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Declining Groundwater Levels in India: Causes and Solutions

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Abstract

India is the world's largest groundwater user, and rapid declines in water tables now threaten food security, urban supply, and ecosystem health. Drawing on national monitoring and recent scholarship, this paper synthesizes the drivers, spatial patterns, and consequences of falling groundwater levels, and reviews technical and policy responses. Overextraction for irrigation—enabled by cheap energy, tubewell proliferation, and water-intensive cropping—remains the dominant pressure, while accelerating urbanization, industrial demand, and contamination (fluoride, arsenic, nitrates) compound risks to public health. Climate variability alters recharge timing and reliability, increasing dependence on pumping. The problem is geographically uneven: severe depletion characterizes large tracts of the north, west, and peninsular hard-rock regions; parts of the east and northeast remain comparatively buffered but face quality hot spots and emerging stress. Socioeconomic impacts include rising pumping costs, borewell failure, livelihood losses, and deterioration of drinking-water safety. A portfolio of solutions is assessed: demand management (crop diversification, micro-irrigation, laser land leveling, energy pricing reform), supply augmentation (rainwater harvesting, managed aquifer recharge), and institutional innovations (monitoring networks, well licensing, community groundwater budgeting, conjunctive use with canals, and wastewater recycling). Evidence from policy shifts in select states suggests that targeted regulation and incentives can stabilize storage seasonally, but durable recovery requires aligning farmer incentives with hydrologic limits, strengthening data transparency, and mainstreaming recharge and reuse in urban design. The paper outlines region-specific pathways to slow, halt, and reverse decline while protecting equity and food systems.

Keywords: Groundwater depletion; India; Irrigation demand; Urbanization; Climate change; Water governance; Managed aquifer recharge.

Introduction

Groundwater, found in aquifers and extracted through wells and tube wells, is an important source of water for irrigation, industries and drinking purposes in India. The development of groundwater in the country has been described as a 'hydraulic revolution'. Of late, there has been considerable media and academic interest in the rapid depletion of groundwater in India. Rapid decline in groundwater level and deterioration in quality is being noticed in many parts of the country. The effects of depleting groundwater resources are evident in parts of both the rural and urban settings. Depleting groundwater levels in India are well-documented. It is predominantly used for irrigation, drinking, and other purposes. India is the largest user of groundwater in the world. It accounts for 25 per cent of the total groundwater extracted globally. The rapid growth of irrigation using groundwater resources over the last three decades constitutes what has been termed as an agricultural groundwater boom. This boom in turn has been one of the major factors in achieving self-sufficiency in the production of food grains in India. One of the major factors responsible for the boom was the Government's push for the intensification and expansion of food-grain production through planned irrigation development and food-grain price-support policies. However, the boom has resulted in high levels of groundwater development in a number of States, leading to rapid declines in the groundwater levels.

Overview of Groundwater in India

Groundwater constitutes the largest source of fresh water on the Indian subcontinent, providing 50–80% of the total fresh water used for irrigation and drinking purposes. India's dependence on groundwater for irrigation, municipal, and industrial purposes has continued to rise over the last 50 years, increasing from an annual abstraction of approximately 5 km3 in 1950, to 230 km3 in 2010. India is experiencing intensive depletion of its groundwater resources in many parts of the country, often in places where the demand for groundwater is significantly apprehended. Over half the groundwater extraction in the country is for irrigation, making agriculture the single largest groundwater consumer in the country. The heavy dependence on groundwater for irrigation and domestic purposes has led to an alarming decline of the resource in many places of the country coupled with the deteriorating quality of groundwater in several parts of India. Overall, groundwater levels in the country have continuously declined at an alarming rate under human interventions since the 1980s. The consequences of the declining groundwater levels (GWL) in the country have a significant regional diversity mainly because of differential hydrogeology, climate, and water use scenarios besides other socio-environmental factors. It is, therefore, essential to prepare regional groundwater scenarios from the overall national trend that can then provide guidelines for region-specific groundwater management solutions to contain and reverse the trend. Not all Indian states are projected to experience groundwater depletion. When comparing the total projected groundwater recharge and withdrawal rate with the status of current groundwater levels, the northern, western, and part of southern India are likely to face severe groundwater depletion in the coming decades; the eastern and north-eastern India are less likely to experience groundwater depletion.

