

Case Study

Groundwater Recharge Potential Index and artificial groundwater recharge in the alluvial soils of the middle Ganga Basin

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Abstract

Recent studies prove the faster depletion of groundwater is a cause of concern in the middle Ganga basin. Most of the groundwater-related studies in the middle Ganga basin deal with groundwater levels and quality aspects. The past studies on groundwater potential are confined to arid and humid zones of India, which leaves ample space for semi-humid to semi-arid, frost-prone, and alluvial region. The basin has alluvial soil due to sediments deposited by the river Ganga. In this study, eight thematic maps were prepared for the assessment of the groundwater recharge potential. These maps are; rainfall, geomorphology, slope, drainage density, lineament density, lithology, Land Use/Land Cover (LULC), and Groundwater Fluctuation (GWF). The weighted overlay of these thematic maps gave the Groundwater Recharge Potential Zone (GWRPZ) map representing the spatial variation of the Groundwater Recharge Potential Index (GWRPI) in the basin, whose value varies from 0.071 to 0.309. A total of 92 artificial groundwater recharge sites have been identified using specialized GIS processes taking into account stream network. The Analytic Hierarchy Process (AHP) based weights classification offers a robust framework for prioritizing and understanding the relative significance of factors affecting groundwater recharge. Alluvial soils are capable of holding large amount of water, and are overlaid by large aquifers. A large number of wells and tube wells have led to the over-extraction of groundwater in the region. This is the reason of the study being carried out despite being a region infested with large aquifers.

Article Highlights

- Groundwater in middle Ganga basin depleting fast, posing a major worry for water supply.
- Maps identify zones to naturally recharge groundwater, offering solutions for water storage.
- Alluvial soil and aquifers in the Ganga basin impacted by over-extraction, affecting groundwater.

Keywords Remote sensing · Groundwater recharge potential zone · Analytic Hierarchy Process · Artificial Groundwater Recharge sites

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1 Introduction

The Ganga River basin, the largest basin of India, is divided into three parts: the upper, the middle, and the lower basins. Among these, the middle Ganga basin holds a significant international importance due to its extensive coverage and high population density. Groundwater is a naturally available freshwater resource (below the earth surface, i.e. sub-surface water) requiring minimal treatment before being suitable for human consumption. Due to this reason, groundwater in India is widely used for domestic, commercial, and irrigation needs. However, this precious resource is under threat due to climate change and over-extraction [1, 2]. The increasing population and higher water demand per capita are the main factors behind over-extraction [3]. Groundwater is the world's most extracted raw material with withdrawal rates currently in the estimated range of $982 \text{ km}^3 / \text{year}$ [4]. About 70% of groundwater withdrawn worldwide is used for agriculture. Almost half of the drinking water in the globe comes from groundwater. Human activity has an indirect impact on water resources through changes in land use, such as urbanization and agricultural growth, and a direct impact on water resources through water use, notably irrigation [5]. This depletion of groundwater can cause very severe problems for the residents of Uttar Pradesh, as it is the most common and freely available source of water in the region [4]. The Gravity Recovery and Climate Experiment (GRACE) satellites have revealed aquifers are depleting, further confirming the adverse situation for the groundwater. At 688 billion cubic metres, India's water withdrawals for agriculture is the highest in the world [6]. The groundwater storage in the Ganga basin is decreasing at a rate of 2.6 cm year^{-1} during the period from 1996 to 2017 [7]. In northwest Indian states (Rajasthan, Punjab, and Haryana), the groundwater levels are depleting at a rate of $4.0 \pm 1.0 \text{ cm yr}^{-1}$ equivalent height of water, or $17.7 \pm 4.5 \text{ km}^3 \text{ yr}^{-1}$ [7]. Uttar Pradesh is not immune to this problem despite being located in the Ganga basin and high annual rainfall cannot counter the extraction rate of groundwater. For the agriculturally important districts of the state, groundwater levels declined suddenly by $\sim 3 \text{ m}$ in 2009–2010 due to long-lasting dry event [9]. All these studies prove that over extraction of groundwater is a big cause of concern [9, 10]. Even the state capital, Lucknow, is witnessing a fast depletion of groundwater levels [10]. Another effect of decreasing groundwater levels is the reduced discharge in the lower reaches of the Ganga river [12].

Groundwater depletion within a large basin-scale interaction with surface water has multifaceted impacts, including reduced base flow and river discharge, affecting aquatic ecosystems and water availability; economic consequences through agricultural losses and increased energy costs; insecurity in drinking water availability, posing health risks; diminished soil moisture and ecology sustenance, leading to habitat loss and altered ecosystems; and long-term sustainability challenges, potentially lasting generations. Furthermore, land subsidence and increased conflicts over water resources can occur, driving migration [11]. Addressing these challenges necessitates integrated water resource management practices, including monitoring, regulation, and conservation, to mitigate the adverse impacts on ecology, the economy, human populations, and the biosphere while ensuring the sustainable use of both surface water and groundwater resources [13].

The groundwater recharge is directly affected by the rainfall amount. Several studies have found a correlation between rainfall and groundwater recharge. The quantity of groundwater recharge as a percentage of net amount of rainfall per year can be around 20% in mountainous regions [9]. But the Ganga basin in this study does not have any mountains. Hence, the percentage of groundwater recharge with respect to rainfall can deviate from this value. This value can be as low as 10% to 15% in the case of arid soils of desert [14]. The desert soils are less permeable than the soil with green vegetation. A significant change in rainfall can cause a similar kind of change in groundwater. Previous studies have confirmed that the groundwater anomaly follows the rainfall anomalies [14]. It has been found that after a meteorological drought year, the groundwater drought can occur after a period of minimum one year. In higher altitudes, the groundwater drought will take longer time to occur than it would in tropics [14]. In the current study, we have used rainfall as the main parameter to calculate the groundwater recharge. In India and many other countries, several researchers have used empirical observations to obtain a relationship between rainfall and groundwater recharge. Each of these equations is useful only for a certain soil type. Artificial groundwater recharge is the only solution to restore the water table to its initial levels, if the natural recharge cannot replenish aquifers. Researchers like Dripps and Bradbury in 2009 used Soil Water Balance (SWB) model to understand the variability of groundwater recharge affected by soil topography, land cover, and climate [15]. The SWB models have always yielded the conclusion that geographical features of a region affect the groundwater recharge. A combination of remote sensing and geographic information system (GIS) is proving beneficial with respect to the groundwater management [16] that can extract information about the geography of a region remotely.

A Groundwater Recharge Potential Zone (GWRPZ) is the area where the rate of groundwater recharge exceeds the rate of extraction of groundwater. This difference in the rates of infiltration and extraction defines the quantity of groundwater recharge. The GWRPZ consists of such landscapes that favor the infiltration of water into the aquifers under the given meteorological conditions. The GWRPZ map is able to provide a comparative assessment of Groundwater Recharge Potential Index (GWRPI) of different regions in the study basin. The study presented by Thakur et al. has presented many studies that use RS and GIS to identify the GWRZ. In such studies, generally a number of thematic maps of factors affecting the Groundwater Recharge (GWR) are prepared using the RS and GIS. The thematic maps are assigned weights on a 1 to 9 scale, and their normalized weights are obtained by the Analytic Hierarchy Process (AHP), which is a Multi-Criteria Decision Making (MCDM) technique [17]. The decision of relative importance is done using the nature of effect of a particular factor on the nature of groundwater recharge. This means that if on decreasing the magnitude of a certain factor, the magnitude of groundwater recharge decreases then that factor's lower magnitude values are assigned lower importance.

Controlling runoff and recharging excess runoff for groundwater augmentation through artificial recharge measures is a crucial hydrological strategy. It involves mapping groundwater recharge potential zones (GWRPZ) to identify suitable areas for replenishing aquifers. Several factors influence recharge, including rainfall (RF), slope, land cover type, geological faults, and more. To map GWRPZ, various techniques are employed, with the AHP being a noteworthy one. AHP facilitates a systematic evaluation of factors' importance and assigns weights to determine suitable recharge zones, thus optimizing artificial recharge efforts for sustainable groundwater management and addressing water resource challenges [19–21]. After evaluating the previous work on groundwater recharge, we sought to employ RS, GIS, and AHP techniques to delineate GWRPZ in the middle Ganga basin (Uttar Pradesh only) and recommend optimal recharge sites for artificial recharge. The research aims to provide a comprehensive understanding of groundwater recharge dynamics, contribute to sustainable water resource management, and facilitate informed decision-making processes. A detailed discussion on the factors affecting the groundwater recharge has been presented to understand the groundwater hydrogeology of the basin. As the Ganga basin is one of the most severely affected basins of the 8 major basins in the world, the study becomes highly relevant for the current scenario. Mapping of GWRPZ in the Ganga Basin, one of the most stressed aquifers among the major 32 aquifers globally, holds immense importance. This work is highly relevant to society as it addresses critical water resource challenges and contributes significantly to sustainable development. The specific objectives of this study encompass providing a comprehensive understanding of groundwater recharge dynamics, which is essential for ensuring long-term water security. By delineating GWRPZ, the research aids in informed decision-making for water resource management, helping policymakers, water authorities, and local communities make sustainable choices regarding water use and conservation. Furthermore, the study offers valuable insights into the factors affecting groundwater recharge, enhancing our knowledge of the basin's hydrogeology. In this study, eight thematic maps have been prepared: (1) Rainfall; (2) Geomorphology; (3) Lithology; (4) Lineament density; (5) Drainage density; (6) Slope; (7) LULC; and (8) GWF. The AHP has been used to calculate normalized weights for the thematic maps and making GWRPZ map. Given the severe stress the Ganga Basin faces among the world's major basins, this research becomes even more pertinent in the current scenario, offering a pathway toward effective groundwater management and the preservation of this vital resource for future generations.

2 Study area

2.1 Geography

The present research focuses on the study area situated within the middle Ganga River basin, the most populous river basin globally, accommodating approximately 400 million residents with a population density of 390 persons per km² [18]. The study area is specifically confined between latitudes 29.742°N to 25.036°N, and longitudes 78.37°E to 82.904°E. Within this region, we consider the middle Ganga basin, encompassed by the River Ganga in the south, the River Sharda, and the River Ghaghara in the north (shown in Fig. 1). The study area contains six rivers, namely the Sai, Ganga, Ghaghara, Gomti, Ramganga, and Sharda, and spans across 27 districts of the Uttar Pradesh state, covering approximately 95,189 km². Figure 1 illustrates the diverse landscape of the study area, consisting of expansive evergreen forests, wetlands, ponds, and human settlements. The Bijnor and Pilibhit districts are intersected by the Shiwalik hills, which lie within the outer Himalayas (Figs. 2 and 3). The upper part of the study area features the Terai region, locally referred to as the seepage zone, covering an area of 20,879 km², characterized by undulating marshlands (Fig. 2). The Terai zone is marked

Fig. 1 A schematic diagram related to the current study in which the rainfall causing groundwater recharge, and the rainfall related runoff leading to groundwater recharge has been studied carefully. The effect of higher mountains in the north and low-lying plains in the south can be properly understood in this figure. The LULC, rivers, and recharge sites duly marks the complexity of the study area

