Water Security: A Geospatial Framework for Urban Water Resilience

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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 wells 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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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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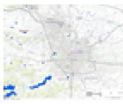
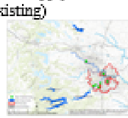
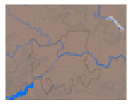
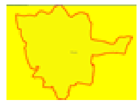
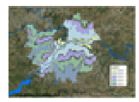
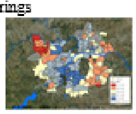
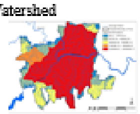
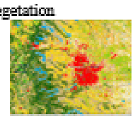
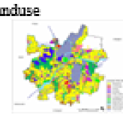
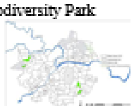
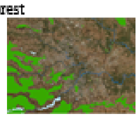
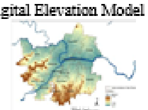
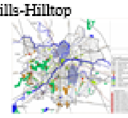
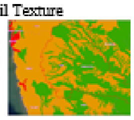
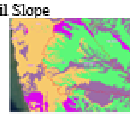
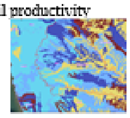
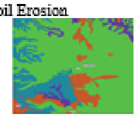
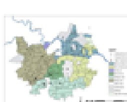
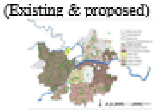
Tables

Table 1. Geospatial Framework: Package of thematic layers related to water resilience

Geospatial Thematic Layers				
Surface water bodies  The major rivers within the city limits include Mutha, Mula, and Mula-Mutha River. Lakes: Pashan Lake, Katraj Lake, and Snake Park Lake. Smaller rivers: Ramnadi and Devnadi.	Water supply sources (Existing)  Dams: Khadakwasla, Panshet, Warasgaon, Temghar, and BhamaAsakhed Ground Water: 399 dug wells, 4820 bore wells.	Geology  The city is underlain by basaltic lava flows of late cretaceous Palaeocene age associated with basic intrusive (Bhukosh GSI 2021).	Groundwater  The sources of groundwater in Pune city are dug wells, bore wells, and springs (India-WRIS 2021).	Aquifer  Pune city has five aquifers in increasing order of the elevations nearly 250 meters (Kulkarni H., and Bhagwat M. 2019).
Springs  Pune spring inventory (ACWADAM 2019) has yielded data on 35 springs out of which 24 are perennial springs and 11 are seasonal. The spring water is clear and likely to be potable.	Watershed  There are 30 small and large watersheds within Pune city. Each basin comprises a network of natural drains discharging stormwater into the Mutha and Mula Rivers.	Wetland  Restoring wetlands, rather than building a costly new water treatment plant.	Vegetation  Pune city witnessed a loss of about 18 sqkm of green spaces areas due to conversion into residential, information technology parks, or traffic use in the past 20 years.	Landuse  43% of the area is under the residential zone, 2% is under the commercial zone, 4% is under the industrial zone, and 16% is under public/semi-public and recreational use.
Biodiversity Park  PMC had reserved Bio-diversity Parks for restoring the local flora and fauna, producing carbon sinks, and creating awareness about nature conversation.	Forest  The total area under reserved, forest, and agriculture as per the land use distribution of Pune city is 2905 ha which is 11.91% of the total area.	Green spaces  Pune city has maintained 20 % green spaces out of which 8% towards recreational and 12% for reserved, forest, and agriculture.	Digital Elevation Model  There is an issue of inequitable water supply throughout the city as the city has undulating topography.	Hills-Hilltop  The total area covered under hills and hill slopes is 5.10%, which governs the city's micro-climate.
Soil Depth  Deep, moderately deep, slightly/moderately shallow (depth>50cm) Extremely shallow (< 10cm) Shallow (25-50cm) Very shallow (10-25 cm)	Soil Texture  Clay, loamy clay, sandy clay, silty clay, sandy clay Loam, silt loam, silt, sandy loam	Soil Slope  Nearly leveled (0-1%),very gently sloping (1-3%), gently sloping (3-8%), Moderately sloping (8-15%), Moderately steep sloping (15-30%), steeply sloping (>30%)	Soil productivity  Highly productive Low productive Moderately low productive Moderately productive Non-productive	Soil Erosion  Moderate, None to slight, slight Severe, Very severe, gullied
Water Supply areas (6)  The PMC service area is divided into 6 water supply areas i.e. Parvati, Pune Cantonment, Vadgaon, Warje, Holkar, and Bhama-Askhed.	Water Supply Zones (141)  PMC has a total of 141 water supply zones including 12 in Parvati, 25 in Pune Cantonment, 32 in Vadgaon, 34 in Warje, one in Holkar, and 37 in Bhama-Askhed.	District Metered Area (DMA) (328)  PMC has a total of 328 DMAs that can be hydraulically isolated to monitor water consumption using water meters.	Water Treatment plants (Existing & proposed)  Existing Water Treatment plants (WTPs): Nine. Proposed WTP: One WTP is under construction at Warje.	Service Reservoirs (Existing & proposed)  Existing service reservoirs (SRs): 58 Proposed service reservoirs:103

