



Groundwater potential mapping of Tawi River basin of Jammu District, India, using geospatial techniques

Md Sarfaraz Asgher · Naveen Kumar ·
Manisha Kumari · Mansoor Ahmad ·
Lucky Sharma · Mohd Waseem Naikoo

Received: 21 May 2021 / Accepted: 29 January 2022 / Published online: 2 March 2022
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2022

Abstract The demand for water is increasing around the world due to population growth, urbanization, industrialization, etc., which is making groundwater a vital natural resource for meeting the growing demand for water. According to the central groundwater report, Jammu district has adequate groundwater potential (GWP) and comes under the safe category. However, the GWP has not been fully utilized, thereby leading to a water shortage in the district. Therefore, this study has been designed to examine the GWP zones in the Tawi River basin of Jammu district using geospatial techniques. For this, several GWP conditioning parameters, such as elevation,

slope, geology, geomorphology, rainfall, soil, land use/land cover, topographic wetness index (TWI), drainage density, lineament density, roughness, and curvature, were utilized. The analytical hierarchy process (AHP) technique was used to evaluate the weights of the selected criteria after a pair-wise comparison of each criterion with the rest of the criteria. The result showed that the high GWP zone accounts for 21.98% of the area, the moderate zone covers an area of 40.54%, the low GWP area accounts for about 34.91%, and only 2.57% of the area lies under the very low GWP zone. The validation of GWP zones using 25 monitoring wells showed an accuracy of 80% in GWP modeling. The findings of this study may be utilized in meeting the rising demand for water in the region.

M. S. Asgher (✉) · N. Kumar · M. Kumari · M. Ahmad ·
L. Sharma
Department of Geography, University of Jammu, Jammu
& Kashmir 180006, Jammu, India
e-mail: sasgher20@gmail.com

N. Kumar
e-mail: nkbhagat258000@gmail.com

M. Kumari
e-mail: malgotramk@gmail.com

M. Ahmad
e-mail: manulone123@gmail.com

L. Sharma
e-mail: imlucky1512@gmail.com

M. W. Naikoo
Department of Geography, Faculty of Natural Sciences,
Jamia Millia Islamia, New Delhi 110025, India
e-mail: waseemnaik750@gmail.com

Keywords Groundwater potential · River basin ·
Geospatial techniques · Analytical hierarchy process

Introduction

Water as a resource is being utilized for multiple purposes including drinking, agriculture, industrial, and domestic all over the globe (Pal, Ghosh et al., 2020; Pal, Kundu et al., 2020; WWDR, 2018). Uneven distribution of water and its injudicious usage, pollution, population growth, rapid urbanization, and erratic rainfall due to climate change make availability of usable water a scarcity (Nabi et al., 2019;

Morote & Hernández, 2016; Yan et al., 2019; Zubaidi et al., 2020). Available water resource manifests itself in the form of surface and groundwater. The demand of water increases with economic development while its quality and quantity are decreasing due to anthropogenic interventions (Wilopo et al., 2021a). The global groundwater system accounts for about 30% of the total freshwater resources (UN WWDR, 2021). Groundwater caters to the 50% of irrigation needs and 90% of drinking water requirements in rural areas around the world. In fact, some major cities rely entirely on groundwater to meet their water requirements (UNESCO, 2021). Groundwater is among the many natural resources that are facing the problems of overexploitation due to its increasing demands (Bierkens, & Wada, 2019). This exploitation is prominent around the world, especially in cities which has resulted in the form of falling water table and decreased surface water flows (Gleeson & Richter, 2016; Roy et al., 2020; Sutanudjaja, 2020). India has also been witnessing tremendous increase in demand for usage across sectors of domestic, agriculture, and industrial (Bhattacharya et al., 2014). The consumption of groundwater for irrigation exceeds 90% of the total groundwater utilization in the country (Schneider, 2018), besides groundwater caters to about 85% rural and 30% urban need of drinking water in India (CGWR, 2017). However, rapid growth in population, increased industrialization and urbanization, and increase in agricultural activities are further accelerating the demand in which availability of groundwater quantity and quality becomes of paramount importance (Arulbalaji et al., 2019; Duan et al., 2016; Jha et al., 2010). Likewise, shift in the cropping pattern, uncertainty of monsoon, scarcity of surface water, and pollution put more stress on groundwater which results in its unsustainable use (Hussein et al., 2017; Patel et al., 2014). As a result, according to World Wide Fund for Nature, more than 30 Indian cities are expected to face an acute shortage of water by 2050. Besides depletion of groundwater, India has been found to be associated with seawater intrusions (Prusty & Farooq, 2020), land subsidence (Kadiyan et al., 2021), climate change (Ferrantet al., 2014), and contamination by arsenic (Shaji et al., 2021), urbanization (Roy et al., 2020), and nitrates (Jayarajan & Kuriachan, 2021). So, managing the usage of the existing groundwater resources and planning its future usage is critical for its sustainable development in

