

Integration of Analytic Hierarchy Process and RS-GIS for Dynamic Groundwater Potential Mapping of Kolhapur District, Maharashtra

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Abstract: Groundwater is an essential resource for agricultural and life support, particularly in areas with unpredictable rainfall and rising water demands. The goal of this study is to identify the Groundwater Potential Zones (GWPZ) in Kolhapur district, Maharashtra, by utilizing an integrated method that incorporates the Analytical Hierarchy Process (AHP), Remote Sensing (RS), and Geographic Information Systems (GIS). This study examines the temporal variations of GWLF, Land use/ Land cover, Rainfall from year 2017 to 2022 along with geomorphology, slope, lineament density, drainage density, soil texture, topographic roughness index (TRI), topographic wetness index (TWI) using Arc-GIS 10.8. Meteorological stress is indicated by a significant decrease in decadal mean rainfall and an increase in low rainfall zones, while unpredictable rainfall and urbanization put further demand on groundwater recharge. While the "Safe" zone continued to dominate, spanning over 80% the "High" potential zone shrank by around from 1279.44 km² in 2017 to 876.96 km² in 2022, while the "Poor" zone grew by almost 57%, according to the study. These results demonstrate how urgently integrated groundwater management and recharge measures are needed. The validation of results shows good accuracy with pre and post monsoon groundwater level data.

Index Terms: Analytic Hierarchy Process (AHP), Geographic Information System (GIS), Groundwater Potential Zone (GWPZ), Weighted Overlay Analysis (WOA)

1. INTRODUCTION

One of the most important natural resources that sustains many facets of both the environment and human life is groundwater. It is necessary for industrial operations, agricultural irrigation, drinking water supply, and ecological sustainability. Around the world, groundwater is frequently the most dependable and accessible supply of freshwater, particularly in arid and semi-arid areas where surface water availability is few or erratic. In India, the reliance on groundwater is particularly significant, as the country supports nearly 17% of the global population but possesses only about 4% of the world's freshwater resources (Dhawan, 2017). Because of this unequal distribution, the demands from the household, industrial, and agricultural sectors have increased, putting further strain on groundwater supplies. Due to fast urbanization, population growth, and climate change, over extraction and groundwater contamination have become serious issues in recent decades. Groundwater levels are declining at alarming rates in several parts of the country, while pollution from agricultural runoff, industrial discharge, and improper waste disposal is deteriorating groundwater quality (Shah, 2009). This situation calls for the creation of effective instruments and plans for the sustainable monitoring, evaluation, and management of groundwater resources. Groundwater study now has more opportunities due to recent technology developments, especially when using geospatial methods. Geographic Information System (GIS) has proven to be a powerful tool in hydrological studies, enabling researchers to manage, analyze, and visualize spatial data related to various environmental parameters (Burrough P. A., 1998). Understanding the spatial variability of groundwater potential requires the integration of several factors, including topography, land use/land cover (LULC), soil type, geology, slope, rainfall, and drainage patterns. GIS makes this possible. In order to delineate watersheds and simulate surface runoff and infiltration pathways, GIS may extract topography variables such as slope and drainage networks using Digital Elevation Model (DEM). For groundwater research, decision-support techniques such as the Analytic Hierarchy Process (AHP) have become more and more popular in addition to GIS. AHP, developed by (Saaty T. L., 1977), is a multi-criteria decision analysis (MCDA) tool that allows for the systematic evaluation of various factors based on expert judgment and pairwise comparisons. The technique ensures consistency in decision-making while allowing the assessment of the relative relevance of several contributing factors. When integrated with GIS, AHP enhances the objectivity and accuracy of groundwater potential zone (GWPZ) mapping by assigning appropriate weights to different criteria (Malczewski, 1999).

AHP and GIS work together to create a strong framework for locating and defining GWPZs. Areas with different levels of groundwater potential can be highlighted on composite maps made possible by this integrated method. These maps are essential for determining priority locations for sustainable water resource management, recharge structure building, and groundwater analysis. This is especially crucial in hard rock regions, like the Kolhapur district, where groundwater availability is frequently confined and aquifers are irregular. Additionally, assessing groundwater potential is essential for assisting with planning and water policy projects. It reduces the effects of water scarcity, particularly in areas that frequently experience seasonal fluctuations in rainfall. By pinpointing areas with high recharge potential, authorities can implement targeted interventions for artificial recharge, conservation, and controlled extraction, thereby promoting long-term sustainability (Murthy, 2000).

1.1 Aim and Objectives of the Study

1. To identify and evaluate groundwater potential zones (GWPZ) of Kolhapur district using Remote Sensing and Geographical Information System techniques and spatial data analysis.

2. Assessing the significance of factors influencing groundwater recharge potential using Analytic Hierarchy Process.
3. To provide with groundwater potential zone maps for sustainable water resources planning for the Kolhapur district.

2. LITERATURE REVIEW

Groundwater is an essential resource, particularly in areas that are semi-arid and have limited access to surface water. Groundwater potential zones (GWPZs) have to be identified using sophisticated methods due to the growing demand for water, climate change, and over-extraction. The Analytical Hierarchy Process (AHP) in conjunction with Remote Sensing (RS) and Geographic Information System (GIS) technology has been frequently used in recent studies to define GWPZ.

(Waikar, 2014) delineated Maharashtra's groundwater zones using RS-GIS and weighted overlay analysis, taking lineament density, drainage, slope, and geology into account. Similarly, (Pancholi, 2022) used AHP in the Dang district of Gujarat and found that, in spite of high monsoon runoff, 89% of the studied region had high groundwater potential. (Verma, 2024) highlighted the susceptibility of slope, geomorphology, and soil to GWPZ variations in Nagpur by incorporating dynamic variables like rainfall, groundwater level fluctuation, and impervious surface extent during a five-year period.

In the Karha River basin in Maharashtra, (Bera, 2020) used AHP and geospatial analysis to classify zones from poor to excellent, and their model was validated in the field. About 85% accuracy was attained by (Arulbalaji, 2019) using 12 thematic layers in the Southern Western Ghats. In a similar vein, (Nair, 2017) used 14 layers to analyse river basins in Kerala and confirmed their findings using spring and well data, achieving a 95% accuracy rate. AHP was successful in allocating weights based on expert assessment and geographical correlation in every study.

3. METHODOLOGY

3.1 Study area

The Kolhapur district of Maharashtra is located between latitudes 15°43' and 17°17' N and longitudes 73°40' and 74°42' E. It covers 7,685 km² and has an average elevation of 546 m above sea level. Karvir, Hatkanangle, Panhala, Shirol, Kagal, Gadhinglaj, Ajara, Chandgad, Radhanagari, Bhudargad, Gaganbavada, and Shahuwadi are the twelve tehsils that make up the district. The Deccan plateau and Sahyadri hills have influenced the terrain of this Deccan Trappean region. Kolhapur has a tropical monsoon climate, with the most of the yearly rainfall coming from the southwestern monsoon, which lasts from June to September. Winter lows are between 14°C and 16°C, while temperatures during the summer are between 34°C and 38°C. The weathering of basaltic rocks and alternating wet-dry cycles are the main causes of soil development, producing layered textures ranging from clayey to sandy loam soils.

3.2 Description of Data acquired

Table 1. describes the specifics of the data used. Kappa statistics for the LULC maps employed range from 0.92 to 1, and their overall accuracy (OA) ranges from 83.33 to 100%. Thus, it was determined that these maps were appropriate for our investigation.

3.3 Preparation of Thematic Layer

Ten factors that affect the presence of groundwater were chosen. Arc-GIS 10.8 software is used to derive input data from satellite, climatic, and hydrologic data. In order to project UTM WGS1984 43N, satellite data was processed and clipped to the study area.

Using the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM), five important topographical and hydrological metrics were extracted: slope, drainage density (DD), lineament density (LD), topographic roughness index (TRI), and topographic wetness index (TWI). In evaluating groundwater potential, these factors are essential since they have a direct impact on subsurface water storage, infiltration, and surface runoff.

Slope

The dynamics of surface water, particularly infiltration and runoff processes, are significantly influenced by slope. While steeper terrains encourage quick runoff, which reduces percolation, areas with gentle slopes allow for better infiltration and groundwater recharging. Using the techniques recommended by (Chatterjee, 2022) and (Schwyter, 2020), the slope map (represented in percentage rise) was created using Arc-GIS Slope tool and then classified into four categories according to groundwater potential influence.

Lineament Density (LD)

DEM file was used to extract lineament characteristics, such as faults, fractures, and joints, which are indicative of structural geological formations. These lineaments facilitate the circulation of water beneath the surface. In accordance with (Pandey, 2022) a lineament density map was produced and categorized into five classes using geometric interval classification.