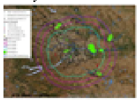
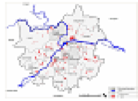
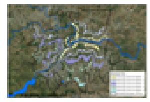
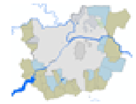
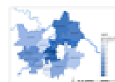
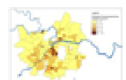
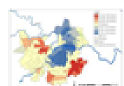
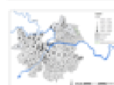
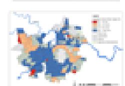
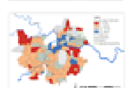
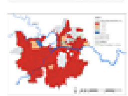
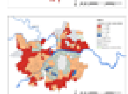
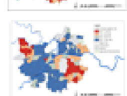
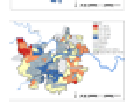
Pump Stations (Existing &Proposed)	Traditional Groundwater Storage Structures, (stepped wells)	Slum areas	Recharge areas for Pune's aquifer system	Administrative boundaries
				
Existing Pump Station:7 Proposed Pump Station: 3	There are 89 step-wells in and around Pune city	Nearly 40% of the Pune population lives in slums. Maximum houses have individual water connections; however, 25% of the households have only shared connections.	A comprehensive application of the practice of Managed Aquifer Recharge (MAR) must be designed for the city.	Pune city has been expanded from 7.74 sq km to a massive 516.18 sq km over the past 70 years.

Table 2. Geospatial Framework: Geospatial maps related to water resilience

Geospatial Maps		
Name	**Description**	**Geospatial Map**
Location map of Pune	Pune city is located in Pune District in the western region in Maharashtra state between 180 32' North latitude and 720 51' East longitudes. It is at an altitude of 560 m above mean sea level.	
Ward-wise per capita water supply (lpcd) and continuity of water (Hour).	Inequitable patterns of water supply across the city. Bhavani Peth and Kasba Vishram areas are getting 358 liters per capita per day (lpcd) and 260 lpcd, respectively, while Ghole Road and Dhankwadi areas are receiving only 139 lpcd and 138 lpcd, respectively.	
Population Density	The core city areas are highly populated ranging from 193 people/ha to 1706 person/ha and benefitted by better availability of water supply and adequate pressure compared to peripheral areas having population density ranging from 42 people/ha to 192 people/ha.	
Hotspot Analysis	Statistically Significant Clusters of High and Low values? Hot Spot (blue): Areas with a high quantity of water supply Cold Spot (red): Areas with a low quantity of water supply	
Spatial Distribution of GWR output parameters	GWR explains variation in water supply, well in the northwest area of the city where the local R^2 value is above 50% . Poor in the northeast and southern part of the city where local R^2 value is below 30%.	
Household-level coverage of direct water supply connections	average: 94.57%, minimum: 64.06% maximum: 100% The remaining 5.43% of households have to pay for privately supplied water to secure reliable access.	
Per capita supply of water	The per capita supply of water varies substantially. The average per capita supply of water in Pune city is found 124 lpcd with a minimum of 51.2 lpcd and a maximum of 366.2 lpcd.	
The extent of Metering Connection	Pune city has very few residential premises with a metering system. Out of 141 water supply zones, about 128 zones are having a percentage of metering connection below 4%, eight zones between 4 to 13%, four zones between 13% to 29%, and only one zone between 29% to 96%.	
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.	
Quality of water supplied	The average quality of water supplied is 91.74%, with a minimum of 55.8% 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 zones.	
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, 26% medium-performing, and 24% low-performing among the 141 water zones in Pune city for their water supply service.	

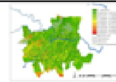
Slope	The raster surface of the percent slope was calculated, and its mean value was then summarized to the water zone level.	