a country like India in which groundwater potential (GWP) mapping is crucial (Anbazhagan, & Jothibasu, 2016). Proper delineation of GWP zones can be utilized to find the location for new abstraction wells to meet the rising demand for water (Ibrahim-Bathis & Ahmed, 2016). Drilling wells at the location where the probability is maximum will significantly reduce the time and cost associated with it. Thus, mapping of underground water can help in the sustainable development and management of groundwater in the country (Suganthi et al., 2013; Anduaem & Demeke, 2019).

Groundwater is not uniformly distributed in space and time throughout the country (Mukherjee et al., 2015). This distribution of groundwater is governed by several factors such as distribution of rainfall, vegetation, geology, slope, geomorphology, land use/land cover (LU/LC), lineament features, and the relationship between these factors (Jha et al., 2010; Anduaem & Demeke, 2019; Nowreen et al., 2021). The amount of rainfall that recharges groundwater is attributed to several factors, namely soil type, groundwater depth, vegetation, and weather patterns (Wilopo et al., 2021b). As such, many researchers have used criteria like drainage density, geology, geomorphology, lineament, rainfall, soil type, LU/LC, lithology, DEM, and slope for the zonation of GWP zones (Jaiswal et al., 2003; Greenbaum, 1985; Gupta & Srivastava, 2010; Gdoura et al., 2015; Mallick et al., 2021). Remote sensing and GIS-based multi-criteria decision model (MCDM) have been widely used for the identification and mapping of these GWP zones (Lakshmi & Reddy, 2018; Allafta et al., 2021; Benjmel et al., 2020; Kolli et al., 2020; Tolche, 2021). Besides, overlay analysis in GIS has been widely used to integrate the different criteria/thematic maps (Kumar et al., 2016; Tolche, 2021). One of the important MCDM method is analytical hierarchy process (AHP) proposed by Saaty (1980). Apart from AHP technique, scholars have also used principal component analysis (Helena et al., 2000), decision tree algorithms (Duan et al., 2016; Razavi-Termeh et al., 2019), machine learning techniques (Lee et al., 2020; Sarkar et al., 2021), ensemble machine learning algorithms (Mallick et al., 2021), etc. to delineate the GWP zones. However, for the present study, AHP has been used as it is easy, authentic, and efficient technique for GWP analysis (Celik, 2019). AHP technique is used to evaluate the weights of different criteria after

a pair-wise comparison of each criterion with the rest of the criteria (Chen et al., 2013). It reduces the subjectivity and biasness in the decision-making process (Saaty, 1990).

