INVESTIGATION ON AQUIFER RECHARGE POTENTIAL OF RAINWATER HARVESTING USING GEOINFORMATICS APPROACH: CASE STUDY OF PUNE CITY, INDIA

NATRAJ VADDADI

A Thesis Submitted to the Graduate School of Naresuan University
in Partial Fulfillment of the Requirements
for the Doctor of Philosophy in Natural Resources and Environment
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By Natraj Vaddadi

has been approved by the Graduate School as partial fulfillment of the requirements for the Doctor of Philosophy in Natural Resources and Environment of Naresuan University

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ABSTRACT

Only about 2.5% of the total water available on earth is fresh water. Groundwater systems have always constituted a pre-dominant and strategic reserve of freshwater storage. In most urban areas, the demand-supply gap of fresh water is especially acute leading to indiscriminate abstraction of groundwater. To aggravate this, very little recharge happens in such areas due to increased run-off of the water due to urbanization, leaving little water available for infiltration. In such conditions, systematic rainwater harvesting and managed aquifer recharge play an important role in augmenting the local supply of water, both from unconfined as well as confined (deep) aquifers.

The main objective of this study was to understand the potential for recharge of the groundwater in the urbanized area of Pune city which is the eighth largest city in India and forms a part of the Pune metropolitan area. The study broadly covers the use of Rooftop Rainwater harvesting for recharge through gravity injection to confined aquifers or deep-seated aquifers and delineation of groundwater potential zones for recharge of surface aquifers.

Accordingly, the calculation of rooftop areas and the creation of spatial maps indicating the potential recharge zones, considering various factors such as the

extent of urbanization, local geology, soil cover, slope, etc. was done. The acquired data was used for analysis to understand the areas with a potential for recharge and to formulate strategies for systematic recharge and scientific water management. The methodology employed a combination of remote sensing data, rooftop areas, geology maps, ward information, population data, well locations in the city, land use/land cover data and other thematic data.

Data for a total of 3074 wells was used to understand their use as potential wells to recharge the deep aquifers. The data was analyzed for several parameters viz. distribution across the zones (wards), status of the well (perennial, etc.), usage, diameter of the wells and the capacity of the pump being used. Further, the percentage of the wells for each of the zones was calculated for the study area. Frequency ratios for each of the considered thematic factors and their sub-classes were calculated for the wells – (both Dug wells and borewells).

An MCDA approach using AHP was used for the delineation of potential groundwater recharge zones for the surface aquifers. The potential recharge zones were identified and then ranked based on their suitability for groundwater recharge. Thematic factors, LULC, Slope, Rainfall, drainage density, type of soil and lithology were considered for the identification of potential recharge zones.

Increasing urbanization along with a burgeoning population has created challenges, mainly an increasing imbalance between demand and supply. The LULC analysis shows that the total built-up area in Pune has increased from 50.87 km^2 in 2003 to 126 km^2 in 2019 which is about half of the city indicating rapid urbanization. Data from Pune Municipal Corporation shows the population of Pune city has increased from 1.7 million in 1981 to 3.31 million in 2011 and is projected to rise to 6.09 million in 2031 and 8.26 million in 2041. According to the World Urbanization Prospects, the entire urban agglomeration of Pune is projected to have a population of 8.1 million by 2030. (WUP, 2014). Considering the above, the city must undertake a systematic groundwater recharge program to supplement the supply of water in the future.

The results of the study of rooftop run-off for rainwater harvesting indicate that an amount of 43.92 MCM (1.6 TMC) of water is available for harvesting. This water can be used for artificial recharge of the wells in the city. On a conservative estimate, even if half of this total rainwater is harvested, the recharge can replenish the groundwater annually by about 21 - 22 MCM (0.7 to 0.80 TMC). This is almost a third of the present-day extraction of groundwater and can help maintain the groundwater balance if used for recharge.

Further, the study of groundwater recharge potential zones shows that roughly 44% of the city has a good to high potential for recharge. The 'groundwater recharge potential zones' map of the study area generated through a weighted overlay analysis was categorized into five zones viz. low, moderate, good, high, and very high potential. The Groundwater potential map shows a coverage of 13.24 km^2 (5%), 124.71 km^2 (50%), 72.92 km^2 (29 %), 8.11 km^2 (3%), and 30.27 km2 (12%) for the above zones, respectively.

From a spatial perspective, the study reveals that high and good potential recharge zones lie mainly in the western part of the city. The central part of the inner city shows low potential for recharge. The analysis of the distribution of wells across the city shows that major extraction is happening towards the Central and Western parts of the city. Most of the wells fall in the Northwest (27%) and Central (26%) parts of the city followed by the West (16%). Another important finding is that only about 18 % of the yielding wells are presently being used for rooftop rainwater harvesting. This indicates a huge potential for using the wells for recharge.

Along with these studies, an experimental RWH system to harness the rooftop run-off was implemented in the field to check the efficacy of the technique. Two methods were used for implementation - Pit based, and PVC cylinder-based filters. These were used for recharge of the confined/deep aquifers in the area of study. Both, the above RWH techniques were found to be effective, though the PVC cylinder-based filter was found to be more cost-effective. This demonstrates that direct gravity injection using low-cost filtration techniques & clean filter mechanisms is a viable and low-cost method to harness the rainwater in the city.

Based on the present study and globally successful practices presented earlier, especially the Integrated Water Resource Management (IWRM) framework, the Integrated Urban Water Management (IUWM) framework and the Managed

Aquifer recharge, it is suggested that a systematic groundwater management framework – the ‘SCARPE’ framework comprising of the following elements - Systems approach, Conjunctive use, Aquifer replenishment, Right recharge mechanism, Protection of Existing sources and community involvement and Effective monitoring and balancing demand and supply be used in Pune city. This will help to maintain the groundwater balance and augment the water resources in the city.

Specifically, it is suggested the three wards of Baner-Balewadi, Aundh and Kamla Nehru Park should initially be targeted for systematic recharge of the existing wells. Dedicated recharge zones should be created in the high-potential areas within the city, where rainwater can be collected and directed into the aquifer.

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TABLE OF CONTENTS

Page

ABSTRACT..C
ACKNOWLEDGEMENTS...G
TABLE OF CONTENTS...H
LIST OF TABLE...K
LIST OF FIGURE..L
CHAPTER I INTRODUCTION...1
Background...1
Objectives of the Study...4
The Study Area..4
Climate..6
Geology...8
Hydrogeology...14
CHAPTER II GROUNDWATER AND RAINWATER HARVESTING.................18
Introduction...18
Groundwater Resources of India...18
Groundwater in Basaltic Terrain...20
Groundwater - Recharge and Potential...23
Rainwater Harvesting...27
Roof Top Rainwater Harvesting..30
Groundwater and sustainability..35
CHAPTER III RESEARCH METHODOLOGY...39
Introduction...39
Methodology..39
1. Step 1: Previous Work and Literature Survey...40
2. Step 2: Data Collection..40

3. Step 3: Data Processing and Analysis 43
4. Step 4: Field Implementation of Rooftop RWH system 46
CHAPTER IV ANALYSIS 53
Introduction..53
LULC Studies 54
Rainfall 56
Groundwater Potential Recharge Zones 60
AHP Analysis Using Multiple Criteria..61
Overlay Analysis: 64
Estimation of recharge potential from rooftops...65
Well Analysis...70
Frequency Ratio...72
CHAPTER V RESULTS & DISCUSSIONS 76
Introduction...76
LULC, Rainfall and Groundwater Recharge 76
Rainfall and Groundwater Potentiality 78
Groundwater Potential Recharge zones with MCDA analysis using AHP. 80
Well Analysis...88
Frequency Ratio (FR) 88
Rooftop Rainwater Harvesting 94
CHAPTER VI SUSTAINABLE GROUNDWATER MANAGEMENT...................96
Introduction...96
Sustainability 96
Groundwater sustainability..97
The UN Sustainable Development Goals (SDGs) and Groundwater......................98
Sustainable Water Management 100
Sustainable Ground Water Management 101
Managed Aquifer Recharge..102
MAR in Urban Water Management 107

Pune and its Groundwater Scenario. 109
Recommendations for Groundwater management in Pune city 111
The SCARPE framework 112
Action Plan 116
CHAPTER VII SUMMARY, CONCLUSIONS & RECOMMENDATIONS 119
Summary 119
Pune City - Groundwater Scenario 126
Conclusions 127
Recommendations for Groundwater management in Pune city 129
In conclusion 129
REFERENCES 131
BIOGRAPHY 156

LIST OF TABLE

Page

Table 1 Typical values of Runoff coefficients for various surfaces 34

Table 2 Data Sources 41

Table 3 Area of classes for different LULC categories 55

Table 4 Rainfall data from 1980 – 2019 59

Table 5 Input parameters for MCDA analysis using AHP 62

Table 6 Pair-wise comparison matrix for the six themes and calculation of normalized weights by the analytic hierarchy process 64

Table 7 Random Consistency Index 65

Table 8 Summary of rooftop rainwater run-off from digitized wards 69

Table 9 Frequency ratio analysis of wells in the study area 73

Table 10 Frequency Ratio analysis of the Groundwater Potential recharge zones......75

LIST OF FIGURE

Page

Figure 1 Map of the study area 5

Figure 2 Annual water requirement for Pune City..6

Figure 3 Temperatures for Pune city from 1981 to 2017..7

Figure 4 100 years rainfall for Pune city from 1901 to 2000.......................................7

Figure 5 Compound pahoehoe flow..9

Figure 6 Fragmented top (Flow top breccia) 10

Figure 7 Bun shaped flow unit...10

Figure 8 Inverted ‘Y’ shape of cylindrical pipes 11

Figure 9 Vesicle cylinders 11

Figure 10 Giant plagioclase basalt...12

Figure 11 Interflow horizons 12

Figure 12 Stratigraphic classification of Western Deccan Province 13

Figure 13 Sheet joints 14

Figure 14 Vertical joints 14

Figure 15 Vesicular Basalt..15

Figure 16 Amygdaloidal basalt...15

Figure 17 Schematic showing the typical generalised internal morphology of a pahoehoe flow. The Image on the left is a photograph..16

Figure 18 Water seepage along the flow unit contacts 17

Figure 19 Formation of a water pool by water seepage through jointed flows 17

Figure 20 Dug well tapping a shallow aquifer..22

Figure 21 Borewell being drilled to tap a deep aquifer 22

Figure 22 Schematic of a Roof Top Rainwater Harvesting system.............................30

Figure 23 Workflow used in the analysis 43

Figure 24 Sample image showing digitisation of roof tops using Google Earth Pro ..46

Figure 25 Schematic of recharge pit 47

Figure 26 Bare pit with brick lining for recharge purposes 48

Figure 27 Schematic of PVC cylinder-based filter (Diameter of pipe is 150 MM) 48

Figure 28 Installed PVC barrel-based sand filter 49

Figure 29 Schematic of stainless-steel mesh-based PVC filter 50

Figure 30 Installed stainless-steel mesh-based PVC filter 50

Figure 31 Graph showing LULC changes of Pune city from 2003 to 2019 55

Figure 32 Changes in Built Up and Barren land over time 56

Figure 33 a) Land cover map of Pune city for 2003 b) Land cover map of Pune city for 2007 c) Land cover map of Pune city for 2011 d) Land cover map of Pune city for 2015 e) Land cover map of Pune city for 2019 58

Figure 34 Rainfall data from 1980 -2019 60

Figure 35 Map showing rooftop rainwater run-off from wards for which rooftop areas were digitized. *(Numbers indicate run-off figures in million cubic meters/year.)* 68

Figure 36 Graph showing number of wells per administrative ward (zone) 70

Figure 37 Graph showing regional distribution of wells 70

Figure 38 Graph showing distribution of type of wells 71

Figure 39 Graph showing status of wells 71

Figure 40 Map showing the spatial distribution of wells across the wards 72

Figure 41 Monthly mean annual rainfall for 100 years from 1901 to 2000 79

Figure 42 LULC Map 81

Figure 43 Slope Map 82

Figure 44 Drainage Density Map 83

Figure 45 Rainfall Map 84

Figure 46 Soil map 85

Figure 47 Geological map showing lithology 86

Figure 48 Map of Ground Water Recharge Potential Zones 87

Figure 49 (a) Land Use and Land Cover (b) Slope (c) Rainfall 49 (d) Drainage Density (e) Soil (f) Geology 92

Figure 50 Frequency map of the Groundwater recharge potential zones 93

Figure 51 UN Sustainable Development Goals 98

Figure 52 Roles of managed aquifer recharge and conjunctive use in integrated water resources management 105

Figure 53 Major determinants of groundwater sustainability 109

Figure 54 Population Growth – Pune City 110

Figure 55 The SCARPE framework 116

CHAPTER I

INTRODUCTION

Background

Water remains a precious and scarce natural resource, even though approximately 71% of the Earth's surface is covered by it. Fresh water which is essential for human consumption and various vital purposes constitutes only 2.5% of the planet's overall water supply. Water is an essential resource for sustenance and human survival. Communities, from the early days of human civilization, have sought areas around rivers, springs, and other water sources to establish settlements. Groundwater systems have always been a vital source and a good reserve of freshwater storage on Earth. Humans have obtained a large part of their potable water requirements from these underground sources. Human settlement, growth, and social development have always been influenced by springs, the surface expressions of groundwater. However, till recently, the ability to extract this resource was limited. Increasing urbanisation and development have had a deep impact on the hydrological systems, particularly in the subsurface component of the water cycle, the groundwater. Improved technology has contributed to the rapid exploitation of groundwater in most countries across the globe.

Even though water as a resource is replenished every year by rains, water scarcity is increasingly being felt in most nations, including highly developed countries. Consequently, the demand for water has increased rapidly while the supply of fresh potable water is decreasing. This is especially so in urban growth centres. Rapidly growing human population, changing climates and frequent droughts are contributing to the above. Coupled with this, the erratic rainfall and uncertainty in monsoon patterns have immensely increased the requirement of water in rural and urban areas and led to over-utilization of groundwater.

As compared to many other countries, India receives sufficient rainfall and is the second wettest country globally. Even with the high rainfall, the country faces a deficit in water availability during summer. According to the Ministry of Water Resources, India, the demand for domestic water is projected to steadily rise, reaching an estimated 47 trillion litres per year by 2025. Domestic consumption is expected to rise by 40%, surging from 41 trillion litres per year to 55 trillion litres per year. Similarly, irrigation requirements are expected to grow by 14%, necessitating around 592 trillion litres annually, compared to the current 517 trillion litres per year (Bhat, 2014).

The demand supply gap is especially acute in urban areas which has led to the indiscriminate mining of groundwater with no restrictions. Added to this, increasing construction activity and the practice of concretising the roads lead to the run-off of water into the drains with very little water available for infiltration. Thus, it is no surprise that the groundwater level is decreasing day by day. Wells which were once productive are drying up especially in summer when the demand is very high.

In this scenario, maintaining the groundwater balance assumes immense importance. Employing various techniques such as recharge pits, check dams, percolation tanks, injection wells and rooftop rainwater harvesting is thus crucial to maintaining the hydrological balance. (Subba Rao, 2022).

Extensive research has been conducted on groundwater recharge from rainfall, exploring various methodologies such as the Thiessen polygon method (Kim et al., 2003), Agricultural non-point source techniques (Mohammed et al., 2004), the water balance approach (Jasrotia et al., 2009), and the Soil Conservation Service Curve Number (SCS-CN) method (Kadam et al., 2012). These methods have been suggested to locate suitable sites for groundwater recharge. Furthermore, several researchers (Senanayake et al., 2016; Adham et al., 2016; Paul et al., 2020) have focused their studies on rainwater harvesting (RWH) for surface recharge to aquifers in non-urban areas, aiming to pinpoint potential sites for such practices.

The majority of India's overexploited groundwater areas are situated in hard-rock terrains, where recharge offers only some relief and serves as a supplementary measure along with other approaches like rainwater harvesting (World Bank, 2010).

A fundamental element in maintaining the water balance of any watershed is groundwater recharge as it influences the availability of groundwater for extraction purposes. The groundwater balance of an area is usually expressed as:

Groundwater Input – Groundwater Output = Change in Groundwater storage

The input is the recharge from precipitation, other sources, and subsurface inflow while several factors, such as groundwater draft, groundwater evapotranspiration, base flow to streams, and subsurface outflow constitute Output. The primary means of recharging most groundwater resources is direct precipitation, which infiltrates into the saturated zone, thereby sustaining the recharge potential of an aquifer.

The recharge processes of groundwater in urban areas differ from those in rural areas. The increase in construction activity and the widespread use of concrete for road surfaces result in heightened runoff of water into drainage systems leaving very little water available for infiltration. In such conditions, systematic rainwater harvesting, or managed recharge are an important means to augment the local supply of water, both from unconfined (shallow) as well as confined (deep) aquifers.

In urban areas, the recharge of groundwater normally takes place by two methods 1) Recharge of rainwater by direct infiltration and 2) recharge from water bodies like lakes, dams percolation tanks. Additionally, in urban areas, recharge also takes place through several other mechanisms like infiltration through storm water drainages, soakways, leakage through sewage lines and direct infiltration in parks and open areas.

Rainwater harvesting is an increasingly important technique for mitigating water scarcity, maintaining the water balance and improving water security in many regions around the world. Rainwater collected and stored from rooftops and various surfaces is increasingly being used for diverse applications, such as irrigation, household consumption, and replenishing groundwater aquifers. The study of the potential of rainwater harvesting in the recharge of deep aquifers especially in urban areas is crucial to the maintenance of the hydrological balance.

Objectives of the Study

The main objective of the present study is to understand the recharge potential of groundwater in the Pune urban and adjoining areas area using the existing dug and bore wells.

The present work broadly covers the use of Rooftop Rainwater harvesting for recharge through gravity injection to confined aquifers or deep-seated aquifers and the identification of groundwater potential zones for recharging surface aquifers.

The specific objectives of the study were to:

1. Mapping existing wells in the urban extent using open-source tools like Open Data Kit and geospatial analysis of the above data in terms of density and correlation to the electoral wards in the city.

2. Roof top area calculation of representative areas across the city for analysis of the potential for recharge and calculation of Rainwater Harvesting (RWH) recharge potential using the above data & other geospatial techniques.

3. Identification of potential recharge zones using Geoinformatics and considering various factors such as the extent of urbanisation, local geology, soil cover, slope, etc.

4. Use of the acquired data and analysis to suggest/formulate strategies for systematic recharge and scientific water management.

The Study Area

The area of study is located in the Western part of the Deccan Volcanic Province and is underlain by basalts of upper Cretaceous to Eocene age. The city is surrounded by hills on its western and southern sides, while the main rivers in the study area are Mula and Mutha. Additionally, two more rivers, namely Pavana and Indrayani flow from the north-western direction. The drainage is dendritic, sub-dendritic and sub-parallel. Structural control in the drainage is evident in many places.

Pune Urban area covers an area of 7,256.46 sq. km and is included in the Survey of India toposheet numbers E43H14 & E43H15. It includes Pune Municipal Corporation (PMC), Pimpri Chinchwad Municipal Corporation (PCMC) and three Cantonment Boards. Of the above extent, Pune Municipal Corporation (PMC, Pune

City) covers 331.26 sq. km (127.90 sq. miles) and has a population of 3.13 million. (PMC, 2017)

Pune city is the eighth-largest city in India and the second-largest city in the state of Maharashtra. The study area lies between 18^0 27’ & $18^0$40’ N – $74^0$39’ & $74^0$00’ E and lies within the Deccan Volcanic Province. (Figure 1).

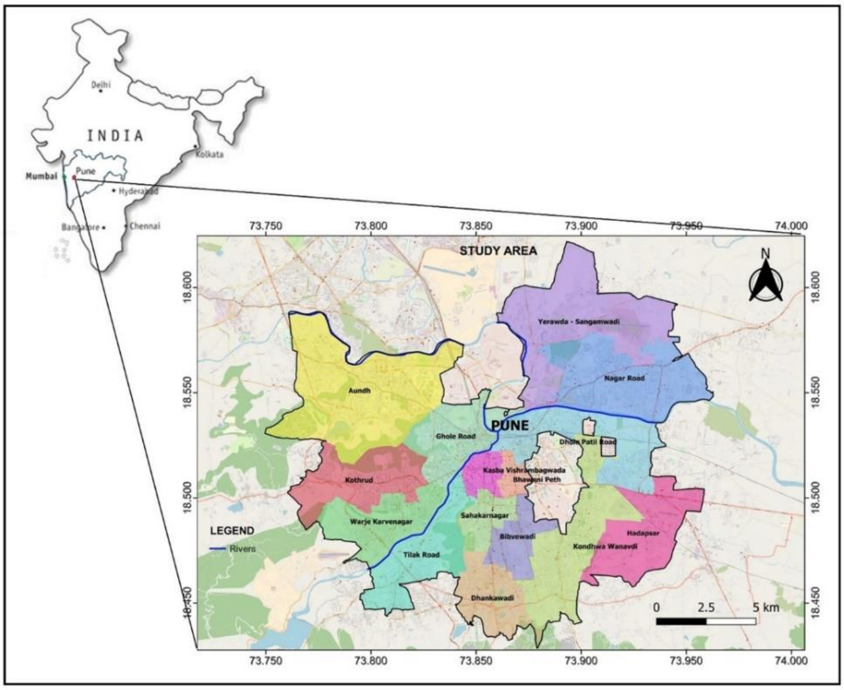


Figure 1 Map of the study area

The annual precipitation is 780 millimetres with maximum rainfall occurring in July. The yearly water demand is 15 thousand million cubic feet (TMC) or 424 million cubic metres (MCM) and per capita consumption in the city averages around 205 litres per capita per day (LPCD). The area experiences three seasons - summer, monsoon & winter and usually faces a shortage of water if the monsoon has failed in the previous year.

The annual water demand for Pune City in 2020 was 424 MCM and the budget for the year 2021-22 was 568.31 MCM. Corresponding to this growth the annual water demand is expected to increase to 23.34 TMC (660.91 MCM) by 2031-

32. (PMC, 2021). The gap between demand and supply necessitates looking for alternative sources of potable water to cater to the shortfall. (Figure 2)

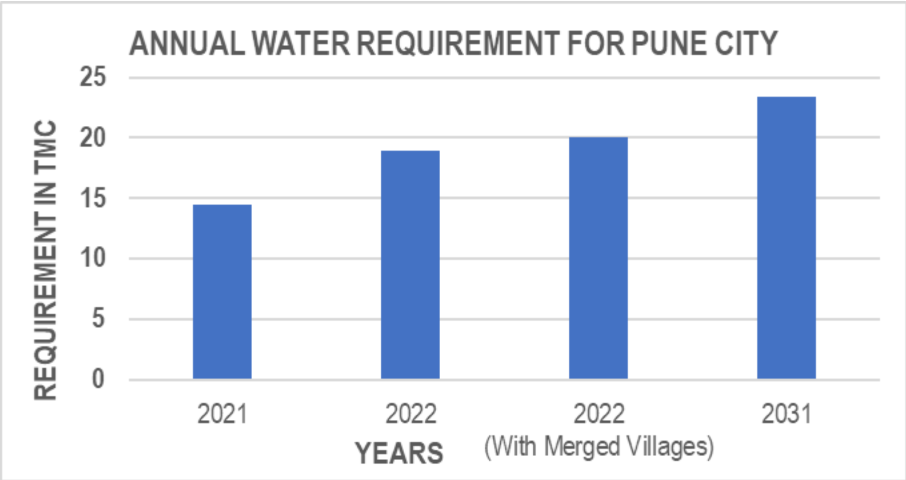


Figure 2 Annual water requirement for Pune City

Climate

Pune has a hot and semi-arid climate. Summer in Pune spans from March to June, occasionally extending until mid-June, with maximum temperatures sometimes soaring to 42 °C. The city's average temperature ranges from 20°C to 30°C. The hottest period of the year is from mid-March to mid-May, where day temperatures range between 35°C to 40°C. The Monsoon season is characterized by moderate temperatures ranging from 25°C to 27°C and lasts from June to October. November sees the onset of winter in which the daytime temperatures average around 26°C, while nights become colder, with temperatures dropping to below 13°C for most of December and January often falling to 5°C or 6°C. Pune's highest temperature of 43.3 °C was recorded on 30th April 1897 while the lowest of 1.7 °C was recorded on 17th January 1935. (Figure 3) often falling to 5°C or 6°C. Pune's highest temperature of 43.3 °C was recorded on 30th April 1897 while the lowest of 1.7 °C was recorded on 17th January 1935. (Figure 3)

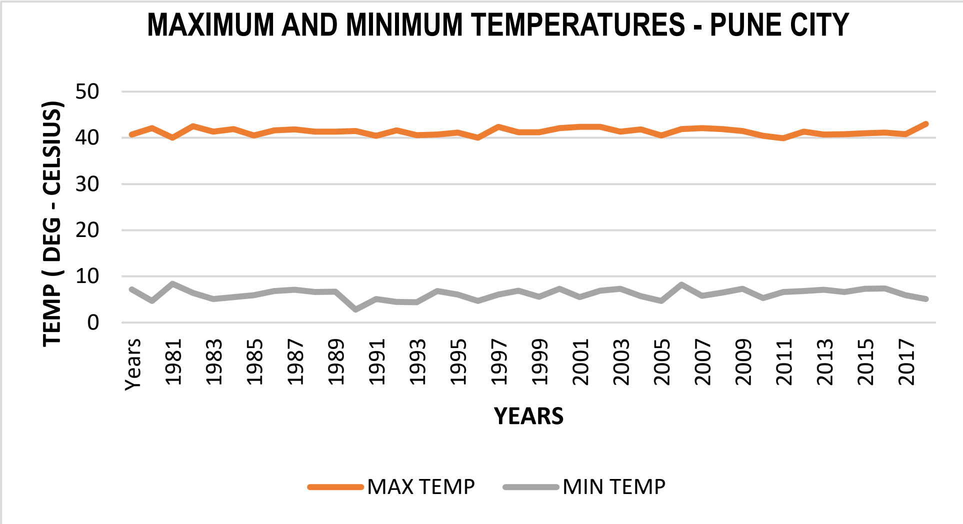


Figure 3 Temperatures for Pune city from 1981 to 2017

Source: PMC Open data portal

The monsoon lasts from June to October, with moderate rainfall and temperatures ranging from 22 to 28 °C (72 to 82 °F). The mean annual rainfall of the city is 780 mm and most of this occurs between June and September. July is the wettest month of the year.

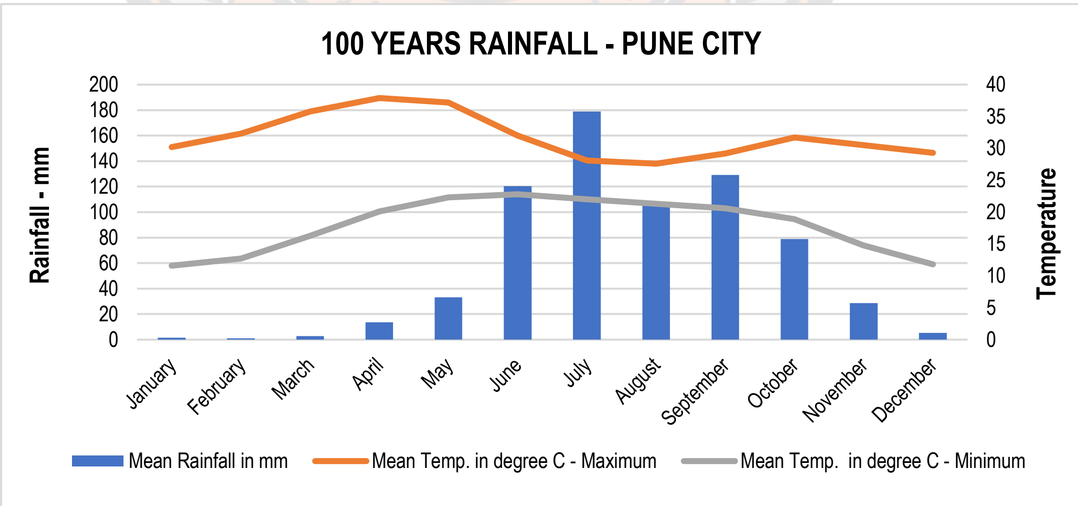


Figure 4 100 years rainfall for Pune city from 1901 to 2000.

Source: Kaggle.com

Geology

The study area falls in the Western part of the Deccan Volcanic Province. The Deccan Volcanic Province (DVP), often known as the Deccan Plateau, represents one of the world's most extensive and well-preserved continental flood basalts. In geological literature, it is also referred to as the Deccan Traps. The term Deccan Trap originates from the Sanskrit word Dakshin, meaning south or southern, and the Swedish word Trapp/Trappa, meaning stairs. This name was first coined by W.H. Sykes in 1833 to describe the step-like or terrace-like topography found in this region.

The Deccan Trap basalts occupy a significant portion of western and central India, covering an aerial extent of about half a million square kilometres and are estimated to have a volume of approximately 512,000 cubic kilometres. Considering the extensions beneath the Arabian Sea, their estimated extent before erosion could be of the order of 1,500,000 square kilometres.

In the Western Ghats, the estimated maximum aggregate thickness of approximately 3000 meters is observed. The basalt flows exhibit sub-horizontal orientations with mild easterly and south-easterly gradients. These basalts are characterized as quartz normative, low-K tholeiites, primarily composed of plagioclase (labradorite-bytownite), augite, occasional olivine, and secondary zeolites as the main mineral constituents. They commonly show intrusions of bodies like dykes, sills, and plugs. Basalt flows are dark grey to greenish grey, black-coloured rocks, with or without recognizable minerals. They may all look homogenous to untrained eyes, but in nature, all the lava flow outpourings are not similar. The individual basalt flows differ in their surface morphology and internal structures. This difference is due to variations in the viscosity of the lava. Accordingly, basalt flows have broadly been classified into two forms: pahoehoe and àa. These are Hawaiian terms and have been used to describe Deccan lava flows, as they show a resemblance to lava flows from Hawaii. Pahoehoe flows (pronounced as *pah-hoy-hoy*) are recognizable by smooth top surface, often displaying rope-like features. In contrast, the àa flows (pronounced as ah-ah) show a spinose flow top with auto-breccia characteristics. A majority of the pahoehoe flows are made up of many small bun-shaped flow units or lobes, and hence are also referred to as compound pahoehoe flows (Figure 5).

Figure 5 Compound pahoehoe flow

Both types of flows exhibit distinct internal morphology, which can be seen if you slice the flow vertically from top to bottom. Such vertical sections of flows can be seen and appreciated along many of the road cuts, excavation pits and wells. Both flows show a three-part zonation but are not similar. The pahoehoe flows have less viscosity as compared to àa flows.

Àa flows typically show a rubbly, vesicular, clinker surface composed of blocks of various sizes. A typical a`a flow can be identified by the presence of a thin clinker zone (though patchy) at the base, followed upwards by a massive and dense core and a fragmented zone at the top. Partially resorbed fragments of the crust are commonly seen within the massive interior of the flow. The upper fragmented zone is known as flow top breccia. Volatiles and gases present in the lava rise towards the top. As the upper frothy material starts to cool, and as the still-hot lava below this cooling crust advances, the upper crust is torn apart. A fragmented top or flow top breccia thus develops, because the viscosity of a`a flows is high, resulting in strain (Figure 6).

Pahoehoe flows are generally compound in nature. Geometrically, all the flow lobes/units exhibit a bun shape with inflated tops and a more or less flattened base. The dimension of a single flow unit varies and can be as small as the one shown in the figure (Figure 7**).**

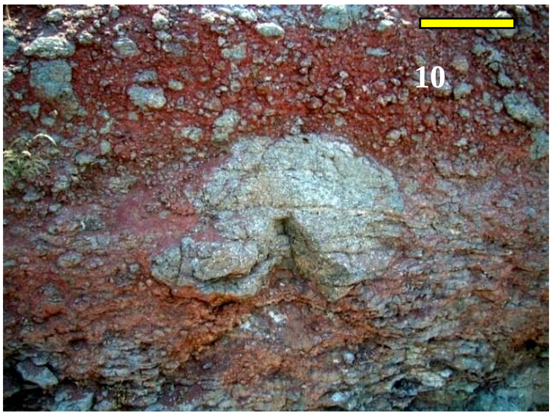


Figure 6 Fragmented top (Flow top breccia)

Figure 7 Bun shaped flow unit

An ideal section of a pahoehoe flow lobe shows the presence of a lower (vesicular) zone, followed upward by a massive central core and upper (vesicular) zone with a thin glassy crust. Pipe vesicles are usually observed in the lower zone, also known as the basal vesicular zone (BVZ). The units' top surface exhibits reddened glassy crusts formed due to chilling. At certain locations, one can see crudely developed ropes and chords on this reddened crust (RC). The thin cylindrical pipes form vertical to the base of the flow, as they are formed by the escaping gas. As the thin cylindrical pipes develop, some tend to coalesce, forming an inverted 'Y' shape (Figure 8). As the volatile and gas bubbles move upwards, they tend to concentrate and collect and the voids thus formed result in vesicle cylinders. Vesicle cylinders are common in the central massive core (Figure 9).

