

Analysis of the water scarcity problem : Factors, impacts and engineering strategies for conservation

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Abstract

This review analyses India's water crisis by examining factors, impacts and engineering strategies through literature from 2000-2025. It identifies climate-induced hydrological stress, unsustainable groundwater extraction, rapid urbanization, and inefficient water infrastructure as key drivers of water scarcity. Impacts on food security, health, and migration are discussed with respect to the India's water-energy-food nexus. Promising solutions include micro-irrigation, fertigation, decentralized wastewater treatment, permeable pavements, desalination, and aquifer recharge systems, all showing strong potential for scale-up. The findings aim to guide planners, engineers, and policy makers towards innovation-driven and participatory water management aligned with SDG 6, while offering transferable strategies for global stakeholders seeking secure and sustainable water future.

Subject Classification: 76B05, 93A30.

Keywords: *Water conservation technologies, Water scarcity, Engineering interventions in water management, Integrated water management, SDG6.*

1. Introduction

Water scarcity is a critical 21st-century challenge, with predictions suggesting it could trigger future global conflicts. In India, a highly populous nation, its implications are especially severe. Scarcity is categorized as physical (due to arid environments, salinity, or inaccessibility) or economic (stemming from mismanagement, political/ethnic conflicts, or neglect) [1], [2], [3]. It manifests in varying degrees—absolute, chronic, seasonal, temporary, or life-threatening—and is measured by per capita annual water availability (PCWA) [4]. Regions are classified as water-stressed (<2000 m³), regularly stressed (1000–1700 m³), chronically scarce (500–1000 m³), or severely scarce (<500 m³) [5], [6]. Although indices like WSI, WPI, and WTA exist, India's Ministry of Jal Shakti adopts PCWA as the standard [7].

India's PCWA has declined from 1900 m³ (2001) to 1,545 m³ (2011) and ~1,368 m³ (2019) [7]. A 2019 NITI Aayog report noted nearly 600 million people face high to extreme water stress, while projections suggest only 50% of required supply will be available by 2030. Quality exacerbates the crisis: India ranks 120th of 122 on the water quality index, with ~70% of supplies polluted [7], [8], [9], [10]. By 2030, over 500 million may lack drinking water access. Even where scarcity isn't perennial, seasonal shortages persist. Globally, two-thirds of people face severe scarcity at least 30 days yearly, half of them in India and China [8]. This study reviews factors, impacts, and engineering strategies to advance SDG 6 through informed technology and policy adoption.

2. Methodology

This study reviews literature (2000–2025) on water scarcity, conservation engineering, and management in India. Using databases like Scopus, Web of Science, and Google Scholar, over 120 peer-reviewed English sources were selected based on relevance to India, empirical/engineering focus, and full-text availability. Commentaries and purely theoretical works were excluded. Literature was categorized into drivers, impacts, governance/management interventions, and engineering solutions, with emphasis on 2021–2025 innovations such as IoT monitoring, decentralized wastewater treatment, and renewable-powered desalination, ensuring an evidence-based, contextually relevant review for Indian water conservation practice.

3. Literature Review

National and global literature on water scarcity and related aspects from 2000 to 2025 was reviewed to understand the nuances of the problem. Socio-economic, political, technological and managerial aspects were found to have been discussed for water challenges at rural and urban level. The findings of the review have been presented below.

3.1 *Macro-Level Drivers and Global/National Policy Perspectives (2000–2009)*

Early 21st-century research in India framed water scarcity as a structural, macro-level, supply-side management challenge [11], [12], [13], [14], [15], [16], [17]. Kumar, Singh, and Sharma [12] analyzed Gujarat's scarcity using Falkenmark's definitions, advocating governance reforms, decentralization, and demand management. Mehta [13], [14] critiqued scarcity narratives in Kutch, arguing that drought and declining rainfall were sometimes instrumentalized to legitimize large dams and construct dominant perceptions—a process termed “Naturalization of Scarcity.” Kumar, Singh, and Sharma [12] examined India's water availability versus demand, promoting a holistic approach that integrates blue and green water flows to meet current needs without compromising future sustainability. Other scholars reviewed scarcity metrics and their limitations, assessed Integrated Water Resource Management (IWRM) in India against global efforts, and warned against overestimating utilizable water resources [11], [12], [13]. Together, these works underscored the urgency of rethinking India's water crisis through integrated, evidence-based strategies

