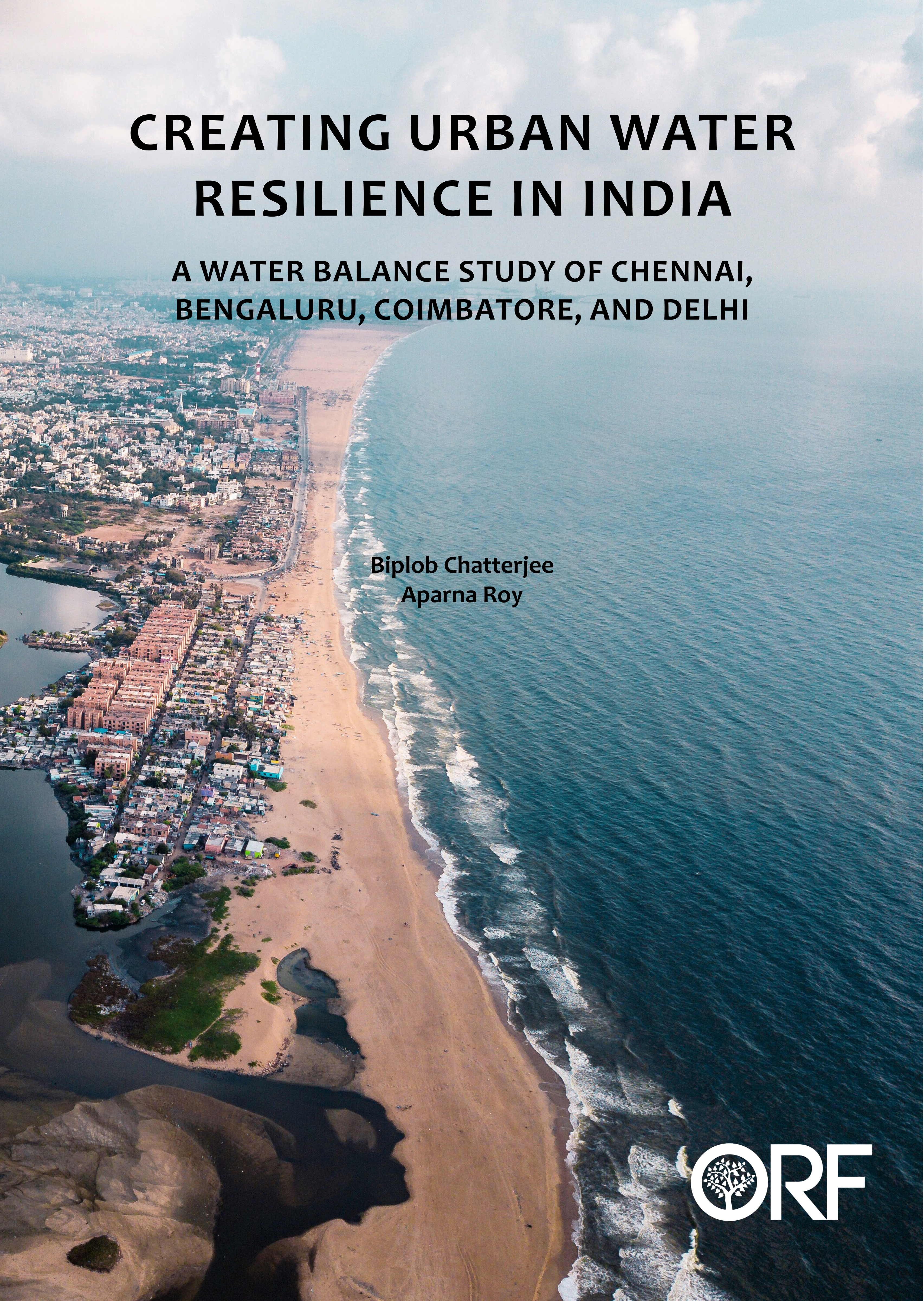

CREATING URBAN WATER RESILIENCE IN INDIA

A WATER BALANCE STUDY OF CHENNAI, BENGALURU, COIMBATORE, AND DELHI

Biplob Chatterjee
Aparna Roy

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Disclaimer: The secondary data used in the report have been acquired from multiple sources, both government and non-government, which are available in the public domain and have been referenced to the best possible. The authors acknowledge that some of the data, including government data, do suffer from lack of accuracy and auditability.

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ABSTRACT

ABSTRACT

The 2021-22 Union Budget announced the launch of the Jal Jeevan Mission (Urban), an ambitious project that aims to provide potable tap water supply to 2.86 crore households by 2024. Even as the programme takes shape, much of urban India continues to face severe water stress conditions due to rapid urbanisation, negligible augmentation of raw water sources, archaic water infrastructure and poor water governance. This study attempts to contribute to the mission's objective by analysing the gaps and constraints in the current urban water balance and the city water budgeting process. Based on primary and secondary data, the study comprehensively analyses the water supply and demand scenarios in four water-stressed cities—Chennai, Coimbatore, Bengaluru and Delhi. A detailed situation analysis has been carried out to map the current scientific understanding of the available water resource (surface and groundwater), its utilisation, the supply infrastructure, available alternative raw water sources, the wastewater discharge and its treatment and reuse, if any. The established processes of urban water balancing and budgeting have been adopted to assess the water supply deficits corresponding to current utilisation and projected future water demand. As global climate change impacts loom large, if India were to succeed in its mission to provide potable tap water to all, not only will it be a domestic game-changer but will also serve as a model for other developing nations.

EXECUTIVE SUMMARY

Much of urban India faces severe water stress conditions due to rapid urbanisation and population growth, coupled with negligible corresponding additions to raw water sources, archaic water infrastructure and governance issues. A substantial number of India's 377 million urban residents face water shortages, while about 200,000 die each year from inadequate or unsafe water supplies.[1] The further deterioration of India's water resources will have ramifications on the health, safety and sanitation needs of its people. This study attempts to establish if a comprehensive water balance approach along with integrated urban water management practices could be the solution to India's urban water woes. Based on primary and secondary data, this study undertakes a comprehensive analysis of the water supply and demand scenarios in four water-stressed cities in India—Chennai, Coimbatore, Bengaluru and Delhi. It analyses the key aspects of urban water management—water source security, distribution, losses due to leaky infrastructure, demand management, water budget optimisation and prudent water governance.

A detailed situation analysis suggests that while Chennai, Bengaluru and Delhi have been constrained by space for growth, Coimbatore has been able to amalgamate large peri-urban areas within the city limits. The populations of Bengaluru grew from about 10,000 per square kilometre in 2001 to 15,000 square kilometre in 2020; of Delhi grew from about 14,000 per square kilometre in 2001 to 20,000 per square kilometre in 2020; and of Chennai increased from approximately 24,000 per square kilometre in 2001 to approximately 47,000 per square kilometre in 2020. However, the population of Coimbatore declined from about 15,000 per square kilometre in 2001 to about 11,000 per square kilometre in 2020. Given their decades-old water supply and sewerage infrastructures, all four cities are dependent on captive sources of raw surface water. Coimbatore and Chennai's captive storages are in the same river basins that drain the two cities, making them vulnerable to unpredictable climate change impacts. Bengaluru and Delhi, on the other hand, draw piped water from extra-basinal captive sources. With between 20 percent to 50 percent water leakages in these four cities, the resultant reduced per capita raw water availability ranges between approximately 10,000 and 30,000 litres per annum. Large peri-urban and slum areas in all four cities do not have piped water supply. Uncertain and low per capita water availability means an increased reliance on groundwater at a unit dwelling level. Between 10 percent to 30 percent of the net raw water resource comes from groundwater in these cities. However, all four cities are currently mining groundwater at 130 percent to 170 percent of the annual dynamic recharge.

Most Indian cities conduct limited or no segregation of grey and black water discharges. Established urban sewage treatment capacities range between 60 percent to 200 percent of the total sewage generation in the four cities studied. However, a large part of wastewater is discharged into unlined stormwater channels, which leads to the contamination of the stormwater drainages and the groundwater aquifers. Most sewage treatment plants function inefficiently and, consequently, most of the treated outflow does not meet the

desired reusable water quality. As a result, the cities face water pollution concerns, such as high total dissolved solids, high electrical conductivity, variable amounts of toxic metal content, low dissolved oxygen, high biological oxygen demand, high chemical oxygen demand, and presence of E-coli in piped water and groundwater due to sewage mixing with leaky pipelines or infiltrating the groundwater systems from unlined conduits.

This report concludes that transitioning from the current linear water balance framework and corresponding governance structure into a circular water balance framework regulated through an Integrated Urban Water Management (IUWM) process is necessary to optimise available water resources. The adaption of circular water balancing within the IUWM and appropriate governance processes will need increased focus on raw water surface/captive source security; the augmentation of aquifer water through conservation; the harvesting and conservation of urban rainwater for either direct use or groundwater recharge; the use of desalinated water wherever feasible; and the capturing, segregation and differential treatment of black and grey water to ensure optimised reuse. Adopting the IUWM process might necessitate the re-laying and replacement of existing water distribution infrastructure, starting from peri-urban or poorer areas. Data suggests that using a circular water balance framework, and by accounting for the conservation of potential rainfall and treated wastewater, gross water availability increases from 350 million cubic metres (MCM) to 950 MCM in Chennai, from 825 MCM to 1350 MCM in Bengaluru, from 70 MCM to 185 MCM in Coimbatore, and from 1550 MCM to 3250 MCM in Delhi—an increase of between 160 percent to 270 percent in all four cities.

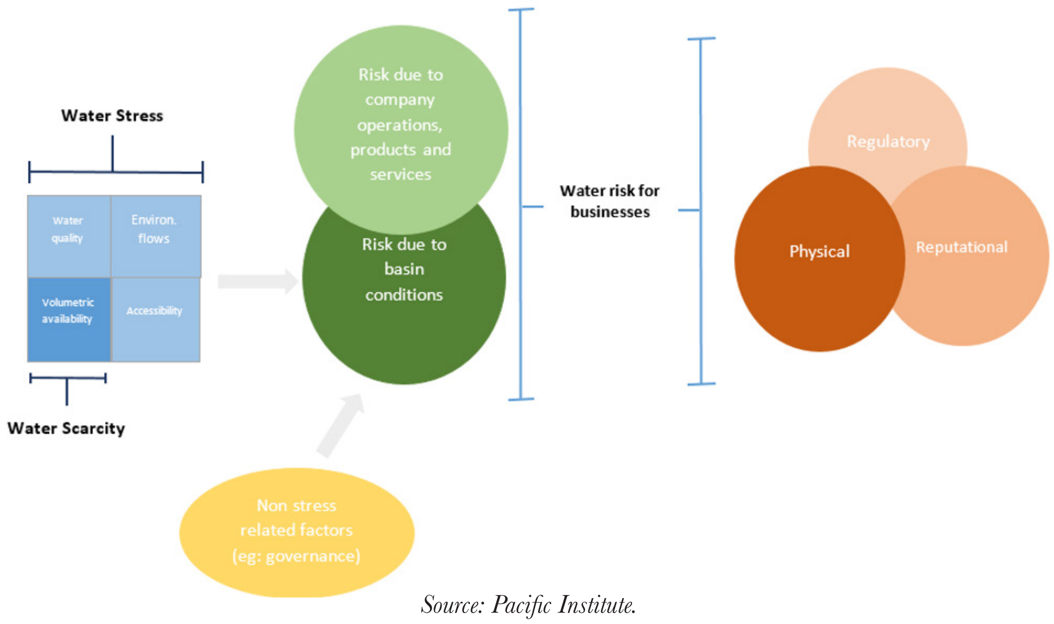
The implementation of circular water balance in an IUWM framework will require significant changes in the current governance model of India's urban local bodies (ULB). The entire water balancing process, the demand analysis, and long-term and short-term water management planning can be based on both legacy and real-time (sensor based) data acquisition. Relevant qualitative and quantitative water information will include the detailed science-based mapping of urban surface water and groundwater sources, water supply and drainage networks, and discharge conduits. The ULBs will need significant training and capacity building to capture, analyse and plan water management in an IUWM framework. Urban citizens will need to be made participants in the IUWM process. Citizens must be encouraged to practice pragmatic demand optimisation and accept that reducing non-revenue water is the key to sustainable urban water security.

The proposed strategy to ensure water security for Indian cities integrates with the Ministry of Jal Shakti's aspiration to provide piped potable water supply to 2.86 crore households by 2024. It also addresses goal 6 (clean water and sanitation) and 6.5 (implement water resource management) of the UN's Sustainable Development Goals.

INTRODUCTION

India is facing severe and sustained water stress conditions, ranking thirteenth among all “water stressed” countries in the World Resources Institute’s Aqueduct Water Risk Atlas.[2] Many parts of the country are experiencing water scarcity and water risks[3] (see Figure 1 for definitions), and the groundwater and surface water storages are severely exploited. In north India, average groundwater levels in the phreatic unconfined aquifers declined by an average of over eight centimetres annually between 1990 and 2014.[4] India’s population will outgrow its current water supply if the approach towards water management and standards of governance do not change. By 2030, India’s water demand is projected to be twice the available raw water supply, implying potential scarcity for hundreds of millions of people and an eventual six percent loss in the country’s gross domestic product.[5] India’s water demand will grow 24 percent by 2025 and 74 percent by 2050, with implications for food security, health and access to resources.[6]

Figure 1: Water Stress, Water Scarcity and Water Risk



Source: Pacific Institute.

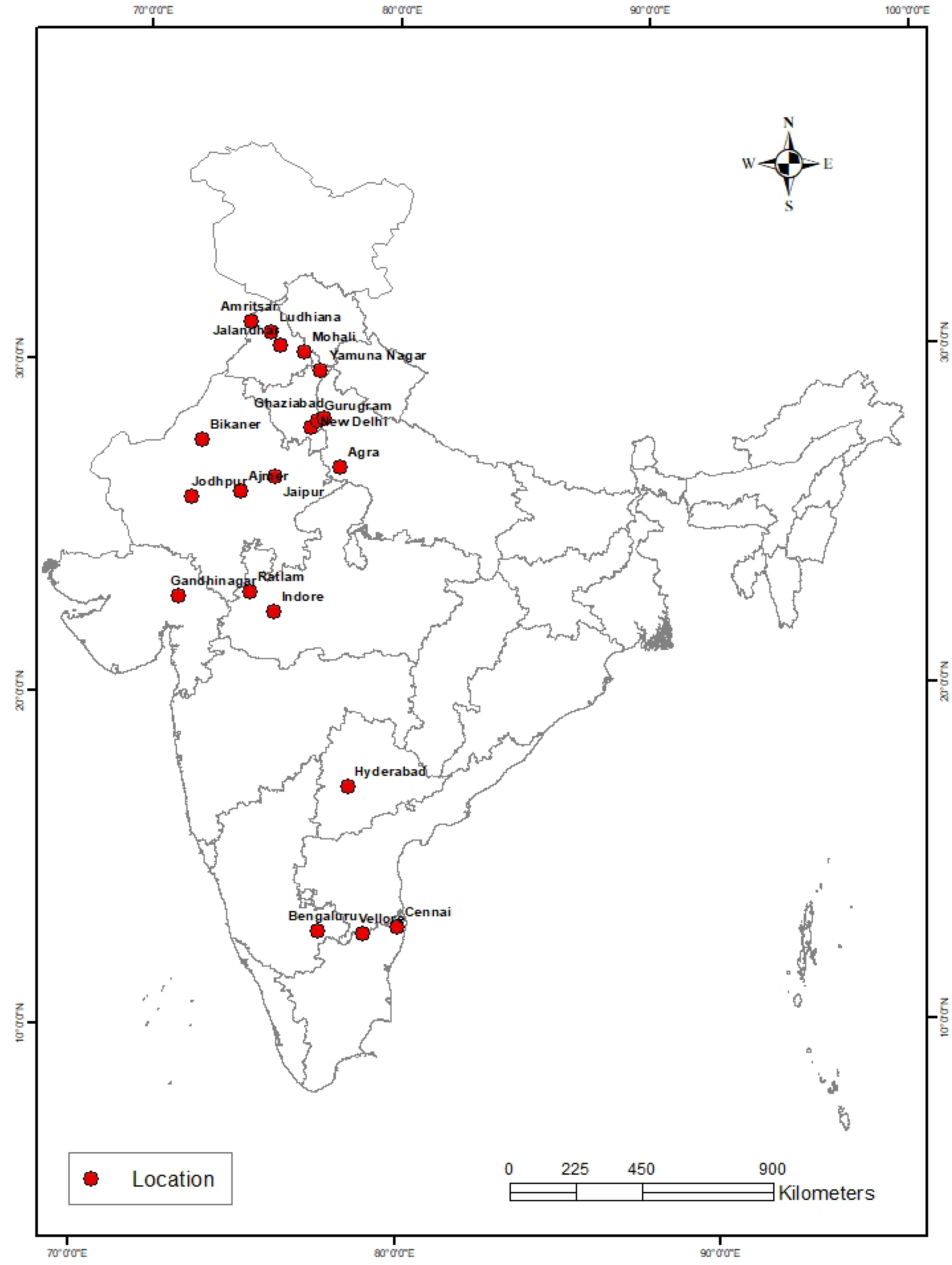
Water Scarcity: Refers to the volumetric abundance, or lack thereof, of water supply. This is typically calculated as a ratio of human water consumption to available water supply in each area. Water scarcity is a physical, objective reality that can be measured consistently across regions and over time.

Water Stress: Refers to the ability, or lack thereof, to meet human and ecological demand for water. Compared to scarcity, water stress is a more inclusive and broader concept. It considers several physical aspects related to water resources, including water scarcity, but also water quality, environmental flows, and the accessibility of water.

Water Risk: Refers to the probability of an entity experiencing a deleterious water-related event. Water risk is felt differently by every sector of society and the organisations within them, and is thus defined and interpreted differently (even when experiencing the same degree of water scarcity or water stress). Nevertheless, water-related conditions, such as water scarcity, pollution, poor governance, inadequate infrastructure and climate change, create risk for many different sectors and organisations simultaneously.

The situation is even more dire in urban India. Chennai ran out of piped water in 2018-2019 following three years of near-drought conditions, and 21 other major Indian cities will soon run out of groundwater if water abstraction continues as normal (see Figure 2).[8] Rapid urbanisation and population growth, coupled with no added raw water sources, archaic water infrastructure and inefficient water governance, means that most Indian cities are ill-equipped to handle the increasing water scarcity and water stress. Climate change impacts will only aggravate the situation; rising temperatures could cause the periodic drying up of captive water sources. Extreme weather events, such as frequent floods and droughts, could also impact economic activities, affecting livelihoods and ecosystems. An effective and integrated approach to water resource management is, therefore, critical for a rapidly urbansing India.

Figure 2: Map Showing the Groundwater-Stressed Cities in India (As of Year 2018)



Source: Ministry of Statistics and Programme Implementation.[9]

DAY ZERO IN CAPE TOWN (2018) VS CHENNAI'S MONSOON FAILURE (2018-2019)

Chennai's water scarcity situation was reminiscent of the Day Zero crisis in Cape Town, South Africa.[10] Chennai saw a near total depletion of all available fresh-water resources in 2019 as a result of a failed monsoon season (2018).[11] All of Chennai's four raw water storages nearly dried out and people resorted to intensive groundwater mining,[12] thereby depleting the city's aquifers as well. Importantly, although Cape Town declared Day Zero after three consecutive years of drought, which led to a near complete exhaustion of surface water storages, the city's aquifers remained relatively unstressed. Chennai's water crisis, however, resulted from a significant depletion of both surface and groundwater storages after a single failed monsoon season.[13]

Table 1 lists the differences in manifestations of water stresses in Cape Town and Chennai. Cape Town's multi-year drought was considered an anomalous hydro-meteorological phenomenon and a potential climate change impact. Chennai, on the other hand, had many similar years of poor rainfall, alternating between normal to high precipitation years. Chennai is not the first city in India to face a major water crisis. Shimla (2018)[14] and Latur (2016),[15] both smaller cities, have seen similar or worse water scarcity periods, indicating a deeper malaise in India's urban water management systems, processes and practices.

TABLE 1: Comparison of Relative Impact of Reduced Precipitation on Cape Town and Chennai

ELEMENT	CAPE TOWN	CHENNAI
Population (Metro)	4 million	9 million
Average annual precipitation	80 cms	140 cms
Period of low precipitation	2015 – 2018	2016 – 2018
Total surface water storage for the city	900 MCM	300 MCM
Did groundwater storage get impacted	No	Yes
Preparation by city corporation for the impact	Extensive; for three years	None in first two years, panic during the 3rd year to do firefighting; water import resorted
Preparation by city residents for the impact	Extensive, with full cooperation of the corporation	None; no training, no preparation
Was this a climate change manifestation	Definitely Yes	May Be

The 2021-22 Union Budget launched plans to provide piped water supply to 2.86 crore household by 2024 to fight India's water woes. The focus is now on water conservation measures, such as rainwater harvesting; the renovation, restoration and rejuvenation of tanks and lakes; reusing wastewater; the construction of recharge structures; desalination; watershed development; and intensive afforestation. The 2020-21 Union Budget allocated INR 11,500 crore for measures to enhance water availability and water resource sustainability.[16]

According to the 2018 National Sample Survey, 48.6 percent of rural households and 57.5 percent of urban households have individual water connections.[17] Between 40 percent to 50 percent of water is reportedly lost in the distribution system due to pipeline leakages and water theft.[18] As per the 2011 Census, only 32.7 percent of urban Indian households are connected to a piped sewerage discharge system.[19] By 2030, urban India is expected to host a larger proportion of the country's population—about 590 million people, up from the current 377 million.[20] A significant portion of India's urban population is already facing acute water shortages, with about 200,000 dying each year due to inadequate or unsafe water supplies.[21] By 2050, India's water requirement in a high-use scenario is likely to be 1,180 billion cubic metrics (BCM), while the current availability is 695 BCM.[22] The gross water availability is lower than this projected demand, at 1,137 BCM. Any further deterioration of the country's water resources will have ramifications for the health, safety and sanitation needs of most of India's population.

The COVID-19 pandemic has highlighted the importance of access to water, sanitation and hygiene in crisis response. In India, shortfalls in infrastructure for water and sanitation have influenced the eventual scale and impact of the pandemic.[23] Critical water infrastructure in many regions of the country is far from adequate and are exposed to increased risk from climate change. It is essential to study India's current water situation in detail and understand the reasons for the emerging water crisis to arrive at a solution for effective water management.

With many Indian cities projected to run low on groundwater and face severe source security challenges,[24] this report aims to answer some critical questions. Given the severity of water shortage, is India taking the most effective and efficient approach to water management? Do Indian cities employ the required technical and institutional capabilities in developing a thorough hydrological understanding of water source and use fundamental scientific information for assessing the urban water balance and corresponding estimation of urban water budget? How can India successfully manage climate and sustainable development? Can the adoption of an integrated water management strategy help restore India's water security and ensure long-term viability?

METHODOLOGY

This report presents an in-depth analysis of the key aspects of urban water management—ensuring urban water source security; water distribution and water infrastructure management; water demand management; water budget optimisation; and prudent water governance. It undertakes a comprehensive analysis of the water supply and demand scenarios in four water-stressed Indian cities—Chennai, Coimbatore, Bengaluru and Delhi—based on primary and secondary data. It emphasises source security and presents a framework to understand the urban water balancing and urban water budgeting processes. Aspects like infrastructure, demand management, governance and community engagement are also discussed.

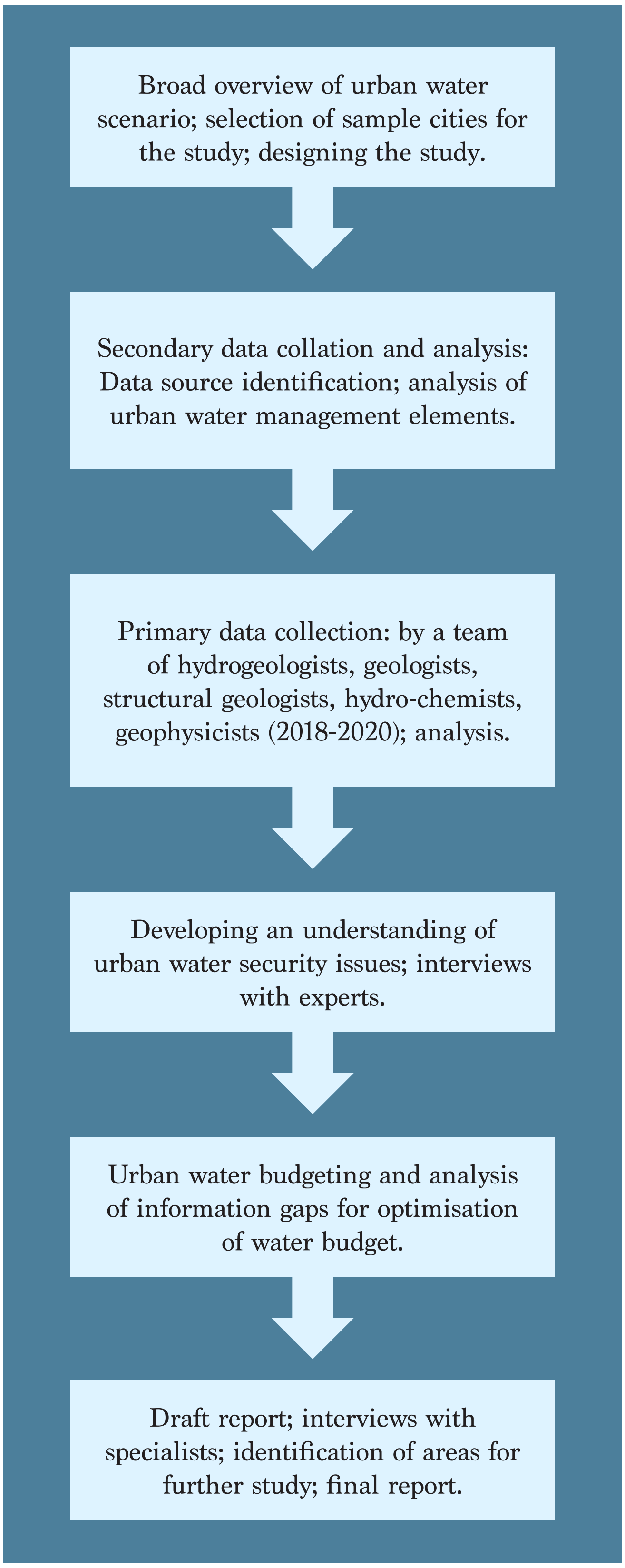
The on-ground primary data collected includes hydrological, hydrogeological and hydrochemical information from Delhi, Coimbatore and Bengaluru and their suburban areas, as well as water supply and demand information through hydro-census surveys. The authors have conducted satellite data study and interpretation of Landsat and Alos Pulsar datasets for Delhi, Coimbatore, Bengaluru and Chennai to understand the geomorphology, stormwater drainage, land-use-land-cover, water bodies (see Figures 28, 29, 30, 31 and 32) and civil interventions in the urban drainages.

The secondary datasets used for the study are:

- Census information (1991, 2001 and 2011) for the four cities
- Information on water storage reservoirs in the four cities
- Available masterplans for the four cities
- Landsat data for urban drainage and waterbody information and changes over the years
- Central Ground Water Board data on dynamic water resources, and state and district groundwater resources
- Public domain information on hydrology, hydrogeology and urban water infrastructure for the four cities
- Hydro-meteorological data from Indian Meteorological Department

The process flow for the study is:

Figure 3: Process Flow for Urban Water Security Study



Broad overview of urban water scenario; selection of sample cities for the study; designing the study.

Secondary data collation and analysis: Data source identification; analysis of urban water management elements.

Primary data collection: by a team of hydrogeologists, geologists, structural geologists, hydro-chemists, geophysicists (2018-2020); analysis.

Developing an understanding of urban water security issues; interviews with experts.

Urban water budgeting and analysis of information gaps for optimisation of water budget.

Draft report; interviews with specialists; identification of areas for further study; final report.

I.

SITUATION ANALYSIS

Terrain, Geomorphology, Geology

Three of the four referenced cities—Coimbatore,[25] Bengaluru[26] and Chennai[27]—are located in the southern part of peninsular India. Bengaluru and Coimbatore have broadly similar hydrogeological settings controlled by hard crystalline granitic rock geology. Chennai,[28] on the other hand, has a hydrogeologically heterogenous setting with an east-west trending spine of hard crystalline rock passing through the middle of the city and flanked on the north and the south by younger, softer, porous and permeable coastal sediments. Delhi, in north India, is situated at the edge of the Indo-Gangetic plains, with soft and permeable Quaternary age Yamuna alluvial and desert sediments overlying the hard fractured Proterozoic quartzites, which mark the northeastern extensions of the Aravalli Range.

Bengaluru is situated on an elevated plateau averaging over 900 metres above mean sea level and is drained by the south-westerly flowing Vrishabhavati River (a tributary of the Arkavati River to the west of the city in the Cauvery Basin) and the easterly flowing Poonaiyar River to the east of the city (see Figure 7). Chennai presents a coastal geomorphology to the east, extending from the pediplained hard crystalline rocks in the west, and is drained by the easterly flowing Cooum, Adyar and Kosasthalaiyar River watersheds (see Figure 8). Coimbatore also presents a pediplain geomorphology and is drained through the middle of the city entirely by the easterly flowing Noyyal River, a tributary of River Bhavani and part of the Cauvery River Basin (see Figure 9). Delhi has a rolling topography in the southeastern part of the city, where the rocks of the Aravalli range are exposed, and is surrounded by relatively flatter alluvial plains. The entire city is situated in the Yamuna River Basin (see Figure 10).

