Water Security: A Geospatial Framework for Urban Water Resilience

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Research Article

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Abstract

Urban water issues impacting sustainable development can be analyzed, modeled, and mapped through cutting-edge geospatial technologies; however, the water sector in developing countries suffers various spatial data-related problems such as limited coverage, unreliable data, limited coordination, and sharing. Available spatial data is limited to the aggregate level (i.e., National, State, and District level) and lacks details to make informed policy decisions and allocations. Despite significant advancements in geospatial technologies, its application and integration at the policy and decision-making level are seldom. The current research provides a unique, holistic Geospatial Framework to measure and monitor water security through geospatial technologies. The study demonstrates the application of the proposed Geospatial Framework from technical and institutional perspectives in water-stressed zones in Pune city showing where and how to solve problems and where proposed actions can have the most impact on creating a sustainable water-secured future. The research encourages cross-disciplinary collaboration, decentralized activity, employing traditional and indigenous knowledge, green infrastructure, watershed management, and nature-based solutions through Geospatial Framework to solve the primary challenges of water and build our cities' resilience. The current research can collaborate with Municipal Corporation mutually beneficial and work towards open-linked geospatial data for water security.

Introduction

Water insecurity remains one of the most pressing resilience challenges worldwide, making indispensable the need for conservation and collaboration between cities, partners, and stakeholders to find an innovative and actionable solution (Rockefeller Foundation 2015). In recent years the development community has come to realize the need for geospatial technologies for water security. Greg & Abbas (2017) provided significant insights into integrating geospatial technologies to solve various sustainable development challenges. Recently, the Ministry of Science and Technology, Govt. of India, encouraged leveraging modern geospatial technologies, which would help improve planning and management of resources and better serve the specific needs of citizens (DST 2021).

The availability of comprehensive and highly accurate geospatial data advances innovation and intensely enhances the preparedness for water resilience. It is necessary to have real-time spatial data on sustainable development measures (Dangermond 2020). Complete datasets increase efficiency in local planning, allow users to take the data offline, analyze geographical context, model, and map to achieve the Sustainable Development Goals (SDGs) (Dangermond 2020, Greg & Abbas 2017, Guan et al. 2012 and United Nations 2019). Guan et al. (2012) explain how geographic interface helps visualize and analyze spatial data at various scales from global to local.

Rockefeller Foundation (2015) selected Pune, India under its 100 resilient cities worldwide based on challenges the city faces, including water insecurity. In this paper, we developed a holistic, digital Geographic Information Systems (GIS) centric framework for water security, including a vast array of spatial maps, wide-ranging spatial thematic layers, and various useful strategies and policies for water
security. Further, the paper shows the applications of the Geospatial Framework exploring the potential areas of water supply within the context of the peripheral villages in Pune city. The framework aims to conform to future improvement and long-term water sustainability.

The current research can collaborate with Pune Municipal Corporation (PMC) in a mutually beneficial manner and work towards open-linked Geospatial data for water security and environmentally sensible urban water management. The Geospatial Framework aims to provide a common platform for geospatially enabled administrative and other water-related thematic data from across a range of sources that can be integrated based on location, as well as ensuring that these data can be integrated with other geospatial information. The framework can be used by diverse stakeholders who are concerned about water security. The Framework is designed considering the need of citizens to have a system of online geospatial data as well as engaging them with communities, promote transparency, and collaborate across departments. Maps give an insight related to spatial interconnection, spatial interdependence, and context for decision-making.

2. Literature Review

2.1 Geospatial data-related challenges in the water sector in India

The water sector in India suffers several data-related problems such as limited coverage, limited coordination, and sharing (NITI Aayog 2019). The Ministry of Jal Shakti, Govt. of India launched a web-based centralized platform of geospatial data called India-WRIS in 2009, which was further revised in 2016 to fulfill water security (India-WRIS 2021). Indian Space Research Organization (Bhuvan, 2009) also provides geospatial data, including several thematic maps related to disasters, agriculture, water resources, and land. However, the data on these platforms are available at an aggregate level (i.e., National, State, district, block-level, and hydrological levels such as basin and sub-basins) and lacks the details required to run any sort of analysis and to make informed policy decisions. Further, PMC (2020) GIS portal provides access to geospatial data, which is limited to visualization purposes and does not allow the user to download the data for any further spatial analysis. Any research efforts need complete datasets with adequate metadata to facilitate their use. Due to the unavailability of comprehensive spatial data, it is difficult to assess the impact of different factors on water resilience, thereby reducing efficiencies in policy formulation, infrastructure maintenance, research, and innovation (NITI Aayog 2019). Goodchild (2007) encouraged creating valuable spatial data, which provide access to not only those who are doing serious geospatial investigations, including GIS professionals, academic scholars, and small GIS organizations but also to the general public who are not GIS professionals. The available spatial data can be used to compose dynamic maps online or offline that can help achieve SDG # 6. Collaboration is the key to achieve SDG # 6, which might be driven from the top but the solution has to be driven from the bottom through engaging the community. Further, decision-makers, planners, and policymakers need to marry scientists and technology to solve real-world issues. Cities need a cross-cutting framework that integrates and aligns a wide range of central and state-level policies for water security.
2.2. Strategies and policies for water security discussed by others