3.2 *Micro-Level Drivers, Demand-Side Management, and Emerging Technologies (2013–2025):*

From the early 2010s, literature shifted toward micro-level drivers, localized impacts, and demand-side management, alongside engineering and technological interventions [18], [19], [20], [21], [22], [23], [24], [25], [26]. Studies reviewed India's surface and groundwater trends amid floods, droughts, and climate change [18], and mapped post-monsoon groundwater deficits in Osmanabad, Maharashtra, to guide local emergency responses [19]. Research linked hydroclimatic variation, cropland expansion, and agricultural practices to 20th-century food self-sufficiency [20], while others highlighted smart water technologies and cautioned that inter-basin transfers may harm water-scarce importing regions. Emphasis grew on water quality alongside quantity, advocating desalination and treated water to advance SDG 6 [21]. An improved Water Poverty Index confirmed water access–development links [22], and trade analyses exposed scarcity-driven inequities [23]. Health studies in northeastern India revealed negative associations between maternal water-collection time and well-being [24], [25]. Collectively, this work underscores localized, technological, and demand-side responses while reaffirming the need for macro-level reform.

3.3 *Urban and Rural Dimensions: A Synthesis*

The literature reveals interlinked urban and rural dimensions of water scarcity. Urban studies highlight infrastructural and behavioral drivers—intermittent supply, ageing pipes, distribution losses, overloaded sewage/stormwater systems, and rising per-capita consumption tied to industrialization and lifestyle changes. Rural studies emphasize resource-level drivers: groundwater over-extraction for irrigation, shifts to water-intensive crops, and limited access to modern irrigation among smallholders. These dimensions are interdependent: urban demand often draws from rural/peri-urban catchments, while agricultural water stress fuels rural-to-urban migration, intensifying urban demand. This supports an integrated, not siloed, rural–urban governance and engineering approach.

3.4 *Research Gap*

Despite extensive literature, an integrated overview of contemporary challenges, causes, effects, and engineering solutions to water scarcity—critically evaluating adoption barriers and governance gaps across rural

and urban India—remains absent. This study addresses that gap by offering a holistic, critically evaluated account of India's ongoing water crisis, bridging fragmented rural and urban perspectives to inform more coherent policy and engineering interventions.

4. Discussion

4.1 *Important factors leading to water scarcity*

As per a World Bank Report, the 21st century has experienced warming levels of 1.5°C-4°C. leading to the flood-drought dichotomy, due to change in rain patterns caused by climate change [27]. The present urban water management infrastructure lacks resilience against such shifts leading to unanticipated water scarcity [28].

Agriculture sector directly bears the brunt of such climate change impacts, and in turn leads to cyclic impacts on the already critical water resources. Studies have shown the huge impact of climate change on various vital crops like wheat and rice [29]. This further causes the farmers to opt for groundwater exploitation to meet their immediate demands [30]. Besides, agricultural pollution caused due to use of chemicals in farming leads to further deterioration of surface and groundwater resources. Further, organic contaminants from agricultural activities like livestock rearing also add to existing water pollution [31]. Lately, the choice of water-guzzling crops to increase economic benefits of farming has also exerted additional pressure on the water resources of India [32].

Globally, rising urban populations are exacerbating water scarcity due to increased demand from domestic use, industry, and food production. Urban areas face additional challenges from water loss during transportation, groundwater over-exploitation, pollution, and wastage stemming from inefficient supply and drainage systems. India faces particularly severe issues, with millions experiencing water scarcity, a situation expected to worsen with continued urban growth [33], [34].

Ill-managed Industrialization leads to water scarcity through unchecked exhaust of liquid pollutants that degrade surrounding land and water resources, rendering it unusable [35]. Large industries often extract excessive water via private borewells, sometimes violating legal mandates [36]. At times, water-intensive industries are set-up without hydrogeological assessment disrupt regional water balance causing surface and groundwater scarcity [37].

Inadequate urban water Infrastructure leads to wastewater management challenges leading to regional and economic water scarcity.

Outdated or poorly maintained treatment plants release substandard effluent, while inefficient sewerage systems cause water pollution [38], [39]. Poorly constructed pipes leaks billions of gallons annually, compounding the water losses [40].