Table 1: Description of data used for GWPZ mapping including temporal and spatial resolution

Data Description	Resolution/ Scale	Temporal	Duration	Data Format	Source
Sentinel LULC	10m	Yearly	2017-2022	TIFF	ESRI website
Shuttle radar topography mission digital elevation model (SRTM DEM)	30m	-	-	TIFF	Open topography
Rainfall	0.25*0.25 degrees	Yearly	2008-2022	NetCDF	IMD website
Soil map	1:5,000,000	-	-	Map	Food and Agriculture Organization Website
Geomorphology map	1:25,000	-	-	TIFF	Bhukosh, Geological Survey of India (GSI) website
GWL data	NA	Yearly	2008-2022	Point	IndiaWRIS, Groundwater Surveys and Development Agency

Drainage Density (DD)

Infiltration potential has an inverse relationship with drainage density, which indicates the amount of surface runoff. excessive DD values signify poor groundwater recharge capacity since they are a sign of excessive runoff and limited infiltration. Using Arc-GIS 's flow accumulation and stream network tools, the DD map was created and categorized into five classes to represent different groundwater potential levels.

Topographic Wetness Index (TWI)

TWI is a terrain-based index that estimates the likelihood of water accumulation in a given area and measures the spatial distribution of soil moisture. Better recharging conditions are found in places with higher TWI values, which are also more susceptible to saturation. The Raster Calculator in Arc-GIS was used to determine TWI using the following formula:

$$TWI = \ln \left(\frac{\alpha}{\tan \beta} \right)$$

where α represents the upslope contributing area and β is the local slope in radians. Based on results from (Mallick, 2019) TWI values in the research region ranged from 2.74 to 24.91 and were categorized using geometric interval classification into five groundwater potential groups.

Topographic Roughness Index (TRI)

Flatter regions, which are better for infiltration and groundwater recharge, tend to have lower TRI values. The Raster Calculator in Arc-GIS was used to create the TRI map, which was then categorized into five categories using the approach that (Riley, 1999) and (Seifu M. A., 2022) supplied. In order to estimate the storage of depressions and the accumulation of water, the TRI considers the surface heterogeneity or roughness of the terrain. It is computed as follows:

$$TRI = \frac{\text{Normal Elevation} - \text{Minimum Elevation}}{\text{Maximum Elevation} - \text{Minimum Elevation}}$$

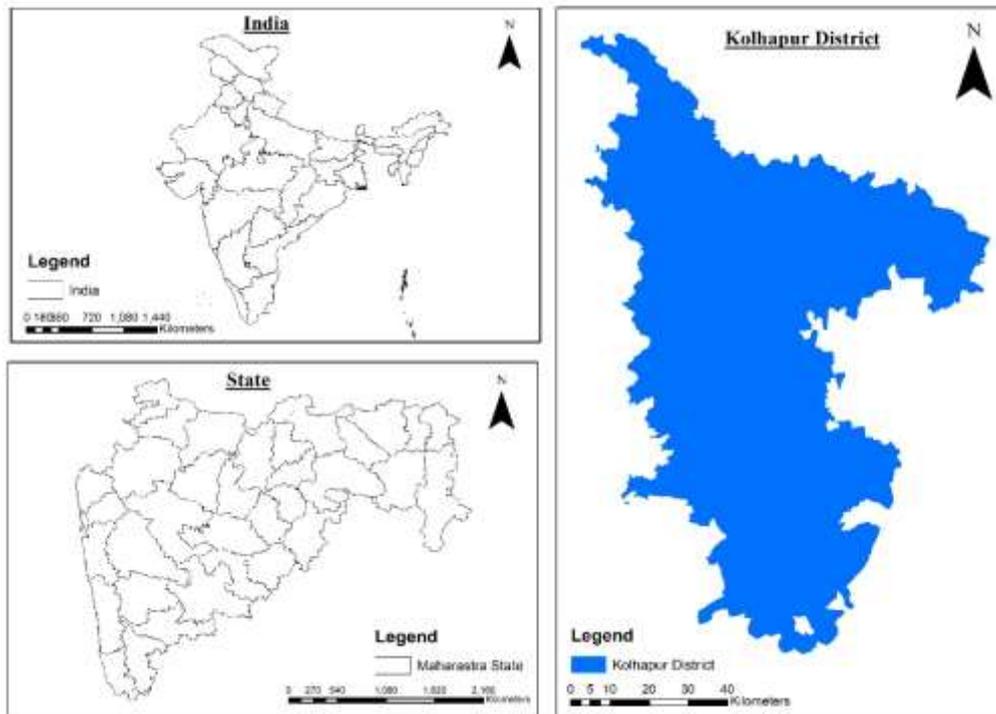


Figure 1: Location map of study area

Groundwater Level Fluctuation

Pre- and post-monsoon groundwater level data from 2008 to 2022 were used to create annual groundwater level fluctuation (GWLf) maps using Inverse Distance Weighting (IDW) interpolation in Arc-GIS. Data gaps in previous years resulted from the measuring stations' varying numbers, which ranged from 27 in 2008 to 37 in 2022. A decadal average GWLf in relation to mean sea level was calculated in order to counteract this. Following georeferencing and resampling to a 10 m resolution, these maps were divided into four categories on groundwater potential.

Soil Texture

The FAO (Food and Agriculture Organization) soil texture, which is imported into Arc-GIS 10.8, has a major impact on recharge capacity and infiltration rates. Clay to fine-textured soils with significant water retention are probably represented by the prevalent soil types, such as Nd51-2bc and Nd49-2bc (Sachdeva, 2021). Other textures that approximate to loamy or mixed textures with different recharge potentials include Vc45-3a, Vc43-3ab, and Hh11-2bc.

Geomorphology

Ten landform features that were obtained by remote sensing comprise the geomorphological landscape. The region is mostly covered by the Pediment-Pediplain Complex and Low Dissected Plateaus, which sustain moderate to high GWP (Upadhyay, 2023). On the other hand, because of their rough terrain and steep gradient, Highly Dissected Plateaus and Hills/Valleys, which occupy smaller areas, have limited recharge capability.

Land use/Landcover

Because land use patterns alter infiltration and runoff, they have a direct impact on groundwater recharge. The area was divided into seven divisions based on the analysis of LULC data from 2017 to 2022: crops, urban area, flooded vegetation, water bodies, forest, barren land, and trees/pasture. The impact of the land cover's temporal variation on groundwater potential was evaluated.

Decadal mean rainfall

Rainfall is a crucial factor in groundwater recharge. Decadal mean rainfall maps were generated by averaging annual rainfall data over ten years. These maps, created through spatial interpolation, highlighting long-term precipitation trends. Based on IMD drought conditions, rainfall was classified into four categories. This classification aids in identifying regions that are water-rich and susceptible to drought.