Table 3. Geospatial Framework: The policies and strategies related to water resilience

Policies/ Strategies	Details	Intent (Autonomous/Planned)	Timing (Reactive/ Concurrent/Anticipatory)	Temporal Scope (Long Term/Short Term)	Spatial Scope (Localized/ Widespread)	Actor (Public/Private)	Remark
Social							
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 & Pri	In Imphal and similar places, community-controlled systems of neighborhood ponds already exist (Anthony 2007). Community-based water supply in Ghana (Akramov, K., and Asante F. 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 & Pri	PMC had started implementing a scheme of recycling 500 MLD treated sewage for irrigation. Augmentation of water supply to Northern areas of Pune from Bhama Askhed dam. Augmentation of Intake works at Khadakwasla dam, Jack well, pump station, and 2500mm diam. pumping main up to Parvati waterworks and 1626mm 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. Groundwater literacy campaigns to educate citizens on the concept of aquifers. Participatory Aquifer Mapping, including a recharge plan	P	C	L	W	Pu&Pr	Housing Societies where densities 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)	The public recharge systems must be based on the identified aquifers in the city. This strategy will include injection recharge at strategic locations.	P	A	L	W	Pu	Instead of a random approach to groundwater recharge, a comprehensive application of the practice of Managed Aquifer Recharge (MAR) must be designed for the city.
Economic							
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	PMC has made it mandatory for all housing schemes with more than 150 tenements to have sewage treatment plants (STPs) & reuse the treated sewage for flushing, gardening, etc. It is mandatory to implement rainwater harvesting in all the layout open spaces/amenity spaces of housing societies

							and new constructions/ reconstruction/ additions on plots having an area not less than 500 sq.m. (PMC 2014).
Encouragement of efficient water use and conservation	Conserve existing and local resources, decreases demand for freshwater in cities. Invest in 100 percent treatment of wastewater, which is more sustainable and affordable. 100 percent metering connection and charging as per consumption	P	C & A	L	W	Pu	Melbourne aimed to reduce water consumption to 155L/p/d ay during draught
DMA concept	District Metering Area (DMA) is the essential element required for monitoring and achieving equitable water pressures.	P	R	L	L	Pu	The water zones in Pune city are further divided into 328 District Metered Areas (DMAs) that can be hydraulically isolated and for which water consumption can be monitored using water meters.
			Environment				
Nature-Based Solutions (NBSs)	NBSs can play an important role in achieving Sustainable Development Goals (SDGs).	P	R	L	W	Pu &Pr	Houngbo (2018) encouraged to employ of sustainable approaches such as traditional and indigenous knowledge like nature-based solutions (NBSs) and green infrastructure.
Protect Natural Recharge Zones	Natural recharge zones that connect watersheds to Pune's aquifers must be protected	P	R	L	W	Pu &Pr	protection of groundwater recharge zones (especially the hilltops, hill-slopes that occupy nearly 2000 hectares in and around Pune city)
Green Infrastructure	Green infrastructure provides clean water, conserves ecosystem values and functions, and provides a wide array of benefits to people and wildlife. (EPA)	P	R	L	W	Pu &Pr	Incorporate blue-green infrastructure, to facilitate urban cooling, and mitigate increased water demand.
Wetlands	Wetlands play a large role in hydrology.	P	R	L	L & W	Pu	There is evidence that wetlands alone can remove 20 to 60% of metals in water and trap 80 to 90% of sediment from runoff.
			Institutional				
The Aquifer Mapping	Comprehensive mapping and registration of all groundwater sources	P	A	L	L	Pu & Pr	Developing a participatory stakeholder database
Groundwater Bill	The government specifies a decentralized structure for the governance of groundwater.	P	A	L	L	Pu & Pr	
Urban-rural Partnerships	Cities work with farmers to promote water conservation in agriculture, to supplement supplies for urban consumption	P	A	L	L	Pu & Pr	
Water Conservation Programmes	Provide incentives to reduce water consumption: Cash Transfer, free audits and training programs, access to conservation techniques	P	A	L	L & W	Pu & Pr	

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	Closed 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	Bhukum Stepwell	5	1.70
2	Malhargad Stepwell	5-10	7.00
3	Koteshwar Mahadev Temple Stepwell	5-10	7.30
4	Sonori Stepwell 3	5-10	8.10
5	Sonori Stepwell 2	5-10	8.20
6	Sonori 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	Ghumtichi 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