In India, the artificial divide between groundwater and surface water has been a key political driver of cumulative mismanagement of the water resources. As highlighted by the Mihir Shah Committee, treating these two resources independently due to insufficient hydrogeological analysis ignores their interconnected hydrogeological cycles [41], [42].

Sectors impacted by water scarcity

The Agricultural sector is both a contributor to and a major victim of water scarcity. Direct impacts include crop failure in vital staples like paddy, wheat, and sugarcane [43], which can reduce national food production and deepen socio-economic imbalances [44]. In severe cases, regional water reallocation constraints cause large negative GDP deviations and ripple effects on global economics [45]. Virtual water scarcity risk in agricultural exports, including from India, underscores these global economic implications [46]. Livestock-dependent occupations also suffer, triggering migration that weakens source-state economies [43], [44], [45], [46], [47].

Water scarcity fuels socio-economic instability at national and international levels. Regionally, it sparks intra-state conflicts that can escalate into inter-state disputes over shared rivers, as seen across India [48]. Unmitigated, these tensions have provoked protests, violence, and property destruction [49]. At a systemic level, extreme scarcity can disrupt the global trade system by unsettling food production, manufacturing, and services [50]. Non-food sectors—land transport, construction, beverages, electricity, and forestry—face indirect economic vulnerability [49], [50].

The health sector bears direct hits through reduced water quantity, quality, and access [51]. Water-related diseases are widespread in populous, fast-growing economies like India [52]. Industrial mismanagement releases toxic chemicals, radioactive sludge, sulphur, asbestos, and solvents, causing anemia, low platelets, headaches, cancer, and skin diseases. Agricultural wastewater and poor management pollute soil and water, undermining food safety and health [52], [53]. In arid regions, dehydration and related conditions rise; in saline areas, distinct

health risks emerge [54]. Domestic scarcity compromises hygiene and sanitation, increasing susceptibility to infectious diseases [54], [55].

Migration is a significant consequence, with water scarcity acting as a key push factor across India. Migrants, already vulnerable in an overpopulated context, face economic instability due to environmental dependence, social insecurity exacerbated during crises like the pandemic, and constitutional inequities [56], [57], [58], [59], [60], [61]. This cycle amplifies urban pressures, health hazards, and social conflict.

4.2 Mitigation strategies to deal with water scarcity

Evolving agricultural practices are central to mitigating water scarcity in rural India. Key measures include optimizing irrigation patterns, crop rotation, and crop switching to lower soil and crop water requirements. Conservation agriculture, particularly conservation tillage, retains moisture and prevents erosion, cutting water use by up to 50% versus conventional methods [62], [63], [64]. Mulching in drylands reduces evaporation, moderates temperature, and maintains soil moisture. Combined, these practices yield multiplicative water-saving effects. Solar pumping further benefits the groundwater economy by lowering policy burdens, carbon footprints, and over-exploitation linked to subsidized electricity [65], [66], [67].

Sustainable urban water management must address industrial and domestic consumption simultaneously [65]. For industry, priorities include advanced wastewater treatment, recycling and reuse, infrastructure repair, conservation measures, and robust pollution monitoring. Domestically, installing household water meters raises awareness and responsiveness; replacing intermittent with continuous distribution curbs wastage; promoting water-efficient fixtures via policy reduces leakage losses; and legislating green building norms while informing RWAs enhances adoption. At city scale, urban planning should integrate stormwater networks for sustainable groundwater recharge during floods [68], [69], [70], [71], [72].

Integrated water management offers a comprehensive framework that complements rural and urban strategies [73]. Urgent actions include curbing groundwater exploitation and accelerating recharge, leveraging domestic and international virtual water trade for conservation, and implementing proven water-pricing mechanisms in agriculture and households. Success hinges on participatory design to ensure stakeholder

proactivity and on aquifer-level hydrogeological studies to ground planning in evidence [74], [75], [76], [77].

4.3 *Engineering and Technological Solutions*

Recent literature highlights technological innovations—smart monitoring, decentralized wastewater treatment, renewable-powered desalination, and permeable pavements—as key to managing India’s water scarcity. These solutions enhance efficiency, reuse, and recharge while reducing reliance on centralized infrastructure and improving climate adaptability. Table 1 (2019–2025) summarizes their benefits, limitations, and sources.