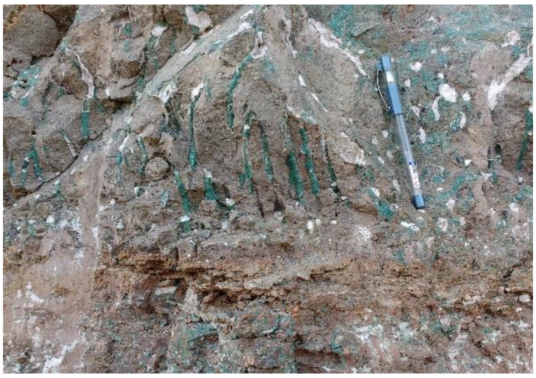


Figure 8 Inverted 'Y' shape of cylindrical pipes

Figure 9 Vesicle cylinders

As the vesicle cylinders proceed upwards, they spread into horizontal sheets. Within the upper vesicular zone, one can recognize the variation in the size of vesicles and amygdales. Joints are developed parallel to the cooling surface, commonly known as sheet joints. Squeeze-ups, wedge-shaped features interconnecting lobes and units and vesicle cylinders, indicating escape of stream of volatiles are also seen at places.

At many places, flows with large (>2-3mm) plagioclase phenocrysts have been identified at different stratigraphic levels. These flows are referred to as Megacryst flows or giant plagioclase basalts (GPBs). GPBs constitute valuable markers in the stratigraphic classification and correlation of flows. (Figure 10)

In many places across the Deccan Traps, interflow layers are present between two successive flows. These layers occur as red, green, or brown (Khaki) coloured bands and are generally referred to as red boles and green boles (Figure 11). They consist of very fine-grained clayey material, comprising tiny fragments of diverse sizes and shapes, including angular, cuspate basaltic shards which indicate their pyroclastic origin. Glass, if present is usually devitrified. Based on the presence of pyroclasts, which range from basic to intermediate composition, the bole beds have been termed tuffs.

Figure 10 Giant plagioclase basalt

Figure 11 Interflow horizons

Based on extensive field studies and taking into account lithological characteristics such as the physical characteristics of the flows and the presence of interflow horizons, the Geological Survey of India has established the lithostratigraphy of the Deccan Traps. The Deccan basalts have thus been divided into four Subgroups and nine Formations based on lithostratigraphy (Godbole et al, 1996). Studies of the geochemistry and paleomagnetic characteristics of the flows have contributed to the establishment of the stratigraphy of the flows.

Based on lithostratigraphy, the lava flow sequences seen in the study area have been divided into four Formations - Indrayani, Karla, Diveghat and Purandargarh Formations which belong to the Sahyadri group. The terms simple flow and compound flow are sometimes used to describe lava flows. The flows belonging to Indrayani, Diveghat and Purandargarh Formations are dominantly of simple nature, while those of Karla Formation show a compound nature. (Figure 12).

Lithostratigraphy		Chemostratigraphy		Magneto-Stratigraphy
Subgroup	Formation	Subgroup	Formation	
			Desur	N
	Mahabaleshwar		Panhala	N
			Mahabaleshwar	N
Wai		Wai		
	GPB - M4			
	Purandargad		Ambenali	R
	Diveghat		Poladpur	R
	Karla		Bushe	R
Lonavala		Lonavala		
	Indrayani		Khandala	R
				R
	GPB - M3		2 GPBs	
	Ratangad with intercalated GPBs		Bhimashankar	
	GPB - Alkuti		GPB	
			Thakurvadi	
Kalsubai		Kalsubai		
				R
	GPB - M2		GPB	
			Neral	R
	GPB - M1		GPB	
			Igatpuri	R
			GPB	
	Salher		Jawhar	R

Figure 12 Stratigraphic classification of Western Deccan Province

Source: modified after Vaidhyanadhan and Ramakrishnan, 2008

The simple flows have a fragmented top, a thin brecciated portion (basal clinker) at the base and a compact, massive core that is jointed. The compound flows are vesicular and amygdaloidal at the top and show a moderate degree of weathering at places. The hard and compact middle section is fractured and jointed and their basal sections are characterized by pipe amygdales. The average thickness of each flow is 10 to 20 meters.

The flows exposed in the study area are dominantly of pahoehoe nature, belonging to the Karla Formation. Towards the far eastern part of the area, a few outcrops of the simple flows of the Indrayani Formation are exposed. The hilly areas in and around Pune city expose the younger flows of the Diveghat Formation, which overlie flows of the Karla Formation.

Hydrogeology

The basalt flows generally exhibit low primary porosity and permeability. The accumulation and transmission of water is a result of the secondary porosity developed due to the presence of openings and cavities, weathering, vertical and horizontal sheet joints and the contact between flows and flow units (Figures 13 and 14).

Figure 13 Sheet joints

Figure 14 Vertical joints

In terms of hydrogeological properties, the flows are usually classified as vesicular basalt (Figure 15) and amygdular basalt (which also includes the flow top breccia (FTB) (Figure 16), jointed basalt and massive, compact basalt. The vesicular/amygdular basalt, jointed basalt and weathered basalt have better water-holding capacity and behave as aquifers, while the massive, compact basalt acts as aquitard or aquifuge. The tuffaceous clayey layer occurring between the flows acts as an aquiclude. Thus, with an alternating sequence of water-bearing zones, the basalt flow sequence acts like a multi-aquifer system. The schematic shows the typical generalised internal morphology of a pahoehoe flow. (Figure 17).

The water-bearing capacity of the rock formations is mainly governed by the porosity which determines the volume available for storage of water. Porosity is in turn dependent on the shape, size, arrangement, and interconnection of voids. The movement of water through the interconnected open spaces is governed by hydraulic conductivity. The capacity to yield water or Storativity, refers to the volume of water that an aquifer will release per unit area of the aquifer and per unit reduction in hydraulic head over the unit area.

The circulation of groundwater occurs in the weathered portion, through the vesicular upper sections and the fractured portions in the massive basalt. The clayey tuffaceous horizons and massive units that lack regular systematic jointing restrict the vertical seepage to the deeper layers. The recharge to deeper horizons generally occurs through deep fractures and fractured dykes. The weathered parts of both vesicular and massive units have better porosity and permeability as compared to the fresh units. The secondary porosity also increases in the lower portion of the flows due to the presence of columnar joints, sheet joints and basal clinkers (Figures 18 and 19).

Figure 15 Vesicular Basalt

Figure 16 Amygdaloidal basalt

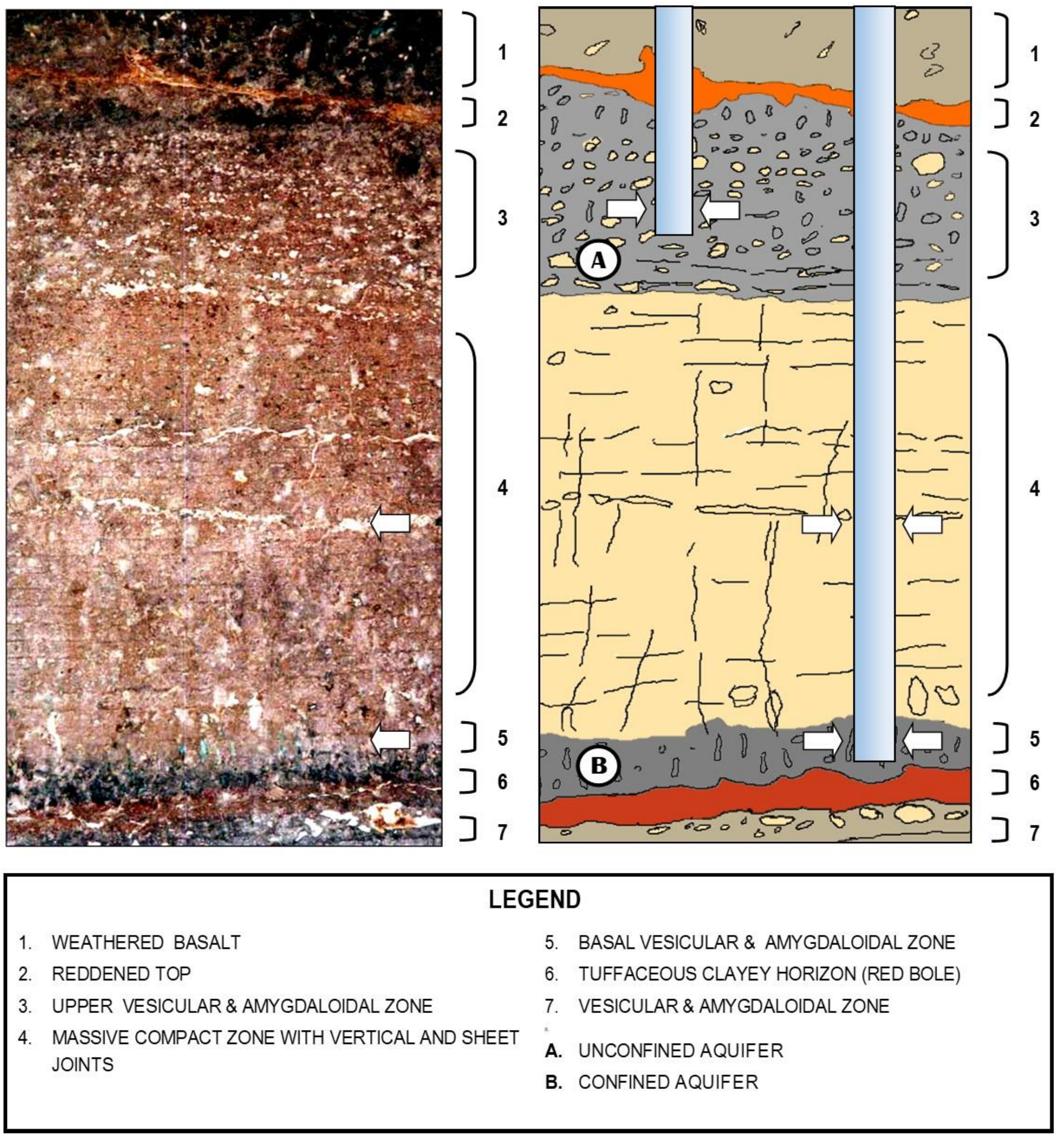


Figure 17 Schematic showing the typical generalised internal morphology of a pahoehoe flow. The Image on the left is a photograph

Figure 18 Water seepage along the flow unit contacts

Figure 19 Formation of a water pool by water seepage through jointed flows

CHAPTER II

GROUNDWATER AND RAINWATER HARVESTING

Introduction

Water is a life-sustaining resource for mankind. Man's survival is dependent on the availability of fresh potable water. Early communities and civilizations were established in the proximity of water sources like springs, lakes, and rivers. Besides surface water, groundwater has been a major contributor from time immemorial to the supply of fresh water to the community. Groundwater is also a significant contributor to surface streams and has a major influence on rivers.

Extensive research has been conducted worldwide on groundwater and its diverse aspects, with particular emphasis on the dynamics of groundwater aquifers. These studies include the study of groundwater movement, subsurface distribution, aquifer characteristics, and the relationships between groundwater and surface water.

In the past few decades, the emphasis has been on studies related to groundwater balance. Consequently, there is a renewed focus on the use of techniques to artificially recharge the groundwater aquifers principally through rainwater harvesting. Artificial recharge is also described as 'Managed Aquifer Recharge (MAR)', or enhanced recharge.

This chapter summarizes the previous work and the literature published concerning the areas of groundwater resources, rainwater harvesting, groundwater recharge in the Deccan basaltic terrain and sustainable groundwater management.

Groundwater Resources of India

Groundwater refers to the water that exists under the Earth's surface in pore spaces, sand, and rocks. It is a vital natural resource that supports a large range of human activities, like agriculture, industry, and domestic use.

Research, over the past decade has revealed that approximately two-thirds of the global population resides in regions that face water scarcity for at least one month each year. About half of these are found in China and India (UN-Water, 2017).

Despite India receiving ample annual precipitation of approximately 4000 x 109 m3, only around one-fourth of it (1123 x 109 m3) can be used (Saha et al., 2018).

As per the Ministry of Jal Shakti, India (2022), the average per capita water availability in India for the year 2021 was 1486 cubic meters and is projected to decrease to 1367 cubic meters by 2031. In recent years, a significant portion of the rising water demand has been fulfilled through aquifers. Groundwater has become increasingly vital for India's agricultural and drinking water security (Vijay Shankar et al., 2011).

Aquifers are underground layers of rock or sediment that are significantly porous and contain water which can be accessed through wells or natural springs. These zones are commonly located below the water table, which is the level below which the ground gets saturated with water. Groundwater systems are complex networks of aquifers, surface water bodies, and recharge areas. Groundwater systems are dynamic and are influenced by a range of factors, including climate, geology, land use, and human activities.

Globally, groundwater aquifers have always constituted a critical reserve of freshwater storage on the Earth. For centuries, human civilizations have sourced a large percentage of fresh water from these underground sources. The ability to extract this resource was limited till the last few decades but improved technology and better drilling methods have resulted in the rapid extraction of this invaluable resource. These groundwater systems could amount to approximately 30% of the global total and as much as 98% of the water, if glaciers and the polar ice caps are discounted (Shiklomanov, 2000).

The reliance of growing cities and numerous medium-sized towns on groundwater is escalating, leading to an estimate that around 1500 million urban residents worldwide depend on wells, boreholes, and spring sources for their water supply (Foster et al., 2003).

All aquifers should have two essential characteristics — the ability to store groundwater (Storativity) and the ability to allow the groundwater to flow (transmissivity). These properties differ significantly depending on the geological formations.

Today in India, approximately 62% of the irrigation needs and about 85% of the rural water supply are met from groundwater. (The World Bank, 2012; Saha, & Ray, 2019; Mukherjee, & Singh, 2020). Added to this nearly 50% of the urban water usage comes from groundwater. The above figures show that in India, groundwater constitutes a crucial resource for the country's potable water and agricultural needs. Groundwater has now become a critical component of India's fresh water supply, both in rural as well as in urban areas. With about 40 million wells, India presents a unique situation of a large and growing dependency on groundwater on one hand and increasing challenges in groundwater management on the other. (Kulkarni et.al, 2023)

Besides the increasing usage in rural communities for agriculture and personal needs, the demand for groundwater in urban and adjoining areas continues to grow. Urbanisation and the growth of cities both vertically and horizontally have increased water stress and have had an extensive impact on groundwater availability and quality. In addition, underground urban structures like water supply, stormwater drainages, sewage lines and tunnels have a major impact on the groundwater systems.

Urbanization leads to major alterations in the frequency and pace of groundwater recharge, typically resulting in a significant increase in volume and a considerable decline in quality. Additionally, urbanization leads to the reduction of the permeability of land surfaces, thereby increasing surface runoff and reducing direct infiltration from rainfall (Foster, 1999).

Groundwater in Basaltic Terrain

Most parts of Maharashtra and large parts of Gujarat and Madhya Pradesh are occupied by basaltic aquifers consisting of multiple flows (traps). Each flow is usually characterised by a vesicular zone at the top and a unit of massive rock at the bottom (Saha, & Agrawal, 2006). The weathered part of the top flow and the vesicular zones of the flows form the aquifers. The thickness of the weathered zone is usually less than 15 metres though weathered zones of 40-metre thickness have also been seen in some parts of Karnataka and Gujarat (CGWB, 2012). The transmissivity of these aquifers is usually within 70 m2/day. Saha et al. (2017) have also reported some smaller basaltic aquifers from Chhattisgarh, Rajmahal Traps in Eastern parts of Jharkhand etc.

Basaltic terrains contain both shallow unconfined aquifers and deep aquifers, and their characteristics vary depending on several factors such as the geological setting, weathering, and fracturing of the rocks.

According to Mukherjee et al. (2020), the shallow basaltic aquifers, formed by the highly jointed upper horizon and the lower part of the highly weathered zone, along with the less weathered and highly jointed horizon of the lower zone, represent the most promising zone for groundwater occurrence. The study further suggests that well yields in the deeper basaltic aquifers are directly influenced by the presence of lineaments, while at shallower levels, they are associated with geomorphic features. Additionally, the discharge of springs is significantly influenced by the aquifers and areas of recharge.

Shallow unconfined aquifers in basalts are typically located near the surface and are often recharged by precipitation and surface water bodies such as streams and rivers. The groundwater in these aquifers is typically unconfined, meaning that it is in contact with the atmosphere, and is susceptible to contamination from surface pollutants. Dug wells (Figure 20) are generally used to tap such aquifers. Shallow unconfined aquifers in basalts are a vital water source for agricultural and domestic use though their yields are dependent on the recharge rates and the availability of surface water sources.

According to Foster et al. (2007), the weathering characteristics and water-bearing properties of hard-rock aquifers, like the Deccan Traps, strictly limit the total groundwater storage available. Additionally, the storage capacity decreases rapidly as the water table falls below the critical horizons within the weathering zone which is typically located at depths of 5-25 metres below the ground, and below the uppermost 2-6 metres of fractured bedrock.

Deep aquifers in basalts are typically located at greater depths, confined and under pressure. These aquifers can be recharged by infiltration of rainfall and by lateral flow from neighbouring areas. The groundwater in deep aquifers is typically of high quality and is less susceptible to contamination from surface pollutants. Bore wells (Figure 21) are typically drilled to tap deep aquifers in basalts. These wells constitute a significant source of water for urban and industrial use, though their yields can be limited due to the low permeability of the rocks. The recharge of confined aquifers also takes a much longer time as compared to unconfined aquifers.

Figure 20 Dug well tapping a shallow aquifer

Figure 21 Borewell being drilled to tap a deep aquifer

The characteristics of both shallow unconfined aquifers and deep aquifers in basalts can be affected by weathering and fracturing of the rocks. Weathering can cause the basaltic rocks to break down and form soil, which can increase the permeability and porosity of the rocks, leading to higher yields of groundwater. Fracturing can create pathways for water to flow through the rocks, increasing the permeability of the rocks and the yield of groundwater.

The Deccan basalts are considered to be low-permeability rocks due to a large degree of heterogeneity. Due to their inherent poor primary porosity and permeability, groundwater occurrence, accumulation and movement in the basalts are controlled by the characteristics and extent of development of secondary porosity. The secondary porosity is usually due to horizontal and vertical joints, contact between flows or flow units and the openings (vesicles) developed within the flow and weathering of the surface flows.

Integrated watershed studies across basins, flow-net analyses, and groundwater modelling by Kulkarni et al. (2000) indicate that the basaltic aquifers have a limited extent, have a high degree of inhomogeneity, and show low hydraulic conductivity.

Groundwater - Recharge and Potential

As the population increases, the requirement for water is increasing rapidly in urban areas. The gap between demand and supply is especially acute in urban areas and has led to the indiscriminate extraction and exploitation of groundwater. Increasing construction activity and the practice of concretising the roads in many cities leads to the run-off of water into the drains thereby leaving little water available for infiltration. As a result, the groundwater levels are decreasing rapidly. Wells that were once productive no longer yield water.

In such a scenario, maintenance of the groundwater balance is crucial to maintaining the water or hydrological balance. Artificial recharge of groundwater using techniques such as the use of injection wells, recharge pits, percolation tanks, check dams, and roof-top rainwater harvesting, is therefore crucial for the restoration of the hydrological balance (Subba Rao, 2022).

The recharge of groundwater is an essential component of the water or hydrological balance of any watershed. It determines the availability of groundwater for extraction. The groundwater balance of an area is usually expressed as:

Groundwater Input – Groundwater Output = Change in Groundwater storage

The input is the recharge from precipitation, other sources, and subsurface inflow. Groundwater draft, groundwater evapotranspiration, base flow to streams and subsurface outflow constitute the output. Most resources of groundwater are directly recharged by the infiltration of rainfall, thereby sustaining the water potential of an aquifer.

India's Central Ground Water Board's National Groundwater Recharge Master Plan for India (2005) offers a comprehensive evaluation of the country's groundwater recharge potential. According to the plan, by implementing dedicated recharge structures in rural regions and rooftop water harvesting structures in urban areas, it is possible to add approximately 36 billion cubic meters to groundwater recharge. This endeavour is estimated to cost around US$6 billion (Rs 25,000 crores). The additional volume of groundwater constitutes approximately 15% of India's current total groundwater consumption (World Bank, 2010).

Physical measurement of the water balance is difficult and involves time-consuming and costly procedures. Numerous methods have been put forth by researchers for the estimation of natural and artificial recharge of groundwater. (Lerner et al., 1990; Scanlon et al., 2002). The use of a specific method to estimate recharge depends upon several factors and the availability of spatial and temporal data. The results vary widely with different methods. According to Scanlon et al. (2002), methods utilizing surface water and data of unsaturated zones offer estimates of potential recharge, while those relying on groundwater data provide estimates of actual recharge. Given the uncertainties involved in the estimation process, they recommend employing multiple methods to obtain more reliable results.

As mentioned earlier, the recharge of groundwater from rainfall has been studied extensively. Many different methods, both empirical and model-based have been suggested. The two most common and simple methods that are used to calculate recharge are

1. Rainfall infiltration factor and
2. Groundwater level fluctuation.

Studies carried out by several workers worldwide on the recharge potential of groundwater give different estimates. Groundwater recharge estimation relies on various methods, amongst which the key methods include numerical models, hydrological budgets, water-table fluctuations, and tracer techniques (Singh et al., 2019). Singh and Kumar (1994) estimated that the recharge by infiltration of rainfall is about 20% of the total rainfall.

Considering the very high levels of construction and concretisation, these figures may not be true for urban areas as most of the rainfall flows away as surface runoff into the drainages and streams. Also, to a large extent, the recharge happens in the surface aquifers and very little reaches the deeper aquifers. According to Ravichandran. et al. (2011) artificial recharge of confined aquifers or deep-seated aquifers with poorly permeable overburden is only possible by injection. This approach ensures instantaneous recharge without any transit or evaporation losses.

Extensive studies have also been carried out to study groundwater recharge by rainwater runoff. These have generally focused on identifying potential sites for surface recharge to the shallow aquifers in non-urban areas. Different methods have been used to study the rainfall-runoff of watersheds and to identify potential sites for groundwater recharge. Some of these are 'Agricultural non–point source' (Mohammed et al., 2004), 'Water balance approach' (Jasrotia et al., 2009), 'Thiessen polygon' (Kim et al. 2003), and 'Soil Conservation Service Curve Number (SCS-CN)' (Kadam et al., 2012). In urban areas, the recharge of groundwater normally takes place by two methods:

1. Recharge of rainwater by direct infiltration and
2. Recharge from water bodies like lakes, dams, and percolation tanks.

Additionally, in urban areas, recharge also takes place through several other mechanisms like infiltration through storm water drainages, soakaways, leakage through sewage lines and direct infiltration in parks and open areas.

An interesting study conducted by Vazquez-Sune et al. (2010) aimed to comprehend the origin and relative contribution of various sources to the total recharge of the aquifers. Their analysis, based on data samples from the aquifers of Barcelona city, reveals that the primary contributors to total recharge are water supply network losses (22%), sewage network losses (30%), rainfall concentrated in non-urbanized areas (17%), runoff infiltration (20%), and the Besos River (11%). Further, they state that a large amount of rainfall flows away as run-off due to the impervious surfaces found in cities thereby reducing surface infiltration.

Khalil et al., (2018) studied the estimated average annual areal recharge for the Mae Klong Basin in Thailand. They compared the estimates obtained from using a hydrological simulation model - Water Evaluation and Planning (WEAP) to those obtained from empirical methods. The recharge estimation using the WEAP model was 23.89% of average annual rainfall as compared to 15.63% to 28.07% recharge estimated by empirical methods.

The geospatial approach and the use of GIS and Remote sensing techniques have been used extensively by researchers to identify potential recharge zones. The use of multi-criteria analysis using thematic layers was found to be very useful for assessing potential groundwater zones in the Sidhi district of Madhya Pradesh, India (Tiwari & Kushwaha, 2020). Duraiswami et al., (2009) carried out studies in a small part of Pune city, India using a multi-criteria (parameter) approach and found that abandoned quarries occupied by water are good locations for groundwater recharge.

Adham et al. (2018) utilized a GIS-based approach to identify potential sites for constructing small dams for rainwater harvesting in Iraq's Western Desert. Their findings indicated that the success of rainwater harvesting (RWH) systems is heavily dependent on their technical design and the identification of suitable sites. In another study, Das et al. (2019) employed the analytical hierarchy process (AHP) and weighted overlay techniques to delineate the groundwater potential zones in the Puruliya district of India and categorized them into three distinct zones. Kadhem & Zubari, (2020) used the weighted overlay method (WOA) multi-criteria decision-making (MCDM) methodology to identify optimal locations for managed aquifer recharge (MAR) locations in Bahrain using various parameters like land use/land cover, geomorphology, geology, soil type, and slope, etc.

As discussed earlier, recharge by surface infiltration varies greatly and is generally limited to unconfined aquifers. Increased urbanisation and migration to cities have led to increased construction and consequently concretising of once green areas leaving less area for natural infiltration. In hard rock areas like basalts, digging wells or pits is not enough to recharge the confined aquifers. In such cases, a conduit (usually a dug well or bore well) is required to channel the harvested rainwater for recharging the aquifer.

Numerous workers have tried to estimate the groundwater recharge potential in hard rock terrain across different parts of India and have arrived at different estimates. Most of the studies prove to show a good recharge potential.

Research conducted by Athavale et al. (1983) focused on estimating groundwater recharge for two basins within the Deccan Traps, situated in the rain shadow zone of western India. The findings indicated an annual increment in the dynamic reserves of phreatic basalt aquifers. Utilizing the tritium tagging method, the mean annual recharge was determined to be approximately 40-60 mm or 7.5-8.5% of the local precipitation during the year 1980. The calculated annual input to the groundwater reserves of the two basins was approximately 31.9 and 35.4 million cubic meters.

Recharge to the Groundwater reserves was estimated as 7.3% and 9.7% of the annual precipitation using the ‘Water table fluctuation’ (WTF) method and 7.5% using the ‘Chloride mass balance’ method (CMB) method by Sharda et al. (2006) based on studies carried out in the semi-arid areas of Kheda district in Gujarat, India.

Gontia and Patil (2012) conducted an assessment of groundwater recharge in the Saurashtra region of Gujarat, India, utilizing the ‘water table fluctuation’ method and comparing it with the total recharge derived from rainfall and water harvesting structures. The study revealed that natural groundwater recharge from rainfall in the area ranged from 11% to 16% of the annual rainfall. The total recharge to the groundwater in the study area was estimated to be 390.29 hectares, with recharge through water harvesting structures contributing approximately 38.53%.

Natarajan et al. (2018) estimated the groundwater recharge at various locations in the Sirumugai area located in the Coimbatore district, of Tamil Nadu using empirical methods and the ‘water table fluctuation’ method. The findings revealed that the average groundwater recharge, based on empirical methods, ranged from 5.51 to 101.20 mm per year, while the water table fluctuation method yielded a range of 67.5 to 340 mm per year for the study area.

Rainwater Harvesting

Rainwater harvesting has been a traditional practice to enhance water availability, particularly in arid and semi-arid regions. In recent times, it has gained significant importance as an essential method to establish sustainable water sources in various regions across the world.

Rainwater harvesting (RWH) has been described and defined variously by different workers over the last few decades. The collection and storage of any farm waters, either runoff or creek flow, for irrigation use was an early definition for water harvesting given by Geddes in the 1950s (Boers, 1994). The water harvesting technique is known by different names in different regions of the world and has led to numerous definitions and classifications (Nasr, 1999).

Critchley (1991) defined water harvesting as the collection of rainwater runoff for productive use. Boers and Ben-Asher (1982) defined water harvesting as a method for inducing, collecting, storing, and conserving local surface runoff for agriculture in arid and semi-arid regions. Oweis, (2004) defined it as the concentration of rainwater through runoff into smaller target areas for beneficial use.

Kahinda et al. (2008) defined it as the collection, storage and use of rainwater for small-scale productive purposes. Rainwater harvesting has been described as a technique by which rainwater that falls upon a roof surface is collected and routed to a storage facility for later use. (Debusk, & Hunt, 2014).

Rainwater harvesting is a simple, low-cost technique that involves the capture and storage of rainwater and/or groundwater. (Aroka, 2010). Rainwater harvesting is the process of capturing, conveying, and storing rainwater for future use. (Liaw, & Chiang, 2014)

According to Kim et al. (2005), rainwater harvesting is one of the best techniques among the different methods for restoring the natural hydrologic cycle and fostering sustainable urban development.

Rainwater Harvesting (RWH) stands as one of the oldest and most prevalent methods employed worldwide to tackle water supply requirements. With advancements in technology, numerous countries are now endorsing the revitalized adoption of RWH practices to meet the escalating water demands arising from climate, environmental, and societal shifts (Amos et al., 2016). Local conditions and the diverse methods practised by farmers in the area are crucial determinants influencing water harvesting techniques (Boers, & Ben-Asher, 1980).

In recent times, the practice of RWH has been neglected especially in cities where the water is supplied directly to the households. However, necessitated by increasing water shortages due to population growth, droughts and pollution, rainwater harvesting is increasingly being used worldwide. (Nolde 2007, Meera and Ahamed 2006). Though there is still a general lack of awareness in the common citizen and a certain apathy by the local governments towards a systematic approach to managed recharge, the increasing demand for water in urban areas of developing countries has renewed the interest in groundwater and Rainwater harvesting.

With the growing requirements for water and the increasing stress on existing water resources, the use of rainwater harvesting has gained recognition as a solution to alleviate water scarcity issues. Gathering and storing rainwater from rooftops and various surfaces serves multiple purposes, such as irrigation, household consumption, and even recharging groundwater aquifers. By implementing systematic rainwater harvesting, it becomes possible to significantly enhance the water supply locally and also aid the recharge of groundwater to both unconfined and confined aquifers.

Different methods of rainwater harvesting are used the world over. Choosing a particular method is based on various factors like the amount of rainfall, the purpose of the water use, and the available resources. Some of the commonly used rainwater harvesting methods are listed below :

1. Rooftop harvesting: This method involves collecting rainwater that falls on rooftops and storing it in tanks or underground reservoirs. The collected water can be used directly for household needs such as flushing toilets, washing clothes, and watering plants.

2. Surface runoff harvesting: This method involves collecting rainwater that runs off from paved surfaces, such as roads, parking lots, and sidewalks. The water thus collected can be used for irrigation or groundwater recharge.

3. Contour farming: This method involves creating ridges and furrows along the contours of sloping land to capture and store rainwater. The stored water is generally used for irrigation purposes.

4. Infiltration trenches: This method involves digging trenches along the contour of sloping land to capture rainwater and allow it to seep into the soil. This method is usually used for groundwater recharge.

5. Percolation pits: This method involves digging deep pits and filling them with coarse gravel or rocks to allow rainwater to percolate into the ground. This is a method that is commonly used for groundwater recharge.

6. Check dams: This method involves building small dams across the flow of a stream or river to slow down the water flow and allow rainwater to percolate into the ground.

7. Rain gardens: Rain gardens are shallow depressions in the ground that are filled with plants and mulch to capture the rainwater and help it percolate into the soil below. These gardens can help reduce stormwater runoff and recharge groundwater.

8. Green roofs: Rooftops covered with vegetation are known as ‘Green roofs.’ Such roofs help to capture rainwater and reduce stormwater runoff. The

vegetation helps to absorb the rainwater and release it slowly over time, which can help reduce the risk of flooding.

Each method of rainwater harvesting has its unique benefits and limitations. Choosing the right method depends on factors such as the amount of rainfall in the area, the proposed use of the harvested water, and the available resources and infrastructure.

