Irrigation Water Resources in India: Status, Sources, Quality Challenges, and Sustainable Management

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Abstract

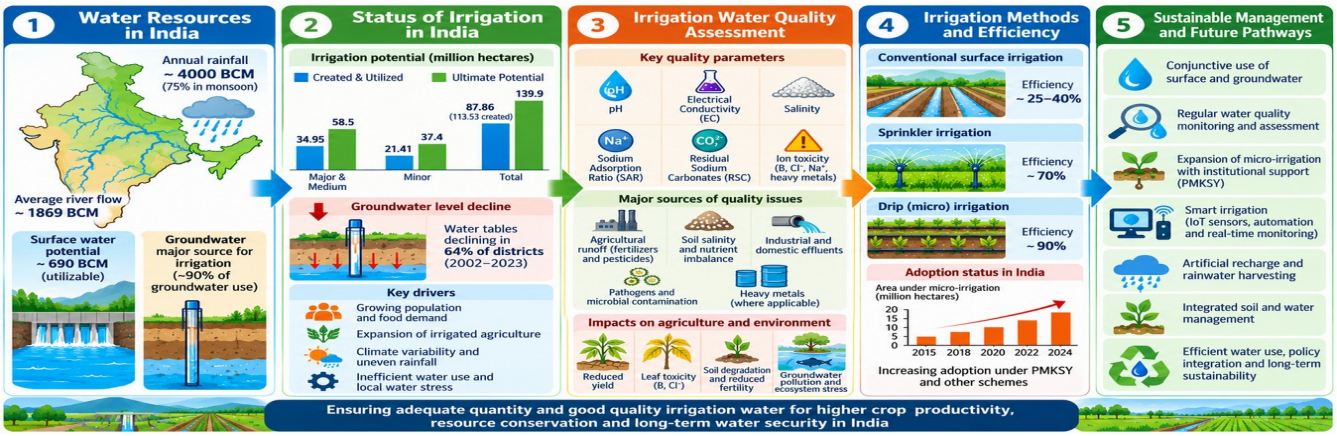
India's per capita water availability has declined over time, placing increasing pressure on agricultural water resources. Groundwater plays a critical role in irrigation, with more than 90% of groundwater withdrawals reportedly used for agricultural purposes. Agriculture also accounts for a substantial share of India's employment. Declining groundwater levels, increasing dependence on irrigation, and the use of inadequately monitored water sources raise concerns regarding the sustainability of water resources and the quality of irrigation water and soil. Improving irrigation water-use efficiency is therefore essential for sustainable agricultural production. Properly designed and maintained drip and sprinkler irrigation systems can improve water-application efficiency compared with conventional surface irrigation, although the reported efficiency values depend on the methods and conditions of assessment.

The Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), launched in 2015, integrates several irrigation-related initiatives, with micro-irrigation serving as an important component. Wider adoption of water-efficient technologies requires accessible institutional support, technical guidance, and effective implementation mechanisms. Irrigation-water quality varies across regions according to rainfall patterns, aquifer recharge, groundwater extraction, and local water-use practices. Important parameters for assessing irrigation-water suitability include electrical conductivity (EC), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), and specific-ion toxicity. Boron and chloride concentrations also require attention because excessive levels can adversely affect plant growth. Furthermore, smart irrigation approaches incorporating wireless communication systems, monitoring tools, sensors, and improved control strategies can support efficient irrigation scheduling and water management. Integrating these approaches with appropriate institutional support and region-specific water-resource planning is essential for improving irrigation efficiency and promoting sustainable agricultural production in India.

Keywords: irrigation water quality; groundwater; irrigation potential; micro-irrigation; salinity; sodium adsorption ratio; smart irrigation; sustainable water management.

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Graphical Abstract:



1. Introduction

For a nation like India, which has just 2.4% of the world's land and 4% of its water resources, efficient use of the water resources that are available is essential. India accounts for 17% of the world's population. Additionally, the average utilizable water resources per capita, which were 5247 m3 in 1951 (1453 m3 in the cited assessment), are predicted to decrease to 1170 m3 by 2050 (CWC, 2015). Eighty percent of groundwater is used by the agricultural sector alone (Harsh, 2017). Groundwater levels are trending downward nationwide, which further suggests that the nation's growth would be hampered by the guaranteed supply of high-quality water (Manivannan et al., 2017). According to Amarasinghe (2007), the flood irrigation system's total efficiency ranges from 25 to 40%. In terms of production growth, energy savings, water-use efficiency, and net return per unit volume of groundwater, micro-irrigation generally outperforms other conventional irrigation techniques (Kumar and Palanisami, 2010; Chandrakanth et al., 2013). Rising food demand will place additional pressure on irrigation water supplies through 2050. Building several artificial conservation techniques may raise the groundwater table and increase agricultural yield (Paul and Panigrahi, 2016). All of these highlight the need of conserving water and increasing water-use efficiency in order to produce more crops per drop. The structure of the paper is as follows. The article first discusses the current state of irrigation in India before moving on to discuss the difficulties facing Indian irrigation systems. The availability of surface and groundwater, as well as different irrigation techniques, are also highlighted in the article. Finally, we go over a number of solutions to these problems, including government initiatives for effective agricultural water management, before coming to a conclusion.