With the growing urban population, it is essential to look at alternative water supply systems instead of relying on centralized infrastructure approaches, i.e., piped water, limiting the option of more environmentally sensitive, flexible, and resilient approaches (Brown et al. 2011, Megdal and Forrest 2015, Civitelli F. & Gruère G. 2017, Houngbo 2018). The additional water supply must be arranged from sources located outside the boundaries of the cities (Lundqvist et al., 2003, Megdal & Forrest, 2015, Civitelli F. & Gruère G. 2017) like Delhi, India, where only 57% of the population has access to the piped water supply. However, 34% of the population obtains water from non-piped sources, such as traditional underground water tanks. Researchers promote increasing freshwater availability to cities i.e. high-value urban uses by reallocating water from low-value agricultural uses (Molle and Berkoff 2006, Kendy et al. 2007). Rural communities can use treated wastewater for irrigation purposes instead of groundwater (Civitelli F. & Gruère G. 2017). Several recent studies have investigated that incorporating green spaces into development to maintain higher levels of evapotranspiration and minimize the impacts of urban development (Walsh et al. 2016, Wright et.al, 2021). Wright et.al, (2021) assessed the effectiveness of different policies related to protecting riparian zone, preserving forest areas, hills, hilltops, and promoting denser development and green neighborhood for water balance to reduce the impacts of urbanization. Few studies have explored the combined effect of the specific sets of location-specific policies for watershed management regional stakeholders (Walsh et al. 2016, Wright et.al, 2021).

The coverage of piped water services is the most reliable drinking water service. However, Houngbo (2018) argues that reservoirs and water treatment plants are not the only water management solutions. Lundqvist et al. (2003) recommended arranging water from sources that are local and sustainable, located outside the boundaries of the cities instead of bringing piped water from farther and farther away. Megdal and Forrest (2015) also encouraged sustainable water management approaches instead of building a new water distribution infrastructure for addressing long-term water scarcity problems. Wetlands also act as natural barriers that soak up and capture rainwater, restrict soil erosion and prevent the impacts of floods. Groundwater resources are the lifeline of India’s water supply in both the rural-agrarian situations and in the growing urban-industrial context. About 50% of urban water supplies are groundwater-based. Houngbo (2018) encouraged to employ of sustainable approaches such as traditional and indigenous knowledge like nature-based solutions (NBSs) and green infrastructure. Traditional urban planning always integrated nature in India, which has shown great potential to improve the management of water resources in urban areas. Green solutions such as preserving the functions of ecosystems, planting trees, restoring wetlands, recycle and harvest water, recharge groundwater, and protecting watersheds have shown great potential to improve the management of water resources in urban areas.

Drinking water supply should not be limited to centralized solutions; instead, decentralized, community-based approaches should be promoted (Anthony 2007, Srinivasan et al. 2013, Civitelli F. & Gruère G. 2017). However, there have been very few decentralized approaches such as community-controlled systems in urban areas in India (Anthony 2007). There is a need for new forms of urban governance and
planning institutions capable of managing both centralized actions by utilities and decentralized actions by millions of households (Srinivasan et al. 2013, Megdal and Forrest 2015, Civitelli F. & Gruère G. 2017) to reduce vulnerability to water shortages.

Local governments are responsible for water supply services in cities. Private sector participation (PSP) in water delivery is still rare in India. National Water Policy of the Government of India (2002) encouraged PSP in water resources. Mathur (2017) encouraged public-private partnerships for municipal water supply in developing countries with a case example of water service delivery improvement in Karnataka. The significant benefits of the private sector include financial sustainability, technical expertise, and operational and management efficiencies (Guardiola 2010, Mathur 2017, Vedachalam et al. 2016, and World Bank 2014). However, some authors argued in their research that privatization could be problematic in lower-income economies and claimed that government-owned utilities are better than private utilities (Crook 2003, Kirkpatrick et al. 2006).

