EAC-PM Working Paper Series

Addressing Groundwater Depletion Crisis in India: Institutionalizing Rights and Technological Innovations

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March 2024

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Abstract: Groundwater, a vital resource essential for sustaining agriculture, rural water supply, and urban consumption, is rapidly depleting in India. With overreliance on groundwater, constituting 62% of irrigation and 85% of rural water supply, India faces an imminent threat exacerbated by population growth, industrial demands, and urbanisation. A University of Michigan study projects a tripling of groundwater depletion rates by 2080, primarily driven by climate-induced intensified withdrawal for irrigation. It highlights the oversight in earlier projections and calls for urgent policy interventions to mitigate this crisis. Proposed measures include rationing power supply, metering electricity usage, regional water resource development, and incentivising farmers for groundwater recharge. The study places India within the global context of groundwater depletion, identifying it as one of the six environmental tipping points. Issues such as declining water quality, aquifer depletion, and land subsidence underscore governance challenges in India, necessitating sustainable management practices. This paper unfolds in three chapters, exploring the problem's causes and impacts, policy measures from various states and globally, and solutions grounded in community rights and artificial recharge. It emphasises the imperative role of institutionalisation, drawing insights from global examples, particularly Latin America, South Africa, Germany, and Australia. The synthesis of global and Indian experiences highlights the need for a holistic approach, starting with institutionalising community rights and complementing it with technological interventions for sustainable groundwater management. The significance of institutionalising formal groundwater rights, detached from land ownership, emerges as a fulcrum for empowering marginalized communities and small-scale farmers. Drawing from global and Indian experiences, the paper argues that institutionalisation, complemented by technological innovations like artificial groundwater recharge projects, constitutes a holistic strategy for sustainable groundwater management. The synthesis of insights from diverse contexts emphasises the urgency of coordinated global efforts centred on rights, responsibilities, and technological innovation to effectively tackle the escalating crisis of groundwater depletion.

1. Introduction

Groundwater in India is a vital resource crucial for sustaining various sectors, particularly agriculture. India heavily relies on groundwater to bridge seasonal gaps in surface water availability, especially during dry spells and erratic monsoon seasons. Relying significantly on groundwater, it contributes approximately 62% to irrigation, about 85% to rural water supply, and roughly 45% to urban water consumption. This heavy dependence on groundwater resources has resulted in strained conditions across several regions of the country (Saha & Ray, 2019). Rapid population growth, agricultural intensification, industrial demands, and urbanization have collectively intensified the stress on groundwater resources. Over-extraction due to excessive pumping, often driven by unregulated agricultural practices and increasing water demands, has led to a decline in water tables in various regions. A study led by the University of Michigan underscores the alarming trajectory of groundwater depletion in India, painting a stark picture of the country's future water security. The report suggests that if current trends persist, the rate of groundwater depletion could triple by 2080, posing a severe threat to both food and water security. The key driver identified is the warming climate, which has forced Indian farmers to intensify groundwater withdrawal for irrigation. This is further corroborated by data from CGWB which suggests that the states of Rajasthan, Punjab, Haryana, and Delhi have been extracting groundwater at a rate of more than 100 per cent.

India, being the world's largest consumer of groundwater, faces a critical challenge that extends beyond its borders. With a population of 1.4 billion, over one-third of whom depend on agriculture for their livelihoods, the implications of reduced water availability are far-reaching (PTI, 2023; Zumbish, 2023). The study reveals that historical data on groundwater levels, climate, and crop water stress indicate a substantial increase in groundwater loss due to the intensified withdrawal by farmers adapting to rising temperatures. What makes the situation more precarious is the oversight in earlier projections that did not account for the adaptive strategy of intensified groundwater withdrawal by farmers. The study, using climate models, projects a tripling of groundwater depletion rates in the future, expanding depletion hotspots to encompass south and central India. This is a cause for concern as these regions play a crucial role in India's agriculture, and the depletion of hard rock aquifers poses a greater challenge for replenishment. The reliance on groundwater for agriculture is substantial, with more than 60% of the nation's irrigated agriculture depending on it (PTI, 2023; Zumbish, 2023). The report emphasizes that despite potential increases in precipitation and decreases in irrigation use, the warming-induced increase in groundwater withdrawal may outpace these mitigating factors. Furthermore, the study reveals that while increased irrigation helps alleviate crop water stress, it comes at the cost of accelerated groundwater depletion over the long term, threatening the sustainability of agricultural practices. The report identifies the need for urgent policy interventions to mitigate the impending crisis (PTI, 2023; Zumbish, 2023).

Suggestions include rationing power supply, metering electricity usage, regional water resource development and allocation, and incentivizing farmers to invest in groundwater recharge. The implementation of such policies is deemed crucial for curbing overexploitation, particularly in regions like northwest India, which currently face severe groundwater depletion. Efforts to reduce overexploitation should also consider adopting groundwater-saving interventions such as efficient irrigation technologies, cultivation of less water-intensive crops, and supplemental irrigation through canals. The report acknowledges the challenges in implementing such measures across millions of households but underscores the necessity to avoid accelerated groundwater depletion under climate change. The research not only calls attention to the immediate threat to India's food and water security but also positions it within the global context. Groundwater depletion, identified as one of the six environmental tipping points by the United Nations University, is reaching critical thresholds. Countries like Saudi Arabia have already surpassed the tipping point, and India, with its massive groundwater consumption, is teetering on the edge (PTI, 2023; Zumbish, 2023). Furthermore, the indiscriminate use of groundwater has resulted in issues such as declining water quality, depletion of aquifers, and land subsidence in certain areas. The governance and management of groundwater in India pose significant challenges due to inadequate regulation, ineffective enforcement mechanisms, conflicting land ownership patterns, and the prevalence of informal groundwater markets. Sustainable management practices, efficient utilisation, and equitable distribution of groundwater resources are imperative to address the growing concerns of depletion and degradation. Strategies that involve community participation, technological interventions for recharge, regulation, and sustainable usage play a crucial role in ensuring the long-term sustainability of groundwater in India.

To comprehensively evaluate the problem pertaining to the rapid depletion of groundwater in India, the following paper is broadly divided into three chapters. The first chapter delves into the problem of groundwater depletion, its causes, and its impact on the social and ecology of India.

The second chapter describes the policy measures undertaken to mitigate or address the problem of rapid depletion using examples from various states and from across the world. The third chapter highlights two solutions, one based on community rights to groundwater, as opposed to the current private ownership of the resource and using methods of artificial recharge of aquifers. This is followed by a brief conclusion.

2. The Situation of Groundwater in India

a. The Problem

India faces a complex challenge regarding its groundwater resources, marked by disparities in distribution, over-exploitation concerns, and geological influences. With only 4% of the world's freshwater resources accommodating 16% of the global population, India grapples with significant disparities in water availability.

Groundwater, pivotal for the country's freshwater supply, is unevenly distributed across regions. The Indo-Ganga-Brahmaputra plains, covering a mere 20% of the geographical area, possess 60% of the country's groundwater resources, accentuating the concentrated distribution. However, these prolific groundwater sources are under threat due to overexploitation, with 1071 out of 6607 assessment units classified as 'over-exploited,' exhausting groundwater faster than it can recharge (PTI, 2023; Zumbish, 2023). This alarming trend jeopardises the sustainability of these vital water sources. Furthermore, the geologically diverse terrain significantly impacts groundwater availability.

While the Himalayas act as a rainshed divide, channelling rainfall into the Indian plains, the alluvium in the Indo-Gangetic region forms extensive and productive aquifer systems (Chatterjee & Purohit, 2009; Saha & Ray, 2019). However, other geological formations, such as semi-consolidated structures in specific valleys or faulted basins, exhibit moderate groundwater yield, and the peninsular region predominantly characterised by consolidated formations poses site-specific groundwater occurrences. Coastal areas boast thick alluvium deposits conducive to aquifer systems but are vulnerable to sea-water intrusion, threatening groundwater quality.