2. Status of Irrigation in India

In India, irrigation accounts for almost 90% of groundwater draw and is the primary user of fresh water. Food security and population growth have increased demand on water resources. The nation has arrived at a point when fresh water availability is steady but water demand from different economic sectors is rising quickly. Furthermore, excessive water consumption damages the ecosystem by causing nutrient contamination, increased salinity, and the loss and deterioration of wetlands and flood plains. India has a chronic water deficit as a result of climate change and inadequate water-resource management. Precipitation has varied greatly in both space and time, with the lowest amount occurring in western Rajasthan (<100 mm) and the highest in Cherrapunji (>11000 mm). In India, the average river flow is estimated to be 1869 BCM, while the annual precipitation is close to 4000 BCM. However, the monsoon season (June to September) receives roughly 75% of the rainfall, which limits the amount of surface water that can be used to 690 BCM. Rainfall contributes 74% to groundwater recharge, with the remaining portion coming from canals, ponds, and other water-saving measures. The nation's total yearly replenishable groundwater capacity is estimated to be 433 BCM. With a groundwater draw of 253 BCM per year, irrigation alone uses about 91% of the draft to irrigate 62% of the nation's entire irrigated land (CGWB, 2017). However, there is variation in groundwater development around the nation. India's net irrigated area (%) has grown from around 18 to 48 percent over the historical period covered by the cited sources as a result of several levels of government involvement. The canal system has deteriorated over time, despite the government placing a lot of focus on maintenance in many five-year plans. Groundwater irrigation has been recognized as a very dependable and self-sufficient irrigation source. Since 1965, groundwater irrigation has advanced significantly.

Table 1. Source-wise Created, Utilized, and Ultimate Irrigation Potential

Source	Irrigation Potential at Independence (Mha)	Created Potential up to 2007–12 (Mha)	Utilized Potential up to 2007–12 (Mha)	Ultimate Potential (Mha)
Major & Medium (Surface Water)	9.7	47.97	34.95	58.5
Minor (Surface Water)	6.4	NA	NA	17.3
Minor (Surface & Groundwater)	12.9	65.56	52.5	81.4
Total (Major, Medium and Minor)	22.6	113.53	87.86	139.9

Source: CWC (2015); DES, GoI (2017).

3. Irrigation schemes and sources

In India, irrigation systems are divided into three categories by the Planning Commission: big (cultivable command area (CCA) >10000 ha), medium (CCA from 2000-10000 ha), and small (CCA <2000 ha). While used irrigated potential (including surface and groundwater) grew to 87 Mha, created irrigation potential climbed from 22.8 Mha to 107.2 Mha (Table 1). The government has placed a high priority on the establishment of the command area underneath canals from 1950–1951. India produced 275.11 million tons of food grains in 2016–17, with a gross irrigated area of 96.46 million hectares and a net irrigated area of 68.38 million hectares. Canal-irrigated land was 8.3 million hectares in 1950–51 and 16.18 million hectares as of 2014–15. The well and tube well, on the other hand, accounted for 63% of the total irrigated area, while in 1950–51 they made up 29%. In spite of this, canals' proportional value has decreased from 40% in 1951 to 24% in 2014–2015. Table 2 shows that, concerningly, the area under groundwater sources is increasing while the irrigated area under canals and tanks has been decreasing between 2009–2010.

Table 2. Net Irrigated Area from Various Sources and Their Relative Contribution

Source	NIA (Mha), 2009–10	Contribution (%), 2009–10	NIA (Mha), 2014–15	Contribution (%), 2014–15
Canal	16.697	26.4	16.18	23.66
Tank	1.638	2.59	1.72	2.52
Wells	39.042	61.72	42.96	62.82
Others	5.88	9.3	7.52	11
Total	63.257	100	68.38	100

Source: DES, MoA&FW, GoI (2018).

Note: Mha = million hectares; NIA = Net Irrigated Area; NA = data not available.

There has been significant geographical diversity in the various irrigation sources. With the exception of Rajasthan's deserts, irrigation is widespread across the nation's alluvial plains. The states with the highest prevalence of well irrigation include Tamil Nadu, Gujarat, Karnataka, Bihar, and Uttar Pradesh's plains. After wells and tube wells, canals are the second most significant irrigation source in India. These areas, which have vast plains, rich soils, and perennial rivers, are being irrigated by the canals. The majority of North India's plains are watered by canals. Other regions include various areas of Peninsular India and coastal lowlands. These states include Karnataka, Tamil Nadu, Uttar Pradesh, West Bengal, Punjab, Rajasthan, Bihar, Andhra Pradesh, Assam, Haryana, and Jammu & Kashmir. The country's rocky plateau region, where the tank irrigation is most prevalent, has erratic and highly seasonal rainfall. The Eastern Madhya Pradesh, Chhattisgarh, Orissa, Interiors of Tamil Nadu and some parts of Andhra Pradesh have more land under tank irrigation.

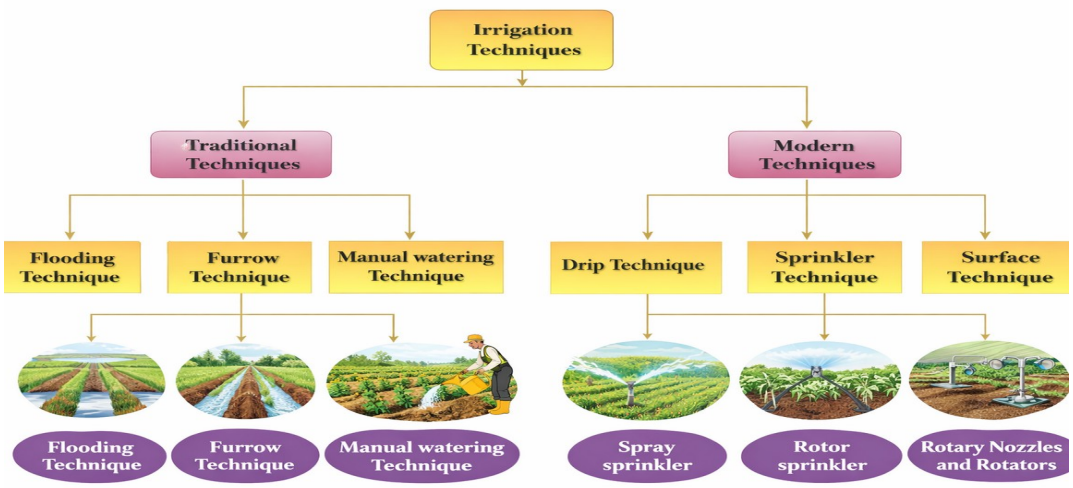


Figure 1: Major irrigation techniques, including surface irrigation, sprinkler irrigation, and drip irrigation, illustrating different methods of water application for agricultural production.