3. Methodology

3.1 Study Area

Pune city is located at the confluence of two major rivers, the Mula and Mutha. The study area covers the current boundaries of Pune Municipal Corporation (PMC). Pune city has been expanded from 7.74 sq km to a massive 516.18 sq km over the past 70 years. The first expansion was to include the 18 villages in 1958, followed by merging 23 villages out of the proposed 38 villages in 1997. The Maharashtra State government proposed a merger of 34 villages in 2014, out of which PMC merged 11 villages with a population of 2.39 lakh and an area of 80.7 sq km in the city's periphery in 2017. After merging the remaining 23 villages recently on June 30, 2021, PMC now has a total of 516.18 sq km of land area within its boundary (Fig. 1). Pune has officially become the city with the largest geographical area in Maharashtra.

3.2 Proposed Geospatial Framework

All the elements of the water cycle, i.e., evapotranspiration, condensation, precipitation, infiltration, surface runoff, river, lakes, soil moisture, and groundwater are interdependent (NWP 2012). Through its multi-dimensional listing, we have tried to cover the entire trajectory from the environmental source of water to supply to distribution in the proposed Geospatial Framework. The proposed framework is designed based on the existing water scenario in Pune city, SDGs, and a review of existing water sustainability templates (national and international). The framework is designed for active management areas (AMAs) to help stakeholders to learn about the water sources that are local and sustainable for instance presence of traditional wells, spring water, green spaces, water bodies, watershed boundaries, wetlands, and groundwater recharge zones.

Water security Geospatial Framework is rich in geographic content and designed with aim of publicly accessible using any of the web browsers. The user may select several thematic layers, overlay, and
analyze spatial patterns and relationships between data sets and download the data for offline spatial analysis. The Framework supports various data formats (i.e., shapefiles, GeoTIFF images, KML, and coverage) and projections. The framework is simple, which can be used by people even without a GIS background. The framework aims to allow the user to visualize, download, upload spatial data, prepare maps, investigate, share and communicate and significantly enhance the ability of non-GIS academics and researchers to conduct their research. The proposed Geospatial Framework includes a package of thematic layers (Table 1), geospatial maps (Table 2), and the policies and strategies related to water security (Table 3). The Framework is not static; it can be expanded with more map layers, new policies, and guidelines.

3.3 Application of Geospatial Framework/ Applying cutting-edge technology

We used Geospatial Framework to identify local resources, which could be an alternative source of water to decrease the demand for fresh water in cities. We explored various thematic layers and maps, which were selected from the Geospatial Framework as ready-to-use content, and analyzed the spatial patterns, spatial interconnections, and spatial interdependence between the features visually. Our exploration criteria are listed in table 4.

Most of the peripheral water supply zones in Pune are water-stressed, which need to be examined for better water supply services. Fig.2 shows the water-stressed zones including Balewadi, Baner West, Baner Hill, Sus Sutarwadi, Baner Gaon Zone 2 in the North-Western region, Paranjpe Layout in the Western region, Nyati Enclave in Southern region, Chandan Nagar zone-1, Kharadi zone 1, 2 and 3 in North-Eastern region, and Gliding center/ Hadapsar Gaon in Eastern region. Currently, the city draws the water of the Mutha river from the Khadakwasla reservoir, while dams at Panshet, Varasgaon, and Temghar reservoirs supplement the storage capacity of Khadakwasla. The Katraj and Pashan lakes are not directly used for water supply by the PMC but play an important role in recharging groundwater which is used by thousands of city dwellers. Groundwater supplies also play a significant role in meeting urban water needs. Currently, Pune city is supplied with 13 TMC water annually out of which about 4 TMC of water is extracted from groundwater in Pune city (ACWADAM 2019). It is important to understand the environmentally sensitive water resources for sustainable and equitable urban water supplies, which we assessed using Geospatial Framework at the regional scale.

We created buffers of 5 km, 10 km, 15 km, and 20 km around the PMC boundary for our analysis purpose. We pulled several thematic layers from the proposed Geospatial Framework in ArcGIS 10.5 and demonstrated the application of the Geospatial Framework to solve water issues. The layers included traditional step-wells, aquifers, springs, natural groundwater recharge zones, hilltops and hill-slopes, wetlands, and watershed boundaries in and around Pune city. Our goal is to identify local resources, which could be alternative water sources to decrease the demand for fresh water in cities. The study does not provide design criteria rather explores the potential areas of alternative water resources within the context.

3.3.1 Exploring Traditional step-wells around Pune city
We explored traditional step-wells, which resemble a funnel, with their size decreasing from top to bottom and their sides are lined with a steep flight of steps. The depth of these step-wells varies considerably depending on the level of groundwater as they penetrate deep into the ground to access groundwater. These step-wells have a small surface area at the bottom and considerable depth below ground. Thus the rate of evaporation of water from them is low.