Historical Context of Groundwater Use

India is the largest user of groundwater in the world (roughly 250 billion m3/year). The quantity of groundwater extraction started increasing gradually in the 1970s and suddenly jumped in the 1990s. Supply of electricity for agriculture at subsidized rates is one of the major reasons for overexploitation. An evaluation of the number of farmers benefiting from subsidized power and the number of wells drilled has shown a strong association with a decline in water-level trend since the early 1990s. The distribution of electricity connections largely follows a similar spatial pattern when compared with the status of groundwater levels. As a key water resource fed by monsoons, groundwater remains the main agricultural water supply in many parts of India. Because groundwater is easier to access than surface water and irrigation infrastructure, it is often the first source farmers turn to for crop irrigation. Access to groundwater allows cultivators to avoid fluctuations in precipitation and reduces the need for surface irrigation infrastructure. The result is that agricultural activity and crop choice often depend on groundwater availability and the economics of groundwater use. Groundwater storage capacity and dependence on groundwater irrigation vary widely across the country as a result of different geological conditions and irrigation infrastructure. Farmers in northern and eastern India rely relatively little on groundwater for irrigation because there is more canal infrastructure and aquifers with high storage capacities. By contrast, farmers in western and southern regions characterize a distinct, and far more vulnerable, group that depends heavily on groundwater—especially in semi-arid and arid regions—where alluvial aquifers are relatively thin and water levels fluctuate significantly within a season.

Current Status of Groundwater Levels

With the critical role of groundwater and its extraction in general understood, the current condition of groundwater across India is discussed before a more detailed examination of its major causes. Data circulated by Central Groundwater Board, Ministry of Water Resources for 2003–04 to 2007–08 shows an increase in the number of groundwater level monitoring stations reporting decline from 40% to 61%, with statewide 68% of locations reporting a falling trend. Analysis of measurements from 11,000 bore wells indicates a net drop of close to two meters in groundwater levels at an average annual rate of roughly 0.5 meters. Seasonal groundwater levels also reflect decreasing storage—for instance, just 7% of shallow wells near Patiala show a rising trend in pre-monsoonal levels. Overall 22% of pre-monsoon shallow wells exhibit deleterious long-term decline of at least 0.5 meters per year, especially in Andhra Pradesh, Gujarat, Haryana, Karnataka, and Punjab. The situation worsens if wells deeper than 50 meters are included. Recharging at the rate of 150 cubic kilometers per annum, India is still losing third of groundwater every year. Following 'launches of major governmental groundwater schemes' in the 1980s, the national annual rate of groundwater level decline escalated to 0.5 meters and reached a decadal decline of 3.4 meters in places such as western Uttar Pradesh and parts of Rajasthan. The official estimate of net groundwater availability for the entire country in 2004 was 432 cubic kilometers per year with 58% being used. These trends challenge the national goal of addressing the country's food security through enhanced harvests and rural development, fueled by the very energy supplied in the hope of easing access to water.

Factors Contributing to Decline

The decline of groundwater levels across India is attributable to several interacting factors. Chief among these is overextraction, particularly for irrigation and drinking water supplies. The last century saw a rapid growth in groundwater extraction, propelled by tubewells and open wells. Cultivation of water-intensive crops such as rice, wheat, and sugarcane exacerbated the problem. Additionally, depletion intensified during the droughts of the 1960s and 1970s when canal water supplies dried up. Currently, most of the ~700 districts classified as overexploited or groundwater-stressed are located in the northern, southern, and western states. These regions also rank high in poverty levels, while the poorest districts are scattered throughout the country. Climate-change-induced shifts in rainfall distribution and frequency have further increased the need for groundwater extraction, contributing to the rapid depletion of resource stocks.