The rapid growth of groundwater usage, especially in agriculture, has significantly reshaped India's irrigation landscape over the past few decades, outpacing the development seen in the prior 2000 years. However, the burgeoning demand for groundwater, largely fueled by subsidies facilitating low-cost pumping technologies, has led to overexploitation (Chatterjee & Purohit, 2009; Singh & Singh, 2002).

The government's initial intention to boost agricultural output and alleviate poverty through these subsidies succeeded during the Green Revolution, ensuring relative food security. Nevertheless, economic shifts coupled with unchanging subsidies have given rise to critical issues. The complex dynamics of groundwater regulation in India, managed at the state level, underscore the varied strategies and instruments adopted across regions (Shah, 2014). State-level policies are influenced by federal initiatives, promoting "Model" forms of groundwater regulation targeting both demand and supply aspects (Birkenholtz, 2017; Foster et al., 2003).

Direct state regulations on the demand side involve mandatory bore-well owner registration, permissions for new bore-well sinking, depth restrictions, and demarcation of protection zones (India Water Portal, 2017). However, these regulations encounter challenges related to monitoring and implementation, resulting in weak enforcement in multiple states (Shah, 2014). Additional strategies include the promotion of water-saving agricultural technologies and community-based groundwater management (Chatterjee & Purohit, 2009; Saha & Ray, 2019). In contrast, supply-side measures encompass the construction of groundwater recharge structures and improved accessibility to surface irrigation (Foster et al., 2003).

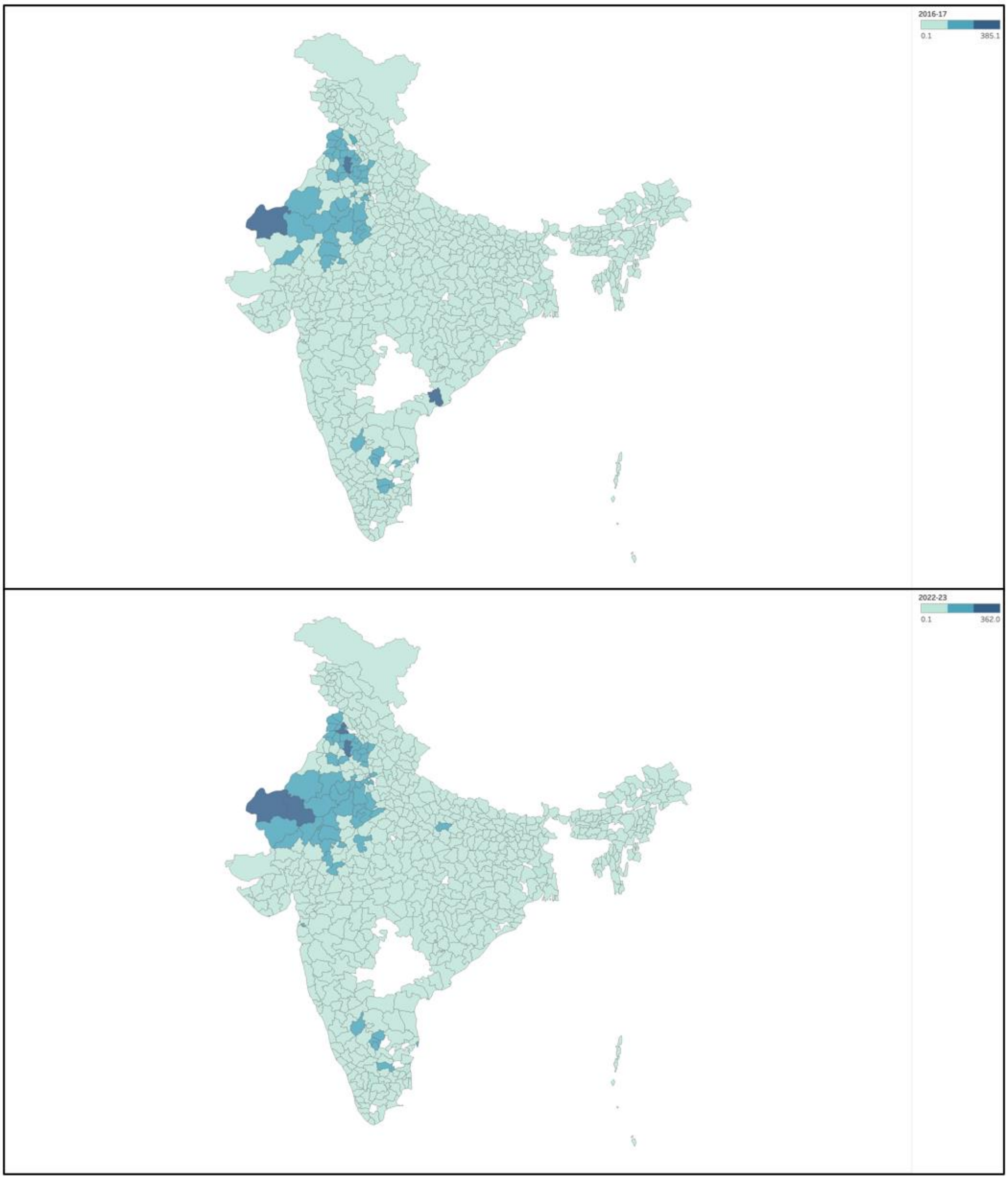

Figure 1 Comparison of Groundwater Extraction in India between 2016-17 and 2022-23[3]
Source: CGWB

Despite the implementation of various demand and supply-oriented approaches to address the groundwater crisis (Shah, 2005), significant and ongoing groundwater depletion persists

[3] The groundwater extraction rate is typically expressed as a percentage of the total available groundwater within an aquifer. It represents the proportion of water withdrawn compared to the aquifer's total storage capacity, indicating usage intensity and potential sustainability concerns. The darker regions imply a higher rate of extraction, which is unsustainable.

throughout India, signalling the inadequacy of these measures. The separation of power usage aims to address electricity access disparities but inadvertently contributes to sustaining an inefficient agricultural sector heavily reliant on groundwater pumping, exacerbating the ongoing depletion crisis. Agriculture, a major electricity consumer, accounted for 18% of power usage in 2013 and nearly 17% in 2015–2016, with demand doubling from 84.7 TWh to 152.7 TWh between 2000 and 2013. However, despite high consumption, the agricultural sector's contribution to electric utilities remains low due to enduring subsidies, politically avoiding tariffs for farmers. India's energy policy since 2001 segregates rural power usage but sustains subsidies, aiming to enhance rural electrification across several states, including Andhra Pradesh, Gujarat, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Punjab, and Rajasthan, covering a population of approximately 500 million (Chindarkar & Grafton, 2019).

India now grapples with severe aquifer over-exploitation and electricity strain from excessive groundwater pumping. While other nations adopted proactive measures like tradable groundwater rights and demand-management strategies, India faces challenges in effectively enforcing groundwater regulations. The historical context reveals a shift from canal-based irrigation to privately-owned groundwater extraction systems, emphasizing the pivotal role of groundwater in agricultural growth. However, this transition led to adverse environmental consequences, with 839 out of 5723 blocks experiencing overexploitation, notably in Punjab and Haryana. Moreover, the extensive reliance on groundwater for irrigation places an enormous strain on the country's electricity supply, with nearly all agricultural electricity consumption attributed to groundwater pumping (Sidhu et al., 2020). This excessive dependence amplifies concerns about climate change impacts, potentially exacerbating rural livelihood challenges and food security threats. Despite the substantial groundwater resource available nationally, regional discrepancies persist, hindering equitable and sustainable groundwater management (Shah et al., 2012).