Jammu district is blessed with many perennial rivers, viz., Chenab, Tawi, Munawar Tawi, and Basantar. But still, the region is facing water shortages (Hakhoo, 2019) especially the Kandi belt which is even experiencing shortage for the drinking purposes (Kumar et al., 2004). On one hand, Shiwalik hills bounding North and Northeastern parts does not allow water to percolate and most of the rainfall goes waste as overland flow (Sharma & Arora, 2015). And on the other, groundwater contamination due to improper disposal of domestic and industrial solid wastes is adding the already water scarcity (Ramshoo et al., 2017). Though the quantity and quality of groundwater resource are adequate and good in Jammu (CGWR, 2018–19) but considering the rapid expansion of impervious surface in the region due to increasing urban population and migration, overexploitation of groundwater and its reduced recharge can threaten the very existence of groundwater aquifers (Murtaza et al., 2020). Thus, scientific and systematic usage and development of groundwater is required to utilize the optimum capacity of the resource (Velis et al., 2017). For this, mapping of the GWP of various segments of a region becomes essential (Pham et al., 2019). However, to the best of our knowledge, there have been relatively few studies that map the GWP zones in India's Jammu area. As a result, in order to cover this research gap, this study will use twelve GWP conditioning characteristics to evaluate the probable groundwater zones in the Tawi River basin in Jammu district.

Study area

Jammu district is flanked to the north and northeast by the Udhampur and Reasi districts, to the east and southeast by Udhampur and Samba districts, to the south and southwest by Rawalpindi (Pakistan), and to the northwest by Rajauri district. The district is located between $74^{\circ} 24''$ to $75^{\circ} 18''$ E and $32^{\circ} 50''$ to $33^{\circ} 30''$ N (Fig. 1). It covers an area of 2342 km² (Ministry of Home Affairs, 2011). River Tawi, known as Surya Putri in ancient literature, is among the important rivers of Jammu district. It has its

source from the Kali Kundi glacier in Doda district. The total length of the river is 141 km and its catchment area is 2168 km² which comes under Jammu, Udhampur, and Doda districts (Karmakar, 2019). The catchment area of Tawi River within Jammu district is 928.94 km² and the elevation ranges between 234 and 1057 m. The physiography of the region mainly consists of Indo-Gangetic plain southernmost part of Shiwaliks. The sub-tropical type of climate characterized by the seasonal reversal of wind direction is found in the study area (CGWR, 2018–19, CGWR, 2017). The average annual rainfall ranges between 113 and 175 cm. During summer season, groundwater table reaches at low level due to consistent higher temperature. With the increase in temperature, water resources are under profound stress due to increasing rate of evaporation and decrease in available quantity of fresh water. As a result, mountain springs and groundwater resources are immensely reduced (CGWR, 2018–19; Farooq, 2016).

Materials and methods

Data sources

The study used digital elevation model (DEM) of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite with a spatial resolution of 30 m, obtained from the United States Geological Survey (USGS) website to prepare elevation, slope, curvature, roughness, and topographic wetness indexes (TWI). Linear Imaging Self-Scanning Sensor 3 (LISS III) data from the Indian Remote Sensing (IRS) satellite Resourcesat-2 was utilized to create the LU/LC map of the Tawi basin. Furthermore, the soil map was obtained from the Jammu and Kashmir Department of Soil Survey (DSS), while the geology and geomorphology maps were taken from the Geological Survey of India (GSI). The data of groundwater depth was taken from the Central Ground Water Board (CGWB), Jammu. The details of the datasets used in the present study are given in Table 1.

Methods

The present study uses AHP for mapping GWP zones in Tawi basin as it is efficient, reliable, and simple method (Celik, 2019). AHP can handle a variety of