Technological interventions for water scarcity are context specific. In rural areas—where land is available, but capital is limited—micro-irrigation, fertigation, groundwater recharge, community rainwater harvesting, and low-energy natural treatment systems are most appropriate. Urban settings prioritize infrastructure efficiency and reuse, favoring decentralized wastewater treatment, IoT-based leak detection, and permeable pavements. Coastal and arid regions benefit most from hybrid renewable-powered desalination.

Evidence indicates a trade-off between accessibility and performance: decentralized, low-tech solutions (rainwater harvesting, recharge structures, mulching, conservation tillage) require lower upfront investment and scale more easily in resource-constrained rural contexts, though their effectiveness is site- and season-dependent. High-tech options (IoT monitoring, renewable desalination, industrial recycling) deliver larger, more consistent efficiency gains but demand higher capital, technical capacity, and—for desalination—careful management of brine disposal impacts.

A well-integrated approach combining engineering design with socio-institutional participation, aligned to local hydrogeology, is essential for sustainable outcomes. The proposed four-layer framework links Drivers (climate variability, over-extraction, urbanization, industrialization, infrastructure deficits) to cascading Impacts (agriculture, health, migration, socio-economic stability), then to Engineering and Policy Interventions, and finally to Sustainable Outcomes (reduced stress, resilience, SDG 6 progress). These layers are interdependent: interventions ignoring governance contexts or adoption barriers are unlikely to succeed. Effective governance and government leadership remain critical to implementing these strategies [92].

Table 1
Latest technological interventions in literature and related important insights

Technology/ Approach	Key Findings/ Demonstrated Benefits	Limitations/ Challenges	Doc Ref
Decentralized Wastewater Treatment (DEWATS)	- Reduces centralized load by 30-40% - Enhances localized reuse and nutrient recovery	- Performance declines without skilled operators - Routine O&M required	[78], [79]
Rainwater Harvesting (RWH)	- Cost-effective in dense urban setting - Domestic RWH can meet 25-40% of annual water demand	- Requires rooftop filtration and maintenance - Seasonal reliability	[80], [81]
Natural Treatment Systems (Constructed Wetlands, Bio-filters)	- Ideal for peri-urban zones 60-90% nutrient removal with low-energy use	- Limited efficiency for industrial effluents - Large land requirements	[82]
Desalination (Solar /Hybrid Systems)	- Suitable for Coastal belts - Renewable-powered RO and MSF units cut energy cost by 20-35%	- Brine disposal issues - High initial capital	[83], [84]
Permeable/ Pervious Pavements	- Reduce urban runoff and flooding by up to 70% - Improve groundwater recharge	- Requires periodic cleaning - Clogging and strength reduction over time	[85]
IoT-based Smart Water Monitoring	Reduction in water losses by 15-25% due to real-time leak detection and flow optimization	- Data reliability concerns - High installation costs	[77], [86]
Micro-irrigation and Fertigation	- Yield improvement of 10-20% - Water savings of 30-50%	- Limited adoption amongst small land holders - Up-front cost impacting adoption	[87], [88], [89]
Groundwater recharge structures (Percolation wells, Infiltration trenches)	- Low-cost technology - May raise water table locally by 1-2m within two recharge seasons	Site-specific hydro-geology limits replication without customization	[77], [90]
Water recycling in industries	Closed-loop reuse systems reduce up to 60% fresh-water intake	Retrofitting in older plants in comparatively technically complex	[90], [91]

4.5 *Critical Analysis: Barriers, Trade-offs, and Case Evidence*

Although micro-irrigation and fertigation deliver 30–50% water savings [87], [88], [89], adoption among smallholders remains low due to structural barriers: fragmented landholdings weakening investment incentives, limited credit access, delayed subsidies, inadequate extension support, and smallholders' risk aversion. Overcoming these constraints demands financing and extension-service reforms alongside technical improvements.

Decentralized systems such as DEWATS and constructed wetlands illustrate a related institutional barrier: their performance depends on consistent operation and maintenance [77], [79], yet rural and peri-urban local bodies frequently lack dedicated technical staff, and responsibility for upkeep is often unclear between municipal and panchayat-level institutions. Without a clear revenue or cost-recovery model, decentralized infrastructure risk falling into disrepair once initial project funding ends — a documented failure mode distinct from, but related to, the technical limitations noted in Table 1.

IoT-based monitoring and renewable-powered desalination, conversely, face barriers rooted in capital intensity and technical capacity rather than land fragmentation: high installation costs restrict deployment to better-resourced municipalities [86], [93], and desalination's viability depends on both coastal proximity and consistent renewable energy supply to offset its otherwise high operating costs [83], [84].