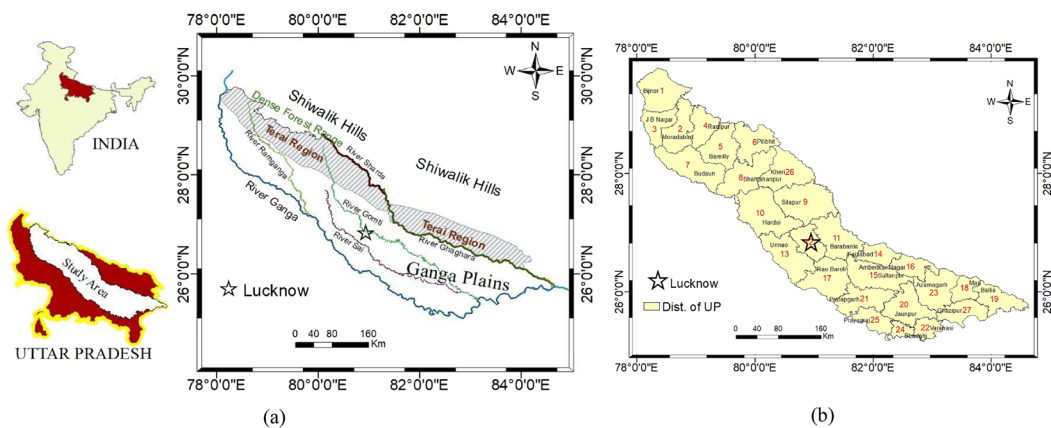
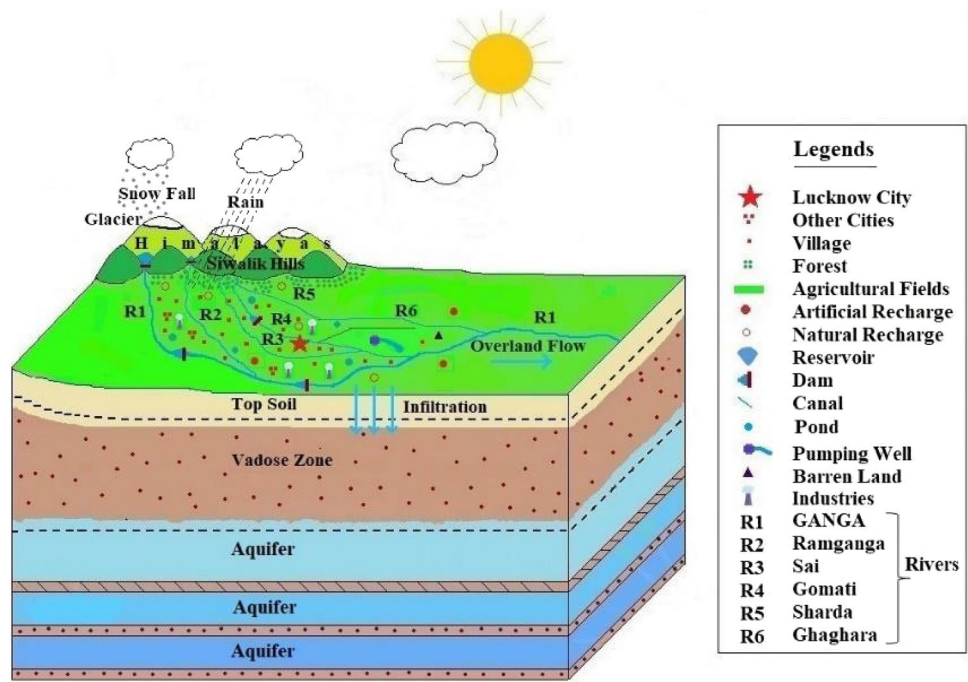


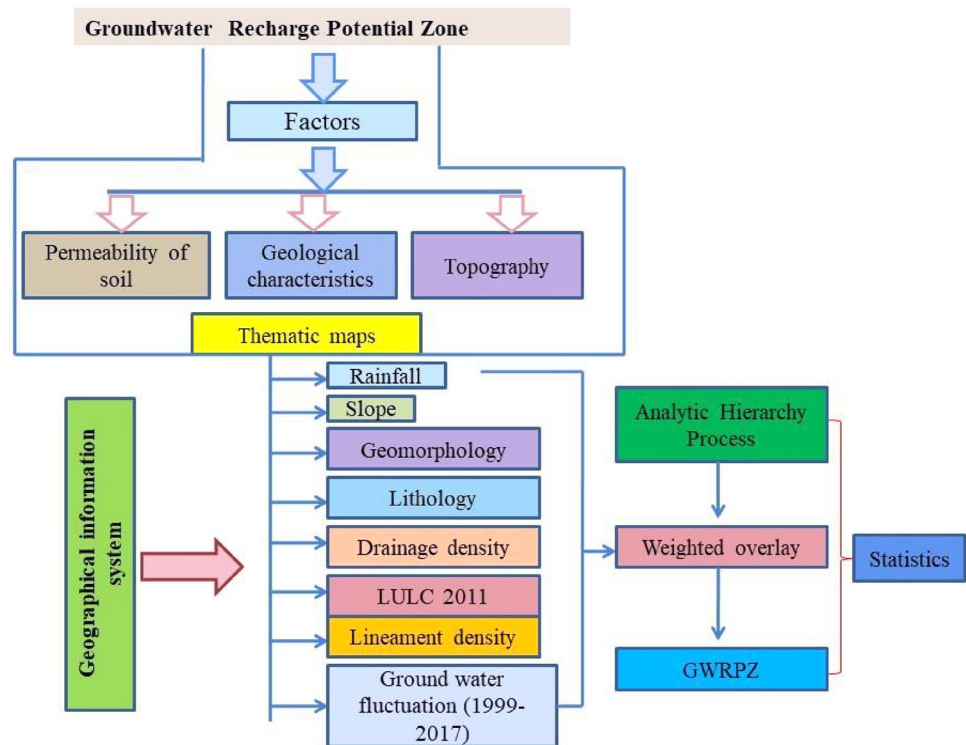
Fig. 2 The study area is located in the state of Uttar Pradesh, India (a). The middle Ganga basin covers an area from the foot-hill region to the central part of the state of Uttar Pradesh, India. The study area is bounded by the rivers Sharda and Ghaghara in the north, and the geologic unit 'Terai' (clay-rich swampy region). The southern region is bordered by the river Ganga. The rivers Ramganga, Sai, and Gomti are the major rivers that flow through the study area. The districts have been shown in (b)

by a flat topography and fine alluvial deposits. The study area's mean altitude stands at 95 m above mean sea level (amsl), with the lowest point at 36 m amsl and the highest at 519 m amsl. A detailed Digital Elevation Model (DEM) has been created in Fig. 4.

2.2 Soil

The study area within the middle Ganga basin is characterized by a diverse range of soils resulting from the deposition of alluvium by the flowing rivers of the Ganga River system. The soil cover varies from sandy to clayey loam, contributing to different soil properties and characteristics across the region. This diverse soil composition influences the hydrological processes, groundwater recharge potential, and agricultural productivity within the basin. The alluvial deposits create a deep layer of fertile soil, facilitating agricultural practices and supporting the region's agricultural output. Understanding the soil properties and their distribution is crucial for effective water management strategies and sustainable land use practices in the middle Ganga basin [4, 7, 8].

Fig. 3 - The flow chart for mapping GWRPZ. The groundwater potential of a certain area is affected by the permeability of the soil, geological characteristics, and topography. The GIS is used to create and store the eight thematic maps of lithology, land use/cover, lineaments, drainage, rainfall, geomorphology, groundwater fluctuation, and slope. The groundwater fluctuation is averaged from 1999 to 2017. The weights of each class of each map are calculated by the AHP. With the help of the Weighted Overlay tool in the GIS software, the GWRPZ can be created



2.3 Climate

The middle Ganga basin's climate is classified as tropical and sub-humid. The region experiences an annual rainfall of 650 mm, with 75% of it received during the monsoon season spanning from June to September. The winter season, from November to February, grants an additional 100 mm to 150 mm of rainfall, which is beneficial for Rabi crops. Pre-monsoon thunderstorms, often referred to as Nor'westers or Kal-Baisakhi, occur from March to May, especially in the eastern portion of the study region. In terms of temperature, the average minimum temperature during winter in the basin stands at 6.4 °C, while in summer, it rises to 21.5 °C. The hottest month in the upper half of the basin is June, whereas in the lower half, it is May. The average maximum temperature recorded is 31.4 °C [22, 23]. The high temperatures during this period create favorable conditions for water seepage into the soil. These ideal temperature conditions persist from March to October. However, as November approaches, the temperature begins to decrease, and in some locations, it can even drop below zero for a few days during January. Overall, understanding the unique geographical and climatic characteristics of the study area within the Ganga River basin is crucial for comprehending various ecological and hydrological processes within the region. The Fig. 1 explains the hydrology of the middle Ganga basin in brief.

2.4 Hydrogeological insights: characteristics of the Aquifer system in the Middle Ganga Basin

The aquifer system in the middle Ganga basin displays a complex and diverse hydrogeological framework, exerting significant influence on groundwater availability and quality. It comprises multiple layers of rock, sediment, and soil, resulting in distinct aquifer types with varying properties and water-transmitting capacities. Predominantly, the alluvial aquifer assumes prominence, characterized by unconsolidated sediments deposited by the Ganga River and its tributaries. These aquifers consist of sand, gravel, and clay, rendering them highly permeable and essential for groundwater recharge due to their substantial water-storage potential. Notably, the alluvial aquifer encompasses various layers, namely the upper, middle, and lower zones, each receiving distinct recharge mechanisms. Localized fractured rock aquifers may exist within the hard rock formations in addition to the alluvial aquifers. These aquifers facilitate water movement and storage through cracks, joints, and fractures. While they exhibit lower permeability