Roof Top Rainwater Harvesting

Rooftop RWH systems have been implemented in many countries as a means of augmenting water supplies, reducing demand for municipal water supplies, and conserving water resources. The use of RWH for groundwater recharge is particularly important in areas where surface water resources are limited or unreliable. In these areas, groundwater can become a vital source of water for various purposes, including drinking, irrigation, and industrial use. However, the overexploitation of groundwater resources can lead to a decline in water levels and reduced availability. Artificial recharge using groundwater through rooftop RWH can help to maintain and even improve the health of the aquifer and ensure its sustainability and is increasingly being used nowadays to maintain the water balance of an aquifer. It is now a common practice globally though still on a very limited scale. (Figure 22)

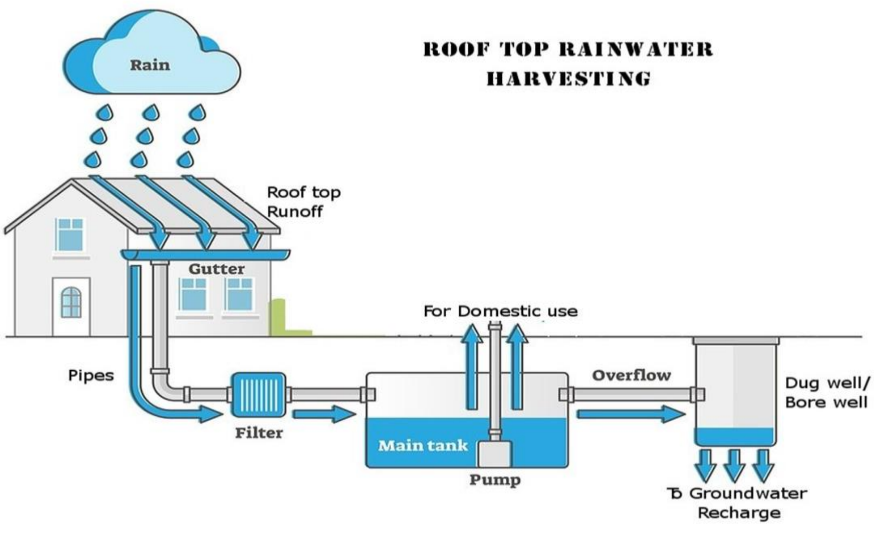


Figure 22 Schematic of a Roof Top Rainwater Harvesting system

Groundwater recharge occurs through two methods – natural and artificial means. Natural recharge involves rainwater or surface water seeping or infiltrating into shallow, unconfined aquifers through exposed and weathered soil surfaces. On the other hand, in artificial methods, the recharge to the aquifer is done by using simple civil structures like check dams, etc. which impound the water (WaterAid in Nepal, 2011).

The Sydney Opera House, Australia, the Parliament House in New Delhi, the Queens Botanical Garden in New York, USA and the cities of Chennai in India and Singapore are prime examples of the effectiveness of rooftop rainwater harvesting in addressing the scarcity of water and providing a dependable source of water.

Major water conservation gains by the use of rainfall-runoff water harvesting from residential building rooftops, especially in residential areas were also reported in Greater Amman and the entire Kingdom of Jordan. A net increase of 2.387 MCM/yr. & 6.229 MCM/yr. were seen for Greater Amman and the Kingdom of Jordan, respectively (Preul, 1994).

Liaw, & Chiang (2014) carried out a study using a survey of households and a simulation model to investigate the feasibility of rainwater harvesting from rooftops for household use in Taiwan. They estimated that approximately 32.4% of domestic water demand can be met from the available potential through RWH. They further concluded that rooftop rainwater harvesting can provide a viable option for providing an alternative water supply in urban areas.

Small dams originally built for flood control around Gadarif city in Central Sudan provide nearly 2200 cubic metres /day of groundwater, which is approximately 12% of the total supply of the city (Ibrahim, M. B., 2009).

In addition to replenishing and storing water for future needs, the implementation of Rainwater Harvesting (RWH) leads to significant water conservation. Installing RWH systems enhances the water self-sufficiency of cities and can effectively defer the necessity for constructing new centralized water infrastructures (Steffen et al., 2012).

Studies by Jebamalar et al. (2012) on RWH systems in Chennai city located in the southern part of India, indicate that the storage capacity increased from 1.7 MCM in 1999-2000 before the implementation of RWH to 32.77 in 2009-2010 after the implementation of the RWH system. The change in storage was calculated using the GEC- 197 norms and water level fluctuation method.

The success of rainwater harvesting relies on several factors, including the annual rainfall patterns, water-retaining capacity, and run-off coefficient of roofs. Remarkably, an extensive green roof can retain as much as 55% of the annual rainfall, effectively controlling urban stormwater run-off and reducing the risk of urban flooding (GhaffarianHoseini et al., 2015).

A study by Rao, & Giridhar (2014) in the igneous terrain of Hyderabad City, India using three monitoring bore wells showed a significant improvement in groundwater levels due to recharge from rooftop RWH. In the study area, artificial recharge of groundwater through rooftop rainwater harvesting was accomplished by constructing three recharge structures, each with a capacity of 100,000 litres. These structures were strategically placed at different locations, and each had two recharge shafts to inject rainwater into both the unconfined and confined aquifer systems.

The use of the Rainwater Harvesting Recharge (RWHR) technique to recharge local aquifers in modern cities is a cost-efficient method as this saves the need for space and the cost required for building water storage tanks (Nachshon et al., 2016).

Nachshon et al., (2016) in their groundwater research on Tel-Aviv, Israel calculated that for the total surface area of Tel-Aviv and an annual precipitation of 550 mm, there was an increase of approximately 5.5 MCM in groundwater recharge. This is 300% higher when compared to non-RWHR conditions.

Campisano et al. (2017) believe that rainwater harvesting is a good alternative approach for water supply in cities across the world. Further, they add that RWH also helps in other ways like benefits like flood control even though many existing RWH systems are focussed solely on the objective of conserving water.

In a study of Rainwater Harvesting Techniques (RWHT) to reduce water scarcity in the drylands of Africa, Tamagnone et al. (2020) found that the use of RWHT can lead to a runoff retention of up to 87%. According to Kadhem, & Zubari's (2020) research on artificial groundwater recharge through rainfall in Bahrain, it is possible to recharge groundwater aquifers within a short period during extreme rainfall events when large amounts of water are available by improving the infiltration through gravity injection wells into the deep aquifers.

A major finding of studies by Campisano et al. (2017) on RWH implementation is that economic constraints and local regulations are a big factor in the implementation and technology selection of RWH systems. Further, they state that despite design protocols having been set up in many countries, recommendations are still often organized only to conserve water without considering other potential benefits associated with the multiple-purpose nature of RWH.

Further, they suggest that Rainwater Harvesting (RWH) is a type of Sustainable Drainage System (SuDS) or Low Impact Development (LID) approach that involves detention-based strategies. RWH can serve as an additional measure to decrease the volume, peaks, and periodicity of urban runoff, provided that the RWH systems are designed properly.

Cholke, S. P. (2019) in a study of the rooftop Rainwater Harvesting Potential of a college Campus in Shrirampur in Maharashtra, India quantified that 78.44 of the demand of total groundwater requirement by the college can be met by doing rooftop RWH in the campus.

By employing RWH systems which are tank-based and other at-the-source technologies, such as urban-catchment distributed detention, the adverse effects of urbanization growth on the stormwater drainage system (Brodie, 2008; Burns et al., 2015) may be alleviated, and it is possible that environmental impacts on receiving water bodies could be mitigated (Hamel and Fletcher, 2014).

The recharge potential of rooftop rainwater harvesting is the capacity of a particular rooftop to harness the water that falls on it in a certain year during all the rainy days. The annual yield of water or the recharge potential is the product of the roof type, the total area, and the annual precipitation in that area.

India receives a significant portion of its rainfall during the monsoon season. The southwest monsoon typically arrives in June and continues until September, while the northeast monsoon occurs from October to December. Pune is in the Western part of India and receives rainfall only from June to September.

The recharge potential of rooftop rainwater harvesting can be calculated using the formula given by Gould (2015) and a co-efficient of 0.80 (concrete roofs) as proposed by Pacey, et al. (1989). (Table 1)

S = R*A*Cr

Where:

S = Potential of roof rainwater harvesting (in litres.)

R = Average annual rainfall in mm.

A = Roof area in Sq. m. Cr = Coefficient of Run-off

Table 1 Typical values of Runoff coefficients for various surfaces

TYPE OF CATCHMENT	COEFFICIENTS
ROOF CATCHMENTS	
Tiles	0.8 -0.9
Corrugated metal Sheets	0.7 - 0.9
GROUND SURFACE COVERINGS	
Concrete	0.6 - 0.8
Brick pavement	0.5 -0.6
UNTREATED GROUND CATCHMENTS	
Soil on Slopes less than 10 %	0.0 - 0.3
Rocky natural catchments	0.2 - 0.5

Source: Pacey, Arnold, & Cullis Adrian, 1989

Based on the formula given by Gould (2015), Vaddadi et al. (2022) estimated the potential for groundwater recharge available from roof-top Rainwater harvesting for Pune city to be 49.05 million cubic meters (MCM) and that effective recharge using RWH techniques could supplement the groundwater annually by about 22 - 25 MCM.

Groundwater and sustainability

Groundwater accounts for approximately 99% of the Earth's liquid freshwater, making it an exceptionally vital resource. Its significance lies in its capacity to provide essential drinking water, ensure food security, adapt to climate variations, support biodiversity, safeguard surface water reserves, and contribute significantly to the attainment of the United Nations' Sustainable Development Goals.

Over the past two decades, a multitude of strategic frameworks and methods have been used worldwide to address the sustainable and systematic replenishment and enhancement of groundwater resources. Brundtland in 1987, defined sustainable development as the idea that human societies must live and meet their needs without compromising the ability of future generations to meet their own needs.

Koh et al. (2020) believe that a sustainable city is a resilient habitat for its inhabitants to plan and manage their current and future well-being by achieving a long-term balance.

Das, & Burke (2013) who worked on Participatory Groundwater Management in Andhra Pradesh believe that an intervention can be termed sustainable only if it has met its stated objectives. Sustainable use of water resources also involves balancing the needs of various stakeholders, including communities, industries, and ecosystems.

According to Alley, & Leake (2004), groundwater sustainability is the development and use of groundwater resources in a manner that can be maintained for an indefinite time without causing undesirable environmental or socioeconomic consequences.

Villholth, & Sharma (2005) suggest that good groundwater management requires the integration of science into management decisions and that its strategies should be focussed on balancing the demand with supply. Mehta (2015) points out that the prevailing approach has primarily focused on resource development rather than resource management. Consequently, this has led to haphazard development and over-exploitation in certain regions, while others have suffered from contamination issues.

Managed aquifer recharge (MAR) is a potential solution to the issue of groundwater depletion and shortages. According to Gale et al. (2006) and Sharma (2011), MAR involves a holistic approach to increasing water availability by utilizing all types of groundwater recharge programs to generate water supplies including the use of sources that would otherwise go to waste. According to Oaksford (1985), Managed Aquifer Recharge (MAR) refers to a deliberate strategy of augmenting groundwater by enhancing the natural replenishment or percolation of surface water into aquifers. This can make more groundwater accessible for extraction.

Managed Aquifer Recharge (MAR), also known as enhanced recharge or earlier referred to as 'artificial recharge,' involves the intentional redirection of surface water to the groundwater reservoir. This is achieved by employing various techniques to modify the natural movement of surface water.

The term Managed Aquifer Recharge was proposed by UNESCO-IHP (2005) as an alternative term for artificial recharge. A detailed environmental and social sustainability assessment of 28 schemes from 21 countries by Zheng et al. (2022) showed that MAR is a sustainable technology. According to UNEP (1998), the basic objective of Managed Aquifer Recharge (MAR) is to increase the availability of groundwater by storing excess surface water for future use and replenishing depleted groundwater aquifers that resulted from over-abstraction thereby enhancing stability However, it is important to note that MAR alone cannot solve the issue of overexploitation of aquifers and may even increase the rates of abstraction. Work by the Global Water Partnership (GWP) in partnership with the Caribbean Environmental Health Institute (CEHI) (2010) shows that it is crucial to incorporate comprehensive planning and operation to ensure the successful and sustainable implementation of MAR projects

According to Dillon et al. (2022), Managed Aquifer Recharge (MAR) is a process that supplements groundwater by utilizing accessible surface water. It works in association with the conjunctive use of surface water and groundwater to maintain water balance. Conjunctive use, as defined by Evans and Dillon (2019), involves the coordinated utilization of both surface water and groundwater to maximize their combined advantages.

One of the most commonly used frameworks in sustainable water management is the Integrated Water Resources Management (IWRM) framework. IWRM is a conceptual framework that aims to depict the complexity of water-related decisions and underscore the significance of balancing perspectives from various stakeholders (Grigg, 2008).

According to Ben-Daoud et al. (2021), IWRM (Integrated Water Resources Management) is a systematic approach that advocates for the coordinated development and management of water, land, and associated resources. Its objective is to optimize economic and social welfare fairly while ensuring the preservation of essential ecosystems' sustainability.

According to Godinez-Madrigal et al. (2019), GWP (2009) and Hooper (2015), the objective of IWRM is to achieve a balance between meeting the increasing water demand for sustaining a growing population's livelihoods and conserving water resources to ensure a sustainable water supply.

Worldwide, several organizations have adopted the IWRM approach, such as the World Water Council (Smith and Clausen, 2015), the Global Water Partnership (GWP, 2000), and global organizations like the United Nations, World Bank, etc. (GWP, 2009).

Integrated Urban Water Management (IUWM) presents a structured approach to planning, designing, and administrating urban water systems. As explained by Biswas (1981), IUWM originates from the broader concept of integrated water management, which involves the holistic management of all facets of the water cycle within a specific catchment area.

According to Rogers (1993) and Fletcher et al. (2007), IUWM considers the roles and interdependencies of the diverse organisations engaged in the management of the urban water cycle. and combines the management of water supply, groundwater, stormwater, and wastewater. Further Fletcher (2015) states that IUWM by its very nature encompasses a much wider scope than the terms solely focused on urban drainage management.

The IUWM framework focuses on integrating different water management elements into one approach, including using MAR to increase water availability, improve water quality, and manage groundwater levels in urban areas. It emphasizes integrating diverse elements of water management into a unified approach, including Managed Aquifer Recharge (MAR) as a method to enhance water availability, and water quality, and effectively manage groundwater levels in urban regions.

The term IUWM gained popularity in the 1990s, as seen by its usage in works by Geldof (1995), Harremoes (1997), and Niemczynowicz (1996). Geldof (1995) was one of the first authors to propose a logical framework that included issues of scale, levels (including institutional and social aspects of management), and assessment thereby contributing to the overall concept of IUWM.

According to Page et al. (2018), Aquifer Storage and Recovery (ASR) is a deliberate groundwater recharge technique in Australia that involves using injection wells and infiltration basins. This method facilitates water recovery, and storage and offers environmental benefits to the aquifer.

Furthermore, Page et al. (2018) propose that Managed Aquifer Recharge (MAR) could significantly enhance urban water management by providing storage options for diverse water qualities to serve various purposes. Das (2019) identifies four major components of the urban water cycle: river water, lake water, groundwater, and recycled grey water. Integrated management of these components forms the foundation of a smart city. Gale et al. (2005) emphasize that a successful application of MAR necessitates a water source, adequate aquifer space for water storage, and appropriate mechanisms for later water recovery for beneficial use. In line with water management, Das et al. (2022) suggest that placing supply and demand management at the core (instead of vice versa) is essential for effective water management.

Managed Aquifer Recharge (MAR) serves the primary objective of augmenting groundwater resources through the storage of surplus surface water for future use, and the replenishment of groundwater levels that may have suffered depletion due to over-extraction, thereby promoting sustainable groundwater development.

CHAPTER III

RESEARCH METHODOLOGY

Introduction

Amongst the various natural resources, groundwater is one of the most valuable. The over-exploitation of groundwater especially in urban areas has led to the depletion of aquifers and caused several environmental problems. One of the main objectives of this work was to understand the potential for recharge of the groundwater in the urbanised area of Pune city. Hence, it is important to identify potential recharge areas both for unconfined as well as confined aquifers. Accordingly, the calculation of rooftop areas and the creation of spatial maps indicating the potential recharge zones, considering various factors such as the extent of urbanisation, local geology, soil cover, slope, etc. was taken up. The acquired data was used for further analysis to formulate strategies for systematic recharge and scientific water management.

Methodology

The methodology employed a combination of remote sensing data, rooftop area data obtained by digitization, geology maps, ward information, population data, well locations in the city, land use/land cover data analysed from Landsat imageries and other thematic data. The process to achieve the overall research objective of estimation of potential groundwater recharge was broadly divided into four broad steps shown below:

Step 1: Previous work and literature survey

Step 2: Data Collection

Step 3: Data Processing and Analysis

Step 4: Field Implementation of rooftop RWH system

1. **Step 1: Previous Work and Literature Survey**

A study of previous work and published literature on the area under study was done initially. This was followed by an in-depth study of published articles and scientific papers on Rainwater harvesting, the use of rooftop runoff in urban areas for RWH, and literature on systematic and managed aquifer recharge in urban areas.

The literature review and previous work related to the area under study have been detailed in Chapter 2

2. **Step 2: Data Collection**

The initial stage of the methodology involved gathering pertinent data. The data used for this study included remote sensing data, thematic maps such as drainage, geology, soil, slope, and rainfall, ward information, population data, and well locations in the city. A summary of the collected data and its source are summarized in Table 2.

2.1 Satellite Data:

The satellite imageries used were Landsat Imageries and the Cartosat DEM from Bhuvan.

Landsat: Landsat 8 imageries were used for LULC studies. Landsat 8, an American Earth observation satellite, was launched on 11 February 2013. It is the seventh of the eight satellites in the Landsat program to successfully reach orbit. It is managed jointly by NASA and the United States Geological Survey (USGS). Georeferenced and atmospherically corrected satellite imagery downloaded from NASA's (National Aeronautics and Space Administration) open-access web portal. (https://earthexplorer.usgs.gov/) was used to create LULC maps for the area under study. Satellite data at a four-year interval for the years between 2003 and 2019 for Pune City was downloaded.

Table 2 Data Sources

Data Type	Resolution / Scale	Thematic layer / Use	Data Source
Landsat 8 OLI/TM	30 m	Land Use / Land Cover	Earth Explorer - USGS
Cartosat DEM	5 m	Slope, Drainage density	Bhuvan - ISRO
District Resource Map - Geology	1: 250,000	Geology (Lithology)	Geological Survey of India
Rainfall Data	0.25 x 0.25 degree	Rainfall	India Meteorological Department.
Soil Map.	1: 250,000	Soil distribution	National Bureau of Soil Sciences and Land Use Planning
Google Earth Pro	-	Rooftop Area	Google Inc
Well data	-	Well density	Field survey and Pune Municipal Corporation

Cartosat: The Cartosat series of optical Earth observation satellites are developed and operated by the Indian Space Research Organisation (ISRO) as part of the Indian Remote Sensing Program. Cartosat-3 serves as a replacement for the Indian Remote Sensing Satellite (IRS) series. Cartosat-3 boasts a remarkable panchromatic resolution of 0.25 meters, positioning it as one of the world's highest-resolution imaging satellites during its launch. This significant enhancement in resolution represents a substantial improvement over the earlier Cartosat series satellites.

Google Earth Pro: Google Earth offers high-resolution three-dimensional satellite imagery, serving various purposes. It involves the integration of satellite images, aerial photographs, and GIS data onto a three-dimensional globe. Google Earth Pro, the open-source satellite imaging software was used to digitise rooftop areas. Rooftop areas from about 35 wards in the city were digitised to provide information on the rooftop areas. The rooftop analysis was conducted to assess the potential for harvesting rainwater from rooftop surfaces in the study area.

2.2 Thematic data:

Geology: Geological data was obtained from the District Resource Map of the Geological Survey of India (GSI, 2001), georeferenced and digitized to obtain the geological map of the area.

Drainage: Survey of India toposheets were used as the reference map by georeferencing and digitisation and for generating the drainage density. Density was calculated using the point density method in QGIS.

Slopes: The slopes for the area were calculated in degrees from a Cartosat DEM image of 5 m resolution.

Soil: Soil data was obtained from the soil map of the Indian National Bureau of Soil Survey and Land Use Planning (NBSS and LUP). The classification of soils given by NBSS and LUP is used in this study.

Rainfall: High Spatial Resolution [(0.25 x 0.25 degree) 'Gridded Rainfall Data Set Over India] data available from India Meteorological Department. was used to create the rainfall map. (https://imdpune.gov.in/cmpg/Griddata/Rainfall _25_ Bin.html).

2.3 Demographic data:

Ward information and population data were obtained from the Pune Municipal Corporation's website to assess the study area's demographic and population density across the city.

2.4 Well data:

Collection of Well data: To achieve the first objective of mapping the area under consideration for groundwater wells (both dug and borehole) a data collection survey tool based on the Open data kit (ODK) was designed and tested by carrying out training and testing of the tool (survey form) at various training workshops conducted on Open data collection tools. The digital survey tool was used to collect data on wells. Important parameters obtained from the survey are geographical location (Latitude and longitude), well depth and water depth. In addition, Open data available from the Pune Municipal Corporation (PMC) was also obtained and used for the analysis. The collected field data using ODK was used to validate the open data sourced from PMC.

Server for collection of data: An important aspect of the survey tool is that the data was collected using an app, uploaded and stored on a server (cloud-based) which was configured specifically for this purpose. The collated data was downloaded and visualized on the geospatial map using QGIS or Google Maps.

3. **Step 3: Data Processing and Analysis**

3.1 LULC study:

The physical and biological cover that includes water, vegetation, bare soil, and/or man-made structures over the surface of land constitutes Land cover. Downloaded Landsat imagery data was used for analysis. The area of study was classified into four land cover classes namely: Barren, Water, Built-up and Vegetation cover. Ground truth measurements from approximately 122 different locations across Pune city were used to train satellite data from 2019 to classify Pune city into four land cover classes namely: Barren, Water, Built-up and Vegetation cover.

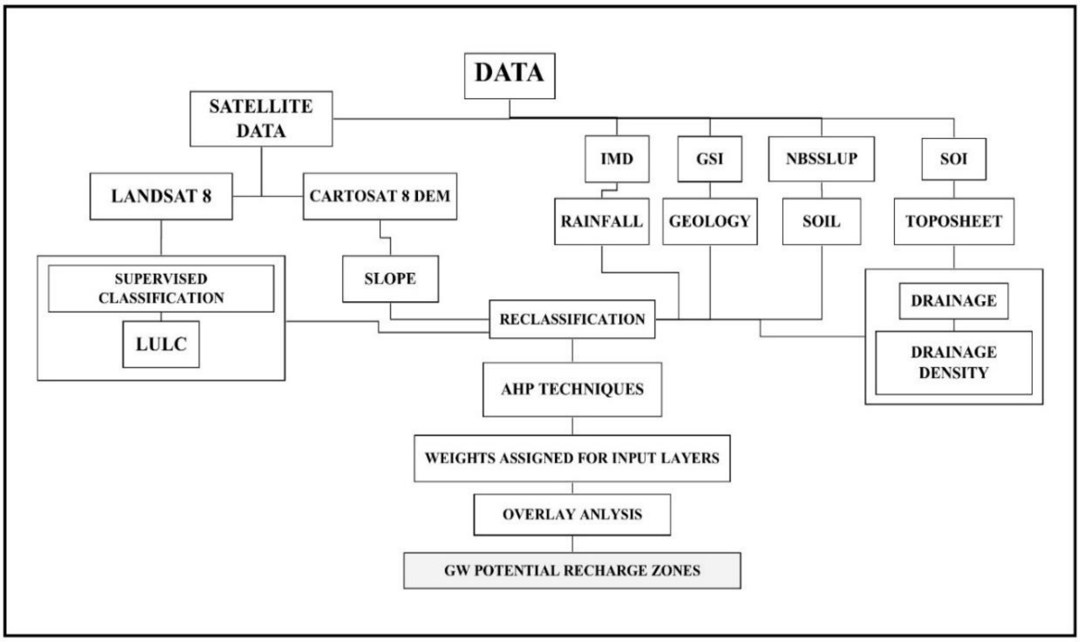


Figure 23 Workflow used in the analysis

The classification was done in GIS software using a function called 'Maximum Likelihood Classifier'. The classifier works by assigning probability weights to each pixel of the satellite image based on our training samples. The priori probabilities allow the function to then classify each pixel into either of the four decided classes, by calculating the maximum likelihood of a pixel to belong in a particular class. The same training samples are corrected for subsequent years based on visual image interpretation of true colour and false colour composite satellite images.

3.2 Thematic maps:

Geospatial data (Table 2) was processed using QGIS software. Four or more discrete classes for each of the thematic layers were obtained by reclassifying the input thematic layer data classes. Weight generation and associated functions like the Consistency Index and Consistency Ratio were calculated by the AHP method in Microsoft Excel. The workflow used for the study is shown in Figure 2.

3.3 Analytical Hierarchy Process (AHP) and Multicriteria Decision Analysis (MCDA):

In the study, an MCDA approach using AHP was used for the delineation of potential groundwater recharge zones. The AHP method which is used to assign weights to criteria based on their relative importance was used to evaluate and rank the multiple criteria. These weights were then used to evaluate the potential recharge zones. The criteria used include land use and land cover, soil type, geology, drainage, slope, and rainfall. The potential recharge zones were identified and then ranked based on their suitability for groundwater recharge.

3.4 Frequency ratio analysis:

The Frequency Ratio (FR) technique/model is employed to assess the likelihood of an occurrence by analysing relationships between dependent variables. The FR method is now widely adopted for mapping groundwater recharge potential zones. This statistical approach is widely utilized to determine the probability of groundwater potential areas by studying the associations between dependent variables, such as springs or wells, and independent variables that influence groundwater occurrence or recharge (Oh et al., 2011; Naghibi et al., 2016).

In this study, a data set consisting of 3074 wells was used to calculate the FR for each of the considered thematic factors. FR values were calculated for each of the classes of the thematic layers and the frequency of the wells

– (both Dug wells and borewells) and FR maps for each of the classes were prepared to understand the relationship of the wells to each of the classes.

3.5 Rooftop area and runoff volume calculation

One of the major aims of the study was to estimate the potential for recharge using rooftop rainwater in parts of Pune city using GIS techniques. A pilot study was initially carried out. For this, 68 apartment buildings from seven areas located in different parts of the city were chosen to carry out a representative study of rainwater that is available for recharge. Rooftop areas of the 68 apartment blocks were digitised using the polygon tool in Google Earth Pro (Figure 24).

Representative rooftop areas were verified by ground checks and from the management of the societies. The surface areas thus obtained were used to calculate the potential. A comparison of physical measurements for 9 representative buildings with the digitised measurements showed a 95% accuracy for the digitisation. Location and some other attributes of 132 wells (bore and dug) were also obtained from across the city to understand the population of wells that are being used for abstraction and those being used for recharge from the precipitation.

Based on the pilot, the digitisation (tracing and measurement) of the rooftops was extended to 35 wards in different areas of the city. The area was then multiplied by the mean annual rainfall and the run-off coefficient to calculate the volume of rainwater that could be harvested. This volume was then used to estimate the potential recharge of deep aquifers.

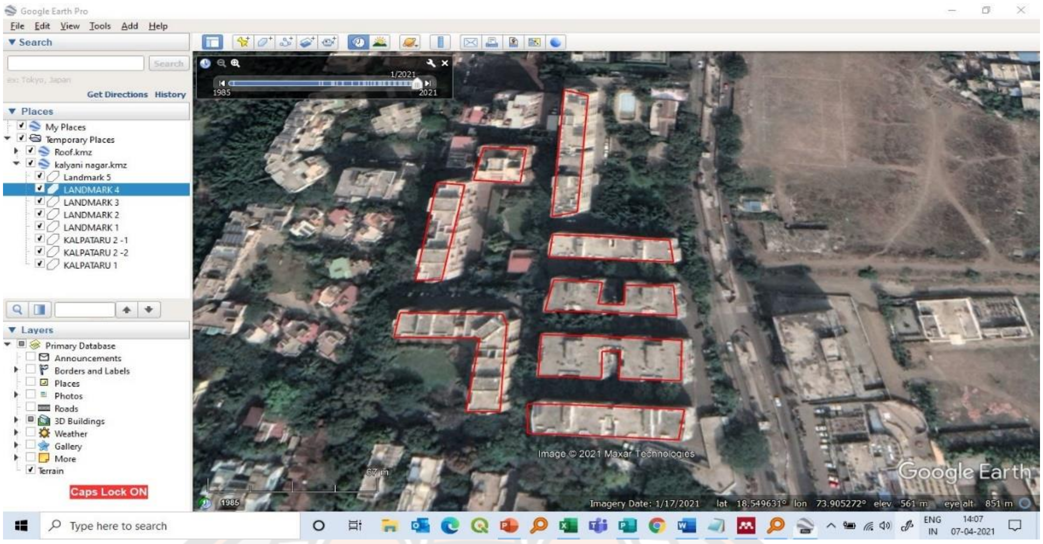


Figure 24 Sample image showing digitisation of roof tops using Google Earth Pro

4. Step 4: Field Implementation of Rooftop RWH system

Surface infiltration and recharge exhibit significant variations and are typically confined to unconfined aquifers. Increased urbanization and migration to cities have resulted in increased construction activities, leading to the concretization of formerly green spaces thereby decreasing the areas for natural infiltration. In hard rock regions, such as basalts, wells or pits are insufficient to recharge confined aquifers. A conduit, usually a dug or bore well, is necessary to channel the harvested rainwater to recharge the deeper or confined aquifers. A generally accepted approach is to use existing boreholes for recharge.

An experimental RWH system to harness the rooftop run-off was implemented in the field to check the efficacy of the technique. About four existing bore wells in a medium-large residential apartment complex were used as recharge wells. For implementation two methods: – 1) Pit based, 2) PVC cylinder with sand filters and 3) PVC cylinder with steel mesh filter was designed and used for recharge of the confined/deep aquifers in the area of study.

4.1 Pit-based filter:

A pit-based setup comprises a square or circular pit containing at least three layers of sand of different sizes and a layer of charcoal or brick (Figure 25). The harvested rooftop water is then channelled into the borehole through this sand filter. In the study, a square pit measuring 2 m x 2 m x 2.6 m was excavated around a pre-existing borewell with the casing of the bore well located at the centre of the pit (Figure 26). The pit is lined with bricks and mortar. Holes were drilled in the casing pipe at the bottom of the pit, and a nylon mesh was wound around the pipe. Various filtering materials were placed in the pit in the layers as shown in the diagram.

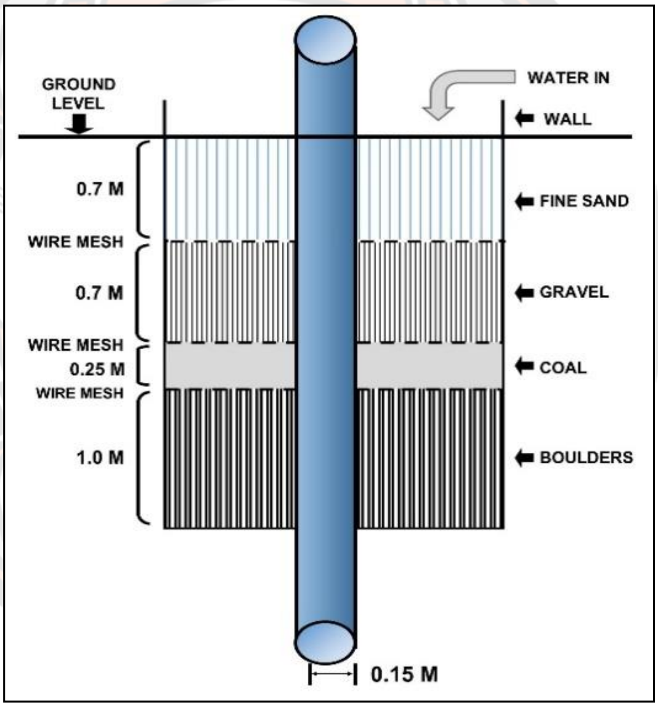


Figure 25 Schematic of recharge pit

Water that falls into the pit is filtered through this four-stage filtration system before it enters the bore through the openings in the casing pipe. The advantage of this system is that it can filter large volumes of water, especially during storms and heavy rainfall situations. The drawback of this pit-based system is the cost of initial construction and the work involved in the regular maintenance. This generally is a deterrent to its implementation by individuals and housing colonies.