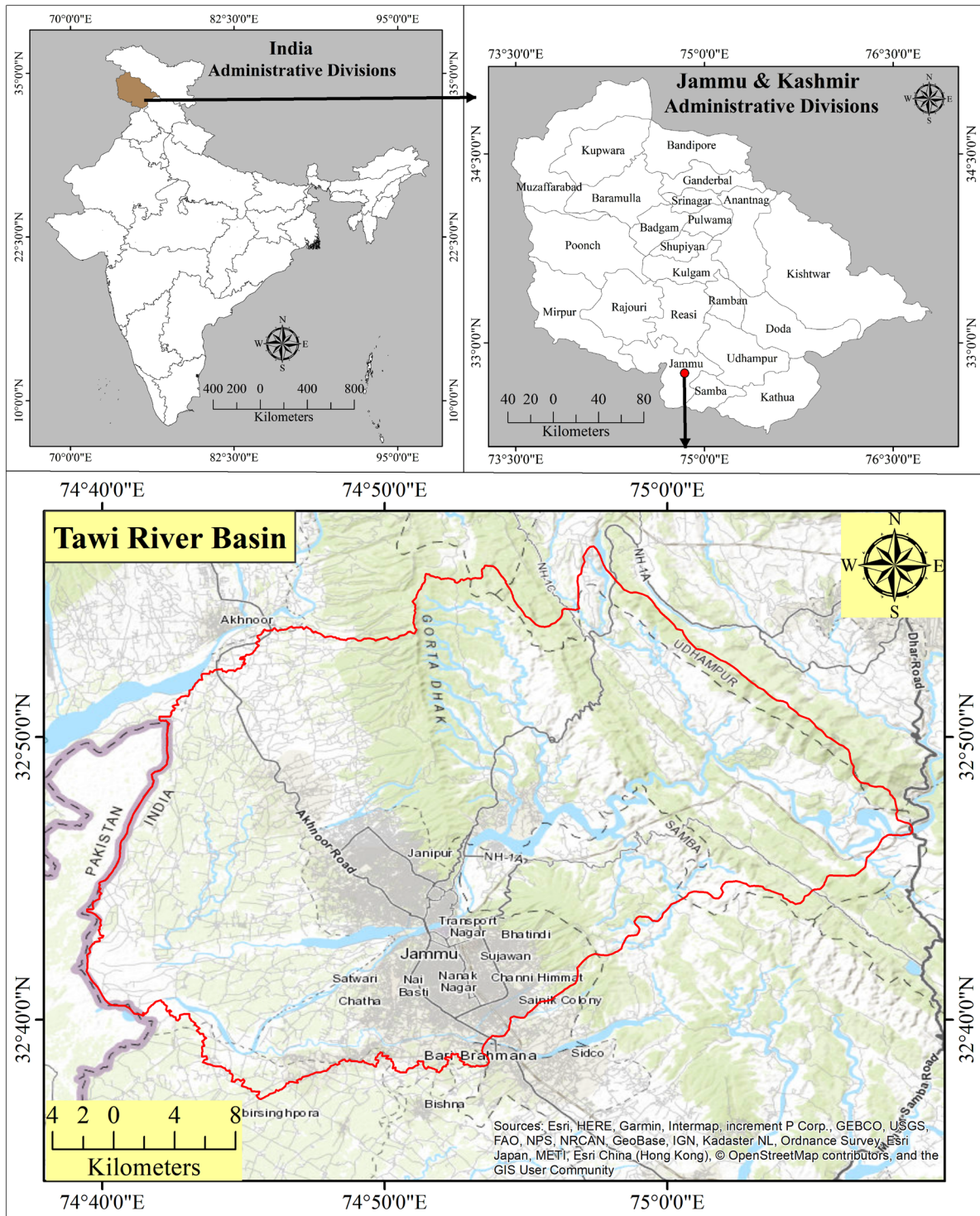


Fig. 1 Location of the Tawi River basin in Jammu and Kashmir

Table 1 Sources of the datasets used in this study

Dataset	Sources	Resolution (m)	Time
ASTER DEM	United states Geological survey (USGS)	30 m	-
IRS LISS III	Bhuvan portal, National Remote Sensing Centre (NRSC), Hyderabad	23.5 m	16 Nov, 2018
Soil	Department of Soil Survey, Jammu and Kashmir	-	
Rainfall	Indian Meteorological department (IMD), Srinagar	-	2010–2020
Geomorphology, geology, and lineament	Bhukosh, Geological Survey of India (GSI)	-	-
Groundwater depth	Central Ground Water Board (CGWB), Jammu	-	2018–2019