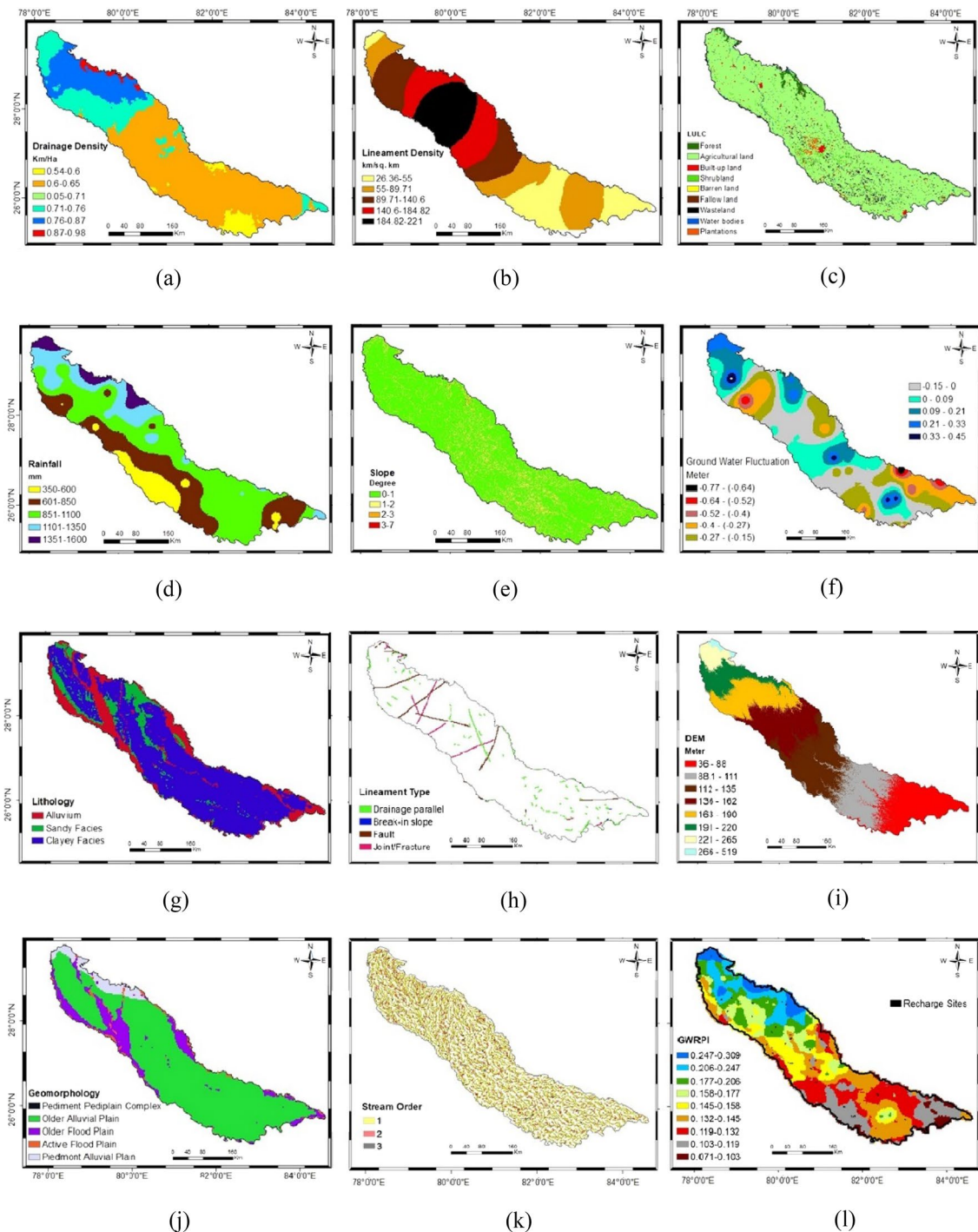


Fig. 4 The drainage density (a), lineament density (b), land use land cover (c), rainfall (d), slope (e), groundwater fluctuation (f), lithology (g), lineament type (h), digital elevation model (i), geomorphology (j), stream order (k), and groundwater recharge potential index map or GWRPZ map (l) are shown. The comparison of all these maps with the district map shown in Fig. 3 can give important information for each district about any of the thematic/spatial maps in this figure

compared to alluvial aquifers, they significantly contribute to groundwater availability. It is crucial to acknowledge that the aquifer system's characteristics, including permeability, porosity, and hydraulic conductivity, play a critical role in dictating recharge rates and groundwater flow pathways. Distinguishing the middle Ganga basin's aquifer system from others globally, several unique features emerge. Firstly, the basin predominantly comprises alluvial

deposits, setting it apart from regions characterized by diverse rock formations. Secondly, it spans a vast area across multiple Indian states, ranking among the world's largest and densely populated alluvial basins. This substantial scale influences high agricultural productivity and water demand within the region. Fourthly, the basin's thickness of alluvial and sedimentary deposits translates to significant groundwater storage potential, thereby playing a crucial role in supporting diverse water needs.

3 Materials and methods

3.1 Data source

The daily rainfall data spanning from 1991 to 2020 was obtained from the 'imdlb' of the Indian Meteorological Department (IMD) in Pune. The data was acquired in NETCDF4 (.nc4) format and converted into the Excel format (.xlsx). In order to decipher the complex aspects of the study area's geological makeup and gain an understanding of the groundwater dynamics, lithology, geomorphology, and lineaments data were carefully obtained from the reputable Bhukosh website of the Geological Survey of India, Government of India. In other studies, in India, rarely employed is the use of Bhukosh data obtained from the online depository developed by Geological Survey of India (GSI), further exemplifying the pioneering nature of our research.

Additionally, our pursuit to comprehend temporal variations in groundwater levels led us to meticulously obtain groundwater level data spanning from 1998 to 2017 from the esteemed Water Resources Information System (WRIS) portal. This renowned portal, meticulously curated, maintains an extensive repository of groundwater level data, meticulously collected by both central and State Water Development Agencies. For our study, we meticulously selected the highly reliable data from the esteemed Central Groundwater Board (CGWB), Govt. of India, which diligently measures groundwater levels from its piezometers four times a year during crucial periods, namely January, pre-monsoon (March/April/May), and post-monsoon (August and November). This carefully collected dataset provides the essential foundation for our insightful analysis, enabling us to unravel the intriguing dynamics of groundwater in the region. The LULC map has been prepared by data obtained from Bhukosh. The lineament was obtained from the Bhukosh. From which, the lineament density map was prepared using the line density tool. The DEM was obtained from Landsat 8 satellite. The DEM was used to make a drainage network of the study area. The focal density tool was used to make the drainage density map.

3.2 Methodology

To facilitate a comprehensive analysis, eight thematic maps were generated using ArcMap 10.8, each portraying essential aspects such as groundwater fluctuation, drainage density, slope, geomorphology, lithology, rainfall, and land-use and land cover (LULC). Combining these maps with appropriate weights derived from the Analytic Hierarchy Process (AHP) was essential for creating the GWRPZ map. The GWRPZ map helps identify areas with high, moderate, and low recharge capacities. The rarity of integrating GWF in other studies underscores the novelty and rigor of our research approach. Additionally, incorporating LULC data in our analysis highlights the significance of the rapidly changing population and land use patterns in the dynamic middle Ganga basin. The utilization of LULC data offers valuable insights into the influence of human activities and urbanization on groundwater recharge, an aspect of paramount importance for sustainable water resource management.

The methodology employed for this study involves three main stages: (a) creating thematic maps that capture crucial geological and hydrological information; (b) determining weights through the AHP to appropriately prioritize the significance of each thematic map in the GWRPZ analysis; and (c) performing overlay analysis to integrate the thematic maps and delineate the suitable artificial recharge sites. The culmination of these efforts is visualized in Fig. 4, which succinctly encapsulates the research flowchart, showcasing the steps and the comprehensive approach adopted for assessing groundwater recharge potential in the study area. By combining diverse datasets from gridded rainfall data to geological attributes and remote sensing-based land use data, our approach presents a rare integration of multi-dimensional information, contributing to a holistic understanding of groundwater dynamics in the middle Ganga basin.

3.2.1 Calculation of weights

In sharp contrast to commonplace methodologies such as fuzzy logic or Boolean, which have garnered prevalence in diverse Indian groundwater investigations, AHP stands as a robust and well-structured approach to multi-criteria decision-making (MCDM). It confers the unparalleled capability to systematically and rigorously juxtapose myriad factors, drawing upon their relative importance in shaping the intricate dynamics of groundwater recharge potential. By harnessing the commanding capabilities of AHP, the study heralds an era of objectivity and rationality in the evaluation of thematic maps, engaging in an intricate web of pairwise comparisons to derive weightage for each map.

3.2.2 Analytic hierarchy Process (AHP)

AHP is one of the most widely used MCDM tools [18, 19] for making complex decisions and calculating the normalized weights in AHP). In assigning the weights, the factors affecting Groundwater Recharge Potential Index (GWRPI) and their relative importance are compared. A pair-wise comparison matrix is created. Now, the criteria weight of the factors is calculated using the normalized weight method. After this, a matrix of order $n \times m$ is prepared, in which n is the number of factors and m is the number of alternatives. Finally, the global score of each alternative can be calculated using the following formula: -

$$G_a = \sum_{c=0}^n w_c \star S_{a,c} \quad (1)$$

where a is the alternative; c is the factor; w is alternative weight; $S_{a,c}$ is the score of alternative a for criteria c ; and G is the global score of the alternative.

The major advantage of AHP over others is pair-wise comparison. The decisions by AHP are good if the consistency is less than 10%. The Consistency Index (CI) gives the measure of consistency, which is calculated by the formula [18, 19]:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

where λ_{max} is the largest Eigenvalue of the matrix.

3.2.3 Weighted overlay analysis

The significance of employing the Weighted Overlay Analysis (WOA), complemented by the AHP methodology, lies in its ability to model suitability based on geographical coordinates and establish precise locations in GIS. This sophisticated approach allows for the seamless resolution of multi-criteria problems, exemplified by site selection and the meticulous mapping of groundwater recharge potential.

3.2.4 Groundwater recharge potential index

In this study, the groundwater recharge potential index (GWRPI) was meticulously derived by incorporating eight crucial parameters that significantly influence groundwater recharge. These characteristics reflect important geological and hydrological elements, including topography, rainfall, soil permeability, local geology, and land-use and land-cover (LULC), among others. Each parameter was assigned a specific weight through the process of weight accumulation, which played a pivotal role in determining the GWRPI or recharge potential score. This methodological approach is consistent with earlier studies, such as Yeh et al. [24], who evaluated groundwater recharge potential using the GWRPI [16]. By employing a weighted linear combination approach, the study calculated the total weights of various polygons in the final integrated layer (after weighted overlay) known as the GWRPZ.

$$GWRPI = \left[\sum_1^8 Weight_{ThematicMap} \Sigma WeightofClass_{ThematicMap} \right] \quad (3)$$

3.2.5 Inverse distance weighted method

Inverse Distance Weighting (IDW) interpolation makes the explicit assumption that variables that are close to one another have a higher degree of similarity than variables that are far apart. IDW uses projected values to make predictions about values at unmeasured sites. Readings that are closer to the projected value have a greater impact on the unmeasured areas than readings that are farther away. IDW makes the assumption that every measured point has a local influence that gets smaller as it gets further away. The term “inverse distance weighted” refers to a weighting method where points closer to the projected location are given a higher weight and those farther away receive a lower weight. In the IDW, a transition matrix is employed to let users indicate the expected degree of surface abruptness along these borders. The general model for z-value interpolation is represented by the following formula:

$$z_{xy} = f(x, y)x \quad (4)$$

Because, the position in relation to known z values, which is the only variable, determines surface height z at every given point (x, y), this model may be regarded as univariate. Earth scientists frequently employ IDW interpolation [26]. Inverse distance weighted interpolation’s general equation is:

$$z_{xy} = \frac{\sum_{i=1}^n z_i w_i}{\sum w_i} \quad (5)$$

where, z_{xy} is the estimated point, z is the control value for the ith sample point, and w is a weight used to gauge the relative significance of each control point in the interpolation process [19]. IDW allows you to control the importance of known points to interpolated values based on their distance from the output point. By defining a higher power, more attention is paid to the closest points and the resulting surface is more detailed (less smooth).

3.3 Groundwater recharge calculation by empirical equations

Since some rainwater will evaporate, transpire, and discharge from the watershed, it might not fully infiltrate or contribute to the groundwater. Rainfall that seeps through replenishes the aquifer below by bringing up the soil’s moisture deficiency. Different empirical connections between recharge and rainfall that were discovered for various places with similar climates were used to evaluate rainfall recharge (rainfall and temperature data). The amount of recharge is influenced by the intensity and duration of rainfall, the subsequent conditions at the upper boundary, the previous soil moisture levels, the depth of the water table, and the type of soil. The assessment of groundwater recharge from precipitation is one of the key components of hydrology and hydrogeology [24, 25]. Table 1 displays all of the formulas that can be used to calculate the groundwater recharge in inches or millimeters [27, 29].