We found several traditional step-wells (Fig. 3) in and around Pune city. We created a buffer of 5 km, 10 km, 15 km, and 20 km around the PMC boundary and overlayed them with step-wells. The study found one step-well i.e. Bhukum stepwell falls within five km, five step-wells between the buffer of 5 to 10 km, 11 step-wells between the buffer of 10 to 15 km, 10 step-wells between the buffer of 15 to 20 km, and several other step-wells fall outside the buffer of 20 km around Pune city (Table 4). The city receives an annual rainfall of 722 mm between June and September, we should effectively use this gift of nature through these community-level structures spread around the city.

The ancient Indian settlement took place not only based upon the presence of rivers, coast, or perennial sources of water but also people settled banking on the presence of these traditional step-wells and rainwater harvesting structures (water tanks). These step-wells were built for water conservations. However, during British rule, many step-wells and water tanks were destroyed as they were found unhygienic and breeding grounds for several diseases. Considering the water shortage today especially in peripheral water supply zones, these step-wells and water storage tanks need to be protected and revived since borewells cannot be the future of the city. The traditional step-wells and rainwater harvesting structures of the past can support our future more sustainably.

3.3.2 Exploring Springs around Pune city

We explored the location of spring water in Pune city, which is majorly ignored as a water source. The use of spring water can fulfill the gap between the municipal water supply and the growing demand across the city. We overlayed the geospatial layer of the Pune spring inventory with the water index layer (ACWADAM 2019), which showed 35 springs, out of which 24 are perennial springs, and 11 are seasonal springs. We identified the presence of springs in many water-stressed zones includes Balewadi, Baner West, Baner Hill, Sus Sutarwadi, Baner Gaon Zone 2 in the North-Western region. ACWADAM (2019) documented discharges and in-situ water quality of these springs and found that spring water is clear and likely to be potable. This water can be used for other non-potable uses too. A detailed water quality assessment is required to check if springs could be an important natural alternative source of water supply at decentralized levels.

3.3.3 Exploring aquifers and recharge zones in Pune city

ACWADAM (2019) documented five types of shallow unconfined (or phreatic) aquifers (Fig. 5), which have a thickness ranging from 10 to 20 m. A comprehensive application of the practice of Managed Aquifer Recharge (MAR) must be designed for the city, based on the main recharge zones identified in each of the five aquifers in the city instead of a random approach to groundwater recharge. The state
regulates groundwater at the regional level, but the regulation process to recharge aquifers on a long-term basis demands local interests. Nearly half the area of these five major aquifer recharge areas for Pune city is paved by residential areas, including gated communities, and multistoried apartment buildings. The other half is covered with mixed land use, including open plots, parks, and gardens, open spaces, private residences, commercial infrastructure, educational institutions, and other public and semi-public buildings. Educational institutions and other public and semi-public buildings with large landscaping can be potential areas for MAR, and the guidelines can be customized as per land cover type for groundwater recharge.

3.3.4 Exploring watershed in and around Pune city

Pune is crossed by many rivers and streams, which rise near the Sahyadris. Watershed management is necessary to prevent stormwater runoff, decrease soil erosion and increase groundwater recharge. Protection of the catchments of the watershed clusters would protect the natural recharge zones. There are 30 watersheds in the Pune city limits (Fig. 6). Rapid urbanization has significantly damaged the natural drainage system with the paved surface in all watersheds, which increases the runoff. Therefore, Wright et.al (2021) recommended condensed development and preserve natural recharge zones for maintaining pre-development water balance (Wright et.al 2021). As cities share their watershed boundaries with rural areas, exploring watersheds help decision-makers, knowing the impacts of development on watershed hydrology.

3.3.5 Exploring Nature-Based Solutions (NBS) in and around Pune city

We further explored some Green infrastructure, i.e., green spaces, hill-topes and hill-slopes, wetlands, surface water bodies, agriculture, and forest areas (Fig. 7). Augmenting green spaces improve the natural hydrological systems in urban areas. Expansion of the urban green spaces is an economical and environmentally friendly approach to deal with stormwater runoff and urban flooding. Still, it can also improve the resiliency and sustainability of the city.

The hilltops and hill-slopes occupy nearly 2000 hectares of land in and around Pune city. Hills with afforestation and reforestation to prevent runoff, decrease soil erosion and increase groundwater recharge. As per the land use distribution of Pune city, the total area covered under hills and hill slopes is 5.10%, which governs the city's micro-climate. However, encroachment of hill slopes by informal settlements resulted in the loss of green covers on the hills hence increasing climate change (PMC, 2014). To restore the ecology and enrich the green cover on these hills, regeneration, afforestation for biodiversity, and protection of these hills are necessary. No permission must be granted for constructions on hilltops (where the slope ratio is 1:5) as well as 100ft around the foothills. Further, biodiversity parks have been proposed in six different locations i.e. Baner – Pashan Lake, Pashan Panchwati, Sutarwadi, Hadapsar, Mohammadwadi, and Kondhwa Budruk in the city. Construction on these parks should not be encouraged such an area must be marked as a no-development zone and preserved as an open space. The total area under reserved forest and agriculture is 2905 ha which is 11.91% of the total area that plays a key role in flood risk management. We explored wetlands around the city, which play an important
role as they capture rainwater, restrict soil erosion and prevent the impacts of floods. We further explored surface water bodies from the India-WRIS portal and found several small water bodies around PMC, which can be an alternative source of water as community-based water supplies to provide safe drinking water, as the community-based approach significantly increases sustainability.