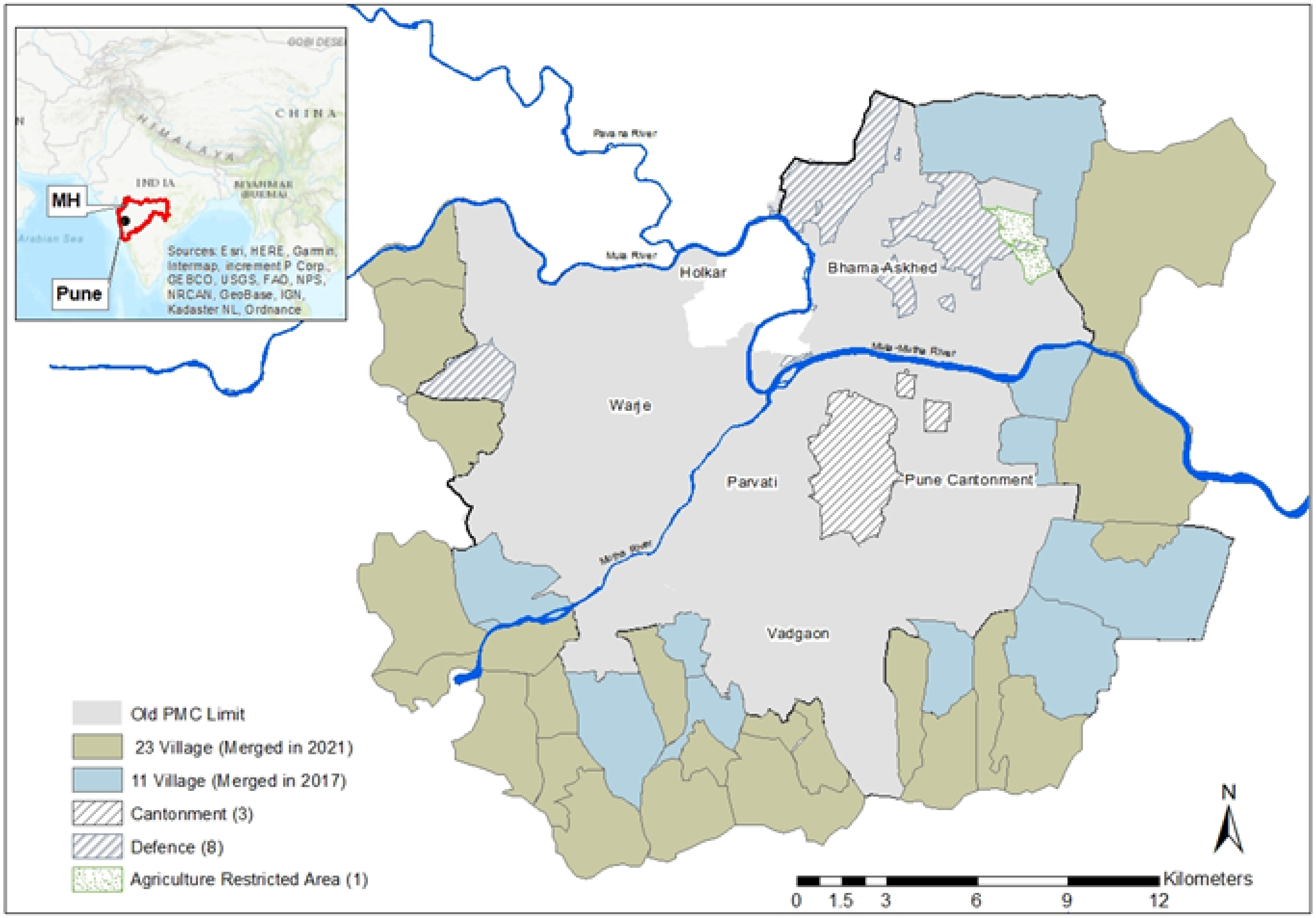


Figure 1

Study area: Pune Municipal Corporation (PMC) Limit

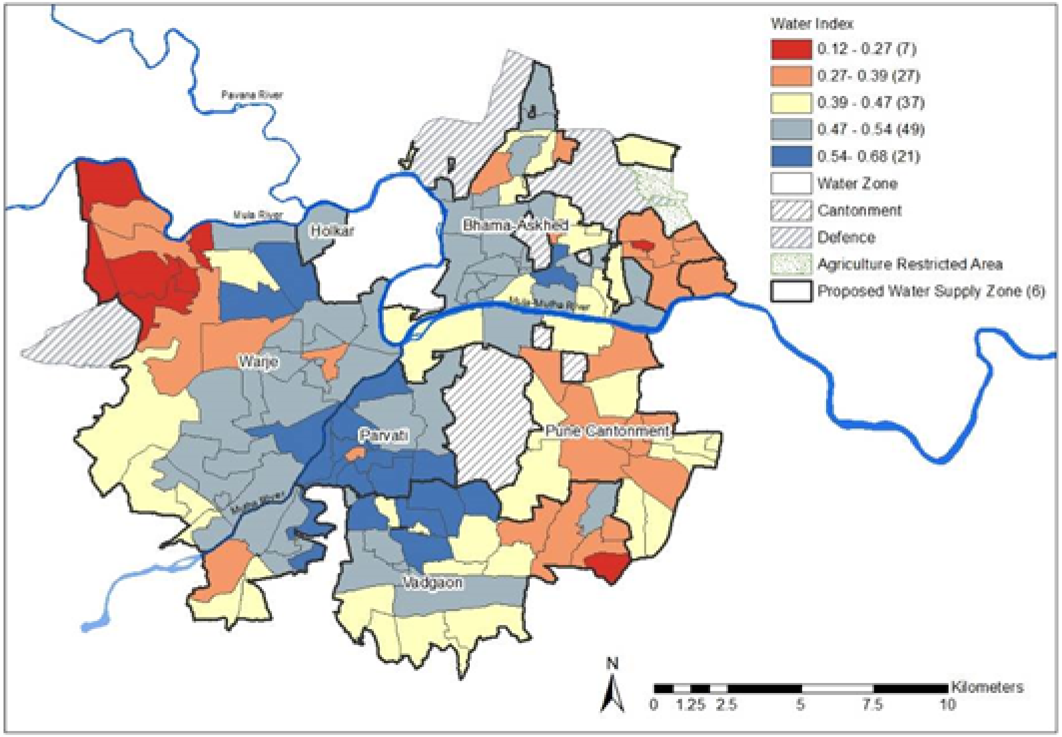