(i) Overextraction of Water

Excessive groundwater extraction is the most important contributor to recent groundwater level declines. National supplies continue to drop despite prohibitively high energy and equipment costs because limited surface-water irrigation maintains the demand while governmental subsidies keep pumping prices artificially low. Present models that integrate subsurface percolation and surface discharge indicate that a quarter of the annual amount of national groundwater reserves are extracted at this rate and a third of pumping is associated with crop production. Irrigation is integral to national stability because nearly 90% of water-derived consumption and 79% of the agricultural production depends on groundwater supplies that have become abundant and affordable as population density increased over the last century. Continued high demand is consistent with expected trends in population and consumption, and is likely to exacerbate current watershed resilience and natural recharge rates if left unchecked. Hence groundwater systems already experience a reduced capacity to accommodate stress including subcontinental droughts during major climate oscillations and human influence on precipitation patterns.

(ii) Agricultural Practices

Agricultural practices are a key factor in the decline of groundwater levels in India. Overextraction of groundwater for irrigation accounts for around 90% of total groundwater extraction in the country. Improved well-digging technology and subsidised electricity to farmers also contribute to overexploitation. Policies such as unrestricted pumping and subsidies for power and pumps result in inefficient water use and a shift to more intensive crops unsuited to water-scarce areas. Growing crops with high water requirements—such as rice in Punjab—further depletes groundwater. For instance, the extent of rice cultivation in Punjab expanded from 10% in 1975 to 38% in 2010, driving a 3.5-fold increase in groundwater withdrawal. Regulatory measures therefore need to reduce subsidies, encourage better irrigation practices, and promote crop choices that require less water.

(iii) Urbanization and Industrialization

Urbanization and industrialization have significantly affected the sustainability of groundwater abstraction, resulting in falling groundwater levels and quality. With a substantial rural-to-urban migration, cities have grown rapidly; for example, the population of Delhi has increased by approximately 2.2% per year since 1981. This rise has led to the proliferation of informal settlements, increased demand for drinking water, and increased sanitation and electricity requirements. Consequently, groundwater has been over-extracted to meet these growing urban demands.

(iv) Climate Change Impacts

Climate change has a significant impact on groundwater systems, which are highly sensitive to climate variability and long-term shifts in temperature and precipitation patterns. Alterations in the timing, intensity, and type of precipitation (e.g., rain versus snow) affect the volume of groundwater recharge, potentially creating serious challenges for the availability of groundwater supplies in the near future. These changes may make it infeasible to meet sustainable withdrawal targets in many countries. India's dependence on monsoon rain makes its water supplies especially vulnerable to climate-induced shifts in precipitation. Higher temperatures are likely to increase demand for water withdrawals across many economic sectors, including agriculture, which accounts for a large share of groundwater withdrawals. This consequence of climate change could intensify groundwater declines over time. Compared to precipitation, temperature changes do not seem to have a discernible effect on recharge in any of India's aquifer systems, or on groundwater levels.

(v) Pollution and Contamination

Groundwater contamination is a global phenomenon jeopardizing human health and groundwater-dependent ecosystems. Sustained flow of contaminants—heavy metals (As, Sb, Cr, Fe, Pb), hydrocarbons, and emerging substances such as pesticides, nanoparticles, and microplastics—threatens groundwater safety, ecosystem services, and sustainable development. Urbanization, agriculture, industrialization, and climate change present significant challenges to groundwater quality, especially in arid and semiarid environments where one-third of the global population depends on groundwater for drinking. Diverse studies analyse contamination sources across extensive geographies and explore remedial technologies. Past decades have focused on chemical contamination, underscoring the importance of correlating climatic and tectonic influences on aquifer evolution and enhancing regional protection strategies. Groundwater possesses inherent advantages over other water sources: reliable supply, consistent quality, minimal evaporation losses, and relatively low development costs. Consequently, increased demand has precipitated over-exploitation and pollution, inflicting substantial socioeconomic costs on low-income populations. India's rapid population growth, urbanization, and industrialization have rendered its groundwater bodies highly vulnerable to depletion and degradation. Sustainable management hinges on comprehension of availability and quality; yet, abstraction frequently proceeds without fundamental knowledge of aquifer dynamics, rendering long-term sustainability uncertain. In India, groundwater stands as the principal drinking water source for 85 per cent of rural and 50 per cent of urban inhabitants and constitutes the dominant irrigation source. Untapped groundwater potential approximates 10 times the annual precipitation, with an exploitable capacity estimated at approximately 45 million hectare-meters. The number of tube-wells increased dramatically from about 300,000 in 1960 to 19 million in 2001, elevating concerns over declining water-table levels and the relative neglect of recharge considerations. Data on water levels and recharge rates remain unreliable and scarcely accessible to the broader scientific community.