Table 1 A list of empirical formulas used in this study for the calculation of the groundwater recharge. These formulas can provide a rough estimate of the groundwater recharge in a certain area. All formulas calculate the values on the basis of rainfall quantity

S. No	Name	Formula
1	UP Irrigation Board formula	$R = 1.35(P - 15)^{0.5}$ here P = inches, and R = inches
2	Krishna Rao formula	$R = 0.30(P - 300)$ here P = mm, and R = mm
3	Chaturvedi formula	$R = 2.0(P - 15)^{0.4}$ here P = inches, and R = inches
4	Braden-Camp formula	$R = 0.32(P - 360)$ here P = mm, and R = mm
5	Amritsar formula	$R = 2.5(P - 16)^{0.5}$ here P = inches, and R = inches

4 Results

4.1 Thematic maps

In this study, eight critical thematic maps were meticulously developed using Arc-GIS 10.8, collectively serving as a foundation for our analysis. These thematic maps, representing drainage density, lineament density, rainfall, slope, LULC, lithology, groundwater fluctuation, and geomorphology, are visually presented in Fig. 4. These maps, crafted through a meticulous fusion of RS and GIS tools, encapsulate critical landscape attributes that significantly impact groundwater recharge dynamics. The subsequent analysis of these thematic maps, guided by the principles of the AHP, unlocks a nuanced understanding of their individual contributions to groundwater recharge potential across the study area. The visual depiction of these thematic maps in Fig. 4 not only serves as a compelling visualization but also signifies the foundational basis for our subsequent explorations into groundwater recharge dynamics, potential zones, and strategic intervention sites.

4.1.1 Drainage density

Figure 4a presents the variation in drainage density across the study area, with a specific focus on how the drainage density changes relative to the distance from the Himalayas. Drainage density, measured in kilometers per hectare (km/ha), reflects the total length of all streams and rivers within a unit area. The drainage density is categorized into distinct classes in Table 2, each corresponding to a range of drainage density values and associated class areas, represented as percentages of the total area. These classes now include: 0.54 to 0.6 km/ha (Class 1), 0.6 to 0.65 km/ha (Class 2), 0.65 to 0.71 km/ha (Class 3), 0.71 to 0.76 km/ha (Class 4), 0.76 to 0.87 km/ha (Class 5), and 0.87 to 0.98 km/ha (Class 6). For instance, Class 1, with a drainage density range of 0.54 to 0.6 km/ha, covers a portion equal to 4.8% of the total area. Similarly, Class 2, Class 3, Class 4, Class 5, and Class 6 cover areas equal to 57.62%, 0.16%, 19.42%, 12.28%, and 1.5% of the total area, respectively. The highest-class area, corresponding to Class 6 (0.87 to 0.98 km/ha), is observed near the foothills of the Himalayas in the Terai region. The drainage density reflects the proportion of the total area covered by densely networked streams and rivers, characteristic of steep slopes and higher precipitation near the mountains. As one moves away from the Himalayas to the SE and SW, the drainage density consistently decrease. The reduced drainage density in regions farther from the Himalayas indicate a smaller proportion of the total area occupied by streams and rivers. Overall, the drainage density of 0.54 to 0.98 km/ha suggests that the middle Ganga basin has a significant network of watercourses that play a crucial role in shaping its hydrological characteristics, including water movement, erosion, sediment transport, and potentially groundwater recharge.

4.1.2 Lineament density

Figure 4b portrays the variation in lineament density within the study area, with a specific emphasis on how this density fluctuates across different sections of the basin. Lineament density measures the total length of linear features, such as faults or fractures, within a unit area, often quantified in kilometers per square kilometer (km/sq. km). It serves as a significant indicator in geology and structural analysis, shedding light on the distribution of linear features across the landscape. The study area encompasses a basin, and the data in Fig. 4B is organized into distinct classes, each corresponding to a specific range of lineament density values. These classes include: 26.36 to 55 km/ha (Class 1), 55 to 89.71 km/ha (Class 2), 89.71 to 140.6 km/ha (Class 3), 140.6 to 184.82 km/ha (Class 4), and 184.82 to 221 km/ha (Class 5). The figure visually represents the spatial distribution of lineament density across the study area. Each class area corresponds to the proportion of the total study area covered by a specific range of lineament density values. The class areas provide a clear understanding of the relative magnitudes of lineament density as a percentage of the total study area. For instance, Class 1, with a lineament density range of 26.36 to 55 km/sq. km, covers an area equal to 22.43% of the total study area. Similarly, Class 2, Class 3, Class 4, and Class 5 cover areas equal to 16.28%, 15.38%, 22.18%, and 23.72% of the total study area, respectively.

The highest lineament density values are observed in the middle section of the basin. This suggests that this region is characterized by a higher concentration of linear features, such as faults or fractures. These linear features might indicate areas of increased groundwater flow [16]. The presence of lineaments leads to better groundwater recharge.

Table 2 - The thematic map name, their class names and values, the geographical area of each class in km² and in percentage cover, the weights calculated by using the comparison matrix of the AHP and finally, the weights of all the eight thematic maps calculated by using the AHP process have been indicated suitably

Thematic map	Class No.	Class name	Class value	% Class area	Class area in Km Square	Weight of Class	Weight of Thematic map
Rainfall			mm				214
	1	Low roinfall	350–600	9.10	8654	0.033	
	2	Medium rainfall	600–850	26.96	25,639	0.063	
	3	High rainfall	850–1100	44.22	42,053	0.129	
	4	Very high raindall	1100–1350	15.10	14,360	0.262	
	5	Heavy rainfall	1350–1600	4.70	4470	0.513	
Geom orphology							214
	1	Pediment pediplain complex		0.01	10	0.074	
	2	Older allerial plain		77.78	73,969	0.018	
	3	Older floodplain		13.79	13,114	0.108	
	4	Active flood plain		3.10	2948	0.155	
	5	Pediment alluvial plain		5.40	5135	0.051	
Slope							0.073
	1	Flat		82.90	78,838	0.388	
	2	Gentle		15.56	14,798	0.255	
	3	Very mild		1.50	1427	0.162	
	4	Mild		0.09	76	0.195	
Drainage density			Km/ha				0.021
	1	Very high	0.54–0.60	4.79	4565	0.03	
	2	High	0.60–0.65	57.58	54,797	0.092	
	3	Medium	0.65–0.71	0.15	152	0.092	
	4	Low	0.71–0.76	19.71	18,754	0.142	
	5	Very	0.76–0.87	16.27	15,482	0.223	
	6	Extremely low	0.87–0.98	1.48	1427	0.461	
Lineament density			Km/ha				0.118
	1	Very low	26.36–55	22.43	21,331	0.033	
	2	Low	55–9.71	16.28	15,482	0.063	
	3	Medium	89.71–140.60	15.38	14,626	0.129	
	4	High	140.60–184.42	22.18	21,093	0.262	
	5	Very high	184.42–221	23.72	22,558	0.513	
Lithology							0.073
	1	Quaternary allurium		19.68	18,716	0.513	
	2	Sandy fories		10.53	10,014	0.351	
	3	Clayey facies		69.7	66,370	0.136	
LULC (2011)							0.073
	1	Fores		1.70	1617	0.2	
	2	Agricultural land		87.80	83,498	0.1	
	3	Bult up land		1	95	0.023	
	4	Shrubland		2.40	2282	0.075	
	5	Fallow land		1.89	1797	0.09	
	6	Wasteland		2.10	1997	0.023	
	7	Waterbodies		0.90	856	0.023	
	8	Plantations		0.90	856	0.18	
Ground water			m			0.014	0.214
Fluctuation	1	Very largy fall	(– 0.77) to (– 0.64)	0.29	276		

Table 2 (continued)

Thematic map	Class No.	Class name	Class value	% Class area	Class area in Km Square	Weight of Class	Weight of Thematic map
	2	Large fall	(− 0.64) to (− 0.32)	1.04	989	0.018	
	3	Medium fall	(− 0.52) to (− 0.40)	2.68	2549	0.025	
	4	Significant fall	(− 0.40) to (− 0.27)	11.61	11,041	0.035	
	5	Little fell	(− 0.27) to (0.15)	18.41	17,508	0.044	
	6	Small dip	(− 0.15) to (− 0.00)	28.81	27,398	0.088	
	7	Little jump	(− 0.00) to (0.09)	19.97	18,991	0.11	
	8	Significant rise	(0.09) to (0.21)	11.07	10,528	0.15	
	9	Medium rise	(0.21) to (0.33)	5.26	5002	0.2	
	10	High rise	(0.33) to 0.45	0.83	789	0.3	

The figure highlights that the lineament density is comparatively lower in the upper and lower parts of the basin. This could signify fewer linear features in these regions, which might be due to differences in geological structures, tectonic history, or other factors influencing the distribution of linear features. The significant difference between these two extremes highlights the spatial heterogeneity of the geological and hydrogeological conditions in the Middle Ganga basin. The areas closer to active tectonic boundaries tend to have higher lineament density (221 km/ha) due to the ongoing geological deformation, while regions farther away experience less tectonic stress and consequently lower lineament density (26.35 km/ha). Lineament density is often used as a broad indicator of structural complexity and potential geological activity within a region. It can aid in identifying areas where tectonic forces have been active, which might influence groundwater flow patterns, landscape evolution, and other geological processes.

The lineament density classes ranging from Class 1 (26.36 to 55 km/ha) to Class 5 (184.82 to 221 km/ha) have distinct implications for drainage density, rainfall, and groundwater recharge. Class 1 suggests sparse lineaments, leading to lower drainage density and potentially uniform runoff dispersion. Class 2 features moderate lineament density, contributing to balanced drainage patterns and improved infiltration. Class 3 indicates higher lineament density, resulting in well-defined drainage paths and efficient runoff conveyance. Class 4 showcases substantial lineament density, leading to complex drainage networks and rapid groundwater recharge. Class 5 represents extremely high lineament density, yielding intricate water channel systems and significant groundwater recharge rates. The varying lineament densities within each class range influence the landscape's hydrological behavior, shaping water flow patterns and influencing storage dynamics [25]. The presence of fault lineaments could be connected to the ongoing tectonic activity between the Indian and Eurasian plates. NE and SE alignments of these faults may indicate the primary directions of fault movement, influenced by the stresses from the convergence of the Indian and Eurasian plates along the Himalayan boundary. Join or fracture lineaments could indicate zones where distinct geological formations or units have come together or fractured. In the context of the Himalayas and the Indian-Chinese Plate, these lineaments could represent areas of geologic complexity, potentially associated with the collision and ongoing convergence of the plates.

4.1.3 Land use/land cover

Figure 4c provides an overview of land cover distribution within the study area, offering insights into the various land use categories across the landscape. This information is pivotal for understanding how different parts of the region are utilized and managed for different purposes. The land cover classes include Forest, Agricultural land, built-up land, shrub land, fallow land, wasteland, water bodies, and plantations. The areas covered by these classes, expressed as percentages of the total study area, are as follows: Forest: 1.7%, Agricultural land: 87.8%, Built-up land: 1%, Shrub land: 2.4%, Fallow land: 1.89%, Wasteland: 2.1%, Water bodies: 0.9%, and Plantations: 0.9%.

The presence of Terai forests covering the northern part of the basin is depicted in the Fig. 2. This suggests a relatively dense forest cover in this region, likely owing to the proximity to the foothills of the Himalayas and the suitable climatic conditions for forest growth. The wetlands are shown to be distributed throughout the entire basin. This could indicate the presence of natural depressions or areas with high water availability, resulting in the formation of wetlands that contribute to the overall hydrology and biodiversity of the region. Built-up areas are observed within a context of

surrounding forests and agricultural land. This arrangement signifies a relationship between urban development and the existing natural and cultivated landscapes. The proximity of built-up areas to forests and agricultural land might have implications for land-use planning and potential ecological interactions.