4. Conventional Measures of Irrigation Water Quality

For more than a century, irrigation water quality has been evaluated primarily in terms of its effects on soil properties, crop growth, and agricultural productivity. Early investigations focused on the chemical composition of groundwater and its suitability for irrigation, particularly in arid and semi-arid regions. Studies by Clark (1917), Schwennesen and Forbes (1917), Scofield and Headley (1921), and subsequent researchers established the importance of dissolved salts, sodium, boron, and other chemical constituents in determining irrigation suitability. Later investigations demonstrated that the long-term use of unsuitable irrigation water could lead to soil salinization, reduced infiltration, and adverse effects on crop development. Although these foundational studies remain relevant, contemporary irrigation water quality assessment increasingly considers the combined effects of conventional chemical parameters and emerging contaminants. Traditionally, electrical conductivity (EC), total dissolved solids (TDS), pH, sodium adsorption ratio (SAR), residual sodium carbonate (RSC), chloride, boron, and specific ion concentrations have been used to assess irrigation water suitability. Electrical conductivity provides an indication of the overall concentration of dissolved salts, whereas SAR helps assess the potential for sodium-induced deterioration of soil structure. Excessive sodium relative to calcium and magnesium can promote clay dispersion, reduce aggregate stability, and impair soil infiltration and hydraulic conductivity. High salinity can also reduce the ability of plant roots to absorb water by lowering the osmotic potential of the soil solution. These effects are particularly important in arid and semi-arid agricultural systems, where high evapotranspiration and inadequate drainage can accelerate salt accumulation in the root zone. Recent reviews continue to identify salinity, sodicity, and associated soil degradation as major constraints on sustainable irrigation and crop productivity (Gupta & Kumar, 2024; Vranešević et al., 2025).

Contemporary irrigation management therefore requires the interpretation of water quality parameters in relation to soil texture, drainage conditions, crop salt tolerance, irrigation frequency, rainfall, and the characteristics of the underlying aquifer. Water with a particular EC or SAR value cannot be considered suitable or unsuitable in isolation, because its effects depend on the interaction between water chemistry and soil properties. Similarly, bicarbonate and carbonate concentrations can influence calcium and magnesium availability and thereby affect sodium-related soil structural problems. Gypsum application, improved drainage, blending of water sources, and selection of salt-tolerant crops may help mitigate some of these risks, but the appropriate intervention must be based on water and soil testing rather than a single universal threshold (Gupta & Kumar, 2024; Vranešević et al., 2025). A major contemporary development is the increasing use of treated or reclaimed wastewater to supplement freshwater supplies for agriculture. Wastewater may provide nitrogen, phosphorus, potassium, and organic matter that support crop growth and reduce dependence on conventional fertilizers. However, its composition varies according to the wastewater source, industrial inputs, treatment technology, and operational performance of treatment facilities. Consequently, the benefits of nutrient recycling must be evaluated alongside the risks associated with salinity, pathogens, heavy metals, and contaminants of emerging concern. A review of wastewater irrigation in India highlighted its potential to support agricultural production while also identifying risks of contaminant transfer to soils and crops when wastewater is inadequately treated or managed (Minhas et al., 2022).

Recent research has also shown that conventional water quality indicators cannot fully capture the potential risks associated with reclaimed wastewater. Even when water meets selected conventional chemical criteria, trace concentrations of pharmaceuticals, personal care products, antibiotic residues, antimicrobial-resistant microorganisms, and other emerging contaminants may remain. The review by Lyu et al. (2022) on reclaimed wastewater irrigation and soil–crop systems identified heavy metals, emerging contaminants, and pathogens as important risk categories requiring continued assessment. The authors also highlighted uncertainties surrounding long-term accumulation, transformation products, and combined contaminant effects. These findings suggest that irrigation water quality assessment should integrate conventional physicochemical measurements with contaminant-specific testing and risk-based monitoring where wastewater reuse is practiced. Another important concern is the transfer of geogenic contaminants from groundwater into agricultural soils and crops. Elements such as arsenic and selenium may occur naturally in geological formations and can enter groundwater under particular geochemical conditions. Where such groundwater is repeatedly used for irrigation, the resulting contaminant loading may affect soil quality and potentially introduce contaminants into edible plant tissues. In addition, the repeated application of contaminated water may alter soil microbial communities and influence the mobility and bioavailability of pollutants. For this reason, irrigation water monitoring should consider not only immediate crop responses but also long-term changes in soil properties, contaminant accumulation, and the potential implications for food safety. The current understanding of irrigation water quality has consequently expanded from a predominantly agronomic assessment to an integrated soil–water–plant–human health framework. Traditional parameters such as EC, TDS, pH, SAR, and RSC remain essential, but they should be supplemented, where relevant, by measurements of trace elements, microbial indicators, pharmaceutical residues, and other contaminants of emerging concern. The selection of monitoring parameters should reflect the source of irrigation water, local environmental conditions, crop type, intended use of the harvested produce, and applicable regulatory requirements. This broader approach provides a stronger basis for protecting soil functions, maintaining crop productivity, and managing the long-term consequences of irrigation with alternative water sources (Partyka & Bond, 2022; Christou et al., 2024).

4.1 Impact of Contemporary Irrigation Water Quality Issues on Soil and Crop Quality

The impacts of irrigation water quality on soil properties and crop productivity remain important, but contemporary research increasingly focuses on the movement, persistence, and biological effects of inorganic and organic contaminants in agricultural systems. The use of treated wastewater and other alternative water sources can support irrigation in water-scarce regions; however, it may also introduce contaminants that are not adequately removed during conventional treatment. These include heavy metals, pharmaceuticals, personal care products, antibiotic residues, pathogens, antimicrobial resistance genes, and microplastics. Their effects depend on contaminant concentration, chemical properties, soil characteristics, irrigation practices, crop species, and exposure duration. Consequently, water reuse decisions require an assessment of both potential agronomic benefits and environmental and public health risks (Lyu et al., 2022; Christou et al., 2024).