The approaches to estimate groundwater potential, utilising methods like water level fluctuation and rainfall infiltration, face limitations, often leading to overestimations that misguide regional water resource planning. Groundwater utilisation statistics depict a significant irrigation potential created from groundwater; however, the country faces a wide disparity between theoretical potential and actual utilisation. This disparity, attributed to multiple factors, including the mismatch between recharge and withdrawal periods, emphasises the complexities in assessing and managing India's groundwater resources. The situation warrants an urgent need for comprehensive and sustainable groundwater management policies, considering geographical variations and socio-economic realities to ensure equitable access and long-term sustainability of this critical resource.

b. **Social and Ecological Impact of Groundwater Depletion**

Groundwater depletion in India has profound social implications, encompassing a spectrum of challenges that impact livelihoods, poverty, and food security. The social cost of rapid declines in water tables is extensively documented, and its effects are particularly pronounced in a country where groundwater irrigation is a cornerstone of agriculture. Case studies reveal that access to groundwater plays a pivotal role in poverty reduction and ensuring food security (Dangar et al., 2021; Sekhri, 2012). In the context of India, where a substantial portion of agricultural practices relies on groundwater, the repercussions of its depletion extend beyond economic concerns to encompass broader societal well-being.

An analysis focusing on district-level data in Uttar Pradesh establishes a direct correlation between groundwater scarcity and food grain production. The findings indicate that a 1-meter decline in groundwater from its long-term mean results in an approximately 8 percent reduction in food grain production (Sekhri, 2012). This is a matter of great significance, considering that groundwater irrigation forms the backbone of agricultural practices in India. The depletion of groundwater resources, particularly in regions where water tables are falling at an alarming rate, poses a serious threat to food production and, consequently, to the food security of the nation. Moreover, an examination of the causal impact of groundwater scarcity on poverty rates reveals that as groundwater depth falls below 8 meters, poverty rates increase by around 11 percent (Sekhri, 2012). This underscores the intricate connection between water availability and economic well-being. The study accounts for various village characteristics, including demographic factors, infrastructure, and geographic variables, providing a comprehensive understanding of the multifaceted nature of the relationship between groundwater depletion and poverty. The social and economic ramifications of this depletion extend beyond individual households, affecting entire communities and exacerbating existing socio-economic disparities.

In Gujarat, where water tables are declining rapidly, an estimate suggests that a 30 per cent reduction in water use can free up a substantial amount of electricity for non-agricultural purposes. The implications of such shifts in resource availability directly impact the daily lives of people, influencing access to basic amenities like electricity. Additionally, the Department of Drinking Water Supply, Government of India, reported that around 15 percent of habitations experienced a transition from full coverage to partial coverage of drinking water due to drying up of sources in 2010 (Ahmed et al., 2014; Dangar et al., 2021; Sekhri, 2012). This underscores the pervasive consequences of groundwater depletion on the availability of a basic necessity, affecting communities across the nation. As groundwater depletion intensifies in north India, satellite-based observations suggest an increase in groundwater storage in Peninsular India. However, the regional disparities in groundwater availability exacerbate social inequalities. The shift towards more groundwater-dependent irrigation in densely populated and highly cultivated areas contributes to environmental challenges. The rise in nonrenewable groundwater use for irrigation, accounting for about 11% of international food trade, further deepens the sustainability, environmental, and ecological challenges facing India. The resulting environmental stress directly influences the social fabric, impacting not only immediate livelihoods but also the long-term sustainability of communities.

In the larger context of climate change, the projected increase in hot and dry monsoon extremes in India adds another layer of complexity to the social impact of groundwater depletion. Changes in sowing and harvesting times, coupled with the decline in root-zone soil moisture, directly affect agricultural practices and crop yields. The implications for food security resonate at the societal level, amplifying the vulnerability of communities dependent on agriculture. The interconnectedness of climate-induced challenges and groundwater availability underscores the necessity of holistic and adaptive strategies to mitigate social vulnerabilities.

In addition to social impact, groundwater depletion in India has far-reaching ecological consequences, influencing various ecosystems, biodiversity, and environmental sustainability. As aquifers are over-exploited to meet the increasing demands for irrigation and other purposes, several interconnected ecological impacts emerge, contributing to environmental degradation on multiple fronts. One significant ecological impact of groundwater depletion is the degradation of groundwater quality. As water tables decline, the remaining groundwater is often subject to increased salinity and contamination. The intrusion of saline water from surrounding areas into depleted aquifers poses a threat to both surface and groundwater quality. The higher salinity levels adversely affect the health of aquatic ecosystems, leading to changes in species composition and potential declines in biodiversity. Moreover, the contamination of groundwater with pollutants further exacerbates these ecological challenges, impacting the overall health of ecosystems (Ahmed et al., 2014).

Land subsidence, a phenomenon closely associated with excessive groundwater extraction, has profound ecological implications. The sinking of land surfaces due to the compaction of aquifer sediments affects ecosystems dependent on stable land levels. For instance, wetlands, which play a crucial role in supporting diverse flora and fauna, are particularly vulnerable to land subsidence. The alteration in land topography disrupts the natural hydrological regime of wetlands, diminishing their capacity to sustain unique ecosystems. The loss of wetland habitats and the potential decline in migratory bird populations are indicative of the cascading ecological effects of land subsidence resulting from groundwater depletion. Sea-level rise is another consequence of excessive groundwater extraction (Ahmed et al., 2014). As aquifers are depleted, less water is discharged into coastal areas and oceans, contributing to a rise in sea levels. This has direct implications for coastal ecosystems, leading to changes in the salinity levels of estuarine and coastal waters. Mangrove ecosystems, vital for coastal biodiversity and serving as a natural barrier against storm surges, face threats due to altered salinity levels. The disruption of coastal ecosystems further endangers marine life, affecting fish populations and the livelihoods of communities dependent on coastal resources.

The reduction in groundwater discharge to streams and rivers due to over-extraction has widespread ramifications for freshwater ecosystems. Many rivers across the world, such as the Indus and Colorado, no longer reach the oceans as a consequence of decreased groundwater contributions. This alteration in river hydrology affects aquatic habitats, fish migration patterns, and nutrient cycling in river ecosystems (Garner et al., 2020). Reduced baseflow to rivers, exemplified by the decline in Ganga river discharge during summer due to groundwater pumping, has detrimental effects on the aquatic flora and fauna dependent on stable flow conditions. Groundwater depletion can also lead to changes in vegetation patterns and land cover, impacting terrestrial ecosystems. Shallow groundwater depletion due to pumping and land-use changes influences vegetation, particularly in regions where groundwater-dependent vegetation types prevail. This can lead to alterations in ecosystem structure and function, affecting the composition of plant communities and the wildlife that depends on them. The loss of vegetation due to groundwater depletion may contribute to habitat fragmentation and a decline in biodiversity.

The pressing social and ecological challenges arising from groundwater depletion in India underscore the critical need for immediate and comprehensive policy reform. The social ramifications, encompassing heightened poverty rates, compromised food security, and disruptions in essential services like electricity and drinking water access, accentuate the urgency of addressing this issue. Given that groundwater is pivotal for agricultural practices, its rapid depletion not only exacerbates socio-economic disparities but also intensifies environmental stressors. Concurrently, ecological consequences, such as deteriorating water quality, land subsidence, sea-level rise, and disturbances to freshwater and coastal ecosystems, emphasise the intricate interplay between groundwater health and overall environmental well-being. Tackling these challenges demands a swift and multi-pronged policy approach that integrates robust governance, active community involvement, and innovative conservation measures. Sustainable groundwater management is imperative to safeguard not only the livelihoods of millions but also to preserve the delicate balance of ecosystems crucial for biodiversity and environmental resilience.