Case evidence in the literature illustrates that these barriers are not insurmountable where governance design is deliberately participatory. Varma et al. [78] recommended a participatory design approach to addressing the water crisis in the village of Karkatta, Jharkhand, in which community involvement in planning and implementation supported more durable adoption of interventions than a purely top-down technical approach [93]. By contrast, district-level analysis of Osmanabad, Maharashtra, illustrates how, absent similarly integrated local institutional capacity, technically sound data on scarcity-affected areas does not by itself translate into effective mitigation without a corresponding local delivery mechanism [18]. Read together, these cases suggest that the primary determinant of whether an engineering intervention succeeds at scale is less its technical performance than the strength of the local institutional and participatory arrangements surrounding it—a conclusion reinforced by the wider governance evidence discussed in Section 4.6.

4.6 Policy, Governance, and Institutional Dimensions

Although governance is widely acknowledged as important in the literature reviewed, it is often treated as a background condition rather than analyzed in its own right. Several specific policy gaps and institutional challenges deserve closer attention.

First, the historical separation of groundwater and surface water governance — groundwater has traditionally been treated in India as a private, land-linked resource with comparatively weak regulatory oversight, while surface water is managed as a state (and, for inter-state rivers, contested inter-state) resource—has produced fragmented and at times contradictory management outcomes, as identified by the Mihir Shah Committee [94] and discussed further by Vyas and Nath [95]. Second, enforcement gaps persist around private and industrial groundwater extraction, with many large users operating without effective monitoring even where formal permitting requirements exist [35], underscoring a gap between policy design and on-the-ground enforcement capacity. Third, water-pricing mechanisms—despite consistent recommendation in the literature as a demand-management tool [77], [87] — remain politically difficult to implement at scale in both agricultural and domestic contexts, reflecting the socio-political sensitivity of water as a resource rather than a purely technical or economic constraint.

Successful governance models do exist and merit wider replication. Community-based and participatory groundwater management approaches—exemplified in the literature by the Jharkhand case discussed above [78]—demonstrate that decentralization and demand management, as advocated early in the literature by [14], and can be operationalized effectively at the local level when supported by appropriate institutional design. At the national policy level, India's Atal Bhujal Yojana scheme for community-led groundwater management represents a broader institutional attempt to formalize this participatory model, illustrating that the governance gap identified in this review is increasingly, if unevenly, being addressed at the policy level [96]. Strengthening the link between such national schemes and the technology-adoption barriers discussed in Section 4.5—for instance, by channeling micro-irrigation subsidies and extension support through the same community institutions established for groundwater management — represents a practical governance opportunity that is currently under-explored in the literature.

4.7 Empirical Snapshot: Current Groundwater and Access Data

The discussion above (Sections 4.1-4.6) draws primarily on the peer-reviewed literature identified through the search strategy in Section 2. To further ground the macro-level and micro-level drivers discussed in Sections 3.1-3.2 and 4.1 in current, real-time administrative data, this subsection presents a compact empirical snapshot compiled from official Government of India sources - principally the Central Ground Water Board (CGWB), Ministry of Jal Shakti, and the Jal Jeevan Mission dashboard - current as of the most recent public releases available at the time of writing (2024-2025 assessment cycles)[10], [92], [96], [97], [98], [99]. These data are presented to complement, rather than replace, the peer-reviewed evidence base, and are discussed critically rather than at face value.

Table 2
National Groundwater Balance, India (2017-2024)

Assessment Year	Annual Recharge (BCM)	Annual Extractable Resource (BCM)	Annual Extraction, all uses (BCM)	Stage of Extraction (%)	Over-Exploited Units (%)
2017	431.9*	392.7*	248.69	63.33%	17.24% (1,186/6,881)
2020	436.15	397.62	244.92	61.60%	n/a (pre-annual cycle)
2022	437.6	398.08	239.16	60.08%	14.19% (1,006/7,089)
2023	449.08	407.21	241.34	59.26%	11.23% (736/6,553)
2024	446.9	406.19	245.64	60.47%	11.13% (751/6,746)

*2017 recharge and extractable-resource Figures are derived from the officially reported year-on-year deltas (CGWB reports that 2024 recharge exceeds 2017 recharge by 15 BCM, and that the extractable resource in 2017 corresponds to a stage-of-extraction of 63.33% on an extraction of 248.69 BCM); they are not independently published as headline figures in the same format as 2020-2024 and are marked here as derived rather than directly reported. Sources: CGWB National Compilation on Dynamic Ground Water Resources of India (2017, 2022, 2023, 2024); Ministry of Jal Shakti parliamentary reply reproducing the 2020-2024 comparative table [10], [91], [92], [96], [97], [98], [99].