4.2. Soil Quality and the Accumulation of Inorganic Contaminants

Repeated irrigation with water containing elevated concentrations of dissolved salts may increase soil salinity and, where sodium is excessive relative to calcium and magnesium, contribute to sodicity. These changes can reduce soil aggregate stability, infiltration, and hydraulic conductivity, while increasing osmotic stress for plants. Wastewater reuse may also introduce additional salts and nutrients. Although nutrients can improve soil fertility and crop growth under appropriate conditions, long-term use without adequate monitoring and drainage may result in an imbalance of soil chemical properties. A 2025 review of the transition from untreated to treated wastewater irrigation emphasized that treatment can reduce several contaminant-related risks but does not automatically eliminate salinity problems or the consequences of pollutants accumulated during earlier irrigation practices (Heyde et al., 2025). Heavy metals and metalloids are another important concern, particularly where irrigation water receives industrial or municipal wastewater inputs or where groundwater contains naturally occurring contaminants. Cadmium, lead, chromium, mercury, arsenic, and other potentially toxic elements may accumulate in soil depending on their concentration, chemical form, soil pH, organic matter content, and interactions with mineral surfaces. Their persistence means that repeated inputs can create long-term environmental concerns even when individual irrigation events produce no immediately visible crop damage. A review focused on India documented concerns regarding the transfer of heavy metals from wastewater-irrigated soils into cultivated products and the implications for environmental and food safety (Minhas et al., 2022).

4.3. Emerging Organic Contaminants and Plant Uptake

The presence of pharmaceuticals and personal care products in reclaimed water has become a significant research topic because conventional wastewater treatment may not completely remove these substances. When reclaimed water is used for irrigation, residual compounds may enter soil, interact with soil organic matter and microorganisms, and become available for plant uptake. The degree of uptake varies with the chemical properties of the compound, the soil environment, the irrigation regime, and the physiology of the crop. A recent review of sustainable wastewater reuse examined the uptake, transport, accumulation, and metabolism of pharmaceutical compounds in plants and identified important knowledge gaps concerning their behaviour within plant tissues (Christou et al., 2024). Research on pharmaceutical and personal care products has also indicated that contaminant accumulation can differ between leafy vegetables and fruit-bearing crops. The amount of irrigation water applied and plant water-use processes may influence the transport and accumulation of these compounds. This is particularly relevant where edible plant tissues are consumed directly and where the irrigation source contains residual pharmaceuticals. However, the presence of a contaminant in irrigation water does not by itself establish a specific level of risk to consumers; the assessment must consider its concentration, uptake, metabolism, persistence, exposure pathway, and relevant toxicological evidence (Lyu et al., 2022).

4.4. Microplastics, Co-contaminants, and Soil–Plant Interactions

Micro plastics and nanoplastics have emerged as additional concerns in agricultural systems receiving wastewater or contaminated surface water. These particles may occur alongside heavy metals, pharmaceutical residues, and other contaminants. Their interactions can influence contaminant mobility and plant responses, although the direction and magnitude of these effects depend on particle size, polymer characteristics, contaminant composition, and exposure conditions. A 2023 review by Naziri et al. of co-contamination in edible plants discussed evidence that simultaneous exposure to microplastics or nanoplastics and other pollutants can alter plant growth, photosynthetic processes, and oxidative stress responses. The review also highlighted variability between experimental systems, indicating that the effects cannot be generalized across all crop species or exposure conditions. More recent reviews have continued to examine emerging contaminants in reclaimed wastewater and their implications for agricultural irrigation. Yakamercan et al. (2025) reviewed contaminants of emerging concern in reclaimed wastewater, emphasizing their potential transfer from soil into edible plant parts and the need for better evidence on environmental persistence, contaminant fate, and risk management. These findings support the inclusion of emerging contaminants in targeted monitoring programmes, particularly where reclaimed wastewater is used repeatedly or where crops are consumed raw.

4.5. Pathogens, Antimicrobial Resistance, and Food Safety

Microbiological quality is a critical component of irrigation water assessment, especially for vegetables and other produce consumed without cooking. Wastewater may contain enteric pathogens, antimicrobial residues, resistant microorganisms, and antibiotic resistance genes. These hazards are not fully described by conventional physicochemical parameters such as EC, TDS, or SAR. Reviews of treated wastewater irrigation have identified the potential for resistant microorganisms and antimicrobial resistance genes to interact with soil and plant-associated microbial communities. The issue is particularly important when edible plant surfaces are exposed directly to irrigation water or when harvested produce receives limited processing before consumption (Partyka & Bond, 2022; Smalla et al., 2023). The use of treated wastewater should therefore be supported by treatment processes appropriate to the intended reuse, routine verification of treatment performance, and risk-based monitoring of microbial and chemical quality. Crop type, irrigation method, exposure of edible plant parts, harvesting practices, and post-harvest handling should also be considered. Where necessary, measures such as avoiding direct contact between reclaimed water and edible portions, using suitable irrigation systems, and implementing produce hygiene controls can form part of a broader risk-management strategy. No single treatment or monitoring measure should be assumed to eliminate all risks.