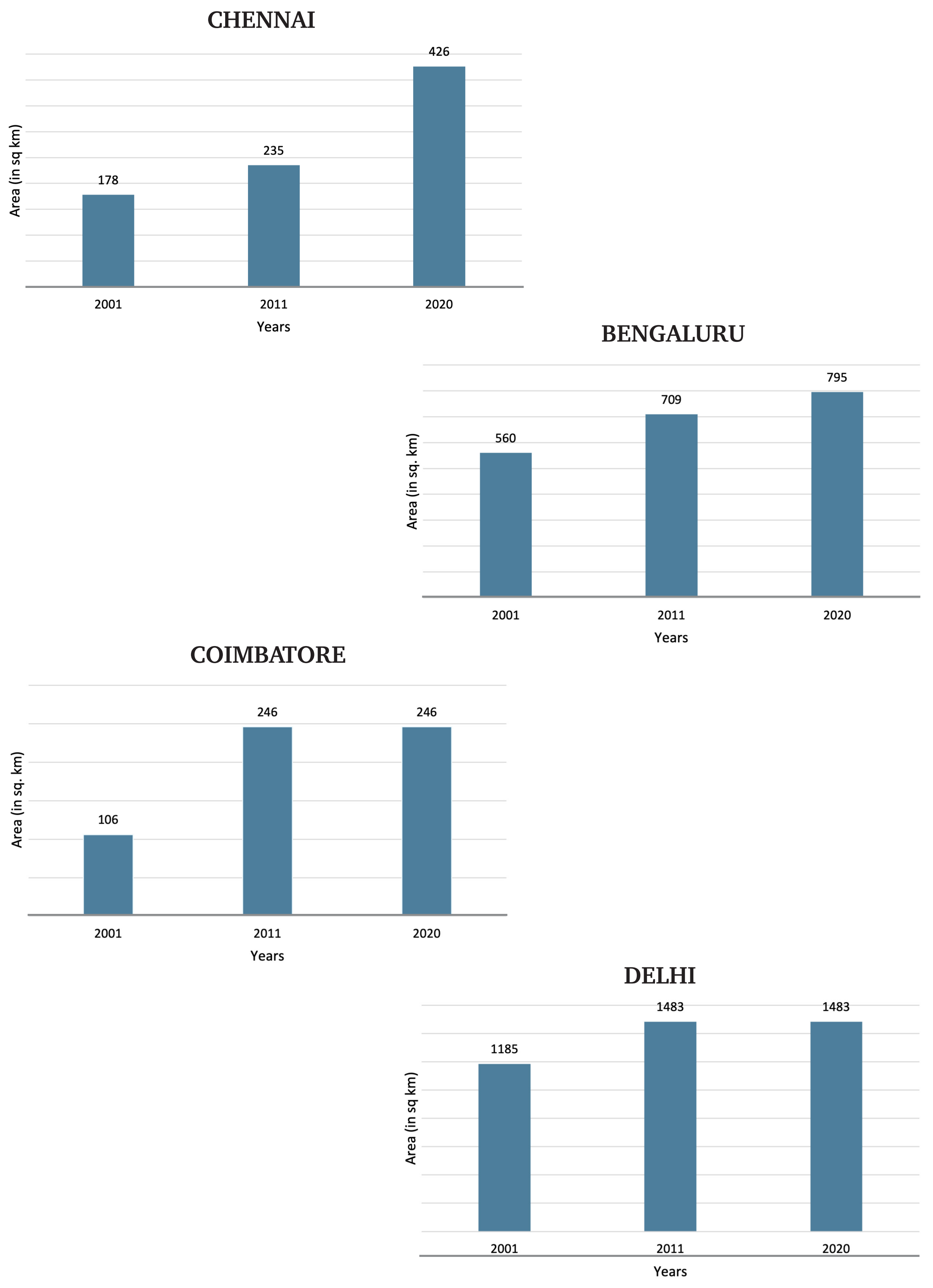
Population and Urban Growth

Chennai, Bengaluru and Delhi saw significant population growth in the last three decades, expanding into very large Tier 1 megapolises, while Coimbatore is a Tier 2 city. The city limits and areas have also expanded variably (Figure 4). All four cities have evolved through ancient traditions of water conservation—for instance, Coimbatore's system tanks were constructed by the Chola Chalukya dynasty[29] and Bengaluru's series of tanks connected through Rajakaluves (canals) were constructed by the Western Ganga dynasty.[30]

Census data has been used to determine the population growth in each of the four cities between 2001 and 2011 (see Figure 5), as well as to make projections for 2020 and beyond.[31,32] Notably, the expansion of the geographical limits of Chennai, Bengaluru and Delhi was constrained in relation to their cities' population growth. The population densities for these three cities increased substantially between 2001 and 2011—from approximately 10000 persons per square kilometre to about 17000 persons per square kilometre in Chennai;[33] from approximately 10000 persons per square kilometre to about 12000 persons per square kilometre in Bengaluru;[34] and from approximately 9000 persons per square kilometre to about 11500 persons per square kilometre in Delhi[35] (see Figure 6). Only Coimbatore city limits expanded significantly to incorporate much of its low populated suburban areas, consequently showing a reduction in the average population density (from approximately 9000 persons per square kilometre in 2001 to about 6000 persons per square kilometre in 2011[36]).

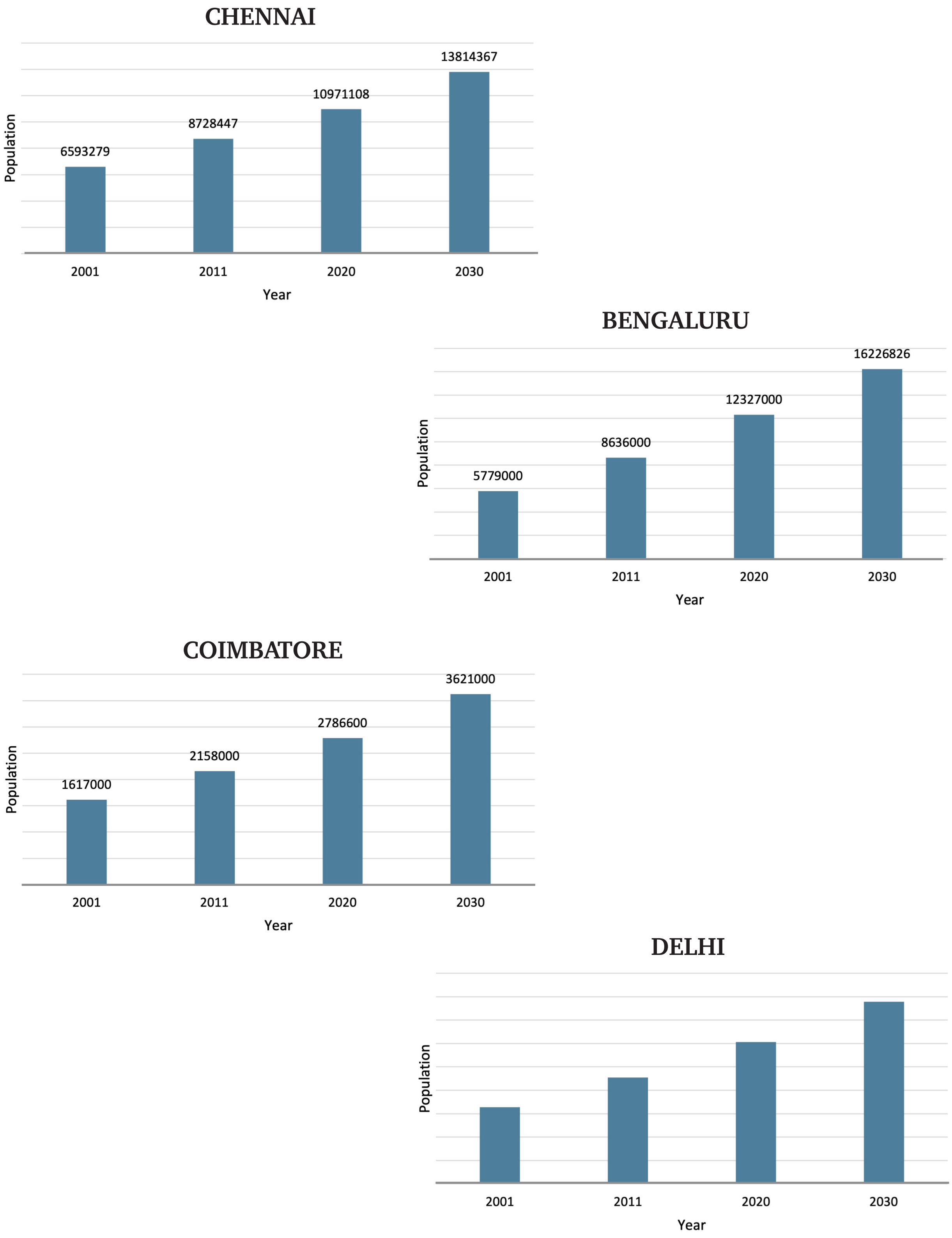
Over the last two decades, India's cities have seen significant population growth due to migration from rural areas, but this has mostly outpaced the expansion of city limits, resulting in excess stress on the available resources.

Figure 4: Growth in Area in Chennai, Bengaluru, Coimbatore and Delhi in 2001, 2011 and 2020 (sq. km)



Source: Authors' estimation using primary satellite data.

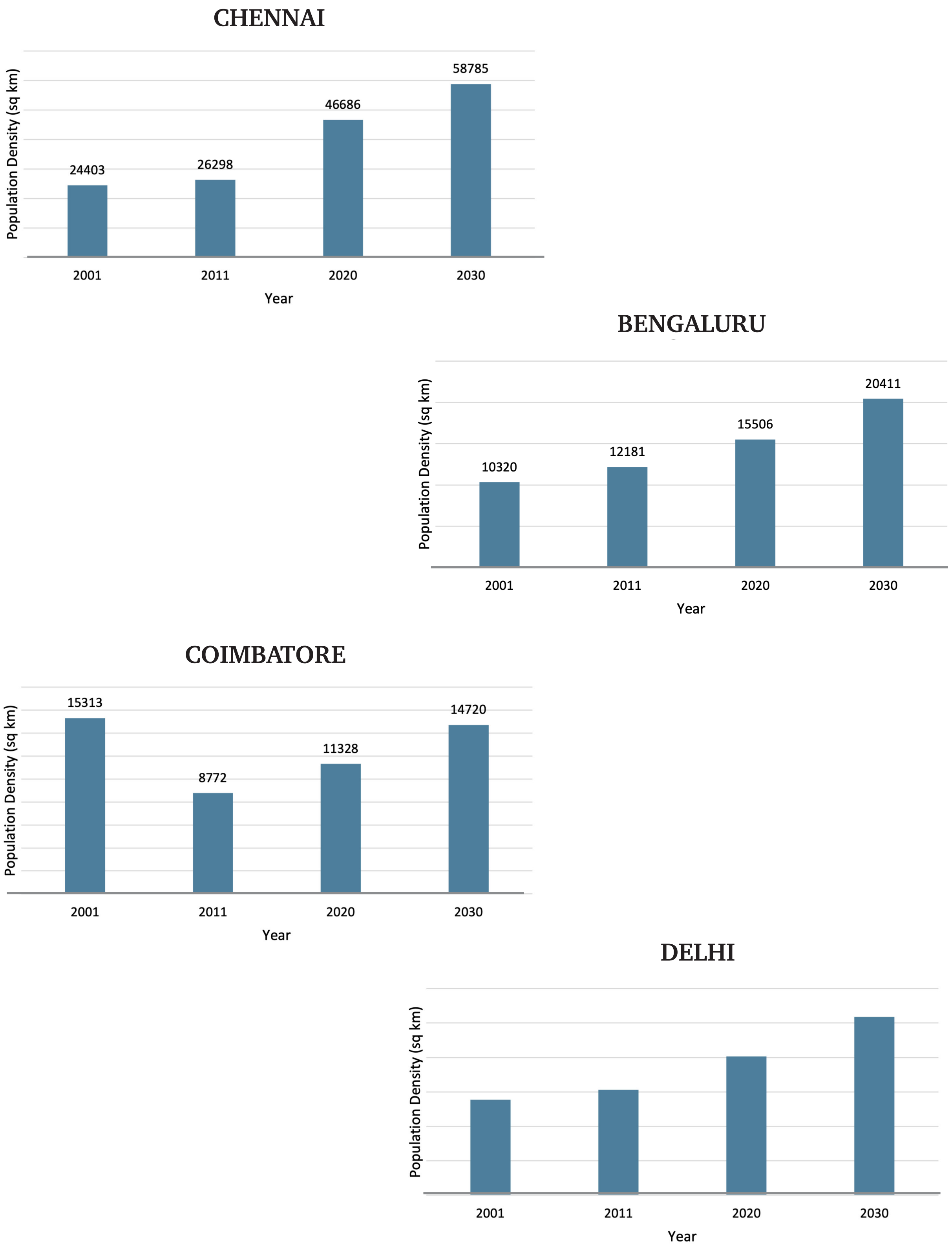
Figure 5: Projected Population Growth for Chennai, Bengaluru, Coimbatore and Delhi (2030)



Source: Census data, 2001 and 2011.[37,38]

Note: Population figures for 2020 are estimates based on Census projections.

Figure 6: Growth in Population Density in Chennai, Bengaluru, Coimbatore and Delhi in 2001, 2011, 2020 and 2030 (per sq.km)



Source: Census data, 2001 and 2011.[39,40]

Note: Population figures for 2020 are estimates based on Census projections.

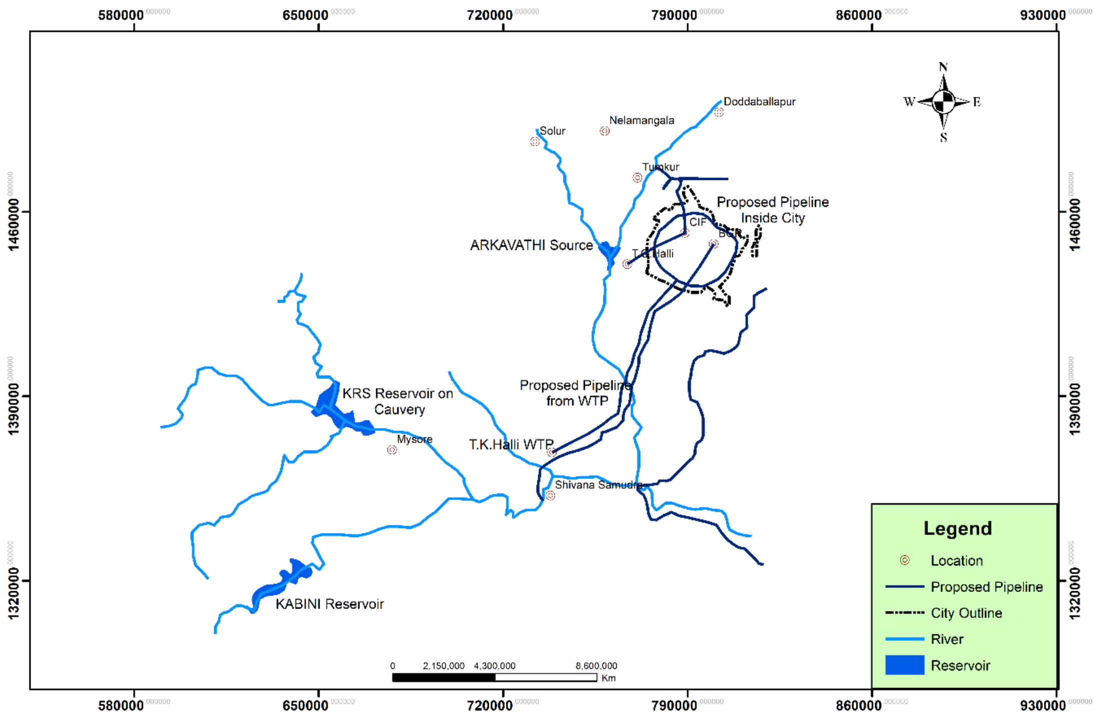
Raw Water Surface Storages

Most of India's larger Tier 1 cities have substantial captive surface raw water sources, which are supplemented by the abstraction of groundwater. However, cities in the Indo-Gangetic plains primarily rely on groundwater abstraction. All four reference cities have captive sources of surface water, and some also have multiple sources of raw water storages (see Table 2). These captive storages are located either within the same watershed that the city is part of or in extra-basinal watersheds. Water is pumped from primary storages and carried through large pipelines to secondary temporary storages within the cities, and supplied to domestic and other urban consumers through the urban water distribution infrastructure after chlorination and treatment. Delhi and Bengaluru's raw surface water storages are remote and extra-basinal, while Coimbatore and Chennai draw water from storages within the same watershed draining the city. Based on primary sources, the authors estimate that the current water supply infrastructure in Chennai, Bengaluru, Coimbatore and Delhi cover between 60 percent to 80 percent of the city areas.

Table 2: Current Surface Water Storage Reservoirs Serving the Freshwater Requirements of Chennai, Bengaluru, Coimbatore and Delhi

CHENNAI	BENGALURU	COIMBATORE	DELHI
Poondi	Chamraja Sagar	Siruvani	Bhakra
Cholavaram	Krishna Raj Sagar	Aliyar	Hatnikund
Red Hills	Kabini	Pillur	Tehri
Chembarbakkam			

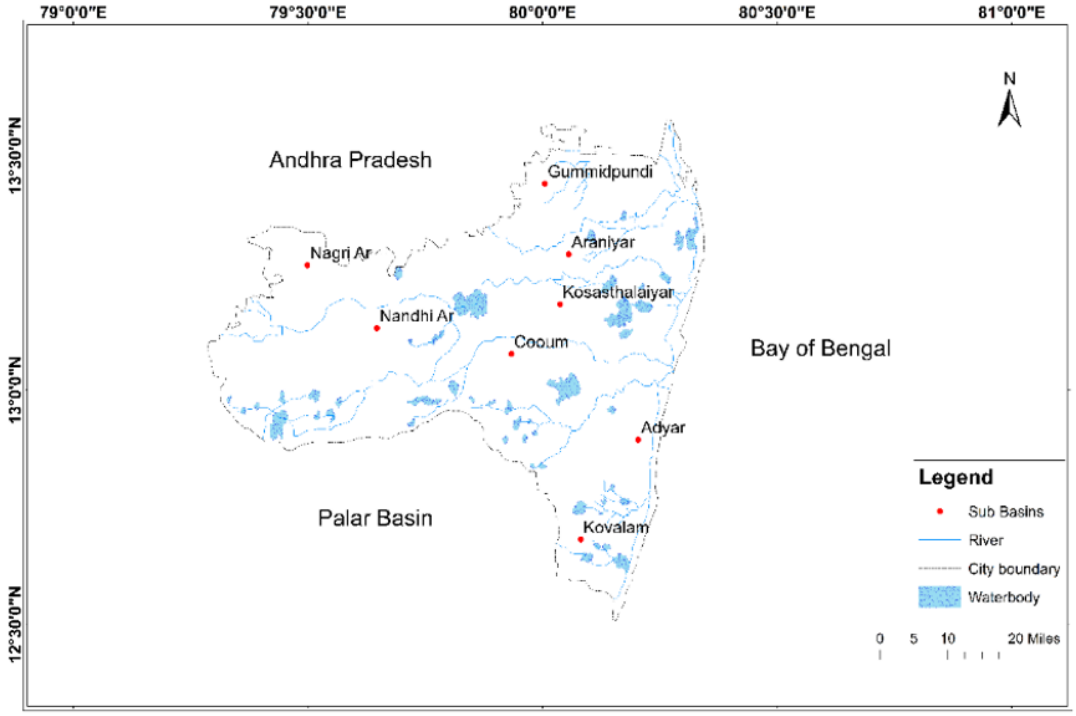
Figure 7: Surface Water Storages Serving Bengaluru



Source: Bangalore Water Supply and Sewerage Board.[41,42]

Note: The surface water storages serving Bengaluru include the Cham Raja Reservoir on River Arkavathy, the Krishna Raj Sagar Reservoir on River Cauvery and the Kabini Reservoir on River Kabini. These storages are part of Cauvery water supply scheme, with a capacity of supplying approximately 1440 million litres per day (MLD) to Bengaluru.

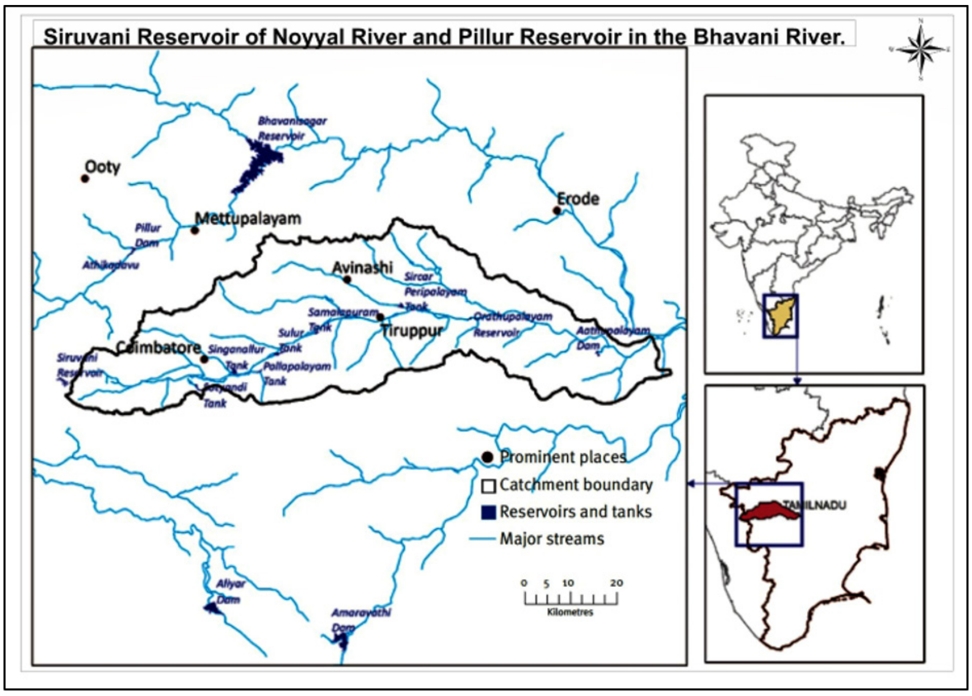
Figure 8: Surface Water Storages Serving Chennai



Source: Chennai Metropolitan Water Supply & Sewerage Board.[43]

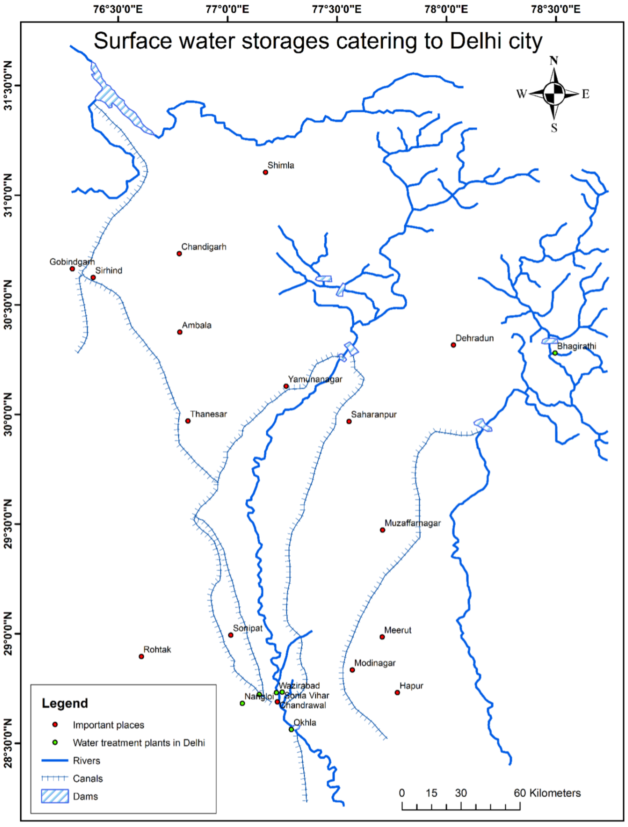
Note: The surface water storages[44, 45] *serving Chennai include Poondi, Red Hills, Chembarbakkam and Cholavaram Reservoirs on the Cooum river, and the Adyar and Kosasthalaiyar River watersheds, which also drain Chennai City.*

Figure 9: Surface Water Storages Serving Coimbatore



Source: Map created by authors using satellite data and primary survey of the Noyyal and Bhavani basin watershed management studies.
Note: The Siruvani Reservoir in the headwaters of Noyyal River and Pillur Reservoir in the Bhavani River are the two major surface water storages serving Coimbatore.[46] *Noyyal is an urban river that flows through the middle of Coimbatore city.*[47]

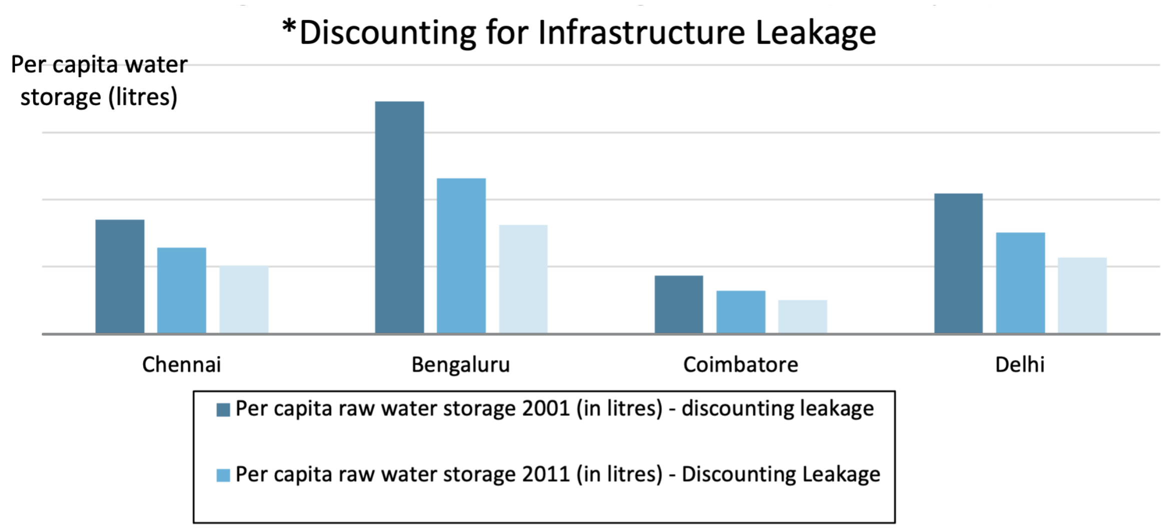
Figure 10: Surface Water Storages Serving Delhi



Source: Based on data from City of New Delhi, Safe Water Network, 2016.[48]
Note: Delhi's water supply is drawn from multiple distant surface water sources at Bhakra Reservoir, the Hatnikund Barrage on River Yamuna and the Tehri Reservoir.[49, 50]

Although Bengaluru, Chennai, Coimbatore and Delhi have seen significant population growth between 2001 and 2020, there has been no corresponding major augmentation of their raw surface water storage capacities. Instead, storage capacities in the source reservoirs and secondary storages are likely to have been adversely impacted due to siltation of the captive reservoirs, as has happened in Chennai (see Figures 11 and 12).

Figure 11: Changes in Available Surface Water Storage (Per Capita)



Source: Authors' own calculations based on Census 1991,[51] 2001[52] and 2011.[53]

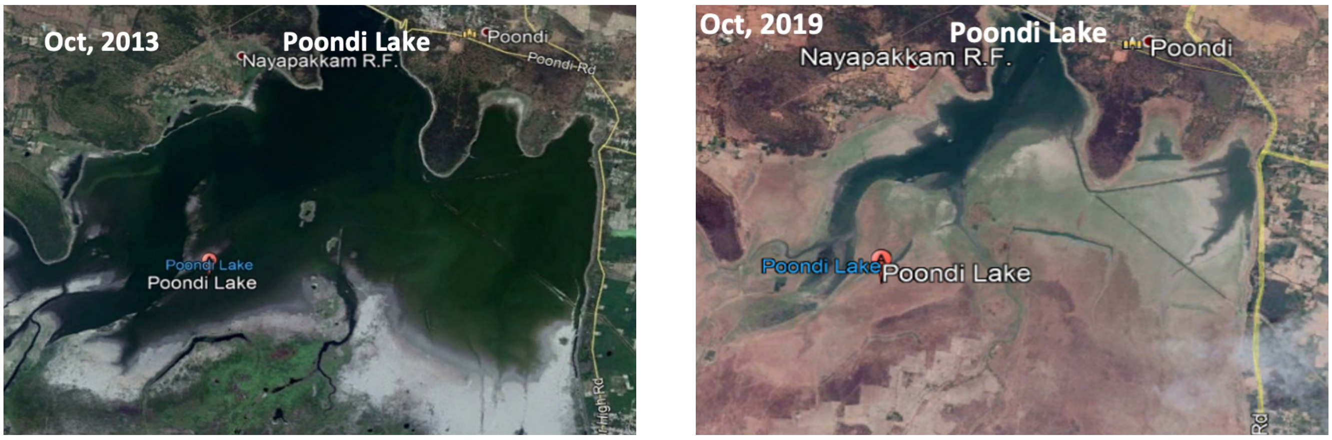
The four cities being studied have now created plans to augment their source raw water surface storages.[54, 55, 56, 57] However, most of these plans have also seen significant delays due to the unavailability of source water or land constraints because of environmental and community issues.