Note that the assessment methodology moved from periodic (roughly triennial) to annual cycles from 2022 onward, and the number of assessment units itself changed across cycles (6,881 in 2017 to 6,746 in 2024) as delineation was refined - a data-comparability caveat that should be read alongside the trend itself.

4.7.1 Macro-Level Validation: National Groundwater Balance Over Time

Table 2 presents the national groundwater balance as jointly assessed by CGWB and State/UT Ground Water Departments across five assessment cycles. It provides direct, current validation of the macro-level structural narrative developed in Sections 3.1 and 4.1: national extraction has remained in the 60% range of extractable resources for nearly a decade, with only gradual improvement.

4.7.2 State-Level Panel: Regional Disparities Behind the National Average

The national average in Table 2 masks sharp inter-state disparity, which is the empirical basis for the ‘regional inequality’ point raised in Section 4.6. Table 3 presents the stage-of-extraction category for major states across three assessment cycles, together with exact figures where officially reported.

Table 3
State-Wise Stage of Groundwater Extraction - Panel Across Assessment Cycles

State	2017 Category	2022 Category	2023/24 Category	2023/24 Detail (where reported)
Punjab	Over- Exploited	Over- Exploited	Over- Exploited	SoE 163.76%; recharge 18.84 BCM, extractable 16.98 BCM, extraction 27.8 BCM (2023)
Rajasthan	Over- Exploited	Over- Exploited	Over- Exploited	SoE 148.77%; extraction 16.74 BCM against recharge 12.45 BCM (2023)
Haryana	Over- Exploited	Over- Exploited	Over- Exploited	SoE 135.74%; recharge 9.55 BCM, extractable 8.69 BCM, extraction 11.8 BCM (2023)
Delhi	Over- Exploited	Over- Exploited	Over- Exploited	Only 5 of 12 districts exceed 100% SoE; high intra-city variation
Dadra & Nagar Haveli / Daman & Diu	Over- Exploited	Over- Exploited	Over- Exploited	Categorical (2024 CGWB report)

Contd...

Tamil Nadu	Critical/ Over- exploited (>25% of units)	Semi- Critical (national average)	Semi- Critical	70-90% band nationally; Chennai city itself over- exploited (see Table 4)
Uttar Pradesh	Critical/ Over- exploited (western UP pockets)	Semi- Critical (national average)	Semi- Critical	Western UP districts remain over-exploited within an overall semi- critical state average
Karnataka	Critical/ Over- exploited (>25% of units)	Mostly Safe (pockets over- exploited)	Mostly Safe	Bengaluru city itself over-exploited at 186.7% (2023-24)
Gujarat	Critical/ Over- exploited (arid west)	Mostly Safe (pockets over- exploited)	Mostly Safe	Arid western districts and Ahmedabad remain semi-critical to over- exploited
Maharashtra	Safe (state average)	Safe (state average)	Safe	State average ~54%; Marathwada and parts of western Maharashtra remain critical
Andhra Pradesh, Assam, Bihar	Safe (state average)	Safe (state average)	Safe	Below 70% state average in all three assessment cycles

Sources: CGWB National Compilation reports (2017, 2022, 2023, 2024); The Tribune (2024) reporting CGWB 2023 state-level BCM figures for Punjab, Haryana, and Rajasthan [100], Vision IAS and Gokulam IAS current-affairs summaries of the 2024 CGWB report's state categorisation (as summarized from [99]). Where exact BCM figures were not independently located for a given state and cycle, the officially reported categorical status (Safe / Semi-Critical / Critical / Over-Exploited) is presented instead of an estimated figure, to avoid overstating precision.

4.7.3 Urban Dimension: City-Level Groundwater Stress

Table 4 disaggregates the state-level picture in Table 3 to the city level, providing direct empirical support for the urban-dimension argument developed in Section 3.3: several state averages classified as 'Safe' or 'Semi-Critical' conceal severely over-exploited metropolitan cores.