characteristics and the consistency ratio can be used to assess the subjectivity of weights (Shekhara & Pandey, 2014; Saranya & Saravanan, 2020). Besides, AHP is a useful tool for determining a result’s consistency and, as such, helps in reducing the bias in decision-making process (Saaty, 1990). The methods of the study involve the preparation of the twelve GWP conditioning parameters using ArcGIS software. Pair-wise matrix was prepared after comparing each parameter with rest of the parameters using AHP technique. While comparing the layers, numeric value based on Saaty’s scale of relative importance was used and then the normalized weight of each layer was evaluated. The accuracy of the pair-wise matrix was determined after computing the consistency ratio. The layers were then integrated using overlay analysis to obtain the GWP index (GWPI). The GWPI was classified into 4 categories to obtain the GWP zones of the study area. At last, the results were validated using average groundwater depth of the monitoring dug wells obtained from Central Ground Water Board. The detailed methodology is shown in Fig. 2.

Satellite data pre-processing and delineation of watershed

Firstly, the atmospheric and radiometric corrections of the downloaded satellite data were done using the ERDAS Imagine software (version 2014). For this, the haze and noise reduction tools were utilized. The watershed boundary of the Tawi River basin was prepared using stream gauge (pour point) method from the ASTER DEM with the help of flow direction and flow accumulation function of spatial analyst tool of ArcGIS 10.5.1 software. The extracted watershed boundary was then utilized for the preparation of the

thematic layers of GWP conditioning parameters like slope, curvature, and soil map.

