

Assessment of Operation and Maintenance Issues in the Rainwater Harvesting Systems of Residential Apartments Built in the Last Decade: A Case Study of Pune

Tanguturu Sai Mahidhar^{1,*}, Aditi Lanke²

Abstract

Despite abundant rainfall, Indian metropolitan centres, including Pune, face severe water crises due to inadequate stormwater management. In response, governmental bodies and sustainable rating frameworks have mandated the integration of rainwater harvesting (RWH) systems within the built environment. However, a significant policy-practice gap persists while RWH systems are frequently installed to meet regulatory compliance, they often fail to achieve their operational objectives due to severe maintenance and functional deficits. This study investigates these persistent performance gaps by analyzing RWH implementations in mid-rise residential apartments built in Pune over the last decade (2015–2025). Employing a rigorous mixed-methods approach, the research utilizes QGIS and Google Earth Pro for spatial mapping and temporal analysis to identify highly water-stressed urban zones. From this analysis, sixteen residential buildings were systematically shortlisted based on building height, construction timeline, geographic vulnerability, and RWH typology. Field surveys and empirical evaluations revealed a profound disconnect, noting that occupants largely lack an understanding of their mandatory RWH systems. To mitigate these challenges and revive operational effectiveness, the study conducted a technical review of commercially available RWH technologies in India, evaluating them for feasibility, cost implications, maintenance requirements, and scalability. Tailored, site-specific system recommendations were then formulated based on catchment potential, spatial constraints, and user demand profiles. Ultimately, this research concludes that the widespread failure of RWH systems in the residential sector stems not from technological inadequacies, but from a critical lack of context-sensitive architectural design, deficient governance, poor user awareness, and inadequate maintenance protocols. Addressing these systemic oversights is paramount for restoring operational efficiency and advancing true urban water resilience.

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INTRODUCTION

The demographic and environmental landscape of India presents a profound paradox: the nation currently accommodates approximately 18% of the entire global human population, yet it simultaneously possesses only a meager 4% of the world's available freshwater resources [1]. Consequently, as the country grapples with holding the highest population density—supporting 1.4 million people in intensely crowded zones—an

alarming estimated 600 million citizens are currently facing conditions of high water stress (Figure 1). This escalating crisis is predominantly driven by the deeply improper and fundamentally unsustainable management of the nation's natural water resources. Consequently, major Indian urban cities find themselves perpetually under the threat of severe water shortages, a reality that persists paradoxically even after these regions receive abundant and heavy annual monsoon rainfall [2].

Although the Indian subcontinent receives an astronomical volume of approximately 4000 billion cubic meters of rainfall annually, the widespread systemic water stress experienced across the country is fundamentally due to the highly inefficient capture, inadequate localized storage, and general mismanagement of the received stormwater runoff. Rapidly expanding urban economic centres, most notably Pune, Bengaluru, Chennai, and Mumbai, have become dangerously dependent on aggressive groundwater extraction. This unchecked extraction is desperately utilized to simply suffice the ever-widening gap between the daily civic water requirements of the populace and the frequently inadequate municipal water supply, a stopgap measure that is disastrously accelerating long-term aquifer depletion [3].

To systematically address this daunting environmental challenge, rainwater harvesting (RWH) has been strongly proposed, heavily promoted, and widely recognized as a highly cost-effective, decentralized, and environmentally sound strategy since the early 2000s [3]. Several Indian state governments, prominently including the state of Maharashtra, have taken the proactive legislative step to legally mandate RWH implementations through stringent regional development control regulations. However, even after the widespread enactment of these progressive legal provisions, multiple independent environmental audits and extensive ground-level field observations consistently indicate a troubling reality: many legally installed systems are either abysmally maintained or entirely non-functional, thereby drastically reducing their intended ecological and infrastructural impact, forcing societies to rely heavily on private tankers (Figure 2) [4].

While the existing body of academic literature extensively discusses, debates, and talks about the initial design phases, technological variations, administrative frameworks, and overarching governmental policies surrounding RWH, only a severely limited fraction of contemporary research critically focuses on the vital post-installation operational performance of these systems within actual residential buildings (Figure 3). This research aims to purposefully address this glaring academic and

Pune: Rainwater harvesting falls into disuse, tankers fill in

Nisha Nambiar / TNN / Updated: May 16, 2022, 05:15 IST

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After a flutter of enthusiasm among hundreds of societies across the city to save and reuse rainwater in the last two decades, the initiative has nosedived as members are unaware of how to use the installed systems.



Rainwater harvesting system at Windsor Avenue building in Wanowrie. The system helped society become tanker-free

PUNE: After a flutter of enthusiasm among hundreds of societies across the city to save and reuse rainwater in the last two decades, the initiative has nosedived as members are unaware of how to use the installed systems. The Pune Municipal Corporation made rainwater harvesting mandatory for new buildings for building permissions and developers have showcased these provisions in all their upcoming projects.

Figure 1. A news article in The Times of India dated 16th May 2022 [3].

Why Pune is clueless about rainwater harvesting

Prasad Kulkarni / TNN / Jun 14, 2023, 12:20 IST

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On average, Pune Municipal Corporation hands out 4,000 building permissions every year. The list includes redevelopment projects as well.



<p>Rainwater harvesting diverts rain into pits that recharge groundwater. Currently, only 5-8% of an estimated 10 lakh...

On average, Pune Municipal Corporation hands out 4,000 building permissions every year. The list includes redevelopment projects as well.

The civic body even offers a discount on property tax for structures with rainwater harvesting (RWH) systems. Yet, it still doesn't have a single empanelled expert citizens can consult with, to get these systems installed.

This lapse has derailed PMC's push to have more rainwater harvesting in the city. The civic body is supposed to verify the RWH units before granting

building permissions. But since it doesn't have any experts it can summon, the verification process has turned into something of a formality — permissions are being given based on just a physical inspection of the pipes and pits.