4.1.4 Rainfall map

Figure 4d presents an overview of the precipitation distribution within the study area, highlighting the variation in rainfall across different parts of the landscape. The data is classified into distinct rainfall ranges, and the areas occupied by each range, expressed as percentages of the total study area, are as follows: 350–600 mm: 9.1%, 600–850 mm: 26.96%, 850–1100 mm: 44.22%, 1100–1350 mm: 15.10%, and 1350–1600 mm: 4.7%. The Fig. 4(d) visually illustrates the spatial variation in rainfall across the study area. Each class area corresponds to the proportion of the total study area covered by a specific range of rainfall values. A clear pattern emerges where the rainfall decreases as the distance from the Himalayas increases. This relationship is indicative of the influence of topography on precipitation patterns.

The mountains act as barriers for moist air coming from the Bay of Bengal, causing it to release precipitation on the windward side (facing the mountains) and resulting in drier conditions on the leeward side (away from the mountains) [22, 23]. The highest rainfall values, exceeding 1350 mm, are observed near the Shiwalik hills, which are the foothills of the Himalayas. This area typically receives the most intense rainfall due to orographic lifting, where moist air is forced to rise over the hills, leading to enhanced precipitation. The basin receives around 80% of its annual rainfall during the monsoon season, originating from the Bay of Bengal. Additionally, notable rainfall during winters, attributed to western disturbances, is observed. These disturbances are weather systems that bring moisture from the Mediterranean region, leading to increased precipitation in some areas.

The annual rainfall classes provided—ranging from 350–600 mm to 1350–1600 mm—signify distinct levels of precipitation with implications for drainage density, runoff, and groundwater infiltration. In areas experiencing 350–600 mm of rainfall, drainage density is moderately defined, and runoff is generally mild due to soil absorption. At 600–850 mm, drainage density increases, leading to more significant runoff potential. Rainfall between 850 and 1100 mm triggers high drainage density, intense runoff, and reduced groundwater infiltration. Heavy rainfall of 1100–1350 mm establishes extensive drainage networks, predominant runoff, and compromised infiltration. In regions with 1350–1600 mm, exceptionally high drainage density corresponds to substantial runoff, heightened flood risks, and minimal groundwater infiltration. These relationships reflect the complex interplay between rainfall, landscape characteristics, and hydrological processes, influencing the distribution of water through streams, soil, and aquifers [17, 24, 28].

4.1.5 Slope map

The slope map is created by using the slope tool of ArcGIS and using DEM as the input raster. Figure 4e provides insight into the topography of the middle Ganga basin, showcasing the variation in slope across different parts of the landscape. The data is categorized into distinct slope classes, and the areas occupied by each range, expressed as percentages of the total study area, are as follows: 0–1 degrees: 82.90%, 1–2 degrees: 15.56%, 2–3 degrees: 1.5%, and 3–7 degrees: 0.15%. The figure visually conveys the spatial variation in slope across the study area. Each class area represents the proportion of the total study area covered by a specific range of slope values.

A discernible pattern emerges where the slope decreases as the distance from the Himalayas increases. This aligns with the general topographical trend in mountainous regions, where the steepest slopes are closer to the mountain range, and the terrain gradually becomes flatter as you move away from the mountains. The elevation of the study area is described, ranging from 519 m in the north to 36 m in the south. This elevation variation is likely to contribute to the observed slope patterns. The higher elevations in the north, closer to the Himalayas, likely contribute to steeper slopes, while the lower elevations in the south are associated with flatter terrain.

The varying slope conditions in the middle Ganga basin create diverse hydrological environments. Flat terrains can act as potential water storage areas, whereas low to moderate slopes enhance infiltration and groundwater recharge [24, 28]. Steeper slopes, although promoting quicker runoff, can still play a role in recharge if managed sustainably. It's important to consider the relationship between slope, land cover, soil characteristics, and vegetation to fully understand the impact on groundwater recharge potential across the region.

4.1.6 Groundwater fluctuation (GWF)

Figure 4f provides insights into the GWF across the study area, illustrating how water levels change over time in different parts of the landscape. The data is classified into distinct GWF classes, and the areas occupied by each range, expressed as percentages of the total study area, are as follows: -0.77 to -0.64 m: 0.29%, -0.64 to -0.52 m: 1%, -0.52 to -0.4 m: 2.68%, -0.4 to -0.27 m: 11.61%, -0.27 to -0.15 m: 18.41%, -0.15 to 0 m: 28.81%, 0 to 0.09 m: 19.97%, 0.09 to 0.21 m: 11%, 0.21 to 0.33 m: 5.26%, and 0.33 to 0.45 m: 0.83%.

The figure visually represents the spatial variation in groundwater fluctuation across the study area. Each class area indicates the proportion of the total study area affected by a specific range of groundwater level change. The northern Terai region experiences a rise in GWF, as evidenced by the presence of positive values in the GWF classes. This suggests that groundwater levels are increasing over time in this area. The rise in GWF might be attributed to factors such as higher recharge from precipitation, favorable hydrogeological conditions, and potential proximity to water sources from the Himalayas. Conversely, the southern part of the basin sees a fall in groundwater fluctuation, evident in the presence of negative values in the GWF classes. This indicates that groundwater levels are declining in this region. The fall in GWF could be related to factors like excessive groundwater extraction, lower recharge rates, and potential aquifer depletion.

4.1.7 Lithology

Figure 4g provides insights into the sediment distribution across the study area, highlighting the composition of different sediment types in different parts of the landscape. The data is categorized into distinct sediment classes, and the areas occupied by each type, expressed as percentages of the total study area, are as follows: Alluvium: 19.68%, Sandy facies: 10.53%, and Clayey facies: 69.79%. The figure visually conveys the spatial distribution of sediment types across the study area. Each class area represents the proportion of the total study area covered by a specific sediment type.

The presence of Alluvium and Sandy facies predominantly in the northern parts of the basin is observed. This suggests that these sediment types are more prevalent in the areas closer to the Himalayas. Alluvium, in particular, is commonly associated with river deposits, often found in floodplains and areas influenced by river dynamics. majority of the study area is occupied by Clayey facies, constituting nearly 70% of the total area. This sediment type likely indicates fine-grained deposits, which can be associated with slower water movement, lower energy environments, and potentially older geological formations.

4.1.8 Lineament map

Figure 4h depicts different types of lineaments within the study area and their directional alignment, specifically in the northeast (NE) and southeast (SE) directions. The lineament types include Drainage parallel, break-in slope, fault, and Join/Fracture. In the Himalayas, lineaments running parallel to drainage patterns could be shaped by tectonic and geomorphic processes associated with the Himalayan uplift. The NE and SE alignments of these lineaments may correspond to the compressional forces resulting from the collision between the Indian and Eurasian plates, influencing drainage alignment.

Break-in slope lineaments in the Himalayas often indicate abrupt topographic changes that could be linked to faults or fractures resulting from tectonic activity. The NE and SE orientations of these lineaments might reflect the dominant stress directions exerted on the landscape due to plate tectonics. Fault lineaments signify fractures in the Earth's crust where movement has occurred.

Lineaments are geological features that can act as preferential pathways for groundwater movement, influencing the direction and speed of subsurface water flow. In areas where lineaments intersect with recharge sites, there is a heightened likelihood of increased groundwater recharge. These intersecting points could facilitate greater infiltration and movement of water through the subsurface, effectively enhancing the recharge potential of the groundwater system. Lineaments can serve as conduits for the rapid movement of water, potentially bypassing recharge sites and leading to reduced opportunities for water infiltration and recharge.

4.1.9 Geomorphology

Figure 4i provides insights into the geomorphological features across the study area, highlighting different landforms and their distribution. The data is categorized into distinct classes representing various geomorphological features, and the areas occupied by each feature, expressed as percentages of the total study area, are as follows: Pediment Pediplain

complex: 0.1%, Older Alluvial plain: 77.78%, Older flood plain: 13.79%, Active flood plain: 3.1%, and Pediment alluvial plain: 5.4%. The presence of a Pediment Pediplain complex indicates a particular type of landform where a gently sloping surface forms between the base of the hills and the adjacent plains. This landform often results from the erosion of rocks from the hills and their deposition on the adjacent plains. The Shiwalik hills could contribute to the materials that form these pediments, and the complex could be influenced by the dynamics of the sediment transport and erosion from the hills.

The significant occupation of the Older Alluvial plain class, suggests that these plains have been formed over an extended period through the deposition of sediments carried by rivers. The Shiwalik hills could play a role in providing the source of sediments that contribute to the formation and gradual expansion of these older alluvial plains. The presence of both Older and Active flood plain classes indicates areas that experience floodplain deposition. These areas could be influenced by the periodic flooding of rivers originating in the Shiwalik hills. The hills might contribute to increased sediment load during floods, leading to the deposition of sediments and the formation of flood plains. The presence of Pediment alluvial plain class signifies a landform that lies between the hills and the adjacent plains, characterized by sediment deposition from the hills. The presence of such a class highlights the interaction between the hills and the adjacent plains in terms of sediment transport and deposition.

4.1.10 DEM map

In Fig. 4j, the Digital Elevation Model (DEM) provides a representation of the elevation variation across the study area, illustrating how elevation changes in relation to distance from the Himalayas. The DEM values vary from 519 to 36 m, with a consistent decrease in elevation as one moves away from the Himalayan region. As one approaches the Himalayas, the land begins to rise significantly due to the tectonic uplift and the presence of high peaks and ranges. These elevations are typical of the foothills and the lower slopes of the mountains. The lower DEM values, such as the 36-m elevation, correspond to relatively flat and low-lying areas, which are often found away from mountainous regions. These plains and lowlands are usually characterized by more gradual elevation changes and are the result of sediment deposition over geological time.

4.1.11 Drainage network

The presence of stream orders 1, 2, and 3 in Fig. 4k with respect to elevation and slope:

1. **Stream Order 1 and Elevation:** Stream order 1 channels are typically found at higher elevations. These smaller streams often originate from springs, runoff, or minor depressions in the landscape. In the context of the study area, these stream order 1 channels are likely to emerge from the elevated regions, such as the Himalayas. The higher elevations provide the necessary gradient for water to flow downhill, initiating the formation of these smaller channels. The presence of stream order 1 channels in Fig. 4l signifies the widespread distribution of these small streams in the elevated areas.
2. **Stream Order 2 and Confluence Zones:** Stream order 2 channels result from the merging of multiple stream order 1 channels. These converging points typically occur in areas where slopes become gentler, and water from different directions comes together. In the study area, these stream order 2 channels might be observed as watercourses that have collected flow from smaller, order 1 channels. The confluence zones of these smaller channels contribute to the formation of slightly larger and more well-defined drainage paths.
3. **Stream Order 3 and Main Drainage Paths:** Stream order 3 channels represent the merging of stream order 2 channels or combinations of stream order 2 and 1 channels. These channels tend to be larger and more significant in terms of water flow. In the context of elevation and slope, stream order 3 channels often follow the main valleys and lowlands, where the terrain is more gradual and the slope is less steep. The convergence of multiple stream order 2 channels in these areas leads to the formation of well-defined and more substantial drainage paths.