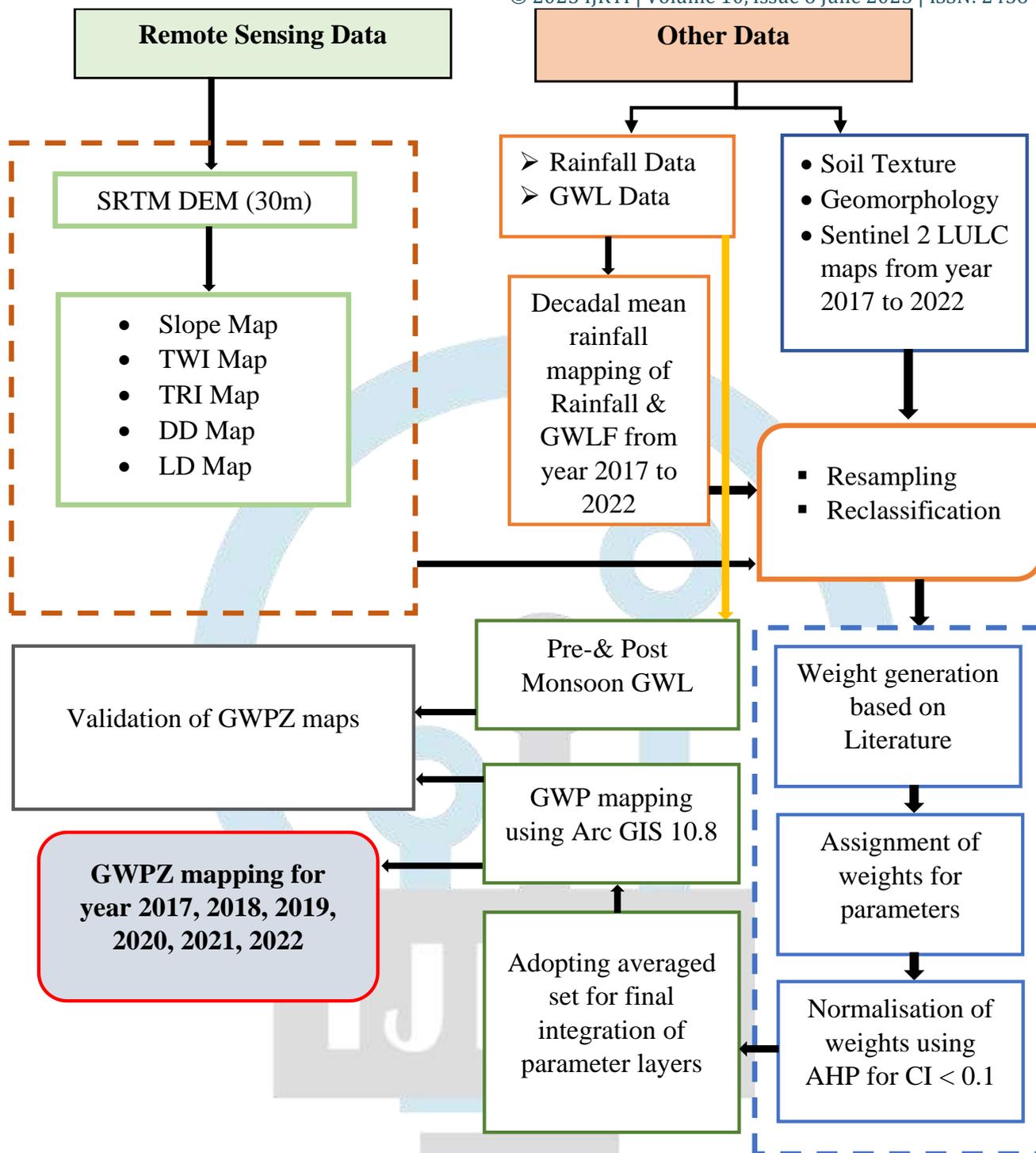


Figure 2: Flowchart in detail showing the approach used in present study

3.4 Assigning weights using Analytic Hierarchy Process (AHP)

Ten thematic levels were used to define groundwater potential (GWP) zones. After a thorough literature review, the relative significance of these thematic levels was assessed using Saaty's Analytical Hierarchy Process (AHP) technique (Saaty, 1987; 2014). The current study considered a range of values documented in earlier literature, including both expert judgment and AHP-based approaches, because the relative importance of influencing factors may differ based on the scale and region of investigation.

The following procedures were engaged in the weight assignment:

- 1] **Pairwise Comparison Matrix (PCM):** A matrix was created by comparing each thematic layer's relative value in pairs. Understanding which layers were more crucial than others was made easier by these comparisons.
- 2] **Normalization and Priority Weights:** After normalizing the PCM, priority weights were determined for each thematic layer according to how it affected the possibility for groundwater.
- 3] **Consistency Check:** To assess the dependability of the comparisons, a Consistency Ratio (CR) was computed. The matrix was deemed appropriate and consistent since the CR value was less than 0.1.

- 4] **Final Weights:** The Weighted Overlay Analysis (WOA) in Arc-GIS was performed using the final weights from this single, consistent matrix.

Depending on how it affected groundwater potential, each subclass within the thematic layers was given a suitability score between 1 (very low), 2 (low), 3 (moderate), 4 (high), and 5 (very high). To make sure that the pairwise comparisons made sense, the consistency ratio which is the ratio of the consistency index to the random consistency index was used as a validation tool. Arc-GIS 10.8 was used to conduct Weighted Overlay Analysis (WOA), the study's last phase. For every year between 2017 and 2022, ten reclassified thematic maps were employed, including ones for rainfall, soil, slope, land use/land cover (LULC), groundwater level fluctuation (GWLF), and others. The significance of each map in affecting groundwater potential was determined by assigning it a normalized weight out of 100. The Groundwater Potential (GWP) maps for each year were then produced by combining these weighted layers using the WOA approach. Figure 1 displays a flowchart of the entire research procedure.

4. RESULTS AND DISCUSSION

4.1 Weight Assignment Using the Analytic Hierarchy Process (AHP)

Ten important factors affecting groundwater potential were given weights using the Analytic Hierarchy Process (AHP). Based on expert opinion and a review of the literature, a pairwise comparison matrix was created using Saaty's 9-point scale (Table 3.4). Geomorphology (GM), Lineament Density (LD), Slope, Drainage Density (DD), Land Use/Land Cover (LULC), Average Groundwater Fluctuation (AGWLF), Decadal Mean Rainfall (DMR), Soil Type, Topographic Roughness Index (TRI), and Topographic Wetness Index (TWI) were among the parameters taken into consideration. With a Consistency Ratio (CR) of 3.42%, well within the permissible range of 10%, normalized weights were obtained from the matrix's principal eigenvector, suggesting trustworthy assessments. Given its dominant role in groundwater potential, geomorphology had the highest weight (0.230). With a weight of 0.158, Lineament Density came next, emphasizing the significance of structural elements. TWI received the lowest weight (0.034), while the other parameters had lower weights (0.120-0.034), suggesting that it had little bearing on the study area. Groundwater potential zones were defined using these weights in a weighted overlay based on a GIS.

Table 2: Pairwise comparison matrix of influencing parameters for groundwater potential zones.

Sr. No.	Parameters	GM	LD	Slope	DD	LULC	AGWLF	DMR	Soil Type	TRI	TWI
1	GM	1	2	3	2	3	3	3	4	4	5
2	LD	0.50	1	2	2	2	2	2	3	3	4
3	Slope	0.33	0.50	1	1	2	2	2	3	3	3
4	DD	0.50	0.50	1.00	1	2	2	2	2	3	3
5	LULC	0.33	0.50	0.50	0.50	1	2	2	2	2	3
6	AGWLF	0.33	0.50	0.50	0.50	0.50	1	2	2	2	2
7	DMR	0.33	0.50	0.50	0.50	0.50	0.50	1	2	2	2
8	Soil Type	0.25	0.33	0.33	0.50	0.50	0.50	0.50	1	2	2
9	TRI	0.25	0.33	0.33	0.33	0.50	0.50	0.50	0.50	1	2
10	TWI	0.20	0.25	0.33	0.33	0.33	0.50	0.50	0.50	0.50	1
Sum	4.03	6.42	9.50	8.67	12.33	14.00	15.50	20.00	22.50	27.00	

Table 3: Normalized pair-wise comparison matrix of influencing parameters for groundwater potential zones.

Parameters	GM	LD	Slope	DD	LULC	AGWLF	DMR	Soil Type	TRI	TWI	Criteria Weight
GM	0.25	0.31	0.32	0.23	0.24	0.21	0.19	0.20	0.18	0.19	0.2320
LD	0.12	0.16	0.21	0.23	0.16	0.14	0.13	0.15	0.13	0.15	0.1587
Slope	0.08	0.08	0.11	0.12	0.16	0.14	0.13	0.15	0.13	0.11	0.1210
DD	0.12	0.08	0.11	0.12	0.16	0.14	0.13	0.10	0.13	0.11	0.1201
LULC	0.08	0.08	0.05	0.06	0.08	0.14	0.13	0.10	0.09	0.11	0.0924
AGWLF	0.08	0.08	0.05	0.06	0.04	0.07	0.13	0.10	0.09	0.07	0.0775
DMR	0.08	0.08	0.05	0.06	0.04	0.04	0.06	0.10	0.09	0.07	0.0675
Soil Type	0.06	0.05	0.04	0.06	0.04	0.04	0.03	0.05	0.09	0.07	0.0528
TRI	0.06	0.05	0.04	0.04	0.04	0.04	0.03	0.03	0.04	0.07	0.0440
TWI	0.05	0.04	0.04	0.04	0.03	0.04	0.03	0.03	0.02	0.04	0.0341

Table 4 The weights and rankings of the various parameters used to map the groundwater potential zones using Saaty's**AHP**

Parameters	Unit	Sub Factors	Rank	Weights in %
Geomorphology	-	Dam and Reservoir	5	23.20
		Flood Plain	5	
		Highly Dissected Plateau	2	
		Low Dissected Hills and Plateau	2	
		Low Dissected Plateau	3	
		Moderately Dissected Plateau	3	
		Pediment Pediplain Complex	4	
		Quarry and Mine Dump	2	
		Water Bodies - Other	4	
		Water Body -River	5	
		Lineament Density	km/km ²	
0.01-0.02	2			
0.03 - 0.06	3			
0.07 - 0.17	4			
0.18 - 0.54	5			
Slope	%			0 - 2.92
2.93 - 3.05		4		
3.06 - 5.97		3		
>5.98		2		
Drainage Density		km/km ²	4.21 - 5	1
	3.41 - 4.2		2	
	2.61 - 3.4		3	
	1.81 - 2.6		4	
	1 - 1.8		5	
LULC	-	Water bodies	5	9.24
		Forest Area	3	
		Flooded Vegetation	4	
		Cropland	4	
		Urban Area	1	
		Bare Land	1	
		Trees/ Pasture	4	
AGWLF	m	<2.5m	1	7.75
		2.51 - 3.5m	2	
		3.51 - 4.5m	3	
		4.51 - 5.5m	4	
		>5.51m	5	
DMR	mm	<930mm	2	6.75

		930.01 - 1.396mm	3	
		1.396.01 - 1508mm	4	
		>1.508.01mm	5	
Soil Type	-	Vc45-3a	5	5.28
		Vc43-3ab	4	
		Nd51-2b	3	
		Nd49-2bc	3	
		Hh11-2bc	2	
		Bv12-3b	1	
		Ap21-2b	2	
TRI	-	0 - 0.03	5	4.40
		0.04 - 0.07	4	
		0.08 - 0.13	3	
		0.14 - 0.22	2	
		0.23 - 1	1	
TWI	-	2.47 - 5.53	1	3.41
		5.54 - 7.02	2	
		7.03 - 9.82	3	
		9.83 - 15.06	4	
		15.07 - 24.91	5	