3. Case Studies: Approaches to solve groundwater depletion issue

a. Examples from India

India's groundwater crisis has prompted state governments to implement policies aimed at reversing the alarming trends of rapidly falling groundwater levels.

Delhi

One of the primary measures adopted by several states is mandated rainwater harvesting, with Delhi leading the way in 2001. The implementation of mandated rainwater harvesting policies in various Indian states, commencing with Delhi in 2001 and subsequently extending to Andhra Pradesh, Tamil Nadu, Kerala, Madhya Pradesh, Rajasthan, Bihar, and West Bengal, represents a regulatory response to counteract the escalating depletion of groundwater resources. The stipulated policy directives mandate the construction of rainwater harvesting structures on building rooftops, subject to specific size criteria. The underlying rationale for such directives is rooted in the intention to harness and utilise rainwater as an alternative source, thereby alleviating the excessive reliance on groundwater extraction However, the effectiveness of these mandates in curbing the decline in water tables has been met with mixed success. While rainwater harvesting presents an environmentally sustainable solution, its impact varies across states due to factors such as implementation, geographical considerations, and community participation.

Gujarat

The decentralised model employed in Gujarat, with a focus on community-led efforts, stands in contrast to the regulatory approach adopted by other states. Originating in response to the severe drought of 1987 in the Saurashtra region, the state's initial efforts to divert runoff to groundwater wells saw widespread adoption by farmers. Over time, these grassroots initiatives evolved, with farmers experimenting with new technologies and constructing check dams in streams and rivers. This decentralised approach gained momentum, aided by the support of non-governmental organisations (NGOs) that shared the financial burden with farmers. In January 2000, the Gujarat government formalised its support through the Sardar Patel Participatory Water Conservation Project. The first phase, lasting from January 17, 2000, to February 20, 2001, saw the construction of 10,257 check dams, with the government initially financing 60 percent of the estimated costs and beneficiaries/NGOs covering the remaining 40 percent. By September 1, 2000, these initiatives demonstrated considerable success, with the government acknowledging the positive impact on groundwater recharge. As the program progressed, it witnessed a substantial increase in pace and scale. By early 2004, almost 24,500 check dams were constructed, and the government enhanced its financing to cover 80 percent of the estimated costs. The geographic distribution of these check dams, as illustrated in Figure 8, delineates their prevalence in the Saurashtra, Kachchh, Ahmedabad, and Sabar Kantha regions. According to government statistics, by the end of March 2012, a total of 70,719 check dams were constructed under the project. Of these, 38 percent were in the Saurashtra region, and 31 percent were in Kachchh or North Gujarat. This initiative unfolded against the backdrop of a larger water crisis, especially in regions like Saurashtra and Kachchh, where groundwater depletion was a looming threat to agricultural sustainability. The timing and intensity of the project reveal a strategic response to the urgent need for sustainable water management in these arid regions. The impact of the Sardar Patel Participatory Water Conservation Project on groundwater levels and recharge in Gujarat is noteworthy. The check dams, by slowing water speed and allowing river water to seep into the ground, facilitated the replenishment of the groundwater supply. This success story of decentralised, community-driven efforts in Gujarat challenges the notion that top-down regulatory measures are the sole solution to groundwater depletion.

In contrast, the Jal Kranti Yojana (JGY) in Gujarat, introduced in 2015, aimed at implementing feeder separation across the state. The rationale behind this policy was to improve the quality of power supply and enhance the efficiency of agricultural electricity usage. However, an empirical analysis of the effects of JGY on groundwater storage in Gujarat reveals a nuanced and potentially contradictory outcome. Utilizing district-level data and employing a difference-in-differences (DiD) analysis, the study assessed the impact of JGY on groundwater storage. The findings from that study indicate an increase in the depth from the soil surface to groundwater until 2004, coinciding with the introduction of JGY (Chindarkar & Grafton, 2019). However, this trend was not sustained, and the depth to groundwater increased from 2008 to 2010, approximately two years after the full implementation of JGY. The results challenge the prevalent belief that JGY, coupled with other policies, contributes to increasing groundwater storage. The study raises concerns about the effectiveness of feeder separation policies in achieving the intended outcomes. The potential discrepancy between policy intentions and observed outcomes underscores the complexity of groundwater management and the need for rigorous empirical evaluation. Therefore, Gujarat's experience with water management initiatives exemplifies the diversity of approaches employed to address groundwater depletion. The decentralised success of the Sardar Patel Participatory Water Conservation Project contrasts with the more recent challenges associated with the Jal Kranti Yojana's feeder separation policy (Bassi, 2014; Chindarkar & Grafton, 2019). These instances emphasise the importance of context-specific, evidence-based water management strategies and the need for ongoing research and evaluation to refine policy interventions and ensure sustainable groundwater practices in the state.

Punjab and Haryana

In Punjab and Haryana, where groundwater depletion poses a severe challenge, the governments have taken legislative steps to tackle the crisis. Rather than solely relying on rainwater harvesting or community-led initiatives, these states opted for regulatory measures to address excessive groundwater extraction, especially in paddy cultivation.

The state of Punjab, known as the breadbasket of India, has long grappled with the challenge of sustainable groundwater management due to extensive agricultural activities and rapid urbanisation. Recognising the critical importance of preserving this vital resource for future generations, the Government of Punjab has implemented various initiatives aimed at conserving, managing, and regulating groundwater resources effectively. These initiatives reflect a comprehensive approach towards achieving sustainability in water management while addressing the diverse needs of agriculture, urban development, and environmental conservation.

Punjab made a significant policy change in 2006 by altering the date when free electricity for operating tube wells was available to farmers. Shifting this critical date to June 10 aimed to discourage the excessive watering practices typically associated with paddy cultivation. This change became law in 2009 as The Punjab Preservation of Sub-Soil Water Act, 2009. Following Punjab's lead, Haryana enacted a similar law in March 2009, known as the Preservation of Sub-Soil Water Act (Sekhri, 2012). These legislative measures imposed specific temporal constraints on paddy cultivation, prohibiting sowing before May 10 and transplanting before June 10. Furthermore, the legislation conferred the authority to destroy, at the farmer's expense, paddy sowed or transplanted prematurely, accompanied by a penalty of ₹10,000 per month per hectare of land in violation of the law. The introduction of these legal frameworks reflects a concerted effort by both states to impose temporal restrictions on groundwater-intensive agricultural practices, notably paddy cultivation, which historically has been a significant contributor to excessive groundwater extraction. The regulatory strategy of Punjab and Haryana signifies a departure from more decentralised and community-involved approaches observed in other regions (Sekhri, 2012). By intervening in the temporal dynamics of paddy cultivation, the states sought to reduce the overall demand for groundwater during critical periods. This legislative stance reflects an institutionalized effort to address the complex interplay between agricultural practices and

One of the cornerstone measures undertaken by the Government of Punjab is the establishment of the Punjab Water Resources Regulation and Development Authority (PWRDA) under the Punjab Water Resources (Management and Regulation) Act, 2020. Endowed with the responsibility of conserving, managing, and regulating water in the state, the PWRDA operates in alignment with the Integrated State Water Plan (ISWP). This institutional framework ensures coordinated efforts towards sustainable water management practices.

To further bolster groundwater management efforts, the state government has instituted a dedicated Directorate of Groundwater Management. This specialised body is entrusted with the task of formulating and implementing strategies for the conservation and efficient utilisation of groundwater resources. By focusing exclusively on groundwater issues, this directorate enhances the state's capacity to address the unique challenges associated with groundwater depletion and contamination.