4. Discussion And Conclusion

Citizens of Pune are worried about the water supply after merging the remaining 23 villages in June 2021. PMC is already under stress as PMC is unable to provide basic facilities to already merged 11 villages in 2017. The merger will help the government to create a land bank. However, there should be a regional plan which can reserve the rights of all agencies like PMC, and fringe villages. PMC should implement a decentralization model as suggested in Geospatial Framework for development.

ACWADAM (2019) estimated about 20% of Pune's water needs are met by groundwater as thousands of housing societies have borewells, and. It is recommended to adopt a comprehensive area-based approach and NBSs. The traditional step-wells need to be protected and revived. The PMC has already taken up its Handewadi project to revive a water percolation pond in southeast Pune, which encourages a large public initiative on sustainable water management. Further, the concretization of streams and nullahs should be stopped, which causes floods and reduce groundwater recharge. We need some policies to govern the use of groundwater.

The current research provides a broad GIS-centric framework for actionable science, which focuses on real context and facilitates geospatial maps and theoretical and practical knowledge to address various water issues such as water scarcity, groundwater management, flood management, and water quality management. Seeing the holistic view of water availability through a geographic interface provides great insight into the entire region and maintains details of each water zones individually.

The initial setup for the Geospatial Framework has been proposed, which can be expanded with new functionality. We can integrate any layer created by any other geospatial group, which we need for water security. We need to persuade PMC to integrate this Geospatial Framework into its existing GIS portal and adopt the environmentally sensitive approach of condense development and protect natural areas, riparian areas, open space, and watersheds in peripheral villages in their planning and zoning.

We conclude that the proposed Geospatial Framework is a valuable, user-friendly, and self-assessment tool, which will enable cities to carry out an objective assessment of their resilience and measure progress against an initial baseline. The current research provides a water resilient Geospatial Framework to implement global SDG # 6 at the local level which is about achieving universal and equitable access to safe and affordable water for all. The Geospatial Framework enables users, including city officials, urban planners, researchers, residents, and consultants, to access and engage with geospatial data, obtain GIS training and resources, and learn how to use the data effectively to drive action on SDG #6. The Framework can be used for better decision-making and policy intervention and to prepare improvement plans at the city level. This is the future of water security, everyone needs to be
Geospatially conscious, and GIS people must bring SDGs into practice. We all need to 'Expand, Intensify, Create, and Solve through this Geospatial Framework. If established and implemented, it will be a demonstration of good practice that can be taken up at the national level.

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Conflicts of interest/Competing interests: 'Not applicable'

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Code availability (software application or custom code): 'Not applicable'

Authors' contributions

The first Author: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data curation, Writing- Original draft, preparation, Visualization

The second Author: Conceptualization, Writing- Reviewing and Editing, Supervision, and Project administration

Ethics approval (include appropriate approvals or waivers): 'Not applicable'

Consent to participate (include appropriate statements): 'Not applicable'