Figure 2. A news article in The Times of India dated 14th June 2023 [4].

practical gap by rigorously examining the specific operational and maintenance challenges that plague RWH systems embedded within mid-rise residential apartments in the rapidly growing city of Pune, specifically focusing on developments that have been constructed and occupied within the last decade [5].

LITERATURE REVIEW

Urban Water Scarcity and Groundwater Depletion in Pune

The municipal water supply architecture of Pune city is primarily and precariously dependent on massive surface water reservoirs, most notably the Khadakwasla dam, which is further strategically supported by a network of upstream dam structures [6]. (Figure 4) However, the city rapid, often unchecked urban expansion—particularly sprawling into the ecologically sensitive peri-urban fringe areas—has dramatically increased the civic reliance on subterranean groundwater extraction through the widespread boring of deep borewells and traditional dug wells [6–28]. Detailed hydrological studies and extensive longitudinal data collection conducted by the Central Ground Water Board (CGWB) explicitly mention a troubling and steady decline in regional groundwater levels over the years, with post-2021 geological data specifically highlighting a sharply accelerated rate of aquifer depletion [7].

Historical spatial mapping of the pre-monsoon depth to water level within the Pune district, specifically dating to May 2011, indicated heavily fluctuating water tables across the topography (Figure 5), generally ranging between 5 and 10 meters in depth strictly within the Pune city limits. Furthermore, a longitudinal analysis tracking the pre-monsoon water level trend across the Pune district from May 2002 to May 2011 highlighted localized pockets of marginal rises interspersed with broader regional falls in the subterranean water table [8]. More recently, highly detailed tracking of the average yearly groundwater levels spanning from 2015 to 2023 clearly reveals that the annual groundwater level pattern closely resembles a continuous sine wave. Under this pattern, up until the year 2021, the measured groundwater levels generally managed to stabilize in a shallow range of 2 to 4 meters; however, marking a stark and concerning environmental shift, the data conclusively show that from the year 2022 onwards, the underlying water levels have consistently and rapidly fallen, signaling severe aquifer distress [9].

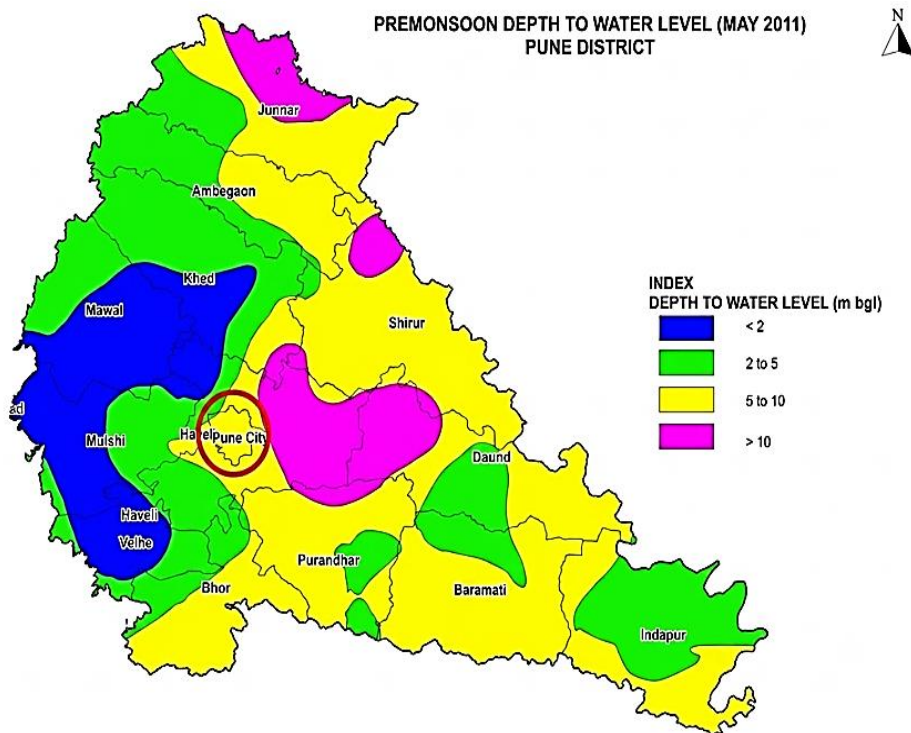


Figure 3. Pre-monsoon depth to water level of Pune district, May 2011.

Source: CGWB.

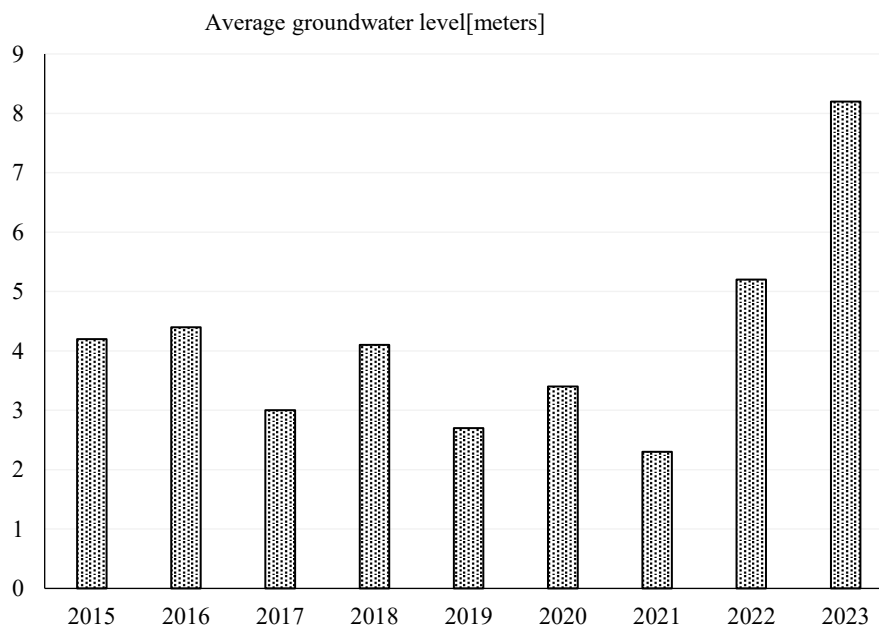


Figure 4. Average yearly groundwater level from 2015 to 2023.