With looming climate uncertainties, India has already begun experiencing changes in the annual precipitation patterns in many regions. This will have uncertain implications on urban water source security, especially if there is primary water dependence on a limited number of discrete captive storages. Having multiple raw water storage availabilities in several basins is a better strategy to mitigate adverse climate change impacts (see Table 2 and Figures 6, 7, 8 and 9). Chennai and Coimbatore, which source water from proximal storage reservoirs located within the same watershed draining the cities, are likely to remain vulnerable to the vagaries of climate uncertainties. In 2018 and 2019, Chennai experienced a failed monsoon cycle and near drought conditions, which led to the drying up of all its surface storages and widespread water scarcity, dubbed as Day Zero by the media (see and Figure 12).[58]

Figure 12: Satellite images of Reservoir Storage Conditions in Chennai (2013 and 2019)

CHEMBARBAKKAM LAKE

POONDI LAKE



CHOLAVARAM TANK

Satellite images from 2013 and 2019 of the Chembarbakkam Lake, Poondi Lake and Cholavaram Tank show that although Chennai received some rains during the northeastern and southwestern monsoon in 2019, this was not sufficient to restore the safe storage levels of the reservoirs.[59] Chennai's experience is an illustration of the need for India's large Tier 1 cities to secure multiple captive distant storages in different basins.

SECURING ADDITIONAL RAW WATER STORAGES FOR CITIES

Groundwater Recharge of Yamuna Floodplains

As Delhi struggled to conserve and replenish groundwater, the state government announced an ambitious pilot project in July 2019—the Delhi Yamuna floodplain water storage project—to create multiple surface reservoirs between Palla and Wazirabad in the alluvial floodplains of Yamuna river. Under this programme, small ponds will be created in the floodplains to collect water from an overflowing Yamuna during the monsoon season, which will then recharge the groundwater aquifers.[60, 61, 62] At the same time, the Delhi Irrigation and Flood Control Department launched a programme to stock the overflowing water from the river in shallow storages in the floodplains. In a pilot, a 25-acre pond is being constructed on the floodplains of Yamuna at Palla to recharge the aquifers, from where borewells can abstract water to meet the local demand. Authorities have installed over 35 piezometers at up to 2 kilometres across the river to monitor the water table and piezometric surfaces in the aquifers.[63]

Securing Water from Krishna River for Chennai

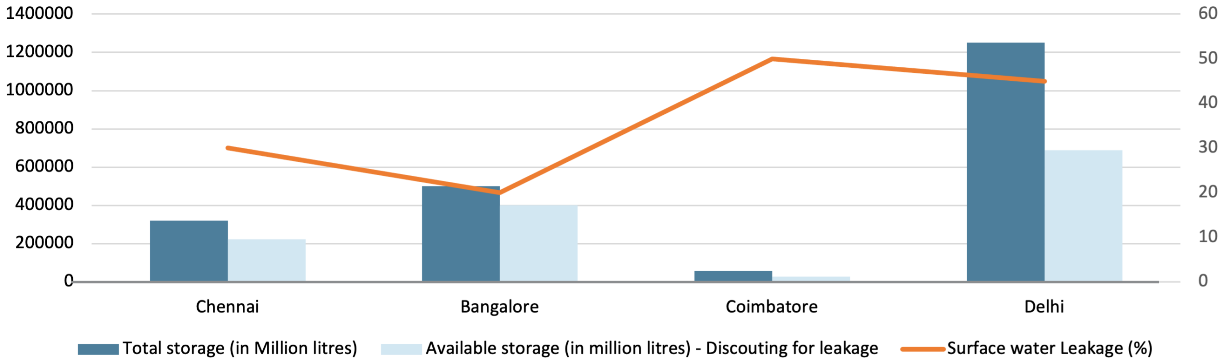
At the height of Chennai's water crisis in 2018-19, tankers were used to supply abstracted groundwater from outside the city limits. Between 700 to 900 Chennai Metro Water Supply and Sewage Board tankers made nearly 10,000 trips a day to freight 100 MLD of groundwater to the city.[64]

The inter-river basin transfer of water to Chennai has generally prevented the drying up of the city's captive reservoirs. Chennai's four lifeline lakes are fed water from Krishna river during times of distress. The city also gets supplies from Veeranam, a giant lake 235 kilometre to the south in Cuddalore district, that depends on discharge from the Mettur dam on the Cauvery river. The supply from Krishna basin has helped Chennai's ensure a captive storage of about 6 billion cubic feet (bcft) of groundwater.[65, 66]

Infrastructure

The surface water distribution infrastructure for Chennai, Bengaluru, Coimbatore and Delhi were developed decades ago, undergoing minor upgrades in subsequent years. The water distribution infrastructure in these cities report distribution leakages of between 20 percent and 45 percent (see Figure 13). If the freshwater resource availability stays unchanged, the registered increase in urban population and deteriorating water infrastructure (and resultant leakages) will translate into a significant reduction in per capita raw water availability, assessed between 2001 and 2011 (the census years) and projected for 2020 (see Figure 11). Based on population growth between 2001 and 2011 and accounting for distribution leakages, the authors estimate that the per capita surface water availability reduced from approximately 70 m^3 to 33 m^3 in Chennai, from approximately 100 m^3 to 43 m^3 in Bengaluru, from 62 m^3 to 24 m^3 in Coimbatore, and from 95 m^3 to 50 m^3 in Delhi. The reduction in per capita raw water availability persists as the reservoirs continue to silt, urban population grows and the distribution infrastructure becomes leakier.

Figure 13: Total Surface Water Storage vs Available Raw Water



Source: Graph created by the authors using available data from respective municipal corporations.
Note: Distribution leakages are shown in line chart with scale in the secondary axis.

Given the population growth between 2001 and 2011 and projected growth for 2020, and the distribution leakages of between 20 percent and 45 percent, none of the four cities meet the Bureau of Indian Standards (BIS) 1172:1993 benchmark of 200 litres per capita per day (or 73 m^3 per capita per year).

India's urban water management systems must prioritise upgrading and replacing major parts of the existing water distribution infrastructure to plug the leakages.

Water Supply to Peri-Urban Regions and Slums

Peri-urban areas are defined as dynamic spaces where rural and urban activities, processes and institutions coexist.[67] India's expanding cities have been absorbing peri-urban areas and slums, where many migrants and the poor live, within their limits. All four reference cities in this study have significant populations living in slums and peri-urban areas with poor infrastructure—in Delhi, about three million people live in urban slums;[69] approximately 30 percent of Chennai's total population lives in slums;[69, 70] Bengaluru city has 597 slum areas, with about 20 percent of the city population residing there;[71] and about 16 percent of Coimbatore's population live in the city's 319 slum areas.[72]

Although all four cities have incorporated the surrounding peri-urban areas within their limits, the urban local bodies (ULBs) have been slow in extending the city water infrastructure (both supply and sewage discharge management) to these areas. The water distribution infrastructure in the peri-urban and slum areas are mostly restricted to a single tap connection with limited water availability for a cluster of houses. Consequently, residents of these areas have resorted to extensive groundwater exploitation to meet their needs.

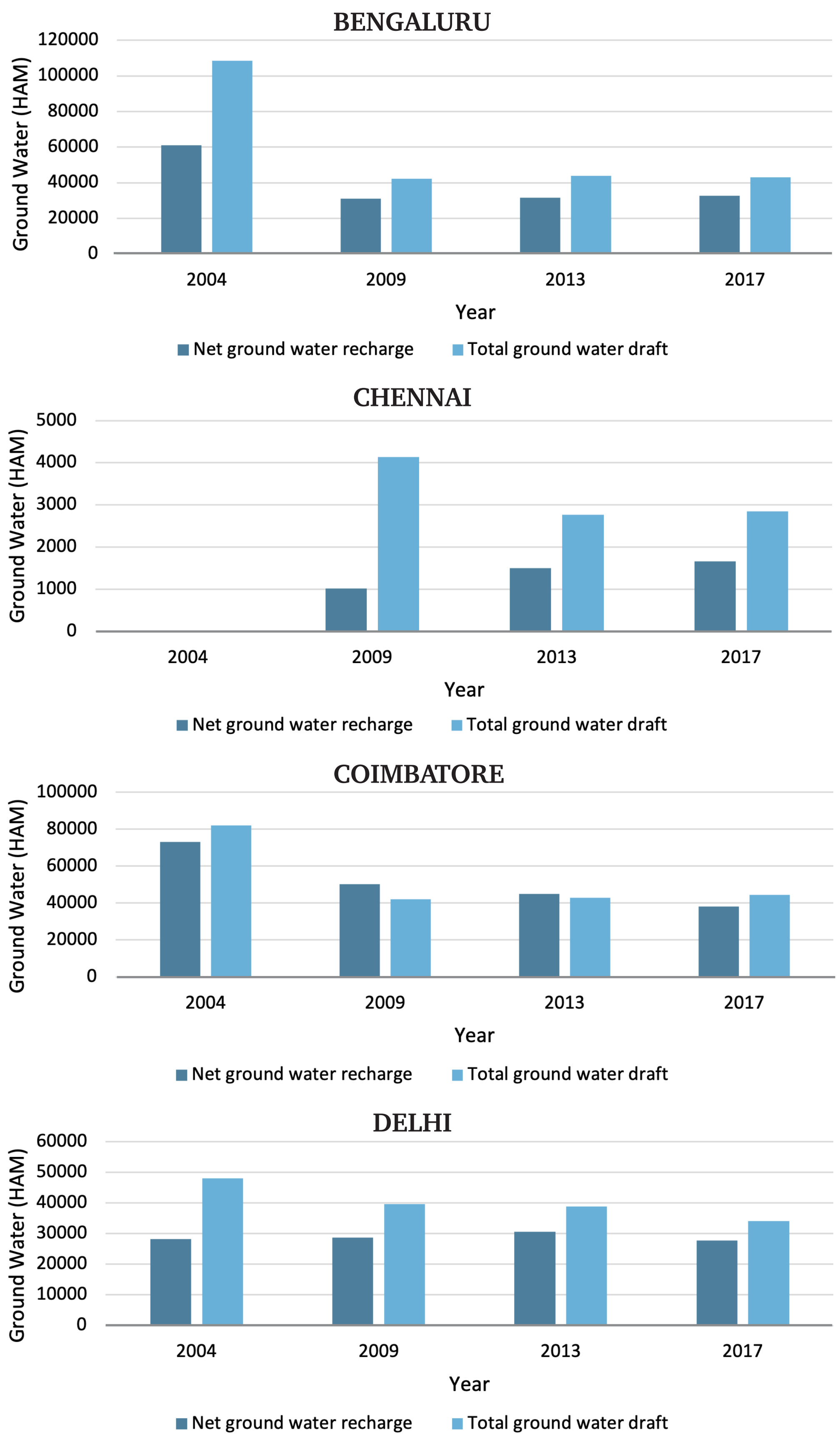
Additionally, informal water vendors have used peri-urban areas to pump out and transfer groundwater to the core urban areas using tankers (earning the moniker of 'tanker mafia'). The tanker vendors resort to aggressive pricing, unreliable water supply, groundwater mining and apparent stealing of agricultural water. In many Indian cities, the peri-urban and slum areas are conflict zones for water equity and water justice due to unsustainable water availability and expanding water scarcity. Infrastructure expansion planning by ULBs has lagged urban expansion in recent years and must now catch up for these areas.

Evolution of Groundwater from Alternative to Critical Urban Water Resource

Groundwater is significant for water supply in India's cities, but it remains a "blind spot in urban water planning"[73] due to a lack of data. Groundwater exploitation in cities has grown exponentially since the 1990s alongside rapid population expansion. The use of groundwater for urban domestic purposes competes with agricultural and industrial demands on the groundwater aquifer within the same hydrogeological boundaries in which the cities are located. This increasing demand for groundwater means that borewells in the cities and industrial sectors are being drilled deeper over time.

Assessment by the Central Ground Water Board (CGWB) for Chennai, Bengaluru, Coimbatore and Delhi suggests that groundwater abstraction is occurring at a rate higher than the dynamic or annual recharge, with the four cities showing overexploited groundwater status since 2011 (see Figure 14).[74] The gap in water supply corresponding to the demand in the cities, which is further accentuated by the inefficient water distribution network, is mostly plugged by an increased groundwater abstraction. While the NITI Aayog has suggested that the groundwater development status be used as a metric to assess the intensity of urban water stress,[75] other empirical observations suggest that groundwater overexploitation is correlated to poor and inefficient water distribution infrastructure, especially in the peri-urban and poorer parts of the city. Any significant drop in the groundwater level below the dynamic water table could make the peri-urban and poorer areas of the city vulnerable to extreme climate uncertainties, much like the drought conditions experienced by Chennai in 2019.

Figure 14: Annual Groundwater Recharge and Draft, Plotted for 2004, 2009, 2013 and 2017



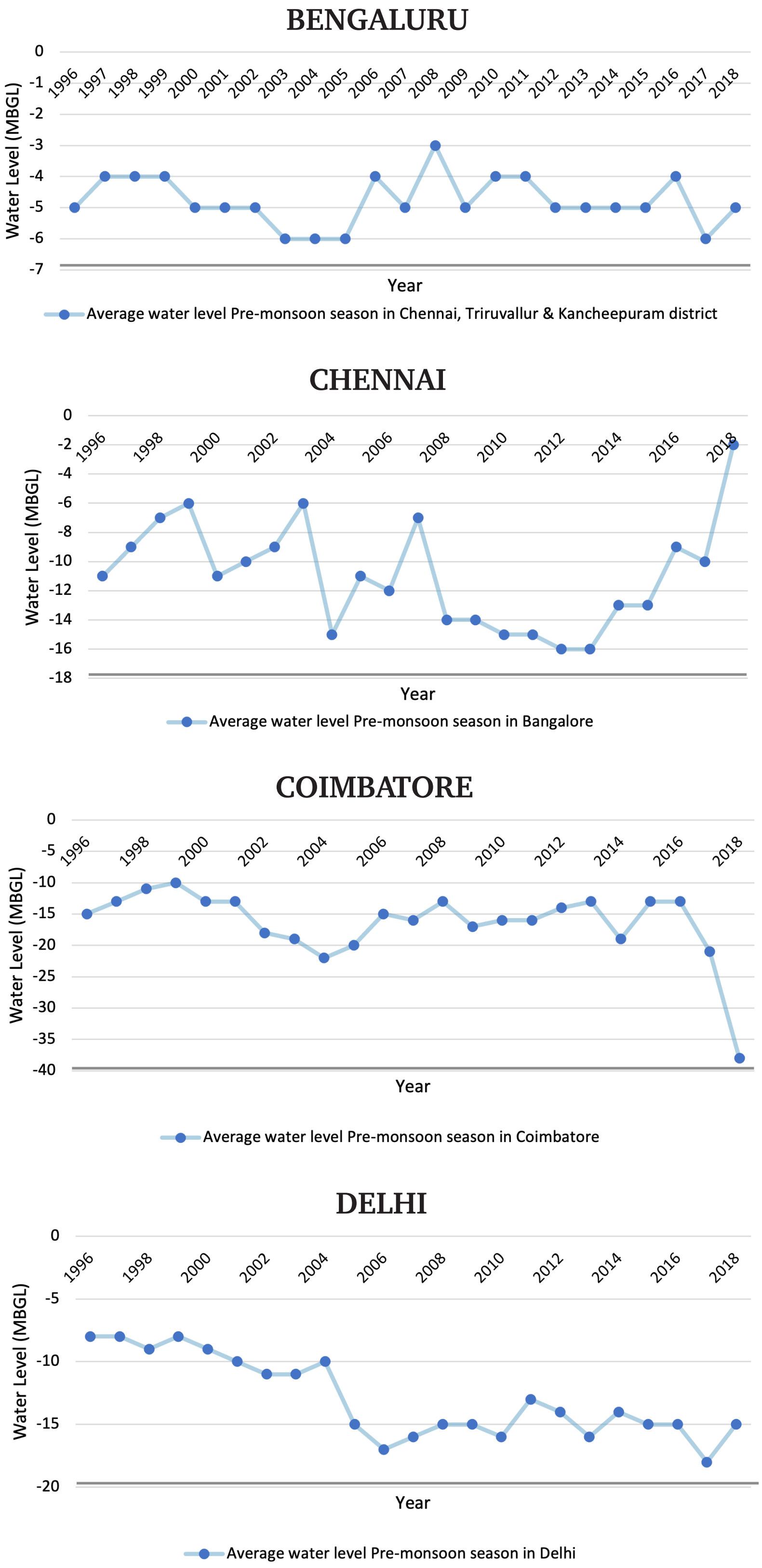
Source: CGWB Annual Dynamic Groundwater Data.[76, 77, 78, 79]

In 2018, Chennai, Bengaluru, Coimbatore and Delhi were included in the NITI Aayog's list of water-stressed cities;[80] all four are seeing groundwater mining conditions due to significantly higher groundwater abstraction than the annual dynamic recharge. India's cities, which have inadequate water supply and inefficient water management systems, rely on unit-based and mostly non-regulated private groundwater abstraction, leading to the indiscriminate pumping and eventual mining of groundwater.

All four cities in this study report overexploitation of groundwater for the four years of data acquired (2004, 2009, 2013 and 2017). Data from Coimbatore and Bengaluru used in this study cover the larger watersheds, with significant agricultural demand as well, while the data from Chennai and Delhi only cover the metropolitan areas.

Delhi and Coimbatore demonstrate a progressive lowering of groundwater levels each year. Chennai's groundwater levels appear to recover after each monsoonal precipitation (Figure 15). In Bengaluru, water levels in the open wells appear to be rising in the perched lithomarge bottom aquifers in the laterite capped areas, although local news reports also suggest deepening water levels in the hard rock aquifers.[81]

Figure 15: Average Water Level of Pre-monsoon Season (1996-2018)



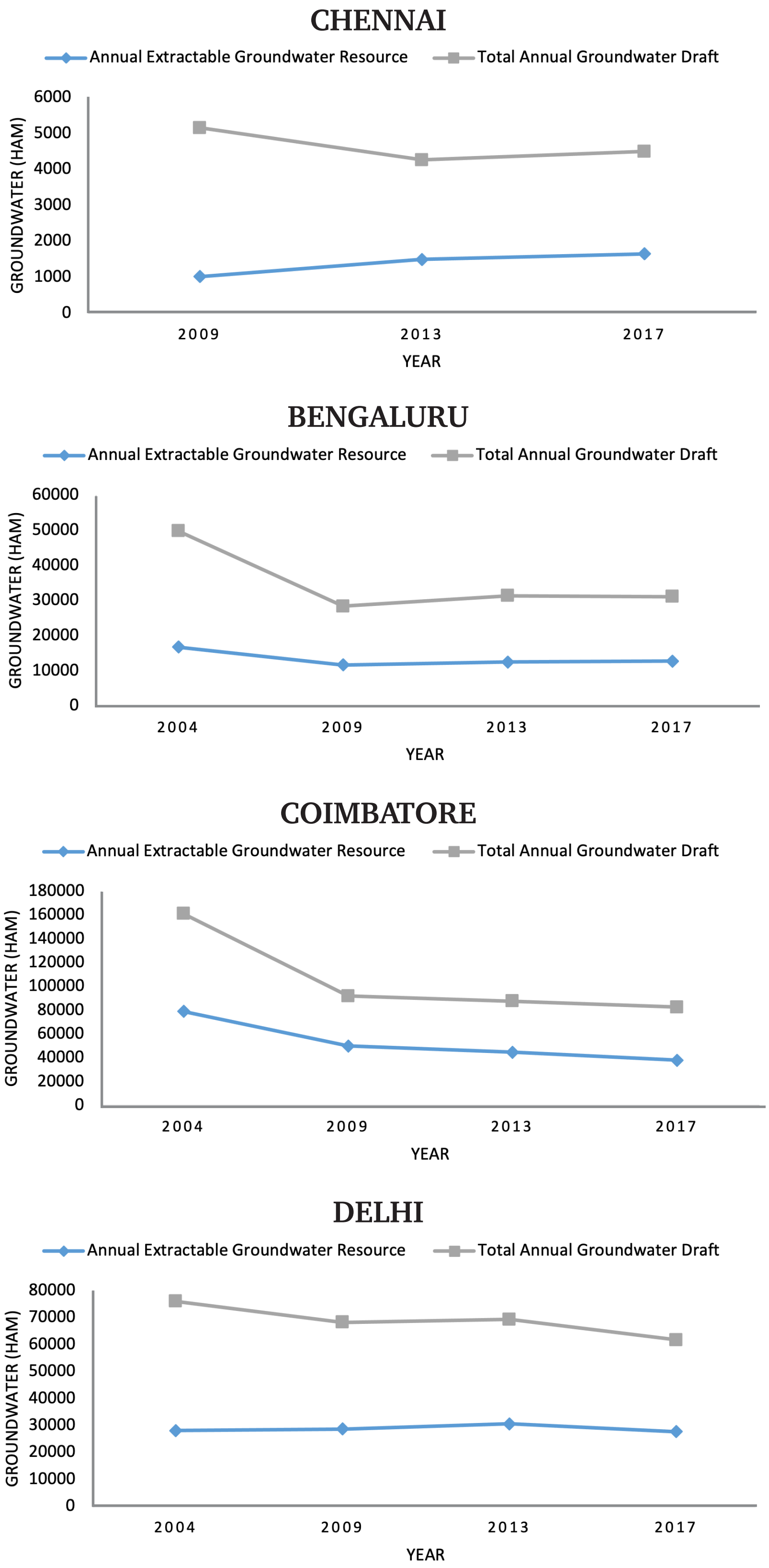
Source: Authors' own graphical representation based on monitoring well data from Central Ground Water Board.[82, 83, 84, 85]

Although Chennai, Coimbatore and Delhi are clearly overexploiting (see Figure 14), the phreatic aquifer is still an important groundwater source in these cities. Bengaluru has a near complete drying of the phreatic aquifer, and the falling groundwater levels indicate that the deeper fracture controlled semi-confined to confined city aquifer is currently being mined out of its limited groundwater storage.

Annual groundwater draft in the four cities is greater than the annual dynamic recharge, making them vulnerable to climate uncertainties, especially droughts.[86]

CGWB data indicates that the annual dynamic groundwater resource generated within the city limits vary in the four cities—from about 10 percent of available surface water for Chennai to 22 percent in Coimbatore, 24 percent in Delhi, and about 65 percent in Bengaluru (Figure 16). Among the four, Bengaluru exploits groundwater the most. Although groundwater is volumetrically smaller than the available surface storages, the groundwater resource plays an extremely critical role in plugging the piped water supply gaps in the cities. On its own, groundwater caters to 30 percent or more of the city areas and the resident population in the four cities. Periods of lower precipitation translate to higher groundwater abstraction in all four cities. It will thus be prudent to restrict the groundwater abstraction within the safe development norms of <70 percent of annual replenishment, as prescribed by the water ministry's Groundwater Resource Estimation Committee (GEC 2015).[87]

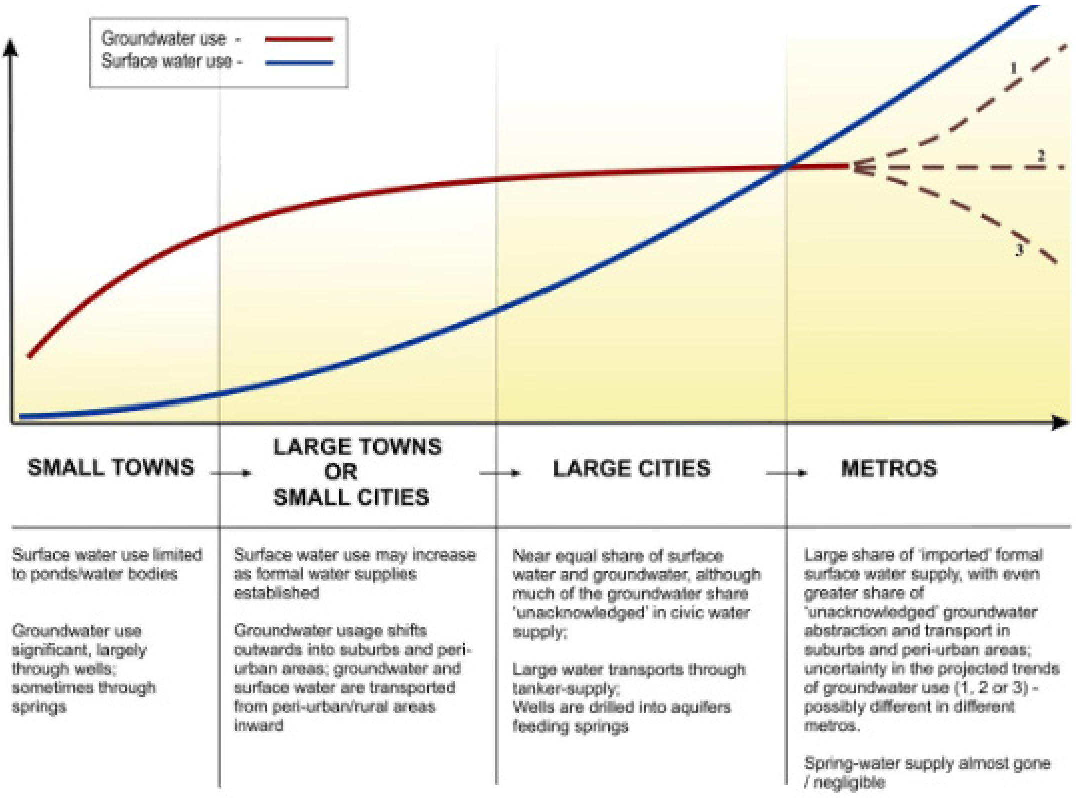
Figure 16: Annual Dynamic Recharge of Groundwater and Corresponding Groundwater Abstraction in Chennai, Bengaluru, Coimbatore and Delhi (2004, 2007, 2013 and 2017)



Source: Authors' plots from Central Ground Water Board's dynamic groundwater resource data.[88]

Static (or stock) groundwater resource available in the aquifers should stay necessarily stored for extreme emergencies. Chennai, Bengaluru, Coimbatore and Delhi report groundwater overdraft of about 170 percent of the annual replenishable resource availability, which locally increases to 400 percent of the annual replenishable resource in smaller sub-watersheds.[89] Primary and secondary data (Figure 17) suggests that most cities are yet to establish an appropriate governance framework to control and manage groundwater exploitation, resulting in both overexploitation and increased pollution of the aquifers.

Figure 17: Generalised Trends of Surface and Groundwater Use across Variously Sized Urban Settlements in India



SMALL TOWNS →	LARGE TOWNS OR SMALL CITIES →	LARGE CITIES →	METROS
Surface water use limited to ponds/water bodies Groundwater use significant, largely through wells; sometimes through springs	Surface water use may increase as formal water supplies established Groundwater usage shifts outwards into suburbs and peri-urban areas; groundwater and surface water are transported from peri-urban/rural areas inward	Near equal share of surface water and groundwater, although much of the groundwater share 'unacknowledged' in civic water supply; Large water transports through tanker-supply; Wells are drilled into aquifers feeding springs	Large share of 'imported' formal surface water supply, with even greater share of 'unacknowledged' groundwater abstraction and transport in suburbs and peri-urban areas; uncertainty in the projected trends of groundwater use (1, 2 or 3) - possibly different in different metros. Spring-water supply almost gone / negligible

Source: Shah and Kulkarni, 2015.[90]

Most small- and medium-sized towns in India have a greater reliance on groundwater. As the surface raw water consumption increases in larger cities and metros, there is a corresponding increase in groundwater abstraction.

Urban Water Quality

While there is a continuous reduction in per capita water availability, India's cities are also seeing progressively deteriorating water quality. A report by the BIS on piped drinking water in 15 state capitals outlined severe quality concerns in most cities, including Chennai, Bengaluru and Delhi.[91, 92] The tests were conducted on chemicals, toxic metals, organo-leptic, bacteriological and physical parameters, as per BIS norms.[93] The report suggests that a vast majority of the samples did not comply with Indian standards (IS 10500:2012)[94] in one or more parameters (see Table 3).