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**Tables**

| Geospatial Framework: Package of thematic layers related to water resilience |
|---|
| **Surface water bodies** | **Water supply sources** | **Geology** | **Groundwater** | **Aquifers** |
| The major rivers within the city include Mitha, Nala, and Mitha-Nalla River. Lakes: Fakhs Lake, Ratna Lake, and Sardhar Lake. Smaller rivers: Kambodi and Dovnik. | Water supply sources (existing) | The city is underlain by basaltic lava flows of late cretaceous Paleocene age associated with basic intrusive (Bhakadi OOI 2021). | The sources of groundwater in Pune city are dug wells, bore wells, and springs (Naud-WRIS 2021). | Pune city has five aquifers in increasing order of the elevations twenty 250 meters (Khalilia K. and Elkahaw M. 2019). |
| **Springs** | **Watershed** | **Wetland** | **Vegetation** | **Landslide** |
| Pune spring inventory (ALhimAD AN 2016) has yielded data on 35 outlets out of which 24 are perennial springs and 11 are seasonal. The spring water is clear and likely to be potable. | There are 23 small and large natural lakes within Pune city. Each basin provides a network of natural drains discharging stormwater into the Mitha and Nala Rivers. | Restoring wetlands, rather than building off waste water treatment plants. | Pune city has maintained a loss of about 18 megas of green spaces area due to conversion into residential, information technology parks, or traffic use in the past 10 years. | 45% of the area is under residential area, 2% is under the commercial area, 4% is under the industrial zone, and 1% is under public semi-public and recreational use. |
| **Biodiversity Park** | **Forest** | **Green spaces** | **Digital Elevation Model** | **Hills, Hilltop** |
| PMC had reserved Biodiversity Status for restoring the local flora and fauna production of Pune city is 2956 ha which is 11.51% of the total area. | The total area under reserved forest, agriculture as per the land use distribution of Pune city is 2956 ha which is 11.51% of the total area. | Pune city has maintained 20% of green spaces out of which 8% towards recreational and 12% for reserved, forest, and agriculture. | There is an issue of insufficiency of water supply throughout the city as the land city has conflicting topography. | The total area covered under hills and hill slopes is 1.10% which governs the city’s micro-climate. |
| **Soil Depth** | **Soil Texture** | **Soil Color** | **Soil productivity** | **Soil Erosion** |
| Deep, moderately deep, slightly inodolently shallow (60-100 cm) Normally shallow (<100 cm) Shallow (25-90 cm) Very shallow (<25 cm) | Clay, loamy clay, sandy clay, silty clay, sandy clay, silty loam, silt loam, silt, silty loam | Nearly levelled (0-7%), gently sloping (5-15%), moderately sloping (10-15%), highly sloping (15-30%), steeply sloping (>30%) | Highly productive, very productive, moderately productive, low productive, non-productive | Moderate, None to slight, slight to severe, Very severe, gullied |
| **Water Supply areas (6)** | **Water Supply zones (14)** | **District metered area (DMA) (527)** | **Water treatment plants (Existing & proposed)** | **Service Reservoirs (Existing & proposed)** |
| The PMC service area is divided into 6 water supply areas: 1. Pavana, 2. Pavana, 2. Pavana, 3. Pavana, 4. Warje, 5. Holkar, and 6. Bhosale-Nashik. | PMC has a total of 141 water supply zones, including 2 in Pavana, 2 in Pavana, 3 in Pavana, 24 in Warje, one in Holkar, and 37 in Bhosale-Nashik. | PMC has a total of 323 DMA that can be hydraulically isolated to minimize water consumption using metering system. | Existing Water Treatment plants (WTP): Nine Proposed WTP: One WTP is under construction at Warje. | Existing service reservoirs (SR): 58 Proposed service reservoirs: 183 |
Table 2. Geospatial Framework: Geospatial maps related to water resilience

| Geospatial Maps                                      | Description                                                                 | Geospatial Map |
|------------------------------------------------------|-----------------------------------------------------------------------------|----------------|
| Location map of Pune                                 | Pune city is located in Pune District in the western region in Maharashtra state between 73° 22' and 73° 51' East longitude. It is at an altitude of 260 m above mean sea level. | ![Location map of Pune] |
| Ward-wise per capita water supply (lpcd) and continuity of water (lpcd) | Irregular patterns of water supply across the city. Bhavani Path and Karla Wadkar areas are getting 318 liters per capita per day (lpcd) and 260 lpcd, respectively, while Ghode Road and Dhamtari areas are receiving only 139 lpcd and 135 lpcd, respectively. | ![Ward-wise analysis] |
| Population Density                                  | The core city areas are highly populated ranging from 193 people/ha to 1706 people/ha and benefitted by better availability of water supply and adequate pressure as compared to peripheral areas having population density ranging from 42 people/ha to 132 people/ha. | ![Population density] |
| Exact Analysis                                       | Statistically Significant Cluster of High and Low value? Hot Spot (blue): Areas with high quantity of water supply Cold Spot (red): Areas with low quantity of water supply. | ![Exact analysis] |
| Spatial Distribution of GWB output parameters       | GWB explains variation in water supply, well in the north-west area of the city where the local R² value is above 20%, Poor in the northeast and southern part of the city where local R² value is below 10%. | ![Spatial distribution of GWB] |
| Household-level coverage of direct water supply connections | Average: 94.57%, minimum: 66.06%, maximum: 100% | ![Household-level coverage] |
| Per capita supply of water                           | The per capita supply of water varies substantially. The average per capita supply of water in Pune city is 234 lpcd with a minimum of 31.2 lpcd and a maximum of 356.1 lpcd. | ![Per capita supply of water] |
| The extent of Viewing Connection                     | Pune city has very few residential premises with a metering system. Out of 141 water supply zones, among 128 zones are having a percentage of metering connection below 6%, eight zones between 6% to 13%, four zones between 13% to 20%, and only one zone between 20% to 30%. | ![The extent of Viewing Connection] |
| Continuity of water supply                           | The continuity of the water supply must be 24 hours however, the water supply in Pune is largely intermittent with an average supply of only 3 hours per day. | ![Continuity of water supply] |
| Quality of water supplied                            | The average quality of water supplied is 01.74%, with a minimum of 55.2% and a maximum of 100% in Pune city. The benchmark for the quality of water supplied is 100%. The performance indicator falls short of service benchmarks, i.e., 100% in various water supply areas. | ![Quality of water supplied] |
| Water index: Water Zone-level performance on Water Supply Service | The results found that 50% of total water zones in the city are high-performing, 25% medium-performing, and 24% low-performing among the 141 water zones in Pune city for their water supply service. | ![Water index: Water Zone-level performance on Water Supply Service] |
Table 3. Geospatial Framework: The policies and strategies related to water resilience