Source: CGWB, WRIS.

RWH Systems and Design Considerations

RWH systems are broadly classified into rooftop and non-rooftop systems, with storage and recharge as the two principal modes of utilization. Effective performance depends on factors such as rainfall intensity, catchment characteristics, runoff coefficients, soil permeability, aquifer depth, and filtration mechanisms. Inadequate attention to these parameters often results in system inefficiency or failure [10].

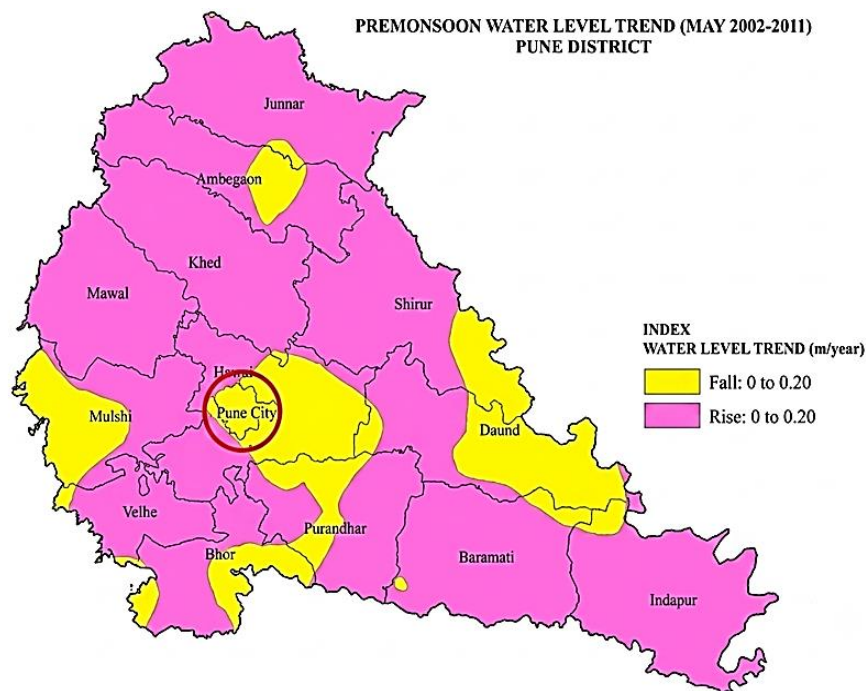


Figure 5. Pre-monsoon water level trend of Pune district, May 2002–2011.
 Source: CGWB.

Regulatory Frameworks and Comparative Analysis

Within the state of Maharashtra, the implementation of RWH infrastructure is strictly mandated through localized development control regulations. Under the Unified Development Control and Promotion Regulations (UDCPR) 2020 guidelines, all layout open spaces, housing societies, and new constructions on plots measuring 500 sq.m. or more must have one or more RWH structures [8]. These governmental mandates are structurally reinforced by voluntary sustainable building rating systems and regional frameworks, such as the MPPCB [18], although a clear divergence in evaluation methodology exists among these frameworks [11].

- *IGBC (Indian Green Building Council)*: Treats RWH as a basic prerequisite for certification, focusing predominantly on the physical provision and installation of the system with flexibility in choosing recharge or storage methods based on-site conditions [12].
- *GRIHA (Green Rating for Integrated Habitat Assessment)*: Follows a stricter, performance-based approach, rigorously mandating that at least 50% of the total site runoff must be actively harvested or recharged into the ground [13].
- *GEM (Green and Eco-friendly Movement)*: Emphasizes performance-based criteria while specifically prioritizing decentralized, low-cost recharge solutions that respond directly to local hydrogeological realities [14].

Case Studies

Lunkhad Greenland, Viman Nagar, Pune

Lunkhad Greenland-2 in Viman Nagar is widely cited in the urban water management literature as one of Pune's earliest and most prominent residential rainwater harvesting (RWH) case studies. Installed in 2003, it serves as a classic benchmark for both the high operational rewards and site-specific technical limitations of urban ground-recharge systems [15].

Mahindra Antheia, Pimpri-Chinchwad Municipal Corporation, Pune

Mahindra Antheia (CTS 6017, Nehru Nagar Road, Pimpri) is a major residential township spread over 24.34 acres with fifteen high-rise towers. It serves as an exemplary case study of large-scale integrated RWH and water conservation in the PCMC industrial belt. It is a successful case study that adopted a dual non-potable water system by linking rainwater harvesting for aquifer recharge with on-

site Sewage Treatment Plant (STP) recycling for flushing/gardening; the society creates a semi-closed urban water cycle [16].

Nisarg Society, Bavdhan, Pune

Located in western Pune along the hilly terrain of Bavdhan, Nisarg Society (developed by Aditya Shagun Developers) serves as an illustrative case study of unplanned internal infrastructure and stormwater/RWH management failure in plotted and gated developments.

Palladium Grand, Dhanori, Pune

Palladium Grand (developed by Raojee Constructions/Shreyas Shelters) in Dhanori, Pune, serves as a critical case study of approval-stage regulatory compliance versus operational reality in mid-scale urban residential complexes [17].

Located in Pune's northeast corridor—an area heavily reliant on groundwater and private water tankers—the society exemplifies how structural operational failures and lack of initial infrastructure impact long-term water sustainability.

Why Mid-Rise Apartments?

The specific focus on mid-rise developments is driven by compelling regional data. The broader construction and real estate industry within the sprawling city of Pune is widely observed to be booming, a fact clearly substantiated by recent municipal statistics detailing localized property registrations. On a statistical average, an immense volume of 16,511 distinct property registrations occurs every month within the region [18]. Crucially, out of this massive monthly volume, a dominant 60% are specifically categorized as residential buildings. Furthermore, detailed tracking from 2016 to 2021, derived strictly from official Pune Municipal Corporation (PMC) records, explicitly states that a mere eight high-rise residential apartments successfully secured official construction approval. This dramatic statistical disparity heavily proves and states that there are vastly more mid-rise apartments currently defining the architectural fabric and urban density of the city of Pune, thus making them the most critical target demographic for infrastructural water studies (Figure 6) [19].