To curtail the overexploitation of groundwater resources, the Punjab Preservation of Sub-Soil Water Ordinance, 2008, has been enacted. This legislation prohibits the early sowing of paddy crops before specified dates, thereby discouraging excessive groundwater withdrawal for irrigation purposes. Violations of these regulations incur penalties, incentivising adherence to sustainable cropping practices and seasonal water usage patterns.

Recognising the imperative of agricultural diversification for mitigating water stress, the Government of Punjab has incentivised farmers to shift from water-intensive crops like paddy to alternative crops such as maize and cotton. By promoting crop diversification under national climate change adaptation programs, the state aims to reduce the reliance on groundwater for irrigation while enhancing the resilience of agricultural systems to changing climatic conditions.

In tandem with promoting sustainable agricultural practices, the Government of Punjab encourages the adoption of Resource Conservation Technologies (RCTs) among farming communities. Subsidies are provided to facilitate the adoption of technologies such as Laser Land Leveling and Zero Tillage, which minimise water usage, soil erosion, and input costs. These measures contribute to enhancing agricultural productivity while conserving groundwater resources.

In a bid to optimise water usage in rice cultivation, the state government promotes the adoption of Medium/Short Duration Rice Cultivars over long-duration varieties. Awareness campaigns conducted at the grassroots level educate farmers about the benefits of these cultivars in terms of water efficiency and yield. Additionally, demonstration plots showcase the viability of adopting sustainable rice cultivation practices, thereby encouraging widespread adoption among farming communities.

Recognising the potential of rainwater harvesting as a sustainable water management practice, the Government of Punjab has mandated the installation of rooftop rainwater harvesting systems in buildings above a specified size. By amending building by-laws, both within municipal limits and in rural areas, the state aims to augment local water resources and alleviate pressure on groundwater reserves. These measures complement broader efforts towards promoting water self-sufficiency and resilience to water scarcity.

Furthermore, the Government of Punjab has invested in the construction of low dams under the Bharat Nirman Program to harness rainwater and facilitate irrigation. These dams play a crucial role in replenishing groundwater aquifers, particularly in water-stressed regions, while also providing supplementary irrigation for agricultural activities. By harnessing natural water resources, these infrastructure projects contribute to sustainable groundwater management and agricultural sustainability.

In Haryana, nearly 60% of villages face groundwater stress, impacting the lives of around 20 million people. The ecological and economic repercussions of this crisis are yet to be fully understood. Over the past five decades, some regions have witnessed groundwater depletion of over a hundred feet. Key challenges include the absence of a robust institutional framework for groundwater governance, stakeholder absenteeism, the prevalence of water-intensive crops, and undesirable stakeholder behavior.

To address these challenges, the Atal Bhujal Yojana has been launched with the support of the central government and the World Bank. The scheme aims to implement Participatory Groundwater Management (PGWM) to enhance groundwater management in targeted areas. It advocates decentralization, water use efficiency enhancement, landscape-based management, and fiscal decentralization. (Desk, 2023)
The program empowers last-mile stakeholders, such as village-level institutions and community members, to make decisions regarding groundwater management. To facilitate this, a Hydrogeological Monitoring Network (HMN) is being established at the gram panchayat level. HMN units will consist of tools like piezometers, rain gauges, and water flow meters, providing data on groundwater quality, quantity, accessibility, and sustainability to the community. (Desk, 2023)

Under the Atal Bhujal Yojana, Water Security Plans (WSPs) will be prepared at the gram panchayat level through community involvement, incorporating indigenous knowledge and HMN data. These plans will help calculate water balances, identify water-intensive activities, and promote water-sensitive practices like crop diversification and micro-irrigation. Local youth trained as para hydrogeologists will play a crucial role in implementing WSPs. Financial incentives are provided to farmers transitioning from water-intensive to water-sensitive crops, along with subsidies for adopting micro-irrigation practices. Traditional water body rejuvenation and decentralized rooftop rainwater harvesting structures are also being promoted. Capacity building and institutional strengthening are integral parts of the initiative, with extensive training sessions planned for stakeholders. Behavioral change communication strategies aim to inform and educate stakeholders through various platforms like Jal Panchayats, exhibitions, and social campaigns. (Desk, 2023)

In conclusion, the Government of Punjab has undertaken a multifaceted approach towards sustainable groundwater management, encompassing regulatory frameworks, institutional capacity building, technological innovation, and community engagement. These initiatives reflect a proactive commitment to safeguarding groundwater resources for present and future generations, thereby ensuring the socio-economic and environmental sustainability of the state. However, ongoing monitoring, evaluation, and adaptive management will be crucial to address emerging challenges and sustainably manage Punjab's groundwater resources in the long term.

Groundwater depletion highlights the state's commitment to sustainable water resource management through statutory means. In Haryana, the Atal Bhujal Yojana seeks to revolutionise groundwater governance by engaging experienced NGOs and adopting a community-led approach. It aims to establish an equitable and sustainable groundwater management system, addressing the challenges posed by climate change and societal heterogeneities. This initiative marks a significant step towards remedying the groundwater crisis and ensuring the well-being of communities, livelihoods, and ecosystems.

Bengaluru: Emerging Groundwater Issue in Urban Setting

Bengaluru's groundwater dynamics are intricately intertwined with its distinctive geographical features and rapid urban expansion. Positioned at an elevation of around 900 meters above sea level, Bengaluru enjoys favourable climatic conditions yet faces considerable logistical hurdles in water supply due to its high altitude. Sitting atop a ridge between the Cauvery and Dakshina Pinakini watersheds, Bengaluru channels rainwater into these rivers through a network of smaller streams. However, extensive exploitation of these water bodies for various purposes, coupled with rampant groundwater extraction, has resulted in their depletion. The Central Ground Water Board classifies all blocks in Bengaluru Urban and Bengaluru Rural districts as overexploited areas. (Palanichamy, 2024)

While traditionally reliant on groundwater and lake water, Bengaluru has increasingly turned to distant reservoirs to meet its escalating water demands. However, these measures have fallen short, particularly in catering to the needs of villages assimilated into the city in 2008. Bengaluru's rapid urbanization has outpaced infrastructural development, leading to acute water scarcity, particularly in peripheral regions lacking basic amenities. The absence of regulatory frameworks exacerbates the situation, with residents resorting to groundwater extraction, tanker water, and bottled water for sustenance. (Palanichamy, 2024)

Although recent years have witnessed higher rainfall, masking the underlying water scarcity issues, the failure of monsoons in 2023 has underscored the precariousness of the city's water situation, especially in areas heavily reliant on groundwater. The absence of clearly defined protocols for drought management, coupled with delayed electoral processes, further compounds the challenges. Additionally, de-siltation activities in lakes diminish groundwater recharge, exacerbating the crisis. (Palanichamy, 2024)

While short-term measures like impending elections and infrastructural expansions offer temporary respite, ensuring long-term sustainability necessitates comprehensive planning. This entails formulating watershed management strategies, stringent regulations governing water usage, and reassessment of agricultural practices. Prioritising rainwater harvesting, water recycling, and judicious urban expansion policies is imperative to mitigate future water crises. (Palanichamy, 2024)

In essence, Bengaluru's water challenges epitomise the broader issues confronting rapidly expanding urban centres. Addressing these challenges demands a holistic approach, integrating geographical considerations, urban planning imperatives, and sustainable water management practices. (Palanichamy, 2024)

b. Examples from the Globe

Groundwater depletion poses a significant threat to water security across the globe. Latin America, with its diverse hydrogeological landscapes and growing water demands, is no exception. However, the region also offers inspiring examples of successful groundwater replenishment policies, providing valuable lessons for sustainable water management practices. One notable case is the free aquifer in San Luis Potosi Valley recharge project in Mexico. This collaborative effort exemplifies long-term planning and stakeholder engagement. Treated wastewater is injected into the aquifer during the rainy season, replenishing depleted reserves and improving quality for downstream communities. However, the contamination of the aquifer has become a concern in recent times (Torres-Rivera et al., 2023). In Chile, the case of Santiago presents a multi-pronged approach to tackling both urban water demand and aquifer depletion. On the demand side, stringent measures such as water metering, leak detection, and public education campaigns aim to curtail urban consumption. Simultaneously, on the supply side, treated wastewater is redirected towards irrigation and aquifer recharge, minimizing reliance on freshwater extraction from the stressed aquifer. This holistic approach emphasizes the interconnectedness of water systems and the need for comprehensive solutions that address both consumption patterns and resource availability (World Bank, 2019).