| Policies/Strategies | Details | Interest (Autonomous/Responsive/Plan/Not Planned) | Timing (Immediate/Concurrent/Sequential) | Temporal Scope (Long/In Term/Short) | Spatial Scope (Local/Regional/Widespread) | Actor (Public/Private) | Remark |
|--------------------|---------|-----------------------------------------------|-----------------------------------------|-------------------------------------|------------------------------------------|------------------------|--------|
| Decentralized Community-based Water Supplies | In the long-run, coverage of piped water services should be expanded as it is the most reliable drinking water service. However, in rural areas where piped water services are lacking, community-based water supplies should be preferred in the short run to provide safe drinking water, as the community-based approach significantly increases sustainability. | A & P | R & A | L | L | Pu & Pr | In impalpable and similar places, community-controlled systems of neighborhood ponds already exist (Adu-Boahen, 2007). Community-based water supply in Ghana (Adeyemo, K., and Asare K. 2009). |
| Large-scale Augmentation of existing Water Supply | Augmented supply with new and non-traditional sources like recycled water, managed aquifer replenishment, and catchment management initiatives | P | C & A | L | L | Pu & Pr | PFMC laid master implementation scheme of recycling 500 MLD treated sewage for irrigation. Augmentation of water supply to Northern areas of Pune State. Bhima Addled dam. Augmentation of lands to works at Khadakwada dam, jhark bell, pump station, and 2500mm diam. pumping main up to Parvati water works and 1500mm diam. pumping main up to Warje waterworks. |
| Participatory Groundwater Management | Participatory Groundwater Management — through protocols and guidelines on the efficient, equitable, and sustainable usage of groundwater. Geographical literacy campaigns to educate citizens on the concept of aquifers. Participatory Aquifer Mapping, including a recharge plan. The public recharge systems must be based on the identified aquifers in the city. This strategy will include injection recharge at strategic locations. | D | C | L | W | Pub/Pr | Housing Societies where denizens of the population are significant and the annual groundwater extraction per unit area is equivalent or more than the annual precipitation on that area. |
| Managed Aquifer Recharge (MAR) | | | | | | | |
| Investment in Small-scale Infrastructure | Household and community-level installation of alternative water infrastructure such as rainwater tanks, grey-water treatment systems, water sensitive urban design structures | A | C | L | L | Pr | PFM has made it mandatory for all housing schemes with more than 150 components to have sewage treatment plants (STPs) and reuse the treated sewage for flushing, gardening, etc. It is mandatory to implement rainwater harvesting in all the layout open spaces in urban areas of housing societies. |
| Encouragements for efficient water use and conservation | P | C & A | I | W | P | Melbourne aimed to reduce water consumption to 1.5 L/p/day during drought. |
| DNA concept | P | R | L | L | Pu | The water zones in Pune city are further divided into 33 DNA: District Managed Areas (DMAs) that can be hydraulically isolated and for which water consumption can be monitored using water meters. |
| Environment | | | | | | |
| Nature-Based Solutions (NBSs) | P | R | L | W | Pr &Pr | Houangjoo (2018) encouraged to employ of sustainable approaches such as traditional and indigenous knowledge aka nature-based solutions (NBSs) and green infrastructure. |
| Protect Natural recharge zones that connect watersheds to Pune's aquifers must be protected | P | R | L | W | Pr &Pr | protection of groundwater recharge zones (especially the hilltops, hill-slopes that occupy nearly 2000 hectares in and around Pune city). |
| Green Infrastructure | P | R | L | W | Pr &Pr | incorporate blue-green infrastructure, to facilitate urban cooling, and alleviate increased water demand. |
| Wetlands | P | R | L | L & W | Pu | There is evidence that wetlands alone can remove 20 to 90% of metals in water and trap 80 to 90% of sediment from runoff. |
| Institutional | | | | | | |
| The Aquifer Mapping | P | A | L | L | Pu & Pr | Developing a participatory stakeholder database. |
| Groundwater Bill | P | A | L | L | Pr & Pr | The government specifies a decentralized structure for the governance of groundwater. |
| Urban-rural Partnerships | P | A | L | L | Pr & Pr | Citizen work with farmers to promote water conservation in agriculture, to supplement supplies for urban consumption. |
| Water Conservation Programmes | P | A | L | L & W | Pr & Pr | Provide incentives to reduce water consumption: Cash Transfer, fine audits and training programs, access to conservation techniques. |
Table 4. Criteria to explore local resources of water