4.2 Trends in Rainfall variation from year 2017 to 2022

By calculating the average of annual rainfall data over consecutive ten-year periods, the Decadal Mean Rainfall (DMR) maps were produced. In order to evaluate rainfall variability and drought potential, these maps were then divided into four meteorological subclasses. With a peak of 1147.92 mm from 2010-2019 and a steady increase from 1044.03 mm from 2008-2017, the DMR demonstrated a period of persistent and comparatively high rainfall throughout the research territory. Rainfall reduced significantly from 2012 to 2021, from this peak to 761.71 mm, suggesting increasing unpredictability and perhaps climate-related changes. A partial recovery was suggested by the DMR's slight increase to 938.13 mm in the following period, 2013-2022. Even said, this amount was still much below the high reached between 2010 and 2019, suggesting a long-term downward trend in rainfall notwithstanding occasional fluctuations. A year-by-year observation from 2017 to 2022 reveals additional regional variations in the distribution of rainfall. The region beneath the <930 mm zone expanded dramatically, expanding by over 200% between 2019 and 2020, indicating a notable increase in areas with little rainfall.

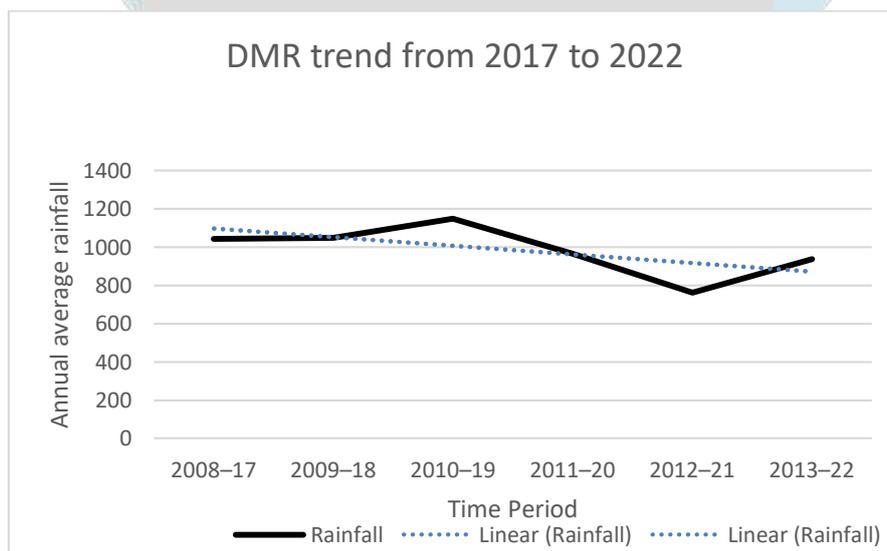


Fig 3: DMR trend from 2017 to 2022

Table: 5 Areal Coverage under various DMR categories, their ranges minimum RF, maximum RF, Decadal mean rainfall values and Std. Deviation

Time	Reclass	Range	Area(km ²)	%Area	Min Rf	Max Rf	DMR	Std Dev.
2008-2017	1	<930	3184.98	41.48168	392.03	2,250.99	1,044.03	390.67
	2	930 -1396	3001.972	39.09816				
	3	1396.01 -1508	469.6632	6.116967				
	4	>1508.01	1021.425	13.3032				
2009 -2018	1	<930	3161.206	41.17204	395.07	2,254.23	1,047.45	390.76
	2	930 -1396	3008.562	39.18398				
	3	1396.01 -1508	474.5673	6.180838				
	4	>1508.01	1033.706	13.46315				
2010 -2019	1	<930	2654.516	34.57283	404.27	2,541.62	1,147.92	438.86
	2	930 -1396	2807.849	36.56986				
	3	1396.01 -1508	609.579	7.939251				
	4	>1508.01	1606.098	20.91806				
2011 -2020	1	<930	3614.115	47.0708	342.52	2,011.34	964.85	357.61
	2	930 -1396	3614.115	39.89237				
	3	1396.01 -1508	451.3932	5.879015				
	4	>1508.01	549.5796	7.15781				
2012 -2021	1	<930	5510.443	71.76887	308.08	1,559.38	761.71	259.85
	2	930 -1396	2142.127	27.89939				
	3	1396.01 -1508	24.4881	0.318937				
	4	>1508.01	0.9828	0.0128				
2013 -2022	1	<930	3731.75	48.60289	392.34	1,952.11	938.13	319.92
	2	930 -1396	2859.13	37.23775				
	3	1396.01 -1508	761.9985	9.924386				
	4	>1508.01	325.1628	4.234971				

At the same time, there was a decline in the spatial coverage of both the very high (>1508 mm) and intermediate (930-1396 mm) rainfall zones, particularly in 2020-2021 and 2021-2022. The 1396.01-1508 mm zone did, however, have a modest increase in 2021-2022, indicating a slight redistribution among the upper rainfall levels. These modifications show a changing rainfall regime, with high-rainfall areas contracting and low-rainfall zones becoming more dominant. The region's groundwater recharge may face difficulties as a result of this trend, which could be caused by regional weather anomalies or more general climate changes.