Table 3: Results of Bureau of Indian Standards Test on Quality of Piped Drinking Water

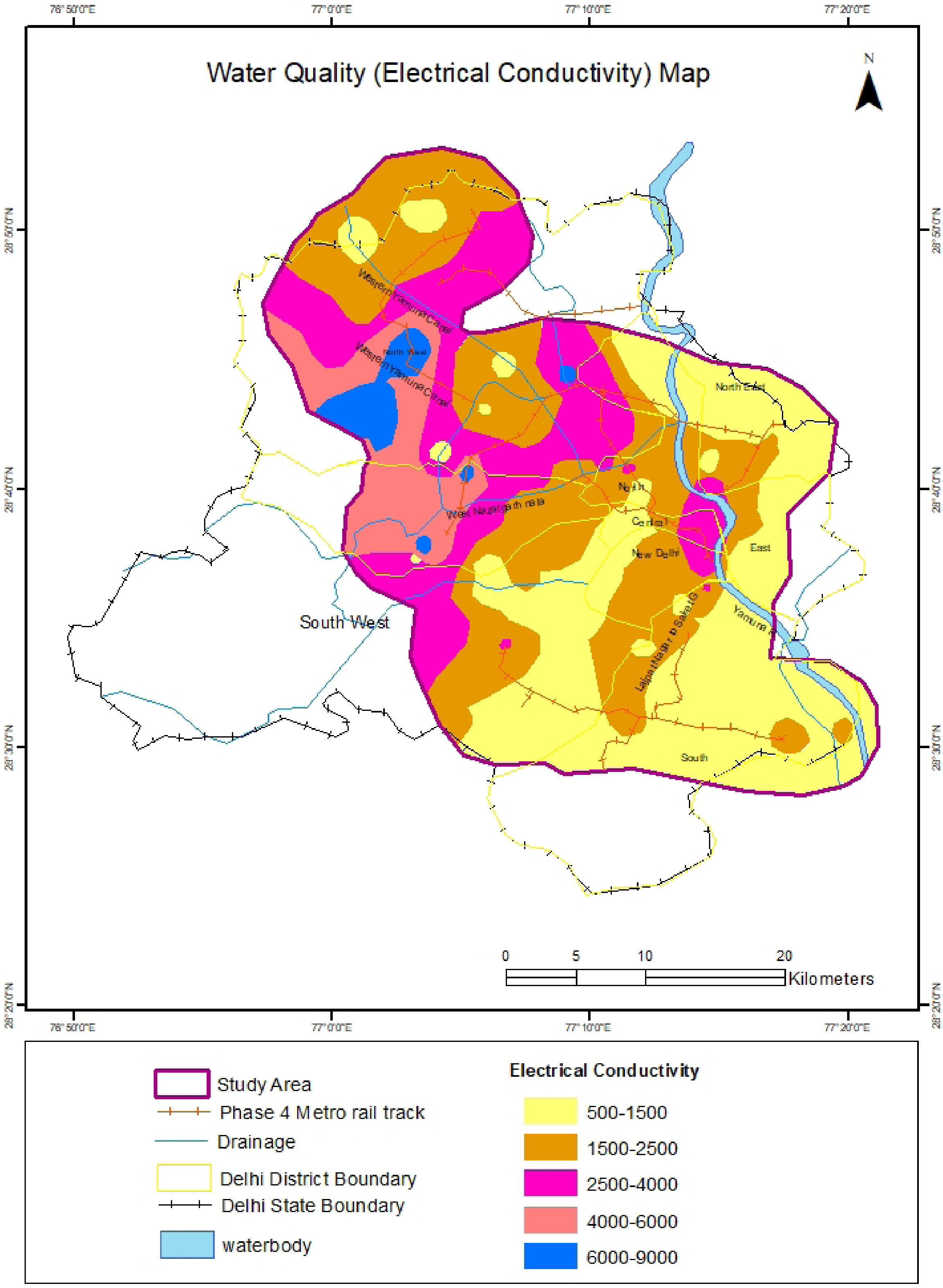
CATEGORISATION	CAPITAL	NO. OF FAILING	NO. OF INDIVIDUAL PARAMETERS IN WHICH SAMPLE FAILING
1	Mumbai	0/10	0
2	Hyderabad	1/10	1
	Bhubaneswar	1/10	1
3	Ranchi	1/10	4
4	Raipur	5/10	3
5	Amravati	6/10	7
6	Shimla	9/10	1
7	Chandigarh	10/10	2
8	Thiruvananthapuram	10/10	3
9	Patna	10/10	4
	Bhopal	10/10	4
10	Guwahati	10/10	5
	Bengaluru	10/10	5
	Gandhinagar	10/10	5
11	Lucknow	10/10	6
	Jammu	10/10	6
12	Jaipur	10/10	7
	Deheradun	10/10	7
13	Chennai	10/10	9
14	Kolkata	9/9	10
15	Delhi	11/11	19

Primary data collected by the authors from Delhi (Table 4 and Figure 18) and Coimbatore (Figure 19 and Figure 20) illustrate the extent of polluted surface and groundwater in these both cities, corroborating the BIS report.

Table 4: Primary Data on Bacteriological Tests in Groundwater Samples Collected from Delhi

SITE NAME	WATER SOURCE	TOTAL COLIFORM	FECAL COLIFORM
Khanpur	Tube Well	90	4
Kanjhawala	Tube Well	Nil	Nil
Narela	Tube Well	Nil	Nil
Jagatpur Gaon	Tube Well	130	6
Baprola	Tube Well	Nil	Nil
Rajouri Garden	Tube Well	Nil	Nil
Ferojshah Kotla	Tube Well	Nil	Nil
Dhansa	Tube Well	Nil	Nil
Kanganheri	Tube Well	Nil	Nil
Mahipalpur	Tube Well	11	Nil
Greater Kailash	Tube Well	2	Nil
Bhatti Khurd	Tube Well	Nil	Nil

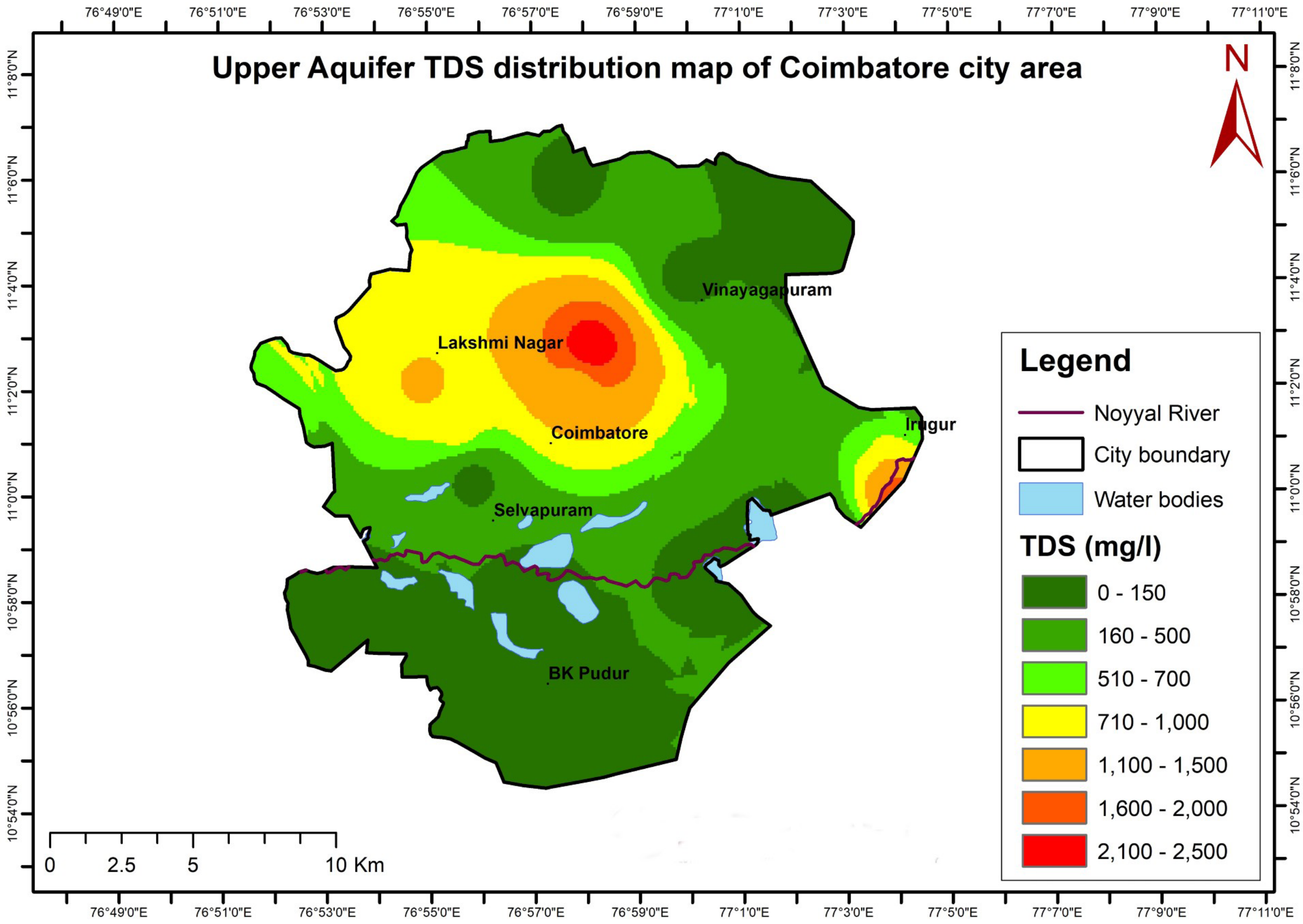
Figure 18: Electrical Conductivity Values in Delhi's Groundwater



Source: Authors' own based on primary data collection.

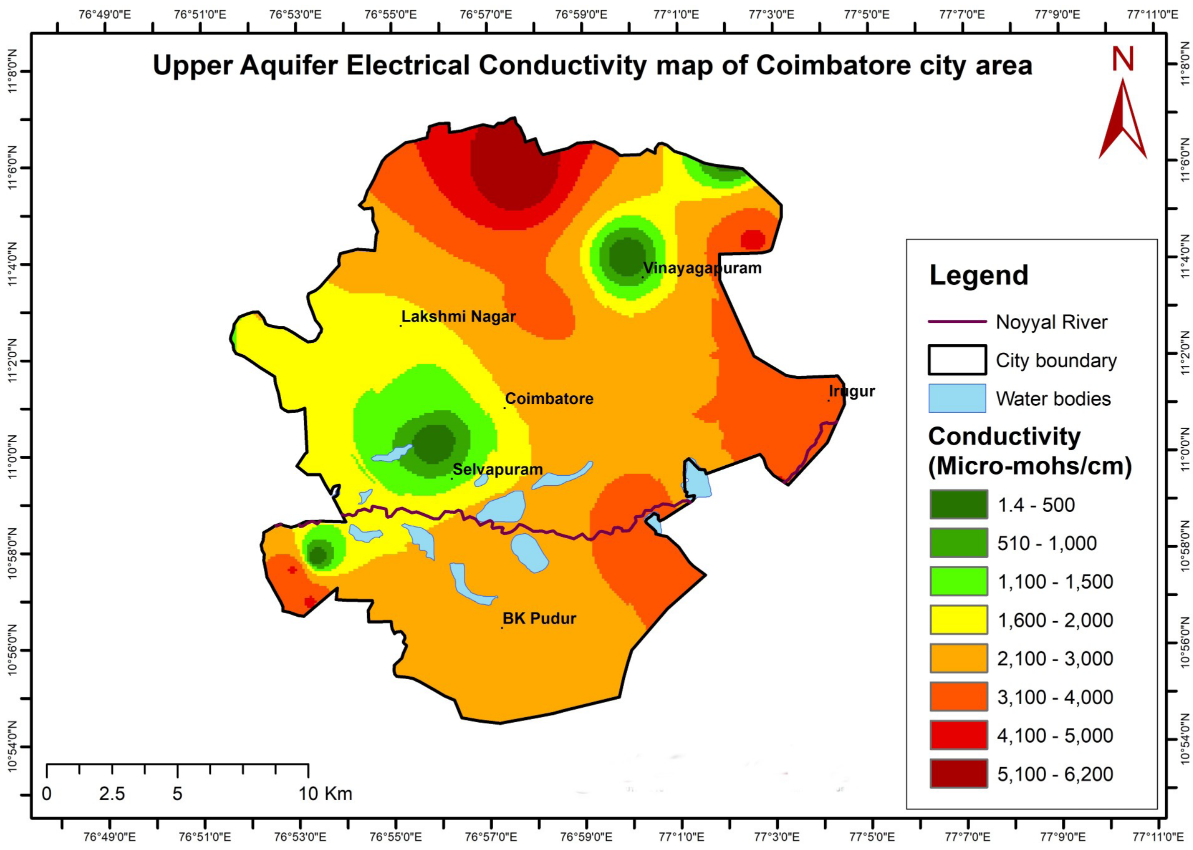
About one-third of Delhi has groundwater (and some surface water) with electrical conductivity (EC) values higher than 3000 micro-mhos/cm (see Figure 18), making it unusable, as per GEC 2015 norms.[95] Higher EC values in the groundwater are correlated to contamination from potential sewage or effluent sources infiltrating from the surface. Most of Delhi is thus experiencing severe groundwater quality concerns.

Figure 19: Total Dissolved Solids Distribution in Phreatic Aquifer of Coimbatore



Source: Authors' own based on primary data collection.

Figure 20: Upper Aquifer Electrical Conductivity Distribution in Coimbatore



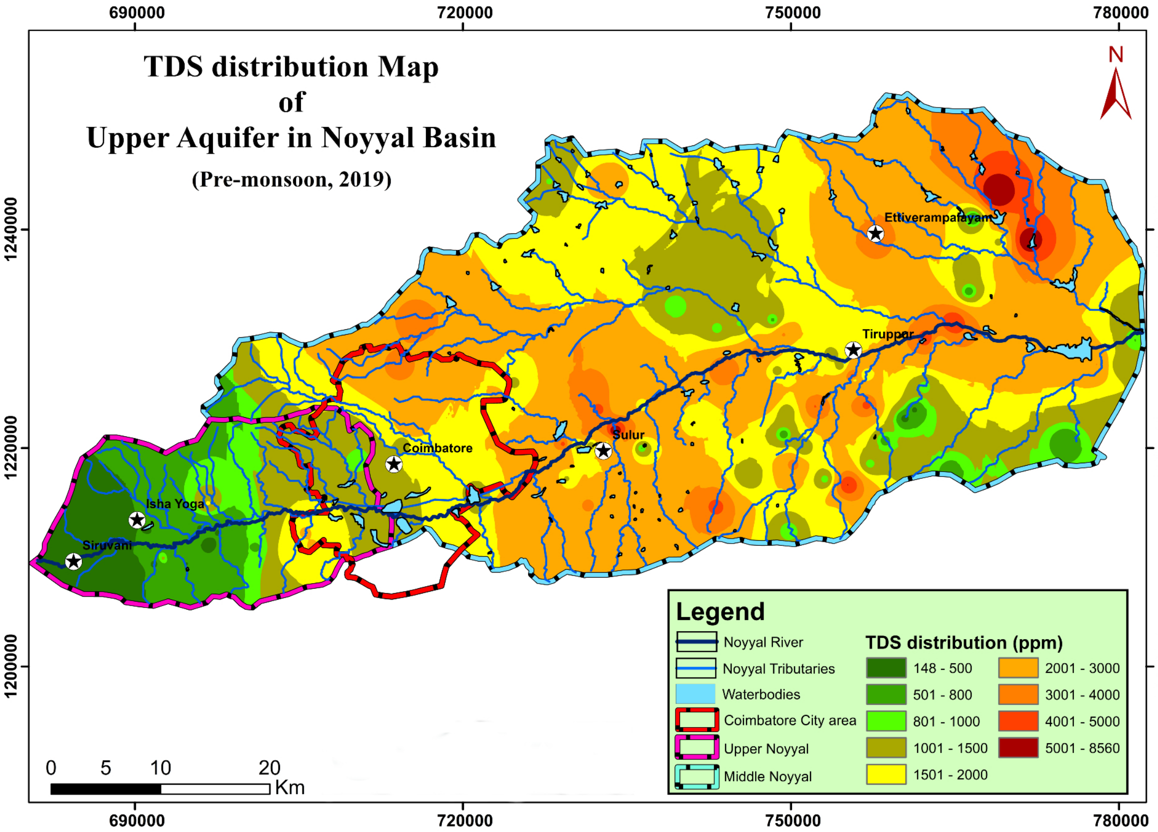
Source: Authors' own based on primary data collection.

The central and northern part of Coimbatore show higher levels of pollution and correspondingly high total dissolved solids (TDS) and high electrical conductivity values (See Figures 19 and 20). The high TDS and EC values are correlatable to potential sewage and industrial effluent contamination through unlined stormwater channels in the city.

Primary and secondary hydro-chemical data indicate that the sub-potability of water quality in Indian cities are primarily caused by humanmade factors, resulting in the mixing of untreated wastewater with freshwater sources. Much of the stormwater urban streams have been converted into unlined sewage and effluent channels. These stormwater streams also receive significant solid waste dumps, which eventually get dissolved, thereby increasing the toxicity in the surface and groundwater.

Analysis of groundwater in Coimbatore suggest a significant deterioration in quality, with moderate to high levels of physical parameters like pH, EC, TDS and alkalinity; cations like calcium, magnesium, potassium; and anions like chloride and sodium.[96] The pre-monsoon TDS map of surface and groundwater primary data sampled from Coimbatore shows an extraordinarily high TDS range of 1000 to > 4500 ppm, confirming significant pollution load in the water (see Figure 21).

Figure 21: Total Dissolved Solid Dispersion Map Of Noyyal Basin Prepared For The Phreatic (Upper) Aquifer Groundwater Sample Data



Source: Authors' own based on primary data collection.

The water quality deterioration in the urban regions of the Noyyal Basin indicates that pristine clean water from the Western Ghats (western portion of the map) flows down and acquires a significant pollution load in Coimbatore, Tiruppur and Erode cities, and potentially transferring a significant pollution load into the groundwater systems (see Figure 21).

Secondary data on the microbial quality of drinking water in Bengaluru suggest that up to 90 percent of water available to the city's peri-urban localities is unfit for human consumption, as per World Health Organization (WHO) standards.[97] High TDS, calcium, magnesium, alkalinity and hardness in source water in the city is of unacceptable potable quality.[98]

The groundwater quality of shallow phreatic unconfined aquifers in cities across India is a major cause for concern. Uncontrolled and poorly designed borewells in many cities have also punctured and connected the polluted top aquifers to the confined aquifers below. Confined aquifers, once polluted, are extremely difficult to remediate. Many cities are seeing the progressive pollution of urban aquifers due to a continuous increase in the nutrient and heavy metals loads from multiple sources. The remediation of polluted aquifers is a complex, expensive and time-consuming process.

Changes in the Urban Water Demand

While the average per capita availability of water has reduced, the demand for water for modern living has continually increased. Gadgets like washing machine, dishwashers, modern showers and flush toilets and centralised air conditioner systems require significantly more water than what was needed in an average household a few decades ago. These changes in living standards have also contributed to increasing water divide and inequity in urban societies. The WHO classifies the supply and access to water in four service categories: no access (water available below five litre per capita per day, or lpcd); basic access (average approximately 20 lpcd); intermediate access (average approximately 50 lpcd); and optimal access (average of 100-200 lpcd).[99] Some Indian cities report a per capita freshwater availability of 75 to 100 lpd for approximately 85 percent of their population and up to 200 lpd or more for the remaining 15 percent.[100]

Table 5: Activity-wise Distribution of Water Consumption in Cities (Percent of Total Consumption by Households Day)

ACTIVITY	ALL 7 CITIES	DELHI	MUMBAI	KOLKATA	HYDERABAD	KANPUR	AHMEDABAD	MADURAI
Bathing	28.2	31.7	23.7	37.1	25.6	29.1	22.8	26.6
Washing Clothes	18.6	14.2	24.3	14.0	20.9	16.3	21.4	18.9
Drinking	4.2	5.0	4.2	2.6	4.3	3.8	4.9	4.9
Cooking	4.2	5.0	4.2	2.6	4.3	3.8	4.9	4.9
Toilets	3.0	3.7	1.7	2.3	3.1	3.2	3.3	4.2
Cleaning House	20.0	16.5	21.6	15.9	24.1	20.1	19.1	25.7
Washing Utensils	7.3	7.0	6.6	11.7	3.5	5.7	12.4	1.9
Others	2.4	5.6	.5	0.3	2.0	6.3	0.9	1.7
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Source: Shaban and Sharma, 2007.[101]

BIS suggests a per capita need of 200 litres per day for a modern housing unit with full flushing systems,[102] while IS 1172-1993 (code of basic requirements for water supply, drainage and sanitation)[103] suggests a minimum water requirement of 135 litres per day for economically weaker sections of society. None of the four reference cities in this study meet the BIS requirements of per capita water availability (see Table 5). Since various agencies recommend different quantities of water for domestic use, a benchmark of 100 lpcd consumption (or availability, as consumption is determined by availability) has been set to identify water deficit households.[104] Available data indicates severe water inequity in India between different economic classes (see Table 6). Multiple indigenous innovations on house utilities will be needed to optimise water demand and usage and promote sustainability and water equity.

Table 6: Area-wise Consumption of Water Per Household and Per Capita Per Day

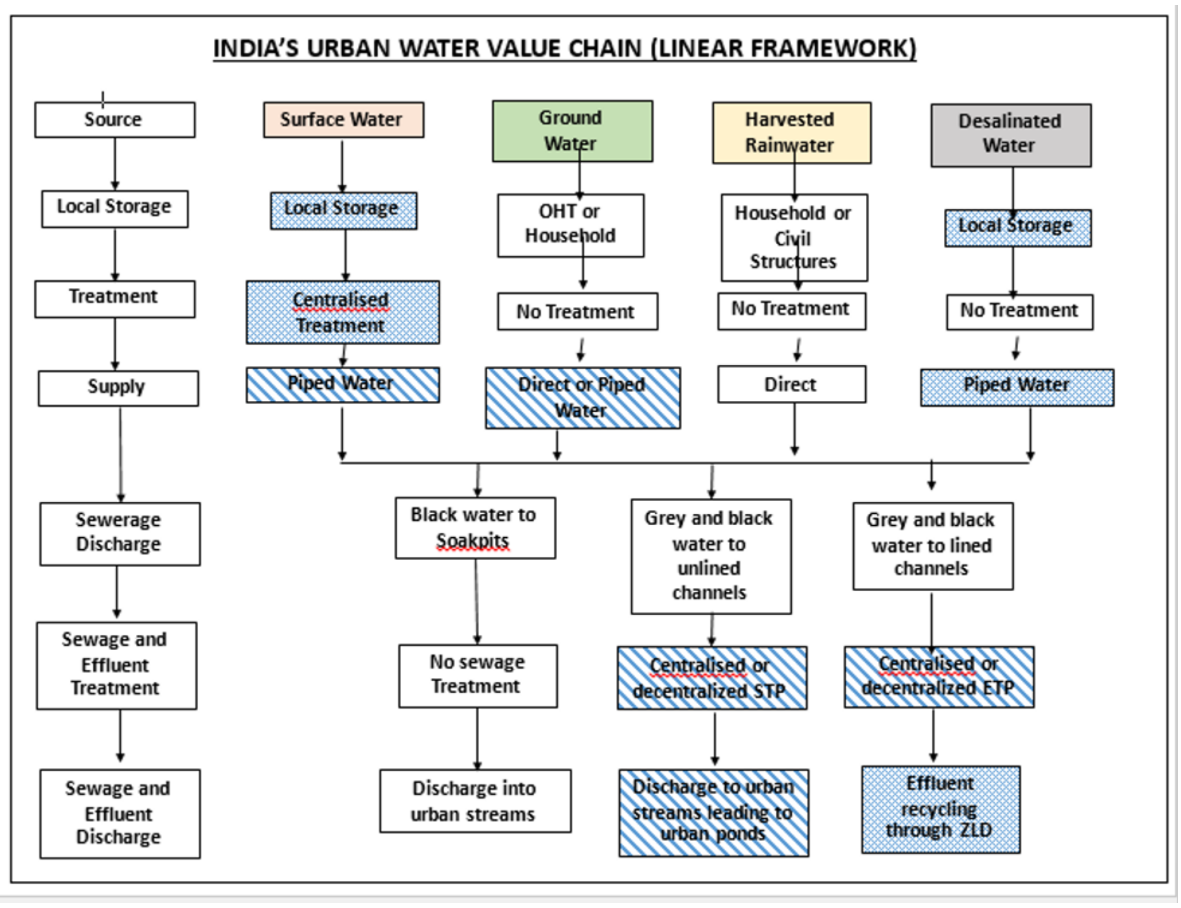
AREA	PER HOUSEHOLD		PER CAPITA		N
	Mean	Std Deviation	Mean	Std Deviation	
High income group (HIG) areas with well-planned building	402.5	230.3	99.9	59.8	551
Middle income group (MIG) areas with well-planned building	396.4	248.6	94.2	57.6	571
Low income group (LIG) areas with well-planned building	393.5	176.4	90.2	40.6	552
Slum areas	398.7	216.8	81.9	41.1	530
Others (mixed areas)	400.5	222.0	91.3	53.1	530
TOTAL	398.3	220.2	91.6	51.5	2734

Source: Shaban and Sharma, 2007.[105]

Urban Water Balance

In Chennai, Bengaluru, Coimbatore and Delhi, raw water flows through a linear supply and value chain from the source to the consumers, and the generated wastewater is eventually discharged downstream through the urban drainage system (see Figure 22). The raw water is brought from a captive storage to the cities through pipelines, stored locally and chlorinated and distributed to consumers. The sewage is discharged into either centralised or decentralised channels leading to centralised or decentralised sewage treatment plants (STPs) or discharged directly into the local stormwater drainage channels. Post-treatment, the sewage is mostly released into stormwater drainages leading to an urban lake (water body) or out of the city through urban stream. Effluents too are either treated through centralised or decentralised effluent treatment plants (ETPs) or released without any clean up (only a few industries have adopted zero liquid discharge, or ZLD, protocols).

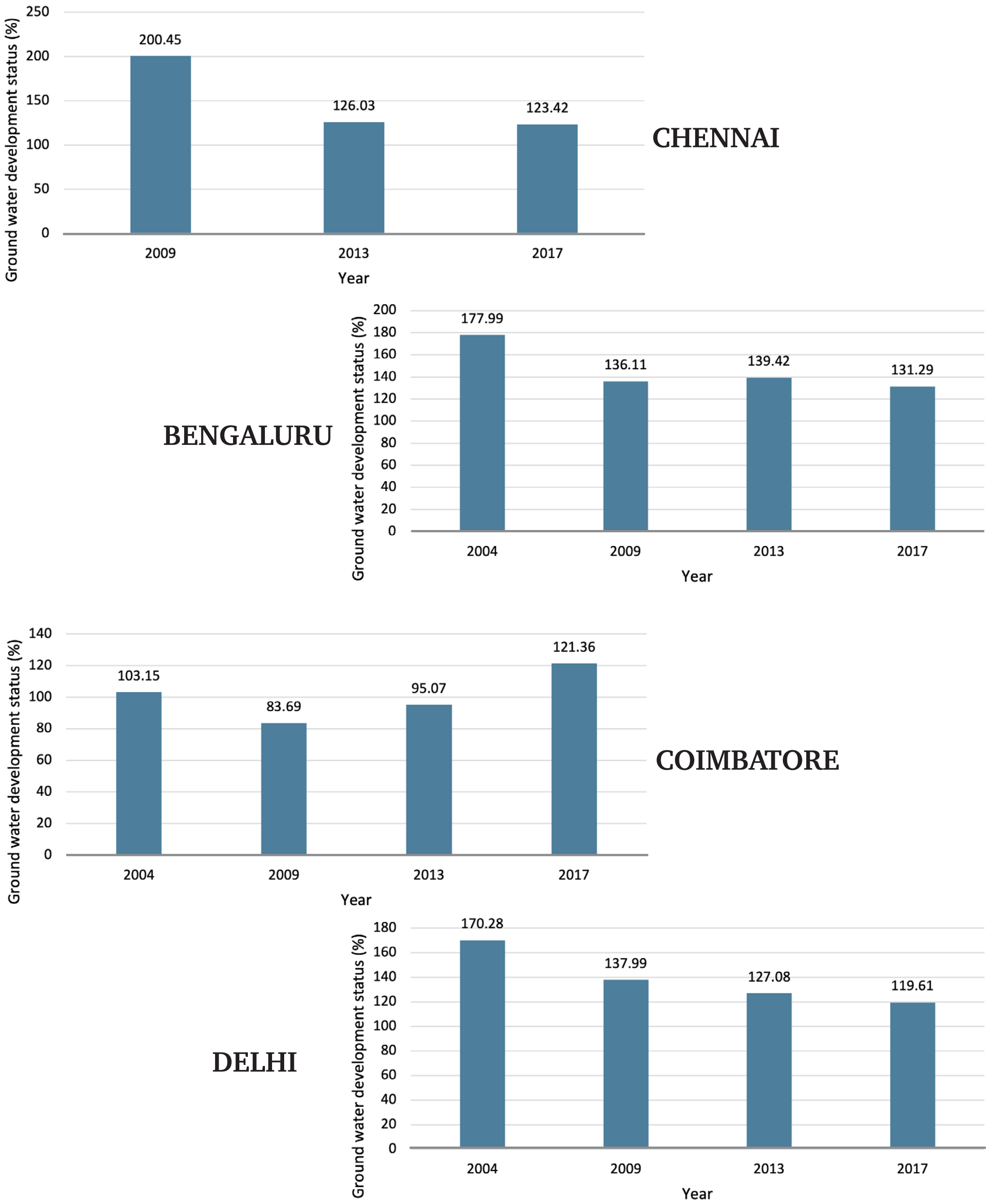
Figure 22: Urban Water Value Chain from Source to Discharge



Note: The primary focus of urban water management systems in Indian cities is water supply to consumers. In the four reference cities, groundwater supply, although a significant component of total supply, is considered a supplementary source. Only part of the discharged grey or black water is STP/ETP treated, to be discharged back into the urban stormwater drainages. Processes that are almost fully accounted are shown stippled in blue, while processes that are partially accounted for are shown diagonally hatched in blue. The processes that are not accounted for in the urban water value chain are in unshaded boxes.

Chennai, Bengaluru, Coimbatore and Delhi are abstracting more groundwater than the annual dynamic recharge of aquifers (see Figure 23). Groundwater is now an extremely significant component of the total urban water utilisation. While Chennai's annual dynamic groundwater recharge adds 10 percent of the total surface water by volume, Coimbatore adds 22 percent, Delhi 24 percent and Bengaluru up to 65 percent (see Figure 24).[106]

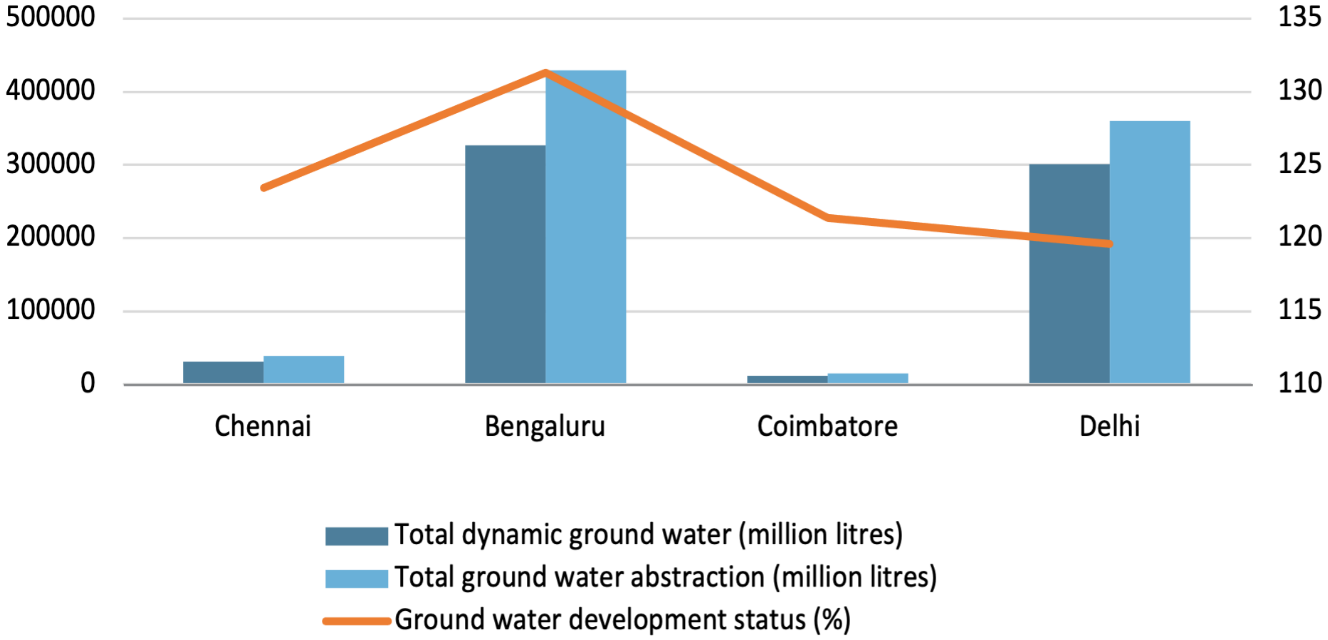
Figure 23: Groundwater Development in Chennai, Bengaluru, Coimbatore and Delhi (2004, 2009, 2013 and 2017)



Source: Data from CGWB, Annual Dynamic Groundwater Resource of India. Years 2004, 2009, 2013 and 2017.[107]

Note: All four cities illustrate groundwater abstraction more than the annual groundwater replenishment in the urban aquifer systems. Groundwater development appears to be reducing over the years, except in Coimbatore, which could be due to increased precipitation and recharge with respect to abstraction.