4.6. Recent Developments and Future Directions

Recent research increasingly treats wastewater reuse as a potential component of sustainable water management rather than simply a disposal route. Properly treated wastewater can provide a more reliable irrigation supply and recycle useful nutrients, potentially reducing pressure on freshwater resources and conventional fertilizers. Nevertheless, safe reuse depends on

effective treatment, water quality monitoring, agricultural management, and appropriate regulatory oversight. Reviews published in 2024 and 2025 emphasize the need to address contaminants of emerging concern, improve treatment and monitoring approaches, and consider long-term soil and crop effects rather than relying only on short-term yield responses (Christou et al., 2024; Heyde et al., 2025; Yakamercan et al., 2025). The research agenda is also expanding towards the combined effects of multiple contaminants, the persistence and transformation of pollutants in soil, the transfer of contaminants into edible tissues, and the consequences of long-term exposure. The 2026 review by Basit et al. further reflects ongoing attention to the links between wastewater irrigation, soil health, vegetable production, and environmental risk management. Such recent work reinforces the need for integrated assessments that combine conventional irrigation water parameters with contaminant-specific analysis and crop- and site-specific risk evaluation.

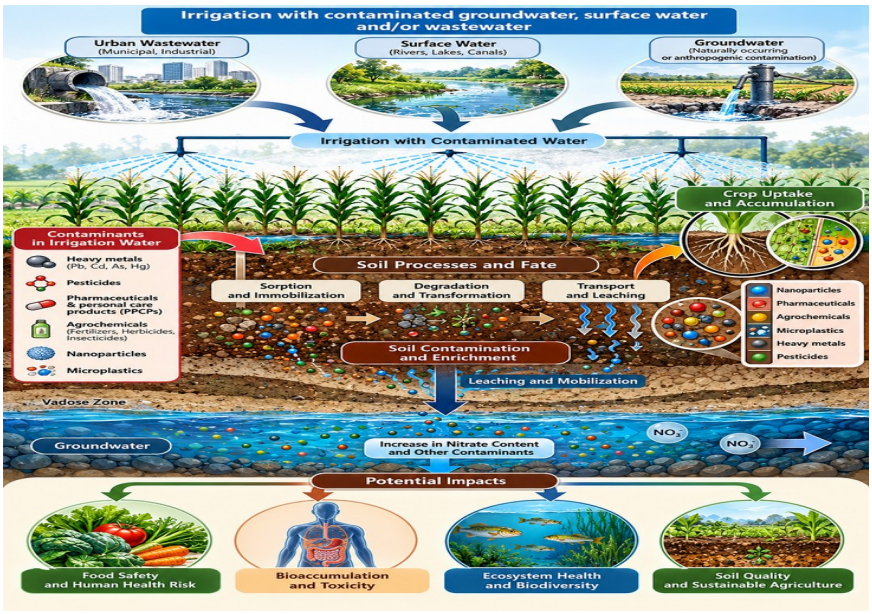


Figure 2. Conceptual representation of the effects of poor-quality irrigation water on soil properties, contaminant accumulation, crop uptake, and groundwater quality.

5. Challenges for Irrigation in India

5.1 Depletion of water table

Between 1991 and 2007, India made investments in public canal networks totaling around 4,000 million US dollars (Dhawan, 2017). However, because of outdated infrastructure, erratic water supplies, and a lack of incentives, the area under canal irrigation shrank by 38 lakh hectares during that time. This suggests that "our governments have not been able to reduce the groundwater depletion despite heavy public expenditure on canals." The primary cause is the growing discrepancy between the potential for irrigation that is generated and that is actually used. Punjab (79% of the land irrigated by tube-wells and wells), Uttar Pradesh (80%), and Uttarakhand (67%), are the states that rely on groundwater for irrigation the most. According to the Central Ground Water Board's (CGWB) 2013 estimate, India's net annual groundwater availability is 398 billion cubic meters (BCM), of which 253 BCM (approximately 64%) are extracted yearly. The country's total annual replenishable groundwater resource is around 433 BCM. The CGWB reports that the groundwater level is dropping in around 39% of the wells. Based on the stage of groundwater removal and the long-term fall in groundwater level, 1,034 of the 6,584 assessment units in the nation (in 15 states and 2 union territories) have been classified as "over exploited" (CGWB, 2017). Technology and policy-driven changes in Punjab's cropping pattern (towards paddy), irrigation source (towards groundwater), and energy source (towards electricity) have resulted in the degradation of groundwater resources (Srivastava et al., 2015). Punjab's agricultural development came at the expense of excessive groundwater use (Singh, 2004, Singh, 2012; Kulkarni and Shah, 2013). The groundwater level in Punjab dropped sharply from 8 meters in 1999 to 15 meters in 2014 due to an annual groundwater draw of 14.56 BCM beyond the sustainable limit (Srivastava et al., 2015; Srivastava et al., 2017). The groundwater table in Punjab is steadily declining as a result of unsustainable groundwater use, with 16 of the province's 22 districts having more than 100% groundwater development. It seems that one of the main reasons Punjab's groundwater table is declining is the 1997 implementation of a free electricity policy for irrigation.

5.2 Uneven rainfall distribution

In India, rain-fed fields make for about half of the net planted area. Thirty-one percent of cultivable land will continue to be rain-fed even after reaching maximum irrigation capability (Suresh et al., 2014). Even in years with sufficient rainfall, there has been a significant variation in rainfall across time and location, and there is a high danger of dry spells during crucial crop stages. Rainfall in India has varied significantly in both space and time. The majority of the rainfall happens from June to October, when the southwest monsoon season begins. It ranges from less than 100 mm in Rajasthan's west to over 2500 mm in the country's northeast (CWC, 2017). In 2013, floods, which are regarded as catastrophic natural disasters, caused damage to crops worth Rs. 3214.99 crore that were planted over 31.58 million hectares. In the same year, 21.13 million individuals were impacted, and the economy suffered a total loss of Rs. 11095.14 crore (CWC, 2015).