4.2 Groundwater recharge potential zone (GWRPZ)

Figure 4l integrates information from eight thematic maps to generate the Groundwater Recharge Zone Map. Thematic maps cover factors like drainage density, lineament density, LULC, rainfall, slope, GWF, lithology, and geomorphology. AHP-assigned weights for these maps are: Drainage Density: 0.021, Lineament Density: 0.118, LULC:

Table 3 Matrix of relative importance for rainfall map classes

	Low	Medium	High	Very high	Heavy
Low	1	0.524	0.256	0.126	0.064
Medium	1.909	1	0.488	0.240	0.123
High	3.906	2.049	1	0.493	0.252
Very high	7.634	4.167	2.029	1	0.510
Heavy	15.847	8.197	3.968	1.961	1

Table 4 Matrix of relative importance for geomorphology map classes

	Pediment pediplain complex	Older allerial plain	Older floodplain	Active flood plain	Pediment alluvial plain
Pediment pediplain complex	1	4.111	0.685	0.477	0.115
Older allerial plain	0.243	1	0.167,	0.116	0.028
Older floodplain	1.460	6.000	1	0.697	0.168
Active flood plain	2.097	8.611	1	1	0.240
Pediment alluvial plain	8.716	35.833,	5972	4.161	1

Table 5 Matrix of relative importance for slope map classes

	Flat	Gentle	Very mild	Mild
Flat	1	1.522	2.395	1.989
Gentle	0.656	1	1.574	1.308
Very mild	0.417	0.636	1	0.831
Mild	1.988	1.306	0.832	1

Table 6 Matrix of relative importance for drainage density map classes

	Very high	High	Medium	Low	Very	Extremely low
Very high	1	0.326	0.326	0.211	0.134	0.065
High	3.077	1	1	0.648	0.413	0.200
Medium	3.077	1	1	0.648	0.413	0.200
Low	4.739	1.543	1.543	1	0.637,	0.308
Very	7.463	2.424	2.424	1.569	1	0.484
Extremely low	15.384	5.011	5.011	3.247	2.065	1.000

Table 7 Matrix of relative importance for lineament density map classes

	Very low	Low	Medium	High	Very high
Very low	1	0.524	0.256	0.126	0.064
Low	1.909	1	0.488	0.240	0.123
Medium	3.906	2.049	1	0.493	0.252
High	7.634	4.167	2.029	1	0.510
Very high	15.847	8.197	3.968	1.961	1

0.073, Rainfall: 0.214, Slope: 0.073, GWF: 0.214, Lithology: 0.073, Geomorphology: 0.214. The resulting Groundwater Recharge Zone Map displays Groundwater Recharge Potential Index (GWRPI) values ranging from 0.309 to 0.071. These values indicate varying potentials for groundwater recharge within the study area.

Thematic map integration using AHP weights enables a holistic evaluation of groundwater recharge potential. Each map contributes insights into environmental/geographical factors influencing recharge, with assigned weights

Table 8 Matrix of relative importance for lithology map classes

	Quaternary alluvium	Sandy facies	Clayey facies
Quaternary alluvium	1	1.461	3.773
Sandy facies	0.513	1	2.580
Clayey facies	0.513	2.849	1

Table 9 Matrix of relative importance for LULC map classes

	Forest	Agricultural land	Bult up land	Shrubland	Fallow land	Wasteland	Waterbodies	Plantations
Forest	1	2	8.696	2.667	2.222	8.696	8.696	1.111
Agricultural land	0.5	1	4.348	1.333	1.111	4.348	4.348	0.556
Bult up land	0.115	0.229	1	0.307	0.256	1	1	0.128
Shrubland	0.375	0.75	3.261	1	0.833	3.261	3.261	0.417
Fallow land	0.45	0.9	3.913	1.2	1	3.913	3.913	0.5
Wasteland	0.115	0.229	1	0.307	0.256	1	1	0.128
Waterbodies	0.115	0.229	1	0.307	0.256	1	1	0.128
Plantations	0.9	1.8	7.826	2.4	2	7.826	7.826	1

Table 10 Matrix of relative importance for GWF map classes

	Very large fall	Large fall	Medium fall	Significant fall	Little fall	Small dip	Little jump	Significant rise	Medium rise	High rise
Very Large Fall	1	0.778	0.56	0.4	0.318	0.159	0.127	0.093	0.07	0.047
Large Fall	1.286	1	0.72	0.514	0.409	0.205	0.164	0.12	0.09	0.06
Medium Fall	1.786	1.389	1	0.714	0.568	0.284	0.227	0.167	0.125	0.083
Significant Fall	2.5	1.944	1.4	1	0.795	0.398	0.318	0.233	0.175	0.117
Little Fell	3.125	2.438	1.75	1.26	1	0.5	0.4	0.293	0.22	0.147
Small Dip	6.25	4.875	3.5	2.5	2	1	0.8	0.587	0.44	0.293
Little Jump	7.875	6.125	4.375	3.125	2.5	1.25	1	0.733	0.55	0.367
Significant Rise	10.75	8.375	5.975	4.25	3.4	1.7	1.36	1	0.75	0.5
Medium Rise	14.286	11.111	7.036	5.682	4.524	2.262	1.81	1.333	1	0.667
High Rise	20.213	15.717	11.226	8.018	6.414	3.207	2.565	1.889	1.417	1

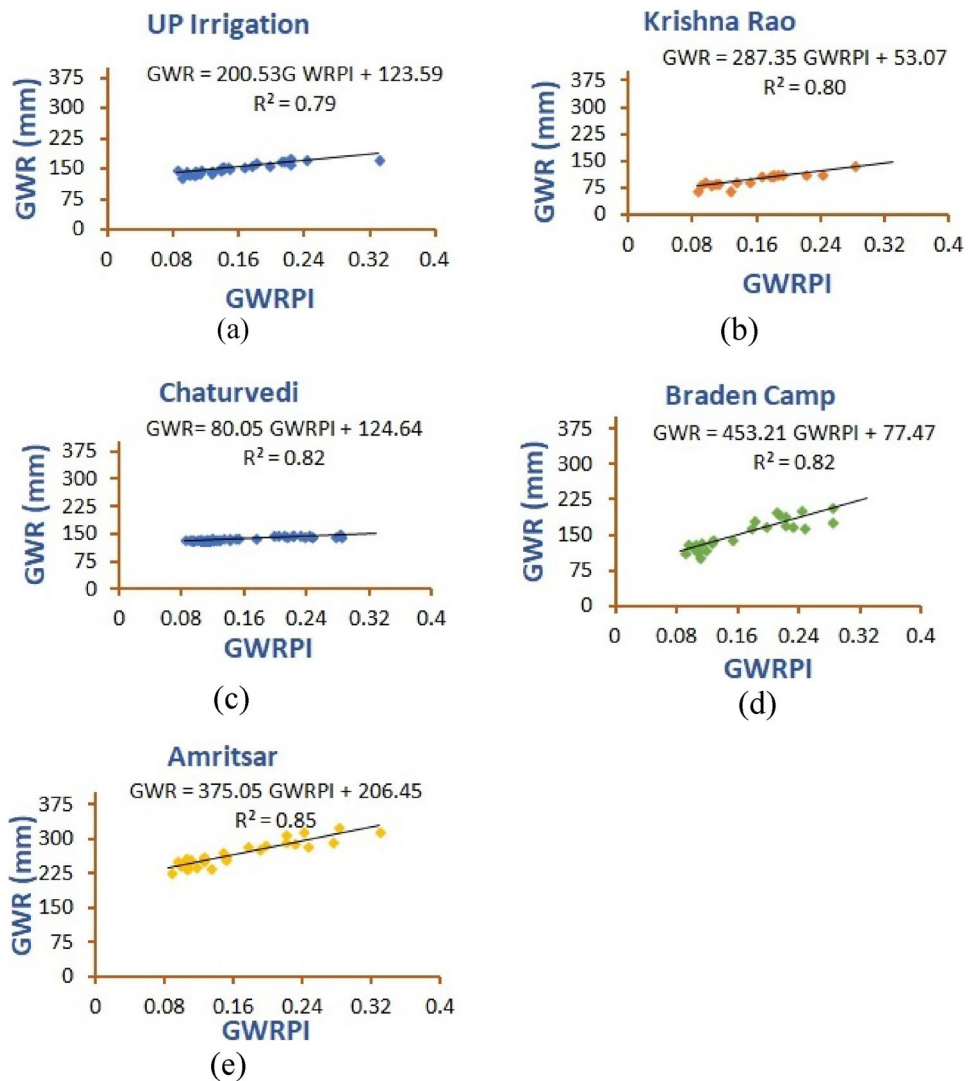
Table 11 Matrix of relative importance for making GWRPZ map from the eight thematic maps

	Rainfall	Geomorphology	Slope	Drainage density	Lineament density	Lithology	LULC (2011)	Ground water fluctuation
Rainfall	1	1	2.93	10.19	1.81	2.93	2.93	1
Geomorphology	1	1	2.93	10.19	1.81	2.93	2.93	1
Slope	0.34	0.34	1	3.48	0.62	1	1	0.34
Drainage density	0.1	0.1	0.29	1	0.18	0.29	0.29	0.1
Lineament density	0.55	0.55	1.61	5.55	1	1.61	1.61	0.55
Lithology	0.34	0.34	1	3.48	0.62	1	1	0.34
LULC (2011)	0.34	0.34	1	3.48	0.62	1	1	0.34
Ground Water	1	1	2.93	10.19	1.81	2.93	2.93	1

Table 12 Consistency index of eight thematic maps and final GWRPZ produced

Thematic map	Consistency Index (CI)
Rainfall	0.093
Geomorphology	0.038
Slope	0.006
Drainage density	0.064
Lineament density	0.032
Lithology	0.018
LULC (2011)	0.051
Ground Water	0.193
GWRPZ	0.117

Fig. 5 Linear relationship between the quantity of ground recharge (inch) and groundwater recharge potential index (GWRPI) of the study area. The various formulas used to calculate the GWR are the UP Irrigation Board formula in (a), Krishna Rao formula in (b), Chaturvedi formula in (c), Braden-Camp formula in (d) and Amritsar formula in (e)



reflecting their relative importance. The GWRPZ map illustrates spatial distribution of recharge zones, revealing areas with diverse recharge potentials. GWRPI values are categorized into distinct classes, representing different ranges of recharge potential: 0.309–0.247, 0.247–0.206, 0.206–0.177, 0.177–0.158, 0.158–0.145, 0.145–0.132, 0.132–0.119, 0.119–0.103, and 0.103–0.071. Two trends are observed in GWRPI values. First, GWRPI values decrease from NE to SW,

implying higher recharge potential in NE. Elevation, precipitation, geology, and land use practices might contribute to this trend. Second, GWRPI values decrease from NW to SE, indicating higher recharge potential in NW.

These two observed trends in GWRPI values align with the broader geological and hydrological patterns in the study area. The intricate interplay of geological, topographical, climatic, and anthropogenic factors contribute to the spatial distribution of groundwater recharge potential. The variations in GWRPI values reflect the complex nature of groundwater recharge processes and highlight the significance of considering multiple influencing factors when assessing groundwater resources. The AHP process gave the relative importance matrices from Table 3, 4, 5, 6, 7, 8, 9, 10 and 11. These tables provide the relative importance of all the eight maps. The CI of all eight maps and that of GWEPZ map has been provided in the Table 12.

4.3 Validation of GWRPZ

Figure 5 presents a linear relationship between the quantity of groundwater recharge (in inches) and the GWRPI for the study area. The figure also displays various formulas used to calculate GWR based on specific methods: UP Irrigation Board formula in (A), Krishna Rao formula in (B), Chaturvedi formula in (C), Braden-Camp formula in (D), and Amritsar formula in (E). Additionally, regression equations are provided to express the relationship between GWRPI and GWR for each formula.

The coefficient of determination (R^2) obtained for these equations are 0.79, 0.80, 0.82, 0.82, and 0.85 respectively. These R^2 values indicate how well the linear regression lines fit the data points. A higher R^2 value suggests a stronger correlation between the GWRPI and GWR as predicted by the formula. These equations establish a quantitative relationship between the GWRPI, which represents the groundwater recharge potential, and the calculated GWR based on different formulas. They provide a way to estimate the expected groundwater recharge quantity using the GWRPI values.