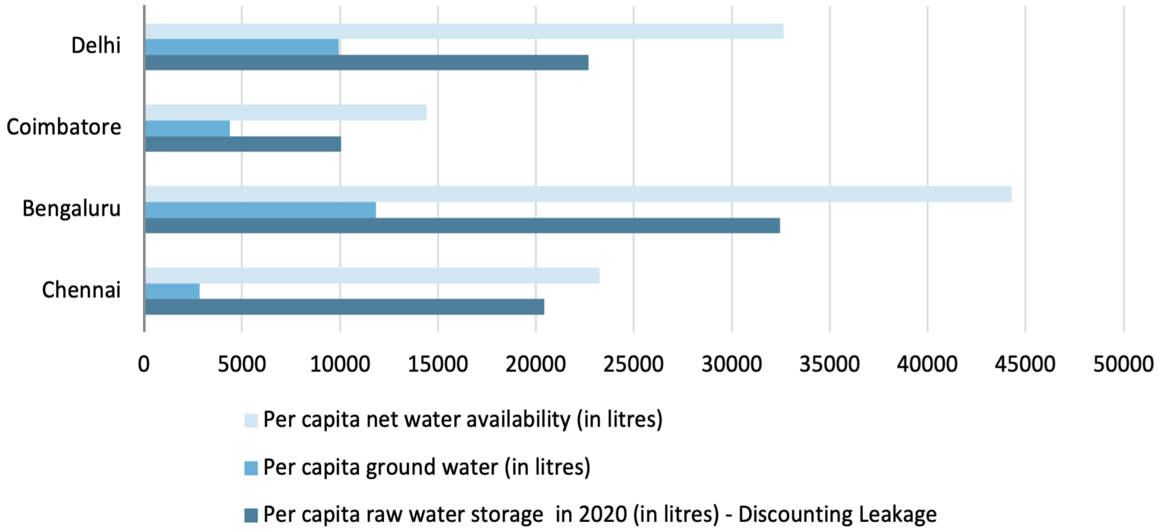
Figure 24: Annual Dynamic Recharge vs Groundwater Abstraction for Chennai, Bengaluru, Coimbatore and Delhi



Source: Data from CGWB, Annual Dynamic Groundwater Resource of India. Years 2004, 2009, 2013 and 2017.[108]
Note: The secondary axis shows the percentage of groundwater mining in each of these reference cities.

After discounting for the distribution leakages of raw captive surface water and adding the available dynamic groundwater, the net per capita (2020 projected population) availability of raw water resource for the four cities studied range from 25 m^3 in Chennai to 45 m^3 in Bengaluru, while Coimbatore has 15 m^3 and Delhi has 32 m^3 per capita raw water availability (see Figure 25). Even with groundwater added, all four cities have less than 75 m^3 per person per year, which is the BIS designated annual minimum water requirement for urban India[109] and a Central Public Health and Environmental Engineering Organisation norm (see Table 7).[110] The primary study conducted by the authors points to significantly greater stress for the poorer and peri-urban parts of the city, with limited access to water infrastructure, thereby highlighting the inequities in the water availability for urban residents in these cities.

Figure 25: Raw Water (Surface and Groundwater) Availabilities for Chennai, Bengaluru, Coimbatore and Delhi



Source: Authors' chart based on available data and analysis.

Table 7: Central Public Health and Environmental Engineering Organisation Norms

CLASSIFICATION OF TOWNS/ CITIES	RECOMMENDED MAXIMUM WATER SUPPLY LEVELS(LPCD)
Town provided with piped water supply but without sewerage system existing planned	70 +15% for leakage
Cities provided with piped water supply where sewerage system exists/planned	135 + 15% for leakage
Metropolitan and Mega cities provided with piped water supply where sewerage system existing	150 +15% for leakage

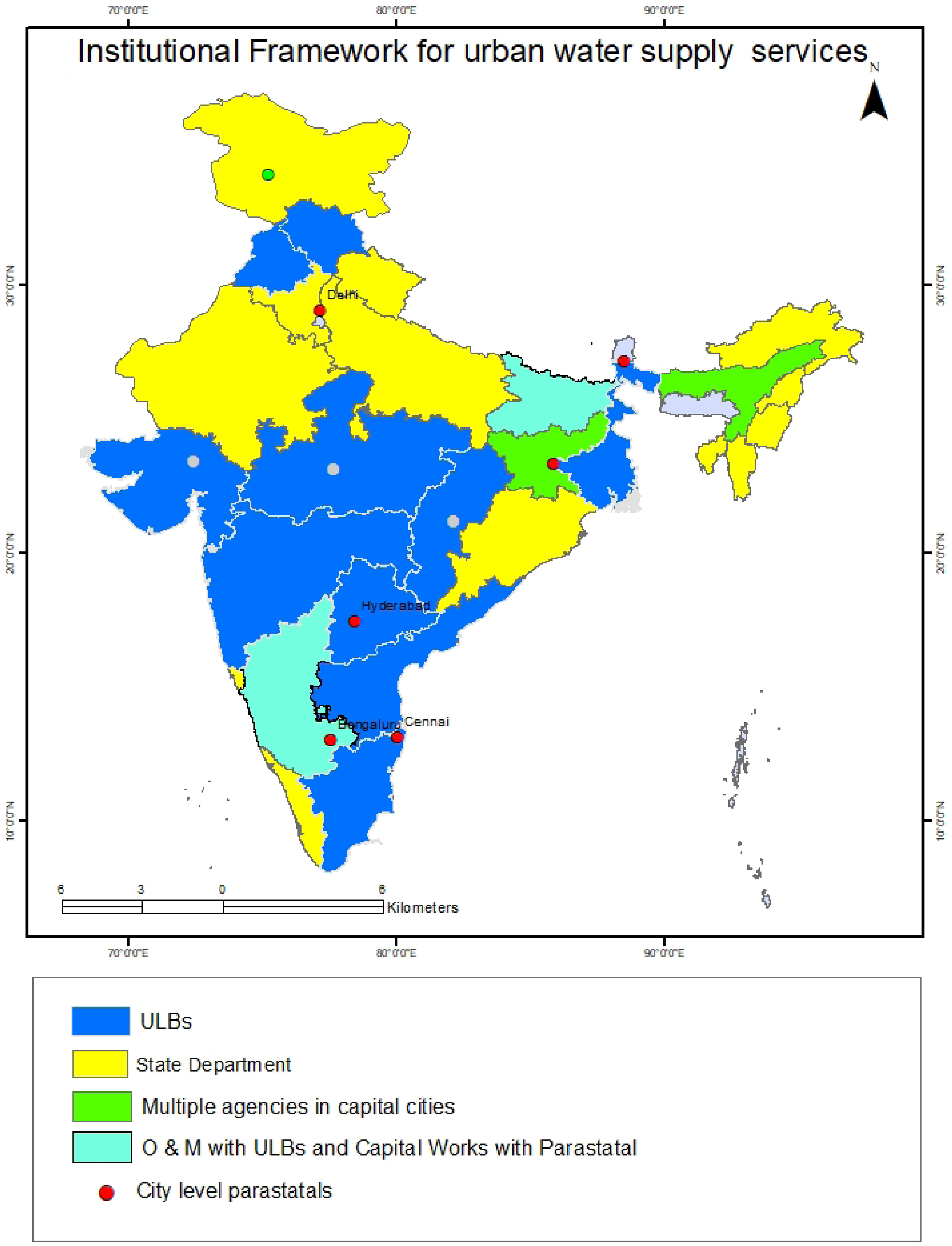
Source: Ministry of Urban Development, 2009.[111]

Urban Water Value Chain and Governance

Water is a state subject in India's federal structure, and the urban water supply is governed by multiple agencies across the country (see Figure 26). In Tier 1 cities, urban water supply and sanitation accountability lies with ULBs, which report to the municipal corporations, while in smaller non-metro cities, the municipal corporations mostly oversee this task directly. The ULBs are also designated as water and sanitation boards, have their own annual budgets and operate like public sector undertakings. For instance, the Delhi Jal Board (DJB) is responsible for water supply in Delhi and reports to all three municipal corporations in the city. Water supply in Chennai is overseen by the Chennai Metropolitan Water Supply and Sewerage Board, and in Bengaluru by the Bengaluru Water Supply and Sewerage Board (BWSSB). In Coimbatore, a Tier 2 city, the Coimbatore City Municipal Corporation is directly accountable for the piped water supply and sewerage management.

However, there are several other agencies that are indirectly involved in the urban water supply value chain. In Bengaluru, in addition to the BWSSB, agencies like the Bruhat Bengaluru Mahanagara Palike (Bengaluru's municipal corporation), Karnataka Lake Conservation and Development Authority and the revenue authorities (in charge of land) are also accountable. Similarly, in Delhi, in addition to the DJB, the municipal corporation and the Delhi Development Authority are also responsible for water management at various levels.

Figure 26: Institutional Framework for Urban Water Supply across India



Source: Crisil Infrastructure Advisory.[112]

Having multiple oversight agencies leads to urban water mismanagement and other governance challenges. India's water boards and corporations are bureaucratised and inefficient. Although the water boards have significant annual capital and expenditure outlays, they have not been able to stall the increasing water stress in Chennai, Bengaluru, Coimbatore or Delhi. The ULBs are mostly led by engineers and manned by clerks, with a limited role for scientists and planners. Data and science-based planning has remained peripheral in the ULB management systems. In Bengaluru, for instance, experts believe that strategies and decision-making processes (for instance, allowing the city's lakes to become sewage receptacles and diverting the half-treated sewage water from these lakes to distant agricultural lands) are being implemented without a fundamental understanding of the science of hydrology and hydrogeology.[113]

The World Bank has expressed concerns about India's urban water governance and ULBs:[114]

> "More than 90% of the urban population has access to drinking water, and more than 60% of the population has access to basic sanitation. However, access to reliable, sustainable, and affordable water supply and sanitation (WSS) service is lagging behind. Are the Services Reliable? No Indian city receives piped water 24 hours a day, 7 days a week. Piped water is never distributed for more than a few hours per day, regardless of the quantity available. Raw sewage often overflows into open drains. Are the Services Technically and Financially Sustainable? Less than 50% urban population has access to piped water. The Non-revenue Water (NRW: due to leakages, unauthorized connections, billing and collection inefficiencies, etc.) is huge, estimated between 40-70% of the water distributed. Operations and maintenance cost recovery through user charges is hardly 30-40%. Most urban operations survive on large operating subsidies and capital grants…."

Urban water management by ULBs is primarily focussed on surface raw water source management. Although there had been some effort towards groundwater conservation, abstraction and management in cities like Chennai, there are negligible conservation efforts in Coimbatore, Bengaluru and Delhi. None of the ULBs or city corporations have made any effort to manage the demand side of the urban water budget (for instance, standardisation or rating of domestic water gadgets, or driving cultural changes towards water optimisation). Some cities like Coimbatore and Delhi are now experimenting with handing over the water distribution and management to private firms.[115]

II.
MITIGATING URBAN WATER RESOURCE SCARCITY

The situation analysis of Chennai, Bengaluru, Coimbatore and Delhi highlights the prevalent water stress and water scarcity conditions that have aggravated in the last two decades due to population growth and no change or a reduction in raw water storage capacity, severe depletion of the groundwater resource and deteriorating water infrastructure.

Given that it will be increasingly difficult to secure additional raw water resources for urban areas, the linear water balance framework currently used by ULBs (see Figure 22) must gradually transition into a circular water balance framework to secure additional resources. ULBs and municipal corporations in Chennai, Bengaluru, Coimbatore and Delhi are using supplies from raw surface water storages as the primary water sources for their water supply needs; groundwater is considered a supplementary resource and remains unaccounted for. Current data and accounting of consumer demand and water utilisation is inadequate to form a rational basis for urban water planning. India's cities do not have data on the differential needs of potable (drinking and washing) and non-potable (flushing and gardening) water, and none of the four reference cities have a comprehensive map of the water source to wastewater discharge, or classification of wastewater into grey and black water components.

Analysing the available raw water resources and demand has revealed the challenges of urban water management in India. There is a general acceptance that the looming water security crisis, stemming from the growing urban population and corresponding increase in water demand, can be addressed by adopting an Integrated Urban Water Management (IUWM) framework. IUWM practices will require the adoption of the following principles:

1. Developing a science-based comprehensive understanding of the hydrology of the water basin that the city is a part of
2. Real-time capture of supplied water and its utilisation data to the last consumer node. Also capturing data on wastewater discharge, segregated and classified as grey and black water
3. Creating an urban water balance, based on principles of recycling, reuse and circularity of available water; integrating the water balance with the city water budget (supply and utilisation)
4. Modernisation of urban water infrastructure to cater to IUWM needs, including supply, utilisation and data requirements
5. Aligning the urban water governance framework to IUWM
6. Engaging with all stakeholders and boosting capacity to adapt IUWM

Integrated Urban Water Management Framework

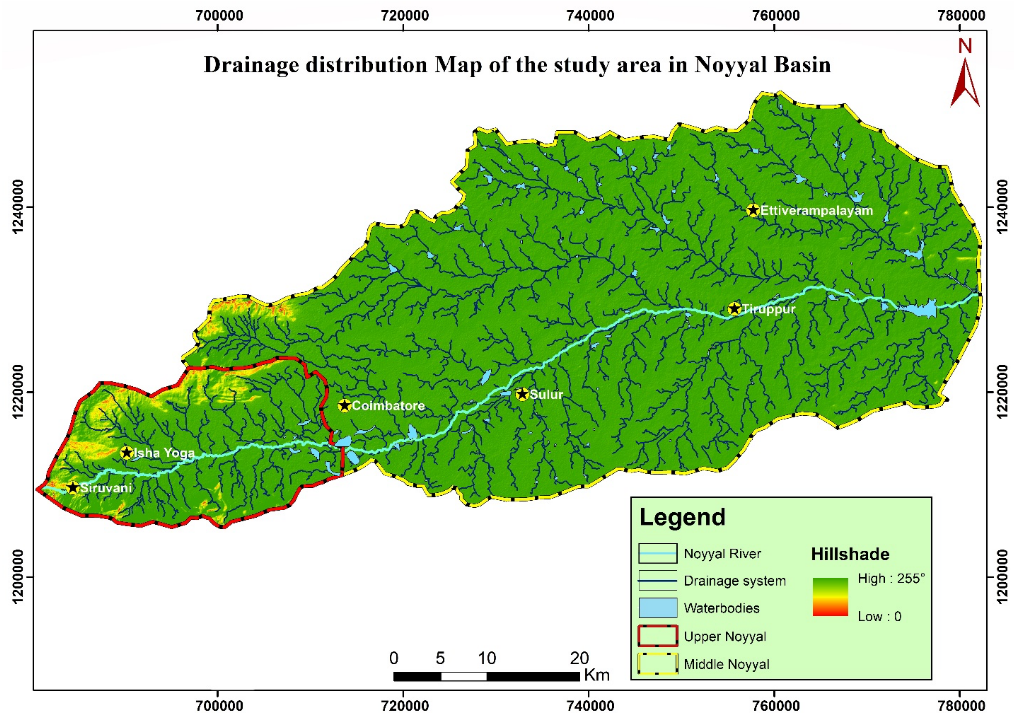
Several areas have been identified that have scope for improvement in the ULBs' current urban water management practices, with an aim to achieve water security for cities through IUWM practices.[116] Cities require a comprehensive review and understanding of various elements of urban water balance and the water budget to transition to the IUWM framework.

1. Augmentation of Surface Storage

Although the raw water storage capacities in many Indian cities need urgent augmentation, especially due to exponential population growth, this has not happened. Chennai[117] and Delhi[118] plan to create new surface storages, but these proposed large storage reservoirs will be constrained by environmental and capital cost constraints.

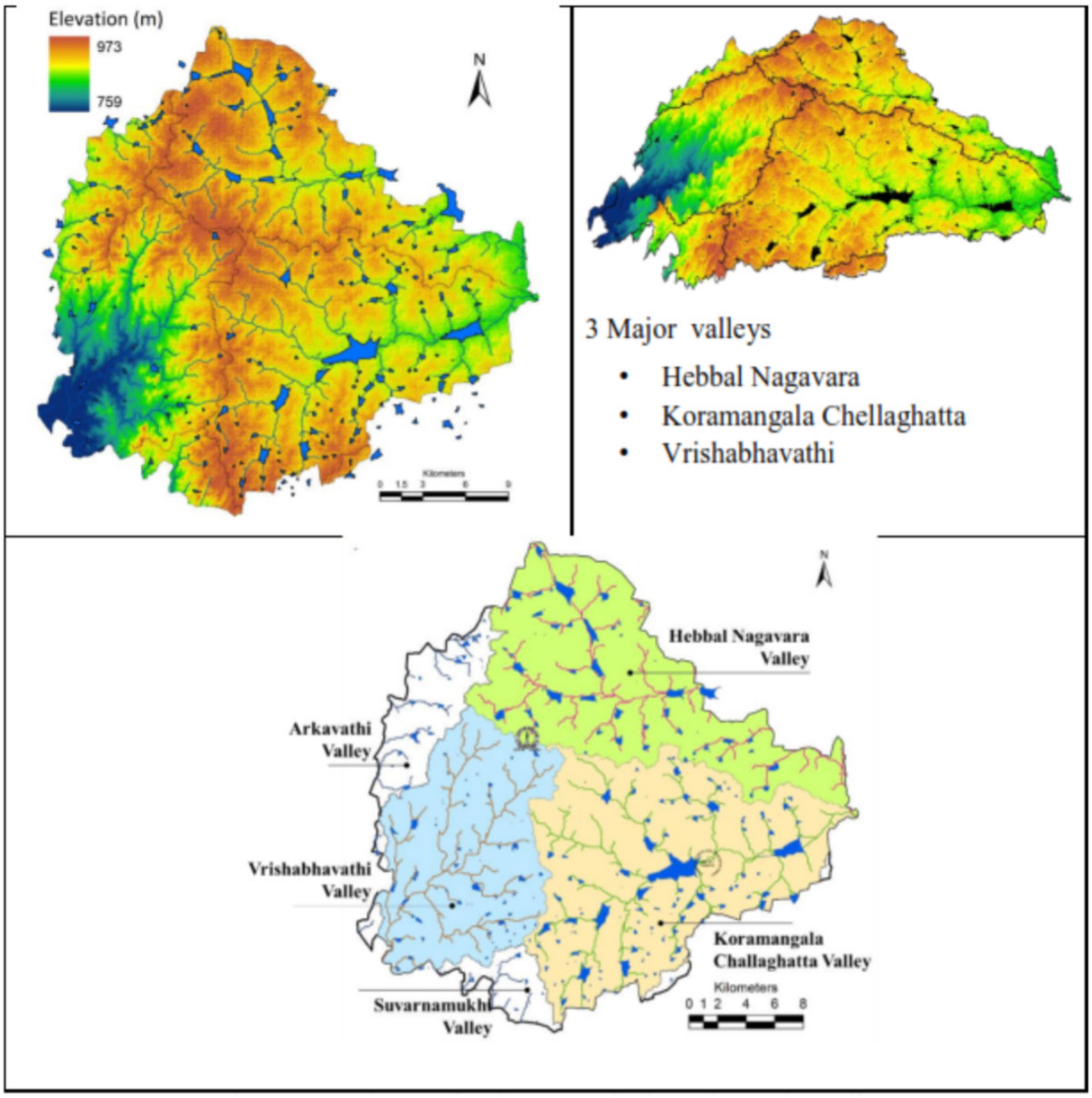
Alternative strategies to augment the surface water storages should be considered given the potential impact of any long-sustained drought or low precipitation. Coimbatore and Bengaluru have a legacy of water conservation practices, including groundwater recharge through connected water storage tanks/lakes using regulated flood water, diverted from the urban streams and rivers. Coimbatore's 'system tanks', which were constructed by the Chalukya Chola kings,[119] divert floodwaters from rivers for storage and for groundwater recharge (see Figure 27). Bengaluru's system of connected lakes[120] has also served a similar purpose (see Figure 28).

Figure 27: 'System Tanks' Along the Noyyal River



Source: Authors' own. Mapped using primary field data and satellite data processing.

Figure 28: Bengaluru's Streams and Connected Lake Network



Source: Ramachandra et al, 2017.[121]

In the past, such tanks and ponds have been effective as percolation/recharge ponds for city aquifers, while doubling as raw water storage reservoirs. Currently, however, these tanks have either been neglected or function as sewage and effluent pits. If remediated and rejuvenated through deepening and cleaning followed by ecological restoration, these tanks are likely to provide significantly increased storage capacities for raw water or percolation tanks for groundwater (see Tables 8 and 9).

Table 8: Changes in Total Area Covered by Water Bodies in Bengaluru, Chennai, Coimbatore and Delhi (in km^2), between 2001 and 2011.

YEARS	BENGALURU	CHENNAI	COIMBATORE	NCT DELHI
2001	10.59	10.44	6.09	14.33
2011	8.08	9.64	5.65	13.7

Source: Estimated by the authors using time series satellite data.

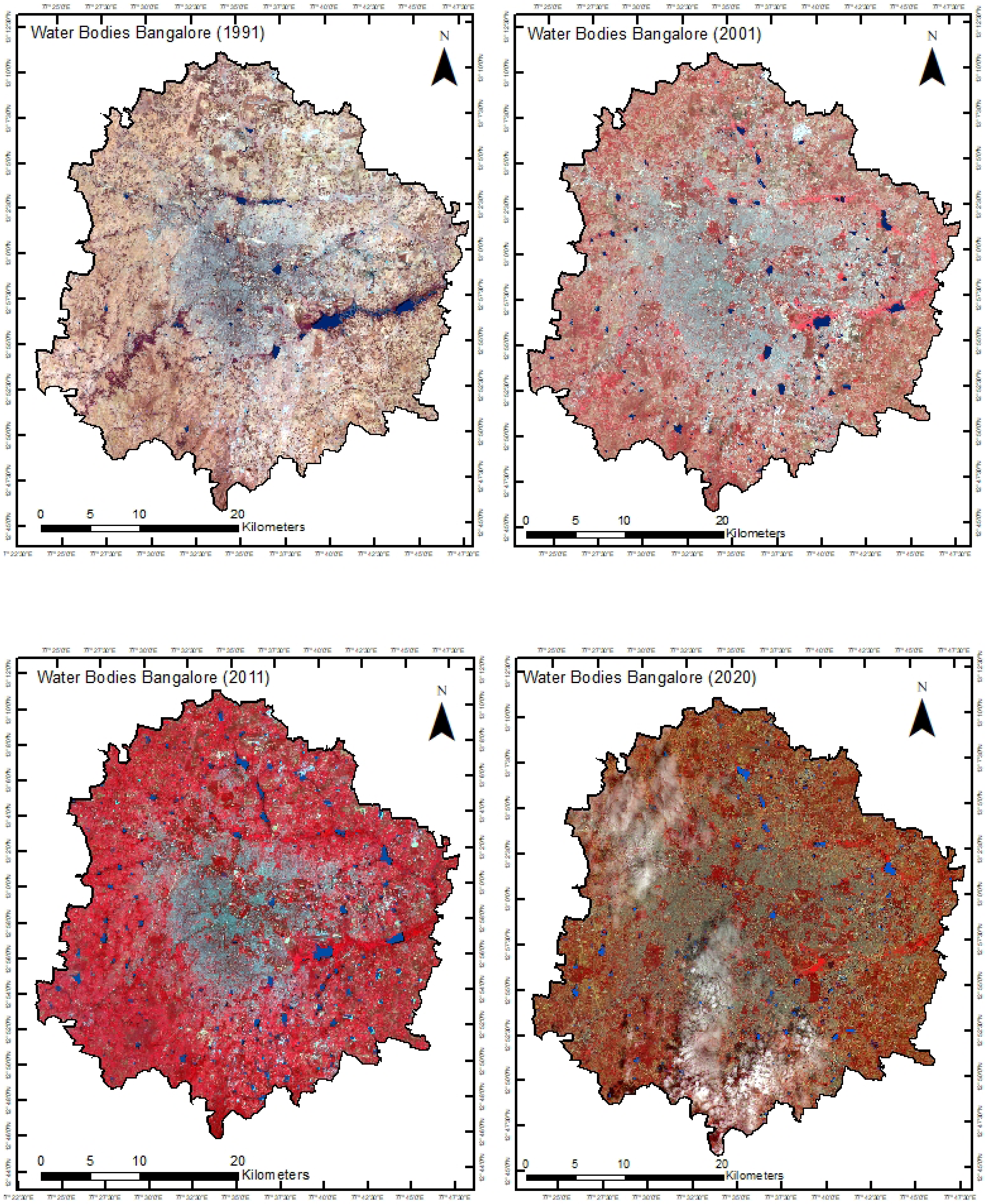
Table 9: Water Storage Capacities within the Larger Metropolitan Limits in the Water Bodies in Bengaluru, Chennai, Coimbatore and Delhi (in million cubic metre)

YEARS	BENGALURU	CHENNAI	COIMBATORE	NCT DELHI
1991	41	40	20	54
2001	32	31	18	42
2011	24	28	17	41
2020	23	27	15	34

Source: Authors' Estimation.

The areas covered by water bodies in Bengaluru, Chennai, Coimbatore and Delhi have shrunk significantly in the years between 1991 and 2020 (see Figures 29, 30, 31, 32 and 33).

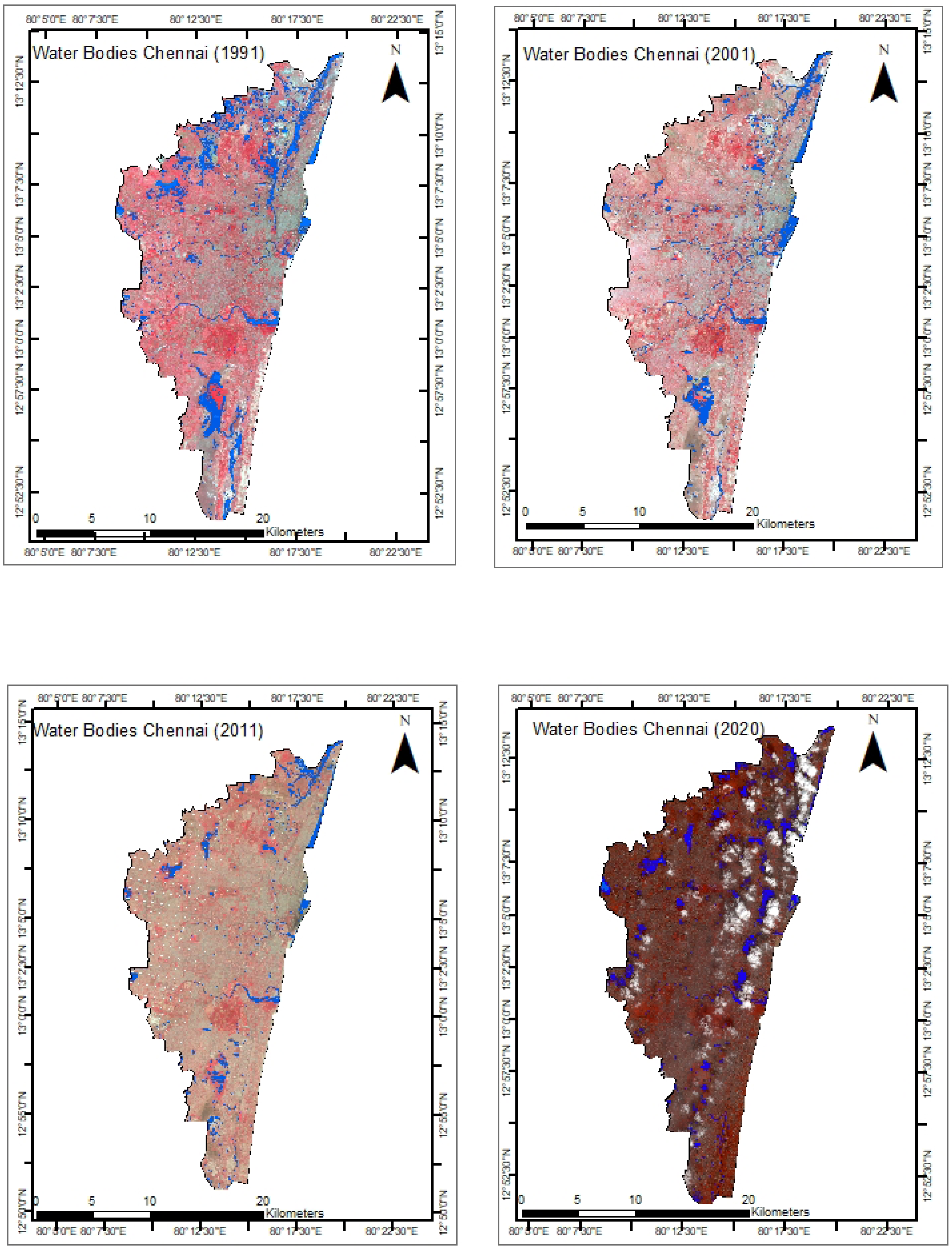
Figure 29: Satellite Images of Time Series Changes in Areas Occupied by Water Bodies in Bengaluru (1991 to 2020)



Source: Landsat 7 imagery data processed by the authors.