Regional Variations in Groundwater Decline

Groundwater levels are declining most rapidly under large patches in the north, west, and south of India. In the northern states, the major groundwater concerns are related to overexploitation and pollution. Because the northern states experience water scarcity, coupled with an increasing population, particularly in the Indo-Gangetic plains, groundwater use has been increasing extensively. Without doubt, this continuous and heavy groundwater mining will lead to depletion and degradation of groundwater resources in the near future. Significant groundwater depletion and degradation have been observed in many major cities and areas, such as New Delhi, Indore, Meerut, Agra, Mussoorie, Ludhiana, and Fatehabad.

In the southern states, groundwater concerns mainly include overexploitation and pollution. Because the southern areas mostly consist of hard rock formations with limited groundwater recharge, even a small increase in groundwater use can severely affect the quality and availability of groundwater. Groundwater is used extensively to meet the requirements of agricultural, industrial, and domestic water, which worsens the situation in most parts of the region. The highest rate of groundwater depletion in western India has been observed in the states of Maharashtra and Gujarat, where overexploitation is the main challenge. Compared to the northern and southern states, groundwater depletion in the western region is more focused in specific areas, such as Saurashtra and Kutch (Gujarat) and Marathwada and Vidarbha (Maharashtra). Increased agricultural groundwater abstraction and a decreasing monsoon rainfall trend have led to severe groundwater depletion in parts of western India.

In the eastern states, the primary groundwater concern is pollution, although overexploitation has become problematic in some places. The eastern region receives abundant rainfall, and there are major rivers, such as the Ganga, Brahmaputra, Mahanadi, and Godavari. Groundwater is not highly developed because of surface water abundance. Both groundwater quantity and quality are high and suitable for human use. Some parts of West Bengal have experienced a decrease in groundwater availability mainly due to an increase in use of groundwater for agricultural purposes. Pesticide and fertilizer pollution have severely impacted groundwater quality in Hooghly and Bardhaman. In specific cases, arsenic contamination in the deltaic tract and Sunderban areas has caused a significant decrease in groundwater quality and availability.

(i) Northern India

India (1.3 billion inhabitants) is the largest groundwater user in the world, abstracting about 250 billion m3, 25% of total global annual value, through about 30 million tubewells. Nearly 60% of irrigated area depends on groundwater, but since the 1990s abstraction has been consistently higher than annual replenishment, leading to over-exploitation of the resource. The northern states, largely dependent on canal and groundwater irrigation, account for over 40% of the developed irrigated area of the country, yet the groundwater table is dropping by 1.0 m per year. Nearly 60% of groundwater-quality problems occur in northern India. The unsustainable rate of groundwater-tubewell irrigation has given impressive agricultural and economic growth, but has far-reaching socio-environmental problems and is fundamentally unsustainable.

(ii) Southern India

Southern India accounts for more than half of India’s irrigated area, with Karnataka, Andhra Pradesh and Tamil Nadu bearing the heaviest extraction burden. The coastal stretch of Tamil Nadu registers the lowest groundwater recharge value of India and is among those areas in the country where groundwater storage has been substantially depleted in recent decades. Andhra Pradesh, however, boasts of some artificial groundwater recharge regions although depletion levels appear to be on the rise. The coastal zone of the rest of the Southern peninsula — Kerala, parts of Andhra Pradesh, coastal Tamil Nadu — predominantly exhibits high groundwater storage in the post-monsoon season. Nevertheless, depletion zones in post-monsoon far exceed recharge pockets. Most of India’s hard-rock terrain is found in the Southern peninsular region; this area has less groundwater availability than the alluvial sites favoured by spatial averaging of GRACE data. Apart from the unavailability of data, hydrogeological factors explain the disparate groundwater-depletion pattern observed between the peninsular and the northern states. Recharge is rendered difficult because rainwater runs off rapidly through the hard-rock landscape. Aquifers barely have any lateral extensions sufficient for transmission of water away from the recharge zone, which means that none of the rainfall that makes it into the subsurface actually contributes towards replenishing remote areas and the decline is mainly due to the natural outflow of the system. Water available close to the surface is used for irrigation until the water level drops below the access limit of borewells. The situation depletes more readily under the prosperous Southern States where subsidized electricity once again intensifies pumping.