Figure 2

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

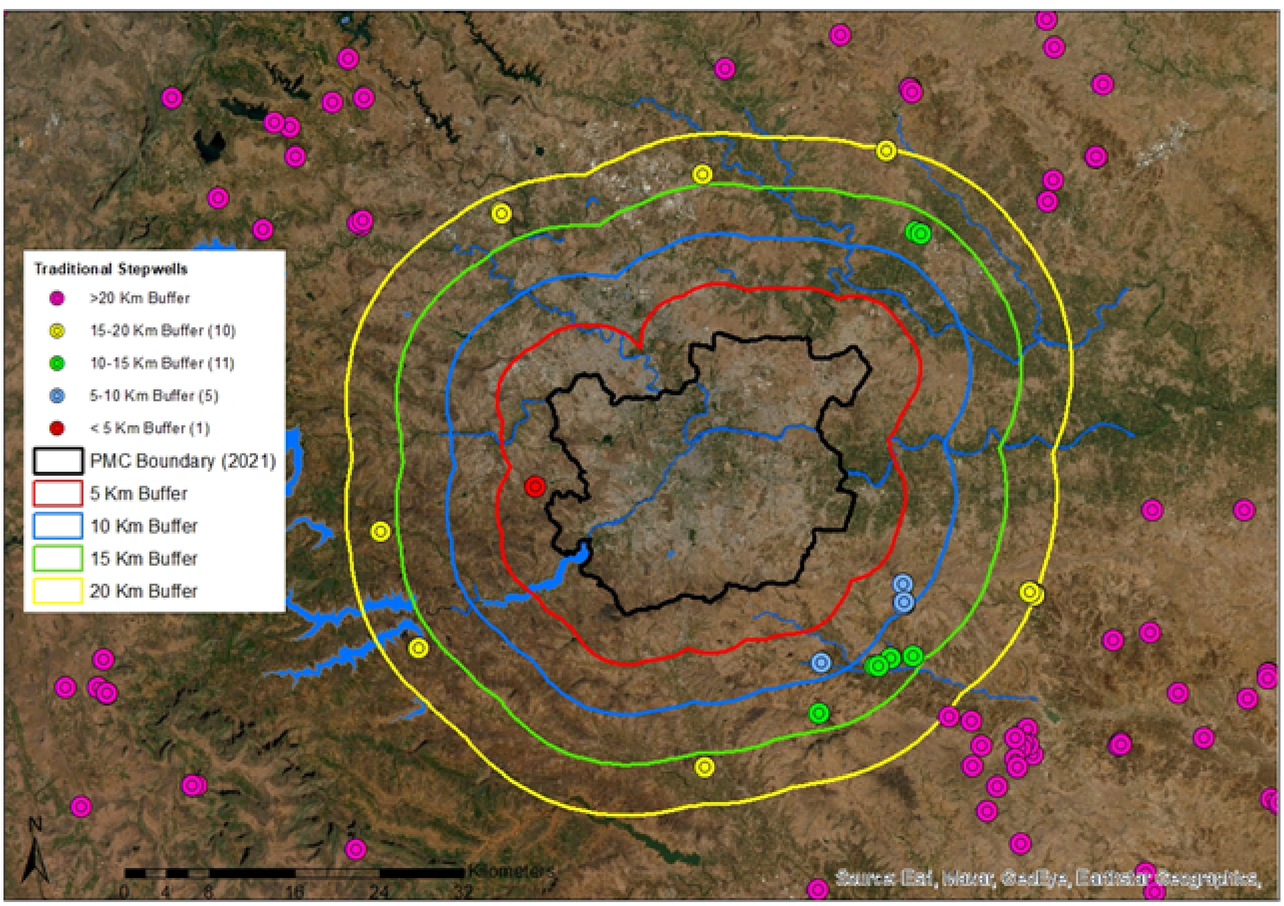


Figure 3