The coefficient (slope) in each equation indicates the rate of change in GWR with respect to changes in GWRPI. For example, in the UP Irrigation Board formula (A), a unit increase in GWRPI is associated with an increase in GWR by approximately 200.53 inches. The intercept term in each equation represents the baseline value of GWR when GWRPI is zero. It accounts for factors other than GWRPI that might influence groundwater recharge.

The equations for different formulas show variations in coefficients and intercepts, reflecting the differences in the methodologies of these formulas. The formulas based on the Krishna Rao, Chaturvedi, and Braden-Camp methods show relatively higher coefficients than the UP Irrigation Board and Amritsar formulas. This indicates a steeper slope of the regression line, suggesting a stronger relationship between GWRPI and GWR in these cases. The Amritsar formula has the highest coefficient of determination (0.85), implying a relatively better fit of the linear regression model to the data for this particular formula. This indicates a higher level of correlation between GWRPI and GWR. The analysis with these regression equations and their corresponding R^2 values serves as a validation approach for the obtained GWRPZ shown in Fig. 4L. The high R -squared values indicate that the GWRPI, as derived from the integration of multiple thematic maps and assigned AHP weights, correlates well with the calculated groundwater recharge.

The positive relationship between GWRPI and calculated GWR reinforces the notion that areas with higher GWRPI values have a higher potential for groundwater recharge, as validated by the calculated GWR using different established methods.

5 Discussion

The AHP weight of 0.214 assigned to the rainfall thematic map accentuates the pivotal role of rainfall in the groundwater recharge [10]. Inside the rainfall map, the class "Heavy rainfall" (1350–1600 mm) carries the highest weight (0.513) because of more groundwater recharge in this region. Additionally, the class "Low rainfall" (350–600 mm) is endowed with a weight of 0.033, suggesting low groundwater recharge in this area.

The weight of geomorphology thematic map is equal to that of rainfall is (i.e., 0.214). Geomorphology of the Ganga basin defines the flow of surface runoff, and rate of infiltration that is highly important in groundwater recharge. Among the various classes within geomorphology, the class "Older flood plain" and "Active flood plains" stands out with a weight of 0.108 and 0.155 respectively. This pronounced weight accentuates the significance attributed to these alluvial plains, highlighting their role in easy infiltration of water into the ground [29], thereby bolstering groundwater recharge. The slope map is endowed with a weight of 0.073, a weight that is relatively diminished when compared to rainfall and geomorphology.

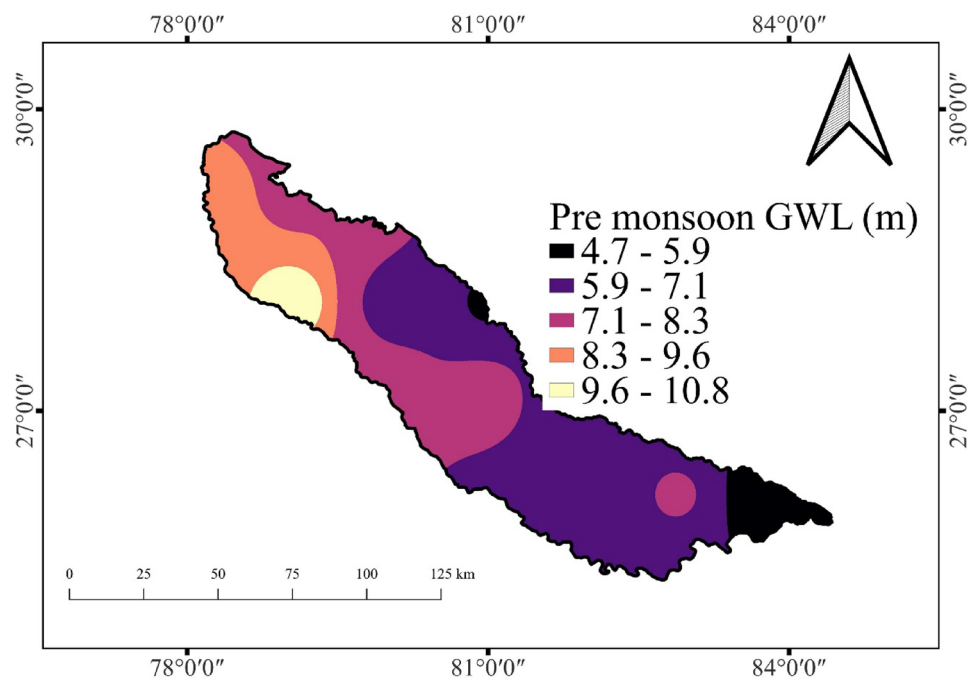
This is feasible because most of the study area is flat, and steep ground is found in very less portion of the middle Ganga basin. Of the various classes, "Flat" surfaces claim the highest weight (0.388). This pronounced weight echoes the substantial role of flat terrains in enhancing water infiltration and supporting groundwater recharge [17, 24, 28]. Such a preference logically resonates with the hydrological principle that flatter surfaces are more conducive to groundwater replenishment. Within the hierarchy of AHP weights, the drainage density map garners the lowest weight of 0.021, indicating its relatively minor role in comparison to other factors. This is because of the flat topography of the basin. Even if the drainage density is high, longer time period of surface water accumulation will lead to significant groundwater recharge. The class "Very high drainage density" commands the lowest weight (0.03), and the highest weight is assigned to "Extremely low drainage density" (0.462). These weights underscore the contrasting preferences for areas exhibiting either high or low drainage densities, indicating the varying permeability of soil in the basin [17, 24, 28].

The lineament density map emerges as a moderately significant factor, assigned a weight of 0.118. The classes have been assigned weights from 0.033 to 0.513 for very low lineament density to very high lineament density.

The lineament density must be assigned a moderate weight because of the alluvial nature of the basin. However, considering the groundwater recharge property of the basin, it has been assigned a higher weight than the other bottom classes. The lithology map is assigned a weight of 0.073 within the AHP analysis, indicating its least importance. This is again due to the lower runoff speed due to flatter terrain in most of the basin. However, due to variations in the lithological characteristics of the basin, a high possibility of differential rate of groundwater infiltration exists in the basin. This is the reason of consideration of this factor in our study. Among the lithological classes, "Quaternary alluvium" holds the highest weight (0.513), signifying its substantial influence on groundwater recharge due to its porous and permeable nature. This class is pivotal in allowing water movement and infiltration, enhancing recharge potential. "Sandy facies" follows with a weight of 0.287, reflecting its contribution to facilitating groundwater flow and recharge, albeit to a lesser extent compared to alluvium. Lastly, "Clayey facies" is assigned a weight of 0.2, indicating its relatively lower contribution to recharge due to its lower permeability, which can hinder water movement.

Within the AHP framework, the LULC thematic map holds a weight of 0.073, signifying a lower importance amongst all the other factors. Among the classes within this map, "Agricultural land" claims the highest weight (0.878), highlighting its dominant influence on recharge potential. "Forest" also plays a role with a weight of 0.017, because the aquifers in the forests may never be used for groundwater extraction. Also, the forested regions already have much higher groundwater recharge potential. This can be seen that the relative importance has been assigned not just on the basis of the groundwater recharge potential but the probability of groundwater extraction. Classes like "Built up land", "Shrubland", "Fallow land", "Wasteland", "Waterbodies", and "Plantations" each contribute with varying weights, reflecting their respective roles in recharge potential. The built-up area is not permeable for the runoff infiltration. The wasteland

Fig. 6 The pre monsoon groundwater level (GWL) of the middle Ganga basin average from 1998 to 2018



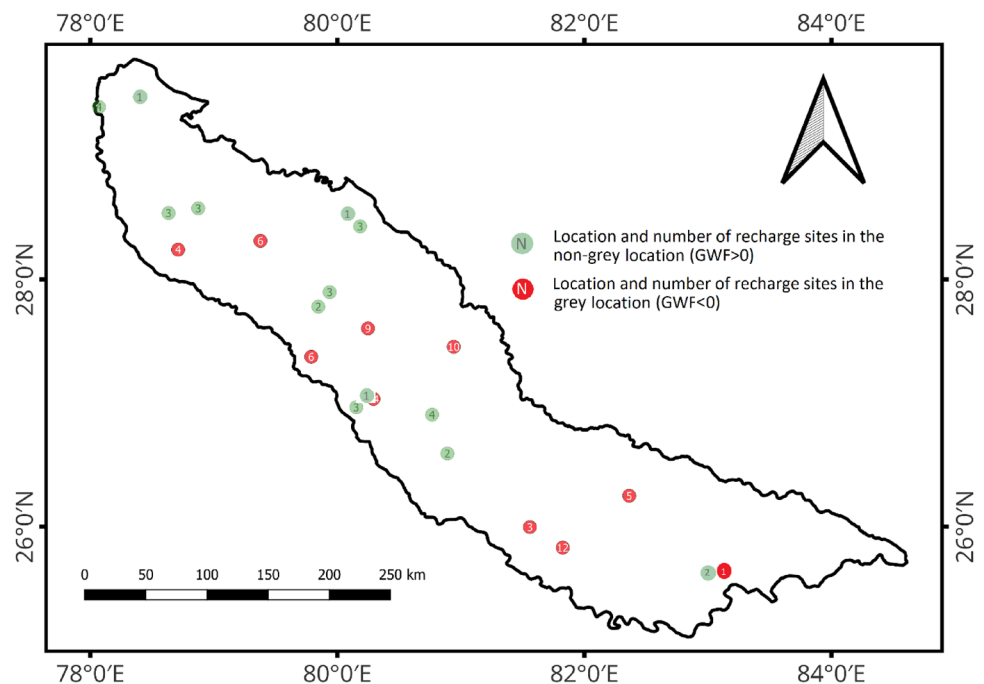
will deteriorate the quality of the water. Other classes cover highly insignificant portion of the basin. The GWF thematic map carries a significant weight of 0.214, underscoring its importance in understanding groundwater dynamics and recharge potential. Among the GWF classes, "Small Dip" (-0.15 to -0.00) has the highest weight (0.2881), signifying its substantial influence on recharge. The groundwater level rise means ample percolation of water into the aquifers. While the groundwater falls means reduction in the groundwater. The groundwater level map before the monsoon is also shown in the Fig. 6. This Fig. 6 has taken into consideration the average of all the GWL from 1998 to 2018. The effect of different discharges in the aquifers over a long time period is visible in it. This figure shows that the groundwater level from below ground level (bgl) is higher in the northeastern basin (near Terai) where the groundwater levels are very high. However, the western portion (Fig. 6) shows quite lower levels of groundwater level (bgl). The southern portion shows the lowest groundwater levels (bgl). This is in accordance with the groundwater recharge potential zone map created in Fig. 4.

The drainage density is intricately tied to the basin's rainfall pattern. High-intensity rainfall events, especially on flat terrains, can lead to increased surface runoff due to limited opportunities for water infiltration [17, 24, 28]. The variations in drainage density across the basin reflect these meteorological responses. This relationship between drainage density, rainfall, and runoff potential underscores the role of topography in shaping the basin's hydrological dynamics. Areas with steeper slopes, characterized by higher elevations, often experience greater surface runoff due to reduced infiltration capacity. This phenomenon accentuates the correlation between topography, slope, and drainage density. Relating these factors to rainfall and groundwater recharge potential adds depth to the understanding of the basin's hydrological processes. Moreover, the influence of lithology, such as alluvium, sandy, and clayey formations, further modulates these interactions. Alluvial plains, which are conducive to surface runoff, can contribute to higher drainage density, whereas clayey areas might have lower drainage density due to reduced runoff potential.