Table 4
City-Level Groundwater Extraction Stage (2023-24)

City	Groundwater Extraction Stage	Category	Contextual Note
Bengaluru	186.70%	Over-Exploited	2023 El Nino-linked rainfall deficit; heavy private tanker dependence
Delhi	>100% (5 of 12 districts)	Over-Exploited	Sharp intra-city variation by socio-economic district
Chennai	127.5% (2023)	Over-Exploited	Agricultural competition in Kaveri basin; coastal seawater intrusion
Hyderabad	Over-Exploited (exact % not separately published)	Over-Exploited	Rising industrial and domestic draw; state (Telangana) average is comparatively low
Ahmedabad	Semi-Critical (exact % not separately published)	Semi-Critical	Better positioned than the four over-exploited metros above
Pune	Safe (exact % not separately published)	Safe	Comparatively higher reliance on surface water
Mumbai	Safe (exact % not separately published)	Safe	Comparatively higher reliance on surface water

Source: OpenCity.in (2025) analysis of CGWB city/district-level 2023-24 data [101]. Precise percentage figures for Hyderabad, Ahmedabad, Pune, and Mumbai were not independently located in the secondary sources reviewed and are reported here only at the categorical level to avoid fabricated precision; readers seeking exact city-level BCM figures should consult the underlying CGWB district-wise reports directly.

4.7.4 Micro-Level, Demand-Side Validation: Rural Tap Water Access (Jal Jeevan Mission)

Table 5 tracks the rural tap-water connection rate under the Jal Jeevan Mission (JJM), the principal ongoing government program addressing the rural, demand-side dimension of water access discussed in Sections 3.2, 3.3, and 4.2 (including the gendered water-collection burden). The consistent upward trend supports the literature's identification of rural water access as an area of substantial, if incomplete, policy progress since 2019.

Table 5
Rural Household Tap-Water Connection Coverage under Jal Jeevan Mission

Date	Rural Households with Tap Connection	Coverage (%)
15 August 2019 (launch)	3.23 crore	17%
01-Feb-25	15.44 crore	79.74%
22-Oct-25	15.72 crore	>81%
15-Dec-25	15.76 crore (of 19.36 crore total)	81.42%

Note: Leading states/UTs (>97% coverage, as of the most recent reporting): Goa, Gujarat, Andhra Pradesh, and several Union Territories. States with comparatively low rural coverage include parts of the North-East and states with more difficult terrain or more recent programme rollout; urban-heavy Union Territories such as Delhi (45%) and Chandigarh (50%) report lower figures for a different reason - JJM's mandate is specifically rural, and these UTs have a very small rural household base, so the low percentage reflects programme scope rather than rural service failure. A 2024 government functionality assessment found that although coverage (infrastructure installed) approached 98%, only around 83% of 'covered' households had actually received water through the tap at least once in the preceding seven days - an important distinction between infrastructure coverage and functional service delivery that should qualify any policy claims based on the headline coverage percentage alone.

Sources: PIB press releases (2025) [97], [99]; Jal Jeevan Mission dashboard/IMIS; data.gov.in Rajya Sabha reply dataset.

The success of any of the above mitigation and engineering strategies against water scarcity hugely depends on the necessary governance and the role of government as a vital stakeholder.

5. Implications

This review's findings imply that state frameworks should mandate water audits, demand–supply mapping, and aquifer-based planning to institutionalize integrated water management. Decentralized systems like rainwater harvesting and greywater reuse ought to be incentivized via fiscal and regulatory tools that address adoption barriers—bundling subsidies with extension support and simplified credit, not just cost reductions. Municipal programs should deploy innovations (micro-irrigation, pervious pavements, solar desalination, IoT leak detection) while building local operation-and-maintenance capacity. Energy–water synergies, low-cost maintenance models, and genuine community participation must be embedded in pilots, with clear pathways to scale. Strengthening on-ground capacity through training engineers, planners,

and community practitioners—especially in participatory design—is critical for sustained success.