Bengaluru's water bodies shrunk by 50 percent between 1991 and 2020 (see Figures 29 and 33).

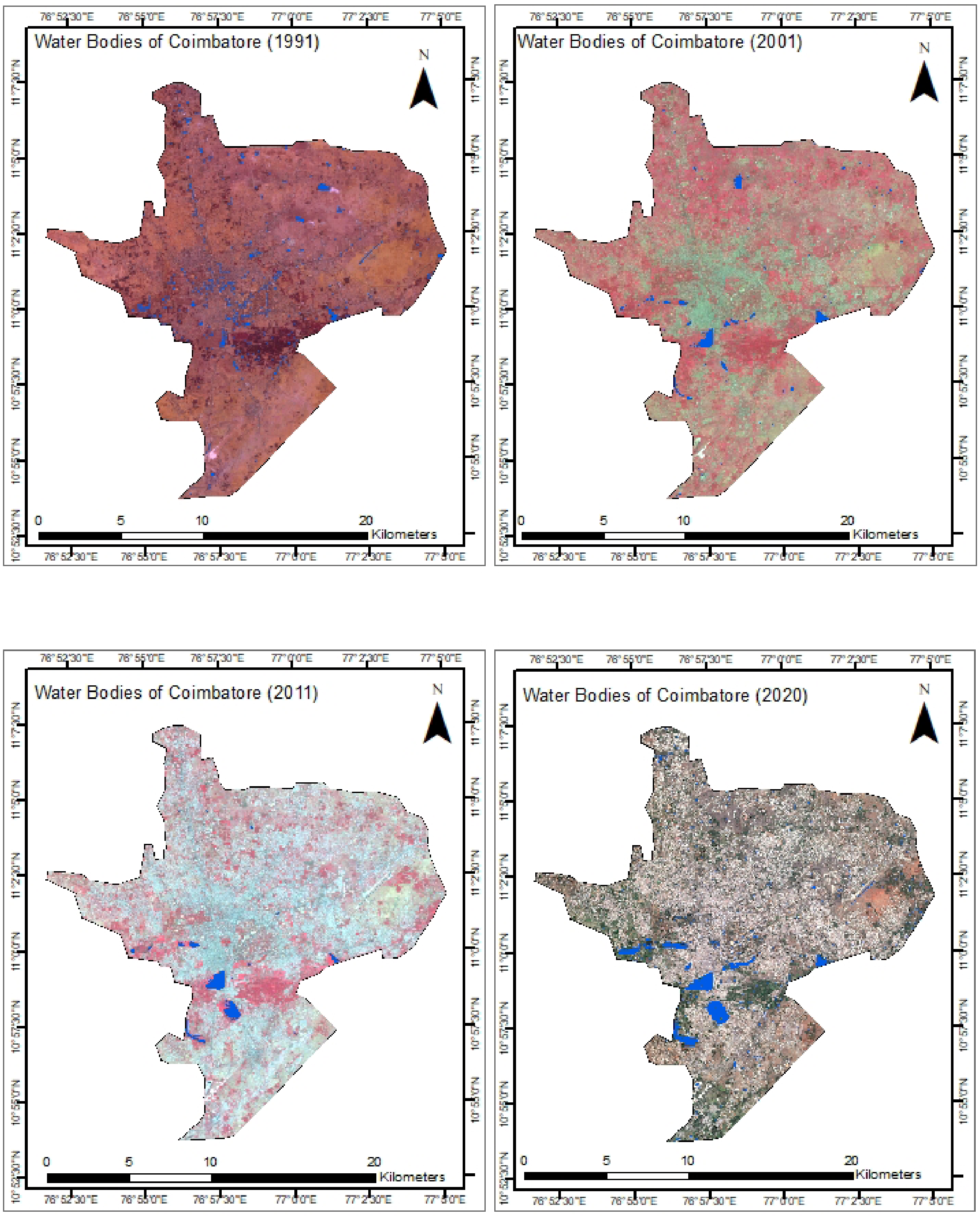
Figure 30: Satellite Images of Time Series Changes in Areas Occupied by Water Bodies in Chennai (1991 to 2020)



Source: Landsat 7 imagery data processed by the authors.

Chennai's water bodies shrunk by 30 percent between 1991 and 2020 (see Figures 30 and 33).

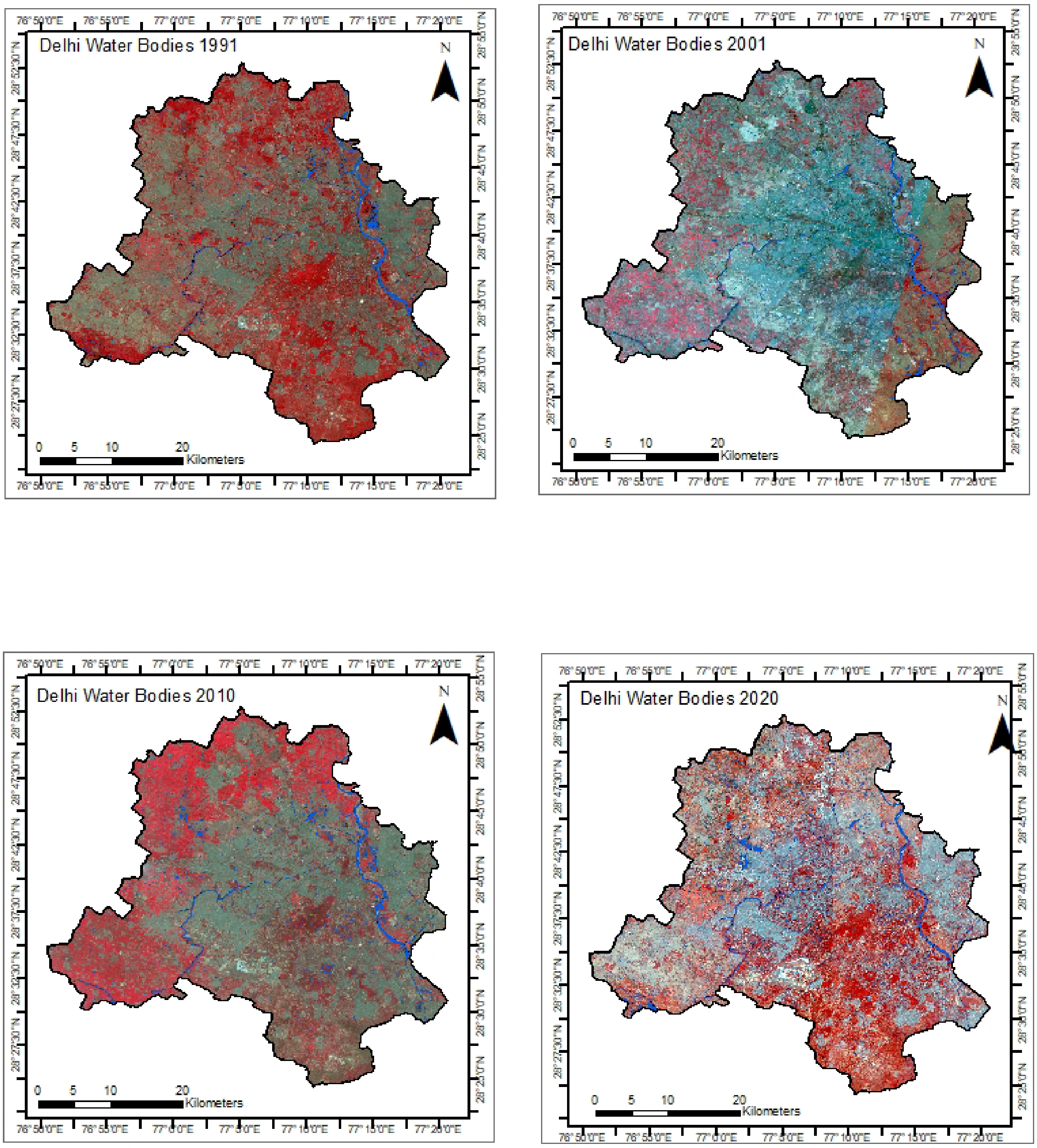
Figure 31: Satellite Images of Time Series Changes in Areas Occupied by Water Bodies in Coimbatore (1991 to 2020)



Source: Landsat 7 imagery data processed by the authors.

Coimbatore's water bodies shrunk by 25 percent between 1991 and 2020 (see Figures 31 and 33).

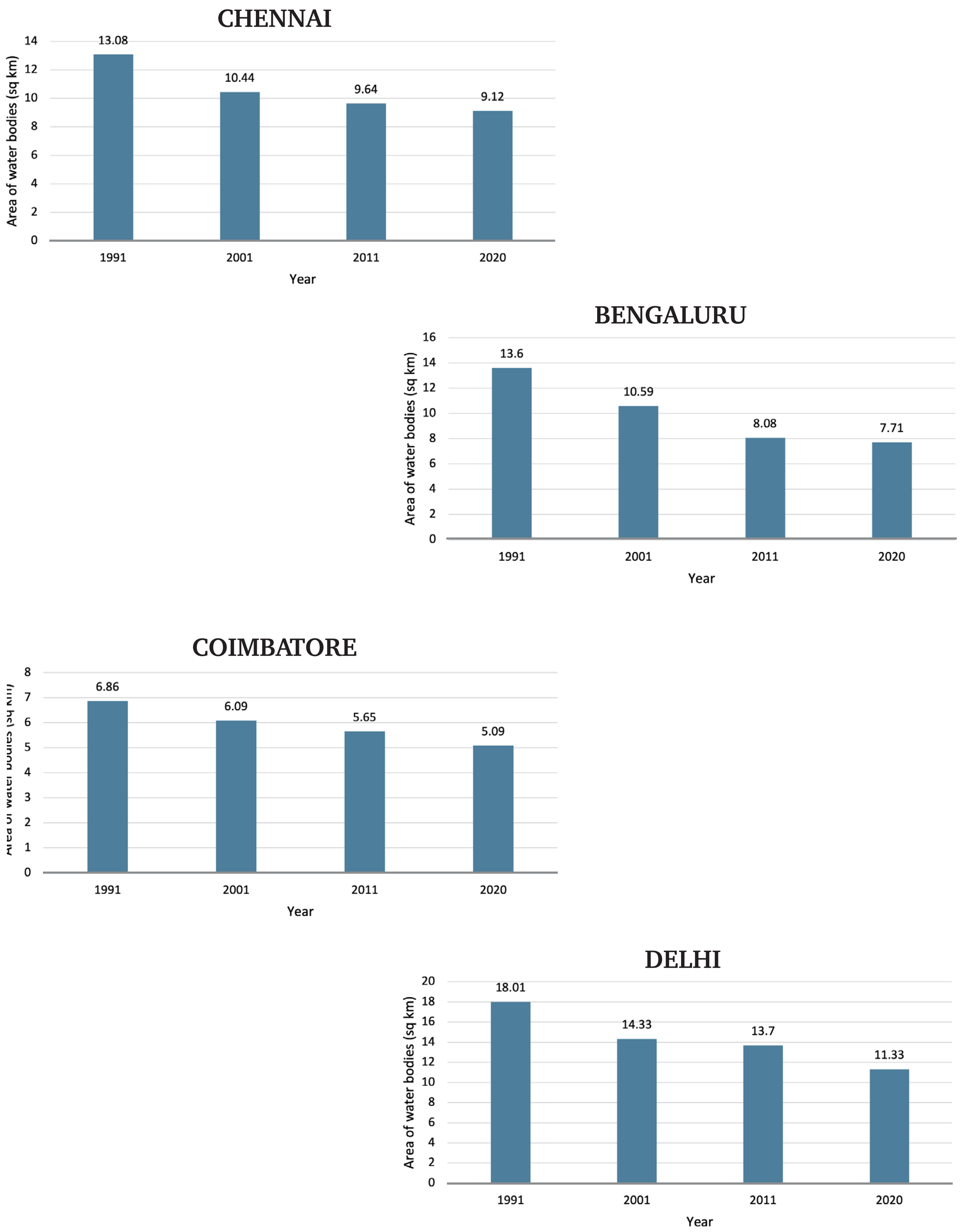
Figure 32: Satellite Images of Time Series Changes in Areas Occupied by Water Bodies in Delhi (1991 to 2020)



Source: Landsat 7 imagery data processed by the authors.

Delhi's water body area shrunk by 40 percent between 1991 and 2020 (see Figures 32 and 33).

Figure 33: Change in Total Area of Water Bodies for Chennai, Bengaluru, Coimbatore and Delhi (1991, 2001, 2011 and 2020)



Source: Estimation of changes in the storage of urban water bodies based on satellite imagery data studied by the authors.

For the city tanks to be effective as storage or recharge ponds, sewage and effluent conduits will need to be lined and segregated from the stormwater drains till the inflow into treatment plants. The STPs and ETPs must be carefully designed and planned for both centralised and decentralised wastewater inputs, and the water quality must be managed to the highest standards prior to the release into the stormwater channels. However, as cities create additional storages, securing extra-basinal raw water sources should be prioritised to mitigate climate change impacts in the future. These strategies will require ULBs to alter their operational practices and standards.

2. Augmentation of Groundwater Storage

Groundwater comprises a significant proportion of the total utilised freshwater in Indian cities. However, Chennai, Bengaluru, Coimbatore and Delhi are all exploiting more groundwater than their annual dynamic replenishment or recharge. For over two decades, most cities have carried out indiscriminate drilling of borewells and have pumped deeper and deeper for groundwater, due to a continuous drop in groundwater levels. Groundwater is likely to continue to play a significant role in the urban water supply. The focus must now shift to groundwater conservation, the recharge and restoration of depleted aquifers, and regulating indiscriminate groundwater pumping.

Applying the IUWM framework in Indian cities will require the groundwater draft to be limited to below the annual dynamic recharge. The pump discharges will also have to be within the safe yield limits, determined through science-based aquifer characterisation. These will require detailed hydrogeological mapping and the installation of telemetric/internet of things (IoT) based aquifer monitoring systems to observe groundwater abstractions, water levels and water quality. Cities that have extremely high groundwater abstraction rates (between 130 percent and 170 percent above the safe development limits for several years), like Bengaluru, may have to restrict groundwater abstraction for at least five years to restore and rejuvenate the phreatic aquifers. In recent years, Bengaluru has made efforts to carry out a direct injection/well recharge, which has resulted in elevated water levels in some perched aquifers in the western part of the city.[122] The sustainability of this rise in the water table will have to be closely monitored. Bengaluru and the other cities studied in this report are currently exhausting their water stock, which needs to be restored to work as emergency storage in case of extreme drought conditions. Cape Town, which faced a Day Zero scenario in 2015-17 due to climate change impacts, had retained most of its groundwater resource for abstraction even after the third year of failed monsoons.[123] Indian cities will be in dire conditions if they do not replenish, recharge and uplift the heavily pumped and severely depleted water tables.

Cities must accord high priority to groundwater conservation efforts too. However, meaningful groundwater conservation can only be successful if the surface raw water distribution network is extended to the last miles of the peri-urban areas. NITI Aayog's caution about the fast-depleting status of groundwater only points to the vulnerability of India's cities during a potential climate emergency.[124] ULBs must focus on science-based groundwater conservation. All favourable hydrogeological response units with high infiltration, high specific yield and high recharge capacities must be identified. The recharge lakes and reservoirs in the city limits should be carefully identified, restored and conserved. The inflow channels into the recharge lakes should be reclaimed from unauthorised constructions and remediated to stop or mitigate future water pollution.

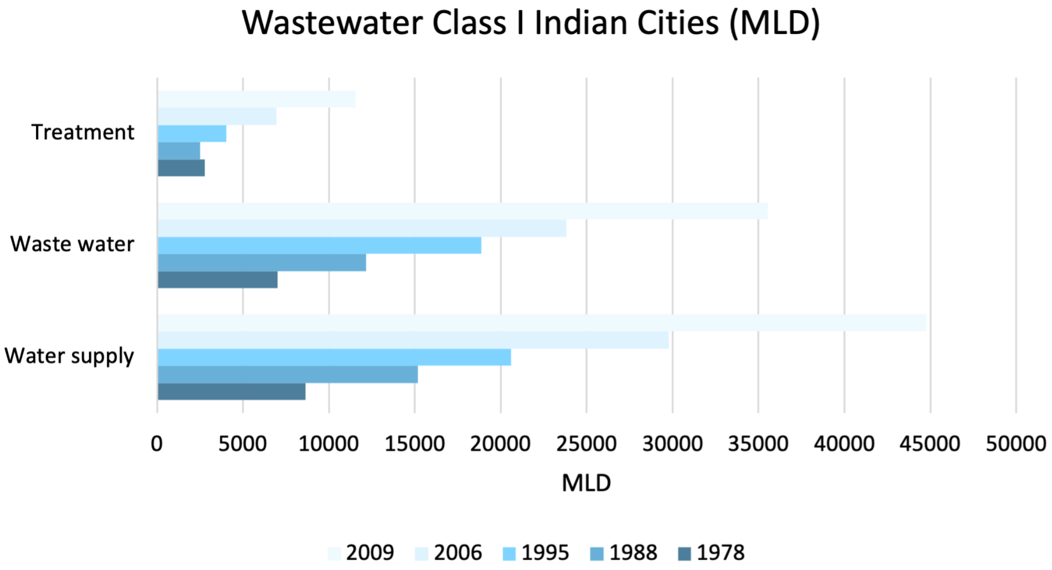
3. Wastewater Treatment and Reuse

The quantum of water supplied and wastewater generated in the Tier 1 and Tier 2 cities have steadily increased over the last four decades (Figure 34 and 35). However, the wastewater treatment capacity requires significant augmentation to capture and treat most of the wastewater.

The status of wastewater treatment and reuse in India can be summarised as:[125]

> "Discharge of untreated sewage in water courses both surface and ground waters is the most important water polluting source in India. Out of about 38000 million litres per day of sewage generated treatment capacity exists for only about 12000 million litres per day. Thus, there is a large gap between generation and treatment of wastewater in India. Even the treatment capacity existing is also not effectively utilized due to operation and maintenance problem. Operation and maintenance of existing plants and sewage pumping stations is not satisfactory, as nearly 39% plants are not conforming to the general standards prescribed under the Environmental (Protection) Rules for discharge into streams as per the CPCB's survey report. In a number of cities, the existing treatment capacity remains underutilized while a lot of sewage is discharged without treatment in the same city. Auxiliary power back-up facility is required at all the intermediate (IPS) & main pumping stations (MPS) of all the STPs."

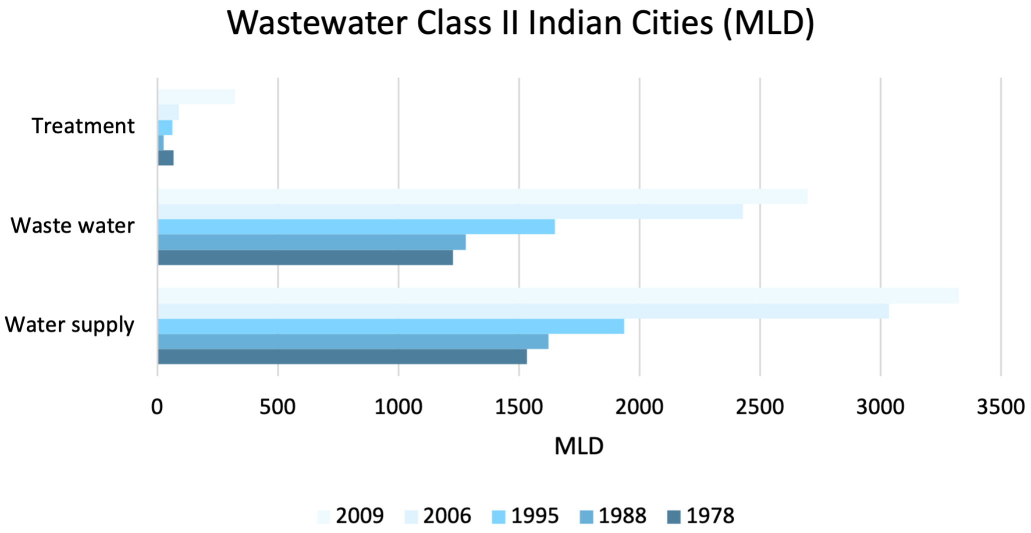
Figure 34: Water Supply, Wastewater Generation and Amount of Treated Wastewater in Tier 1 Indian Cities (1978 to 2009)



Source: National Status of Waste Water Generation & Treatment, 2019.[126]

Water supplied to Tier 1 Indian cities increased from 8.6 billion litres per day (1978) to 44 billion litres per day (2009), the generated wastewater increased from 7 billion litres per day (1978) to 35.5 billion litres per day (2009), while the treated wastewater in the entire country increased from 2.7 billion per day (1978) to 11.5 billion per day (2009).

Figure 35: Water Supply, Wastewater Generation and Amount of Treated Wastewater in Tier 2 Indian Cities (1978 to 2009)



Source: National Status of Waste Water Generation & Treatment, 2019.[127]

Water supplied to Tier 2 Indian cities increased from 1.5 billion litres per day (1978) to 3.3 billion litres per day (2009), the generated wastewater increased from 1.2 billion litres per day (1978) to 2.8 billion litres per day (2009), while the treated wastewater in Class 2 cities of the entire country increased from 67 million litres per day (1978) to 324 million per day (2009).

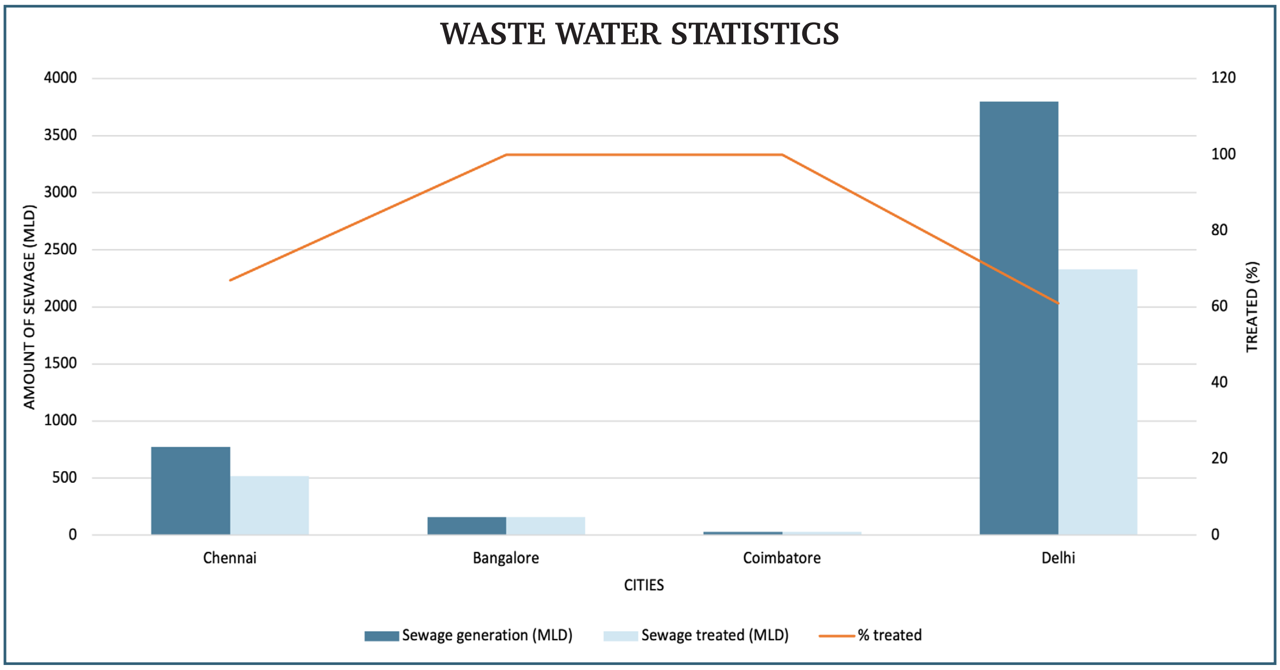
All four cities in this study have installed significant centralised sewage treatment capacities (see Table 10 and Figure 36), ranging between 60 percent (Delhi) to >100 percent (Chennai) of the generated wastewater. There is, however, no segregation of wastewater into grey and black water in Indian cities.

Table 10: Sewage Generation and Treatment Capacities for Chennai, Bengaluru, Coimbatore and Delhi (in 2020)

REFERENCE CITY	SEWAGE GENERATION (MLD)	SEWAGE TREATMENT CAPACITY (MLD)	SEWAGE TREATMENT (MLD)	PERCENT TREATED	ANNUAL TREATED WATER DISCHARGE (MILLION LITRES) IN 2020	ANNUAL PER CAPITA TREATED WATER (LITRES)
Chennai	772	520	520	67	189800	17299
Bengaluru	158	264	158	100	57670	4678
Coimbatore	27	70	27	100	9855	3536
Delhi	3800	2330	2330	61	850450	28076

Source: Authors' own based on data compiled from multiple secondary studies.[128, 129, 130, 131]

Figure 36: Sewage Generation and Treatment Capacities for Chennai, Bengaluru, Coimbatore and Delhi



Source: Authors' own graph based on data from National status of wastewater generation and treatment.[132]

The sewage management protocols for most Indian cities are similar. Centralised sewage discharge and treatment cover only limited parts of the core area of the cities. The poorer areas either do not have toilets or do not have sufficient water supply to use toilets efficiently. Non-core areas, where private water sources are available, either use soak pit toilets or dispose their sewage water to stormwater drainages. There is no segregation of black and greywater. Additionally, the stormwater drainages receive solid waste and dissolve this into the water it carries. Black and grey water are directed through sewage channels or unlined stormwater channels to mostly centralised STPs. The STPs are inefficient and the discharged water, even in cities like Bengaluru and Delhi, carry frothy and partially treated water through unlined stormwater channels. Decentralised smaller capacity STPs are installed and operational in few discrete localities, mostly in the new gated communities, which are regulated by new legislation. Most of the STP and ETP treated water is discharged into the stormwater drainages or diverted to urban water bodies. Bengaluru, for instance, plans to exchange the STP treated water with farmers in neighbourhood regions.[133] A large quantity of the sewage from India's cities, especially peri-urban regions, is directly channelled into the stormwater drainages and further into the urban ponds that function as settling tanks for the city's sewage. These urban ponds also function as recharge ponds for the city's aquifers and continue to pass the polluted surface or stored water into the groundwater systems.

If treated efficiently, sewage and effluent discharges have about 80 percent recoverability post-treatment as raw water.[134] Cities that are staring at continually reducing per capita raw water availability must consider more efficient recycling and reuse of treated sewage and effluent water. Only about half of human activity (drinking, bathing, washing, cleaning) requires potable freshwater, while the rest (flushing, gardening, car washing) can be met by treated STP or tertiary treatment plant discharge. Similarly, some industries and industry clusters in India have started working on ZLD processes, which should become the norm for water-stressed cities. Significant changes in the water distribution and sewage management infrastructure design are needed for wastewater reuse. Cities must segregate freshwater and recycled water distribution channels, and create segregated discharge channels for grey and black water and for industrial effluents leading to the STPs or ETPs. The wastewater treatment plants could be decentralised in the peri-urban areas to address the capital and land requirements. The greywater can be treated and returned for reuse by domestic and industrial consumers, while the black water can be treated and discharged after relevant quality checks through stormwater drainages to cascading bioremediation ponds or diverted to farm irrigation networks or discharged as environmental flows for the urban rivers.

While Indian cities are aggregating significant wastewater treatment capabilities through STPs, the management of such facilities needs greater attention. In no Indian city has an STP been able to generate any additional water resource for city-based reuse.

Cities like Tel Aviv (Israel), Singapore and Stockholm (Sweden) segregate grey and black water for reuse and generate additional water resources and other useful components through recycling. Mekorot, Israel’s water utility corporation, reuses 90 percent of Tel Aviv’s wastewater for agricultural and industrial purposes.[135] In Singapore, a four-stage treatment process to convert wastewater into potable water caters to 30 percent of the city-state’s water needs, and is currently used for industrial purposes.[136] Stockholm has an elaborate system of treating wastewater to retrieve biogas, fertilizer and heat.[137] Increasingly, water-stressed cities around the world are segregating their potable and non-potable water supplies and household discharge. With the dwindling per capita availability of water, Indian cities must consider supplying at least a part of the non-potable water budget from treated wastewater, optimising the freshwater demand. India’s cities would do well to learn to convert wastewater into a resource.

4. Rainwater Harvesting

India has an average annual precipitation of about 120 cms, with over 75 percent of rain falling during the four-month monsoon season.[138] Harvested rainwater could prove a cheap source to augment the freshwater resource, at least at a unit dwelling level, for India's cities during the rainy months and a little beyond. Wherever there is enough land available, in-stream interventions in urban streamlets can help create additional storages and recharge potential.