5.3 Poor irrigation efficiency

Poor irrigation efficiency is caused by inadequate off-farm and on-farm infrastructures as well as poor maintenance, such as unlined canals and farm channels. The measured average irrigation efficiency is 38%, which is much less than the intended efficiency. 70% is the average conveyance efficiency. As a result, there is room to minimize losses brought on by inadequate irrigation infrastructure, such as unlined canals and channels. Likewise, the efficiency of on-farm applications is just 50%. Watercourse lining was projected to minimize water loss by 22.5% (Arshad et al., 2009). Cracks, degraded mortar, and lined wall structural collapse are the most likely sources of water leaks. In many command areas, the canal water supply is insufficient and erratic owing to the lack of control buildings and regulating gates. Additionally, canal breaches often result in the relocation of thousands of people, the ruin of land and property, and damage to expensive crops valued at millions of Rupees. Furthermore, when breach failures take place during periods of high demand, they may potentially result in water shortages. Overtopping, internal erosion, structural flaws, and piping are some of the reasons why embankments collapse.

5.4 Huge and increasing gap between created and utilized irrigation potential

The potential that has been developed has not been fully used. By the conclusion of the Eleventh plan, 87.86 million hectares of irrigation potential had been used, compared to 113.53 million hectares of potential that had been developed, indicating a 25.67-million-hectare discrepancy (CWC, 2015). Delays in the development of on-farm projects such as field channel construction, land levelling or shaping, and the adoption of the warabandi system, as well as the time farmers take to transition from dry to irrigated farming, are the primary causes of this underutilization of created potential.

5.5 Frequent droughts and groundwater overuse

In India, the frequency of drought years has considerably risen. There have been five droughts in the previous 16 years (since 2000), compared to 10 drought years between 1950 and 1989. Meteorologists predict that the frequency will rise from 2020 to 2049. India's below-average agricultural yields are caused by water constraints brought on by the absence of monsoons. More than 60% of the country is affected by drought, with major drought-prone areas like Rajasthan (Western India), Andhra Pradesh (Southeastern India), Odisha (Eastern India), Telangana (Southeastern India), Southern and Eastern Maharashtra (Western India), and Northern Karnataka (South-Western India) being the most affected. During droughts, increased groundwater consumption may aid in overcoming these crucial times. But as a consequence of the misuse and degradation of groundwater quality, there is less groundwater accessible for agriculture than before, which puts further strain on agricultural output. Water supply is an issue in Gujarat, a semiarid northern region in Western India that is one of the most heavily irrigated areas of the country. This is because over 90% of the farms' total income comes from groundwater irrigation. It is important to note that in some Latur tehsils, not even 304 meters below the surface, there is water. The water table in Latur dropped by 3.5 to 4.0 meters in only one year (2015–16).

6. Water Management Options

As the agriculture sector alone consumes about 80% of the total withdrawal of water, so its management becomes pivotal for food security. Supply-side management practices include watershed development and water resource development through major, medium and minor irrigation projects; and development of drainage system to avoid salinity and water logging problems. Demand management practices include enhancement of water use efficiency, optimal crop plans and balancing virtual water trade. This section presents some water management practices below.

6.1 Infrastructural development for adequate and regular water supply

In several commands, the canal water supply is insufficient and erratic. Conjunctive water use must be promoted in order to address this. In addition, the construction of suitable infrastructure is necessary to augment groundwater and canal water.

6.2 Drainage for water logging and salinity in major irrigation commands

The problem of water logging and salinity requires conjunctive water use with emphasis on groundwater pumping to dewater the aquifer. Further, drainage system should be put in place using suitable horizontal pipe drainage, vertical pipe drainage and optimally designed multiple well point drainage system.

6.3 Improving irrigation efficiency

Due to significant seepage loss, unfair distribution, and delayed supply, conventional irrigation techniques have poor irrigation efficiency. An important factor in increasing water-use efficiency is micro-irrigation. Irrigation efficiency is increased when sprinkler and drip irrigation are used where appropriate. Irrigation efficiency may be raised by more canal automation, volumetric supply measurement, irrigation system benchmarking, water audit/budgeting, and suitable water price. A significant amount of water is lost as a consequence of the nation's flood irrigation system. By properly constructing the irrigation system to minimize water conveyance loss, greater irrigation efficiency was attained. Adoption of water-saving technology, such drip and sprinkler irrigation systems, has been shown to be very successful in increasing yields while simultaneously conserving water. According to a comparison of different irrigation techniques, drip irrigation has the greatest application efficiency of 90%, with an overall efficiency range of 80% to 90%. Water efficiency may also be increased with the use of new agronomic techniques as precision farming, subsurface irrigation, ridge-furrow sowing, and raised bed planting. Increasing irrigation efficiency is also aided by water cost. De-subsidizing will aid in lowering irrigation and conserving groundwater in Punjab, India, where groundwater is overused as a result of free power for irrigation.

6.4 Smart Irrigation Systems

Through the integration of new technologies, countries are working to improve agricultural efficiency. Enhancing irrigation efficiency is essential for sustainable agricultural production. Smart irrigation approaches can improve irrigation efficiency through wireless communication technologies, monitoring devices, and improved control strategies for irrigation scheduling.

With the widespread adoption of Internet of Things (IoT) technology in agriculture, supported by advances in digital technology and embedded sensors, agricultural sensors are becoming increasingly intelligent, integrated, and compact. Agricultural sensors include soil, weather, crop, and water sensors. These multi-sensing devices provide important support for collecting data relevant to agricultural productivity. Studies have examined the applications of smart sensors, Wireless Sensor Networks (WSNs), and the IoT in agriculture (Hamami & Nassereddine, 2020; Lakhwani et al., 2019; Velmurugan et al., 2020; Yang et al., 2021). Other reviews have investigated ways to improve agricultural water productivity and water-use efficiency (Farooq et al., 2019; Harmanny & Malek, 2019; Koech & Langat, 2018; Ullah et al., 2019; Yu et al., 2021).