Floodplains often possess a higher potential for groundwater recharge due to their relatively flat topography and slower flow velocities. These characteristics allow for increased water retention and longer retention times, promoting greater opportunities for infiltration and groundwater replenishment. Comparing all these interconnected factors—rainfall, topography, slope, DEM variation, drainage density, lithology, and geomorphology, the intricate web of interactions can be understood that shape the hydrological behavior of the study area. Understanding these relationships is paramount for effective water resource management and planning in the region.

Figure 7 depicts the classification of recharge sites based on their respective categories within grey and non-grey zones. The graphical representation showcases dot corresponding to each category, with the total number of sites in each category being the sum of the numbers within the dots. The grey zone encompasses areas with low recharge potential and negative groundwater fluctuation, while the non-grey zone comprises areas with high recharge potential and positive groundwater fluctuation. The total count of recharge sites amounts to 92, divided into two categories: 62

Fig. 7 Classification of recharge sites as per its category in grey and non grey zones. The total number of sites can be calculated in each category by adding the numbers in the dots. The grey zone has been defined as the one which has low recharge potential and negative groundwater fluctuation. The non-grey zone has been defined as the one which has high recharge potential and positive groundwater fluctuation



in the grey zone and 30 in the non-grey zone. It is important to note that these sites are strategically situated along the third-order streams, highlighting their direct relationship with the hydrological network. By segregating the sites into grey and non-grey zones, this approach furnishes insightful understanding regarding the interplay between recharge potential and groundwater fluctuations. Some of these sites can be present on lineaments also, that can help swift recharge of aquifers.

On the other hand, approaches like fuzzy logic and Boolean might submit to inflexible predetermined guidelines and arbitrary cutoff points, which could result in results that are too vague and subjective. A striking facet distinguishing this study is the conscientious incorporation of an extensive array of classes encompassing factors that profoundly impact groundwater recharge. The dexterous curation of a comprehensive inventory of factors, subject to rigorous empirical investigation to glean their relative significance, stands as a testament to the profound rigor underpinning this undertaking. Such an assiduous approach lays bare the intricate interplay of diverse hydrological facets and their nuanced contributions to the mercurial realm of groundwater recharge potential. To summarize, the skillful application of AHP in this groundbreaking investigation leaves the evaluation of groundwater recharge potential with a higher level of analytical ability and decision-making effectiveness. The methodical and professional features of AHP provide reassurance when assessing the significant impact of theme maps on this complex procedure. Moreover, the empirical pursuit of diverse factors and their relative importance unfurls the tapestry of accuracy and comprehensiveness, amplifying the significance of this research endeavor. As such, it provides a wealth of information to the field of groundwater studies, expanding our knowledge of the mysterious groundwater recharge dynamics in the middle Ganga basin.

By assigning weights to each raster using AHP, the analysis ensures a consistent and meaningful interpretation of importance across all levels while establishing relative significance within the layer. This pivotal aspect enhances the robustness and reliability of the results, ensuring that the weighted overlay analysis criteria can effectively capture the varying influences of different factors on groundwater recharge potential. Unlike previous traditional studies, this research is able to strategically connect high rainfall areas with high lineaments, in contrast to low drainage and no built-up areas, thanks to the unique combination of AHP and weighted overlay analysis. This discerning integration facilitates the creation of accurate groundwater recharge potential zones, affording a lucid understanding of the interplay between diverse hydrological factors. This study stands out due to its logical and organized ranking of the variables influencing groundwater recharge, which gives it an unmatched ability to understand the complexities of groundwater dynamics. This level of sophistication and precision elevates the significance of the research, fostering deeper insights into the intricate groundwater recharge processes in the middle Ganga basin.

The groundwater recharge potential's geographical distribution throughout the study area is comprehensively represented by the GWRPZ. This integration of diverse parameters and their respective weights ensures a holistic evaluation of the factors affecting groundwater recharge potential, enabling a deeper understanding of the intricate interplay between geological, hydrological, and land-use attributes. As a fundamental part of the GWRPZ analysis as a whole, the GWRPI is important for determining the region's potential for groundwater recharge. Through the integration of several parameters and their respective contributions, the GWRPI offers significant insights into regions possessing greater or lesser potential for recharge. This knowledge is invaluable for decision-makers, water resource managers, and stakeholders, as it enables them to identify regions with optimal recharge capabilities, as well as areas that may require intervention or conservation efforts to enhance groundwater recharge. Consequently, the GWRPI facilitates evidence-based decision-making and contributes to sustainable water resource management practices in the context of groundwater recharge dynamics.

The State Government of Uttar Pradesh and the Central Government have taken up several targeted missions for water resource development, augmentation, conservation, and public awareness. (Note: The Cost is given in Indian Rupees (Rs.). Rs. 1000 crore = Rs. 10 billion). Atal Bhujal Yojana (Total Budget: Rs 6000 crores): This is a Central Government funded scheme that aims to improve groundwater management through community participation and management. The scheme envisages people's participation through the formation of water budgets, the preparation and implementation of Gram-panchayat-wise water security plans, etc. [30, 31]. Jal Jeevan Mission (Budget: 3,60,000 crores): This is a central government scheme launched in 2019 with a total estimated cost of Rs 3.6 lakh crores for a period of 5 years (2019–2024). Jointly with the Central funds and the State Government fund, the State Departments are implementing this mission for the renovation, rejuvenation, and development of water bodies, the construction of rainwater harvesting structures, check dams, weirs, and other similar structures to conserve surface runoff and recharge groundwater. In the mission, GIS & RS data are extensively used, and field-related data on groundwater levels and water quality are also being analysed [32, 33]. Khet Talab Yojana: This is a State Government scheme that aims to rejuvenate traditional water bodies like tanks and ponds to enhance the water storage capacity in rural areas.

Under the scheme, the State Government provides 50% subsidy to the farmers for developing water harvesting structures [34]. Mission Amrit Saroar (Total Budget (Central + State Government): Approx Rs 3,00,000 crores): The mission's goal is to revitalize and improve 75 water bodies in every district of the nation in honor of Azadi ka Amrit Mahotsav, which commemorates 75 years of Indian independence [35]. Mukhyamantri Jal Bachao Abhiyan: This scheme aims to create awareness among the people about the importance of water conservation and encourage them to adopt water-saving practises. The mission is also targeted for the rejuvenation of village ponds [36].

Namami Gange Programme (Budget: 20,000 crores): This is a central government flagship programme developed and implemented for abatement of pollution, conservation, and rejuvenation of the National River Ganga and its tributaries. Among the program's main goals are pollution management, cleaning the surface of rivers, riverfront development, monitoring industrial effluent, afforestation, raising public awareness, maintaining the environment, etc. [37]. National Plan for Conservation of Aquatic Eco-systems: This program is for the conservation of wetlands and lakes, and is promoted by the Ministry of Environment, Forest and Climate Change (MoEFCC) [38]. Pradhan Mantri Krishi Sinchai Yojana-Har Khet ko Paani (PMKSY-HKPP): This is a Central Government funded scheme developed to improve irrigation efficiency in agriculture through the promotion of micro-irrigation, the construction of check dams, and other similar structures for agriculture sustainability with the vision of 'per drop, more crop' [39]. Rural Water Supply and Sanitation Project: This is a part of the National Rural Drinking Water Program initiated with a total fund of Rs 3000 crores with the objective of providing water security for all [40].

5.1 Other projects

National Hydrology Project (Rs 3680 crores): This project aims to improve the water resource management in the country by enhancing the availability, accessibility, and quality of hydro-meteorological data. National Rural Drinking Water Mission (2019–2022) Budget: Rupees 70,000 crores. This program aims to provide safe drinking water to the rural population, including the state of Uttar Pradesh. The above schemes reflect the state government's commitment to the conservation and management of water resources through the construction of check dams and other similar structures.

While this study has offered valuable insights into groundwater recharge potential, several avenues for further research and exploration emerge:

1. Temporal analysis: Conducting a temporal analysis of groundwater recharge potential and fluctuation patterns can reveal seasonal variations and long-term trends that might impact recharge zones differently over time.
2. Validation and ground truthing: The results obtained from this study could be validated through field measurements and groundwater level monitoring to confirm the accuracy of the modeled recharge potential.
3. Climate change impact: Investigating how changing climate conditions might influence groundwater recharge potential and whether the current classification holds under different climate scenarios.
4. Hydrological modeling: Utilizing hydrological modeling techniques could provide a dynamic perspective on groundwater recharge potential by incorporating factors such as soil properties, evapotranspiration, and land cover changes.
5. Social and economic implications: Extending the analysis to incorporate socioeconomic factors could offer insights into the impacts of human activities and land use on groundwater recharge, as well as identifying areas where intervention might be needed.
6. Policy formulation: The study outcomes could inform policy decisions and groundwater management plans, promoting sustainable utilization and protection of groundwater resources.
7. Spatial Expansion: Expanding the study area to encompass neighboring regions could provide a broader understanding of regional variations in groundwater recharge potential and facilitate more holistic resource management strategies.

In conclusion, this study serves as a stepping stone for deeper research into groundwater recharge potential assessment. The comprehensive approach and AHP-based weighting system provide a solid foundation for future investigations, policy formulation, and sustainable water resource management practices.

6 Conclusion

This study has conducted a thorough and exhaustive analysis to assess the Groundwater Recharge Potential Index (GWRPI) in the middle Ganga basin. For this purpose, eight thematic maps were created: rainfall, geomorphology, Land use Land cover (LULC), drainage density, lineament density, slope, lithology, and Groundwater Fluctuation (GWF). Through the implementation of the Analytic Hierarchy Process (AHP), various thematic maps have been integrated, yielding invaluable insights into both the GWRPI and the key factors that influence it. Remarkably, the outcomes of this investigation underscore the paramount significance of three fundamental factors in determining groundwater recharge potential. Specifically, the study reveals that rainfall, geomorphology (with a notable emphasis on older alluvial plains), and groundwater fluctuation (GWL rise or fall) collectively wield the most substantial influence, as reflected in their highest calculated normalized weight of 0.213. Conversely, other factors, while not negligible, have been accorded relatively lower weights due to the unique characteristics of the Middle Ganga Basin. The soil's permeable nature and the predominantly flat terrain have led to minimal consideration of drainage density and slope in the analysis. Similarly, LULC has been assigned relatively lower weights, considering the dominance of categories such as Agriculture and Forests.

The delineation of artificial groundwater recharge sites into grey zones, indicating low recharge potential with a negative GWF, and non-grey zones, indicating high recharge potential with a positive GWF, provides a nuanced understanding of the meteorological and hydrogeological parameters at play. The rigorous application of the AHP-based weight classification system not only quantifies the influence exerted by each individual factor but also establishes a resilient framework for their prioritization. These findings extend far beyond the confines of this study, holding immense implications for effective groundwater resource management, judicious land use planning, and the cultivation of sustainable development practices. Ultimately, the insights gleaned from this research possess the potency to steer decision-making processes, guiding the utilization of groundwater resources in a manner that is both efficient and sustainable. In particular, the study's outcomes offer an invaluable guide for shaping policies and actions aimed at harnessing the potential of groundwater resources within the middle Ganga basin.

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Data availability The data used in this study will be made available as per the request of the concerned authority.

Declarations

Competing interests The authors declare no competing interests.

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