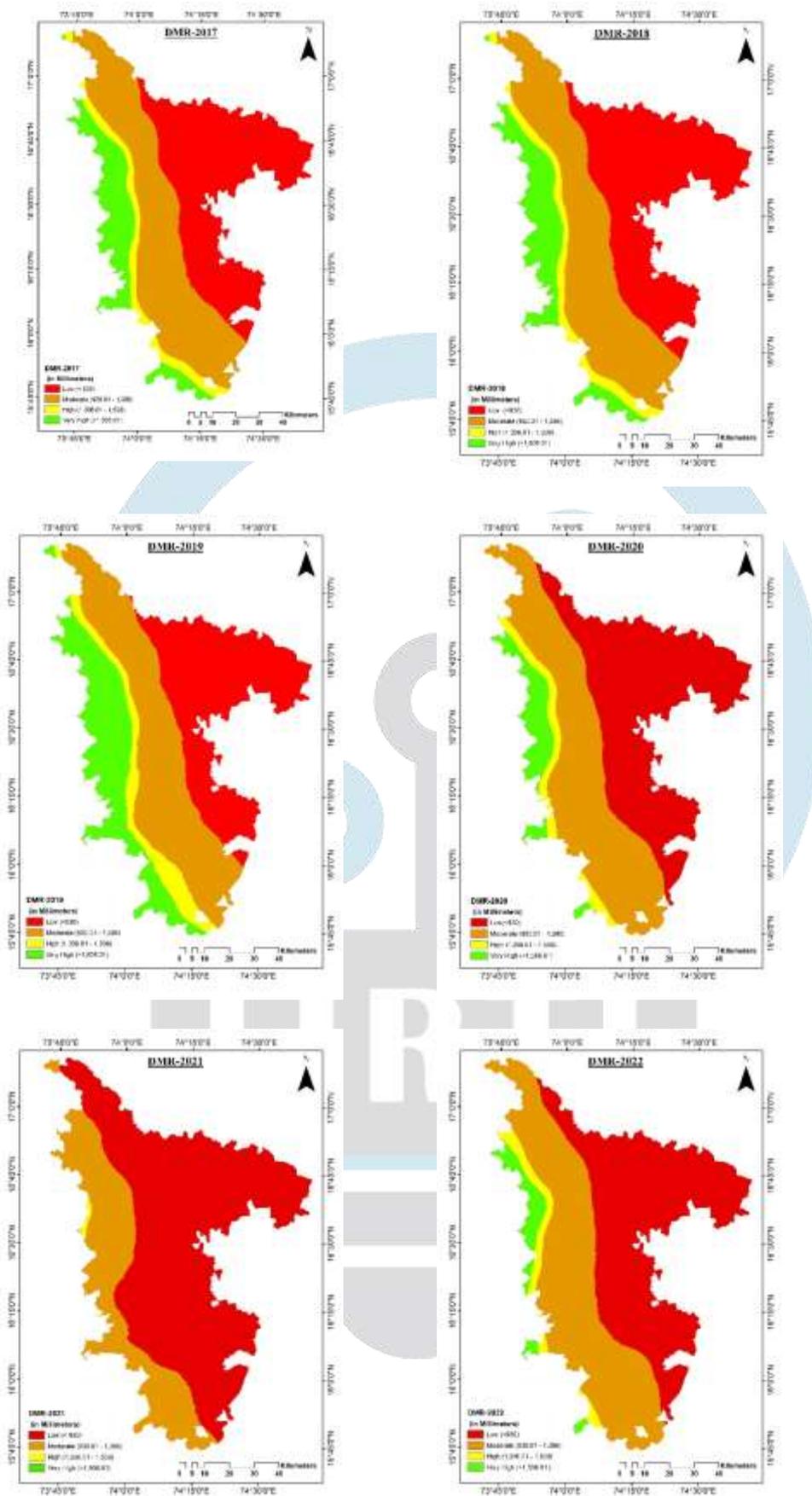


Fig 4: Decadal Mean Rainfall maps from 2017 to 2022

4.3 Temporal Changes in Land Use/Land Cover from year 2017 to 2022

Significant changes in land cover during the research period are revealed by the analysis, urban areas increased by 29%, from 3536 km² to 4568.25 km², reflecting the region's continued urbanization and infrastructure development. This extension may have a detrimental effect on groundwater recharge and decrease infiltration zones. Perhaps as a result of increasing waterlogging occurrences, shifting drainage patterns, or seasonal hydrological fluctuations, a striking increase of more than 120% was noted in flooded vegetation. A consistent 7% decrease in forest cover indicates continued land degradation or deforestation, which may have a negative impact on groundwater recharge by lowering soil permeability and vegetative cover. During the five years, bare land fluctuated significantly before declining by about 70%, most likely as a result of vegetation regeneration, land reclamation, or changes in methods for managing land. On the other hand, there were very slight seasonal or inter-annual fluctuations in agriculture and water bodies. In a similar vein, pastureland and tree cover had only slight variations, reaching a high in 2021 and then dropping to levels close to those of 2017.

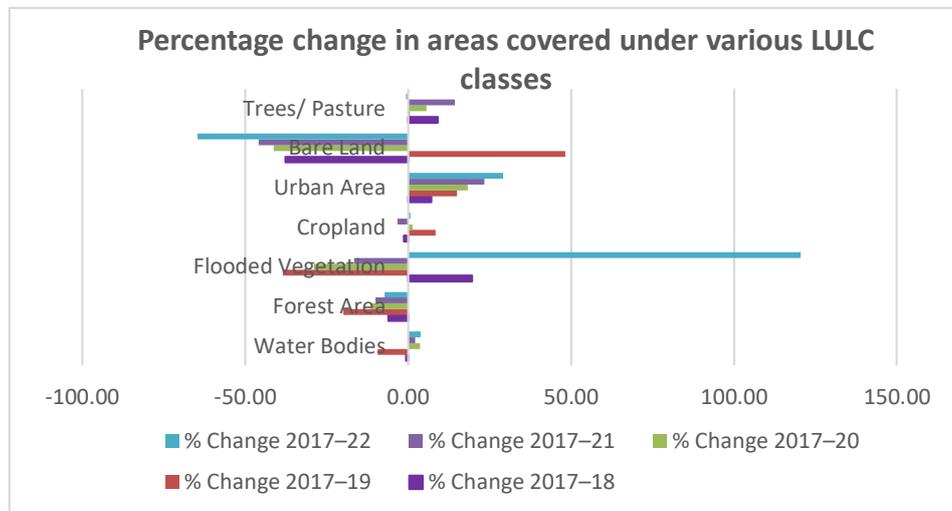


Fig 5: Percentage change in areas covered under various LULC classes

All things considered, the LULC dynamics show the impact of both anthropogenic (such as urbanization and deforestation) and natural (such as seasonal cycles and vegetation recovery) influences. Since changes in surface cover have a direct impact on patterns of runoff, infiltration, and evapotranspiration, these shifts are essential to comprehending variations in groundwater recharge zones.

4.4 Trends in Groundwater Level Fluctuation from year 2017 to 2022

Groundwater stress is gradually increasing throughout the district, according to the AGWLF analysis conducted between 2017 and 2022. There were few variations in 2017, suggesting a steady equilibrium between withdrawal and recharge. This year serves as a baseline for comparison because certain areas displayed early indicators of stress. In the eastern and southern regions, groundwater stress increased by 2018. This was probably brought on by increased irrigation, decreased rainfall, and over-extraction. North-central regions showed some recovery in 2019, indicating better recharging due to moderate extraction and advantageous monsoon conditions. The southern areas were still under stress, though. Due to inadequate recharge and heightened demand, particularly during the pandemic, high-stress zones expanded into the central and western regions in 2020, making the situation worse. Uneven variations occurred in 2021; some northern regions experienced improvement, whereas pressure persisted in the middle and southern zones. With extensive, severe variations, particularly in the central, south-eastern, and southern regions, 2022 was the most crucial year. This points to a hydrogeological dilemma brought on by inconsistent rainfall and long-term overuse. The region under <2.5 m fluctuation increased from about 35% in 2017 to over 80% in 2022, according to graph analysis, whereas the 2.51-3.5 m category had a significant reduction. Zones that fluctuated by more than 3.5 meters stayed mostly stable. These findings point to a growing pattern of groundwater stress, highlighting the urgent need for targeted management and recharge measures.