Methodology

This study adopted a mixed-method research approach, integrating geospatial analysis, field investigations, technical assessment, and qualitative stakeholder interviews. This research enabled a comprehensive evaluation of the operational status, maintenance practices, and effectiveness of RWH systems in residential apartment complexes.

Spatial analysis was undertaken using QGIS integrated with groundwater data, ward-wise water supply records, and Pune Municipal Corporation Development Plan maps [12–15]. Based on hotspot analysis (Figure 7), Ambegaon Pathar and Dhankawadi emerged as the most suitable study locations because they exhibit increasing groundwater stress while simultaneously experiencing rapid residential development [20]. Sampling was adopted to identify representative apartment buildings.

Selection criteria included:

- Construction between 2015–2025
- Mid-rise apartments (G+5 to G+12)
- Residential occupancy
- Presence or declaration of RWH systems
- Location within identified water-stressed zones

Using these criteria, 16 apartment complexes were selected for detailed investigation, representing different site sizes, occupancy levels, sources of water supply, and RWH configurations, enabling comparative assessment (Figure 8). A field survey and a detailed inspection of each RWH system were undertaken to document various components of the harvesting system, and structured questionnaires

were administered to residents, society committee members, and maintenance personnel. Semi-Structured Interviews with facility managers and maintenance staff provided qualitative information.

Secondary information was obtained to verify compliance and compare field observations with approved documentation and field investigations, and commercially available RWH technologies in India were evaluated (Figure 9). Suitable technologies were recommended for each apartment based on the roof catchment area, annual rainwater potential, available space, and expected demand [21].

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Pune records 13,253 property registrations in August 2025: Report



1. Rent House in Chennai
2. House for sale in Bangalore
3. Rent House in Bangalore
4. Rent Flats in Bangalore
5. Rent Flats in Pune
6. Rent House in Coimbatore
7. Rent House in Hyderabad
8. House for sale in Hyderabad
9. Flats in Hyderabad
10. Rent Flats in Hyderabad
11. Rent Flats in Mumbai

Figure 6. News article on property registration.

Pune Records 14,421 Property Registrations In April 2025

By : Timesproperty@timesofindia.com

Date: 16 May, 2025

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Figure 7. An article published in housing.com regarding April 2025's property registration.

Spatial Analysis

Identification of water-stressed zones in Pune was based on groundwater data and ward-wise water supply information. This data was cross-checked with development plans created by the PMC, and Ambegaon Pathar and Dhankawadi were selected due to high groundwater dependence and rapid development.

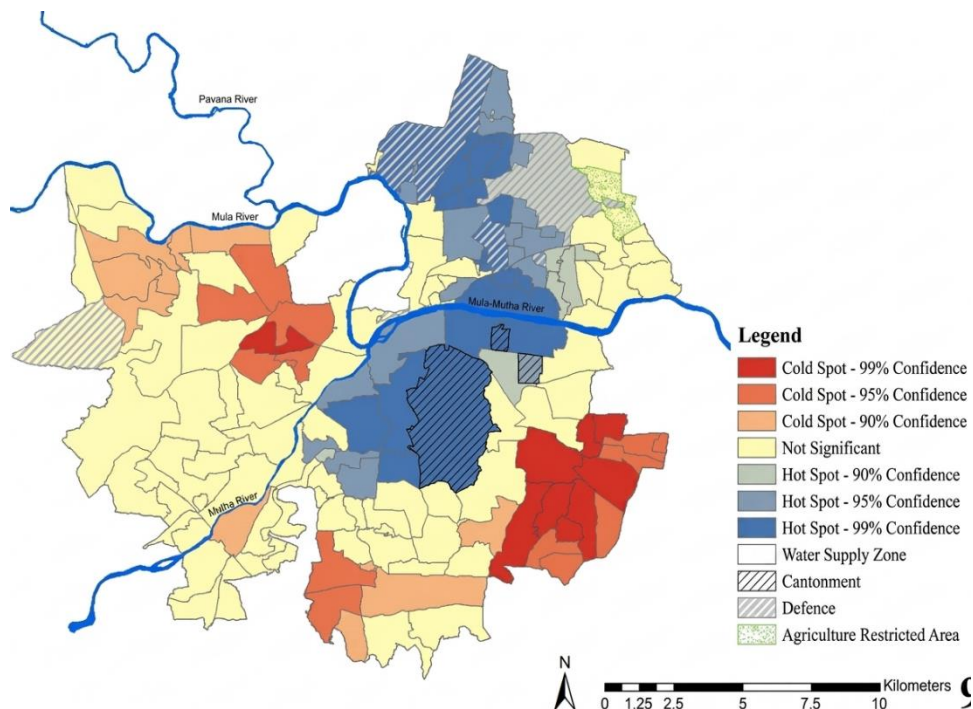


Figure 8. Hot spot and cold spot analysis: areas with a high quantity of water supply are shown in blue (hot spots), and areas getting a very low quantity of water are shown in red (cold spots) [12].

