusion, climate variability will intensify pressure on regional water resources, highlighting the urgent need for judicious and regulated water use. Future research must prioritize understanding crop moisture dynamics and hydrological processes under evolving climate scenarios to develop more resilient agricultural and water management strategies.

Aligning technological solutions with socio-economic realities and policy frameworks

Effective frameworks, policies, regulations, and organizations that oversee water management, allocation, and conservation are essential to ensuring equitable, sustainable, and efficient water use. However, past challenges in enforcing groundwater regulations have hindered progress (Smith and Urpelainen, 2016). Overcoming these challenges requires a comprehensive approach that combines legal reforms, institutional strengthening, and active community involvement. The water regulatory framework must be enhanced by amending existing laws to enforce stricter penalties, mandating usage permits, introducing fixed water meters, limiting energy subsidies, and regulating private tubewell installations. In 2020, the Punjab Water Regulation and Development Authority (PWRDA) was established to oversee and regulate water use in the state. Furthermore, water regulation should be integrated into agricultural policies to promote the adoption of low-water-demand crops and water-saving technologies.

Institutional mechanisms require substantial reforms to ensure effective enforcement and monitoring. These mechanisms should incorporate real-time monitoring technologies, such as GIS and IoT systems, to track water usage patterns and groundwater levels. Enhanced coordination among central, state, and local bodies is crucial for aligning policies and enforcement strategies. Additionally, canal water allocation should be closely linked to groundwater recharge initiatives to maintain a balance in water usage. Point sources of pollution, including industrial wastewater discharges (such as from injection wells), improper waste management in both domestic and industrial sectors, and municipal sewer discharges, pose significant threats to both rivers and groundwater. To address these issues, strict enforcement of water quality standards should be prioritized, and such discharges should be explicitly prohibited by law.

Engaging and empowering local communities, such as Water User Associations, to monitor and regulate water use can foster a sense of ownership and accountability. Educational campaigns should be launched to raise awareness about the consequences of over-extraction and the importance of water conservation. Financial incentives and targeted subsidies for farmers adopting sustainable practices or diversifying crops can encourage behaviour change and drive adoption of water-saving technologies. The *Pani Bachao Paisa Kamao Scheme (PBPK)* is a promising initiative aimed at saving water and electricity by offering monetary incentives to farmers who improve groundwater-use efficiency in crops. Scaling up and effectively implementing this scheme can have a significant impact on water conservation. By aligning technological solutions with socio-economic realities and supporting efforts at the policy, institutional, and community levels, the state can transition towards a more sustainable and resilient agricultural system, ensuring the long-term conservation of its vital water resources.

Conclusion

Punjab is facing a severe water crisis, exacerbated by the over-reliance on groundwater extraction, an unsustainable rice-wheat cropping system, and declining canal water availability. This paper has examined the current challenges and highlighted the urgent need for technological and agronomic interventions to promote sustainable water use in agriculture. Solutions such as crop diversification, efficient irrigation practices, straw mulching, and water-saving technologies like drip irrigation provide viable pathways to reduce the water deficit. However, achieving meaningful change requires a multi-faceted approach that combines technological innovation with effective policy enforcement, farmer education, and behavioural change. Integrating climate change adaptation strategies, groundwater regulation reforms, and incentives for adopting water-efficient practices is essential for long-term success. By aligning technological solutions with socio-economic realities and strengthening policy frameworks, Punjab can transition towards a sustainable, resilient agricultural system that ensures the long-term conservation of its vital water resources.

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