Some freshwater-stressed Indian cities, like Bengaluru, have embarked on regulatory compliance for new constructions to ensure the installation of rainwater harvesting systems. Suppose all of the 70 percent of the average runoff coefficient is available in the four reference cities. In that case, the harvestable rainwater potential will range from 55 percent (Bengaluru and Delhi) to 160 percent (Coimbatore) of the total available raw water storage (surface and groundwater) (see Table 11). Chennai and parts of Bengaluru have significant groundwater recharge potential because of their hydrogeological features and have demonstrated successful aquifer rejuvenation through a direct recharge of open wells or by injecting harvested rainwater into recharge wells.[139]

Table 11: Rainwater Harvesting Potential of Chennai, Bengaluru, Coimbatore and Delhi

CITY	AREA (SQ KM)	AVERAGE PRECIPITATION (CM)	RAINWATER RUNOFF POTENTIAL (HAM) (70% OF TOTAL PRECIPITATION)	RAINWATER HARVESTING POTENTIAL (MCM) IF 100% OF RUNOFF POTENTIAL IS HARVESTED
Chennai	320	31	351	417
Bengaluru	500	327	827	456
Coimbatore	56	12	68	107
Delhi	1250	301	1551	830

Source: Authors' assessment.

However, most parts of Bengaluru and Coimbatore, which have extremely complex hard rock hydrogeology,[140] are currently resorting to mining groundwater from a depth greater than 200 metres. Some phreatic aquifers have dried out in these cities, while the deeper semi-confined fracture-controlled aquifers with extremely low storativity have available groundwater. The known hydrogeology and aquifer characterisation, including the heterogeneity of phreatic and deeper aquifers, will further require sophisticated high-resolution hydrogeological mapping to develop a more detailed aquifer characterisation than that available through the Central Groundwater Board database. Such mapping will also require sophisticated use of integrated tools like ground and airborne geophysical studies, downhole geophysics surveys and acoustic televiewer logging, remote sensing, detailed geological-structural mapping studies, pumping tests of existing groundwater borewells, recharge tests, watershed characterisation and various other studies. Rainwater harvesting and the strategy of direct recharge to the bedrock through engineered interventions can only be designed based on an analysis of detailed geological-geophysical-structural-hydrogeological-remote sensing-geomorphological datasets. Harvested and treated wastewater can be diverted to the percolation tanks to recharge the urban phreatic aquifer. Rainwater in hardrock hydrogeological conditions can also be harvested for direct potable use through a basic filtration process. Modern apartments or residential complexes, which have larger unit areas, can consider engineered storages in their basements to harvest from the maximum quantity of usable precipitation.

5. Desalinated Water

As desalination processes become cheaper, purified ocean water, near shore brackish groundwater or saline aquifers could become viable sources for urban water supply, at least in India's coastal cities. Over 150 countries are already desalinating water for potable use for about 300 million people,[141] and many emerging technologies could lower desalination costs. Desalination could progressively become an important component of the potable water resource as energy and capital costs decrease, and the environmental impact of disposing of concentrated brine water becomes manageable. The operating cost of desalination plants is as low as INR 0.02 per litre in some parts of the world.[142] However, the installation of desalination plants is capital intensive. Chennai has established a desalination capacity of 200 MLD through two plants, with a third planned (550 MLD capacity). Gujarat is also constructing several desalination plants, sourcing water from seawater and saline water aquifers along the coast. Issues like concentrated brine disposal and carbon footprint management will need attention if India were to undertake extensive desalination.

6. Modernisation of Water Supply Infrastructure

Plugging the current leakages could augment India's freshwater supplies by up to 50 percent in some cities. This can only be done through the systematic replacement of archaic water distribution infrastructure across the country. There is much to learn from the modern infrastructure in places like Tel Aviv and Singapore, which have dual piped water supplies. These cities also segregate their discharge at the source as grey and black water, with about 90 percent of urban wastewater leading to the city STPs.

Peri-urban areas, most of which are still unconnected to the water distribution system, should be prioritised for infrastructure extension. India's smart cities must create their own water infrastructure and management codes for sustainable water management. Newer infrastructure should also consider sensor-based real-time data acquisition systems, fed to a Supervisory Control and Data Acquisition (SCADA, command and control type) system to monitor and manage a sustainable water supply. This will help establish real-time demand, utilisation and supply, and segregate revenue and non-revenue water from all the freshwater and secondary water sources in various parts of the city.

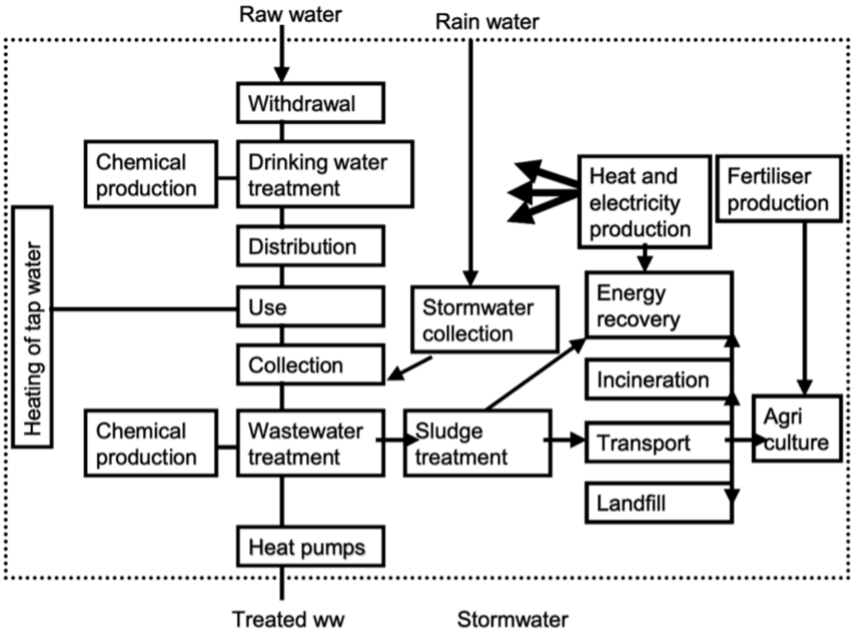
7. Urban Water Demand Optimisation

While ULBs must adopt a new water management framework for water security and sustainability, urban communities will also have to embark on a progressive cultural transition to optimise water demand at a unit level. Water dispensing gadgets must improve for greater water efficiency.[143] Individuals and communities have to value and pay for water and agree to install IoT-connected water meters, linked to centralised command and control systems. Communities and city corporations must strive to convert most water utilisation into revenue water, including groundwater abstraction and recycled water. Direct supplies through water tankers should be restricted to emergency supplies only. Communities and individuals must make the best use of rainwater harvesting potential in all concretised and paved areas of the city. Civil society, educational institutions and government outreach programmes can play a role in driving this cultural change.

8. Urban Water Balance in a Circular Resource Management Framework

Traditionally, the larger city corporations in India have managed their water budgets with surface water as the major input and groundwater as a supplementary source. The water distribution infrastructure of the four reference cities in this study—Chennai, Bengaluru, Coimbatore and Delhi—have been designed based on the available raw surface water storages. Occasionally, the existing infrastructure also caters to supply from groundwater sources. In recent decades, and as illustrated in the four cities, the available raw surface water storages and abstracted groundwater are insufficient to meet a fast-growing urban population's needs. Ensuring urban water security requires a thorough review of the available resource, the current water management protocols and water budget optimisation processes. Indian cities will have to adopt the IUWM protocol for planning and operations (see Figure 37).[144]

Figure 37: Integrated Urban Water Management Framework for an Urban Water System



Source: Ludin and Morrison, 2002.[145]

This framework not only aims to recover the supplied raw water volumetrically but also to capture and recycle the nutrients and energy through the IUWM framework.

Data Capture

A comprehensive water budgeting process needs detailed and scientific mapping of surface and groundwater resources, and a map of the urban watershed and of the water distribution network and discharge channels. Time series information about surface water flow data (volume and quality) of past and current water utilisation data (ideally, in real-time) is also needed to carry out the surface and groundwater resource and flow modelling. The additional required hydrological information includes mapping and detailed characterisation of the surface and aquifer storages at an urban sub-watershed level. The safe yield for each aquifer should also be determined through adequate pumping tests. All urban water bodies, their volumetric capacities, and their inflow and outflow conduits must be mapped in detail and the urban surface water-groundwater interaction must be clearly understood. Cities must dynamically update information about the water distribution network, down to the last household, with clearly identified grey and black water discharge conduits.

India's water stakeholders lack such a comprehensive database as described. Given the absence of such datasets, the scientific understanding of elements impacting the water balance and budget has never been attempted. Available datasets on surface water or groundwater from the India Meteorological Department, the Central Water Commission and the CGWB are extremely coarse in resolving a detailed (and time series) assessment and projections of water resource demand. Decision support systems based on datasets at such a low resolution will have several shortcomings and risks. At the same time, the municipal corporations and ULBs do not have adequate information about the city's demand and supply and available reusable wastewater. A sustainable centralised water supply scheme catering to every urban household should only be based on a scientific, reliable and dynamically updating raw water resource, and real-time supply and utilisation information. The urban infrastructure upgrade and water management plan for India's cities will have to be appropriately redesigned based on such detailed information.

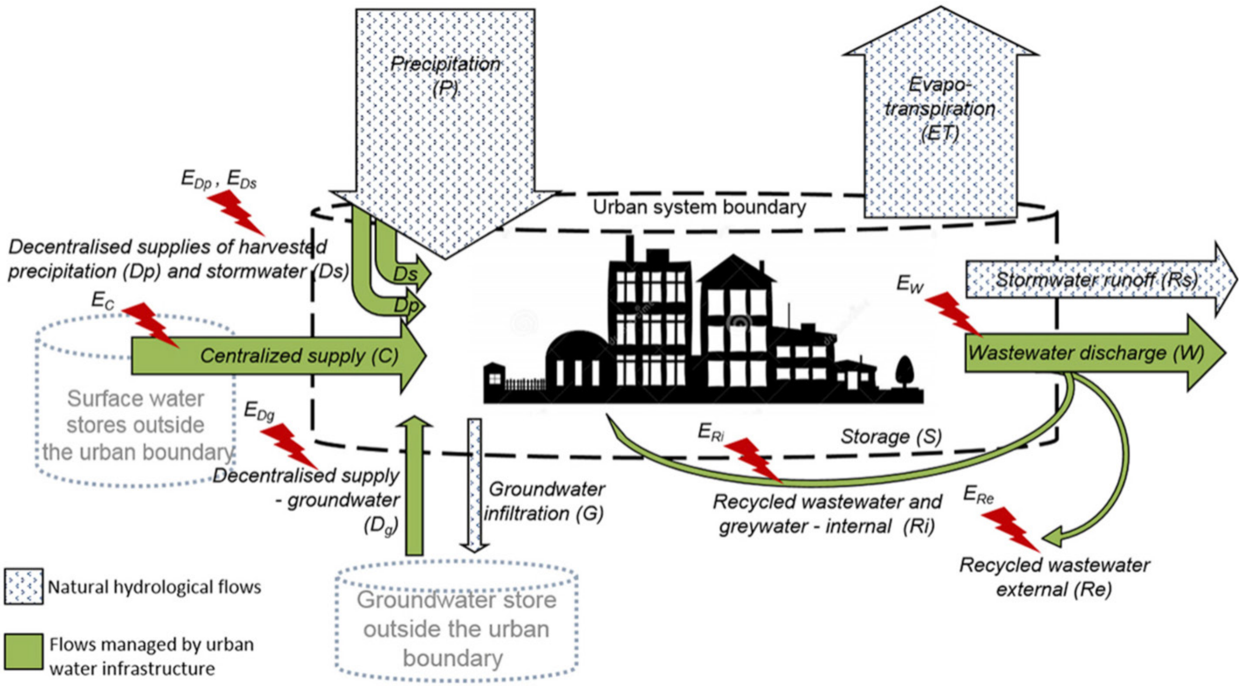
Urban Water Balance (Governance)

No Indian city has embarked on a full spectrum, data-based, detailed water balancing exercise. Given the vulnerabilities and risks facing urban India, cities must establish a detailed water balance to migrate their water governance systems to the IUWM framework.

Two different urban water balancing models are available: The first is based on the concept of urban metabolism,[146] a model constructed on material and energy flow analysis within the city bounds. This model's components include water volume, nutrients in the water, waste generated, and urban energy. Although this model is complex, it considers the qualitative and quantitative aspects of urban water during modelling. This model also takes the water-energy nexus into account.

The second model is a water mass balance method of determining the water balance. It is more commonly used for water balancing and budgeting. This framework for water budgeting takes into account both natural and anthropogenic factors (see Figure 38).[148]

Figure 38: Mass Balance Framework for Urban Water



Source: Faroogui et al, 2016.[149]

Based on the available data and the ease of collection, the authors propose adapting the mass balance approach to create urban water balance in India in a circular resource utilisation framework. The urban water balance should be based on a comprehensive assessment of all available water resources, including the raw water inputs from surface water, groundwater and rainwater harvest, the recycled wastewater inputs and water available from any additional source like desalinated water. In the next five years, the authors suggest that city corporations collect sufficient data to eventually consider transitioning to the urban metabolism framework for water balancing. The progressive transition from the mass balance to urban metabolism framework will allow ULBs the desired capacity building and cultural transition through improved training and the development of management protocol and capacity. This will also require redesigning, re-laying and establishment of modern urban water infrastructure.

Adopting a mass balance framework will require the segregation of water demands into potable and non-potable use. This framework recognises the need for an efficient sewage and effluent recycling system for treated wastewater (greywater) reuse to cater to some of the city’s non-potable water needs. The efficiently treated black water can be directly discharged to the urban streams or diverted to urban ponds. Implementing treated wastewater reuse will require the creation of treated/recycled water redistribution infrastructure and community participation in the decision-making process.

Additional freshwater inputs may be available to all cities if appropriate centralised or decentralised (unit-based) rainwater harvesting protocols are implemented. Cities and communities can decide on either direct reuse or groundwater recharge of the harvested rainwater. For India’s coastal cities, desalinated water could provide additional potable water, gradually becoming more affordable with lowered energy costs.

Raw water source conservation will be extremely critical for sustainable freshwater supplies to the cities. Freshwater surface storages must be carefully maintained, monitored and managed for sustainability. Groundwater storage capacities must be hydrogeologically understood, and appropriate conservation strategies should be adopted to restore the aquifers or augment the available resources. The availability of new freshwater sources for cities will see some challenges. However, if the cities are planning to acquire new distant storages, it will be prudent to secure distant multi- and extra-basinal sources to mitigate climate change impacts.

The other big challenge for ULBs will be to re-lay a new water supply, distribution and discharge network that will cater to both raw potable water and non-potable treated wastewater distribution. ULBs should address water supply leakages for the optimal performance of the city’s water budget. Wastewater will have to be appropriately managed for recycling and reuse after treatment and managing the environmental flows in the urban streams.

Urban Water Balance through a Circular Water Budgeting Framework

Most ULBs manage water distribution and sanitation in an ad-hoc linear water budgeting framework (see Figure 38). No city in India has established water balance through scientifically collected resource and utilisation data. For urban water security, a scientifically determined water balance and budget are prerequisites for adopting an IUWM process. A linear and an ad-hoc urban water balance framework, where raw water is for single use and discharge, has led to severe water stress in most Indian cities, increasing as the population grows and demand expands. Thus, Indian cities must adopt a circular water balancing framework based on the mass balance approach. Such a water balance exercise will require an accounting of all the surface water and groundwater storage components, inflow and outflow water components, the utilisation components, and recycled water.

A standard water balance equation is: Water Inflows = Water Outflows + Changes in Storage

Water inflows in a city corporation's water budget generally include direct precipitation into an urban watershed, inflows into remote urban storages or groundwater inflow into the urban aquifers. Secondary sources like desalinated water can add to available city water accumulated through inflows.

Water outflows include evapotranspiration of stored and soil water and stream runoff. River discharges and surface runoff and groundwater outflow from the urban aquifer bounds will also add to water outflow.

The urban storages will include the captive urban storages and in-city short term water storages before purification and supply, as well as the annual dynamic groundwater recharge. Additionally, the harvested rainwater and catchment inflow into urban water bodies will also count as urban storage.

Thus, an urban water balance equation without any urban abstraction will look like:

Equation 1

$$(P + Ic + Iu + Gwi + Ds) = (T + Rs + Gwo) + (Src + Sc + Suw + Gwd + Hr)$$

Inflow components = Outflow + Storage

1. P: Direct precipitation
2. Ic: Inflow into captive storage

3. Iu: Inflow into urban watershed
4. Gwi: Groundwater inflow into urban aquifer
5. Ds: Annual desalinated water
6. T: Evapotranspiration
7. Rs: Surface runoff
8. Gwo: Groundwater outflow from urban aquifer
9. Src: Remote captive storage
10. Sc: City storage
11. Suw: Urban water body
12. Gwd: Annual dynamic groundwater addition to the aquifer
13. Hr: Harvested rainwater

The domestic and industrial water utilisation, the groundwater abstraction and corresponding discharges, and the treated wastewater in a linear water balance framework change the water balance equation to:

Water inflow = Water outflow + Water Storage Changes + Consumptive Domestic and Industrial Water Use + Wastewater Discharge + Return Flow (from supply leakages, from wastewater discharges)

This makes the water balance equation of a linear resource utilisation framework look like:

Equation 2

$$(P + Ic + Iu + Gwi + Ds) = (T + Rs + Gwo) + (Src + Sc + Suw + Gwd + Hr) + (Wcd + Wci) + (Dww) + (Ls + Drf)$$

14. Wcd: Consumptive domestic water use
15. Wci: Consumptive industrial water use
16. Dww: Wastewater discharge
17. Ls: Return flow, supply leakages
18. Drf: Return flow, wastewater discharges

Based on the linear value and supply chain framework described above (also see Figure 22), the four referenced cities' water balance have been established in this study. The summarised water balance is presented in Equation 1 and 2. While there is no urban water balance available for any city in India, the ad hoc water governance practices consider surface and groundwater storages as available storages, and supplied surface water and abstracted groundwater as utilisation. Also, leakages are generalised and the STP and ETP discharges and surface run-offs are partially accounted as outputs. Precipitation and inter-basin transfers to the captive urban storages are partially accounted as inputs.

An urban water balance equation in a circular water management framework will include the wastewater recycling components. Treated wastewater could have three distinct components:

19) Rww: Recycled wastewater, which will add to the water inputs and
20) Sww: Wastewater discharge to the urban storage
21) Dwwo: Wastewater discharge outflow

Thus, the urban water balance equation in a circular water resource utilisation framework will look like:

<u>*Equation 3*</u>

$$(P + Ic + Iu + Gwi + Ds + Rww) = (T + Rs + Gwo) + (Src + Sc + Suw + Gwd + Hr + Sww) + (Wcd + Wci) + (Dwwo) + (Ls + Drf)$$

Equation 3 provides the framework for most optimised urban water balance for urban water budgeting. This optimised water balance framework includes recycled water for reuse as inflow, the treated wastewater for storages in urban water bodies, and the treated wastewater discharged as environmental flows for urban streams. This framework includes all unconventional water inputs, such as rainwater harvesting (as storage) and desalinated water (as water inflow).

The available water data and comprehensive available water resource at the city level (see Table 12) and at the per capita level (see Table 13) for Chennai, Bengaluru, Coimbatore and Delhi are presented. India's urban water planners have banked on the availability of stored raw water resource (surface and groundwater) for supply. However, with an increasing population in a city constrained for expansion, urban water planners must consider transitioning to a circular water management framework based on a comprehensive urban water balancing exercise.

Table 12: Optimised Budgetary Estimation of Urban Water Availability for the Reference Cities

URBAN WATER BALANCE (For Entire City)						
Name of City	Total Surface Storage Available MCM	Total Groundwater Available (in MCM)	Total Raw Water Storage (SW + GW) in MCM	Total Rainwater Availability (in MCM)	Total STP Treated Water Availability (litres)	Total Water Balance (in MCM)
Chennai	320	31	351	417	190	958
Bengaluru	500	327	827	456	58	1341
Coimbatore	56	12	68	107	10	185
Delhi	1250	301	1551	830	850	3232

Table 13: Optimised Budgetary Estimation of Urban Water Availability for the Reference Cities

URBAN WATER BALANCE (Per Capita)						
Name of City	Total Per Capita Surface Storage Available (litres)	Total Per Capita Groundwater Available	Total Per Capita Raw Water Storage (SW + GW) in litres	Total Per Capita Rainwater Availability (in litres)	Total Per Capita STP Treated Water Availability (litres)	Total Annual Per Capita Water Availability (in litres)
Chennai	29168	2830	31998	38053	17299.98	87351
Bengaluru	40561	26515	67077	37019	4678.348	108774
Coimbatore	20096	4375	24471	38313	3536.568	66321
Delhi	41266	9934	51200	27417	28076	106693

CONCLUSION

This study is an attempt to develop a holistic understanding of the challenges of urban water management in India. Extensive primary and secondary datasets have been collected and analysed. There is no reference urban water balance study available from any city in India. The analysis presented in this report aims to establish a framework and understand the gaps in adopting protocols for creating urban water balance and for urban water security and sustainability.

Water source security is critical in mitigating any climate uncertainty in India's cities. This will mean finding additional surface storages, augmenting surface water flow, restoring city ponds, rejuvenating groundwater aquifers and remediating the polluted hotspots. Climate risk resilience will require source security, water demand optimisation, optimisation of the surface and groundwater abstraction, and replacement and modernisation of the current leaky water distribution infrastructure. Cities must also aim to reduce water distribution inequities. Surface and groundwater source sustainability and management will require detailed scientific mapping of all water flows, surface water-groundwater interactions, mapping of supply and demand nodes, time series trend analysis of all the dynamic datasets, and the real-time monitoring of water supply, abstraction and utilisation at the urban sub-watershed level. Such a dynamically updating dataset and corresponding analysis could form the backbone of any integrated urban water management framework and the protocols for India's ULBs.

Indian cities will be required to re-lay and modernise their water supply infrastructure based on their projected demand (for at least the next 50 years) for potable and non-potable water. Correspondingly, the discharge, treatment, recycling and reuse of grey and black water will need to be prioritised. Cities must establish new centralised and decentralised STPs and ETP infrastructure. The water distribution infrastructure must cover the peri-urban and slums areas and such upcoming spaces.

This study demonstrates the need to create 'modern' sensor-based data collection and IoT-based connected infrastructure for urban water management. Urban population growth will necessitate water demand optimisation, which will require long-term community engagement aimed at a cultural transformation of the citizenry towards developing a water consciousness.

The current governance practices of India's city corporations and ULBs need urgent review. City corporations must upskill their staff to develop a comprehensive science and data-based governance structure. City corporations must control ad hocism in the decision-making process of planning, designing, laying and managing the water distribution and discharge infrastructure. To reduce the non-revenue water, citizens will have to be convinced about water's value and accept a pay-per-use system for all elements of supplied water. The IUWM framework will necessitate a paradigm shift in the city corporations' and ULBs' water governance practices.

The priority areas for water governance for urban water security in India are:

1. Science-based mapping and analysis of all surface and groundwater resources; mapping water distribution and water discharge nodes and channels and their characteristics; mapping all inflow, outflow and storage elements of a comprehensive water balance; detailed water balance and budgeting for the city for every urban sub-watershed
2. Prioritising raw surface water and groundwater source security; considering securing multi-basin surface water sources for the city and focusing on source conservation to mitigate against climate uncertainties
3. Monitoring groundwater abstractions; ULBs must work to rejuvenate dry aquifers
4. Identifying potable and non-potable water demands, based on utilisation data and census data projections; creating dedicated infrastructure to supply part of the non-potable needs from STP treated wastewater stock
5. Phasing out old water distribution infrastructure and replacing it with modern, digitally-connected water distribution and wastewater discharge and management infrastructure
6. Installing telemetric data capture systems using sensor-based technology/IoT to monitor all nodes of water supply, demand and reuse
7. Establishing a centralised command and control system (such as SCADA) for water management in the ULBs; capturing all data and information digitally, and using large data analytics and machine learning for water management processes.
8. Bringing most urban water supply under revenue water

The ULBs will be expected to:

9. Establish and re-lay appropriate water supply infrastructure to
   - Reduce leakage losses
   - Separate grey and black waste-water discharges
   - Enable dual supplies of potable and non-potable (recycled) water
   - Take supplies to the peri-urban and slum dwellings
   - Reduce water distribution leakages and inefficiencies
10. Line all the sewage channels; ensure no sewage discharges in the stormwater streams; mitigate contamination of sewage and effluents with stormwater and groundwater sources
11. Fingerprint all effluent and sewage water, and establish a realtime dynamic data collecting protocol to monitor the pollution footprint, detect pollution sources and mitigate water pollution at the source
12. Develop a comprehensive strategy for surface and groundwater source conservation in the urban watershed to ensure water availability during climate exigency, if any

13. Establish an appropriate and modern governance mechanism at the corporation, state and central level, and retrain water management engineers and administrators
14. Educate and boost consumers' capacity to develop a comprehensive understanding of resource availability, the value of water and water conservation; develop a strategy to train consumers to optimise their water utilisation

The proposed strategy to manage water security for Indian cities integrates well with the aspiration to provide piped potable water supply to 2.86 crore households by 2024. The UN’s Sustainable Development Goals (SDG) to ensure the availability and sustainable management of water and sanitation for all (SDG 6) and the target to govern and manage water resources in integrated formats (SDG 6.5) offers countries like India significant opportunities to advance their broader development and climate agendas effectively across sectors with longer-term viability. However, several challenges remain, including mapping and plugging the information gaps; educating managers, communities and individuals; raising funding to modernise water supply infrastructure; creating command and control systems; changing statutes to ensure pay-per-use of water (and decreasing non-revenue water); and leading a comprehensive cultural change in the way consumers look at water. India must learn from countries that have moved from being water-scarce to water surplus by initiating a cultural shift. Indian cities have the opportunity to innovate and lead the way in developing resilience towards climate change impacts in the domain of water security.

GLOSSARY

AQUIFER	An aquifer is an underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt) from which groundwater can be extracted using a water well.
UNCONFINED AQUIFER	Unconfined aquifers are those into which water seeps from the ground surface directly above the aquifers.
ABSTRACTION	Groundwater abstraction is the process of taking water from a ground source, either temporarily or permanently. Most water is used for irrigation or treatment to produce drinking water
GREY WATER	Grey water is all the wastewater generated from households or office buildings without fecal contamination, i.e. all discharges except for the wastewater from toilets. Sources of grey water include sinks, showers, baths, washing machines or dishwashers.
BLACK WATER	Black water is waste water discharges from the toilets, including a mix of urine, feces and flushwater
PERCHED AQUIFER	It is an aquifer that occurs above the regional water table. This occurs when there is an impermeable layer of rock or sediment (aquiclude) or relatively impermeable layer (aquitard) above the main water table/aquifer but below the land surface.
AQUICLUDE	It is a geological formation which is impermeable to the flow of water. It contains large amount of water in it but it does not allow water to permit and does not yield water because of its high porosity.
STORATIVITY	Storativity or the storage coefficient is the volume of water released from storage per unit decline in hydraulic head in the aquifer, per unit area of the aquifer. Storativity is a dimensionless quantity, and is always greater than 0.
SPECIFIC YIELD	Specific yield (Sy) is the ratio of the volume of water that drains from a saturated rock (due to gravity) to the total volume of the rock or the amount of water measured in gallons per minute a well will produce when pumped.
ELECTRICAL CONDUCTIVITY	It is the measure of a material's ability to allow the transport of an electric charge. Its SI is the siemens per meter, (A2s3m−3kg−1) (named after Werner von Siemens) or, more simply, Sm−1.
WATER TABLE	The water table is the upper surface of the zone of saturation. The zone of saturation is where the pores and fractures of the ground are saturated with water.