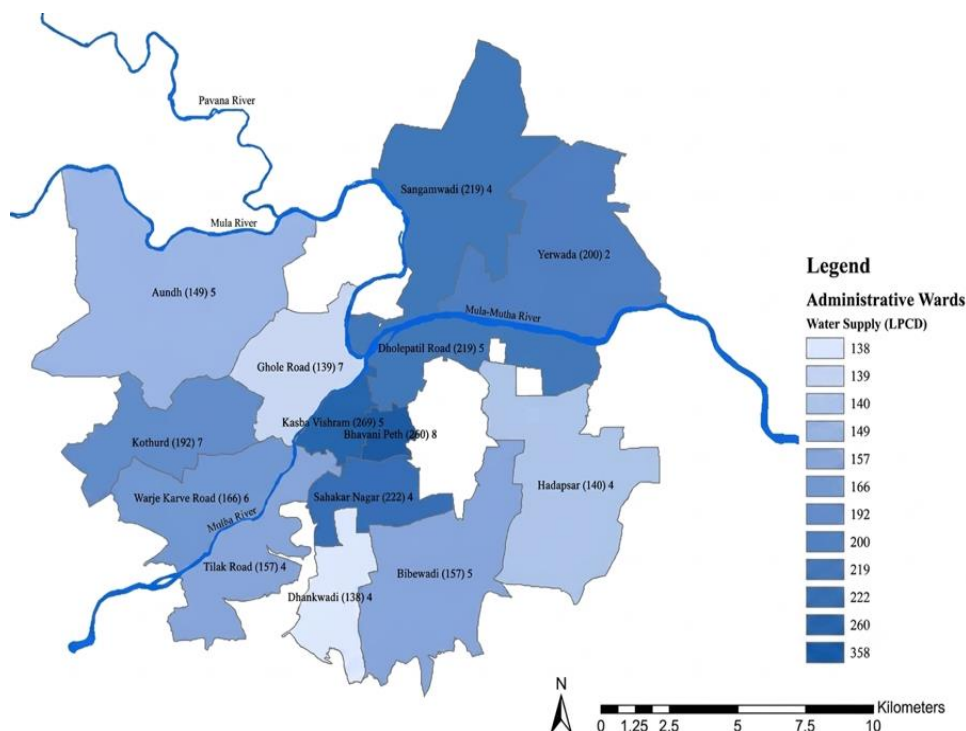
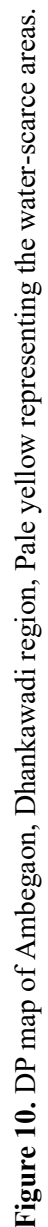


Figure 9. Ward-wise per capita water supply (LPCD) [12].



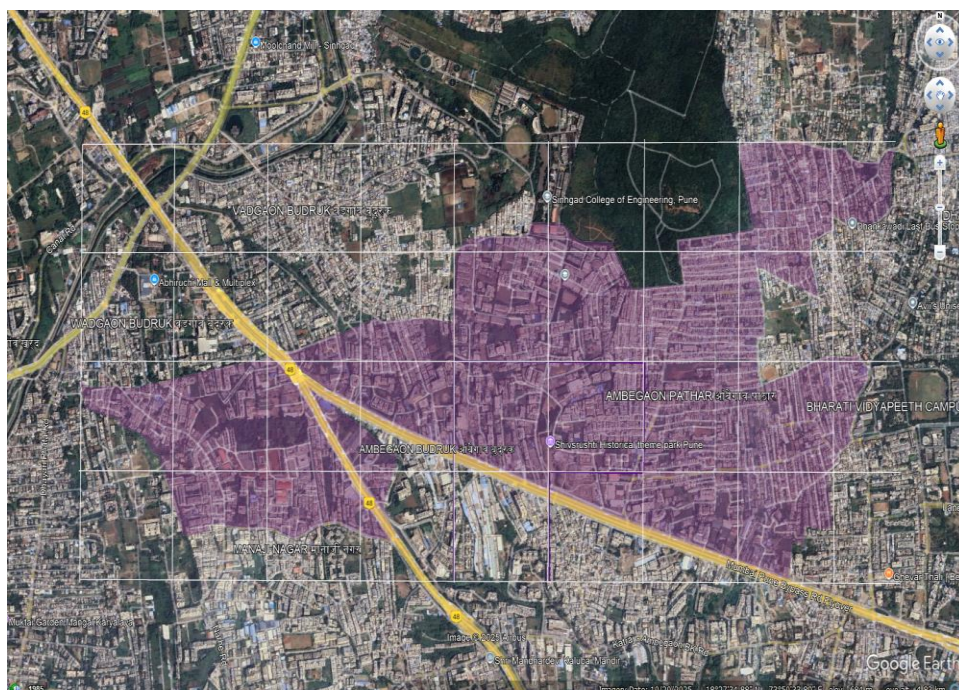


Figure 11. Overlay of Ambegaon Pathar Ward on Google Earth Pro, where the map is divided into a 500×500 m grid for temporal analysis.

Temporal Mapping

To isolate developments matching the required age profile, a highly systematic 500×500 m geographic grid-based temporal analysis, specifically covering the exact construction decade of 2015–2025, was rigorously conducted [22]. This advanced spatial tracking was executed using a combination of QGIS software and high-resolution historical satellite imagery via Google Earth Pro (Figure 10). This method allowed researchers to visually isolate and identify all newly constructed mid-rise buildings that were demonstrably constructed in this specific, recent timeline by directly overlaying the Ambegaon Pathar Ward boundary onto the segmented satellite grid.

Sample Selection

Ambegaon Pathar and the neighboring parts of Dhankawadi were selected as the primary study areas due to their high dependence on groundwater, rapid construction activity, and reported water stress. (Figure 11) To isolate developments matching the required age profile, a systematic $500 \text{ m} \times 500 \text{ m}$ geographic grid-based temporal analysis was conducted covering the construction decade of 2015–2025. (Table 1) Using a combination of QGIS software and high-resolution historical satellite imagery via Google Earth Pro, all newly constructed mid-rise buildings in the specific timeline were visually isolated [23]. From this mapping, exactly sixteen distinct apartment buildings, ranging from G+5 to G+12 floors, were meticulously shortlisted based on their construction period, building height classification, and geographic location within the identified water-stressed zones.

Primary Data Collection

The on-site data collection phase was highly rigorous. Carefully structured questionnaires, deeply detailed site engineering observations, and in-depth personal interviews were simultaneously conducted to fully assess the implemented system type, ongoing routine maintenance practices (Figure 12), historical financial maintenance costs, current user awareness levels, and ultimate hydrological performance. Furthermore, regulatory compliance claimed regarding the systems was strictly cross-verified utilizing official document submissions logged with the state regulatory body, MahaRERA [24].