| Sr. No. | Criteria                                      | Required Data in Geospatial Framework                                  |
|---------|-----------------------------------------------|-----------------------------------------------------------------------|
| 1       | Explore water-stressed zones                  | Geospatial map of Water Index: Water Zone-level performance on Water Supply Service |
| 2       | Watershed boundaries                          | Watershed boundaries layer                                             |
| 3       | Paved area less preferred                     | Landuse Land Cover                                                     |
| 4       | The presence of aquifers is most preferred    | Aquifers layer                                                         |
| 5       | Closed to Springs preferred                   | Springs layer                                                          |
| 6       | Presence of Wetlands                          | Wetlands layer                                                         |
| 7       | The presence of traditional step-wells is preferred | traditional water recharge structure layer                           |
| 8       | Presence of green spaces                      | Landuse Land Cover                                                     |
| 9       | Close to Waterbodies preferred                | Landuse Land Cover                                                     |
| 10      | Presence of biodiversity Park                 | Biodiversity Park                                                      |

Table 4. Traditional Step-wells in and around Pune City

| Sr.No. | Name                                      | Buffer (Km) | Distance (Km) |
|--------|-------------------------------------------|-------------|---------------|
| 1      | Bhaskum Stepwell                          | 5           | 1.70          |
| 2      | Malhargad Stepwell                        | 5-10        | 7.00          |
| 3      | Koteshwar Mahadev Temple Stepwell         | 5-10        | 7.30          |
| 4      | Sosori Stepwell 3                         | 5-10        | 8.10          |
| 5      | Sosori Stepwell 2                         | 5-10        | 8.20          |
| 6      | Sosori Stepwell 1                         | 5-10        | 8.30          |
| 7      | Bhagirathi Kund                           | 10-15       | 10.20         |
| 8      | Sardar Purandare Wada Stepwell            | 10-15       | 10.50         |
| 9      | Saswad Stepwell                           | 10-15       | 10.80         |
| 10     | Pimple Jagtap Stepwell                    | 10-15       | 11.10         |
| 11     | Pimple Jagtap Stepwell                    | 10-15       | 11.20         |
| 12     | Narayanpur Stepwell                       | 10-15       | 11.40         |
| 13     | Kumbharvalan Stepwell                     | 10-15       | 12.40         |
| 14     | Chakreshwar Mahadev Mandir Kund           | 10-15       | 13.60         |
| 15     | Shree Baneshwar Mahadev Mandir Stepwell    | 10-15       | 14.00         |
| 16     | Kadve Stepwell                            | 10-15       | 14.8          |
| 17     | Mhasoba Devasthan Stepwell                | 10-15       | 15.0          |
| 18     | Baneshwar Temple Stepwell                 | 15-20       | 15.4          |
| 19     | Baman Doh                                 | 15-20       | 15.6          |
| 20     | Ghamtichi Vihir                           | 15-20       | 15.6          |
| 21     | Kendur Stepwell                           | 15-20       | 16.8          |
| 22     | Ambale Village Stepwell                   | 15-20       | 17.3          |
| 23     | Davaleshwar Mandir Stepwell               | 15-20       | 17.7          |
| 24     | Ambale Stepwell                           | 15-20       | 17.8          |
| 25     | Ambale Stepwell                           | 15-20       | 17.9          |
| 26     | Shivri Stepwell                           | 15-20       | 18.0          |
| 27     | Takarawadi Stepwell                       | 15-20       | 19.8          |

Figures
Figure 1

Study area: Pune Municipal Corporation (PMC) Limit
Figure 2

Water Stressed zones based on low Water Index (i.e. below 0.39)
Figure 3

Traditional Step-wells (Groundwater Storage Structures) in and around Pune City Source: www.indianstepwells.com

Figure 4

Location of springs in and around Pune City
Figure 5

Recharge zones identified in each of the five aquifers in the city.
Figure 6

Watershed boundaries in Pune

Figure 7

Green spaces, hill-topes and hill-slopes, and Wetlands