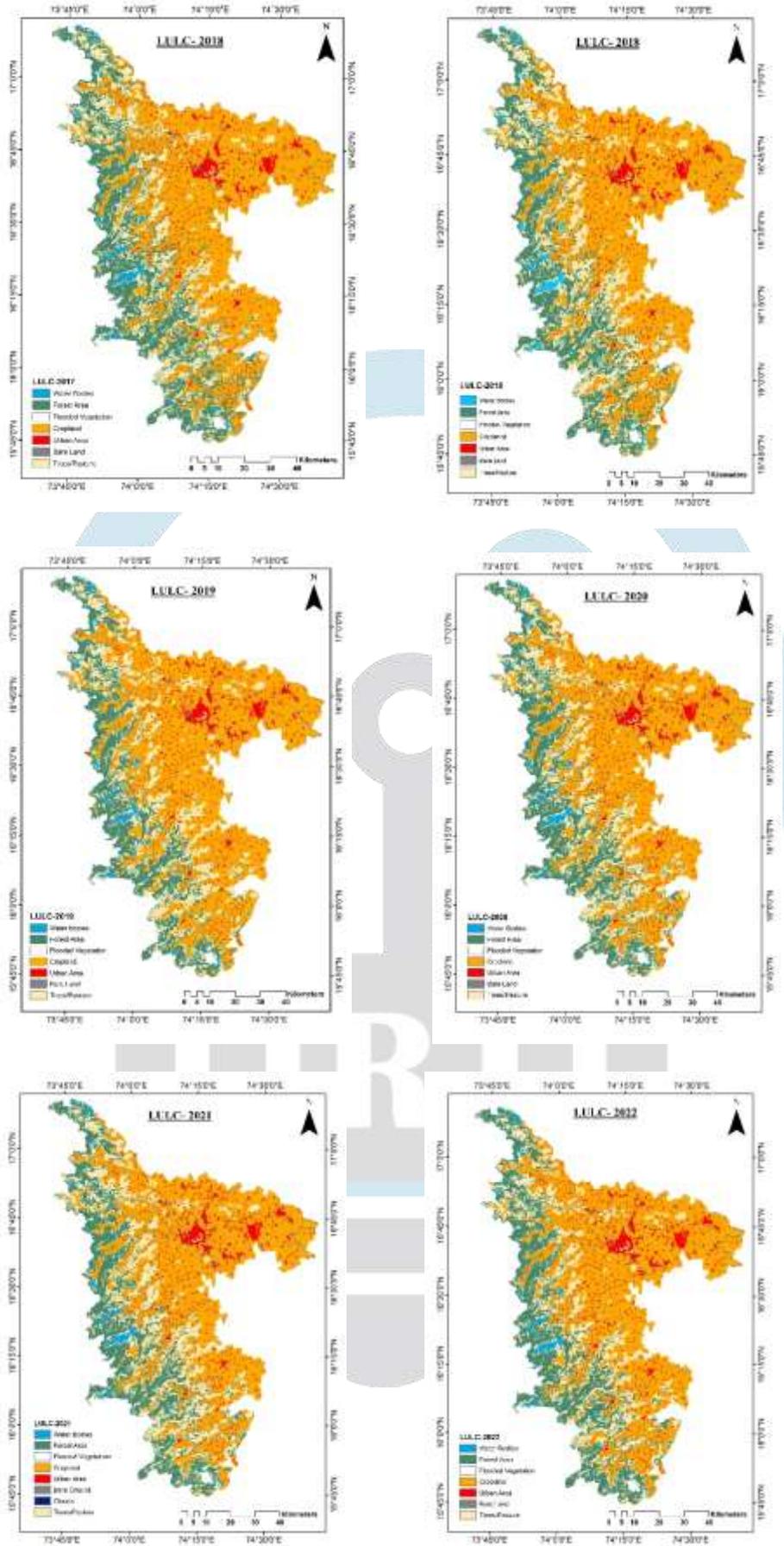


Fig 6: LULC Maps from year 2017 to 2022

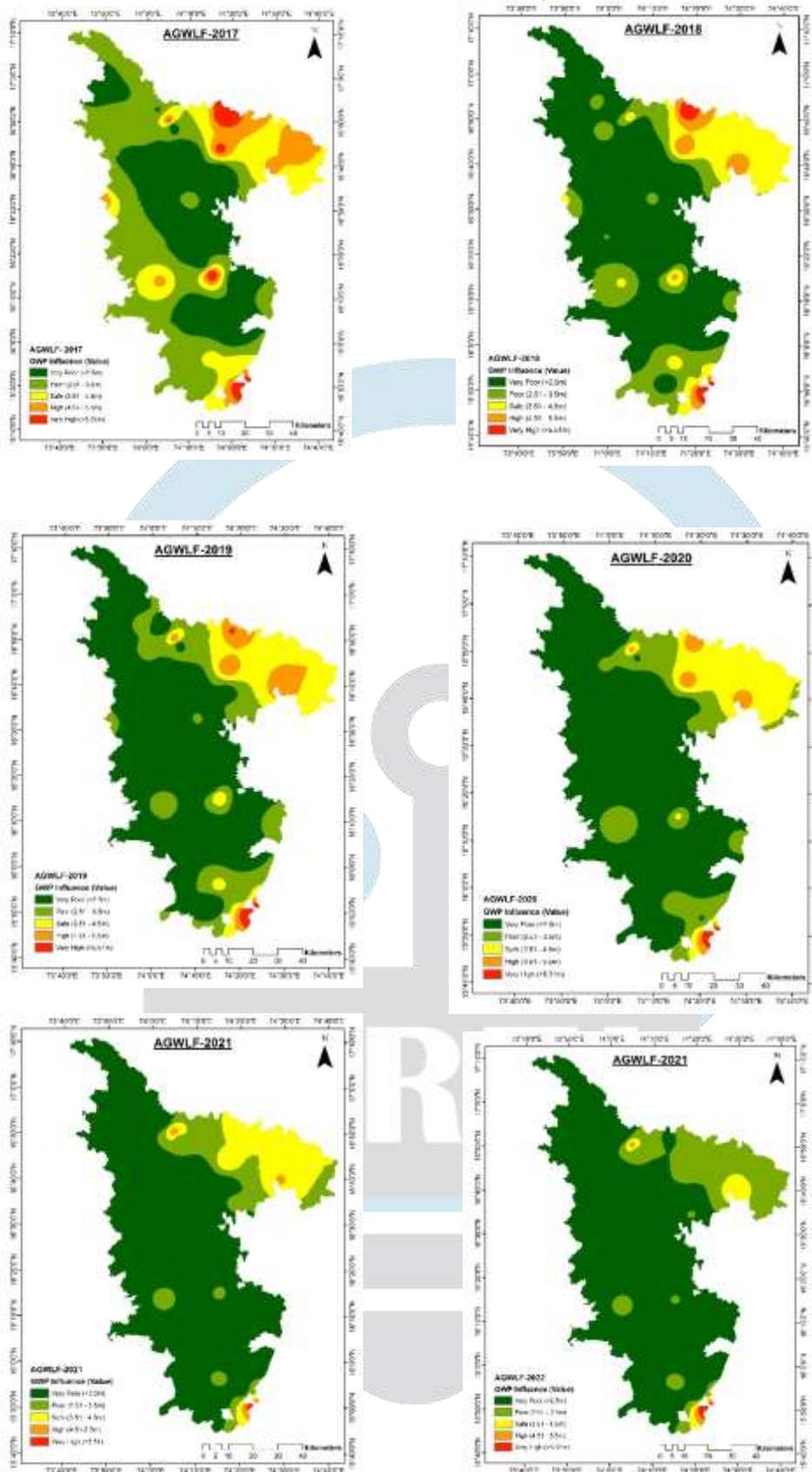


Fig 7 : AGWLF maps from year 2017 to 2022

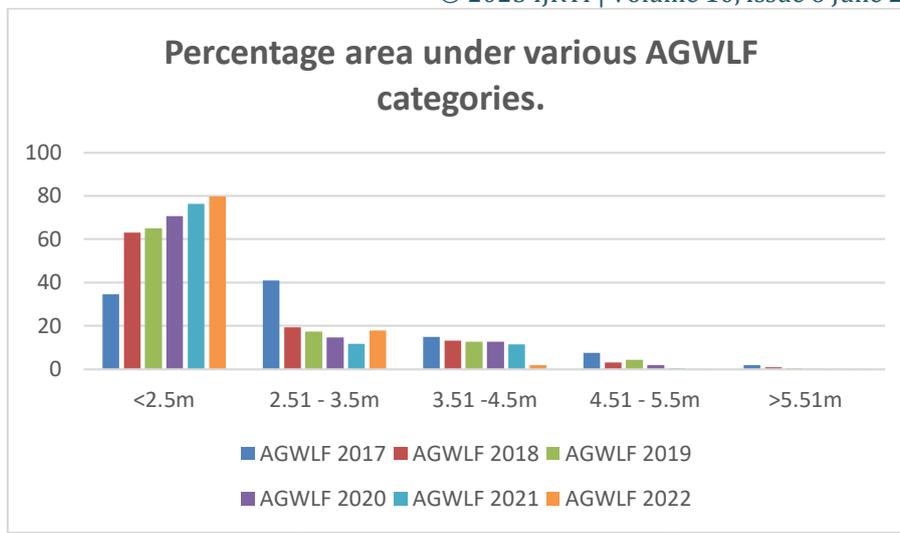


Fig 8: Percentage area change under AGWLF category

4.5 Effects of other Groundwater influencing factors

In Kolhapur district, the spatial variance of groundwater potential is greatly influenced by a number of different thematic layers in addition to DMR, AGWLF, and LULC.

Recharge processes are supported by geomorphology, particularly in the pediment-pediplain complex, which makes up more than 56% of the study region and is located in the Safe to High GWP zones. Groundwater recharging along their floodplains is facilitated by river systems such as the Varna, Dudhganga, and Ghatprabha. With multiple bodies of water, the southeast region also exhibits high GWP when infiltration is allowed by the nearby rocks and soils.

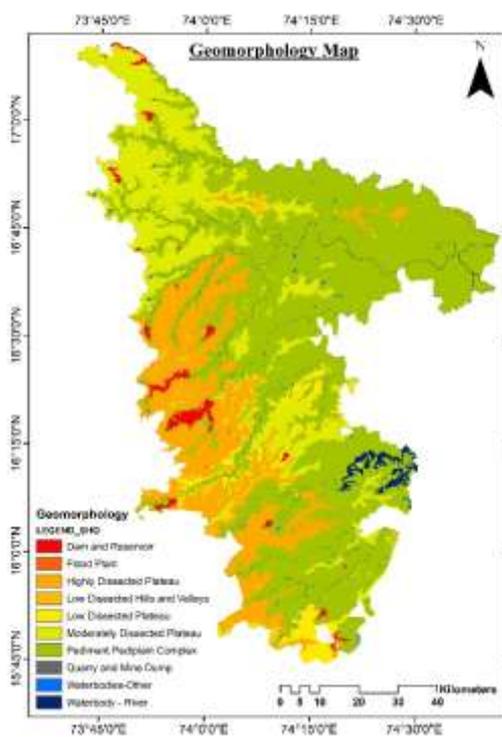


Fig 9: Geomorphology Map of Kolhapur district

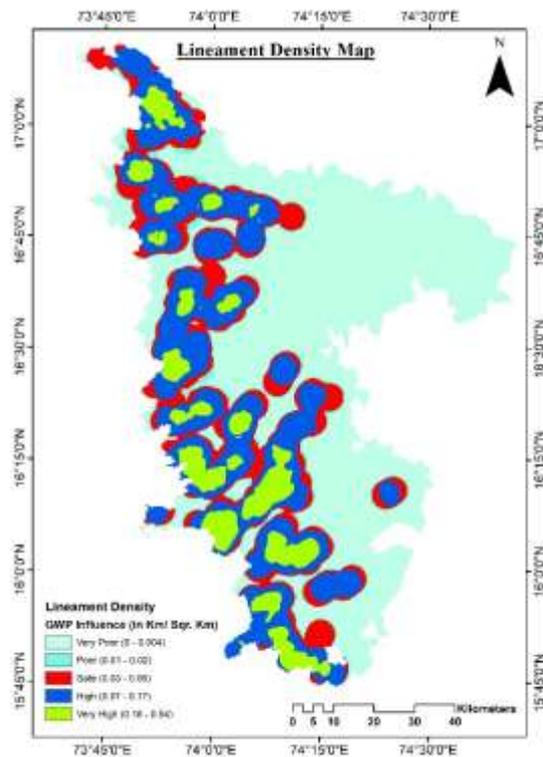


Fig 10: Lineament Density map of Kolhapur district

Groundwater recharge is improved by lineament density through fissures and fractures. Zones with higher lineament densities are associated with High to Very High GWP. On the other hand, because excessive runoff decreases infiltration, drainage density has a negative effect on recharging. More than half of the region is classified as having a lineament density that is between moderate and safe advantageous structural circumstances. Another important consideration is slope: steeper slopes (>3.05%) encourage runoff and decrease infiltration, whereas places with a slope of 0-3.05% enhance recharging and are classified as High Influence Zones. High slopes make up about 37% of Kolhapur, especially along the northeast-southwest axis. The predominant soil type Ap21-2b (~4997

km²), which is most likely sandy-loamy, has a high potential for recharge, according to soil texture study. For water harvesting systems, other moderately permeable soils (Vc45-3a, Bv12-3b) are appropriate. Because of their low permeability, clayey soils (Nd49-2bc, Nd51-2b) have a low potential for recharge.