Figure 26 Bare pit with brick lining for recharge purposes

4.2 PVC cylinder with sand filter.

The cylindrical plumbing pipe-based PVC filter was constructed by utilizing standard-sized plumbing materials readily accessible in the local hardware stores. It employs the conventional method of three or four stages of water filtration, utilizing locally available sand as the medium. The filter consists of three varying sizes of sand and gravel which filter the water before it is channelized into the borewell. (Figures 27 & 28).

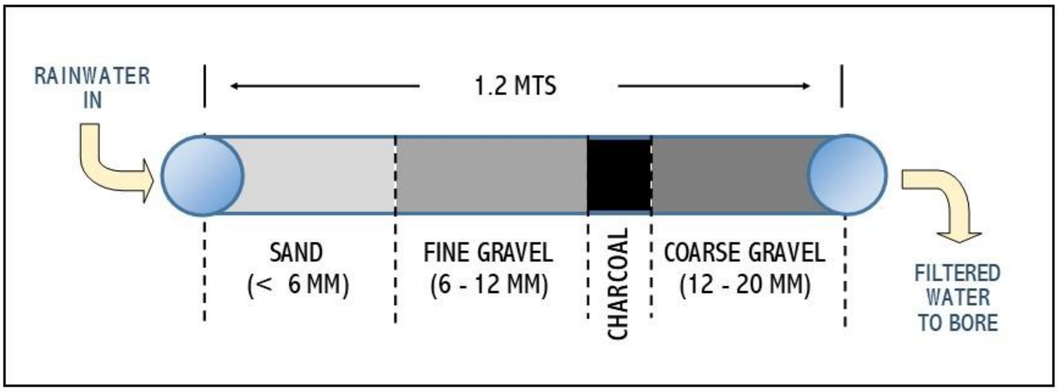


Figure 27 Schematic of PVC cylinder-based filter (Diameter of pipe is 150 MM)

The low construction cost of the PVC filter system makes it advantageous over the pit-based system. However, periodic cleaning of the filter presents a challenge, requiring either complete removal of the sand or backflushing under pressure.

Figure 28 Installed PVC barrel-based sand filter

4.3 PVC cylinder with a steel mesh filter.

To address the above challenges, another PVC pipe-based filter was designed and constructed using stainless steel mesh as the filtering medium. (Figures 29 and 30). The filter is constructed using a 100 mm diameter PVC pipe with stainless steel filter mesh wrapped around it. This barrel is enclosed within a larger 150 mm diameter PVC pipe. Water flows from the rooftops through the inner pipe, screening out leaves and debris before passing through to the outer cylinder and being channelled to the borewell for recharge. The quality of the water is maintained by using a drain plate on the roof and employing a first-flush system to drain out the first rainwater of the season.

This filter is cost-effective, with a prototype constructed for less than 50 USD. With mass production, the filter's cost can be further reduced. Additionally, the filter is lightweight, easy to assemble, and simple to clean using a backflush method. The filter's lifespan is dependent on the grade of the PVC pipe utilized and is estimated to be approximately 15 years. The lifespan can be significantly increased if protected from direct sunlight.

The detailed analysis to delineate the potential zones and calculate the groundwater available from run-off are presented in the next chapter.

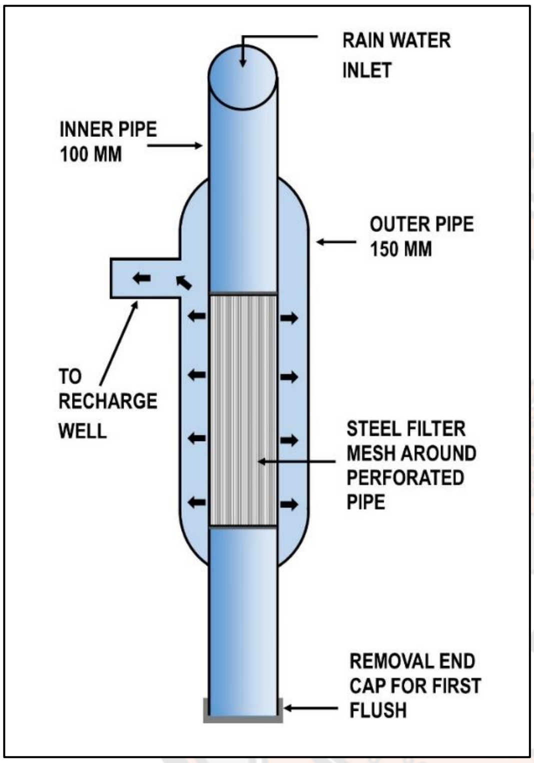


Figure 29 Schematic of stainless-steel mesh-based PVC filter

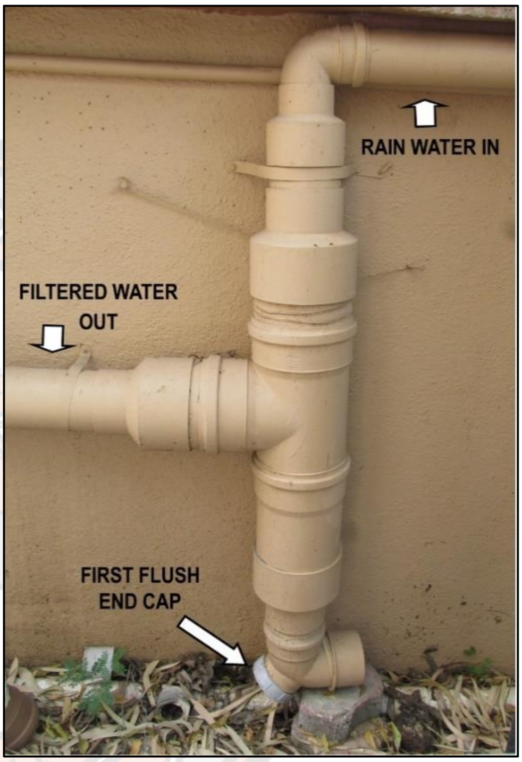


Figure 30 Installed stainless-steel mesh-based PVC filter

CHAPTER IV

ANALYSIS

Introduction

The rapid urbanization of cities has resulted in a significant increase in the demand for natural resources, especially for good quality water for both domestic and industrial consumption. Inevitably, there is also an increased requirement for water for irrigation and agriculture to cater to the needs of the growing population. This puts a major challenge on city planners and state officials to provide an adequate quantity and quality of water.

Water is a crucial resource for sustainable development and the survival of humanity and ecosystems alike. The rapid growth of cities has brought about anthropogenic changes that have caused environmental and social changes in the urban environment. As populations and the demand for housing increase, cities expand and industrial growth accelerates, resulting in enormous pressure on both land and resources and essential resources like water. Therefore, providing an adequate quantity and quality of water is a major challenge for the city administration.

The hydrological system in urban and peri-urban areas is deeply affected by urban development. Groundwater depletion and the decreasing availability of groundwater have become major concerns globally. Thus, there is a need for effective management strategies to conserve and replenish groundwater resources. Groundwater recharge processes in urban areas differ significantly from those in non-urban areas. The increasing construction and concretising practices result in water runoff into drains, leaving very little water available for infiltration. In such conditions, managed recharge by harvesting rainwater can play a critical role in augmenting local water supply from both unconfined and confined aquifers.

This study investigates the potential of rooftop rainwater harvesting (RWH) for recharging both unconfined and confined aquifers in an urban context. Using RS and GIS techniques, the study aimed to identify potential groundwater recharge zones using a multicriteria analysis approach and the Analytic Hierarchy Process (AHP) and to determine the recharge potential from rooftop rainwater harvesting for recharge through direct injection to confined or deep-seated aquifers for Pune city.

This chapter details the work carried out which includes the identification of zones with potential for artificial recharge across Pune city, considering urban factors like land use and other factors. Analysis of the Frequency ratio and the calculation of Rainwater Harvesting (RWH) recharge potential using roof-top areas and other geospatial techniques are also discussed.

LULC Studies

Most cities in the world are facing the increasing problems of urban spread, loss of vegetation/agricultural land, environmental pollution, and rapid population increase. Further, the rate of increase in population, industrial development and urbanization has increased manifold in recent years. The urban growth for India is ~30 % (2011 census). Also, the UN State of the World Population Report of 2007, states that by 2030, 40.76% of the country's population is expected to reside in urban areas.

Land cover encompasses the various physical and biological elements that overlay the Earth's surface, encompassing water bodies, vegetation, exposed soil, and artificial structures. Understanding geographical LULC change in urban areas is the first step in formulating strategies for guiding environmentally sustainable growth. By analysing changes in urban areas, rate of changes and trends using multi-temporal remote sensing images, essential information to get insights on the relationship between urban expansion and the varying social, environmental, and economic conditions can be gathered.

Keeping in mind the objective of the present work, an analysis of the land useand land cover changes that have occurred in Pune city over the last two decades was conducted by studying satellite data from 2003 to 2019. Ground truth measurements from 122 locations across Pune city were used along with geometrically referenced and atmospherically corrected satellite imagery downloaded from NASA's (National Aeronautics and Space Administration) open-access web portal (https:// earthexplorer.usgs.gov/) to classify Pune city into four land cover classes namely: Barren, Water bodies, Built-up and Vegetation cover. The classification was done in GIS software using a function called 'Maximum Likelihood Classifier'. The classifier works by assigning probability weights to each pixel of the satellite image based on our training samples. The priori probabilities allow the function to then classify each pixel into either of the four decided classes, by calculating the maximum likelihood of a pixel belonging to a particular class. The same training samples are corrected for subsequent years based on visual image interpretation of true colour and false colour composite satellite images. The different categories used, and their respective areas areshown in Table 3 and Figure 31. Figure 32 shows the changes in the area with time over the two decades for Built-up and Barren land LULC classes. The land cover maps of Pune city for 2003, 2007, 2011, 2015 and 2019 generated from the above studies are shown in figures 33a to 33e.

Table 3 Area of classes for different LULC categories

	2003 area (km^2)	**2007 area (km^2)**	**2011 area (km^2)**	**2015 area (km^2)**	**2019 area (km^2)**
Barren	164.7153	160.4835	137.6829	106.7562	86.3532
Water	1.8747	3.0951	2.412	1.8792	2.0754
Built-up	53.8758	58.9257	77.4297	108.279	125.64
Vegetation	30.0177	27.9792	32.9589	33.5691	36.4149
Total	250.4835	250.4835	250.4835	250.4835	250.4835

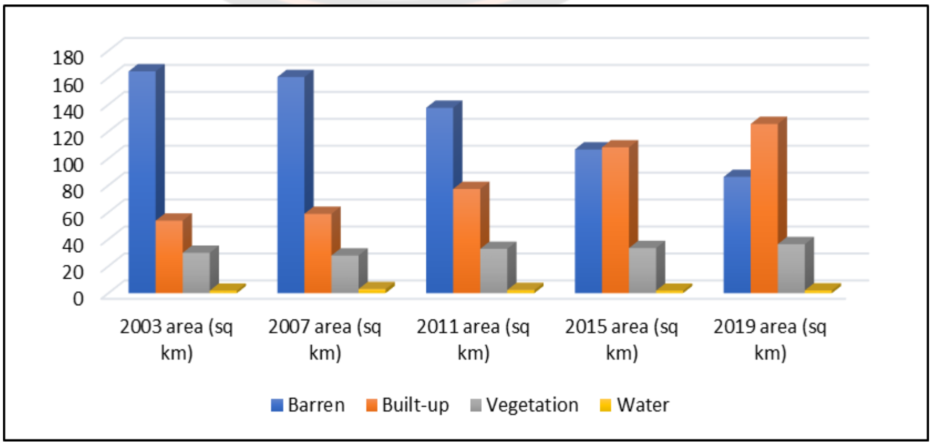


Figure 31 Graph showing LULC changes of Pune city from 2003 to 2019

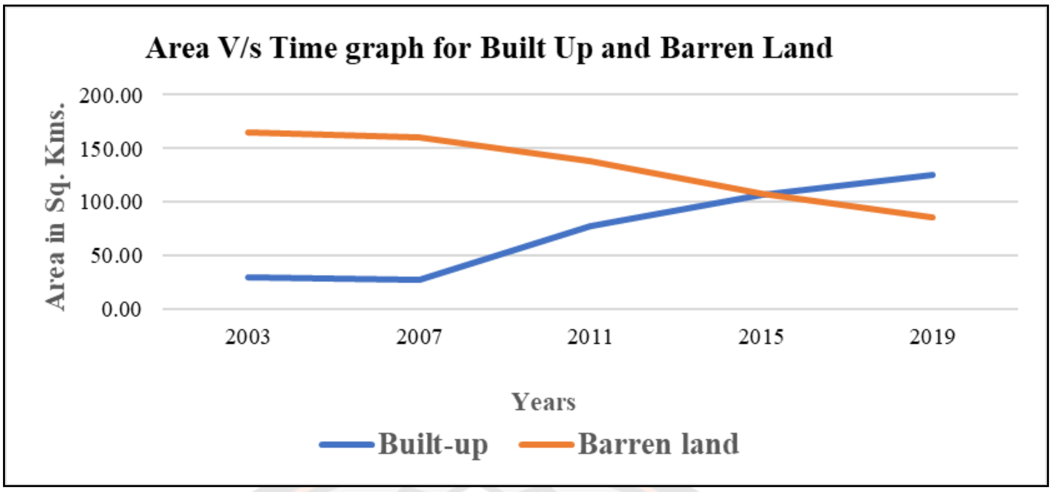
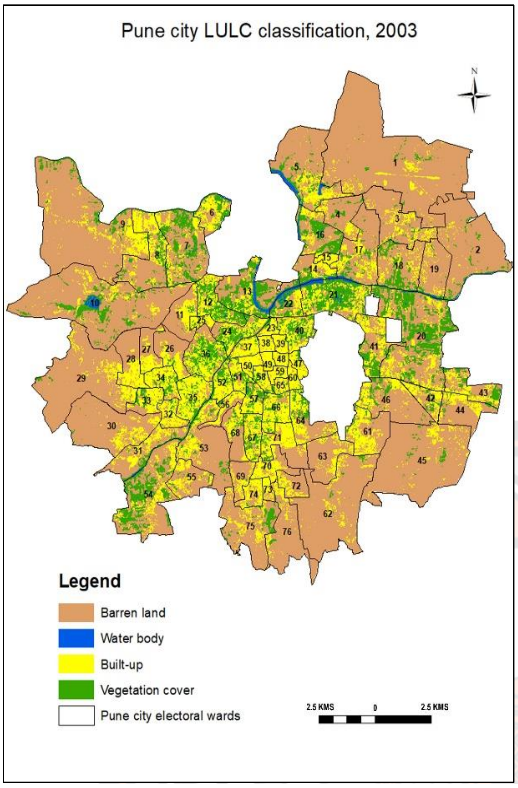


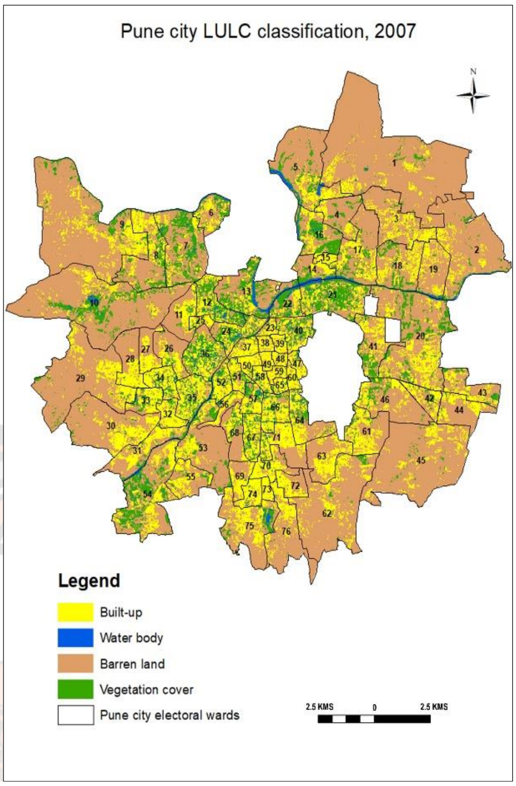
Figure 32 Changes in Built Up and Barren land over time

Rainfall

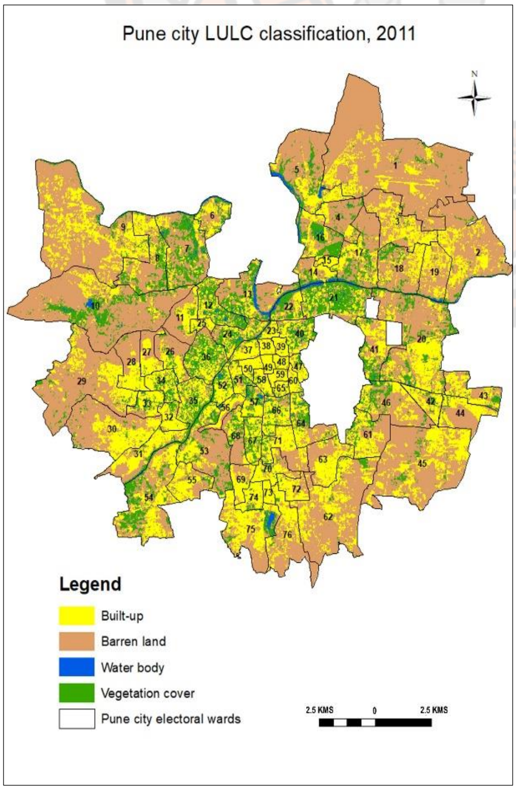
Rainfall is essential to recharge. Groundwater is formed by rainwater infiltrating the ground. Using tritium injection studies, Rangarajan and Athavale (2000) estimated a linear relation between natural recharge and rainfall for prominent hydrogeological units like basalt, granites, sediments, and alluvium. Rudra et al. (1993) believe that precise input of rainfall, considering both temporal and spatial aspects, plays a pivotal role in accurately modelling runoff and the transportation of non-point source pollutants in any hydrologic or water quality model.



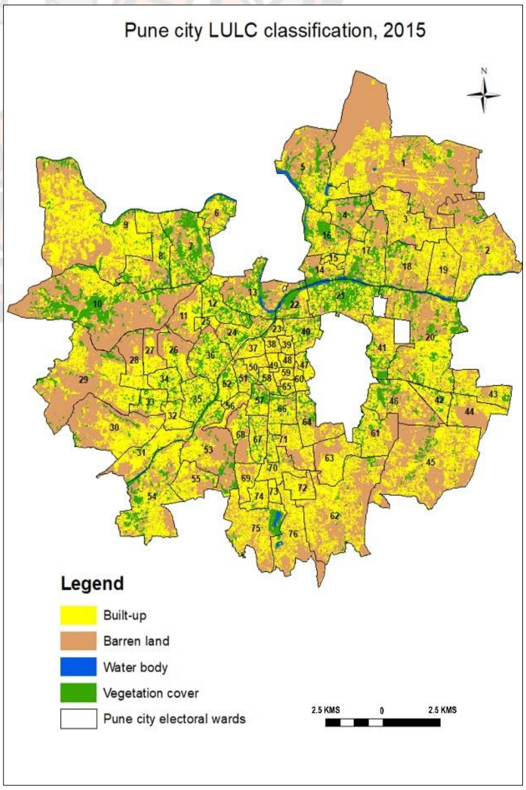
a) Land cover map of Pune city for 2003



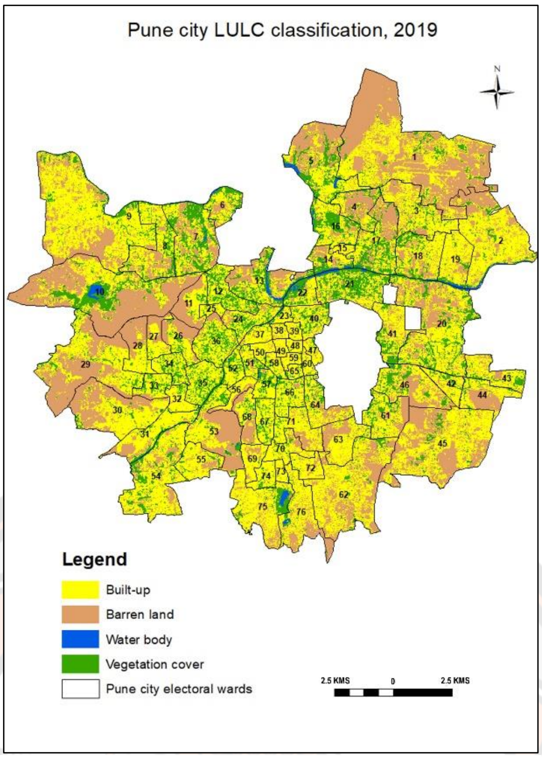
b) Land cover map of Pune city for 2007



c) Land cover map of Pune city for 2011



d) Land cover map of Pune city for 2015



e) Land cover map of Pune city for 2019

Figure 33 a) Land cover map of Pune city for 2003 b) Land cover map of Pune city for 2007 c) Land cover map of Pune city for 2011 d) Land cover map of Pune city for 2015 e) Land cover map of Pune city for 2019

Pune has a tropical wet and dry climate, with three distinct seasons - summer, monsoons and mild winter. The city receives rain from the southwest monsoon between June and September. Maximum rainfall occurs in July. The availability of water for rooftop harvesting is directly related to the annual precipitation.

Open data available with the Pune Municipal Corporation (PMC) was used to calculate the mean annual precipitation in the study area. The mean yearly rainfall for the period 2000 to 2022 is 1061.363 mm. However, analysis of records from the same source for the period 1980 to 2019 shows a mean annual rainfall of 798.773 mm. (Table 4, Figure 34). An average figure of 780 mm is considered for computation in this study as there is a variation of rainfall from West to East in the study area.

Table 4 Rainfall data from 1980 – 2019

Years	Total Rainfall (mm)	Years	Total Rainfall (mm)
1980	749.1	2000	558.3
1981	792.5	2001	548.6
1982	551.8	2002	424.7
1983	762.1	2003	459
1984	906.3	2004	913.3
1985	629.1	2005	1338.4
1986	570.1	2006	1266.9
1987	718.9	2007	864.5
1988	946	2008	756.6
1989	668.6	2009	823.2
1990	902.4	2010	1058.3
1991	1013.3	2011	941.5
1992	640.7	2012	519.4
1993	743.1	2013	774.1
1994	966.2	2014	829
1995	627.6	2015	829.2
1996	803.9	2016	672.9
1997	1025.8	2017	921
1998	800.7	2018	490.1
1999	732.7	2019	1411

Source: Open data portal of PMC

The rainfall map for the Multicriteria analysis was created using the High spatial resolution (0.25x0.25 degree) gridded rainfall data set over India] data available from the India Meteorological Department (IMD). This data was then converted to rainfall point data by using the IMD data converter. This point data was then interpolated to create the Rainfall map. (https://imdpune.gov.in/cmpg/Griddata/ Rainfall_25_ Bin. html).

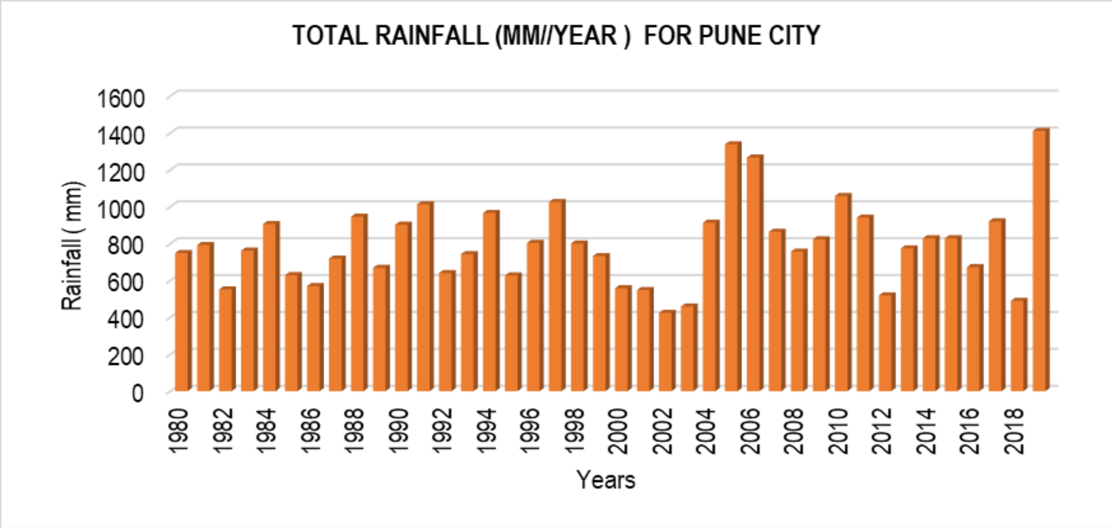


Figure 34 Rainfall data from 1980 -2019

Source: Open data portal of PMC

Groundwater Potential Recharge Zones

Artificial recharge methods, particularly rainwater harvesting (RWH), are being implemented worldwide to enhance the availability of fresh water. The process of recharging groundwater is significantly affected by various surface characteristics, including Land Use/Land Cover (LULC), rainfall, geology, soil types, drainage, and lineaments/fractures. Consequently, six essential parameters, namely LULC, Soil, Rainfall, Slope texture, Drainage density and Geology, were taken into account to create a groundwater recharge potential map. The choice of these factors is based on an extensive literature review and considers expert opinion. GIS-based Multi-criteria analysis and the Analytical Hierarchy Process (AHP) techniques were used to delineate potential zones for artificial recharge across the area under investigation. The use of AHP allows for a systematic evaluation of the potential recharge zones, considering various factors such as LULC, soil infiltration, precipitation, slope, and land use.

AHP Analysis Using Multiple Criteria

AHP (Analytic Hierarchy Process) is a widely employed decision-making approach in management to establish priorities when dealing with multi-criteria decision problems. It uses a structured mathematical process based on expert knowledge. AHP was first developed by Saaty (1987). Though introduced as a management tool, it has been used across disciplines as an effective tool for dealing with complex decision-making. AHP converts multi-dimensional complexity into a single-dimensional scale of priorities (Choosumrong et.al., 2012).

The AHP process has found extensive application in GIS to standardize the assigned weights of various thematic layers. Groundwater level depends on a range of factors, including geology, drainage density, lineament, rainfall, and land use (Choudhari et al., 2018). Numerous scientific investigations have commonly employed criteria such as lithology, geomorphology, geology, drainage density, type of soil, lineament characteristics, rainfall patterns, land-use patterns, and proximity to rivers as key indicators for delineating groundwater zones (Prasad et al., 2008; Das, & Pal, 2019; Maity, & Mandal, 2019).

In the study, the choice of influencing factors or themes and the weights of different thematic layers were determined through a combination of literature survey, published data, and expert opinion of Zolekar, & Bhagat (2015) (Table 5). In addition, several local Geologists and hydrologists were also consulted for the choice of factors and relative weights of the themes to ensure proper evaluation. The workflow employed in this study is illustrated in Figure 23.

After the ranking of the criteria, the weight for each criterion was calculated by using AHP to get a Pairwise Comparison Matrix (PCM) for the main decision criteria being used (Table 6). The AHP process involves a PCM of the various criteria which influence a particular process to derive priority weightages. By assigning weights and performing calculations, the PCM reveals the significance of each criterion in comparison to others. This methodology draws upon the works of Saaty R.W (1987), Saaty T. L. (1990), and Saaty T. L. (2008). Based on PCM, the relative weight matrix and the normalized principal eigenvalue were derived to determine the percentage of contribution of each criterion.

In doing a pairwise comparison, the relative significance of a set of criteria is established to assess their suitability for a specific objective. This comparison and rating of criteria are carried out using a continuous 9-point scale, as described by Saaty in 2008.

Table 5 Input parameters for MCDA analysis using AHP

Rank	Thematic Layer	Class	Class Description	Weight / Sub Rank	Area (Sq. Km)	Area (%)	Normalized Weight from AHP
1	**LULC**	4	Vegetation	4	36.42	15.00	0.41
		3	Water	3	2.08	1.00	
		2	Barren land	2	86.37	34.00	
		1	Construction	1	125.65	50.00	
2	**Slope**	0 - 5°	Flat Surface	6	189.52	75.28	0.23
		5 - 10°	V. Gentle slope	5	44.39	17.63	
		10 - 15°	Gentle Slope	4	12.06	4.79	
		15 - 20°	Moderate Slope	3	4.37	1.73	
		20 - 25°	Steep Slope	2	1.07	0.42	
		< 25	Very Steep Slope	1	0.36	0.14	
3	**Drainage Density**	< 80	Very Low Drainage	4	46.62	19	0.14
		160 - 80	Low Drainage	3	115.06	46	
		240 - 160	Moderate Drainage	2	78.89	32	
		> 240	High Drainage	1	9.83	4	
4	**Rainfall**	> 4.8 mm/day	High Rainfall	4	29.62	11.83	0.11
		4.1 – 4.5 mm/day	Moderate Rainfall	3	142.63	56.95	
		3.8 – 4.13 mm/day	Low Rainfall	2	55.28	22.07	
		< 3.8 mm/day	Very Low Rainfall	1	22.93	9.16	

Table 5 (Cont.)

Rank	Thematic Layer	Class	Class Description	Weight / Sub Rank	Area (Sq. Km)	Area (%)	Normalized Weight from AHP
5	**Soil**	Type 1 (118*)	Loamy, mixed and iso-hyperthermic, moderate stoniness	5	104.44	42	0.07
		Type 2 (76*)	Clayey skeletal, strongly calcareous, strong stoniness	4	0.36	0	
		Type 3 (216*)	Fine, Clayey, moderately calcareous, moderate stoniness	3	4.96	2	
		Type 4 (266*)	Fine, Strongly Calcareous, Clayey, montmorillonitic	2	4.89	2	
		Type 5 (244*)	Clayey, Calcareous, moderate salinity, Fine.	1	135.86	54	
6	**Geology**	Karla Formation.	Dominantly compound pahoehoe flows	4	128.59	51	0.04
		Diveghat Formation.	Dominantly Àa and simple flows with thick FTB (Fragmented tops)	3	61.67	25	
		Indrayani Formation.	Àa flows with thick FTB (Fragmented tops)	2	58.91	24	
		Purandargarh Formation.	Àa and simple flows with thin FTB (Fragmented tops)	1	1.35	1	

Note: In Ranks - 6 = Highest and 1 = lowest
* Soil types – Figures in parentheses indicate Index number as per NBSS & LUP map.

The following steps were adapted to allocate and normalize weights of the different thematic layers using the AHP technique – (1) Definition of criteria., (2) Assigning scaled ranks (weights) to each criterion based on literature survey and expert opinions, (3) Establishing pairwise comparison metrics (P) using the scaled ranks, (4) Computing the geometric mean, (5) Calculating normalized weights, and (6) Determining the consistency ratio to ensure the coherence of judgments.

Each of the six thematic layers has four or more sub-classes, thereby making the relationships between these interdependent classes complex. The relationship between the factors and their relative importance is derived using the AHP. The result of the AHP is the assignment of normalized weights which are then used in the weighted overlay analysis.

Table 6 Pair-wise comparison matrix for the six themes and calculation of normalized weights by the analytic hierarchy process

Matrix		LULC	Slope	Drainage Density	Rainfall	Soil	Geology	Normalized principal Eigenvector
		1	2	3	4	5	6	
LULC	1	1	3	5	3	5	5	0.41
Slope	2	1/3	1	3	3	3	5	0.23
Drainage Density	3	1/5	1/3	1	2	3	5	0.14
Rainfall	4	1/3	1/3	1/2	1	3	3	0.11
Soil	5	1/5	1/3	1/3	1/3	1	3	0.07
Geology	6	1/5	1/5	1/5	1/3	1/3	1	0.04

Overlay Analysis:

The final weights are obtained from the calculation of the principal Eigenvector of the PCM. To assess the consistency of the pairwise comparison in AHP, the Consistency Index (CI) is derived from the maximum Eigenvalue (λmax). The λmax is calculated by summing the product of each element in the relative weights (the Eigenvector) with the respective column total of the original comparison matrix.

The CI is determined by the equation below.

$$CI = -(\lambda max \ - \ n)/n - 1 \qquad \text{……………. Eq. 1}$$

Where λmax is the largest Eigenvalue of the matrix and can easily be determined from the matrix mentioned, and n is the number of factors or criteria being considered. In this case, the λmax obtained is 6.539 and the CI is 0.108.