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

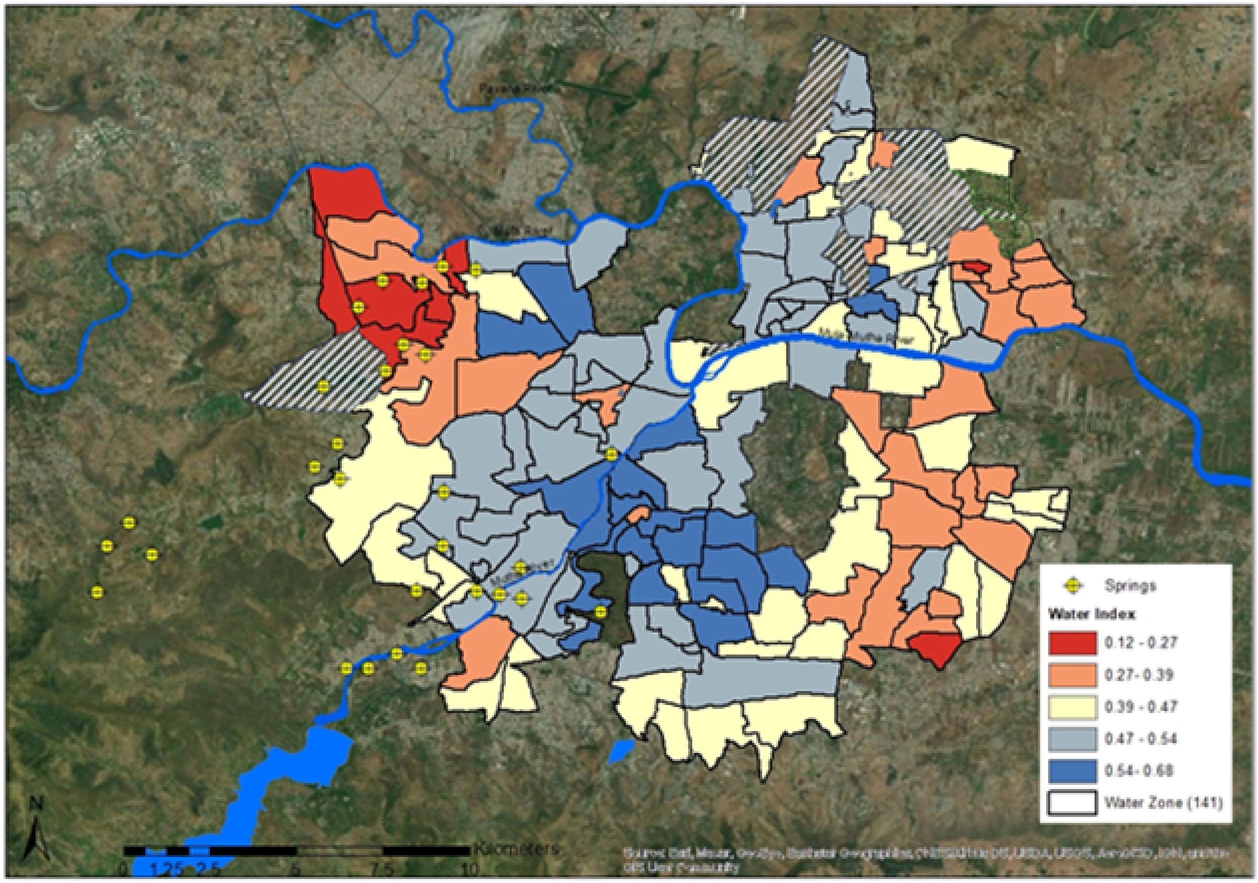


Figure 4

Location of springs in and around Pune City