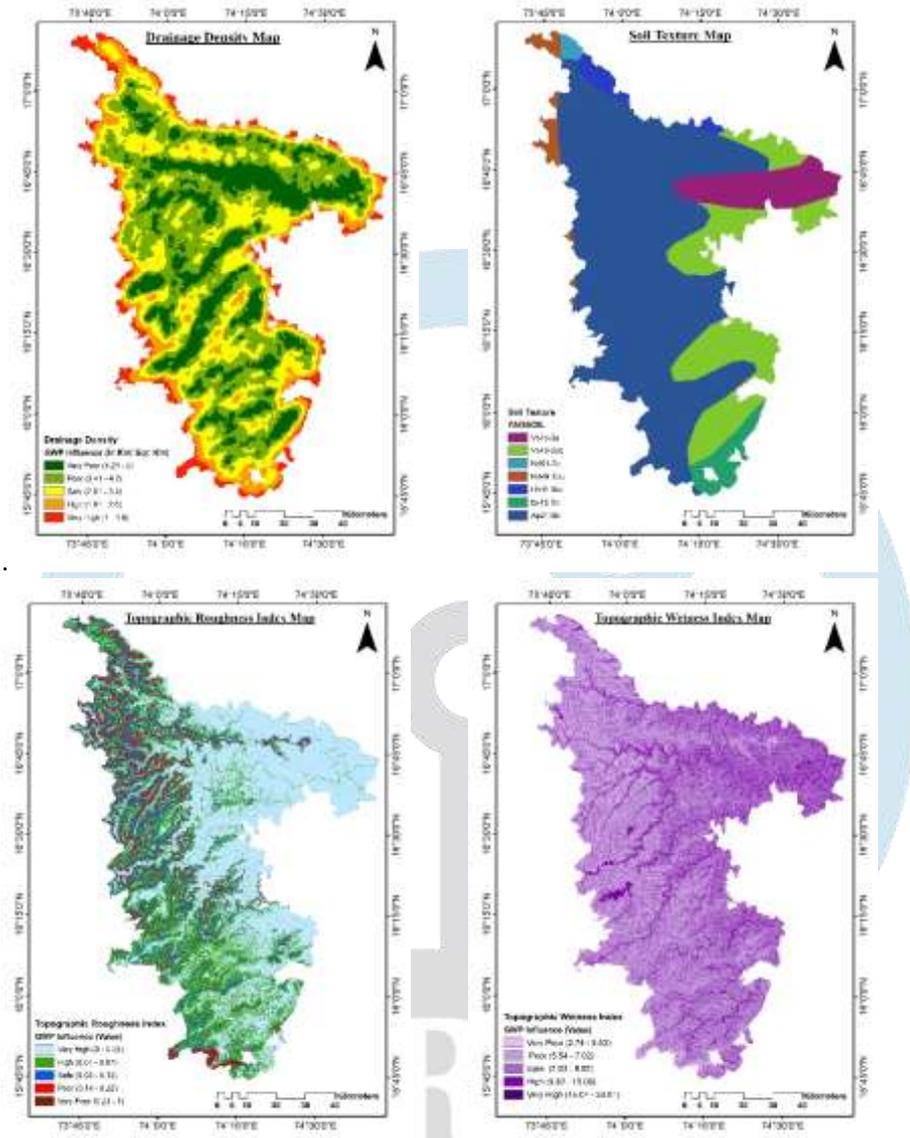


Fig. 11: a) Drainage Density Map, b) Soil texture Map, c) TRI Map, d) TWI Map

According to the Topographic Roughness Index (TRI), 79% of the region is classified as having High to Very High recharge zones due to its flat to moderately undulating terrain. Due to significant recharge, just 7% of the terrain is categorized as harsh or very rough runoff. The majority of the region falls between the Safe (40.8%) and Poor (38.5%) recharge categories, according to the Topographic Wetness Index (TWI). The majority of High and Very High zones (13%) are found in flat, artificially created areas and valley bottoms. On higher slopes, Very Poor zones (7.7%) have little possibility for recharge.

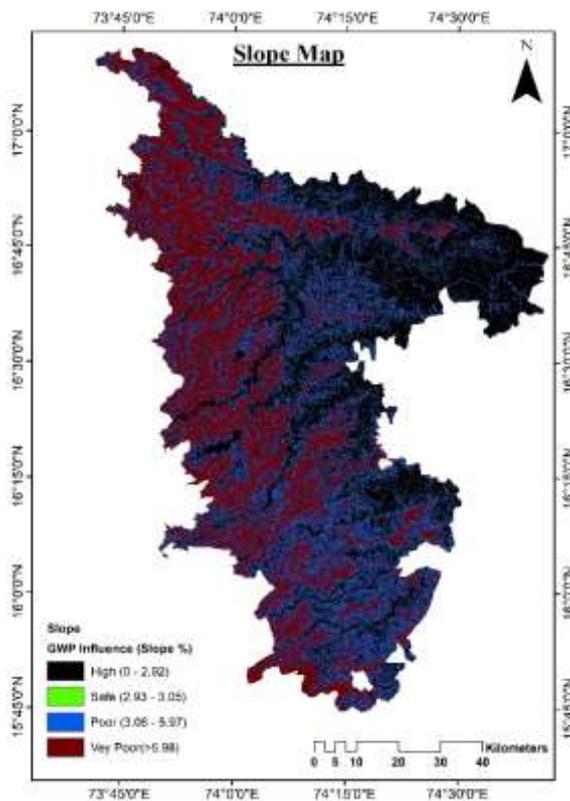


Fig 12: Slope Map

4.5 Dynamics of Groundwater Potential from 2017 to 2022

From 2017 to 2022, the Kolhapur district's groundwater potential zones consist of Poor, Safe, and High are distributed as shown in Figure. Over 6000 km², or over 80% of the research region, are regularly covered by the "Safe" category. This dominance suggests a steady groundwater regime that is appropriate for both residential and agricultural uses, with balanced recharge and withdrawal. From 295.70 km² in 2017 to 464.12 km² in 2022, the "Poor" category grew by more than 55%, suggesting the emergence of stress zones that may be brought on by decreased recharge, over-extraction, or shifting land use. A little decrease in 2022 can be the result of transient surface or climatic changes. The "High" GWP area, on the other hand, decreased by almost 32%, from 1279.44 km² to 876.96 km², indicating a loss in recharge capacity in previous aquifer-rich zones, most likely as a result of increased water use, urbanization, or deforestation.