To validate the appropriateness of the CI, Saaty (1990) proposes the use of the Consistency Ratio (CR). The CR is calculated as the ratio of the CI to the Random Consistency Index (RCI). The value of RI for selected 'n' values is as per the Consistency Index suggested by Saaty (1990). (Table 7)

$$CR = CI / RC \qquad \text{……… Eq. 2}$$

The comparison matrix is consistent if the resulting CR is less than 10%. Saaty (1990). If the CR is more than 10%, it becomes necessary to rework the comparison matrix and recalculate the weights to get a better weighting scheme.

The CR obtained was 0.087 (8.8%) which is less than the threshold limit (0.1). This indicates that the weight assignment for the parameters used in this study is consistent.

Table 7 Random Consistency Index

Number of factors	1	2	3	4	5	6	7	8	9	10
Index	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: after Saaty, 1990

Estimation of recharge potential from rooftops

The popularity of rainwater harvesting (RWH) has been steadily increasing, driven by the successful implementation of RWH as an alternative urban water source in various countries, including Japan, China, Singapore, Australia, and the United States (Campisano et al., 2017).

To manage water sustainably, it is essential to recognize the importance of rain and utilize rainwater efficiently at its point of origin. Rainwater harvesting (RWH) presents an opportunity to address water shortages and crises. The most practical approach is to capture rainwater where it falls and store it properly, either on the surface or in the aquifer, for future use when required.

Groundwater recharge practices using rainwater harvesting contribute to restoring the water balance. Recharge to groundwater from rainfall has been studied extensively and numerous methods have been proposed for estimation of natural and artificial recharge of groundwater. However, most of these studies pertain to the recharge of surface aquifers. In addition to the delineation of potential recharge zones for surface aquifers, the present study covers the use of Rooftop Rainwater harvesting for recharge through direct injection to confined aquifers or deep-seated aquifers.

As previously mentioned, India receives a significant portion of its rainfall during the monsoon season. The southwest monsoon typically arrives in June and lasts until September, while the northeast monsoon extends from October to December. Pune, situated in the western part of India, usually experiences rainfall only from June to September.

A pilot study was undertaken initially to understand the efficacy of the use of rooftop run-off for rainwater harvesting. For this, 68 apartment buildings from seven areas located in different parts of the city were chosen to carry out a representative study of rainwater that is available for recharge. Rooftop areas of the 68 apartment blocks were digitised in Google Earth Pro using the polygon tool. (Figure 24).

Representative rooftop areas were verified by ground checks and from the management of the societies. The surface areas thus obtained were used to calculate the potential. A comparison of physical measurements for nine (9) representative buildings with the digitized measurements showed a 95% accuracy for the digitization.

Encouraged by the results of the pilot, digitization (tracing & measurement) of the rooftops was extended to 35 wards in different areas of the city. Rooftop surface areas were digitized and calculated in Google Earth Pro. The digitized rooftops were compared with the area of the surrounding plot to understand the ratio of rooftops to the adjacent paved areas. This was done for several representative areas across parts of the city and an estimate of the rooftop to the paved areas was arrived at. The rooftop to built-up area ratio obtained was in the range of 30 to 50 % with an average of about 40% being occupied by rooftops.

The recharge Potential of rooftop rainwater harvesting is the capacity of a particular roof to harness the water that falls on it during all the rainy days across the year. The annual yield of water or the recharge potential is the product of the roof type, the total area, and the annual precipitation in that area.

The recharge potential of rooftop rainwater harvesting in seven representative areas of Pune city was calculated using the formula given by Gould (2015) and a co-efficient of 0.80 (concrete roofs) as proposed by Pacey, et al. (1989).

$$S = R \times A \times Cr \qquad \text{……… Eq. 3}$$

Where:

S = Potential of roof rainwater harvesting (in litres.)

R = Average annual rainfall in mm.

A = Roof area in Sq. m.

Cr = Coefficient of Run-off

Representative rooftop areas were verified by ground checks and from the management of the societies. The surface areas thus obtained were used to calculate the potential. A comparison of physical measurements for nine (9) representative buildings with the digitized measurements showed a 95% accuracy for the digitization.

The total rooftop area from the wards was then multiplied by the average annual rainfall and the run-off coefficient to calculate the volume of rainwater that was available from the rooftops The roof top rainwater run-off obtained by using the above-mentioned formula and other parameters are shown in Figure 35 and summarized in Table 8.

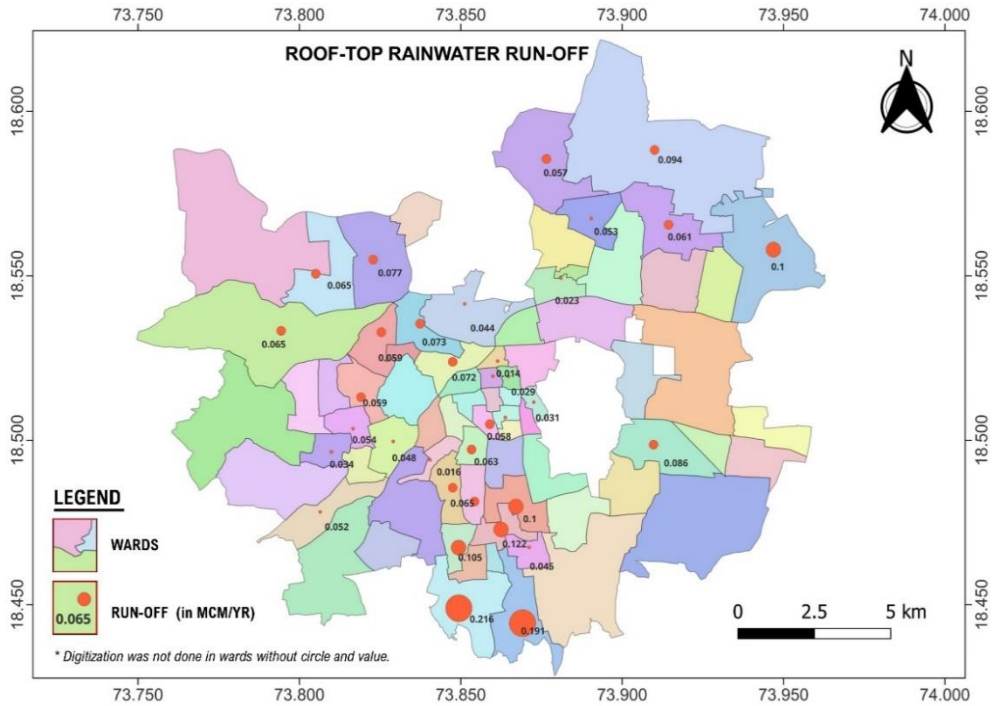


Figure 35 Map showing rooftop rainwater run-off from wards for which rooftop areas were digitized. ***(Numbers indicate run-off figures in million cubic meters/year.)***

Table 8 Summary of rooftop rainwater run-off from digitized wards

S. No	Ward number	WARDS	No of polygons (Approx)	TOTAL ROOFTOP AREA /TYPE m^2 (R)	(S =R*A*Cr) Runoff (m^3)	Million Cubic metres (MCM)
1	1	Lohegaon Airport	950	150135.30	93684.43	0.0936844
2	2	Kharadi Infotech Park	750	160146.90	99931.67	0.0999317
3	3	Vimannagar Sanjay Park	605	97405.00	60780.72	0.0607807
4	4	Nagpur Chawl	421	84557.10	52763.63	0.0527636
5	5	Vishrantwadi Mhaske Vasti	400	91780.96	57271.32	0.0572713
6	7	Pune University	321	123500.31	77064.19	0.0770642
7	8	Aundh ITI	304	103625.10	64662.06	0.0646621
8	10	Pashan Sutarwadi	501	104087.86	64950.82	0.0649508
9	11	Janwadi-Gokhalenagar	300	93757.60	58504.74	0.0585047
10	12	Model Colony	372	117692.00	73439.81	0.0734398
11	13	Narveer Tanajiwadi	156	71216.80	44439.28	0.0444393
12	14	Deccan College	135	36267.80	22631.11	0.0226311
13	23	Junabazaar Kumbharwada	116	23096.40	14412.15	0.0144122
14	24	Balgandharva	300	115398.80	72008.85	0.0720089
15	26	MIT - Kelewadi	285	94427.60	58922.82	0.0589228
16	31	Shivane - Warje - Ramnagar	420	82683.41	51594.45	0.0515944
17	33	Dahanukar Colony	206	54736.70	34155.70	0.0341557
18	34	Gujrat Colony	300	86641.90	54064.55	0.0540645
19	35	D. Mangeshkar Hospital	300	76360.10	47648.70	0.0476487
20	38	Kasba Peth	270	43892.40	27388.86	0.0273889
21	39	KEM Hospital	240	46790.70	29197.40	0.0291974
22	46	Wanavdi - Ramtekdi	300	137406.40	85741.59	0.0857416
23	47	Arunkumar Vaidya Stadium	160	49817.10	31085.87	0.0310859
24	56	Sarasbaug Parvati	63	25396.90	15847.67	0.0158477
25	57	Kadakmal Ali Hirabaug	647	100424.46	62664.86	0.0626649
26	58	Mahatma Phule Smarak	483	92889.10	57962.80	0.0579628
27	59	Kashewadi Gurunanaknagar	362	62853.20	39220.40	0.0392204
28	67	Aranyeshwar Taware Colony	950	145543.59	90819.20	0.0908192
29	68	Sahakarnagar - Taljai	619	104876.29	65442.80	0.0654428
30	69	Dhankawadi Padmavati	1504	167969.63	104813.05	0.1048130
31	70	Bibvewadi and KK Market	1200	195532.58	122012.33	0.1220123
32	71	Shivaji Market, Gultekdi	816	160630.57	100233.47	0.1002335
33	72	Upper Indiranagar	348	71675.17	44725.30	0.0447253
34	75	Katraj Dairy	2150	345702.73	215718.51	0.2157185
35	76	Katraj Maulinagar	2074	306571.77	191300.78	0.1913008
		TOTAL	**19328**	**3825490.22**	**2387105.90**	**2.3871059**

Annual Precipitation in mm: 780 mm | Run-off coefficient: 0.8

Well Analysis

Data for a total of 3238 wells obtained from the Pune Municipal Corporation and other field surveys were studied to understand their use as potential recharge wells. The data was analyzed for distribution across the zones (wards) for some other parameters like the state of the well (perennial, etc.), usage, the diameter of the wells and the capacity of the pump being used. The distribution of wells across the different areas within the city and the percentage of the total wells for each of the areas (administrative wards) is shown in Figure 36.

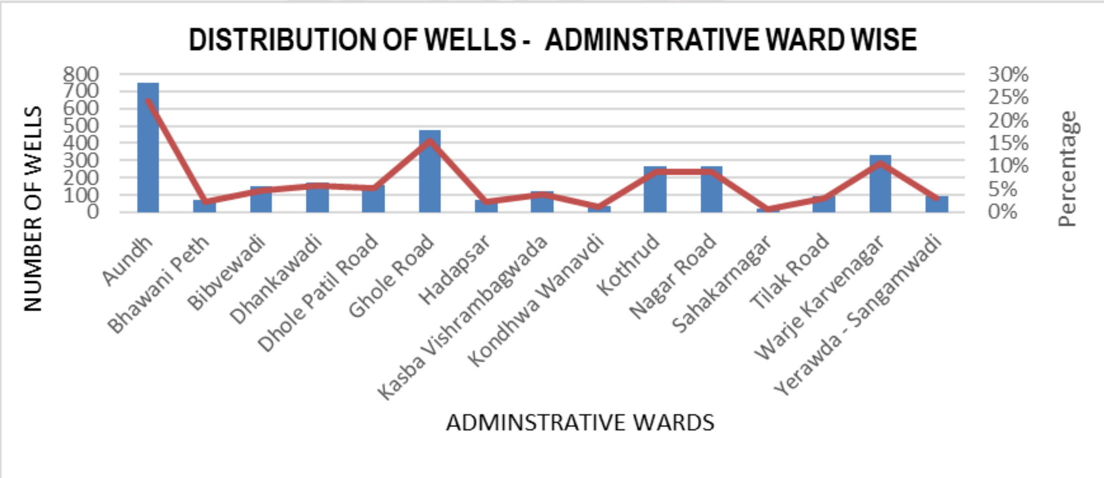


Figure 36 Graph showing number of wells per administrative ward (zone)

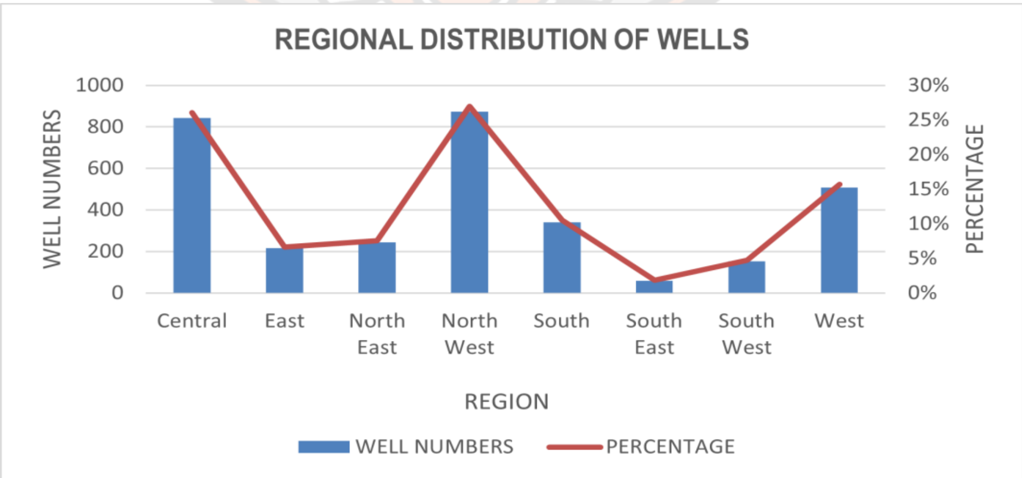


Figure 37 Graph showing regional distribution of wells

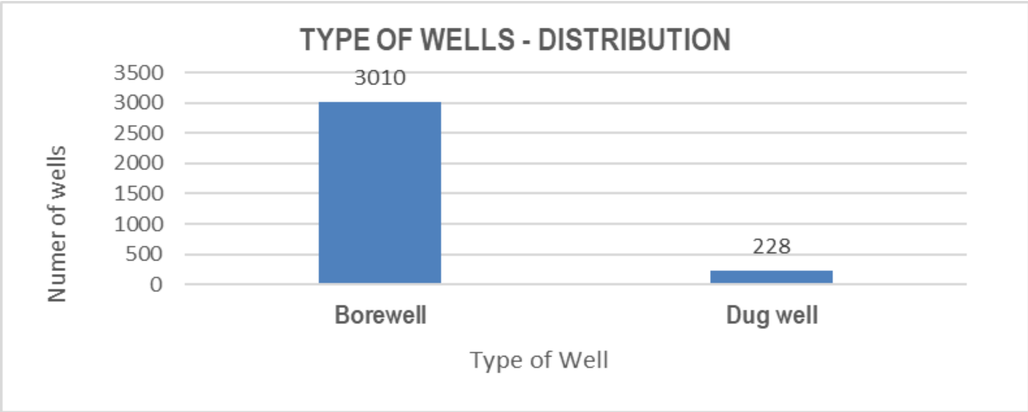


Figure 38 Graph showing distribution of type of wells

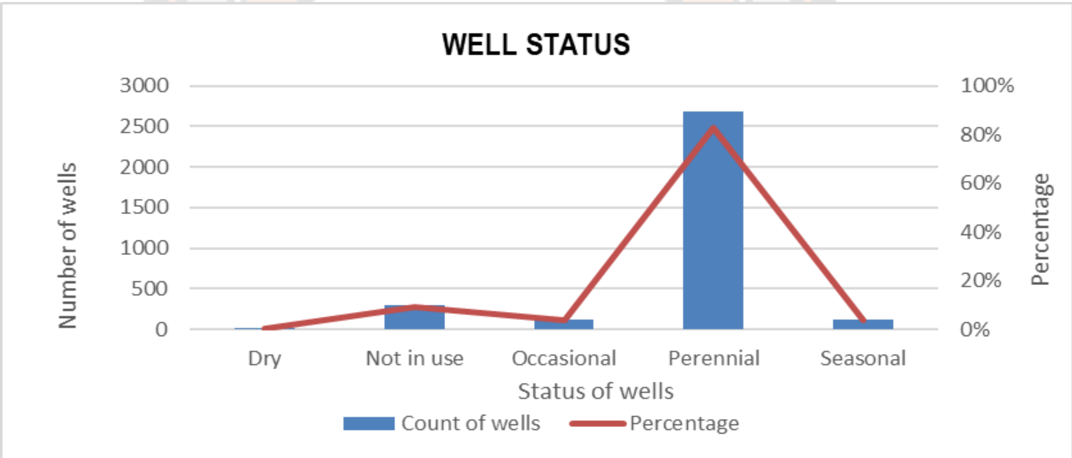


Figure 39 Graph showing status of wells

A random field survey of 135 wells owners was done to understand the population of wells that are being used for rainwater harvesting for recharge of the wells, The survey indicated only 22 (18 %) of the yielding wells, are presently being used for rooftop rainwater harvesting.

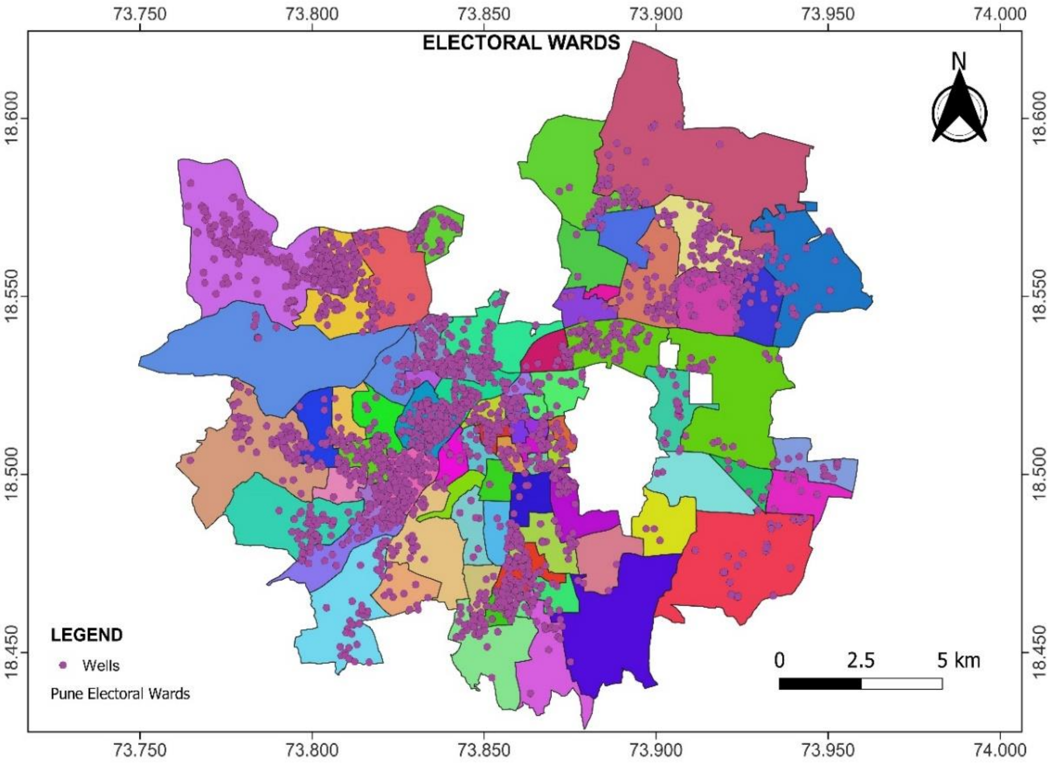


Figure 40 Map showing the spatial distribution of wells across the wards

Frequency Ratio

The Frequency Ratio (FR) technique is a data-driven model that utilizes the locations of existing wells to analyze the spatial relationships between different variable classes and well locations. In the case of groundwater, the FR model operates on the principle that the existence of water in a particular location indicates a high groundwater potential (GWP). When a significant number of wells are situated within a specific variable class, covering a comparatively small area of the study region, the FR model concludes that the characteristic represented by that variable class contributes to a high GWP.

In this study, a dataset consisting of 3074 wells was used to compute the FR for each of the considered thematic factors. FR values were determined for the classes within the thematic layers, considering both dug wells and borewells. Table 9 shows the FR analysis of wells in the study area for each thematic factor.

Table 9 Frequency ratio analysis of wells in the study area

Thematic Factor (A)	Index number (in map) (B)	Description (C)	Weight / Rank (D)	Percentage Area (% of pixels in the class) (E)	% of Wells (pixels) in the class (G)	Frequency Ratio (G/E)
LULC	4	Vegetation	4	14.54%	18.70%	1.29
	3	Water	3	0.83%	0.07%	0.08
	2	Barren	2	34.48%	10.37%	0.30
	1	Settlement	1	50.16%	70.86%	1.41
Slope	0 - 5	Flat Surface	6	75.28%	74.84%	0.99
	5 -10	Very Gentle	5	17.63%	21.94%	1.24
	10 - 15	Gentle Slope	4	4.79%	2.86%	0.60
	15 - 20	Moderate Slope	3	1.73%	0.33%	0.19
	20 - 25	Steep Slope	2	0.42%	0.03%	0.08
	25 - 31.2842	Very Steep Slope	1	0.14%	0.00%	0.00
Rainfall	4.1972 -- 4.7962	High Rainfall	4	62.50%	24.57%	0.39
	3.8402 -- 4.1972	Moderate	3	26.64%	62.09%	2.33
	3.6312 -- 3.8402	Low	2	9.32%	10.77%	1.16
	3.4712 -- 3.6312	Very Low Rainfall	1	1.53%	2.57%	1.68
Drainage Density	0.425129 -- 80	Very Low Drainage Density	4	19%	12%	0.64
	80 -- 160	Low Drainage Density	3	46%	57%	1.24
	160 -- 240	Moderate Drainage Density	2	32%	28%	0.89
	240 -- 306.809	High Drainage Density	1	4%	3%	0.68

Table 9 (Cont.)

Thematic Factor (A)	Index number (in map) (B)	Description (C)	Weight / Rank (D)	Percentage Area (% of pixels in the class) (E)	% of Wells (pixels) in the class (G)	Frequency Ratio (G/E)
Soil	077 + 118	077 - Loamy, mixed and isohyperthermic 118 - Loamy, mixed and isohyperthermic, with moderate stoniness	5	42%	25%	0.60
	076	Clayey skeletal, strongly calcareous, strong stoniness	4	0%	0%	0.00
	216	Fine, Clayey, moderately calcareous, moderate stoniness	3	2%	0%	0.07
	266	Fine, Strongly Calcareous, Clayey, Montmorillonite	2	2%	3%	1.63
	244	Clayey, Calcareous, moderate salinity, Fine,	1	54%	72%	1.33
Geology	5	Dominantly compound pahoehoe flows	4	51%	74%	1.44
	6	Àa and simple flows with thick FTB (Fragmented tops)	3	25%	14%	0.57
	4	Àa flows with thick FTB (Fragmented tops)	2	24%	12%	0.50
	7	Àa and simple flows with less thickness of FTB (Fragmented tops)	1	1%	0%	0.00

Note: * For Weight / Rank, 6 is the Highest & 1 is the lowest.

The FR analysis was also done across Groundwater potential zones derived from the MCDA analysis. Table 10 shows the Frequency Ratio (FR) analysis of the Groundwater Potential recharge zones.

Table 10 Frequency Ratio analysis of the Groundwater Potential recharge zones

	Description	Value	Percentage Area (% of pixels in the class) (E)	% of wells (pixels) in the class (G)	Frequency Ratio (G/E)
GWPRZ	V. LOW POTENTIAL	1	1%	1%	0.44
	LOW POTENTIAL	2	32%	35%	1.07
	MODERATE POTENTIAL	3	46%	46%	0.98
	GOOD POTENTIAL	4	7%	3%	0.37
	HIGH POTENTIAL	5	13%	17%	1.27

The results and discussions for the work detailed in this chapter are dealt with in the next chapter.

CHAPTER V

RESULTS & DISCUSSIONS

Introduction

Rapid urbanization has led to significant anthropological, environmental, and social changes, particularly in terms of groundwater recharge potential. As urban areas expand to satisfy the needs of the increased population, the provision of essential resources such as energy, education, healthcare, and, above all, water, is being strained beyond its limits. A report by the United Nations has warned that land use changes caused by urbanization, river channelization, and other human activities can impact catchment storage capacity and groundwater recharge, leading to increased water-related disasters (UN Water, 2016). As a result, it is crucial to implement systematic and scientific water management, particularly in the area of artificial groundwater recharge.

The main results and discussions about the principal objectives of the study viz. the delineation of prospective zones for artificial recharge across the city considering urban factors like land use and other factors and the analysis/calculation of Rainwater Harvesting (RWH) recharge potential using roof-top areas and other geospatial techniques are dealt with in this chapter.

LULC, Rainfall and Groundwater Recharge

Land use and land cover (LULC) changes can have a significant impact on groundwater recharge. In addition, variations in rainfall patterns can affect the amount and timing of groundwater recharge. Land use and land cover changes are often driven by human activities, such as urbanization, deforestation, and agriculture expansion. These changes can result in alterations in the soil structure and vegetation cover, leading to changes in the infiltration rates and water-holding capacities of the soil. As a result, the amount of water that can infiltrate and recharge the groundwater gets reduced.

Rainfall patterns can also impact groundwater recharge. In many regions, groundwater recharge is primarily driven by rainfall infiltration into the soil. Changes in rainfall patterns, such as increased intensity or duration, can affect the amount and timing of rainfall that infiltrates into the soil and recharges the groundwater.

LULC studies examine the interaction between humans and the environment, and how these interactions influence the patterns and processes of land use and land cover. Remote sensing techniques, such as satellite imagery, are often used in LULC studies to analyze the patterns and changes in land use and land cover. These techniques provide valuable information on the physical and biological characteristics of the land and enable researchers to detect changes in land use and land cover that may not be visible through ground observations alone. Remote sensing data has been widely used for mapping and analysing LULC changes over different periods. Numerous studies have been carried out to map LULC classes and monitor their changes using remote sensing data like Landsat, SPOT and SAR images.

Pan et al. (2011) investigated the impact of Land Use Change on Groundwater Recharge in the Guishui River Basin, China. According to their findings, only 21.16% of the precipitation contributes to groundwater recharge, with 72.54% being lost through evapotranspiration. Further, the yearly groundwater recharge rate decreases in the following order: cropland, grassland, urban land, and forest. Land use changes have led to a reduction of 4 × 106 m3 in yearly groundwater recharge in the study area. This decrease primarily stems from growth in urban areas and rural settlements, along with a reduction in cropland.

The LULC analysis for this study was based on Landsat 8 Satellite imageries of 30 m Resolution for the year 2019 (Vaddadi et al., 2022). The study area was classified into four classes Barren Land, Settlement, Water Bodies and Vegetation based on a Supervised Classification study (Figure. 2). The analysis shows that a major part of the study area is occupied by constructions or built-up area that occupies about 125 km^2 (50%). About 86 km^2 (34%) is occupied by barren land. Vegetated areas and water bodies which are very good for infiltration together constitute 39 km^2 (16%).

From the above, it can be observed that there has been a steady decrease in barren land and an equally uniform increase in built-up area since 2003. The LULC analysis shows that the total built-up area in Pune has increased from 50.87 km^2 in 2003 to 126 km^2 in 2019. Furthermore, vegetation cover has decreased at the borders of Pune city. It can be observed that most of these are agricultural lands that have been either cleared or converted to barren and built-up areas. This increase in built-up area over the years has reduced the overall area available for recharge.

Rainfall and Groundwater Potentiality

Rainfall serves as the primary and major source of groundwater recharge. The rate of surface runoff and infiltration is influenced by the volume, duration, and intensity of the rain. During periods of long-term low precipitation, surface runoff tends to be high, and infiltration into the ground is limited. Additionally, the yearly average rainfall plays a significant role in groundwater recharge. Higher amounts of rainfall indicate a greater groundwater potential, while lower amounts suggest a lower groundwater potential.

Lerner et al. (1990) provided conceptual definitions for recharge mechanisms, categorizing them as follows: direct recharge (the infiltration of precipitation directly followed by percolation through the unsaturated zone to reach a groundwater body), indirect recharge (percolation from riverbeds to the water table) and localized recharge (the accumulation of precipitation in surface water bodies, followed by concentrated infiltration and percolation through the unsaturated zone to reach a groundwater body).

A study carried out in the Gaza Strip by Mushtaha et al. (2019) reveals that while the overall long-term average rainfall and recharge in the area remained unchanged, there was a significant variation in the long-term average of runoff (a difference of 42.6%). This variation can be attributed to differences in spatial rainfall estimation and the impact of factors such as soil texture and changes in land use.

Since the availability of water for rooftop harvesting is directly related to the annual precipitation it becomes important to understand the variation in precipitation. In the present study area, one observes a clear spatial variation in precipitation across

Pune from West to East and consequently, the recharge is also likely to vary. The rainfall also shows a temporal variation. Data for 100 years for the period 1901 to 2000 sourced from the India Meteorological Department (IMD) and compiled by Bardia (2020) shows a mean annual rainfall of 699.9 mm (Figure 41). February shows the minimum precipitation (1.1 mm) and July with maximum precipitation (179 mm) followed by September (129 mm) and June (120.4 mm) are the wettest months. This is validated by the differences in the density of wells as we proceed from West to East.

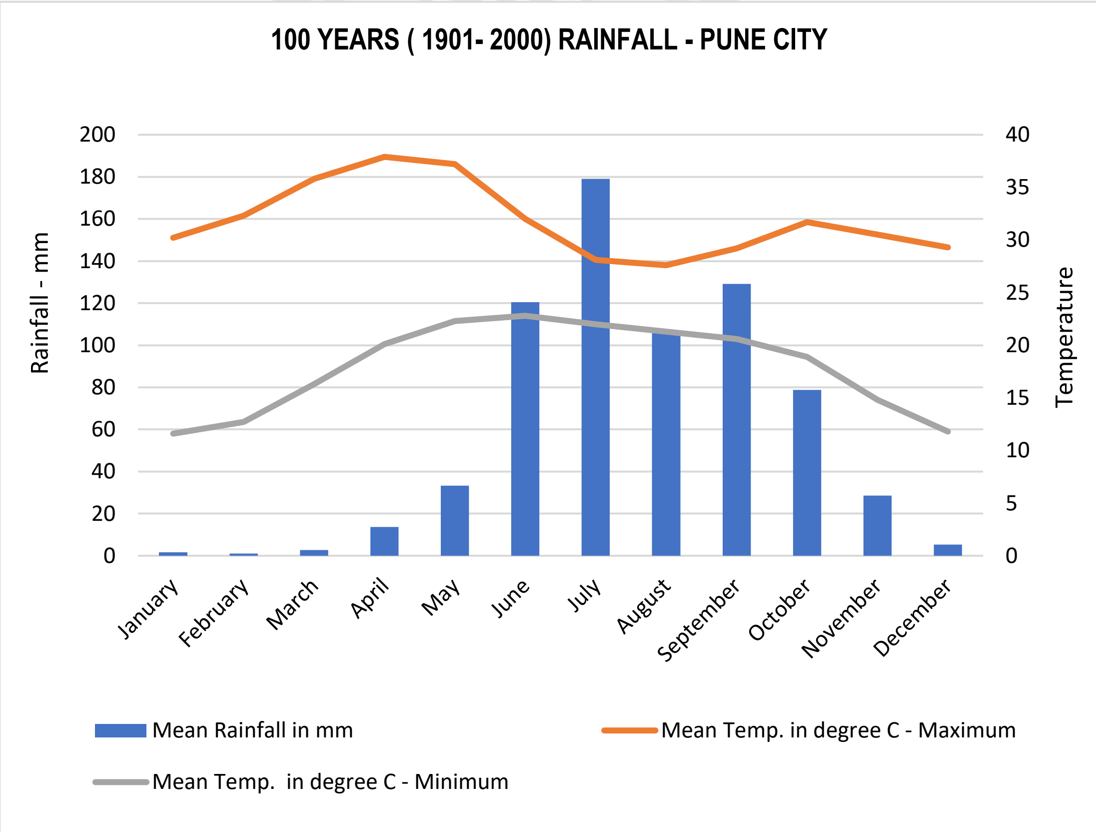


Figure 41 Monthly mean annual rainfall for 100 years from 1901 to 2000

Source: Bardia, 2020

Groundwater Potential Recharge zones with MCDA analysis using AHP.