Moving beyond urban contexts, the Los Negros irrigation system in Bolivia showcases the power of community-based management. Supported by NGOs, local communities have implemented traditional irrigation improvements and watershed protection measures, leading to increased recharge and sustainable water utilization. This bottom-up approach empowers communities and fosters a sense of ownership over water resources, highlighting the importance of community participation in successful replenishment initiatives. Market-based mechanisms also offer promising avenues for replenishment (IIED, 2012). The Guandu River Basin water market in Brazil presents a unique example where water users, including industries and farmers, trade water allocations to optimize usage and incentivize conservation. This scheme promotes efficient water allocation and generates revenue for aquifer recharge projects, demonstrating the potential of economic incentives to drive sustainable water management. Finally, a strong legal framework is crucial for effective groundwater replenishment (Saucedo-Ramírez et al., 2022). The Costa Rican groundwater management law serves as a model, regulating extraction, prioritizing recharge, and promoting sustainable water use. Such comprehensive legal frameworks provide a stable foundation for long-term success and ensure compliance with established regulations.

Examining instances from South Africa, Germany, and Australia provides insights into the multifaceted nature of groundwater governance and highlights the need for comprehensive strategies. In the Sandveld region of South Africa, local policy changes have been instigated in response to pressing issues of water scarcity and environmental degradation. The over-abstraction of groundwater for irrigation and the clearing of natural vegetation for potato production triggered a national response. The South African government declared the over-abstraction and ecological degradation of Sandveld aquifers, leading to collaborative multi-stakeholder processes (Knüppe et al., 2016). These initiatives involved conservationists, commercial farmers, and local municipalities. The resultant 'Biodiversity Best Practices for Potato Production' agreement, established in 2007, represents a commitment to sustainable practices that balance economic interests with environmental recovery. Germany's Spreewald region offers another illuminating case, where the implementation of the European Water Framework Directive (WFD) in 2000 played a pivotal role in shaping local groundwater management policies. The WFD, with its goal of achieving the 'good ecological status' of water bodies by 2015, prompted the development of a maintenance and development plan in 2001. The plan, influenced by the WFD and the Biodiversity Stewardship Program, explicitly focuses on promoting sustainable groundwater use and nature conservation. The challenges posed by opencast lignite mining and low natural water availability are considered in the context of maintaining ecological integrity (Knüppe et al., 2016). Australia's Murray-Darling Basin (MDB) stands out as a beacon for recognizing the interconnectedness of surface water and groundwater.

The National Water Initiative and the MDB Authority underscore the importance of conjunctive management, emphasizing the integrated approach to surface and groundwater resources. Sustainable groundwater management within the MDB aligns with environmental watering principles, recognizing the indispensable role of groundwater in sustaining economic, social, and environmental values (Doble et al., 2023).

While these examples shed light on successful groundwater management practices, challenges persist on a global scale, particularly when dealing with transboundary aquifers. In regions like the Tigris and Euphrates River Basins in the Middle East, rapid groundwater decline is linked to complex transboundary water resource issues. The disparities in laws, regulations, and socio-political conditions across multiple countries exacerbate the challenges associated with shared aquifers. Addressing these complex challenges necessitates an integrated and collaborative approach. Stakeholder engagement, adherence to global directives such as the WFD, and the establishment of authoritative governance bodies are crucial components of effective groundwater management. The Murray-Darling Basin Authority's basin-scale governance exemplifies how comprehensive structures can mitigate transboundary issues, highlighting the importance of cohesive and adaptive governance frameworks in managing shared groundwater resources. In conclusion, the global landscape of groundwater management reflects both the alarming threats of depletion and inspiring examples of innovative replenishment strategies. Latin America, exemplified by initiatives like the aquifer recharge project in Mexico and the case in Chile, demonstrates that collaborative, multi-pronged approaches involving recycled water, community-based management, market-based mechanisms, and stringent legal frameworks can effectively address water security challenges. These cases highlight the role of stakeholder engagement, long-term planning, and the recognition of interconnected water systems. The experiences from diverse regions, such as South Africa, Germany, and Australia, further emphasize the need for comprehensive strategies in groundwater governance. While successful practices have been identified, the persistence of challenges in transboundary regions like the Tigris and Euphrates River Basins underscores the urgency of global collaboration, adherence to international directives, and the establishment of robust governance structures. As the world grapples with escalating water crises, these lessons provide a roadmap for sustainable groundwater management, where environmental, social, and economic imperatives align to secure the future of this vital resource.

4. Possible Solutions to Groundwater Depletion

a. Usage of rights to tackle groundwater depletion

Groundwater rights have become a contentious issue pivotal to tackling the depletion crisis in India. The absence of clearly defined and enforceable groundwater rights has led to the emergence of an informal market for this resource (Doble et al., 2024). Although these unregulated markets have contributed significantly to food security and poverty alleviation, their unstructured nature has raised sustainability concerns due to unsustainable extraction practices (Kemper, 2007; Mukherji, 2007b). The lack of well-defined groundwater rights exacerbates the unsustainable usage patterns, as the absence of institutional frameworks and discrepancies in financial capacities among landowners perpetuate erratic extraction behaviors (Bassi, 2014) The notion of instituting formalized groundwater rights detached from land ownership has emerged as a promising avenue to address this challenge. Such a system could potentially ensure fairer resource distribution and enable regulatory control over extraction rates. However, integrating these rights into the current legal framework requires significant institutional restructuring, technological innovations, and policy integration to effectively govern this indispensable resource (Kemper, 2007).

The transition towards formalized groundwater rights necessitates a comprehensive understanding of local contexts and active community engagement. It holds the promise of empowering marginalized communities and small-scale farmers by granting legal entitlement to groundwater resources (Saleth, 1994). The formalization of rights might also act as collateral, offering enhanced financial opportunities for these underprivileged groups.

Nevertheless, implementing a formalized groundwater rights system is not devoid of challenges. It requires rectifying historical imbalances in resource access, especially between smallholder farmers and larger landowners, through the equitable distribution of entitlements (Kumar et al., 2013b). One of the pivotal determinants of groundwater extraction rates is the significant influence wielded by electricity subsidies in the agricultural sector. Policies governing electricity supply to agricultural tube wells, often subsidized, have exerted a notable impact on groundwater abstraction rates. For example, subsidy schemes, as observed in regions like Balochistan province, have prompted considerable investments leading to increased tube well development and subsequent access to groundwater for irrigation.