UNITS OF MEASUREMENT USED IN THE REPORT

COMPONENTS	UNITS OF MEASUREMENT
Population	Numerical values
Rainfall or Precipitation	Centimeter, cm
Area of city limits	Square kilometers, sq km or km^2
Population density	Per square kilometers
Volume of water	Litres
	Million litres (1 million litres = 10^6 litres)
	Million cubic metre, MCM (1 MCM = 10^9) litres)
	Billion cubic metre, BCM (1 BCM = 10^12) litres)
	Hectare metre, HAM (1 HAM = 10^9 litres)
Water level	Metres, m
TDS	Part per million (ppm)
	milli gram per litre (1 ppm = 1mg/l)
Conductivity	Micro-mohms/ centimeter
Ground water abstraction	Hectare metre, HAM (1 HAM = 10^9 litres)
Ground water development status	Percentage (%)
Surface water storage capacities	Cubic meters
	Cubic kilometers (1 km^3 = 10^9 m^3)
Sewage generation and treatment	Million litres per day (MLD)

ENDNOTES

1. NITI Aayog, "Composite water management index: a tool for water management," 2018, https://niti.gov.in/writereaddata/files/document_publication/2018-05-18-Water-index-Report_vS6B.pdf
2. Adequate Water Risk Atlas, *World Resources Institute*, October 2013 https://www.wri.org/resources/maps/aqueduct-water-risk-atlas
3. Peter Schulte, "Defining Water Scarcity, Water Stress, and Water Risk," *Pacific Institute*, February 4, 2014, https://pacinst.org/water-definitions/.
4. Josep Xercavins i Valls, "Water Scarcity," *Tesis Doctorals En Xarx,* https://www.tdx.cat/bitstream/handle/10803/6987/09CAPITOL7.pdf?sequence=10&isAllowed=y
5. Sagar Singh, "Water conservation in Maharashtra," *Let me Breathe*, https://letmebreathe.in/2020/03/12/water-conservation-in-maharashtra/#:~:text=By%202030%2C%20the%20country's%20water,importance%20of%20groundwater%20in%20India%3F
6. Upali A. Amarasinghe, Tushaar Shah, and B.K.Anand, "India's Water Supply and Demand from 2025-2050: Business- as- Usual Scenario and Issues," *International Water Management Institute*
7. Schulte, "*Defining Water Scarcity, Water Stress, and Water Risk*," https://pacinst.org/water-definitions/ available at https://pacinst.org/water-definitions/
8. Anusuya Datta, "Not Just Chennai, Satellite Data Portends Major Water Crisis Across Globe," The Wire, July 5, 2019, https://thewire.in/environment/chennai-water-crisis-global-shortage-world-resources-institute
9. Government of India, Ministry of Statistics and Programme Implementation, "Drinking Water, Sanitation, Hygiene and Housing condition in India, NSS 76th round", report no.584, July – December 2018
10. Craig Welch, "Why Cape Town is running out of water, and who's next," National Geographic, March 05, 2018, https://www.nationalgeographic.com/news/2018/02/cape-town-running-out-of-water-drought-taps-shutoff-other-cities/
11. Bhasker Tripathi, "Bengaluru, Delhi, Chennai among 21 Cities to Run out of Ground Water by 2020," *Firstpost*, Monday, September 28, 2020, https://www.firstpost.com/tech/science/indias-water-crisis-bengaluru-delhi-chennai-hyderabad-among-21-cities-to-run-out-of-groundwater-by-2020-4590221.html#:~:text=As%20we%20said%2C%2021%20Indian,by%202030%2C%20the%20report%20said.
12. Sujith Sourab Guntoju, Mohammad Faiz Alam and Alok Sikka, "Chennai water crisis: A wake-up call for Indian cities," *Down to Earth*, August 5, 2019, https://www.downtoearth.org.in/blog/water/chennai-water-crisis-a-wake-up-call-for-indian-cities-66024
13. Paul P. Murphy and Gianluca Mezzofiore, Chennai, "India, is almost out of water. Satellite images show its nearly bone-dry reservoirs," *CNN*, June 20, 2019, https://edition.cnn.com/2019/06/20/world/chennai-satellite-images-reservoirs-water-crisis-trnd/index.html
14. Harish K Thakur, "ART20193693 shimla water crisis symptomizes a greater malaise," *International Journal of Science and Research* (ResearchGate), December 2018
15. "Water crisis returns to haunt Latur," *Business Standard*, May 18, 2019, https://www.business-standard.com/article/news-ani/water-crisis-returns-to-haunt-latur-119051800520_1.html
16. "Budget 2020: Govt allocates Rs 11,500 crore for Jal Jeevan Mission for FY21," *Financial Express*, February 1, 2020, https://www.financialexpress.com/budget/budget-2020-govt-allocates-rs-11500-crore-for-jal-jeevan-mission-for-fy21/1846403/
17. Government of India, Ministry of Statistics & Programme Implementation, "*Drinking Water, Sanitation, Hygiene and Housing condition in India, NSS 76th round*", report no.584, July – December 2018
18. Mahreen Matto, "India's water crisis: The clock is ticking," *Down to Earth*, June 21,2019, https://www.downtoearth.org.in/blog/water/india-s-water-crisis-the-clock-is-ticking-65217#:~:text=Lack%20of%20proper%20maintenance%20of,piped%20water%20in%20urban%20areas.&text=Looking%20at%20the%20current%20situation,need%20for%20a%20paradigm%20shift
19. Government of India, Ministry of Statistics & Programme Implementation, "*Drinking Water, Sanitation, Hygiene and Housing condition in India, NSS 76th round*", report no.584, July – December 2018
20. Sankhe, S., I. Vittal, R. Dobbs, A. Mohan, A. Gulati, J. Ablett, S. Gupta et al. "India's urban awakening: building inclusive cities, sustaining economic growth" *McKinsey Global Institute* 2010.
21. NITI Aayog, "Composite water management index: a tool for water management," 2018, https://niti.gov.in/writereaddata/files/document_publication/2018-05-18-Water-index-Report_vS6B.pdf
22. R K Shivpuri, 'WATER- A Crisis, Challenge and Solutions,' Education Post, August 19, 2020,

https://theeducationpost.in/water-a-crisis-challenge-and-solutions-2/#:~:text=As%20per%20the%20report%20of,day%20availability%20is%20695%20BCM

23. Abhijit Mukherjee, S. Suresh Babu, and Subimal Ghosh. "Thinking about water and air to attain Sustainable Development Goals during times of COVID-19 Pandemic." *Journal of Earth System Science* 129, no. 1 (2020): 1-8.
24. NITI Aayog, "Composite water management index: a tool for water management," 2018, https://niti.gov.in/writereaddata/files/document_publication/2018-05-18-Water-index-Report_vS6B.pdf
25. A.Subburaj, "District Groundwater Brochure, Coimbatore District, Tamil Nadu," South Eastern Coastal Region, Chennai, Central Ground Water Board, Government of India, Ministry of Water Resources, November 2008, http://cgwb.gov.in/District_Profile/TamilNadu/Coimbatore.pdf
26. Government of India, Ministry of Water Resources, "Ground Water Information Booklet, Bangalore Urban District, Karnataka," Ministry of Water Resources, Central Ground Water Board, March 2013, http://cgwb.gov.in/District_Profile/karnataka/2012/BANGALORE_URBAN-2012.pdf
27. T. Balakrishnan, "*District Groundwater Brochure,* Chennai, Tamil Nadu," South Eastern Coastal Region, Chennai, Central Ground Water Board, Government of India, Ministry of Water Resources, November 2008, http://cgwb.gov.in/District_Profile/TamilNadu/chennai.pdf
28. Dr. M. Senthilkumar et al, "Aquifer Mapping and Ground Water Management, Chennai" Ministry of Water Resources, Central Ground Water Board, Government of India, March 2017, http://cgwb.gov.in/AQM/NAQUIM_REPORT/TAMILNADU/chennai%20Aquifer%20system.pdf
29. Bai M. Glory, "Irrigation and economic development in tamilnadu from 1947 1967 ad.," Department of History, Manonmaniam Sundaranar University, India. https://shodhganga.inflibnet.ac.in/handle/10603/20878
30. Rohan D' Souza, "When lakes were tanks," *Down to Earth*, June 11, 2015, https://www.downtoearth.org.in/coverage/when-lakes-were-tanks-45815
31. India 2001, Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, 2001, https://censusindia.gov.in/
32. 2011 Census Data, Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, 2011, https://censusindia.gov.in/2011-common/censusdata2011.html
33. District Census Handbook Chennai, Directorate of Census Operations, Tamil Nadu, 2011, https://www.censusindia.gov.in/2011census/dchb/3302_PART_B_DCHB_CHENNAI.pdf
34. Office of Registrar General and Census Commissioner, India, Ministry of Home Affairs, Government of India, https://censusindia.gov.in/
35. Demographic Profile, Delhi, http://delhiplanning.nic.in/sites/default/files/2%29%20Demographic%20Profile.pdf
36. District Census Handbook Coimbatore, Directorate of Census Operations, Tamil Nadu, 2011
37. India 2001, Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, 2001
38. 2011 Census Data, Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, 2011
39. India 2001, Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, 2001
40. 2011 Census Data, Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, 2011
41. Sangeeta (San) Banerjee, "Bangalore's Water Supply Situation," Bangalore Water Supply and Sewerage Board, February 24, 2010. An excerpt from the presentation made by BWSSB (Bangalore Water Supply and Sewerage Board) detailing the Water Supply situation in Bangalore. The presentation was made in The Water Workshop conducted on 6-Dec-2009, by ApartmentAdda.com for RWAs.
42. "About Bangalore Water Supply and Sewage Board," Bangalore Water Supply and Sewerage Board, https://www.bwssb.gov.in/com_content?page=3&info_for=4
43. With Reference to Mean Sea Level, Chennai Metropolitan Water Supply & Sewerage Board, September 28, 2020, http://123.63.203.150/public/lake.htm
44. "With Reference to Mean Sea Level"
45. Balambal Usha et. al., "Climate Variability and its impacts on runoff in the Kosasthaliyar sub-basin, India," *Earth Sciences Research Journal* 1794-6190, May 31, 2014
46. Tamil Nadu Water Supply and Drainage Board, Water Supply Improvement In Distribution System To Extended Areas (Kurichi, Kuniyamuthur, Thudiyalur, Vellikinaur, Villankurichi, Chinnavedampatti, Saravanampati & Kalapatty) of Coimbatore City Corporation, Tamil Nadu Water Supply and Drainage

Board. https://www.twadboard.tn.gov.in/

47. Veena Srinivasan, D. Suresh Kumar, Pennan Chinnasamy, Swati Sulagna, D. Sakthivel and P. Paramasivam Sharachchandra Lele, “Water Management in the Noyyal River Basin,” *Ashoka Trust for Research in Ecology and the Environment,* February 2014
48. Sukirti Vinayak and Poonam Sewak, Drinking Water Supply For Urban Poor: City of New Delhi, *Safe Water Network*, October 2016, https://www.safewaternetwork.org/sites/default/files/Safe%20Water%20Network_Delhi%20City%20Report.PDF
49. Bhim Singh Rawat, “Haryana Riverbed Mining 2019: Yamuna Robbed of Minerals, Flows,” *South Asian Network on Dams*, Rivers and People, January 22, 2020
50. Sukirti Vinayak and Poonam Sewak, Drinking Water Supply For Urban Poor: City of New Delhi, *Safe Water Network*, October 2016, https://www.safewaternetwork.org/sites/default/files/Safe%20Water%20Network_Delhi%20City%20Report.PDF
51. 1991 Census Data, Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, 2001. https://censusindia.gov.in/DigitalLibrary/TableSeries.aspx
52. 2001 Census Data, Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, 2001. https://censusindia.gov.in/2011-common/census_data_2001.html
53. 2011 Census Data, Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, 2011
54. Water Crisis in Bengaluru- BBC Report appeared in News Papers on 12th February - Response of BWSSB, https://www.bwssb.gov.in/images/upload/pdfs/Final_Report_on_BBC_news.pdf
55. GVR Suba Rao “KRMB panel to discuss plan for water supply to Chennai,” July 16, 2020. https://www.thehindu.com/news/national/andhra-pradesh/krmb-panel-to-discuss-plan-for-water-supply-to-chennai/article32106620.ece
56. “DJB approves projects of water augmentation, clean Yamuna, groundwater rejuvenation,” Delhi Jal Board, Government of NCT of Delhi, May 29, 2019, http://www.delhijalboard.nic.in/content/djb-approves-projects-water-augmentation-clean-yamuna-groundwater-rejuvenation
57. Water Supply, Coimbatore City Municipal Corporation. https://www.ccmc.gov.in/ccmc/index.php/department/water-supply
58. “Dry end to monsoon season, all time low rainfall in city: Met,” *The Times of India*, December 23, 2018, https://timesofindia.indiatimes.com/city/chennai/dry-end-to-monsoon-season-all-time-low-rainfall-in-city-met/articleshow/67211934.cms)
59. Paul P. Murphy, “Chennai, India, is almost out of water. Satellite images show its nearly bone-dry reservoirs,”CNN, June 20, 2019, https://edition.cnn.com/2019/06/20/world/chennai-satellite-images-reservoirs-water-crisis-trnd/index.html
60. “Yamuna floodplain water storage project on fast track,” The Hindu, July 11, 2019, http://nwda.gov.in/upload/uploadfiles/files/yamina.pdf
61. Debjit Sinha, “Yamuna floodplain water storage project begins! Arvind Kejriwal calls it ‘landmark’ for Delhi,” Financial Express, August 13, 2019, https://www.financialexpress.com/infrastructure/yamuna-floodplain-water-storage-project-begins-arvind-kejriwal-calls-it-landmark-for-delhi-top-facts/1674001
62. Pretika Khanna, “How does Delhi plan to store flood water in Yamuna floodplain,” LiveMint, July 27, 2019, https://www.livemint.com/news/india/how-does-delhi-plan-to-store-flood-water-in-yamuna-floodplain-1564202049949.html
63. Shivam Patel, “Delhi: Water storage plan at Palla gets new push with creation of pond,” The Indian Express, July 19, 2020, https://indianexpress.com/article/cities/delhi/delhi-water-storage-plan-at-palla-gets-new-push-with-creation-of-pond-6512776/
64. Sujith Sourab Guntoju, Mohammad Faiz Alam, Alok Sikka, “Chennai water crisis: A wake-up call for Indian cities,” *Down to Earth*, August 5, 2019,. https://www.downtoearth.org.in/blog/water/chennai-water-crisis-a-wake-up-call-for-indian-cities-66024
65. TR Vivek, “How good fortune and planning have helped Chennai avert water crisis this year,” Hindustan Times, April 30, 2020, https://www.hindustantimes.com/india-news/how-good-fortune-and-planning-have-helped-chennai-avert-water-crisis-this-year/story-MStSLbmioc9GHynuRnkT2I.html
66. Sujith Sourab Guntoju, Mohammad Faiz Alam and Alok Sikka, “Chennai water crisis: A wake-up call for Indian cities,” Down to Earth,, August 5, 2019, https://www.downtoearth.org.in/blog/water/chennai-water-crisis-a-wake-up-call-for-indian-cities 66024#:~:text=Of%20Chennai's%20total%20requirement%20of,worst%20days%20of%20the%20crisis.&text=The%20city%20of%20Chennai%20has,%2C%20Cholavaram%2C%20Redhills%20and%20Chembarambakkam.
67. Vij, Sumit, Anshika John, and Anamika Barua. "Whose water? Whose profits? The role of informal water

markets in groundwater depletion in peri-urban Hyderabad." *Water Policy* 21.5 (2019): 1081-1095.

68. Abhijit Banerjee, Rohini Pande and Michael Walton, “Delhi’s Slum-Dwellers: Deprivation, Preferences and Political Engagement among the Urban Poor,” *International Growth Centre*, Working Paper, October 2012
69. Chennai City Census 2011 data, Census 2011 https://www.census2011.co.in/census/city/463chennai.html#:~:text=Chennai%20Slums%202011&text=of%20Slums%20in%20Chennai%20city,total%20population%20of%20Chennai%20city.
70. Saharan, Tara, Karin Pfeffer, and Isa Baud. "Shifting approaches to slums in Chennai: Political coalitions, policy discourses and practices." *Singapore Journal of Tropical Geography* 39, no. 3 (2018): 454-471.
71. “Major Slum Areas in Top Ten Cities of India,” Walk Through India, http://www.walkthroughindia.com/lifestyle/major-slum-areas-in-top-indian-cities/#:~:text=Rajendra%20Nagar%20Slum%20Bengaluru,Bengaluru%20population%20reside%20in%20slums.
72. “Rajiv AwasYojana (RAY) scheme: Executive Summary,” Coimbatore City Municipal Corporation site, https://payment.ccmc.gov.in/DwnldForms/SMARTCITY/CITY_PLANS/b.%20slum-free%20city%20action%20plan-Final.pdf
73. Mihir Shah, “*Urban water systems in India: a way forward*,” No. 323. Working Paper, 2016.
74. Dynamic Ground Water Resources of India Reports, Central Ground Water Board (CGWB), Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, Government of India, http://cgwb.gov.in/Dynamic-GW-Resources.html
75. NITI Aayog, "Composite water management index: a tool for water management," 2018, https://niti.gov.in/writereaddata/files/document_publication/2018-05-18-Water-index-Report_vS6B.pdf
76. Dynamic Ground Water Resources of India Reports, Central Ground Water Board (CGWB), Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, Government of India,http://cgwb.gov.in/Dynamic-GW-Resources.html
77. “Dynamic Ground Water Resources of India Reports”
78. Ibid “Dynamic Ground Water Resources of India Reports”
79. Ibid “Dynamic Ground Water Resources of India Reports”
80. NITI Aayog, "Composite water management index: a tool for water management," 2018, https://niti.gov.in/writereaddata/files/document_publication/2018-05-18-Water-index-Report_vS6B.pdf
81. Sahana S, “Bengalureans fret as borewells dry up, tankers cost a bomb,” April 8. 2019, IIJNM. http://newsnet.iijnm.org/bengalureans-fret-as-borewells-dry-up-tankers-cost-a-bomb/
82. Ground Water Data Access, Central Ground Water Board (CGWB), Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, Government of India. http://cgwb.gov.in/GW-data-access.html
83. “Ground Water Data Access”
84. “Ground Water Data Access”
85. “Ground Water Data Access”
86. NITI Aayog, "Composite water management index: a tool for water management," 2018, https://niti.gov.in/writereaddata/files/document_publication/2018-05-18-Water-index-Report_vS6B.pdf
87. “Report of the Ground Water Resource Estimation Committee,” India Environment Portal, Ministry of Water Resources, River Development & Ganga Rejuvenation Government of India, October 2017
88. Dynamic Ground Water Resources of India Reports, Central Ground Water Board (CGWB), Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, Government of India. http://cgwb.gov.in/Dynamic-GW-Resources.html
89. Bhasker Tripathi, “Bengaluru, Delhi, Chennai Among 21 Cities to Run Out of Groundwater by 2020,” *Firstpost*, July 9, 2018, https://www.firstpost.com/tech/science/indias-water-crisis-bengaluru-delhi-chennai-hyderabad-among-21-cities-to-run-out-of-groundwater-by-2020-4590221.html.
90. Mihir Shah and Himanshu Kulkarni, "Urban water systems in India." Economic & Political Weekly 50, no. 30 (2015): 57
91. Write Read Data available at http://164.100.117.97/WriteReadData/userfiles/Categorization.pdf
92. Press Information Bureau, “Union Minister of Consumer Affairs, Food & Public Distribution Shri Ram Vilas Paswan releases Water Quality Report for State Capitals & Delhi as analysed by BIS,” November 16, 2019, https://pib.gov.in/PressReleseDetail.aspx?PRID=1591825
93. “Drinking Water — Specification (Second Review),” Bureau of Indian Standards, 2012
94. Product Manual for Drinking water According to IS 10500 : 2012, Bureau of Indian Standards, October 2020. https://bis.gov.in/wp-content/uploads/2020/10/PM-IS-10500.pdf
95. Report of Ground Water Estimation Committee, GEC 2015, Ministry of Water Resources, River

Development & Ganga Rejuvenation Government of India. http://cgwb.gov.in/Documents/GEC2015_Report_Final%2030.10.2017.pdf

96. Thangavelu, A , "Mapping the groundwater quality in Coimbatore city, India based on physico-chemical parameters." *IOSR Journal of Environmental Science, Toxicology and Food Technology*, Vol 3, Issue 4 (Mar – Apr 2013), pp 32-40
97. Sheeba, Jalagam, Venkatasubramainan, "Drinking water contamination from peri-urban Bengaluru," India, *Current Science*, Vol 113, No 9, 1702, Nov 10, 2017
98. Jerome and Pius, "Evaluation of water quality index and its impact on the quality of life in an industrial area in Bengaluru, South India," *American Journal of Science and Industry Research*, 2010, 1(3); 595-603
99. Guy Howard and Jamie Bartram, "Sanitation Water, and World Health Organization. Domestic water quantity, service level and health," No. WHO/SDE/WSH/03.02. *World Health Organization*, 2003.
100. Abdul Shaban, R N Sharma, "Water Consumption Patterns in Domestic Households in Major Cities," *Economic and Political Weekly*, June 9, 2007
101. Shaban and Sharma, "Water Consumption Patterns in Domestic Households in Major Cities"
102. Indian Standard IS 1172 : 1993 Code of basic requirements for water supply, drainge and sanitation (Fourth Revision), *Bureau of Indian Standards*, http://dasta.in/wp-content/uploads/2015/04/CB_Code_2002.pdf
103. Indian Standard Code of Basic Requirements for Water Supply, Drainage and Sanitation (Fourth Revision), *Bureau of Indian Standards*, February 1993. http://dasta.in/wp-content/uploads/2015/04/CB_Code_2002.pdf
104. Abdul Shaban, R N Sharma, "Water Consumption Patterns in Domestic Households in Major Cities," *Economic and Political Weekly*, June 9, 2007
105. Shaban and Sharma, "Water Consumption Patterns in Domestic Households in Major Cities"
106. Annual Dynamic Ground Water Resources of Chennai, Bengaluru, Coimbatore and Delhi 2017, Central Ground Water Board (CGWB), Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, Government of India. http://cgwb.gov.in/Dynamic-GW-Resources.html
107. "Dynamic Ground Water Resources of India Reports," Central Ground Water Board (CGWB), Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, Government of India. http://cgwb.gov.in/Dynamic-GW-Resources.html
108. "Dynamic Ground Water Resources of India Reports"Indian Standard IS 1172 : 1993 Code of basic requirements for water supply, drainge and sanitation (Fourth Revision), *Bureau of Indian Standards*, http://dasta.in/wp-content/uploads/2015/04/CB_Code_2002.pdf
109. "Guidance Notes for Continuous Water Supply (24 x 7): A Guide to Project Preparation, Implementation and Appraisal," Ministry of Urban Development, Government of India, 2009, http://cpheeo.gov.in/upload/uploadfiles/files/Guidance%20Note%20for%20Continuous%20Water%20Supply.pdf
110. "Guidance Notes for Continuous Water Supply (24 x 7): A Guide to Project Preparation, Implementation and Appraisal"
111. Abhay Kantak, "Urban Water Sector," *CRISIL Infrastructure Advisory*,http://mohua.gov.in/upload/uploadfiles/files/PPT_CRISIL_Water_Sector_0.pdf
112. Telephonic Interview with K C Subhash Chandra, Bengaluru based senior hydrogeologist and Former Member on the expert panel in the Karnataka Groundwater Board. . Date March 15, 2019. Time: 12:10 pm.
113. "Urban Water Supply in India," The World Bank, July 14, 2011, https://www.worldbank.org/en/news/feature/2011/09/22/urban-water-supply-indi
114. Paras Singh, "Delhi Jal Board to hand over water, sewage lines to private companies," *The Times of India*, September 25, 2020, https://timesofindia.indiatimes.com/city/delhi/delhi-jal-board-to-hand-over-water-sewage-lines-to-private-companies/articleshow/78306641.cms#:~:text=NEW%20DELHI%3A%20The%20operation%2C%20management,responsibility%20of%20the%20water%20utility.&text=These%20private%20firms%20will%20be%20appointed%20for%2010%20years
115. Peter van der Steen First SWITCH Scientific Meeting University of Birmingham, UK 9-10 Jan 2006 http://www.switchurbanwater.eu/outputs/pdfs/WP1-1_PAP_IUWM_towards_sustainability.pdf
116. GVR Suba Rao, "KRMB panel to discuss plan for water supply to Chennai," *The Hindu,* July 16, 2020. https://www.thehindu.com/news/national/andhra-pradesh/krmb-panel-to-discuss-plan-for-water-supply-to-chennai/article32106620.ece
117. "DJB approves projects of water augmentation, clean Yamuna, groundwater rejuvenation," Delhi Jal Board, Government of NCT of Delhi, May 29, 2019. http://www.delhijalboard.nic.in/content/djb-approves-projects-water-augmentation-clean-yamuna-groundwater-rejuvenation
118. Veena Srinivasan, D. Suresh Kumar, Pennan Chinnasamy, Swati Sulagna, D. Sakthivel and P. Paramasivam

Sharachchandra Lele, “Water Management in the Noyyal River Basin,” *Ashoka Trust for Research in Ecology and the Environment*, February 2014

119. T.V. Ramachandra, Vinay S and Bharath H. Aithal, “Frequent Floods in Bangalore: Causes and Remedial Measures,” *Indian Institute of Science*, August 2017
120. Ramachandra et al, “Frequent Floods in Bangalore: Causes and Remedial Measures”
121. Shree Padre, “A Million Wells for Bengaluru,” *Civil Society*, November 1, 2019,https://www.civilsocietyonline.com/cover-story/a-million-wells-for-bengaluru/
122. G. Thomas LaVanchy, “Beyond 'Day Zero': insights and lessons from Cape Town (South Africa),” Hydrogeology Journal (ResearchGate), April 2019
123. NITI Aayog, "Composite water management index: a tool for water management," 2018, https://niti.gov.in/writereaddata/files/document_publication/2018-05-18-Water-index-Report_vS6B.pdf
124. “National Status of Waste Water Generation & Treatment,” Order of the National Green Tribunal regarding effluent discharge standards for STPs, 30/04/2019, *ENVIS Centre on Hygiene, Sanitation, Sewage Treatment Systems and Technology*, May 8, 2019, http://www.sulabhenvis.nic.in/Database/STST_wastewater_2090.aspx
125. ENVIS Centre on Hygiene, Sanitation, Sewage Treatment Systems and Technology, 2019
126. ENVIS Centre on Hygiene, Sanitation, Sewage Treatment Systems and Technology, 2019
127. Murugesana, A., N. Bavana, C. Vijayakumar, and T. Vignesha. "Drinking Water Supply And Demand Management In Chennai City-A Literature Survey," *International Journal of Innovative Science, Engineering & Technology*, Vol. 2 Issue 3, March 2015.
128. Sukirti Vinayak, Poonam Sewak et. Al., Drinking Water Supply for Urban Poor: City of New Delhi, *Safe Water Network*, October 2016, https://www.safewaternetwork.org/sites/default/files/Safe%20Water%20Network_Delhi%20City%20Report.PDF.
129. “Ukkadam STP, Coimbatore Co-treatment Case Study,” This study was commissioned by Sanitation Capacity Building Platform (SCPB), the platform focuses on Ministry of Housing and Urban Affairs, MoHUA focus on urban sanitation https://scbp.niua.org/sites/default/files/Coimbatore_0_0.pdf
130. “Waste Water Treatment and Reuse,” Urban Waters Bangalore, http://bengaluru.urbanwaters.in/wastewater-treatment-and-reuse-49/#:~:text=Currently%2C%20Bengaluru%20generates%201400%20MLD,by%20BWSSB%2FBBMP%20in%20Bengaluru.&text=Most%20of%20Bengaluru's%20wastewater%20flows%20downstream%20untreated.
131. Order Of The National Green Tribunal Regarding Effluent Discharge Standards For Stps, April 30, 2019 Updated on May 8, 2019. http://www.indiaenvironmentportal.org.in/files/file/revised-standards-STPs-NGT-Order.pdf
132. “Koramangala-Challaghatta valley project: IISc has proposed an outcome study, Karnataka HC told,” *The Times of India*, November 29, 2019. https://timesofindia.indiatimes.com/city/bengaluru/koramangala-challaghatta-valley-project-iisc-has-proposed-an-outcome-study-karnataka-hc-told/articleshow/72297761.cms
133. Authors’ interview with Dr. Arunangshu Mukherjee, Advisor and Principal Consultant, Geovale Services, personal communication dated January 15, 2020. Time: 11:30 am
134. “Wastewater Treatment and Effluent Reuse,” *Mekorot Israel National Waters and Co*., https://www.mekorot.co.il/Eng/newsite/Solutions/WastewaterReclamation/Pages/default.aspx.
135. Martin Jacobson, “Singapore Water Management,” *World Wide Fund for Nature*, March 1, 2012, https://wwf.panda.org/?204587/Singapore.
136. Robert Brears, “Stockholm turning wastewater into resourcewater,” February 22, 2019, We are Water Foundation. *Smart Water Magazine*. https://smartwatermagazine.com/blogs/robert-brears/stockholm-turning-wastewater-resourcewater
137. Government of India, Ministry of Earth Sciences, Rainfall Statistics of India – 2015, by Dr. (Mrs.) Surinder Kaur and M. K. Purohit, Report No. ESSO/IMD/HS R. F, 2015
138. Elangovan A and Seetharaman R (2010): Groundwater responses to artificial recharge of rainwater in Chennai, India: A Case Study in an Educational Institutional Campus, *Indian Journal of Science and Technology* (ResearchGate), January 2010
139. Subhash Chandra KC and Hegde GV, “Hydrogeological conditions of Bengaluru: A Review,” *Journal of the Geological Society of India* (ResearchGate), April 2016
140. Bekele Debele and Christopher Ward, “The Role of Desalination in an Increasingly Water Scarce World,” World Bank Group, March 2019, https://idadesal.org/wp-content/uploads/2019/04/World-Bank-Report-2019.pdf.
141. Dr S C Lahiry, “Is desalination worth its salt?,”, India Water Portal, October 6, 2016,https://www.

indiawaterportal.org/articles/desalination-worth-its-salt

142. Government of India, Ministry of Earth Sciences, Rainfall Statistics of Indian 2015.
143. Margareta Lundin, Gregory M. Morrison, "A life cycle assessment based procedure for development of environmental sustainability indicators for urban water systems," *Urban Water* 4 (2002) 145–152 (ResearchGate), June 2002
144. Lundin et al, "A life cycle assessment based procedure for development of environmental sustainability indicators for urban water systems"
145. C. Kennedy, S. Pincetl , P. Bujne, "The study of Urban Metabolism and its Applications to Urban Planning and Design," *Environmental Pollution* 159 (2011) 1965e1973 (National Library of Medicine), November 17 2010, https://pubmed.ncbi.nlm.nih.gov/21084139/.
146. Tauheed A. Farooqui, Marguerite A Renouf and Steven J. Kenway, "A Metabolism Perspective on Alternative Urban Water Servicing Options Using Water Mass Balance," *Water Research* Volume 106 (National Library of Medicine), Pages 415-428, December 1, 2016, https://pubmed.ncbi.nlm.nih.gov/27750130/.
147. Farooqui et al, "A Metabolism Perspective on Alternative Urban Water Servicing Options Using Water Mass Balance"

India launched the Jal Jeevan Mission (Urban) in February 2021—an ambitious project that aims to provide potable tap water supply to 2.86 crore urban households by 2024. The initiative is much needed: Large parts of urban India face severe water stress conditions due to rapid urbanisation, negligible augmentation of raw water sources, archaic water infrastructure, and poor water governance. This study analyses the gaps in the current urban water balance and the constraints to city water budgeting processes. Using primary and secondary data, it conducts a comprehensive analysis of the water supply and demand scenarios in four water-stressed cities—Chennai, Coimbatore, Bengaluru, and Delhi. It undertakes a situation analysis to map the current scientific understanding of available water resources, their utilisation, the supply infrastructure, alternative raw water sources, wastewater discharge, and its treatment and reuse.

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