Anthropogenic alterations, which are a consequence of increasing urbanization lead to a major impact on natural resources like water especially, in terms of recharge potential. Urbanization quantitatively affects various aspects, including a reduction in groundwater levels, a decrease in the area covered by the aquifer, and alterations in the direction of groundwater flow (Khazaei et al., 2004).

1. **Thematic layers**

To implement effective artificial recharge methods, it is important to determine potential recharge zones, especially in urban areas. Several spatial factors come into play when considering potential zones for recharge by RWH. Besides rainfall, other factors like the slope of the land, and soil texture also play a crucial role in the recharge. The ranking of the criteria used in the study is shown in Table 5.

Land Use/Land Cover impacts the rate of surface runoff, infiltration, and utilization of the groundwater (Senanayake et al., 2016). Urbanization, especially concretisation leads to increased run-off and surface flow thereby reducing the water available for recharge. The LULC of an area is thus a particularly important influencing factor in recharge in an urban context. The greater the concretisation, the less the recharge and hence LULC was given the highest attribute rank. Within LULC, the built-up area was given the lowest weight. Water bodies, wetlands and vegetated areas are reported to have high infiltration rates. (Figure 42)

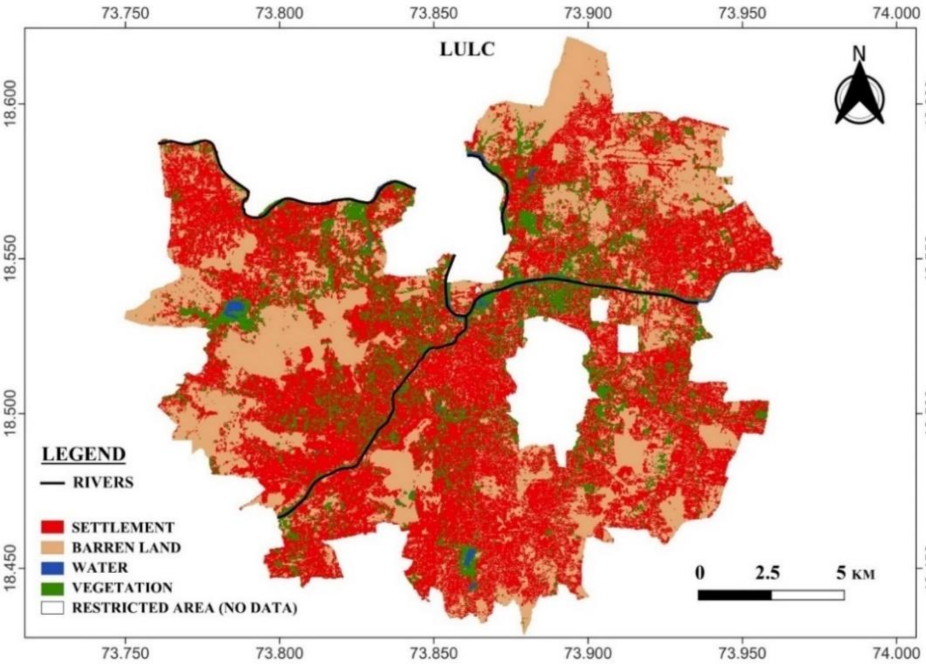


Figure 42 LULC Map

The **Slope** of an area influences rainfall infiltration and is an important parameter in recharge potential. Infiltration will be higher in low-slope areas where surface flow and run-off are less and where it takes more time to travel downstream, as compared to high-slope areas where the run-off is higher and quicker (Rajaveni et al., 2015).

The slopes for the area were calculated in degrees from a Cartosat DEM image of 5 m resolution. The slopes were classified into six classes with slopes from 0°-31°. The maximum areal extent in the area was in the range of 1°-5° (Flat surface). About 189 km^2 (75%) of the study area is flat and conducive to infiltration. (Figure 43).

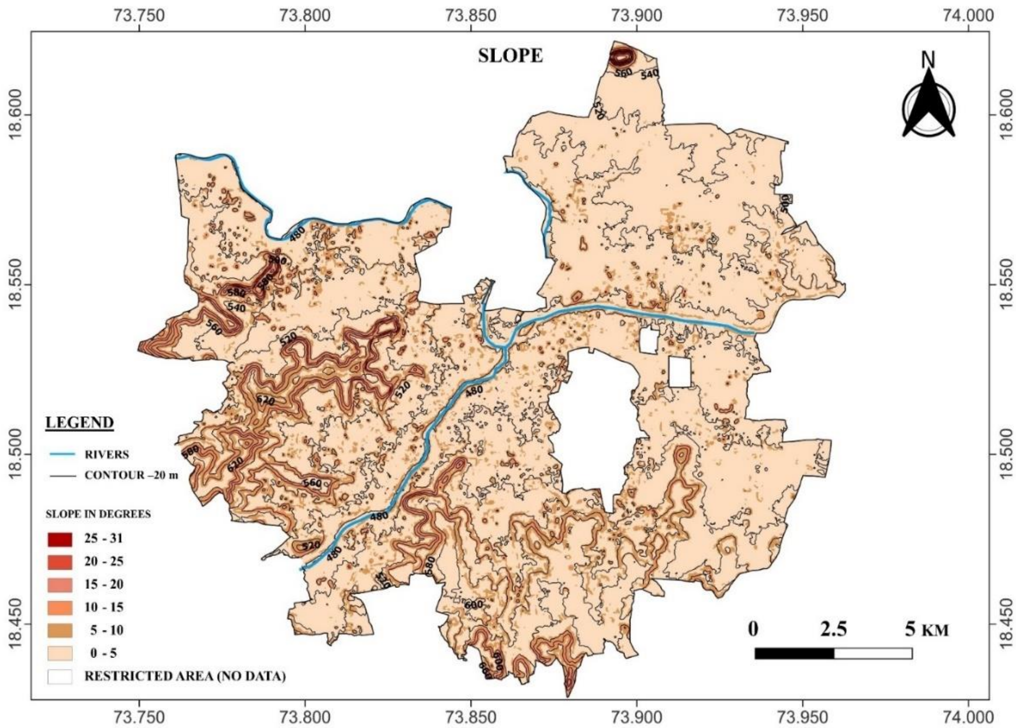


Figure 43 Slope Map

Drainage density is a significant parameter that affects the recharge potential of groundwater. Compared to regions with high drainage density, areas with low drainage density experience more infiltration, leading to the formation of favourable groundwater potential zones. (Shekhar and Pandey, 2014). Drainage was digitized from the toposheet, and the density was calculated using the point density method in QGIS. The obtained densities were classified into four classes which ranged from 0.43 – 306.80. Of these classes, the areas occupying low and very low density which are good for groundwater infiltration occupy about 162 km^2 (65 %) of the area. An area with moderate density occupies an area of 79 km^2 (32 %) and is also suitable for recharge. The drainage class with the least density was given the highest weightage on account of the lower number of drainages per unit area. (Figure 44).

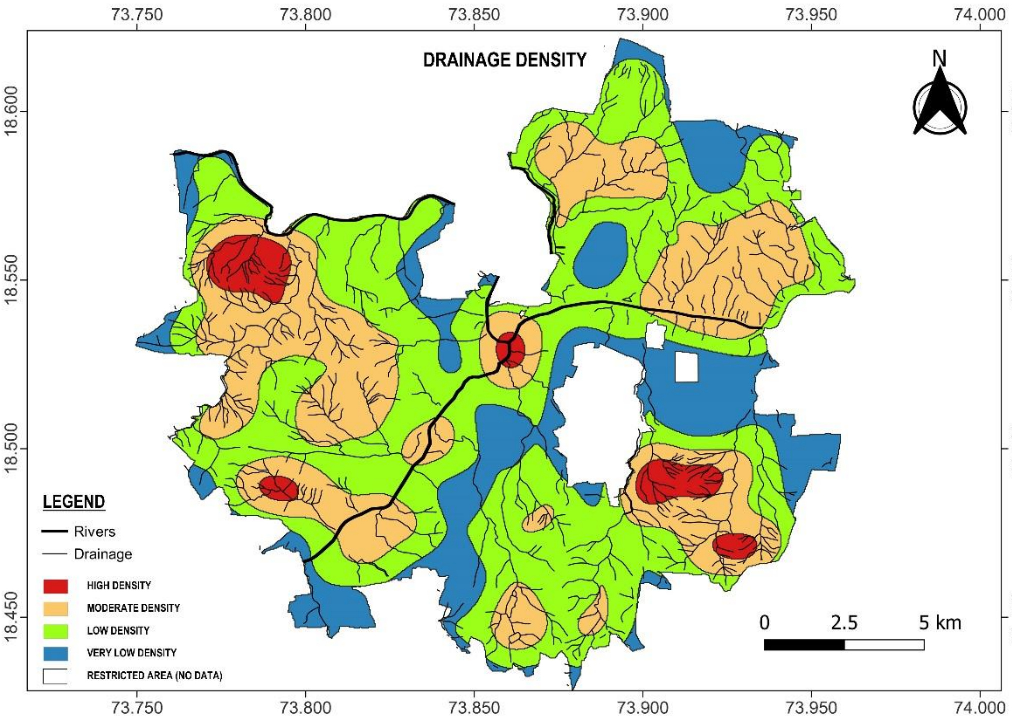


Figure 44 Drainage Density Map

Rainfall is essential to recharge. Groundwater originates from the infiltration of rainfall into the ground. According to Mondal and Ajaykumar (2022), rainfall is the basic source of groundwater recharge, whereas irrigation areas, rivers, ponds, lakes, etc., are the secondary sources of groundwater recharge. Grid-based rainfall data with a resolution of 0.25 x 0.25 degrees downloaded from the India Metrological Department (IMD) site was converted to Rainfall point data by using the IMD data converter. This point data was then interpolated in QGIS software using the inverse distance weighted interpolation (IDW) method to create the rainfall map (Figure 45). The software generates an Inverse Distance Weighted (IDW) interpolation of a point vector layer. Inverse distance weighted methods are based on the premise that the interpolating surface will be influenced primarily by nearby points and less influenced by points that are farther away. (Pai et al., 2014).

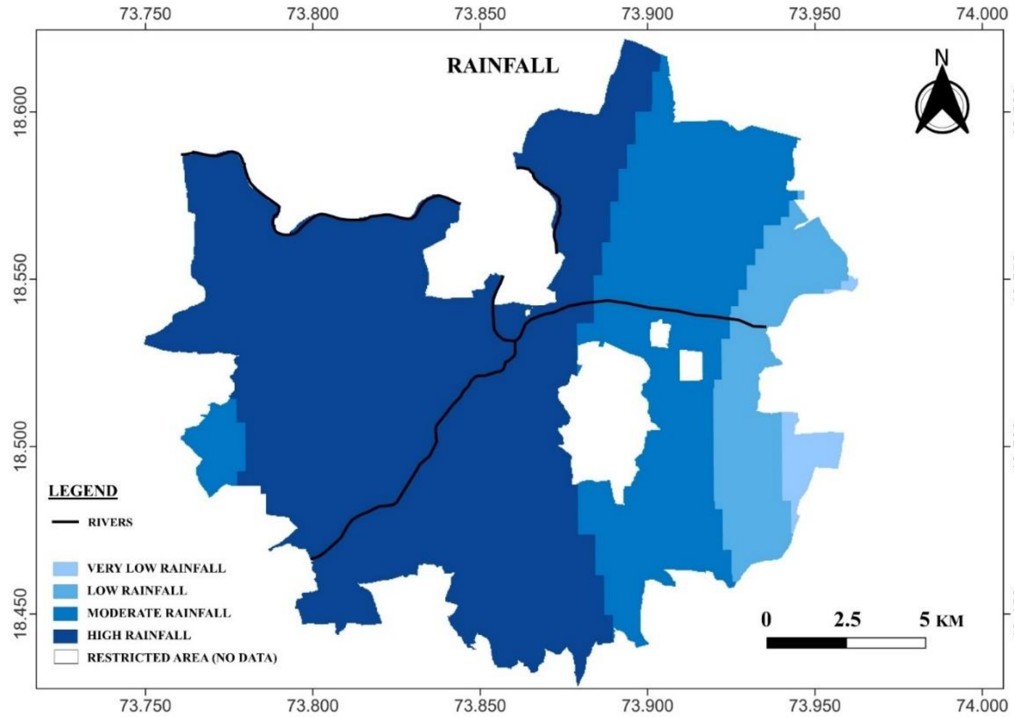


Figure 45 Rainfall Map

Though rainfall is a key factor for assessing the suitability of a region for harvesting it was ranked much lower than LULC and slope since it was found that a major part of the city area is built up leading to run-off instead of infiltration.

The rainfall in the area ranged between a high of 4.79 and a low of 3.47 mm/day. Based on this, the study area was re-classified into four classes high, moderate, low, and very low rainfall. These occupy 11.83%, 56.95%, 22.07% and 9.16% respectively.

Soil texture is a crucial parameter that influences the infiltration of rainfall into the ground. The rate and quantity of infiltration are dependent on the grain structure, size, and shape of the soil particles. Both soil texture and hydraulic characteristics (permeability) play a role in influencing the rate of infiltration.

The Soil map was obtained from NBSS and LUP. It was then clipped to the study area and used to create the soil type vector data The classification of soils given by NBSS and LUP is used in this study. The study area exhibits five broad textural classes or types of soil (Figure 46). About 42% (104 km^2) of the area is occupied by loamy, mixed and iso-hyperthermic, moderate stoniness soil which is good for infiltration. Fine Clayey and calcareous soil occupies 136 km^2 (54%) of the area. The other layers together constitute only about 4% of the area. According to Cornell University (2010), Sandy loams, Loams, Clay loams or Clay soils have an infiltration capacity of 0.4 to 0.8, 0.2 to 0.4 and less than 0.2 inches per hour respectively. Considering the texture and its sand content, Type 1 soil (loamy, mixed, and iso-hyperthermic soil) was given the highest rank and Type 5 soil (clayey soil) the lowest rank.

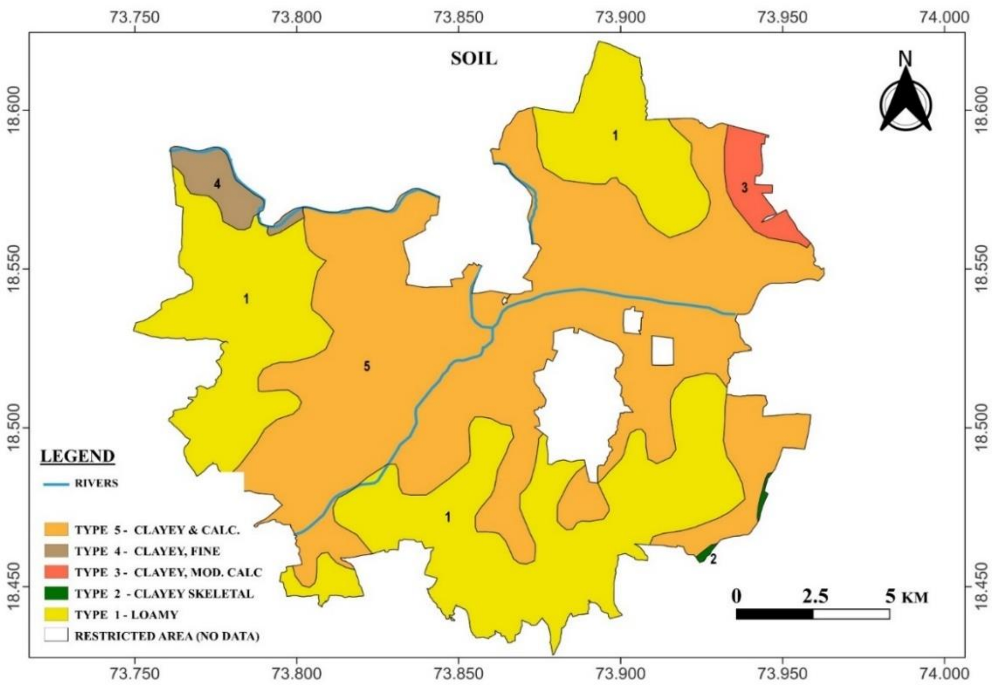


Figure 46 Soil map

The **lithology** of an area determines the infiltration capacity as different rocks exhibit different properties. Porosity varies from one type to another and has a direct effect on the recharging capacity (Senanayake et al., 2016). The lithology was derived from the District Resource Map of the Geological Survey of India (GSI, 2001). The resource map was georeferenced and digitized to obtain the geological map of the area. The area contains basaltic flows belonging to four different formations namely, Karla, Diveghat, Indrayani and Purandargarh Formations, each exhibiting distinctive characteristics (Figure 47) A major part, about 129 km^2 (51%) of the area is occupied by the Karla Formation constituted of dominantly compound pahoehoe flows. Other lithologies like àa and simple flows with thick fragmented tops, known as Flow Top Breccia (FTB), predominantly àa flows with thick FTB and àa and simple flows with thin FTB constitute 25%, 24% and 1% of the area, respectively. Being vesicular, the compound pahoehoe flows show maximum recharge potential. According to Kulkarni et al. (2000), the weathering and jointing of the vesicular amygdaloidal basalt and the joints within the compact basalt create the aquifers. Àa flows being compact and dense do not exhibit much infiltration capacity.

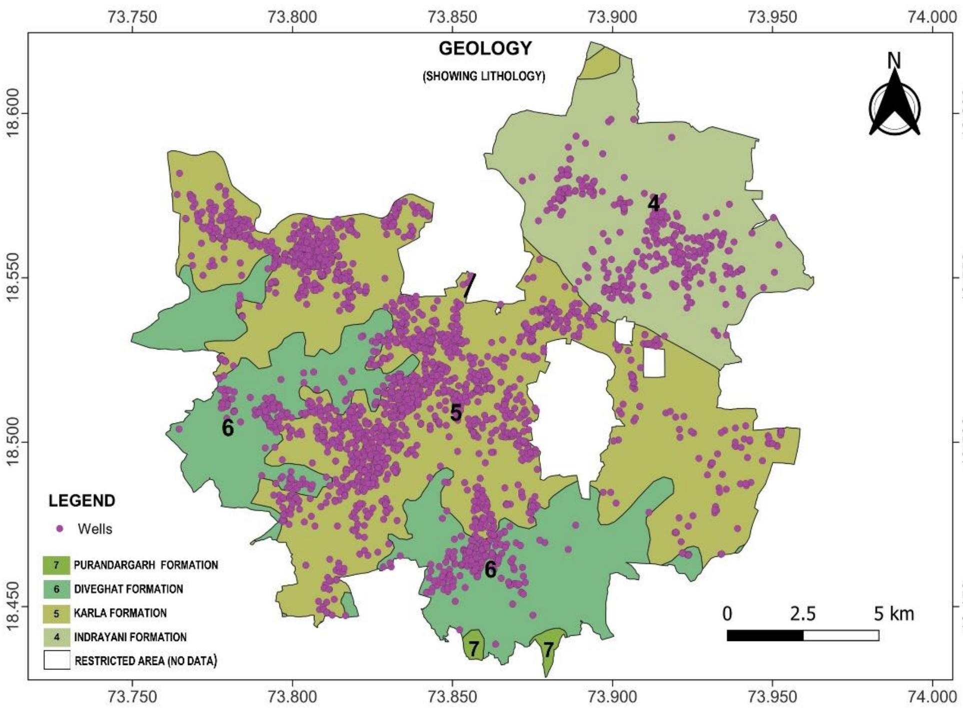


Figure 47 Geological map showing lithology

The **Groundwater recharge potential zones map** of the study area was generated using various thematic factors viz. LULC, rainfall, slope, drainage density, soil and lithology using the weighted overlay analysis have been categorized into five zones viz. low, moderate, good, high, and very high potential. The Groundwater potential map (Figure 48) shows the coverage of 13.24 km^2 (5%), 124.71 km^2 (50%), 72.92 km^2 (29 %), 8.11 km^2 (3%), and 30.27 km^2 (12%) for the above zones, respectively.

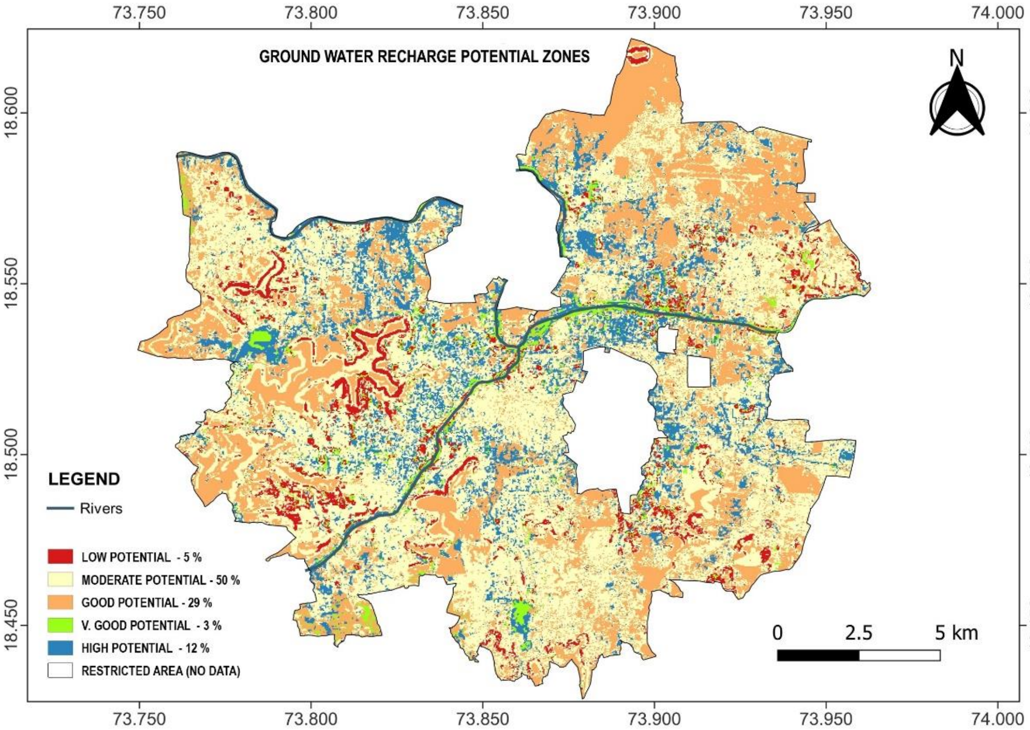


Figure 48 Map of Ground Water Recharge Potential Zones

Assessment of potential zones within the study area reveals that the high and good potential zones lie towards the western part of the city. The central part of the inner city which is mainly a built-up area shows low potential for recharge. Earlier studies by Vaddadi et al. (2022) on rooftop rainwater harvesting estimated the total water available for Rainwater harvesting in Pune city to be 49.05 million cubic metres (MCM) and that effective recharge using RWH techniques could supplement the groundwater annually by about 22-25 MCM.

Well Analysis

The study indicates that the number of bore wells (3010) outnumber the dug wells (228) by a large margin (Figure 38). Usage analysis of wells indicates that 2681 (83 %) wells are perennial and are being used for abstraction, especially in summer months. Many of these are used around the year for gardening purposes. 251 (8 %) of these wells were used seasonally or occasionally. Dry or 'not in use' wells constitute 306 (9%). (Figure 39) Further a representative survey of 135 well owners showed that only 22 (18 %) of the yielding wells, are presently being used for rooftop rainwater harvesting.

Further analysis of the distribution across regions in the city shows that the majority of wells fall in the Northwest (27%) and Central (26%) parts of the city. These are followed by the West (16%). This indicates that major extraction is happening more towards the Central and Western parts of the city. (Figure 37)

The maximum number of wells fall in the administrative wards of Aundh (Northwest), followed by Ghole Road (Central) and Karvenagar (West) wards. (Figure 36). A ward-wise analysis shows the maximum number of wells are in the Baner-Balewadi ward (418 wells) followed by Aundh (200) and Kamla Nehru Park ward (180). One of the possible reasons for the large number of wells in Baner-Balewadi could be because this area was earlier not a part of the PMC and there was no organized water supply to this suburb. Another reason could be due to the construction boom which started in the 2000's during which most of the water required for the construction activities was extracted from borewells.

Frequency Ratio (FR)

The Frequency Ratio (FR) technique or model is used to determine the possibility of an occurrence based on relationships between dependent variables. It has been extensively used in various geospatial studies, especially in Landslide mapping and predicting landslide-prone areas and has proved to be effective. When the frequency ratio value is large, the relationship between the landslide and the influencing factor is stronger (Jaafari et al., 2014).

The Frequency Ratio (FR) method is now a widely used technique for mapping groundwater recharge potential zones. The FR is a bivariate statistical method utilized to assess the likelihood of groundwater potential areas by establishing relationships between dependent and independent variables, such as bore wells and groundwater influencing factors respectively (Oh et al., 2011, Naghibi et al., 2016).

The Frequency Ratio (FR) technique is a model that uses data to integrate the positions of existing wells and analyse the spatial correlations between variable classes and well locations. The FR model is based on the principle that the presence of water at a particular location indicates a high Groundwater potential (GWP). When a considerable number of wells are found within a specific variable class, which covers a comparatively small area of the study region, the FR model infers that the characteristic represented by that variable class contributes to a high GWP. The Frequency ratios in the study areas were computed as follows:

$$\text{Frequency Ratio (FR)} = \frac{Pw/Tw}{Pc/Tc} = \frac{\%\,Well}{\%\,Class\ Pixels} \qquad \ldots\ldots\ \text{Eq. 4}$$

Where

FR is the frequency ratio of the sub-classes,

Pw is the number of Well pixels located in each class,

Tw is the total number of Well pixels in the study region,

Pc is a number of pixels in each class and

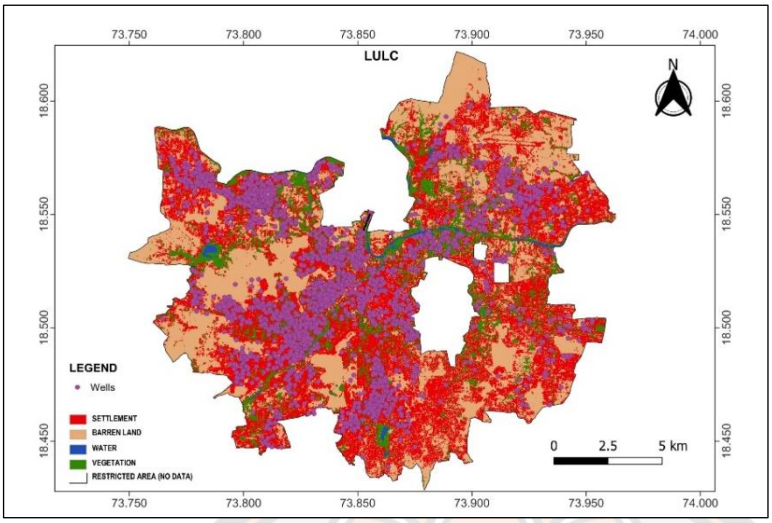
Tc is a total number of pixels in the thematic layer.

As mentioned earlier, data from 3074 wells was used to calculate the FR for each of the considered thematic factors. The calculations and results of the Frequency ratio are given in Chapter 4 (Tables 9 & 10). The FR maps for each of the thematic factors are shown in Figure 49 (a to f).

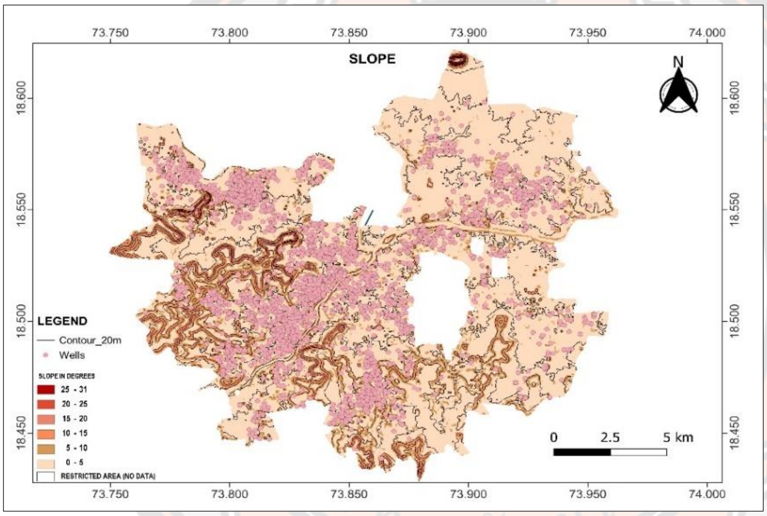
The relationship between the various factors and groundwater potentiality shows rainfall with an FR value of 2.33 having the highest value amongst all the factors. The next highest is soil with a value of 1.63. Interestingly for rainfall, the moderate class shows the largest value indicating that there could be a higher run-off in the area with high rainfall.

For soil, the class with fine, strongly Calcareous, Clayey and which is Montmorillonite (Index – 266) shows the highest value. The relation with LULC shows the highest FR value of 1.41 in the settlement or built-up area. While seeming anomalous this could be because the maximum number of wells and maximum extraction happens in the populated areas.

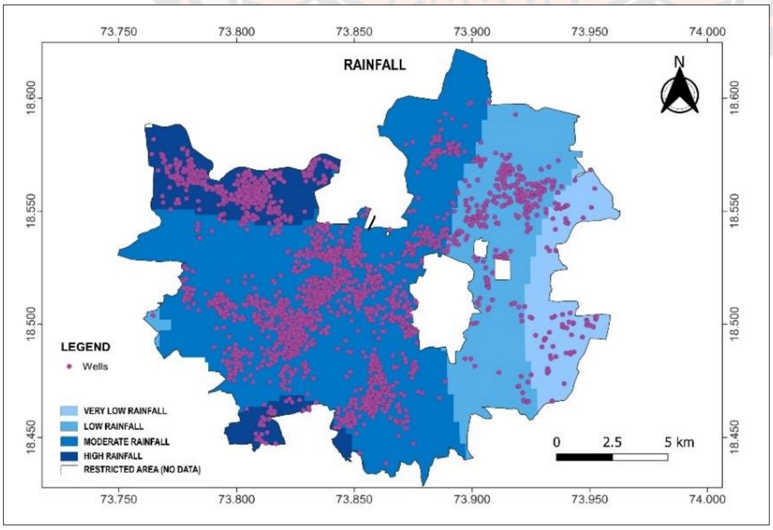
The analysis of drainage density shows that the high FR value is concentrated within the low and moderate-density zones. The slope's FR value is highest in the 'very gentle' class, followed by the flat areas, and it decreases with an increase in the degree of slope. Among the geological units, the highest FR value of 1.44 is observed in the dominantly compound pahoehoe flows, indicating a high likelihood of the presence of groundwater in these lithounits.