However, concerns have arisen about the long-term sustainability of such practices and their effects on groundwater resources (Ananda & Aheeyar, 2020). Various initiatives to address groundwater governance challenges in India have showcased diverse approaches and varying impacts. Managed aquifer recharge initiatives aimed at methodically enhancing groundwater replenishment have displayed disparate outcomes across different Indian regions. While some community-driven efforts have shown promise, their effectiveness is contingent upon local hydrogeological conditions and community involvement. Additionally, policies regulating energy pricing and usage, like the Jyotigram Scheme in Gujarat, which allocated specific electricity feeder lines to regulate groundwater usage, have been instrumental (Bassi, 2014). Nonetheless, these policies have raised concerns about their differential impacts on marginalised and landless farmers heavily reliant on groundwater markets. The discourse on groundwater rights transcends legal frameworks, embracing a complex set of social, economic, and environmental dimensions. Achieving equilibrium between promoting agricultural productivity, ensuring equitable water access, and safeguarding groundwater sustainability remains a formidable challenge. Attempts to introduce permit-based systems or community-managed groundwater initiatives have faced limitations in curbing over-exploitation (Bassi, 2014).

Effectively establishing formal groundwater rights, distinct from land ownership, demands vigilant monitoring mechanisms, participatory governance models, and technological advancements to ensure compliance and prevent over-extraction. The success of this endeavour is contingent upon comprehensive legal frameworks, institutional reforms, and collaborative governance structures. Achieving consensus among stakeholders and fostering collaboration among diverse interest groups are pivotal in ensuring the sustainability and efficacy of this proposed solution (Kumar, 2007). In summary, the establishment of formal groundwater rights emerges as a crucial strategy in mitigating India's depletion crisis, albeit requiring extensive legal, institutional, and technological reforms, coupled with inclusive governance structures, to ensure equitable access and sustainable management of this vital resource.

b. Need of a fresh look at Groundwater rights?

Granting community rights over groundwater emerges as a pivotal solution to address the escalating challenges of depletion in India. The predominant paradigm of considering groundwater as private property, often owned by individuals or companies, has proven inadequate. The inherent technical characteristics of groundwater challenge the notion of exclusive ownership, as the extraction from one plot invariably affects adjacent areas. The dynamics of interconnected water tables negate the efficacy of delineating groundwater rights solely based on land ownership. Recognizing this, the notion of common property rights gains prominence, signifying collective ownership by a community of users.

In the Indian context, constitutional provisions like the 73rd Amendment empower Panchayats with the authority to manage water resources, aligning with the principles of common property rights. Undivided co-ownership, as outlined in the Indian Easements Act of 1882, exemplifies a form of common property with respect to groundwater (Ananda & Aheeyar, 2020; Bassi, 2014; Jenifer, 2012). However, challenges arise concerning its impermanence, making it unsuitable for the long-term and sustainable management of groundwater. In light of this, embracing community-centric approaches becomes imperative. A shift towards community-based ownership entails collective responsibility and equal access, mitigating the exploitative tendencies observed under private ownership. Public property rights, vested with the state, offer another viable framework. The Constitution of India designates water as a state subject, emphasizing the role of the state in defining, managing, and enforcing the rights to groundwater usage. The Public Trust Doctrine, affirmed by the Supreme Court, posits that certain resources like water are held in trusteeship by the government for the free and unimpeded use of the general public. This perspective aligns with the idea of groundwater as a Common Property Resource, challenging the conventional understanding of private ownership (Jenifer, 2012).

The inadequacies in existing groundwater legislation in Tamil Nadu highlight the urgency for policy reforms. Current acts, predominantly focused on a licensing system, lack specificity in addressing the diverse challenges posed by overexploited areas. Legal loopholes, such as the exemption of certain pumps and wells from licensing requirements, contribute to contraventions and hinder effective regulation (Jenifer, 2012). There is a noticeable absence of provisions for regular scrutiny of well licenses, renewal mechanisms, and depth specifications, leading to a regulatory vacuum. To address these gaps, a comprehensive set of reforms is essential. Elevating the role of local users by granting community rights is a key step. Empowering communities with authority in managing groundwater resources enhances accountability and ensures a more nuanced understanding of local water demands. Technical knowledge dissemination among community members facilitates informed decision-making and efficient resource utilization. Additionally, a bottom-up organizational structure prioritizes the role of groundwater users, fostering a sense of ownership and responsibility (Bassi, 2014; Garner et al., 2020).

Ensuring transparency and awareness of policies among the public is crucial. The dissemination of acts and policies in local languages is vital for community engagement. Provisions for the renewal of licenses, regular scrutiny, and data maintenance by government departments on aquifer characteristics can contribute to effective groundwater management. Restricting new well construction in overexploited regions, coupled with an emphasis on improving surface water resources, aids in reducing reliance on groundwater. Separating groundwater rights from land rights is pivotal. Clearly delineating private, public, and common property rights associated with groundwater establishes a more robust legal framework. Making groundwater a common property, regulated by the government, minimizes the risk of overexploitation and misuse. The synergy between community-centric approaches, regulatory reforms, and technological interventions offers a holistic pathway toward sustainable groundwater management, addressing the pressing issue of depletion in India.

c. Artificial Groundwater Recharge in India

Artificial groundwater recharge projects play a pivotal role in addressing water scarcity and sustaining aquifer systems in India, particularly in arid and semi-arid regions where normal rainfall is insufficient to generate moisture surplus through natural infiltration. The focus of these initiatives extends beyond replenishing depleted aquifers; they encompass diverse objectives such as combating saltwater encroachment, enhancing water filtration, controlling land subsidence, managing waste disposal, and even facilitating oil recovery from partially depleted fields. Despite the extensive use of artificial groundwater recharge methods in developed nations, their adoption in developing countries like India has gained momentum only recently. In India, various states have undertaken significant studies and projects to implement artificial recharge techniques. In Maharashtra, research on percolation tanks in the Sina and Main River basins has contributed to understanding their efficacy. Similarly, in Gujarat, artificial recharge has been conducted in both the Central Mehsana area and coastal Saurashtra, utilizing methods such as injection wells, connector wells, infiltration channels, and recharge basins. The choice of recharge method depends on geological, hydrological, and morphological features, with spreading methods, including channels, pits, and ponds, proving more economical in some areas. Dual-purpose connector wells, supplying water to deep aquifers by gravity and extracting water through periodic pumping, demonstrated efficiency in the Central Mehsana area (Batanagar Institute of Engineering & Mukherjee, 2016).

Tamil Nadu and Kerala have focused on percolation tanks in the Noyil Ponani and Vattamalai River basins, emphasizing the importance of periodic de-silting for maintenance. Additionally, studies in Jamnagar District in Gujarat explored the use of naturally occurring basaltic dykes to retain groundwater. The Ghaggar River basin witnessed experiments with injection wells, revealing that controlled pressure injection significantly increased recharge rates compared to gravity flow. However, the success of injection wells hinged on managing clogging issues through careful source water quality control and periodic well cleansing. Watershed management practices, aimed at minimizing soil loss in erosion gullies, have been recognized as indirect contributors to groundwater recharge in various parts of India (Batanagar Institute of Engineering & Mukherjee, 2016). Despite the technical feasibility demonstrated by numerous artificial recharge experiments, the economic and institutional aspects remain critical but somewhat elusive considerations. Full-scale operations are limited in India and Asia, resulting in incomplete cost information. The costs associated with groundwater recharge are influenced by factors such as source water availability, conveyance facilities, civil constructions, land, and groundwater pumping and monitoring facilities. The nature of artificial groundwater recharge projects in India highlights their significance in addressing water challenges (CGWB, 2007). The choice of recharge methods and their economic viability depend on a nuanced understanding of local geological and hydrological conditions. While technical feasibility has been substantiated through various experiments, comprehensive assessments considering economic and institutional aspects are crucial for the sustainable implementation of artificial groundwater recharge initiatives in the diverse hydrological environs of India.