(iii) Western India

Groundwater depletion in western India is primarily concentrated in Gujarat and Rajasthan. With a 60% annual withdrawals-to-availability ratio, the groundwater situation here is alarming. In Rajasthan, the regions of western Mewar, Bundi, Kota, Tonk, northern Shekhawati, and southeastern Marwar are rapidly becoming groundwater deserts, with levels falling by over 1,000 mm annually while recharge ranges between 200 and 500 mm. In Gujarat, the Kachchh-Baroda zone experiences more than 1,200 mm of annual depletion against less than 500 mm of recharge. Block-wise data from 2011–2013 indicate that about 71% of the blocks are overexploited. Groundwater decline in western India also correlates with increased failure rates of borewells, including a 31.7% failure rate in Mahisagar district, Gujarat. Declining groundwater levels have led to significant livelihood and employment losses; for instance, in Tonk, Rajasthan, an estimated 93,000 man-days of rural employment were lost due to lack of access to groundwater-based irrigation in 2013. Compared to the north, the groundwater situation also severely impacts the south-western and north-western sectors of eastern India. Here, the typical pre-monsoon water table depth ranges between 4 and 8 m below ground level, but it is gradually falling at an estimated rate of 0.1 to 0.3 m a"1. Areas with extensive groundwater development are more prone to depletion of piezometric heads.

(iv) Eastern India

Eastern India has received considerable summer rainfall but this has not been sufficient to recharge a heavily exploited resource. From 1996 to 2014, groundwater levels declined at 7.9 b1 2.5 cm/yr in West Bengal, b7.8 b1 0.5 cm/yr in Chhattisgarh, b710.3 b1 3.7 cm/yr in Odisha, and b78.2 b1 0.7 cm/yr in Jharkhand. In these states, larger water withdrawals than recharge since 2000 have caused rapid groundwater depletion and induced nationwide stress. For example, groundwater levels declined in West Bengal at b713.2 b1 1.3 cm/yr from 2003 to 2013. Timely interventions are required because future demands in these states are projected to increase by 25 634% until 2050. On the other hand, Assam has observed rising groundwater levels at +10.4 b1 2.7 cm/yr, suggesting a less stressed resource.

Technological Solutions

Annually India receives ~4000 billion m3 of precipitation; surface flow is ~1869 billion m3, groundwater availability 432 billion m3. Groundwater is delivered in large quantities with great quality and low cost, making it an indispensable source for irrigation, drinking water and industry—a major factor responsible for the green revolution. Since 1970 water millions of groundwater structures have been drilled. In the last 25–30 years groundwater tables are on decline in almost all over the country. Forty-two percent of India's blocks/ mandals/ talukas are over-exploited, which contains 200 million populations. Tamil Nadu stands with 14% of blocks/mandals /talukas in over-exploited category. The detailed analysis of groundwater table decline, water balance system, climate change and precaution measures have been investigated and described elsewhere. An addition to existing solutions such as groundwater regulations and artificial recharge is a scientific, targeted cropping pattern that equilibrates the water balance, stabilizes groundwater levels and optimizes water use. East and South India have very good groundwater potential, but groundwater table is declining comparatively faster than India's average. At Chengalpattu, Tamil Nadu, annual rainfall is 1200 mm during the past 35 years, and groundwater table is declining at 150 cm every year, which means maximum 1800 mm groundwater has already lost. Artificial Rainwater harvesting and Recharge Calibres (AHRC) structures are the only solutions available to reduce this alarming trend of decline.