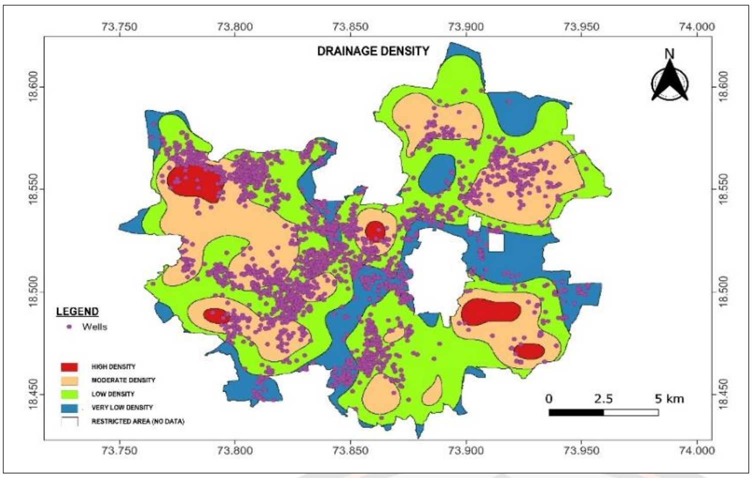
(a) Land Use and Land Cover



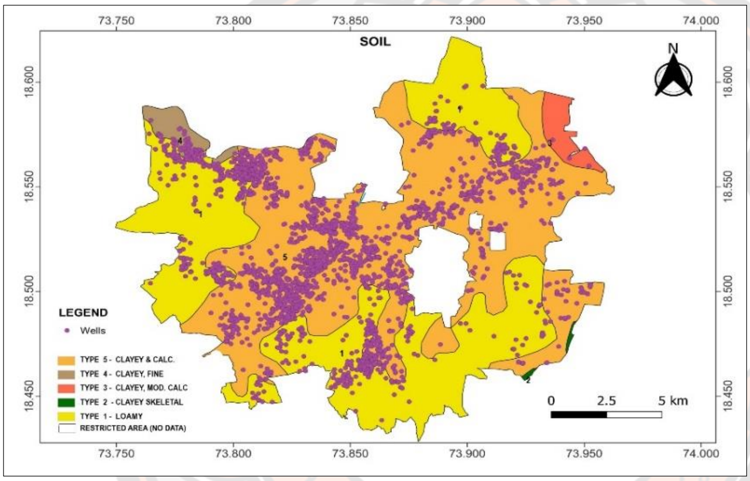
(b) Slope



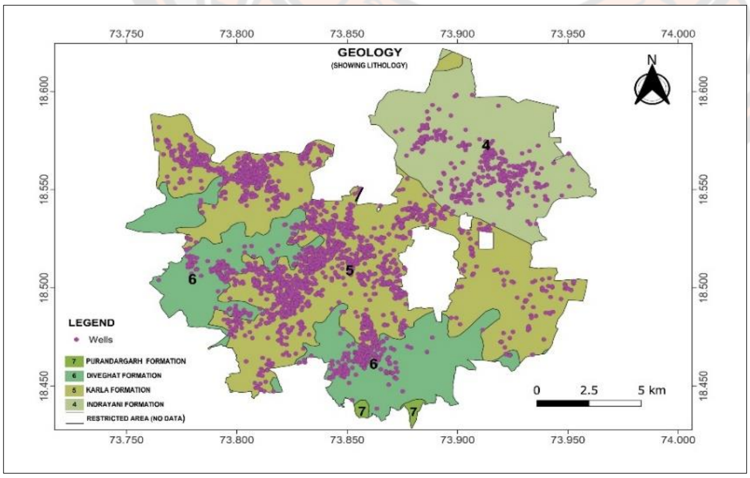
(c) Rainfall



(d) Drainage Density



(e) Soil



(f) Geology

Figure 49 (a) Land Use and Land Cover (b) Slope (c) Rainfall 49 (d) Drainage Density (e) Soil (f) Geology

The relation with groundwater potential zones mapped by AHP shows the FR value is the highest in the High Potential zone followed by the low and moderate potential zones. Notably, high to moderate potential zones occur in the Central and Northwestern parts of the study area. Moderate rainfall and low slope categories and the presence of the pahoehoe flows present in these areas significantly influence the infiltration of water into the ground. (Figure 50).

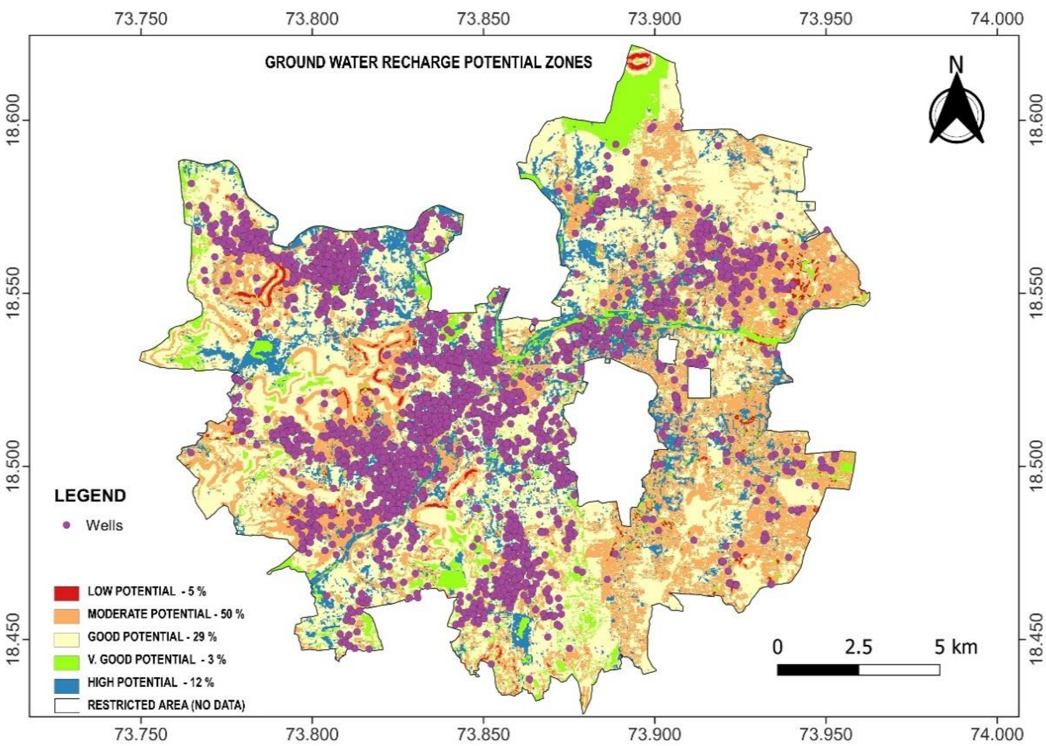


Figure 50 Frequency map of the Groundwater recharge potential zones

Rooftop Rainwater Harvesting

The recharge processes in urban areas and non-urban areas differ significantly. Natural infiltration is limited due to urbanisation. Increasing construction activity and the practice of concretising the roads lead to the run-off of water into the drains with very little water available for infiltration. In the Pune Metropolitan region, the water level during post-monsoon in urban areas is shallow (< 3 Meters below ground level) and therefore augmenting groundwater at shallow depths is not feasible. (Paranjape, & Pawar, 2006). According to the latest survey by the Central Ground Water Board, CGWB, this is no longer true as the water levels now fall in the second zone where water levels fall between 3 to 10 meters below ground level (mbgl).

The estimated groundwater availability for Pune city in 2007-08 as per Groundwater Survey and Development Agency (GSDA), Maharashtra was 34 million cubic meters (MCM) while annual consumption in the city was estimated as 24 MCM. (SANDRP, 2016). Considering the projected increase in population by about 1.3 million between 2011 & 2021, the annual use can be estimated to have increased by about 9 MCM to 33 MCM.

A survey of dug wells and borewells in the Pune district by the Vasudha Foundation (2022) revealed that groundwater extraction in Pune has doubled from 2 TMC (Thousand million cubic feet) in 2011 to 4 TMC in 2019. (Kulkarni et al., (2023) estimated the annual groundwater extraction averaged over the Pune Municipal Corporation (PMC) area to be about 100 MCM (3.53 TMC) per year.

Considering this big dependence on Groundwater, it becomes important to gauge the potential for recharge of aquifers. In such conditions, systematic rainwater harvesting, or managed recharge can play a crucial role in augmenting the local supply of water, both from unconfined as well as confined aquifers. Understanding the potential for Rainwater harvesting (RWH) using the rooftops and existing wells is the first step in fulfilling a social need to increase the availability of potable water.

A representative field survey of 135 wells owners indicated that only 22 (18 %) of the yielding wells, are presently being used for rooftop rainwater harvesting This indicates that there is a large scope for rooftop rainwater harvesting using direct /gravity injection technique for recharge.

To understand the potential, a pilot study was carried out initially to understand the efficacy of the use of rooftop run-off for rainwater harvesting. As per that study, the total water availability in a year works out to approximately 49.05 million cubic metres (MCM) or 1.73 TMC (Thousand million cubic feet or billion cubic feet) considering unit run-off of 624 litres per square metre, and rooftop surface area of 99.5 sq. km. (Vaddadi et al., 2022)

The results of the detailed study incorporating 35 representative wards of the 76 electoral wards indicate a total availability of water for recharge from the rooftops to be 15 million cubic metres. The digitised rooftops of buildings had a total rooftop area of 3.82 sq. kilometres and covered approximately 5% of the total ward area. An amount of 43.92 million cubic metres is obtained considering the above figures and by extending these results to the 76 wards. This amounts to 1.6 TMC of water which can be used for harvesting and artificial recharge of the wells in the city.

On a conservative estimate, even if half of this total rainwater is harvested, the recharge can supplement the groundwater annually by about 21 - 22 MCM (0.7 to 0.80 TMC). This can cater to a major part of the annual groundwater requirement of Pune City.

The analysis from the present study to understand the recharge potential from rooftop rainwater harvesting for Pune City highlights the fact that almost a third of the present-day extraction of groundwater can be recharged through rooftop rainwater harvesting. Direct gravity injection using low-cost filtration techniques & clean filter mechanisms can become a viable and low-cost method to harness the rainwater.

CHAPTER VI

SUSTAINABLE GROUNDWATER MANAGEMENT

Introduction

This study has been carried out to understand the potential of rooftop rainwater harvesting as a potential method to carry out the recharge of the groundwater aquifers. Despite the widespread implementation of groundwater recharge at an individual or community level, there has been a lack of a systematic and scientific approach to groundwater recharge and maintaining the balance between demand and supply in the area under study. Globally, numerous methods have been used and several strategic frameworks have been developed over the last two decades to approach groundwater recharge and augmentation in a sustainable and systematic manner. The following paragraphs outline the concept of sustainability and some of the common frameworks in use globally. Based on the present study, the chapter explores a method that can be used in the local context and suggests a framework that can be used locally to ensure the sustainability of the groundwater resources. Further, it highlights the steps that can be taken on a strategic (Macro / institutional) or a local (micro) level to tackle the issue of excess groundwater abstraction and depletion and implement systematic groundwater recharge and aquifer management.

Sustainability

Sustainable development posits that human societies should strive to exist and fulfil their needs in a manner that does not jeopardize the capacity of future generations to satisfy their own needs (Brundtland, 1987). Broadly the term seeks to integrate three facets – economic, environmental, and social (or socio-political). Further, it refers to the strategic approach of structuring a society to ensure its viability in the long run. It involves consideration of present and future needs, including the conservation of natural resources and the environment, as well as promoting social and economic fairness.

It is being increasingly accepted that in the present age – Anthropocene, human activities are having a progressively damaging impact on the Earth’s systems leading to undesirable consequences. It is now becoming important to understand the role of various human activities like mining, petroleum exploration, groundwater extraction and land use changes especially seen in relation to the phenomenon of geohazards such as landslides, floods and other aspects like soil degradation and climate change.

The key to a sustainable city is to effectively sustain and support its large population for the long haul by harmonizing economic viability, environmental integrity, and social equity. Resilience, as defined by UNISDR (2005), refers to the ability of a system, community, or society exposed to various hazards to adapt, achieve, and uphold an acceptable level of functioning and structure. As per Koh et al. (2020), a sustainable city serves as a resilient habitat, where its residents can strategize and govern their present and future well-being, ensuring a lasting equilibrium between environmental integrity, social equity, and economic viability. According to Das & Burke (2013), the sustainability of an intervention may be assessed by whether its intended objectives are met and sustained after the withdrawal of the initiative.

Groundwater sustainability

Groundwater, the concealed water resource beneath the Earth's surface, accounts for roughly 99% of the planet's liquid freshwater. Its significance lies in its capacity to provide potable water, maintain food security, adapt to climate variability, sustain biodiversity, preserve surface water resources, and contribute towards the accomplishment of the United Nations' Sustainable Development Goals.

Many regions worldwide are grappling with the depletion and contamination of groundwater, posing a significant obstacle to socio-economic progress and putting the supply of water, food, and ecosystems at risk. One of the crucial water challenges confronting the world today is to maintain the significant benefits that groundwater development has provided while avoiding excess depletion of this vital resource.

Unfortunately, groundwater issues and opportunities are often ignored in national and international policies intended to foster sustainable development, climate adaptation, and biodiversity. However, with the use of innovative techniques in groundwater development and management, groundwater can continue to be a valuable resource for society both today and in the future.

The UN Sustainable Development Goals (SDGs) and Groundwater

The Sustainable Development Goals (SDGs) adopted by the United Nations in 2015 are a set of 17 goals that call for action by all the countries globally that aim to improve health and education, reduce inequality, ensure universal access to basic services, eradicate poverty, end unsustainable consumption patterns, spur economic growth while tackling climate change and protecting our natural resources (Figure 51). Many of the SDGs are intimately interconnected and require better management of natural resources (land, water, or minerals).

Groundwater plays a crucial role in several of these goals, including Sustainable Development Goal 6 (SDG 6), which aims to give access to clean water and sanitation for all and the mission of Sustainable Development Goal 11 (SDG 11) is to make cities, safe, inclusive and resilient.

Figure 51 UN Sustainable Development Goals

Source: United Nations, 2015

Groundwater is a finite resource that is subject to depletion, contamination, and overexploitation. To achieve SDG 6, effective groundwater management practices are needed to ensure the sustainable use of this resource. This requires the development and implementation of policies, technologies, and practices that promote sustainable groundwater use.

One of the key challenges in achieving SDG 6 is addressing the issue of overexploitation which generally leads to the depletion of groundwater resources. Overexploitation occurs when the rate of groundwater extraction exceeds the rate of recharge, leading to reduced water levels and reduced groundwater storage. This can have significant impacts on water availability for domestic, agricultural, and industrial use, as well as on the environment and ecosystems that depend on groundwater.

To address this challenge, effective groundwater management practices are needed, including measures to regulate groundwater extraction, promote water conservation and efficiency, and encourage the use of other water sources. Groundwater recharge techniques, such as artificial recharge, can also be used to increase the rate of recharge and replenish groundwater.

In addition to SDG 6, groundwater sustainability is also essential for achieving other SDGs related to food security, climate action, and biodiversity conservation. Groundwater plays an important role in providing water for irrigation and agricultural needs, which is essential for ensuring food security (SDG 2). It also plays a critical role in mitigating the impacts of climate change, such as droughts and floods, by providing a buffer against variability in surface water resources (SDG 13).

Achieving SDGs related to water requires addressing several challenges related to groundwater sustainability. These challenges include overexploitation, contamination, and poor governance, as well as the need for better data and information on groundwater resources and their use.

To address these challenges, several strategies and approaches can be adopted, including the development and implementation of effective groundwater governance frameworks, the promotion of sustainable groundwater use practices, and the use of innovative technologies to monitor and manage groundwater resources. In addition, there is a need for greater investment in research and development to improve our understanding of groundwater resources and their use, as well as to develop and promote innovative solutions to address the challenges facing groundwater sustainability. Achieving the SDGs will require the development and implementation of effective groundwater management practices, policies, and technologies, as well.

Sustainable Water Management

Sustainable Water Management (SWM) is a comprehensive notion that covers diverse aspects of water resource management, encompassing both surface water and groundwater. It plays a vital role in sustainable development and shares common concerns with sustainability (Russo, 2014).

According to Mays (2006), SWM is described as the effective management of water resources, ensuring the present needs of all water users are met without compromising the availability of water for future generations. To be effective, SWM must align with societal goals and uphold the integrity of ecological, environmental, and hydrologic systems (Loucks, 1999). SWM is the responsible and efficient use and management of water resources in a manner that ensures their long-term availability and quality, while also considering the social, economic, and environmental needs of communities. It involves the adoption of practices, policies, and technologies that promote the conservation, protection, and sustainable use of water resources.

A key aspect of sustainable water management is the conservation of water resources through measures such as water-use efficiency, water recycling, and rainwater harvesting. This includes adopting technologies such as low-flow showerheads and toilets and using water-efficient appliances and irrigation systems. It also involves the use of Rainwater harvesting from rooftops and other surfaces for immediate use and for aquifer recharge through various means.

The sustainable management of water resources also involves balancing the needs of different stakeholders, including communities, industries, and ecosystems. This includes promoting the equitable distribution of water resources and ensuring that the allocation of water resources considers the needs of different stakeholders. It involves adopting an integrated approach to water resource management considering the interconnectivity of different aspects of water resource management, such as surface water and groundwater resources, and integrating water management with land-use planning and ecosystem management.

Sustainable Ground Water Management

Groundwater management is an essential component of sustainable water management, as groundwater is a critical resource for many regions around the world especially in urban areas where it has become an essential commodity.

To ensure sustainable management of a groundwater resource, it is essential to manage demand so that it aligns with the recharge rate, whether it is natural, managed, or incidental. Sustainable water management especially in the context of groundwater is of utmost importance for ensuring water security, ecological sustainability, and socio-economic development. Sustainable management of groundwater resources involves various measures aimed at ensuring the long-term availability and quality of groundwater resources. This includes measures such as managing groundwater recharge, reducing groundwater extraction rates, controlling pollution, and promoting efficient use. Villholth, & Sharma (2005) propose that effective groundwater management necessitates the incorporation of scientific knowledge into decision-making processes.

To ensure the sustainable management of groundwater in India, several aspects demand attention. Mehta (2015) emphasizes the importance of viewing groundwater not in isolation but as part of a broader framework that encompasses artificial recharge, conservation, conjunctive use, and water-conscious land use planning, all tailored to suit the available water resources.

Hence it becomes imperative that a groundwater management plan is necessary for sustainable groundwater management. A groundwater management plan is a comprehensive strategy that outlines how groundwater resources will be managed and used sustainably. It typically includes measures such as setting limits on groundwater abstraction, implementing monitoring programs to track groundwater levels and quality, and establishing policies to promote efficient water use. The focus of groundwater management strategies should be on achieving a balance between water demand and the availability of supply (Villholth, & Sharma, 2005).

Another important aspect of sustainable groundwater management is the implementation of best practices for groundwater recharge. This can be achieved through measures such as rainwater harvesting, artificial recharge, and the use of permeable surfaces to allow for natural infiltration. In addition, the use of other sources of water, such as recycled water and desalinated water, can help alleviate pressure on groundwater resources.

Effective monitoring and regulation mechanisms are also essential for sustainable groundwater management. This includes the implementation of policies and regulations that support the sustainable use of groundwater resources, as well as monitoring and reporting systems to track the status of groundwater resources and ensure compliance with regulations.

A critical aspect of sustainable groundwater management is the participation of local communities and stakeholders. The involvement of local communities in groundwater management can help to ensure that groundwater resources are used sustainably and equitably. As per a UN-Habitat report in 2005, ensuring water sustainability in a city necessitates strong engagement from stakeholders. This involvement is crucial as it guarantees that water management plans for the city are designed with due consideration of the specific needs, interests, and experiences of all local stakeholders. According to Villholth (2005), the intrinsic characteristics of groundwater, namely its invisibility and widespread distribution, pose significant challenges to its management. Dealing with a multitude of individual users across extensive regions and accurately monitoring their water usage becomes extremely challenging, even in developed countries.

Managed Aquifer Recharge

Over the past few decades, numerous discussions on solutions for addressing the issue of groundwater depletion have taken place. Managed aquifer recharge (MAR) is one such potential solution. It involves a holistic approach to increasing water availability by utilizing all types of groundwater recharge programs to generate water supplies including the use of sources that would otherwise go to waste (Gale et al. 2006; Sharma, 2011). This approach, as defined by Oaksford (1985), involves the planned augmentation of groundwater through efforts to increase the natural replenishment or percolation of surface water into aquifers, resulting in more groundwater available for extraction.

Managed Aquifer Recharge (MAR), formerly referred to as 'artificial recharge,' involves the deliberate redirection of surface water to the groundwater reservoir through the alteration of the natural movement of surface water by using a variety of techniques, Recognizing the growing significance of community involvement in water resources management, the term "Managed Aquifer Recharge" (UNESCO-IHP, 2005) emerged as a more fitting replacement for 'artificial,' shedding the negative connotations associated with the previous term.

Managed aquifer recharge (MAR), also known as groundwater replenishment, water banking, or artificial recharge, involves intentionally recharging water into aquifers for future retrieval or environmental advantages (IAH 2022). An extensive evaluation of 28 schemes across 21 countries conducted by Zheng et al. (2022) demonstrated that MAR is an environmentally and socially sustainable technology. This nature-based engineering approach is expected to play a progressively crucial role in adapting to climate change by enhancing water supply, and environmental flows, and promoting the recycling of treated wastewater.

The primary objective of Managed Aquifer Recharge (MAR) is to increase the availability of groundwater resources by storing the excess surface water for future use and replenishing depleted groundwater levels resulting from over-abstraction thereby enhancing stability (UNEP, 1998). However, it is important to note that MAR alone cannot solve the issue of overexploitation of aquifers and may even increase the rates of abstraction. Therefore, to ensure the successful and sustainable implementation of MAR projects, it is crucial to incorporate comprehensive planning and operation as an integral component of watershed-wide or national water management strategies that promote rainwater harvesting and reuse (CEHI, & GWP, 2010).

Dillon et al. (2022) state that Managed Aquifer Recharge (MAR) enhances groundwater resources with the available surface water. It works in tandem with conjunctive use practices, facilitating the sustainability of water supplies and accomplishing management goals such as ecosystem protection. for both groundwater and surface water. (Figure 52). Evans and Dillon (2019) define conjunctive use as the coordinated utilization of surface water and groundwater to maximize their joint benefits while minimizing the potential undesirable physical, environmental, and economic impacts that may arise from relying solely on one source or the other.

Moreover, as per Zheng et al. (2021), Managed Aquifer Recharge (MAR) can play a crucial role in advancing water security and equity objectives in rural developing regions. This can be achieved by empowering vulnerable communities to take charge of self-management and maintenance of local MAR schemes.

Over the past two decades, several alternatives to address the challenges caused by the depletion of groundwater have been discussed (Sakthivel, 2015). Several frameworks have been suggested and used to implement Managed Aquifer Recharge (MAR) in urban areas all over the world. Some of these are:

1. The *Integrated Water Resource Management (IWRM)* framework: This framework emphasizes the need for a holistic approach to water management and includes the use of MAR as one of the tools for achieving this goal. It addresses the economic, social, and environmental aspects of water management, and encourages the participation of stakeholders in the decision-making process.

2. The *Water-Sensitive Urban Design (WSUD)* framework: This framework focuses on the integration of water management into the planning and design of urban areas. It includes the use of MAR to manage stormwater runoff and recharge aquifers in urban areas.

3. The *Adaptive Water Management (AWM)* framework: This framework emphasizes the need for a flexible and adaptive approach to water management, given the uncertain and changing nature of water resources. It includes the use of MAR as a method to adapt to changing water availability and quality, and to build resilience to drought and other water-related challenges.

4. The *Climate Resilient Water Management (CRWM)* framework: Climate Resilient Water Management (CRWM) sets CRWM apart from conventional water management approaches by focussing on three key areas: water resource management, management of extreme events such as floods and droughts, and the establishment of an enabling environment.

5. The *Integrated Urban Water Management (IUWM)* framework: This framework focuses on the integration of different water management elements into one comprehensive approach, including the use of MAR as a means of increasing water availability, improving water quality, and managing groundwater levels in urban areas.

6. The *Sustainable Urban Drainage Systems (SUDS)* framework: This framework focuses on the management of surface water runoff in urban areas and includes the use of MAR as a means of reducing the volume of runoff and improving the quality of runoff water.

7. The *Climate-Smart Water Management (CSWM)* framework: This framework focuses on the integration of water management with climate change adaptation and mitigation strategies. It includes the use of MAR to increase water availability improve water quality and adapt to the impacts of climate change on water resources.

8. The *Sustainable Groundwater Management (SGM)* framework: This framework focuses on the sustainable management of groundwater resources and the protection of groundwater quality. It includes the use of MAR to ensure the sustainability of groundwater resources and to protect groundwater quality.

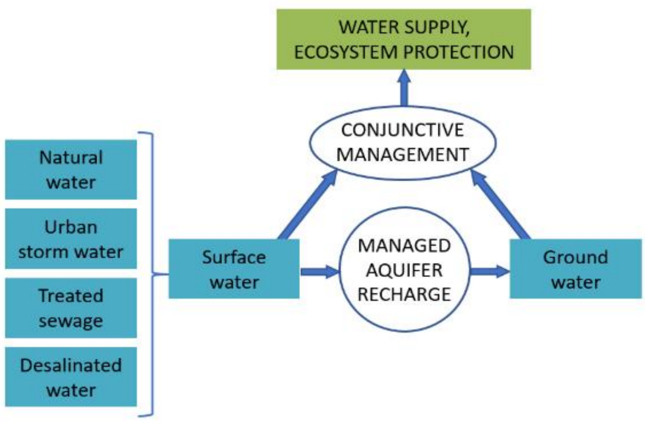


Figure 52 Roles of managed aquifer recharge and conjunctive use in integrated water resources management

Source: Dillon, & Arshad, 2016

Among these frameworks, the IWRM (Integrated Water Resources Management) framework is one of the most widely employed. It serves as a conceptual model designed to capture the intricacies of water-related decisions and emphasizes the significance of balancing various stakeholder perspectives (Grigg, 2008).

According to the Global Water Partnership (GWP), Integrated Water Resources Management (IWRM) is described as a process that fosters the harmonized development and responsible management of water, land, and associated resources. Its goal is to maximize economic and social well-being equitably while ensuring the sustainability of essential ecosystems. (Ben-Daoud et al., 2021). The goal of IWRM is to achieve the sustainable management of water resources to protect the environment, ensure fair distribution of water for social reasons, and enhance economic efficiency in water usage (GWP, 2004, 2009).

According to Godinez-Madrigal et al. (2019), GWP (2009) and Hooper (2015), the objective of IWRM is to achieve a balance between meeting the increasing water demand for sustaining a growing population's livelihoods and conserving water resources to ensure a sustainable water supply. Several organizations worldwide have adopted the IWRM approach, such as the World Water Council (Smith and Clausen, 2015), the Global Water Partnership (GWP, 2000), and international organizations like the United Nations, World Bank, etc. (GWP, 2009).

In an urban context, the Integrated Urban Water Management (**IUWM**) framework is often used. Sustainable urban development means focusing on the relationships between water, energy, and land use, and diversifying sources of water to assure reliable supply. According to Biswas (1981), Integrated urban water management (IUWM) originates from the broader concept of integrated water management, which involves managing all aspects of the water cycle across a catchment area. In the urban context, it considers the roles and interactions of the various institutions involved in the management of the urban water cycle (Rogers, 1993) and combines the management of water supply, groundwater, wastewater, and stormwater (Fletcher et al., 2007). Integrated urban water management (IUWM) by its very nature encompasses a much wider scope than the terms solely focused on urban drainage management (Fletcher, 2015).

Integrated Urban Water Management (IUWM) offers a comprehensive structure for strategizing, designing, and handling urban water systems. It is a dynamic and adaptable process that embraces change and empowers stakeholders to foresee the repercussions of interventions effectively.

The term IUWM gained popularity in the 1990s, as evidenced by its usage in works by Geldof (1995), Harremoes (1997), and Niemczynowicz (1996). Geldof (1995) was one of the first authors to contribute to the underlying concept of IUWM, by proposing a logical framework that addressed issues of scale, levels (including institutional and social aspects of management), and assessment. While the principles of IUWM may differ somewhat between authors, they generally align with those commonly accepted in the field.

MAR in Urban Water Management

According to Page et al. (2018), deliberate recharge of groundwater using specialized structures like injection wells and infiltration basins can enable the recovery and use of water or its storage, thereby offering environmental advantages to the aquifer. This approach, known as Aquifer Storage and Recovery (ASR) in Australia, is an example of managed recharge. By enhancing the natural rates of groundwater recharge through MAR, it's possible to create a significant water source for urban areas where impervious surfaces have disrupted the natural recharge patterns.

Further, Page et al. (2018) suggest that MAR could play a crucial role in enhancing urban water management by offering storage options for diverse water qualities that serve various purposes.

With the increasing adoption of green infrastructure and water-sensitive urban design practices in cities, the urban stormwater quality is anticipated to be enhanced, leading to a rise in the volume of collectable water. Das (2019) identifies four key components of the urban water cycle: river water, lake water, groundwater, and recycled grey water. The integrated management of these water cycle components forms the fundamental basis of a smart city.

According to the Caribbean Environmental Health Institute (2010), certain fundamental conditions need to be met for the implementation of Managed Aquifer Recharge (MAR) in urban areas including:

1. The identification of a suitable aquifer that can store water or facilitate water table recovery, along with the procurement of land for recharge purposes.

2. The identification of available run-off which is surplus during the wet season or other potential water sources.

3. The determination of the most cost-effective recharge method that aligns with the specific site conditions.

To achieve these requirements, geological, hydrological and hydrogeological investigations must be conducted. The initial two stages of locating suitable areas can be accomplished by mapping pertinent topographical, hydrological, geological, climatological, and land-use parameters.

The Central Ground Water Board, India and several other Indian agencies have over the years carried out studies to find solutions to the looming water crisis (Das, 2019). A few of the solutions which have been put forward are:

1. Conjunctive use should form the cornerstone of water supply planning to mitigate water scarcity, rectify waterlogging, and improve productivity, particularly in canal command areas.

2. In urban areas, a comprehensive approach that integrates all components of the water cycle can help address water shortages and ensure sustainability and fairness.

3. Scientific and technological advancements can enhance knowledge in water management and complement traditional practices.

The availability of groundwater resources is primarily influenced by the physical environment, but the way groundwater is utilized is shaped by both the socio-economic and institutional environments. These factors include the nature of economic activities, patterns of population density, societal norms, as well as legal, administrative, macroeconomic, and political institutions. The sustainability of groundwater resources is thus dependent on this wide range of interrelated factors (World Bank, 2010). (Figure 53)

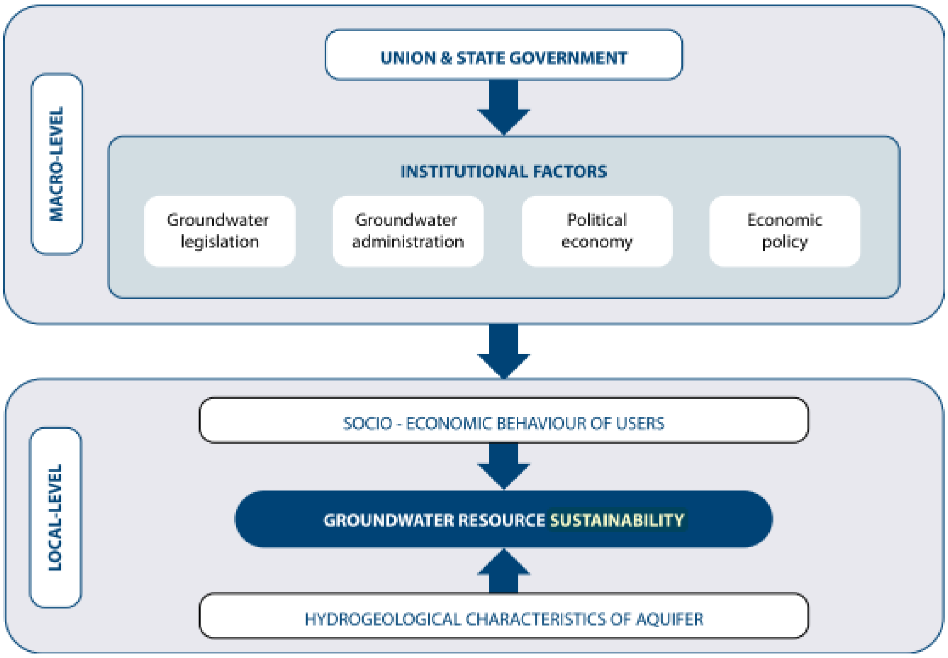


Figure 53 Major determinants of groundwater sustainability

Source: World Bank, 2010

Pune and its Groundwater Scenario.

According to NITI Aayog (2018) India's central think tank, twenty-one (21) cities in India including Delhi, Chennai, Hyderabad, and Bengaluru may run out of groundwater in the not-so-distant future. According to current trends in water resource development, it is projected that all known aquifers will be depleted by 2050 (Das et al., 2022). The imbalance in the water cycle created by unscientific urbanization has led to water shortages. The rapid urbanization of Pune city in the last decade with a burgeoning population has created similar challenges mainly an increasing imbalance between demand and supply.

Data obtained from Pune Municipal Corporation shows the population of Pune city has increased from 1.7 million in 1981 to 3.31 million in 2011 (Figure 54) and is projected to rise to 6.09 million in 2031 and 8.26 million in 2041. According to the World Urbanisation Prospects, the entire urban agglomeration of Pune is projected to have a population of 8.1 million by 2030. (WUP, 2014)

According to Butsch et al. (2017), Pune City experienced significant growth in the period 1992 to 2013, with built-up areas expanding by approximately 82.5 sq. km at an annual rate of 3.9 sq. km, Using the SLEUTH urban growth model simulations they estimate that the city will witness an additional 67.1 sq. km of built-up area, bringing the total to 206.4 sq. km by 2030.