Table 1. Table summarizing the interview with the occupants of apartments.

Occupant issue	Cause and impact
Financial Burden	High operation and maintenance (O&M) costs cause irregular upkeep [26].
Filter Clogging	Monsoon silt causes system failure.
Efficiency Loss	Deferred desilting reduces performance.
Off-Site Loss	Poor geology redirects water (<i>Apt 01</i>).

Survey on Rain water harvesting, a research work by Ar. T. Sai Mahidhar; M. Arch, Second year.

1. Name of the apartment/ अपार्टमेंटचे नाव: Niraman Arua
2. Location/ Address/स्थान/पत्ता: Ambegaon, Budruk
3. No. of flats/ फ्लॅट्सची संख्या: 325 (A + B)
4. Site Area/ साईट: 2.75 Acres.
5. Underground water tank size/ भूमिगत पाण्याच्या टाकीचा आकार: 7' x 7' x 10'
6. Overhead water tank size/ ओव्हरहेड पाण्याच्या टाकीचा आकार: → Drinking - 30k Domestic - 10k
7. Rain water harvesting/ पावसाचे पाणी साठवणे: Yes/होय ☒ No/नाही ☐ Don't know/माहित नाही ☐
8. Do you know the purpose of RWH/ तुम्हाला RWH चा उद्देश माहित आहे का? Yes/होय ☒ No/नाही ☐
9. Water purchased from tankers every month/ annually, दरमहा/वर्षाला टँकरमधून खरेदी केलेले पाणी:
10. Tanker size/ टँकरचा आकार: 12 - 13 tankers (10k lits)
11. Capacity of RWH tank/ पावसाचे पाण्याच्या टाकीचा आकार: 7' x 7' x 10'
12. Reasons for defunction of Rain Water Harvesting/ रेन वॉटर हार्वेस्टिंगच्या विघाडाची कारणे:
 - Maintenance Costs/ देखभाल खर्च, ☐
 - RWH is not recharging the bore well or open well/ पावसाचे पाणी बोअरवेलमध्ये राहत नाही ☐
 - Financial problem/ आर्थिक समस्या, ☐
 - Energy consumption/ ऊर्जा वापर ☐
 - Quality of rain water/ पावसाच्या पाण्याची गुणवत्ता ☐
 - High ground water level/ भूजल पातळी जास्त, ☐
 - Installation of wrong system/ चुकीची प्रणाली बसवणे, ☐
 - Not aware of how to operate/ कसे काम करायचे हे माहित नाही ☐
 - Mistake in the proper sizing of the tank/ टाकीच्या योग्य आकारात चूक, ☐
 - Quantity/ प्रमाण जास्त, व्यवस्थापित करणे कठीण ☐
1. Willingness to reuse or adapt RWH/ RWH चा पुनर्वापर किंवा अनुकूलन करण्याची इच्छा
 - No GW
 - Recharge .

Figure 12. In-field survey questionnaire.

RESULTS AND DISCUSSIONS

Status of RWH Systems

Although RWH systems were approved for most buildings, only eight out of sixteen buildings had operational systems (Figure 13). All functioning systems relied exclusively on recharge-based methods, primarily due to space constraints and perceived maintenance challenges associated with storage systems (Table 2).

Key Findings

Although most buildings declared RWH systems during statutory approval, field investigations revealed that only eight of the sixteen buildings possessed operational systems.

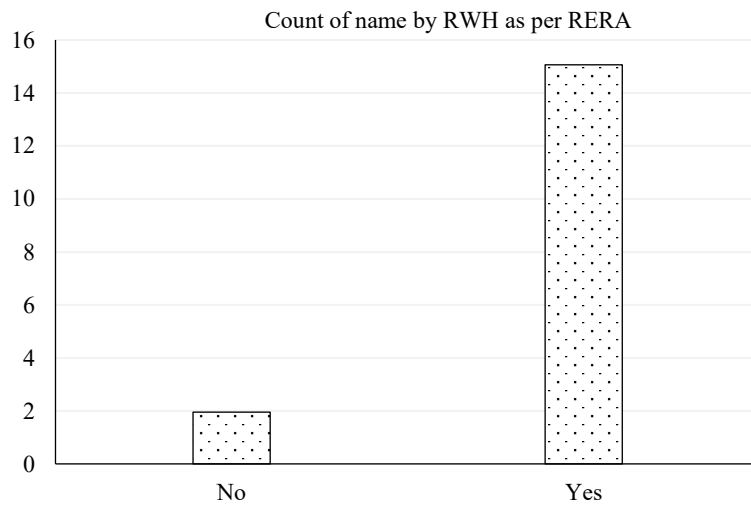


Figure 13. Graph explaining the number of rainwater harvesting systems installed in the selected study areas as per MahaRERA.

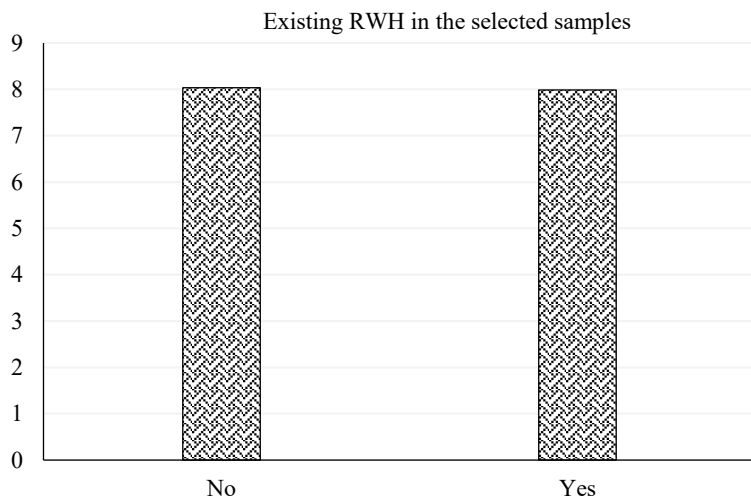


Figure 14. Graph explaining the number of rainwater harvesting systems installed in the selected study areas as per the in-field survey.