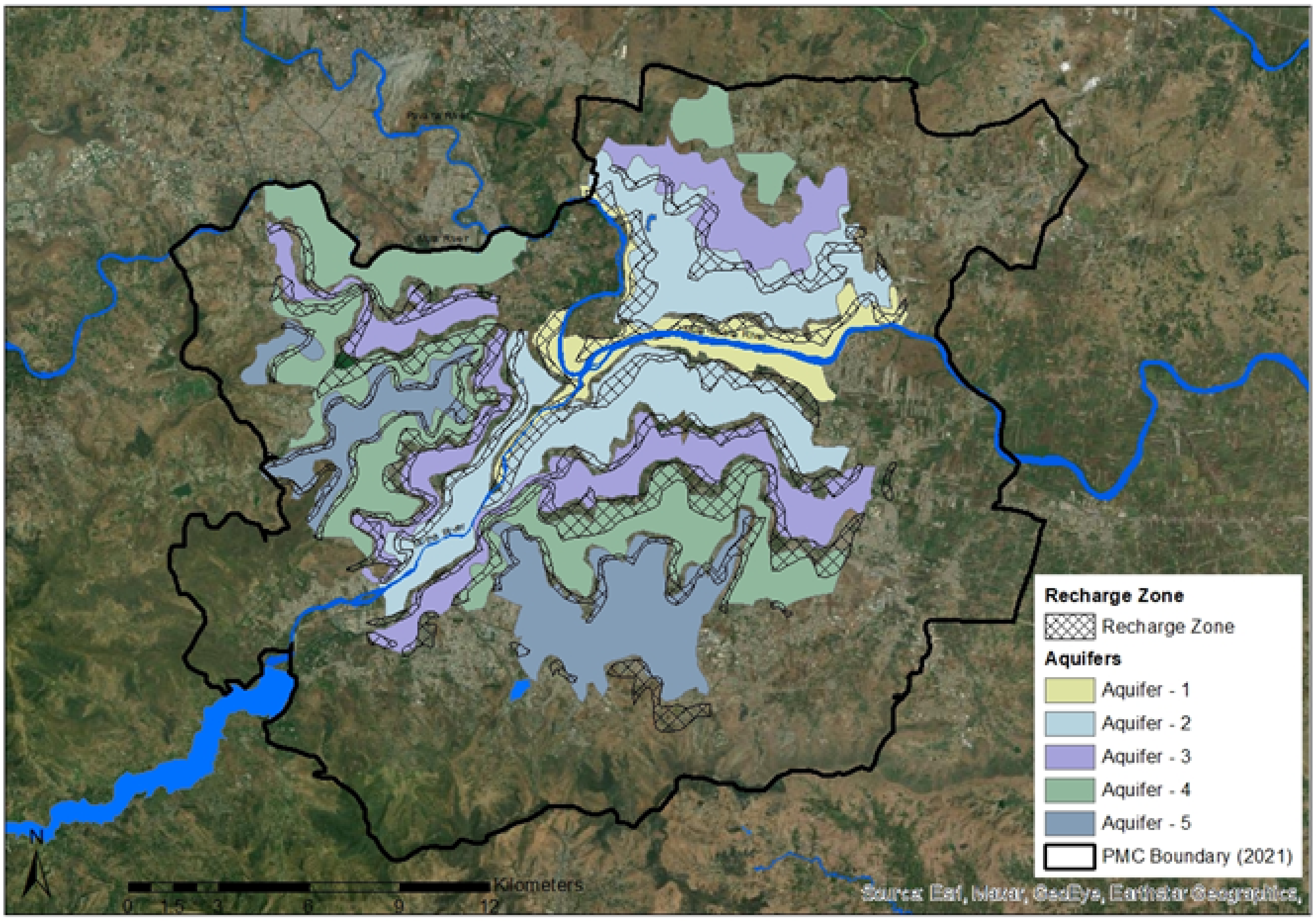


Figure 5

Recharge zones identified in each of the five aquifers in the city

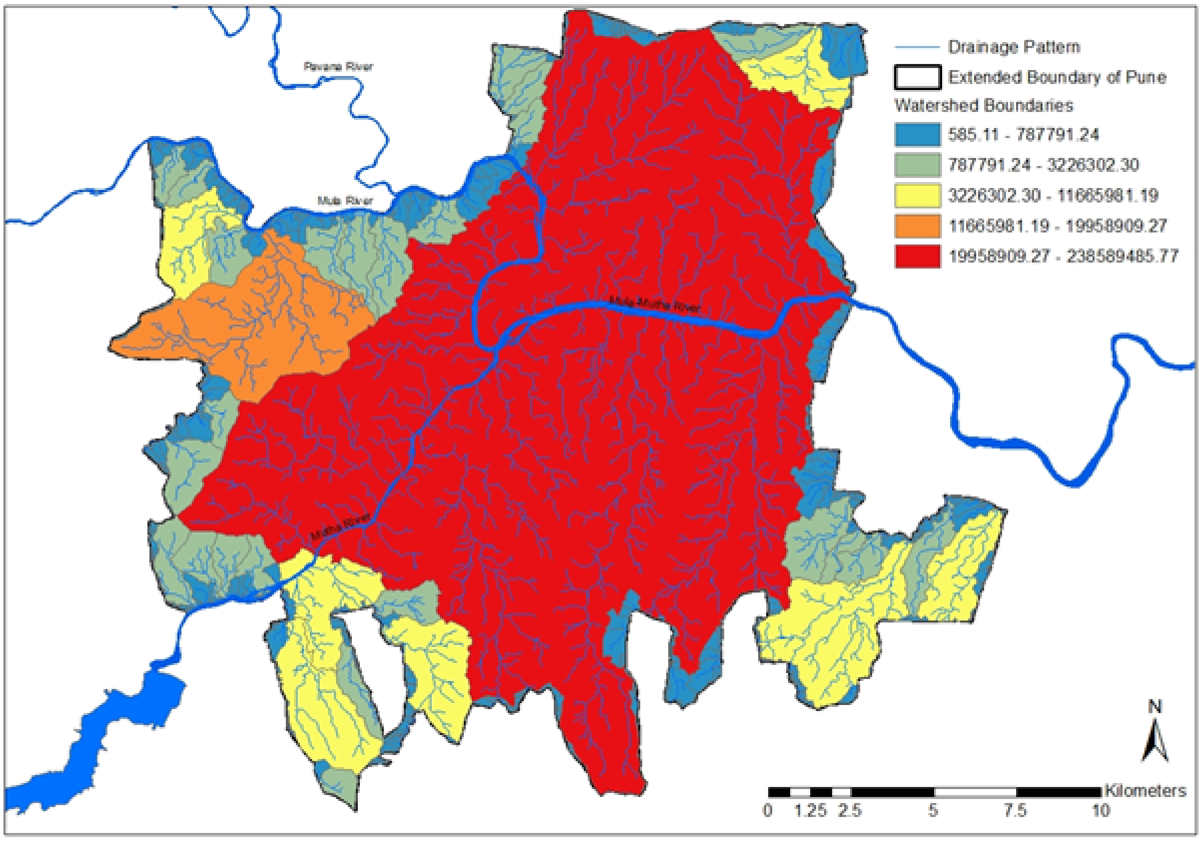