6. Future Research Directions

Future research on India's water scarcity should prioritize: (a) long-term life-cycle economics of decentralized technologies (DEWATS, permeable pavements, IoT monitoring) across diverse settings; (b) institutional design features sustaining community-managed systems post-funding; (c) socio-economic and behavioral studies on credit, tenure, and extension barriers limiting smallholder adoption of micro-irrigation; (d) integrated decision-support tools combining hydrogeological, economic, and social data for aquifer/basin-scale planning; (e) climate-resilience assessments of interventions under variable rainfall and climate scenarios; (f) gender-disaggregated research on water-collection burdens

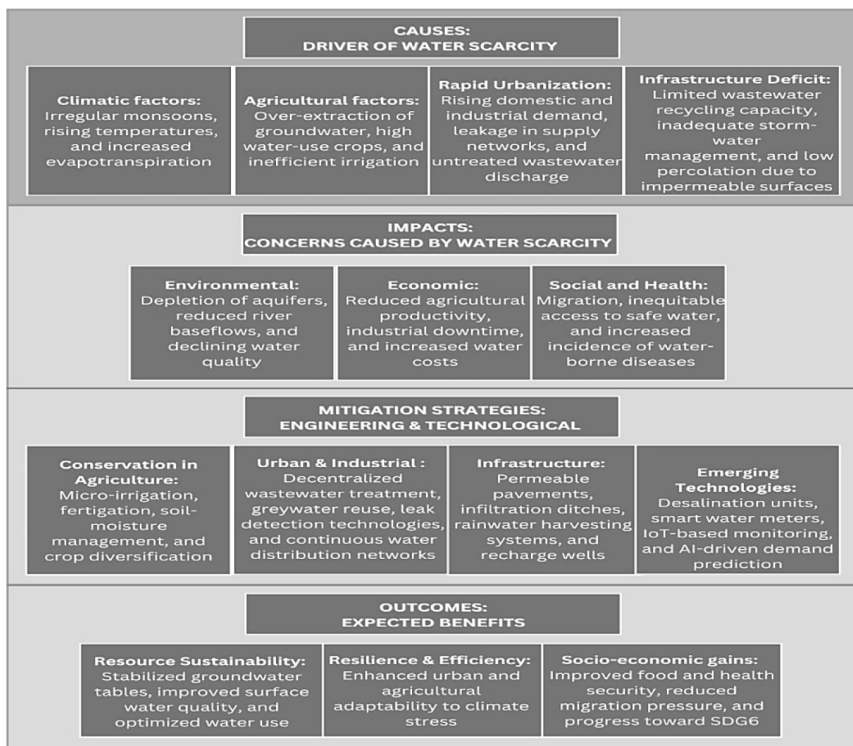


Figure 1

Proposed Framework for Water scarcity Problem in India

and impacts on women's health, education, and economic participation; and (g) empirical studies on integrating groundwater-surface water governance and linking national schemes with local technology-adoption incentives. The Causes, drivers and impacts of water scarcity is already discussed in the literatures. Also the mitigation strategies and expected benefits are also highlighted in the literature. The synthesis of both the problem, mitigation strategies along with the expected outcomes is presented in Figure 1.

7. Limitations of the Review

This narrative review has four key limitations. First, it follows a systematic search and thematic categorization but not a formal protocol (e.g., PRISMA), so screening and risk-of-bias assessments are not fully reproducible. Second, it relies solely on secondary literature, lacking primary field data or stakeholder interviews to validate adoption-barrier and governance analyses (Sections 4.5–4.6). Third, its India-centric focus means applicability to other developing-country contexts remains unverified. Fourth, heterogeneity in cost, performance, and scale metrics across studies prevented quantitative meta-analysis; thus, Section 4.4's cost-effectiveness discussion is an interpretive synthesis, not a pooled estimate. These limitations motivate the future research priorities outlined in Section 6.

8. Conclusion

India's water crisis stems from climatic variability, unplanned urbanization, unsustainable agriculture, and inefficient infrastructure, with fragmented responses worsening the cycle. Effective mitigation requires coupling governance and policy reforms with context-specific engineering solutions: advanced irrigation, groundwater recharge, and community rainwater harvesting in rural areas; wastewater recycling, IoT leak detection, and pervious-pavement stormwater management in urban settings. Strengthening links among scientific innovation, hydrogeological assessment, stakeholder participation, and regulation can enhance resilience. Future research should prioritize cost-effective, institutionally durable decentralized systems; rigorous cost-benefit and performance evaluations; and gender- and equity-responsive policy design. Embedding these conservation-engineering principles with governance reforms can advance sustainable stewardship and timely SDG 6 achievement.

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