(i) Rainwater Harvesting

Augmentation of groundwater resource is possible through rainwater harvesting and artificial recharge, including recharging surface runoff. Structures such as percolation tanks, check dams, Nala bunds, and gully plugs are appropriate for this purpose. Roof-top rainwater harvesting can augment groundwater storage, with water stored in dedicated tanks. Regulation of groundwater development is necessary to ensure sustainable management, particularly in critical areas. The expansion of technologies facilitating extensive groundwater extraction, the variable nature of the resource, demographic growth, and lack of infrastructure, manpower, and awareness render attempts to restrict exploitation challenging. Effective legislation, such as the Gujarat groundwater management Act, requires broad support. Maintaining water supplies for agriculture involves non-exploitative withdrawal by sensitive crops or alternative sources where resources are stressed. Strategies include encouraging shift of non-sensitive users to lower-quality aquifers, limiting withdrawal rights for water-inefficient industries, and offering subsidies to improve irrigation efficiency in peri-urban areas.

(ii) Water Recycling and Reuse

Water recycling and reuse–particularly large-scale treatment and industrial recycling–offer the potential to reduce reliance on freshwater and groundwater allocations while decreasing the volume of wastewater requiring disposal. High water consumption and resultant groundwater depletion, especially in arid and semi-arid areas where water is scarce and rainfall unreliable, present significant challenges. Pollution of groundwater due to waste disposal into surface water bodies or direct discharge into sinkholes or wells is another pressing concern. Rainwater harvesting, combined with more efficient recycling and reuse of wastewater, presents an important avenue toward addressing water shortages in many water-scarce regions. Consumption patterns can be modified through efficiency improvements, behavioral changes, and changes in water use. Public outreach efforts aimed at raising awareness among individual homeowners, private businesses, governmental water management agencies, developers, and design professionals can effectively foster sustainable water management and conservation practices.

(iii) Innovative Irrigation Techniques

Innovative irrigation techniques have attracted attention as a means of reducing groundwater extraction without reducing agricultural productivity. Groundwater depletion in India remains an important environmental concern. Poor crop choices and inefficient irrigation technologies have exacerbated this problem in recent decades, particularly in northern and western India despite high levels of precipitation. Groundwater withdrawal has increased to meet the demand for irrigated rice cultivation in areas where surface water is unavailable or unreliable. Extended drought conditions throughout the 2000s also increased farmersˆ dependence on groundwater, resulting in marked declines in water table levels and depletion of major aquifers at a sub-annual scale.

Improvements in water use efficiency across irrigation and crop production systems can contribute to addressing groundwater stress; appropriate crop choices further reduce overexploitation. Scenario analyses reveal that a combination of technological interventions and suitable crop choices can substantially lower unsustainable groundwater extraction from both irrigated agriculture and domestic sectors, even as population growth and changing consumption patterns increase overall demand.

Rapid shifts in groundwater use have outpaced the development of robust legal and institutional frameworks governing resource allocation. In many less-favoured dryland areas, water scarcity and vulnerability to drought incentivise small-scale investments in groundwater abstraction. Water rights remain linked to land ownership, rendering aquifers de facto open-access resources. The absence of formal mechanisms to regulate drilling, abstraction, and allocation has led to unchecked overexploitation in numerous rural communities. Under water-pricing regimes permitting free abstraction, practices with irrigation intensities incompatible with local water availability prevail, resulting in rebound effects that exacerbate depletion.

Future Prospects and Strategies

Future prospects for groundwater management in India are intimately entwined with the way the problem is framed today. Trends as on date indicate that time is running out for a large proportion of India's population that depends on groundwater. Yet the process of declining groundwater levels is multi-dimensional, with stark regional contrasts. In schemes to deal with declining groundwater levels, it is therefore necessary to both take account of the regional dimensions and examine the deeper systemic issues underlying groundwater depletion at the national level.