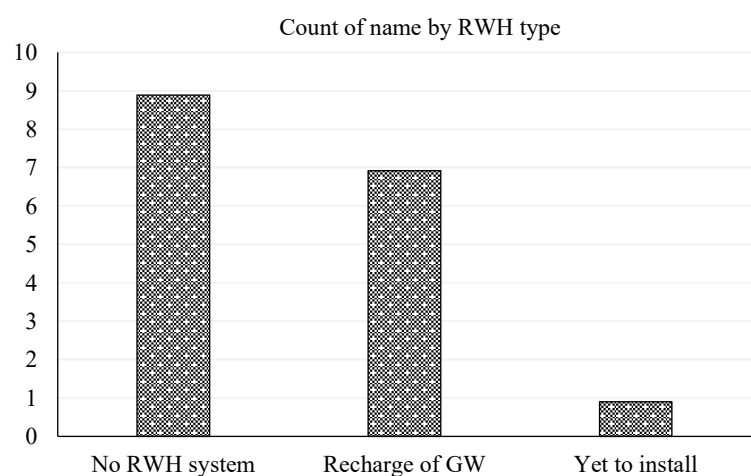


Figure 10. Graph explaining the type of rainwater harvesting system installed in the selected samples of the study.

Table 2. Collection of data post the field survey.

Name	Location	Site area (Sq.mt.)	Built-up area (Sq.mt.)	No. of floors	No. of tenements	Sources of water supply	Possession date	RWH as per RERA	RWH	RWH type	Catchment area(sq.mt.)
Apartment 01	Ambegaon	11100	30166.03	G+11	308	Corporation, tanker	2024	Yes	Yes	Recharge	1184
Apartment 02	Ambegaon	350	8634.88	G+8	40	Corporation, tanker	2023	Yes	Yes	None	200
Apartment 03	Ambegaon	15000		G+11	92	Borewell	2020	Yes	Yes	Recharge	800
Apartment 04	Ambegaon	2264.96	4738.21	G+11	62	Corporation, borewell, tanker	2023	Yes	Yet to install	None	431
Apartment 05	Ambegaon	2100	4672.76	G+6	42	Corporation and borewell	2024	Yes	Yes	Recharge	864
Apartment 06	Ambegaon	2856.3	3378.96	G+11	174	Corporation and borewell	2019	Yes	No	None	307
Apartment 07	Ambegaon	8676.38	8185.31	G+9	72	Corporation, tanker	2019	No	No	None	1750
Apartment 08	Ambegaon	2300	10828.4	G+10	138	Corporation, tanker	2025	Yes	Yes	Recharge	937
Apartment 09	Ambegaon	1150	2895.5	G+6	48	Corporation, tanker	2022	Yes	No	None	458
Apartment 10	Ambegaon	2100	2832	G+7	56	Corporation and borewell	2023	Yes	No	None	567
Apartment 11	Ambegaon	14600	4236.18	G+11	65	Borewell, tankers	2016	Yes	No	None	560
Apartment 12	Ambegaon	1019.47	1835.03	G+7	34	Corporation, tanker	2022	Yes	No	None	262
Apartment 13	Ambegaon	2865	17167.29	G+12	120	Corporation and borewell	2023		No	None	1431
Apartment 14	Dhankawadi	970	1368.52	G+7	6	Corporation and borewell	2022	Yes	Yes	Recharge	196
Apartment 15	Dhankawadi	500	1600	G+5	12	Corporation and borewell	2025	Yes	Yes	Recharge	320
Apartment 16	Dhankawadi	500	2400	G+8	15	Corporation and borewell	2025	Yes	Yes	Recharge	300

This indicates a 50% functional efficiency, highlighting a substantial gap between regulatory compliance and actual implementation.

Several systems existed only on paper, while others had become non-functional because of neglected maintenance and poor operational planning. All operational systems relied exclusively on groundwater recharge rather than rainwater storage (Figure 14). The field survey identified several recurring technical issues and no comprehensive servicing after project completion [25–28].

Operational and Maintenance Challenges

Key issues identified include:

- Clogging of filters due to inadequate pre-filtration and irregular cleaning [24].

- Improper sizing of recharge structures
- Absence of hydrogeological assessment prior to installation
- Annual maintenance costs ranging between ₹18,000–25,000, leading to reluctance among residents [26].
- Lack of trained maintenance personnel and standard operating protocols

A notable finding was the migration of recharged water to adjoining properties in certain locations, highlighting the importance of site-specific subsurface analysis (Figure 15).

Policy-Practice Gap

This study highlights a clear disconnect between policy mandates and on-the-ground performance. RWH is often implemented as a regulatory formality rather than a functional water management strategy.

Summary of Findings

- *The policy-practice disconnect:* Despite RWH systems being declared in the MahaRERA approval documents for most of the buildings, on-ground verification revealed that only eight out of the sixteen studied apartments possessed actively functioning systems.
- *System typology bias:* 100% of the actively functioning systems observed in the field utilized groundwater recharge methodologies rather than storage. This is driven largely by spatial constraints, limited awareness of available technologies, and a general reluctance among societies to manage the higher maintenance demands of physical storage.
- *Financial and technical maintenance barriers:* Operational efficiency is severely hampered by poor maintenance protocols, the absence of trained building personnel, and high annual maintenance costs (ranging from ₹18,000 to ₹25,000), which residents are highly reluctant to bear.
- *Subsurface design failures:* A critical localized issue was observed where recharged rainwater did not augment the site's own groundwater table but instead migrated to adjoining neighborhood properties owing to unfavorable subsurface geological conditions and an absence of pre-installation hydrogeological testing.