5. Way Forward

A comprehensive approach is imperative in addressing the escalating global crisis of groundwater depletion, with institutionalisation emerging as the foundational step. The discourse surrounding groundwater management, as evident in both global and Indian contexts, underscores the imperative need to institutionalise sustainable practices.

A collaborative approach of all level of governments

Groundwater depletion in India presents a complex challenge with profound implications for agriculture, industry, and public health. To effectively tackle this issue, concerted efforts and cooperation are required among various levels of governance, including the central government, state governments, and municipalities.

At the national level, the central government assumes a pivotal role in formulating policies and regulations pertaining to groundwater management. It establishes overarching frameworks and guidelines aimed at promoting sustainable use of groundwater resources across the country. Additionally, the central government provides crucial financial support to states through centrally sponsored schemes. Initiatives such as the Atal Bhujal Yojana and the National Rural Drinking Water Programme exemplify efforts to improve groundwater management practices by allocating central funds for conservation and recharge projects. Moreover, the central government invests in research and development endeavours to enhance understanding of groundwater dynamics, identify depletion hotspots, and develop innovative solutions for conservation and recharge. Facilitating inter-state cooperation and negotiations on transboundary aquifer management and river water sharing further underscores the central government's role in ensuring equitable and sustainable utilisation of groundwater resources.

At the state level, governments play a critical role in regulating groundwater usage within their jurisdictions. They enact state-level laws, regulations, and policies governing extraction, recharge, and conservation activities. Recognising the diverse hydrogeological conditions and water usage patterns across different regions, states tailor their approaches to groundwater management accordingly. State governments issue permits for groundwater extraction and establish monitoring mechanisms to track extraction rates, water levels, and quality. They also promote the adoption of water-efficient irrigation techniques, crop diversification, rainwater harvesting, and groundwater recharge methods through awareness campaigns, subsidies, and incentives. Additionally, state governments invest in capacity-building initiatives to enhance institutional capacity at the state and district levels for effective groundwater management.

At the local level, municipalities assume responsibility for implementing regulations and initiatives aimed at conserving groundwater resources within their jurisdictions. They formulate bylaws governing groundwater use and oversee infrastructure projects for water supply, sanitation, and stormwater management to reduce dependence on groundwater and promote alternative water sources. Municipalities also play a vital role in raising public awareness about groundwater conservation through educational campaigns, workshops, and community engagement initiatives. Moreover, they monitor groundwater levels and quality within their limits, enforce regulations on borewell drilling, and penalise violations to deter unsustainable extraction practices.

Rights-based approach

The journey towards effective groundwater management begins with a rights-based approach, particularly the formalisation of groundwater rights detached from land ownership. The Indian scenario vividly illustrates the complexities associated with groundwater depletion and the vital role of institutionalisation. The absence of well-defined and enforceable groundwater rights has led to unregulated markets, raising sustainability concerns. However, the proposed shift towards formalised groundwater rights offers a promising solution. This involves not only rectifying historical imbalances but also empowering marginalised communities and small-scale farmers through legal entitlement to groundwater resources. The intricate balance between promoting agricultural productivity, ensuring equitable water access, and safeguarding groundwater sustainability in India hinges on comprehensive institutional restructuring, technological innovations, and collaborative governance structures. Moreover, the global landscape provides inspiring examples of how effective institutionalization can mitigate groundwater depletion. Latin American countries showcase initiatives such as the Guayaleo aquifer recharge project in Mexico, emphasizing long-term planning and stakeholder engagement. Similarly, the Capuchino aquifer case in Chile highlights a multi-pronged approach, addressing urban water demand and aquifer depletion through stringent measures and treated wastewater redirection. These examples underscore the significance of comprehensive strategies involving recycled water, community-based management, market-based mechanisms, and stringent legal frameworks. The experiences from diverse regions like South Africa, Germany, and Australia further emphasize the critical role of comprehensive strategies in groundwater governance. Regulatory interventions, as witnessed in Punjab and Haryana, demonstrate an institutionalized effort to curtail excessive groundwater extraction. Legislative measures altering the dynamics of groundwater-intensive agricultural practices highlight the commitment to sustainable water resource management through statutory means.

Conclusion

In this narrative, the formalization of groundwater rights becomes a linchpin, reflecting the shift towards community-centric approaches that empower local stakeholders. This transition is crucial not only for achieving sustainable groundwater management but also for fostering a sense of ownership and responsibility among communities. The synthesis of global and Indian examples paints a compelling picture – institutionalization, anchored in community rights, is the cornerstone for addressing the multifaceted challenges of groundwater depletion. However, institutionalization alone is not adequate. Technological interventions, as demonstrated by artificial groundwater recharge projects, play a pivotal role in complementing institutional frameworks. Initiatives like those in Maharashtra, Gujarat, Tamil Nadu, and Kerala showcase the importance of spreading methods, injection wells, and watershed management in replenishing depleted aquifers. The economic and institutional aspects remain critical considerations for the sustainable implementation of these projects, highlighting the need for a nuanced understanding of local geological and hydrological conditions. In essence, the solution to groundwater depletion requires a holistic approach. It begins with the institutionalization of community rights, providing a robust foundation for sustainable groundwater management. Technological interventions then augment these institutional frameworks, ensuring that replenishment initiatives are economically viable and environmentally sound. The synthesis of global and Indian experiences underlines that addressing groundwater depletion is not just a local or national concern; it demands a coordinated global effort centered on rights, responsibilities, and technological innovation.

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Appendix

Table 1. Extraction Rate of Groundwater in India in 2016-17

State	**Extraction Rate (%)**
Andaman And Nicobar Islands	2.90
Andhra Pradesh	0.95
Arunachal Pradesh	0.28
Assam	11.25
Bihar	45.76
Chandigarh	89.04
Chhattisgarh	44.43
Dadra And Nagar Haveli	31.34
Daman And Diu	0.60
Delhi	119.61
Goa	33.50
Gujarat	63.89
Haryana	137.14
Himachal Pradesh	86.37
Jammu And Kashmir	28.06
Jharkhand	27.73
Karnataka	0.80
Kerala	51.27
Lakshadweep	65.99
Madhya Pradesh	54.78
Maharashtra	0.51
Manipur	1.43
Meghalaya	2.28
Mizoram	3.82
Nagaland	0.99
Odisha	42.18
Puducherry	74.33
Punjab	164.97
Rajasthan	224.40
Sikkim	0.06
Tamil Nādu	80.94
Telangana	NA
Tripura	7.88
Uttar Pradesh	70.18
Uttarakhand	0.71
West Bengal	44.60

Table 2. Extraction Rate of Groundwater in India in 2022-23

State	Extraction Rate (%)
Andaman And Nicobar Islands	1.37
Andhra Pradesh	28.30
Arunachal Pradesh	0.42
Assam	12.58
Bihar	44.76
Chandigarh	75.41
Chhattisgarh	47.17
Dadra And Nagar Haveli	131.53
Daman And Diu	170.70
Delhi	99.13
Goa	21.37
Gujarat	51.68
Haryana	135.74
Himachal Pradesh	34.95
Jammu And Kashmir	24.20
Jharkhand	31.38
Karnataka	66.26
Kerala	54.55
Ladakh	37.05
Lakshadweep	61.72
Madhya Pradesh	58.75
Maharashtra	53.83
Manipur	7.99
Meghalaya	4.58
Mizoram	3.70
Nagaland	3.76
Odisha	46.33
Puducherry	70.27
Punjab	163.76
Rajasthan	148.77
Sikkim	5.54
Tamil Nādu	73.77
Telangana	38.65
Tripura	9.92
Uttar Pradesh	70.76
Uttarakhand	51.69
West Bengal	44.81