Consider the northern, southern and western regions first. The causes are different in these areas, and therefore different measures will be necessary. While over-exploitation has played a major role in the northwest and southern states, little over-exploitation is observed in parts of the eastern region. The decline here is mainly a result of changing natural conditions: rainfall variability and climate change. Overexploitation, on the other hand, is on such a massive scale in the northwest that projected climate scenarios would make even total groundwater regulation insufficient to reverse the decline. In the eastern parts of the country where water-logging and water salinity are increasingly becoming a problem, the prospects of groundwater are bleak and different types of interventions will be needed. The extent to which the discussions in these lines of action reflect the government's focus on reversing unreplenishable groundwater depletion, on conservation and efficient use of water, or on ensuring distributional equity remains to be seen. Sustainable groundwater management requires the determination of appropriate withdrawal limits in the context of social equity. In spite of the recognition of the overexploitation problem and the introduction of policies and regulations, unsustainable groundwater abstraction continues throughout most of India.

The following policy recommendations arise from a large base of research focused on water management in India. Two pressing challenges hamper open-access groundwater management: incentive misalignment, where benefits of conservation are public but costs are private; and sketchy regulatory enforcement. These characteristics induce inefficient water use and waste, contributing to a 15–20% rate of groundwater depletion. Although diffuse, incomplete data complicate analysis, 200 meters (approx. 660 feet) serves as a rough threshold between manageable and critically depleted wells. High spatial and temporal variability creates complex trajectories; some locations manage depletion successfully, others see accelerating decline. Overextraction has increased irrigation demand and induced pollution.

The Gujarat government has allocated US$200,000 for pilot well-monitoring schemes, servicing approximately 1,000 wells and providing approximately 50 digital readers. Regulators plan to use monitoring well data to assess efficacy of stricter enforcement methods, including depending on bypass meters and undertaking audits. Groundwater use remains highly subsidized, and shallower wells fare better economically due to substantially lower drilling costs. Electrical subsidies for groundwater operate at a vast scale with significant socioeconomic impact, and increasing tariffs and regulation are viewed as politically infeasible; political economy pressures thus strongly constrain policy options. Physical interventions that slow depletion include dimensional improvements to canals, laser leveling, and drip irrigation. Demand-side measures include incentivizing micro-irrigation with a cost-sharing program—partially offsetting private cost increases from crop switching—and reforming electricity subsidies. Irrigation potential remains below potential, so conservation should not limit agricultural output. Current policy debates limit discussion to a narrow range of alternatives that sidestep political economy constraints.

Conclusion

Groundwater stands as the world's largest accessible source of freshwater and plays a pivotal role in supporting continued economic growth and food production in India. It constitutes nearly 90% of the irrigation water supply and 85% of the drinking water supply in the rural areas of the country. Various groundwater sources, including dug wells, tube wells, hand pumps, springs, etc., have been used for drinking and irrigation purposes in India, supplying freshwater from the unconsolidated and consolidated (fissured hard rock) aquifer systems.

The ever-increasing demand for food, along with the depletion of surface water resources for irrigation, has resulted in the pronounced overexploitation of groundwater in northwestern and southern India, which has manifested in reports of declining groundwater levels, increasing drying of wells, deepening of the water table, and decreasing freshwater levels in coastal areas; for some such areas, the rise in groundwater extraction with respect to existing groundwater resources is reported to be as high as 80%–90%. Overexploitation of groundwater resources under such scenarios not only renders the resources unsustainable but also accentuates the detrimental (environmental) effects of groundwater pumping. One such significant consequence in India is the reported CO_2 emissions associated with groundwater extraction. Currently, pumping groundwater from an average depth of 50 m to supply water for irrigation purposes is estimated to result in a CO_2 emission of nearly 29 Tg/year in India.

Water-policy changes implemented after 2012 have caused groundwater storage to increase in parts of western India. Such effects are more pronounced during the monsoon season, with groundwater storage changes averaging 2–4 cm of equivalent water height. These findings outline the importance of updated models and remote sensing products for monitoring global water storage changes that help evaluate how changes in water policy (for example, water cess, regulation, and subsidy control) and anthropogenic activities affect aquifer storage.

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