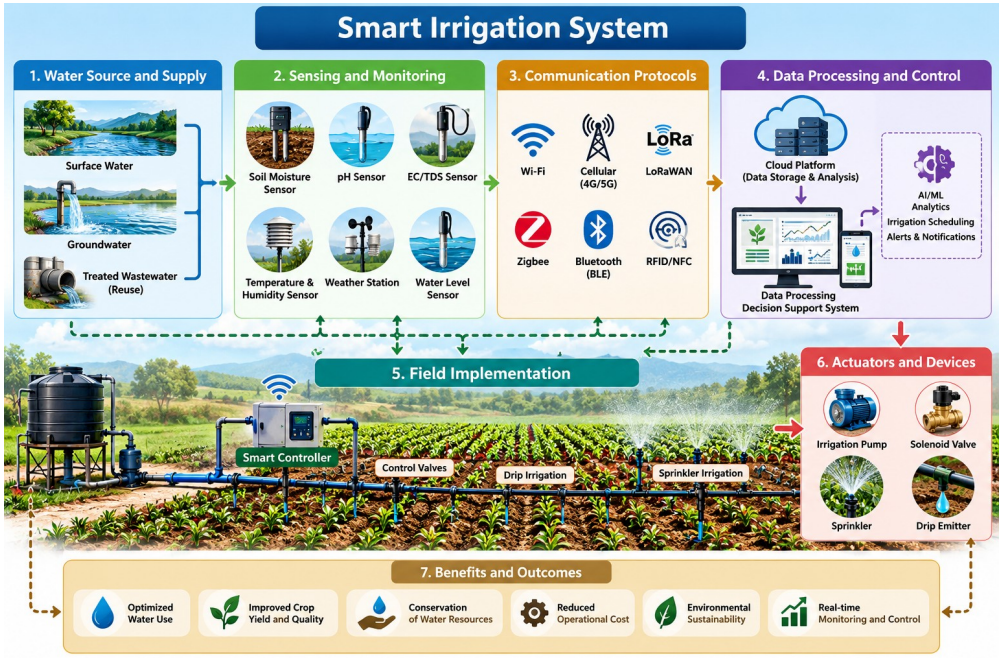


Figure 3: Conceptual framework of a smart irrigation system integrating water sources, sensor-based monitoring, wireless communication, data-driven decision support, and automated irrigation control for efficient and sustainable water management.

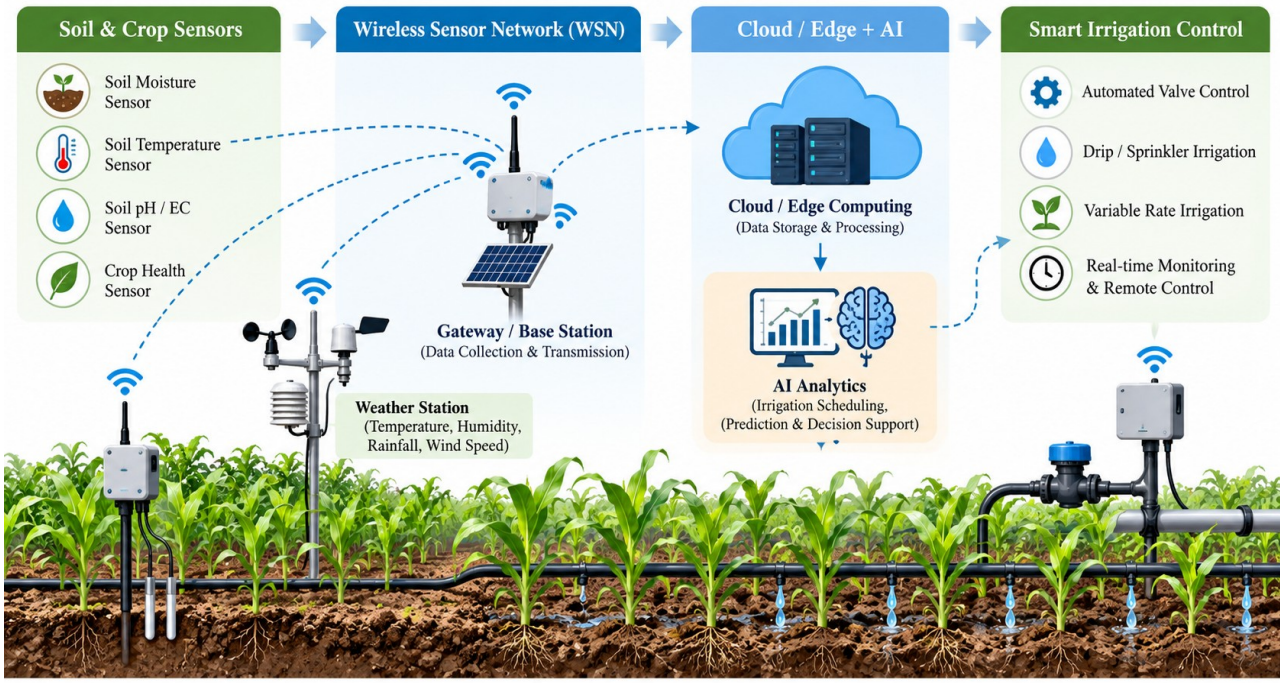


Figure 4: Monitoring techniques in smart irrigation, illustrating soil, weather, crop, and water monitoring; wireless data acquisition and communication; cloud/edge computing; AI-based analytics; and real-time decision support for efficient irrigation management.

7. Smart Irrigation System Monitoring

To improve water-use efficiency, factors affecting plant growth and development need to be monitored. Contextual monitoring in intelligent irrigation systems requires the collection of real-time data on soil conditions, plant health, and climatic variables in cultivated areas using advanced communication technologies (Abioye et al., 2020).