Figure 6

Watershed boundaries in Pune

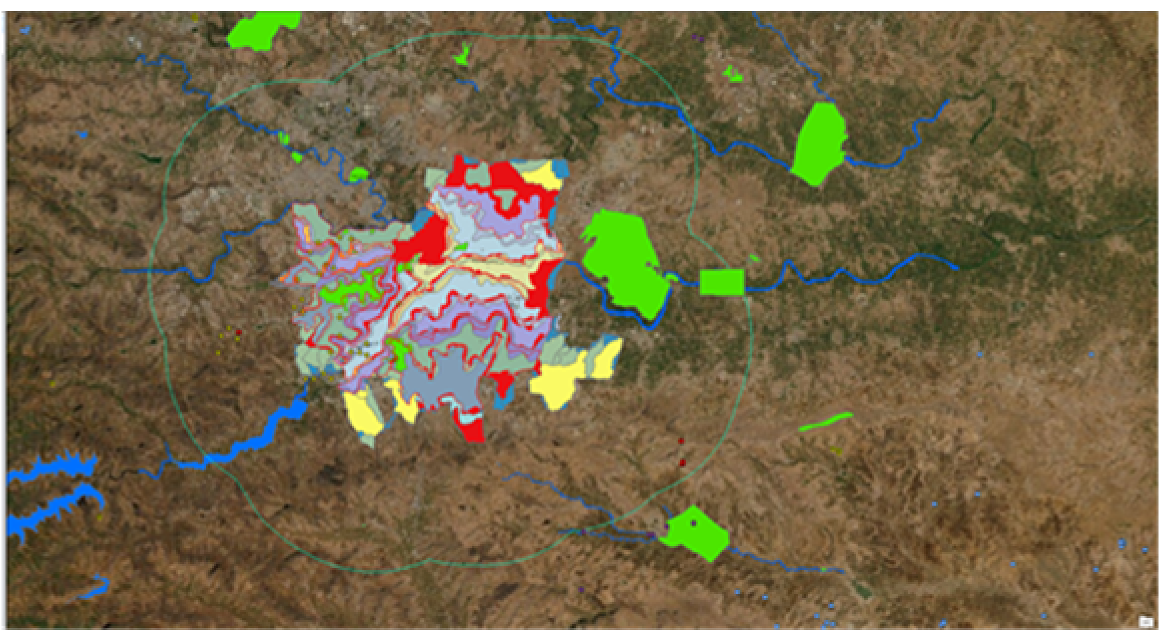


Figure 7

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