TECHNOLOGY REVIEW AND RECOMMENDATIONS

Comparative Evaluation of Available RWH Technologies

To address the operational challenges identified during the field surveys, a detailed review of RWH technologies currently available in the Indian market was undertaken. The assessment focused on technical feasibility, initial investment, operation and maintenance (O&M) requirements, and ease of integration into existing residential layouts. Tailored recommendations were formulated based on-site conditions, catchment potential, and spatial constraints [29, 30].

- *Underground RCC/HDPE High-Density Polyethylene Sumps:* Suitable for capacities of 5,000 to 50,000 L, these systems require high initial civil work investments (₹3–6 per liter) and medium-tech O&M, including pre-monsoon cleaning and waterproofing checks.
- *Modular Underground Polypropylene (PP) Tanks:* Highly efficient for 100 to 300 sq.m. catchments, these block-assembled systems are space-saving and require low maintenance, with costs ranging from ₹6,500 to ₹9,800 per cu.m. of storage.
- *Rooftop Rainwater Filters (Inline/Pressure):* Essential for removing contaminants, these units, sized for 100 to 500 sq.m. of roof area, require medium O&M, involving filter cleaning every three months and eventual media replacement [16–23].
- *Borewell/Injection Wells:* Deep recharge wells (10–30 m depth) are highly suitable for large apartment layouts. They require high-tech initial assembly (₹25,000–₹60,000 per well) but offer high recharge capacity, provided pre- and post-monsoon desilting is maintained [21].

Table 1. Recommendations for the selected samples.

Name	RWH	Site Area(sq.mt.)	Catchment area (Sq.mt.)	Annual rainwater potential (meters)	Runoff coefficient of Roof	Volume of rainwater from roof (cu.m.)	Volume of rainwater from roof(L)	No. of tenements	Recommended storage potential (KLD)	Recommendations based on availability of space (Huge) and economics (low, medium-tech)	Recommendations based on availability of space(less) and economics (High and medium)
Apartment 01	Yes	11100	1184	0.49	0.9	522.1	522144.0	308	166320	RCC or HDPE Sump, single or multiple	Large modular PP tanks
Apartment 02	No	350	200	0.49	0.9	88.2	88200.0	159	85860	RCC or HDPE Sump, single or multiple	Large modular PP tanks
Apartment 03	Yes	15000	800	0.49	0.9	352.8	352800.0	143	77220	RCC or HDPE Sump	Large modular PP tanks
Apartment 04	Yes	2265	431	0.49	0.9	379.9	379918.3	62	33480	RCC or HDPE Sump	Large modular PP tanks
Apartment 05	Yes	2100	864	0.49	0.9	381.0	381024.0	42	22680	Overhead tank with rooftop rainwater filters	Underground sumps with desilting chambers
Apartment 06	No	2856.3	307	0.49	0.9	135.5	135465.6	174	93960	RCC or HDPE Sump, single or multiple	Large modular PP tanks
Apartment 07	No	8676.4	1750	0.49	0.9	771.8	771750.0	72	38880	RCC or HDPE Sump	Large modular PP tanks
Apartment 08	Yes	2300	937	0.49	0.9	413.2	413217.0	138	74520	RCC or HDPE Sump	Large modular PP tanks
Apartment 09	No	1150	458	0.49	0.9	202.0	201978.0	48	25920	Overhead tank with rooftop rainwater filters	Underground sumps with desilting chambers
Apartment 10	No	2100	567	0.49	0.9	250.0	250047.0	40	21600	Overhead tank with rooftop rainwater filters	Underground sumps with desilting chambers
Apartment 11	No	14600	560	0.49	0.9	247.0	246960.0	65	35100	RCC or HDPE Sump	Large modular PP tanks
Apartment 12	No	1019.5	262	0.49	0.9	115.6	115606.9	34	18360	Overhead tank with filters	Underground sumps with rooftop rainwater filters
Apartment 13	No	1115.5	436	0.49	0.9	192.3	192276.0	23	12420	Overhead tank with rooftop rainwater filters	Underground sumps with rooftop rainwater filters
Apartment 14	Yes	970	196	0.49	0.9	86.2	86216.8	6	3240	Overhead tank with rooftop rainwater filters	Underground sumps with rooftop rainwater filters
Apartment 15	Yes	500	320	0.49	0.9	141.1	141120.0	12	6480	Overhead tank with rooftop rainwater filters	Underground sumps with rooftop rainwater filters
Apartment 16	Yes	500	300	0.49	0.9	132.3	132300.0	9	4860	Overhead tank with rooftop rainwater filters	Underground sumps with rooftop rainwater filters

Insights

The findings demonstrate that the effectiveness of harvesting rainwater depends far more on post-installation management than on initial construction.

The study indicates that current regulations successfully encourage installation but provide insufficient emphasis on long-term operation, maintenance, monitoring, and performance verification. Another important insight is that architectural design rarely incorporates maintenance accessibility.

Components such as filters, recharge pits, inspection chambers, and desilting units are often difficult to access, resulting in irregular maintenance and eventual system failure (Table 3). From a governance perspective, the study suggests that compliance verification should extend beyond the approval stage. Periodic post-occupancy audits by municipal authorities or third-party agencies could ensure that systems remain operational throughout the building lifecycle. The research demonstrates that successful urban RWH requires an integrated framework combining context-sensitive design, hydrogeological investigation, preventive maintenance, resident participation, institutional monitoring, and technology selection.

CONCLUSION

This study demonstrates that the failure of RWH systems in mid-rise residential apartments is not due to technological inadequacy but to deficiencies in design contextualization, maintenance planning, governance, and user engagement. Regulatory compliance alone is insufficient to ensure long-term functionality. Effective RWH requires integrated planning, hydrogeological assessment, regular maintenance, and active participation from residents. Strengthening these aspects can significantly enhance urban water resilience in rapidly growing Indian cities.

For complexes with excess captured water but low internal non-potable demand, systems can be optimized strictly for external landscape use [13].

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