Cloud computing, edge computing, artificial intelligence (AI), and the Internet of Things are important for improving irrigation efficiency and agricultural productivity. Technologies such as IoT-based crop and soil monitoring, AI-based data analysis for decision-making, automated irrigation systems, and weather measurement and forecasting can support crop management, help identify plant diseases and insect-related problems, and reduce farmers' reliance on manual labor. Sensors and IoT devices can be used to monitor agricultural fields. Edge computing enables field data to be collected and processed, while cloud-based systems can support further analysis and decision-making. This can help optimize the use of water, fertilisers, and pesticides while supporting crop productivity (Angelis et al., 2022). Wireless Sensor Networks (WSNs) have advanced significantly and are widely used in agriculture. Their application to irrigation monitoring and control can support more rational and efficient water use (Singh & Sharma, 2022). Smart irrigation monitoring also depends on suitable methods for measuring soil moisture. Reviews have assessed different soil-moisture estimation techniques (Sharma et al., 2018), while studies have discussed oven-drying methods for determining water content in peaty soils (Li et al., 2018) and the use of dielectric soil sensors for irrigation automation (Vera et al., 2021).

8. Government Initiatives on Irrigation Management

8.1 Water management organizations

Water management institutions such as the Central Ground Water Board (CGWB) for groundwater resource management and the Central Water Commission (CWC) for integrated and sustainable development were founded. "General Guidelines for Water Audit and Water Conservation" have been developed by CWC and CGWB. All state governments, relevant central ministries, and other utilities have received these recommendations in order to formulate their own unique rules. Some state governments, including those in Punjab, Gujarat, and Maharashtra, are providing subsidies for irrigation-related expenses in accordance with these criteria.

8.2 Subsidy to improve efficiency of irrigation system

The government has concentrated on improving irrigation efficiency in order to lessen water shortages and irrigation water demand. Both the federal and state governments are offering substantial incentives to boost the uptake of effective irrigation techniques like micro-irrigation in an effort to improve water-use efficiency. These include the districts of Karnataka's South and North Interior (Southern India); Andhra Pradesh's Rayalseema (Southern India's coast); Maharashtra's Vidarbha and Marathwada; western Uttar Pradesh, Rajasthan, and the Bundelkhand region (Northern India); and Madhya Pradesh (Central India).

8.3 Various schemes launched by central government led emergence of micro-irrigation

In 1992, 2006 (Centrally Sponsored Scheme on Micro Irrigation), 2010, (Nation Mission on Micro Irrigation), and 2014 (National Mission for Sustainable Agriculture), the Central Government placed a strong emphasis on micro-irrigation since it understood its relevance. In 2015, the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) was introduced, using micro-irrigation as a crucial element and encompassing all irrigation programs. Watershed development and the construction of infrastructure to provide water to crops are included in this program. The government launched all of these programs and initiatives with the explicit goal of increasing water production and efficiency by growing more crops per drop of water. Nevertheless, in regions that are consistently water-stressed and where previous interventions have failed, a specific solution is still needed. Present policy thinkers and planners would be better able to improve governance structures and comprehend important indicators that may support data-driven decision-making if they have a thorough understanding of both international best practices and India's unique community-based interventions models.

9. Impact of Government Initiatives on Micro-Irrigation

9.1 Status of micro-irrigation in India

Table 3 reports state-wise cumulative coverage under the Per Drop More Crop (PDMC) programme for 2015–16 to 2023–24. The reported total is 8,345,840 hectares (approximately 8.35 million hectares). These programme-specific figures describe coverage during the stated reporting period and should not be interpreted as the total national stock of micro-irrigation installations. They highlight the uneven distribution of adoption and the continuing need for locally appropriate technical and institutional support.

Table 3: State-wise area covered under Micro Irrigation through PDMC from 2015-16 to 2023-24 (till date) and percentage.

S. No.	State/UT	Area covered under Micro Irrigation in hectare [2015-16 to 2023-24]	% to total coverage in the Country[2015-16 to 2023-24]
1	Andhra Pradesh	919780	11.02
2	Bihar	28258	0.34
3	Chhattisgarh	148146	1.78
4	Goa	875	0.01
5	Gujarat	1087039	13.02
6	Haryana	168336	2.02
7	Himachal Pra.	12235	0.15
8	Jharkhand	34675	0.42
9	Jammu & Kashmir	1104	0.01
10	Karnataka	1801629	21.59
11	Kerala	5608	0.07
12	Madhya Pradesh	356091	4.27
13	Maharashtra	938089	11.24
14	Odisha	95475	1.14
15	Punjab	15173	0.18
16	Rajasthan	708193	8.49
17	Tamil Nadu	1097910	13.16
18	Telangana	326338	3.91

S. No.	State/UT	Area covered under Micro Irrigation in hectare [2015-16 to 2023-24]	% to total coverage in the Country[2015-16 to 2023-24]
19	Uttarakhand	32257	0.39
20	Uttar Pradesh	355116	4.26
21	West Bengal	95964	1.15
22	Arunachal Pradesh	12442	0.15
23	Assam	44356	0.53
24	Manipur	15894	0.19
25	Mizoram	8559	0.1
26	Nagaland	19180	0.23
27	Sikkim	12971	0.16
28	Tripura	4145	0.05
29	Ladakh	3	0.000036
	Total	**8345840**	

Source: Ministry of Agriculture & Farmers Welfare Note: The state entries sum to 8,345,841 ha, which is 1 ha above the reported total of 8,345,840 ha; the supplied source figures are retained.

10. Conclusion

Groundwater is now the main source of irrigation in India. However, there is a significant discrepancy between the actual and exploited surface water potential. It is now essential to transition to effective water-saving technology and alternate irrigation sources, such as canal water and rainwater collecting, due to the ongoing reduction in per capita water supply and groundwater extraction. Frequent droughts, poor irrigation efficiency, and rapid water table depletion all point to an impending water catastrophe if the current pattern of water use is not changed. In order to use runoff water, irrigation infrastructure must be significantly enhanced to collect rainfall and expand storage capacity. Well-designed drip irrigation systems can achieve application efficiencies approaching 90%, depending on site conditions and management. Furthermore, the nation's food security and water resource conservation will be greatly aided by micro-irrigation and an ideal crop plan. The commerce in virtual water should be balanced rather than focused on exports. It is important to inform farmers about the several government programs that might help them reach their full potential, which isn't always the case in certain areas.

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