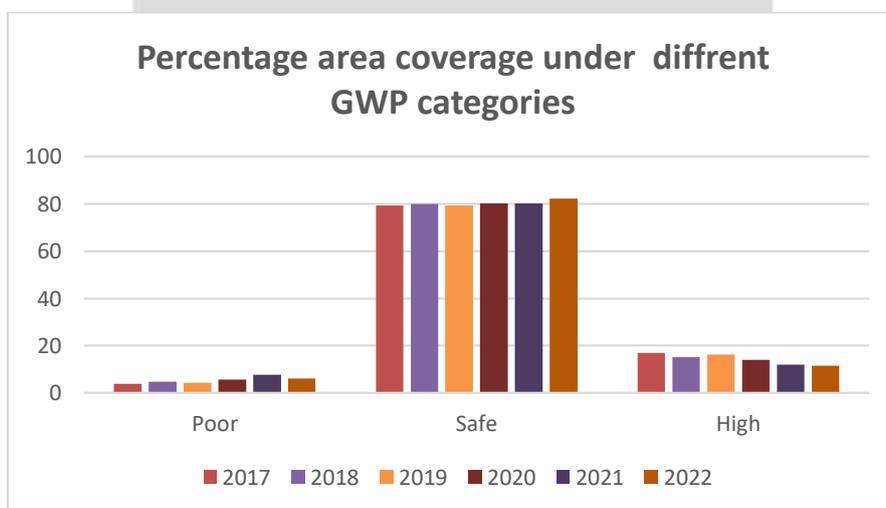


Fig 13: Percentage area coverage under different GWP categories

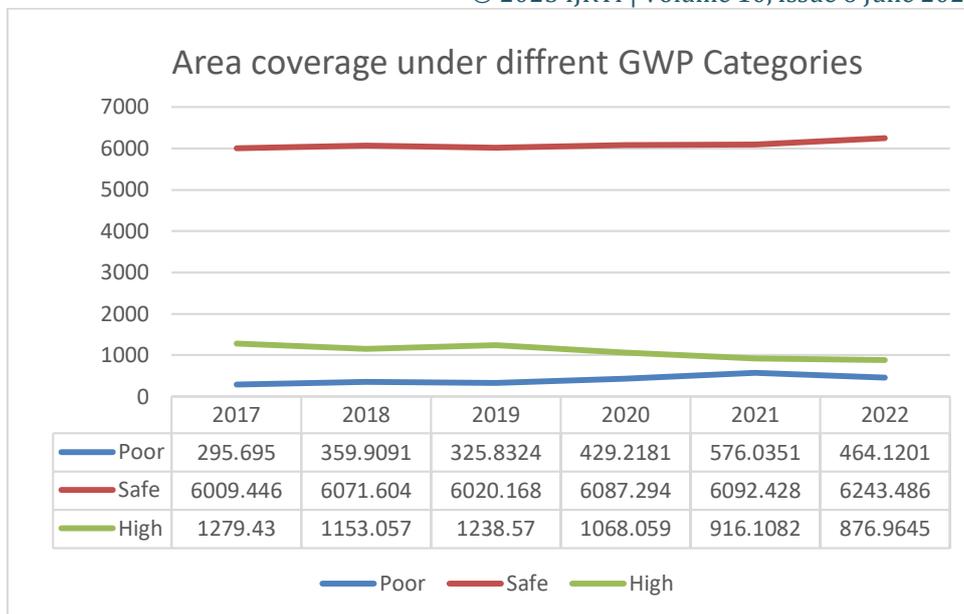


Fig 14: Trend of Area coverage under various GWP categories

The shift from High to Poor zones indicates increasing stress, even though the Safe category still predominates overall. This emphasizes the necessity of sustainable groundwater management techniques such as restricted extraction, artificial recharge, and land use planning. Because of their lower topographic roughness and higher rainfall (>1044 mm), the northwest, southwest, and south are better suited for groundwater recharging. Significant recharging is supported by the Panchganga river basin's wide floodplains and permeable alluvial layers. Furthermore, the Deccan Trap basalts that cover a large portion of Kolhapur offer storage in fractured zones, particularly those close to streambeds, which improves the possibility for recharge in these locations.

4.7 Validation of GWP Maps

Groundwater level (GWL) data from the Groundwater Surveys and Development Agency (GSDA), Kolhapur, was used for validation in order to guarantee the accuracy of the Groundwater Potential (GWP) maps based on Weighted Overlay Analysis (WOA). In order to compare groundwater dynamics across seasons, the GSDA monitors GWL twice a year, in May (pre-monsoon) and September (post-monsoon). Only measuring stations (MS) with pre- and post-monsoon records were used for validation, which was done for the years 2017-2022. 66 (2017), 61 (2018), 80 (2019), 68 (2020), 63 (2021), and 65 (2022) were the stations utilized annually.

Table 6: Overall Accuracy Assessment from year 2017 to 2022

Year	2017	2018	2019	2020	2021	2022
Overall Accuracy	63.63	68.85	72.5	64.70	71.42	69.23

The MS sites were georeferenced and converted into a vector layer. Both the GWP zonation maps and the GWL maps intersected this. Only that MS were taken into consideration for validation, where effective recharge was shown by the post-monsoon GWL rising by at least one meter. By contrasting each MS's location with the anticipated GWP category on the map, the accuracy assessment was carried out. The ratio of correctly categorized pixels to the total number of validation points inside each GWP class was used to compute overall accuracy. The trustworthiness of the GWP classification was supported by the validation, which showed that many stations within High and Safe GWP zones showed expected GWL increases following the monsoon. There is a need for finer-scale recharge and abstraction monitoring, nevertheless, as several stations in Safe zones only displayed a slight increase in GWL, maybe as a result of local extraction or microclimatic impacts.

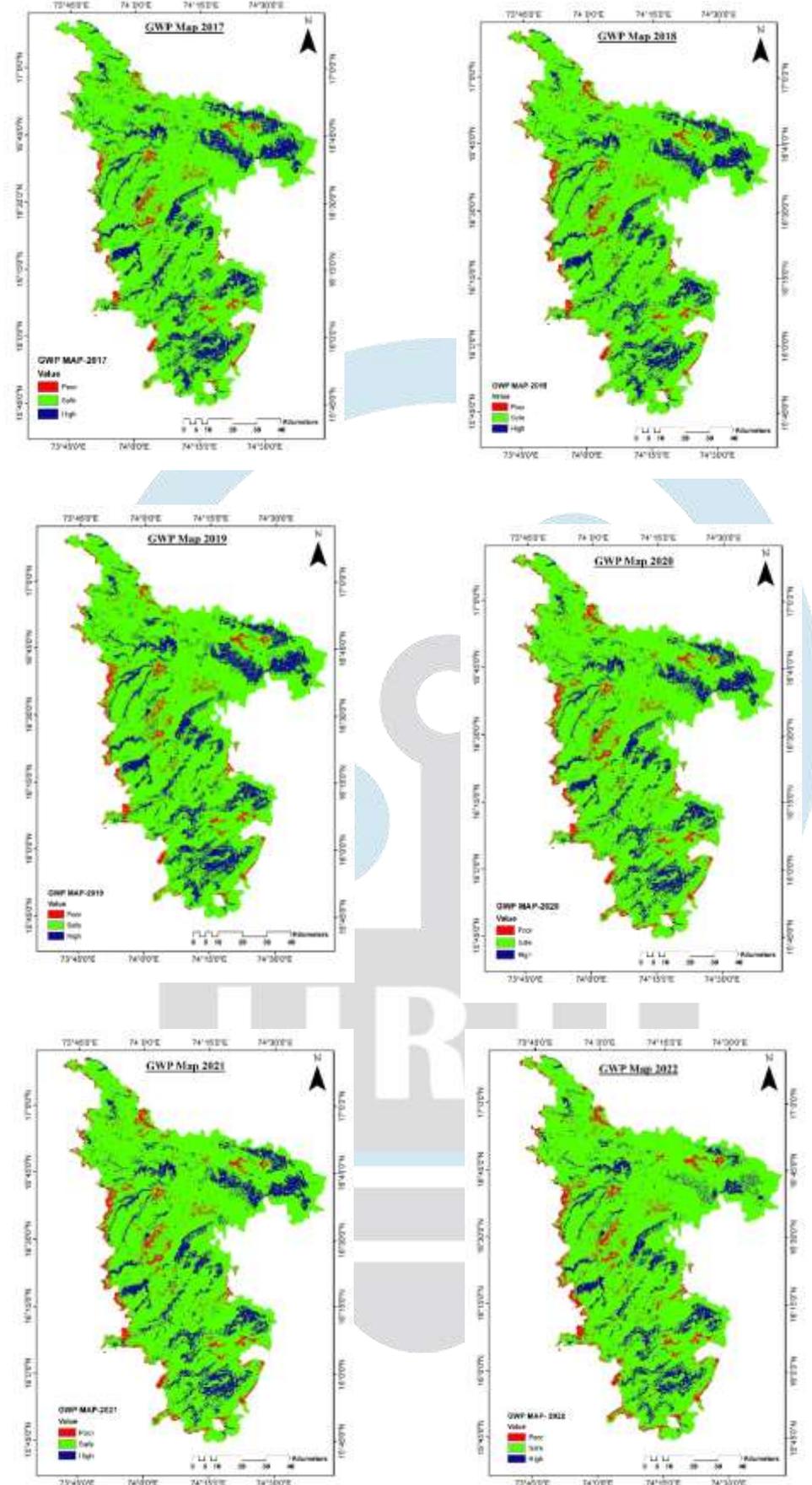


Fig 15: GWP Maps from year 2017 to 2022

5. CONCLUSION

Significant changes in the region's groundwater conditions, land use, and rainfall patterns are revealed by the study. As climate variability increased, peak rainfall from 2010 to 2019 (1147.92 mm) drastically decreased from 2012 to 2021 (761.71 mm). Even though rainfall increased slightly between 2013 and 2022 (938.13 mm), a rise in low-rainfall zones (<930 mm) following 2019 suggests that climate change is still occurring. Forest cover decreased by 7% and urban areas increased by 29% as a result of urbanization and land degradation. Seasonal waterlogging and poor drainage are probably to blame for the 120% increase in flooded

vegetation. Furthermore, almost 70% of the land is currently classified as bare ground, indicating limited vegetation recovery and environmental stress. After 2018, groundwater stress increased as a result of excessive use and inadequate recharge. By 2022, regions with the fluctuation of shallow water levels (less than 2.5 meters) rose to 80%. Deep-stress zones (>3.5 m) are still relatively small, but they pose more recovery difficulties. Floodplains and sandy-loamy soils, which promote recharge, make up more than 56% of the region. Rough terrain and clayey soils, however, make it difficult. Only 13% of the area is highly suitable for recharge, according to TRI and TWI analyses; the remaining area has moderate to low potential. The majority of groundwater potential zones are still "safe" (>6000 km²/year), but between 2017 and 2022, "Poor" zones grew by 55% and "High" zones decreased by 32%. This suggests that aquifers are under more stress. Whereas basaltic areas (Deccan Trap) continue to be more susceptible to stress, recharge is more successful in valleys with alluvial deposits.

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