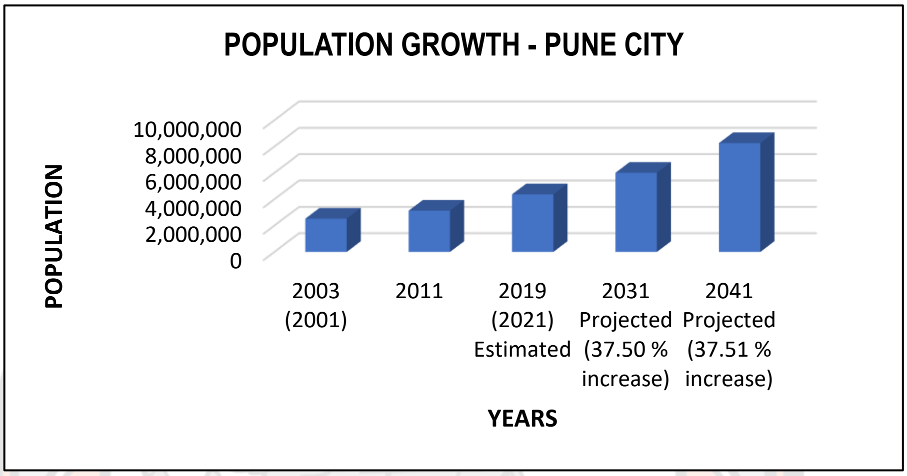


Figure 54 Population Growth – Pune City

Source: Pune Municipal Corporation, 2011

The annual water demand for Pune City in 2020 was 424 MCM and the budget for the year 2021-22 was 568.31 MCM. With population growth, the annual water demand will increase to 23.34 TMC (660.91 MCM) by 2031-32. (Pune Municipal Corporation, 2021). (Figure 2)

The estimated groundwater availability for Pune city in 2007-08 as per Groundwater Survey and Development Agency (GSDA), Maharashtra was 34 million cubic meters (MCM) while annual use by the city was estimated as 24 MCM. (SANDRP, 2016). Kulkarni et al. (2018) used the percentage of sewage in the water supply to perform a reverse calculation and determined that the estimated groundwater extraction for Pune City was 2.39 TMC in 2011. They also approximated that the extraction rate to have increased to almost 4 TMC in 2019.

Based on the data presented, it is evident that Pune City much like other urban areas across the country will soon face a water crisis. The gap between demand and supply necessitates looking for alternative sources of potable water to cater to the shortfall. Consequently, the availability of groundwater assumes importance. To address this problem, MAR using rooftop rainwater harvesting is a promising solution and represents an appropriate management strategy to mitigate the potential water scarcity issue.

Despite the widespread implementation of groundwater recharge, the process of MAR is neither easy nor straightforward. According to Gale et al. (2005), the effective implementation of Managed Aquifer Recharge (MAR) necessitates three essential elements: a source of water, adequate space in the aquifer to store the water, and mechanisms to retrieve the water later for beneficial purposes. According to Kulkarni et al., (2019), accurate comprehension of the groundwater footprint in urban water management holds significant importance. This understanding serves as the initial step towards evaluating groundwater sustainability, which is necessary for ensuring long-term, efficient, and fair urban water supplies.

Groundwater is a shared resource that is frequently overdrawn, leading to overexploitation, depletion of the water table, and drying up of rivers during non-monsoon months, resulting in a water crisis. Therefore, there is a need for scientific development, management, and optimization of water resources through an integrated approach that maximizes yield per unit of water. Das et al. (2022) suggest that supply and demand management (and not vice versa) should be at the core of water management.

Recommendations for Groundwater management in Pune city

In the current study, a two-pronged approach to the subject of groundwater recharge in Pune city was used. It covers the use of Rooftop Rainwater harvesting for recharge through gravity injection to confined aquifers or deep-seated aquifers and the delineation of groundwater potential zones for recharge of surface aquifers. Along with this, a systematic study of the distribution of about 3000 groundwater abstraction structures (dug wells and borewells) was also carried out to understand the density distribution of wells and frequency ratio across the different zones.

The study first identified the areas (including ward-wise) through a multi-criterion and an analytical hierarchy method using the various thematic factors that influence groundwater recharge. The analysis of the data helped to delineate the groundwater recharge potential zones in which the high and moderate potential zones were identified. The analysis of the total rooftop area and the total amount of water (run-off) available for rainwater harvesting was also part of this study. A systematic study of dug wells and borewells helped to identify potential areas in the city (wards/areas) for use in rainwater harvesting. An overlay of the frequency ratio on the Groundwater recharge potential map derived in this study indicated the areas that could constitute the priority zones for recharge in Pune city. (Chapter 5, Figure 50)

The SCARPE framework

A systematic and comprehensive approach is vital to manage groundwater sustainably. Any groundwater management plan should be comprehensive and take into consideration not just groundwater but also different aspects of integrated water management.

Based on the present study and globally successful practices presented earlier, especially the Integrated Water Resource Management (IWRM) framework, the Integrated Urban Water Management (IUWM) framework and the Managed Aquifer recharge, it is suggested that a systematic groundwater management framework – the SCARPE framework be used in Pune city. This will help to maintain the groundwater balance and augment the water resources in the city.

Salient features of the framework are outlined below, which if implemented will go a long way to maintain the groundwater balance in the city and augment the water supply to its residents.

The SCARPE framework proposes a methodical and structured process to ensure the long-term availability and quality of groundwater resources while meeting the water demands of the urban population. The framework includes measures such as setting limits on groundwater abstraction, implementing monitoring programs to track groundwater levels and quality, and establishing policies to promote efficient water use. The principal elements of the SCARPE framework (Figure 55) include the following elements:

S - Systems Approach

C - Conjunctive Use

A - Aquifer replenishment

R - Right Recharge mechanism

P - Protection of Existing sources and community involvement.

E - Effective monitoring and Balancing demand and supply

Systems Approach

A systems approach to groundwater sustainability for an urban area involves a comprehensive and holistic strategy to manage, protect, and replenish groundwater resources.

Pune City should consider a groundwater management plan that takes into account environmental, social, and economic factors. It should integrate different water management elements into one comprehensive approach, including using MAR to increase water availability, improve water quality, and manage groundwater levels in urban areas.

The Pune city council should establish a centralised Water management / Groundwater cell that coordinates the roles and interactions of the various departments and institutions involved in the management of the city's water cycle. Its principal function will be to manage the different aspects of water supply, groundwater, wastewater, and stormwater. It should foster collaboration among relevant government agencies, local authorities, and stakeholders.

Conjunctive Use

The Pune Municipal Corporation (PMC) should adopt integrated water resource planning in terms of conjunctive use that considers surface water, groundwater, and related ecological and environmental factors.

Conjunctive water use should form the basis of water supply planning, and aim to mitigate water scarcity, address waterlogging, and enhance productivity, especially within canal command areas.

Aquifer replenishment

A precise knowledge of the groundwater footprint in urban water management is of paramount significance. It serves as the foundational step in assessing groundwater sustainability, an essential factor in securing long-term, effective, and equitable urban water supplies. Several essential prerequisites must be satisfied for the successful replenishment and the deployment of Managed Aquifer Recharge (MAR) within urban areas. These are

1. Finding a suitable aquifer and securing land for recharging water.
2. Identifying surplus runoff or other water sources.
3. Choosing a cost-effective recharge method based on site conditions.

The initial phases of identifying appropriate locations can be completed through the use of maps of relevant topographic, hydrological, geological, climatological, and land-use factors published by the Geological Survey of India, the state's Groundwater Development Agency and other institutions.

Recharge mechanism

An important aspect of sustainable groundwater management is the implementation of best practices for groundwater recharge. Different measures such as rainwater harvesting, artificial recharge, green roofs and the use of permeable surfaces to allow for natural infiltration can be used.

The use of best practices like RWH, MAR, permeable surfaces, and green roofs should be implemented and encouraged by the PMC. However, for this, an accurate understanding of the groundwater footprint in urban water management is imperative and can help in determining the most appropriate technique to be used in the local area.

Protection of Existing sources, regulation & monitoring

Protecting existing sources of groundwater and the existing natural recharge zones is vital to sustaining groundwater sustainability. The city council should identify such areas through a scientific process and declare these as protected areas.

Efficient monitoring and regulatory systems are very important for the sustainable management of groundwater. This encompasses enacting policies and rules promoting the sustainable utilization of groundwater reserves, along with establishing monitoring and reporting frameworks to monitor groundwater resource conditions and ensure adherence to regulations.

Groundwater monitoring should be strengthened and periodic reappraisal surveys should be conducted to monitor the groundwater regime effectively. PMC should continuously assess groundwater conditions and adjust management strategies as needed.

Effective balancing of demand and supply

The focus of groundwater management strategies should be on achieving a balance between water demand and supply

The city council (PMC) should devise and implement water-efficient technologies and practices to reduce water demand in the city. In addition, it should implement techniques such as ‘Demand Forecasting’ to develop long-term projections for water demand to implement infrastructure planning.

It should encourage water conservation practices and technologies among urban residents and industries and Implement demand management strategies to reduce excessive groundwater extraction.

Besides the above elements, a critical aspect of sustainable groundwater management is the participation of local communities and stakeholders. The involvement of local communities in groundwater management can help to ensure that groundwater resources are used sustainably and equitably. This element consists broadly of two elements**:** (i) Educating the community about the importance of groundwater resources and (ii) Engaging with local stakeholders, including residents, businesses, and NGOs, in decision-making processes by creating educational campaigns and outreach programs to educate the public on the benefits of RWH and the importance of protecting and preserving groundwater resources.

To ensure the success and sustainability of groundwater balance and sustainability initiatives, it is imperative to adopt a systematic approach and consider factors beyond the physical resource and its availability and use a comprehensive water management strategy that incorporates effective planning and operation and one that emphasizes the adoption of rainwater harvesting and reuse. The SCARPE framework can be the starting point for such an initiative.

Figure 55 The SCARPE framework

Action Plan

Based on the studies carried out as a part of this study and the above framework, the following actions are suggested to balance the groundwater demand and supply in the city. These are at both Macro (Institutional) as well as Micro (local) levels and from a techno-scientific perspective.

Strategic level (Macro)

1. Introduction of Groundwater legislation to regulate water usage within recharge potential.

2. Making rainwater harvesting systems mandatory for large buildings and institutions, such as hospitals, universities, and government buildings.

3. Implementing a city-wide rainwater harvesting program, where all buildings are required to have RWH systems in place, such as rooftop harvesting and cisterns.

4. Integrated water resource planning in terms of conjunctive use that considers surface water, groundwater, and related ecological and environmental factors.

5. Protect and restoring the existing natural recharge zones.

6. Development of public recharge systems at a city-wide scale that aligns with the identified recharge zones in this study and other studies done on aquifers.

7. Developing regulations and incentives to encourage the use of RWH at an individual as well as at the community level.

At a local and operational level (Micro)

1. Incorporating rainwater harvesting systems into the design of new developments, such as housing complexes and commercial centres.

2. Implementation of decentralized rainwater harvesting - The integration of point source recharge using dug wells & bore wells across individual houses and housing societies.

3. Creating dedicated recharge zones, especially in high-potential areas within the city, where rainwater can be collected and directed into the aquifer.

4. Development of man-made water bodies wherever possible and specifically in high potential recharge zones for tapping of rainwater to improve the groundwater recharge.

5. Building permeable pavements and green roofs to increase the amount of water that can be captured and stored for aquifer recharge.

6. Developing a network of recharge wells and injection systems to efficiently distribute captured rainwater into the aquifer.

7. Developing a monitoring and management system for aquifer recharge, to ensure that the water is being used sustainably and efficiently.

8. Partnering with local organizations and community groups to educate the public about the benefits of RWH and how they can participate in recharge efforts.

9. Creating educational campaigns and outreach programs to educate the public on the benefits of RWH and the importance of protecting and preserving groundwater resources.

10. Groundwater monitoring should be strengthened, and periodic reappraisal surveys should be conducted to monitor the groundwater regime effectively.

11. Obtain more realistic values of groundwater levels by continuously updating the estimation with the availability of progressive data.

12. Regularly monitoring and testing the water quality and quantity in the aquifers to ensure that they are healthy and safe for use.

From a scientific and technical perspective.

1. Hydrogeological exploration should be intensified to identify potential aquifers that are yet to be discovered.

2. Use of mathematical modelling to get a better understanding of the aquifers and groundwater flow regime.

3. Research to understand the long-term impacts of RWH on aquifer recharge and water resources in the city.

4. Undertaking research that focuses on developing cost-effective and user-friendly techniques for remediating groundwater pollution.

To ensure the success and sustainability of groundwater balance and sustainability initiatives, it is imperative to consider factors beyond the physical resource and its availability and use a comprehensive water management strategy that incorporates effective planning and operation and one that emphasizes the adoption of rainwater harvesting and reuse.

CHAPTER VII

SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Summary

Water is a scarce natural resource, even though 71% of the land is covered by water. Only about 2.5% of the total water available on earth is fresh water and can be used for human consumption. From time immemorial, groundwater systems have constituted a pre-dominant and strategic reserve of freshwater storage on the Earth. The demand supply gap is especially acute in urban areas which has led to the indiscriminate mining of groundwater with no restrictions. Added to this, increasing construction activity and the practice of concretising the roads lead to the run-off of water into the drains with very little water available for infiltration. Groundwater recharge processes in urban areas are different from those in non-urban areas. In such conditions, systematic rainwater harvesting, or managed recharge plays an important role in augmenting the local supply of water, both from unconfined (shallow) as well as confined (deep) aquifers.

Considering the above, the present work was taken up to understand the recharge potential of groundwater in the Pune urban areas and adjoining suburbs using the existing dug and bore wells. The present study broadly covers the use of Rooftop Rainwater harvesting for recharge through gravity injection to confined aquifers or deep-seated aquifers and the delineation of groundwater potential zones for recharge of surface aquifers.

Pune City is the second biggest city in the state of Maharashtra and the eighth biggest city in India and forms a part of the Pune metropolitan area. The study area lies between 18º27’ & 18º40’ N – 74º39’ & 74º00’ E. The city is bounded by hills on the West and on the South. The two main rivers running through the study area are Mula and Mutha Rivers. The annual precipitation is 780 millimetres with maximum rainfall occurring in July. The annual water demand of the city is 424 million cubic metres (MCM) or 15 thousand million cubic feet (TMC) and the per capita consumption in the city averages around 205 litres per capita per day (LPCD).

The study area falls in the western part of the Deccan Volcanic Province (DVP) which is one of the most extensive and well-preserved continental flood basalts in the world. The DVP is mainly constituted of basaltic flows which are dark grey to greenish grey, black-coloured rocks, with or without recognizable minerals. The individual basalt flows differ in their surface morphology and internal structures. These flows have broadly been classified into two: pahoehoe and àa. These are Hawaiian terms and have been used to describe Deccan lava flows, as they show a resemblance to lava flows from Hawaii.

Àa flows generally have a rubbly, vesicular, clinker surface composed of blocks of varied sizes. A typical àa flow can be identified by the presence of a thin clinker zone (though patchy) at the base, followed upwards by a massive and dense core and a fragmented zone at the top. Pahoehoe flows are mostly compound in nature. In geometry, all the flow lobes/ units are bun-shaped units with more or less flattened bases and inflated tops. An ideal section of a pahoehoe flow lobe shows the presence of a lower (vesicular) zone, followed upward by a massive central core and upper (vesicular) zone with a thin glassy crust. Pipe vesicles are usually observed in the lower zone, also known as the basal vesicular zone (BVZ).

Based on lithostratigraphy, the lava flow sequences seen in the study area have been divided into four Formations - Indrayani, Karla, Diveghat and Purandargarh Formations all of which belong to the Sahyadri group. The terms simple flow and compound flow are also used to describe the lava flows. The flows belonging to the Indrayani, Diveghat and Purandargarh Formations are dominantly simple, while those of the Karla Formation show a compound nature.

The basalt flows generally exhibit low primary porosity and permeability. The accumulation and transmission of water is a result of the secondary porosity developed due to the presence of openings and cavities, weathering, vertical and horizontal sheet joints and the contact between flows and flow units. In terms of hydrogeological properties, the flows are usually classified as vesicular basalt and amygdular basalt (which also includes the flow top breccia (FTB) jointed basalt and massive, compact basalt.

The water-bearing capacity of the rock formations is mainly governed by the porosity which determines the volume available for storage of water. Porosity is in turn dependent on the shape, size, arrangement, and interconnection of voids. The movement of water through the interconnected open spaces is governed by hydraulic conductivity. Storativity, also known as yield capacity, refers to the volume of water discharged from an aquifer per unit area of the aquifer and per unit reduction in hydraulic head over a given area.

In this context, it is important to understand the complex nature of the basaltic aquifer systems as major parts of Maharashtra and large geographical areas in Gujarat and Madhya Pradesh are occupied by these basaltic aquifers comprising of multiple flows (traps). Broadly the aquifer systems in basalts are of two types – Unconfined (shallow) and confined (Deep) aquifers. Unconfined aquifers in basalts are typically located near the surface and are often recharged by precipitation and surface water sources such as streams and rivers. Dug wells are generally used to tap such aquifers. Confined aquifers are typically located at greater depths and can be confined or semi-confined, meaning that they are not in contact with the atmosphere and are under pressure. These aquifers are recharged by infiltration and by lateral flow from neighbouring areas and generally take many years to be recharged.

In hard rock areas such as basalts, digging wells or pits may not be enough to recharge the confined aquifers, and a conduit is required to channel harvested rainwater for recharging the deep aquifers. In such cases, recharge by injection is the only method for artificial recharge of confined or deep-seated aquifers with poorly permeable overburden.

In urban areas, the water demand often exceeds the supply, leading to the over-extraction and exploitation of groundwater. This problem is exacerbated by construction and the concretization of roads, which prevents water from infiltrating the ground, leading to a decrease in groundwater levels. Recharge of groundwater in urban areas by rainwater normally takes place by two methods:

1. Recharge by direct infiltration and
2. Recharge from water bodies like lakes, dams and percolation tanks.

Additionally, recharge also takes place through several other mechanisms like infiltration through storm water drainages, soakaways, leakage through sewage lines and direct infiltration in parks and open areas.

According to the Ministry of Jal Shakti, India (2022) the per capita average water supply in India in the year 2021 was 1486 cubic metres and is likely to reduce to 1367 cubic metres in 2031. In recent times, a significant portion of the rising water demand has been fulfilled from aquifers, with groundwater steadily becoming the cornerstone of India's agricultural and drinking water security. Not only in agriculture but also in rapidly growing cities and numerous medium-sized towns worldwide, the reliance on groundwater is escalating rapidly. Urbanisation and the growth of cities both vertically and horizontally have increased water stress and have had an extensive impact on groundwater availability and quality.

To restore the hydrological balance and maintain groundwater levels, it is essential to recharge the groundwater using various techniques such as rooftop rainwater harvesting, recharge pits, check dams, percolation tanks, and injection wells.

Systematic rainwater harvesting or managed aquifer recharge can play a vital role in augmenting the local supply of water, both from unconfined as well as confined aquifers. Understanding the potential for rainwater harvesting using rooftops and existing wells is the first step in fulfilling a social need to increase the availability of potable water.

Maintenance of the groundwater balance is crucial to maintaining the overall water or hydrological balance. Hence, it becomes important to understand and identify potential recharge zones where artificial recharge techniques can be used to restore the hydrological balance, especially in urbanized areas where areas for natural recharge are dwindling at a very fast pace. A geospatial approach and the use of GIS and Remote sensing techniques have been used extensively by researchers to identify potential zones for such recharge. The use of multi-criteria analysis using thematic layers is very useful for assessing potential groundwater zones all over the world.

Rainwater harvesting (RWH) has been described and defined variously by different workers over the last few decades. Rooftop RWH systems have been implemented in many countries as a means of augmenting water supplies, reducing demand for municipal water supplies, and conserving water resources. The use of RWH for groundwater recharge is particularly important in areas where surface water resources are limited or unreliable. Artificial recharge of groundwater through rooftop RWH can help to maintain and even improve the health of the aquifer and ensure its sustainability and is increasingly being used nowadays to maintain the water balance of an aquifer. It is now a common practice globally though still on a very limited scale.

Different methods of rainwater harvesting have been used all over the world for artificial recharge. Rainwater harvesting is an age-old practice, especially in arid and semi-arid environments to increase the availability of water. It has become an increasingly important method of providing a sustainable water source in many regions around the world. The choice of a particular method depends on various factors such as the amount of rainfall, the purpose of the water use, and the available resources.

The main objective of this study was to understand the potential for recharge of the groundwater in the urbanised area of Pune city. Accordingly, the calculation of rooftop areas and the creation of spatial maps indicating the potential recharge zones, considering various factors such as the extent of urbanisation, local geology, soil cover, slope, etc. was done. The acquired data was used for analysis to understand the areas with a potential for recharge and to formulate strategies for systematic recharge and scientific water management.

The methodology employed a combination of remote sensing data, rooftop data obtained by digitization, geology maps, ward information, population data, well locations in the city, land use/land cover data analysed from Landsat imageries and other thematic data. The overall process involved four broad steps: i) Literature survey ii) Data Collection, iii) Data Processing and Analysis and iv) Field Implementation of the rooftop RWH system.

Data for a total of 3074 wells was used to understand their use as potential wells to recharge the deep aquifers. The data was analysed for distribution across the zones (wards) and some other parameters like the state of the well (perennial, etc.), usage, the diameter of the wells and the capacity of the pump being used. The distribution of wells across the different zones and the percentage of the total wells for each of the zones was calculated for the study area. Frequency ratios for each of the considered thematic factors were calculated from the above data for each of the classes of the thematic layers and the frequency of the wells – (both dug wells and borewells).

Along with these studies, an experimental RWH system to harness the rooftop run-off was implemented in the field to check the efficacy of the technique. Four existing bore wells in a medium-large residential apartment complex were used as recharge wells. Two methods were used for implementation: i) Pit-based, and ii) PVC cylinder-based filters were designed and used for recharge of the confined/deep aquifers in the area of study. Both these techniques were found effective though the PVC cylinder-based was found to be more cost-effective.

An MCDA approach using AHP was used for the delineation of potential groundwater recharge zones for the surface aquifers. The AHP method which is used to assign weights to criteria based on their relative importance was used to evaluate and rank the multiple criteria. These weights were then used to evaluate the potential recharge zones. The criteria used include land use and land cover, soil type, geology, slope, drainage, and rainfall. The potential recharge zones were identified and then ranked based on their suitability for groundwater recharge.

A pilot study of 68 apartment buildings located in different parts of the city was initially taken up to carry out a representative study of rooftop rainwater which is available for recharge. Digitization (tracing & measurement) of the rooftops was extended to 35 wards across the city. Rooftop surface areas were digitized and calculated in Google Earth Pro and were compared with the area of the surrounding plot to understand the ratio of rooftops to the adjacent paved areas. The rooftop to built-up area ratio obtained was in the range of 30 to 50 % with an average of about 40% being occupied by rooftops.

Understanding geographical LULC change in urban areas is the first step in formulating strategies for guiding environmentally sustainable growth. By analysing changes in urban areas, rate of changes and trends using multi-temporal remote sensing images, essential information to get insights on the relationship between urban expansion and the varying social, environmental, and economic conditions can be gathered. From the studies, it can be observed that there has been a steady decrease in barren land and an equally uniform increase in built-up area since 2003. The LULC analysis shows that the total built-up area in Pune has increased from 50.87 km^2 in 2003 to 126 km^2 in 2019. Furthermore, vegetation cover has decreased at the borders of Pune city. It can be observed that most of these are agricultural lands that have been either cleared or converted to barren and built-up areas. This increase in built-up area over the years has reduced the overall area available for recharge.

Data for 100 years for the period 1901 to 2000 shows a mean annual rainfall of 699.9 mm. February shows the minimum precipitation and July with 179 mm followed by September (129 mm) and June (120.4 mm) are the wettest months. In addition to the temporal variation, the rainfall in the area also shows a spatial variation. This is validated by the differences in the density of wells as we proceed from west to east.

To implement effective artificial recharge methods, it is important to determine potential recharge zones, especially in urban areas. Many spatial factors come into play when considering potential zones for recharge by RWH. Besides rainfall, other factors like the slope of the land, and soil texture also play a crucial role in the recharge. Thematic factors, LULC, Slope, Rainfall, drainage density, type of soil and lithology were considered for the identification of potential recharge zones.

The concept of sustainable development emphasizes that human societies should thrive and fulfil their needs while ensuring the capacity of future generations to meet their own needs remains intact (Brundtland, 1987). Broadly the term seeks to integrate three facets – economic, environmental, and social (or socio-political).

Groundwater plays a crucial role in several of the United Nations' Sustainable Development Goals (SDGs). Sustainable Development Goal # 6 (SDG 6) aims to ensure the supply of clean water and sanitation for all. SDG 11 aims at making cities inclusive, safe, resilient, and sustainable. To achieve SDG 6, effective groundwater management practices are needed to ensure the sustainable use of this resource. This requires the development and implementation of policies, technologies, and practices that promote sustainable groundwater use.

One of the key challenges in achieving SDG 6 is addressing the issue of overexploitation which generally leads to the depletion of groundwater resources. Sustainable water management (SWM) is a broad concept that encompasses various aspects of water resource management, including surface water and groundwater. Sustainable water management especially in the context of groundwater is of utmost importance for ensuring water security, ecological sustainability, and socio-economic development. Sustainable management of groundwater resources involves various measures aimed at ensuring the long-term availability and quality of groundwater resources. This includes measures such as managing groundwater recharge, reducing groundwater extraction rates, controlling pollution, and promoting efficient use.

Managed Aquifer Recharge (MAR), also known as enhanced recharge and formerly referred to as 'artificial recharge,' involves intentionally diverting surface water to the groundwater reservoir through various techniques. Over the past two decades, several alternatives to address the challenges caused by the depletion of groundwater have been discussed. Several frameworks have been suggested and used to implement Managed Aquifer Recharge (MAR) in urban areas all over the world.

Of all these frameworks, one of the most commonly used frameworks is the *Integrated Water Resource Management (*IWRM*)* framework. It describes the complexity of water decisions and the importance of balancing stakeholder viewpoints. Another popular framework, the Integrated Urban Water Management (IUWM) provides a framework for planning, designing, and managing urban water systems. It is a flexible process that responds to change and enables stakeholders to predict the impacts of interventions. The IUWM framework focuses on the integration of different water management elements into one comprehensive approach, including the use of MAR as a means of increasing water availability, improving water quality, and managing groundwater levels in urban areas.

Pune City - Groundwater Scenario

The rapid increase in population and urban expansion of Pune City over the last two decades has led to the challenges associated with water resources and their sustainability in the city. Demand now outstrips supply, especially in the fringe areas and there is inequity in supply. As mentioned earlier, estimates of population growth by the PMC show that the population is likely to reach 8.26 million in 2041. Growth studies by Butsch et al. (2017) that the built-up area is likely to increase to 206.4 square kilometres.

Work by some organisations like the Vasudha Foundation shows that groundwater extraction in Pune has doubled from 2,000 million cubic feet (2 TMC ft) in 2011 to 4 TMC ft in 2019 (Vasudha Foundation, 2022). It has also been estimated that the groundwater usage within the PMC limits is about 100 MCM (3.53 TMC) per year (Kulkarni et al, 2023). Considering this big dependence on groundwater, it becomes important to gauge the potential for the recharge of aquifers especially through artificial means.

Despite the widespread implementation of groundwater recharge at an individual or community level, there has been a lack of a systematic and scientific approach to groundwater recharge and maintaining the balance between demand and supply in the area under study.

Conclusions

1. From an analysis of published literature, it can be concluded that Pune City is facing an impending water crisis towards the end of this decade. Consequently, the city must look at a holistic approach to water management especially in managing its groundwater resources.

2. The results of the detailed study of rooftop run-off for rainwater harvesting incorporating 35 representative wards of the 76 electoral wards indicate that an amount of 43.92 MCM (1.6 TMC) of water is available for harvesting. This water can be used for the artificial recharge of the wells in the city. On a conservative estimate, even if half of this total rainwater is harvested, the recharge can replenish the groundwater annually by about 21 - 22 MCM (0.7 to 0.80 TMC). This is almost a third of the present-day extraction of groundwater.

3. The 'groundwater recharge potential zones' map of the study area generated through this weighted overlay analysis has been categorized into five zones viz. low, moderate, good, high, and very high potential. The Groundwater potential map shows coverage of 13.24 km^2 (5%), 124.71 km^2 (50%), 72.92 km^2 (29 %), 8.11 km^2 (3%), and 30.27 km2 (12%) for the above zones, respectively. This shows that roughly 44% of the study area has a good to high potential for recharge.

4. Further, the study reveals that the high and good potential recharge zones lie in the western part of the city. The central part of the inner city shows low potential for recharge. This may be because the area is mainly built-up.

5. Analysis of the wells indicates that a major portion (83 %) are perennial and are being used for abstraction, especially in summer months. These wells can be used for recharge during the monsoon.

6. Analysis of the distribution of these wells across the city shows that major extraction is happening towards the Central and Western parts of the city. Most of the wells fall in the Northwest (27%) and Central (26%) parts of the city. These are followed by the West (16%).

7. Ward-wise distribution shows that a maximum number of wells fall in the administrative wards of Aundh (Northwest), followed by Ghole Road (Central) and Karvenagar (West) wards.

8. A ward-wise analysis shows that the maximum number of wells are in the Baner-Balewadi ward (418 wells) followed by Aundh (200) and Kamla Nehru Park ward (180).

9. One of the possible reasons for the large number of wells in Baner-Balewadi could be because this area was earlier not a part of the PMC and there was no organized water supply to this suburb. Another reason could be due to the construction boom which started in the 2000's during which most of the water required for the construction activities was extracted from borewells.

10. A representative survey of 135 well owners showed that only 22 (18 %) of the yielding wells, are presently being used for rooftop rainwater harvesting.

11. Frequency ratio analysis of the wells, to probe the relationship between various thematic factors and well density shows that rainfall has the highest value of 2.33. Interestingly for rainfall, the moderate class shows the largest value indicating that there could be a higher run-off in the area with high rainfall and better infiltration happens with moderate rainfall happening over an extended period.

12. Direct gravity injection using low-cost filtration techniques & clean filter mechanisms is a viable and low-cost method to harness rainwater.

Recommendations for Groundwater management in Pune city

Considering the fact that Pune city is facing an impending water crisis, the city must look at a holistic approach to water management especially in managing its groundwater resources.

Based on the results obtained from the study and globally used concepts of IWRM, IUWM and MAR it is suggested that Pune City should use an Integrated Urban Water Management framework. Towards this end, a systematic groundwater management framework, the SCARPE framework is proposed to integrate important aspects related to maintaining the groundwater balance and augmenting the water resources in the city.

The SCARPE framework proposes a methodical and structured process to ensure the long-term availability and quality of groundwater resources while meeting the water demands of the urban population. The framework includes measures such as setting limits on groundwater abstraction, implementing monitoring programs to track groundwater levels and quality, and establishing policies to promote efficient water use. The principal elements of the SCARPE framework are illustrated in Figure 55. It is suggested that specific actions be taken up in the city for a systematic aquifer recharge within the overall framework of SCARPE. A detailed action plan is given in Chapter 6.

In conclusion

In the quest for sustainable urban water management, adopting an Integrated Urban Water Management framework is pivotal. This holistic approach transcends traditional water management paradigms by recognizing the interconnectedness of various facets of water resources. Central to this is the emphasis on achieving the delicate groundwater balance and augmenting water resources, thereby ensuring that our cities have a reliable and sustainable supply.

Integrated planning, in conjunction with community engagement, establishes the foundation for effective policy and regulatory frameworks. The key to the rapidly changing and dynamic urban landscape is using an adaptive management approach that is supported by continuous monitoring and research & innovation.

Long-term planning and Inter-departmental cooperation based on a systematic approach, conjunctive use and aquifer replenishment while safeguarding existing sources through the right recharge mechanisms is vital to the issue.

Systematic Aquifer Recharge emerges as a valuable tool in this journey, serving as a testament to the significance of resource assessment and demand management. By forecasting demands and enhancing recharge methods through artificial recharge, we can bolster our urban water resilience.

Community involvement is the cornerstone of this endeavour, for it takes a collective effort to preserve our precious water sources. In the quest for sustainability, effective monitoring and balancing of demand and supply are also crucial. It is only through the collective and conscientious efforts of all the stakeholders that a prosperous and water-secure tomorrow can be realised for any city.

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