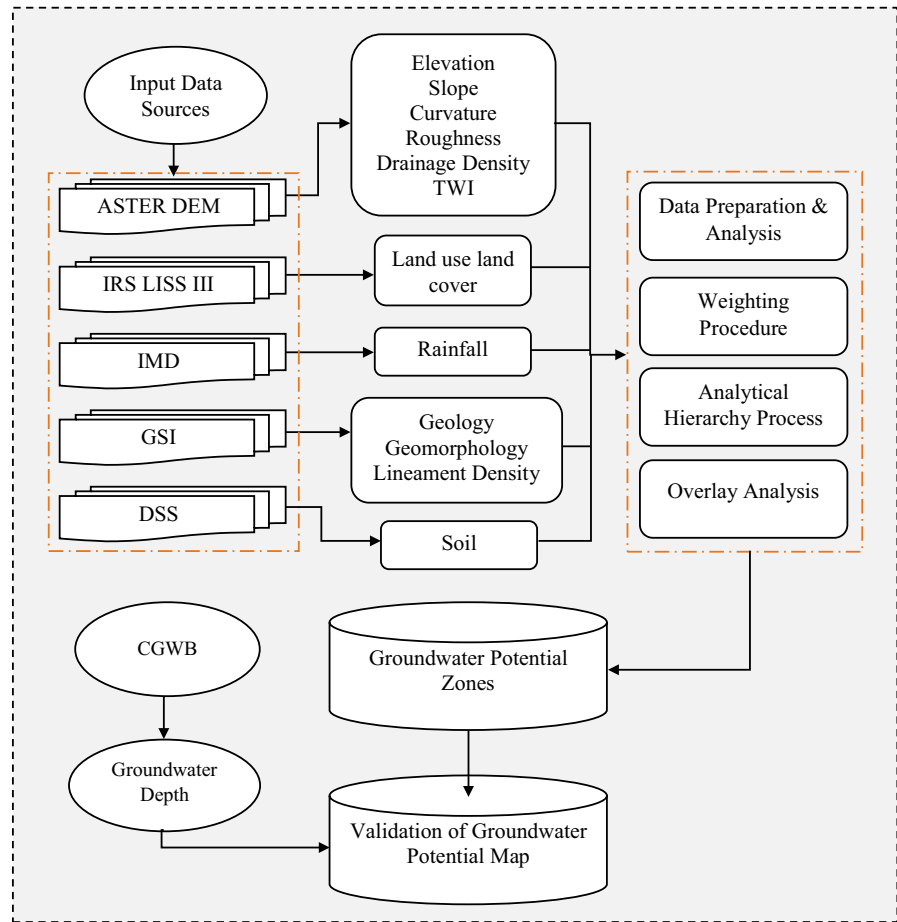
LU/LC classification

Numerous techniques have been developed for the LU/LC classification using the satellite datasets since the beginning of Landsat era in 1970s (Phiri & Morgenroth, 2017). The most popular techniques for the LU/LC classification from satellite data are maximum likelihood classifier (MLC), K-means clustering, random forest, artificial neural network (ANN), etc. (Kumari et al., 2021; Naikoo et al., 2022; Talukdar et al., 2020). In this study, the supervised classification technique using MLC was utilized for the LU/LC classification from the IRS LISS III data by using level I classification scheme of National Remote Sensing Centre (NRSC, 1995). The level I LU/LC classification scheme of NRSC has a total of 8 LU/LC classes of which six LU/LC classes were identified in the study area, i.e., forest, agricultural land, river bed, scrubland, built-up area, and water bodies.

Preparation of the groundwater conditioning parameters

Generally, nine to thirteen GWP conditioning parameters are used for the mapping of GWP zones (Mallick et al., 2021). However, in this study, twelve GWP conditioning parameters were used, viz., soil, slope, rainfall, elevation, LU/LC, lineament density, drainage density, geology, geomorphology, topographic wetness index (TWI), roughness, and curvature. These layers play an important role in groundwater recharge and hence become important in the delineation of GWP of the study area.

Fig. 2 Flowchart of the methodology for delineating groundwater potential zones



Different methods were used to prepare these layers. ASTER DEM was used to prepare elevation map, drainage density map, TWI map, roughness map, curvature map, and slope map. The geo-referenced soil map obtained from the Department of Soil Survey was geo-rectified and digitized using ArcGIS software. The rainfall map was created in ArcGIS 10.5.1 by interpolating the average yearly rainfall data from several meteorological stations using the inverse distance weighting (IDW) interpolation method (Wen & Wuing, 2012). The geomorphology map was created using a dataset taken from the Bhukosh web page (Geological survey of India, 2021). Geology map of northwestern Himalayas was used to digitize the geology map of the study area. Lineament map downloaded from Bhukosh was used to prepare the lineament density map using linear density tool in ArcGIS (Suganthi et al., 2013).

Weighting procedure using AHP

AHP model involves the use of expert's knowledge to evaluate the weight of different layers. It involves the construction of pair-wise matrix using Saaty's scale (Saaty, 1987) as shown in Table 2. Numeric values have been assigned while comparing two criteria based on the relative importance (Rajaveni et al., 2017; Andualem & Demeke, 2019).

After comparing each layer with the rest of the layers based on their relative importance, pair-wise matrix has been constructed (Machiwal et al., 2011). Using pair-wise matrix under AHP model, the normalized weights of each individual layer have been calculated (Table 3).

To evaluate the accuracy of the applied AHP model in pair-wise comparison, the consistency ratio (CR) has been calculated using Eq. (1) and Eq. (2) (Saaty, 1980).

Table 2 Saaty’s scale of relative importance (Saaty, 1980)

S. no	Explanation	Intensity of relative importance
1	If criterion A and Criterion B are equally important	1
2	If criterion A is moderately more important than criterion B	3
3	If criterion A is strongly more important than criterion B	5
4	If criterion A is very strongly more important than criterion B	7
5	If criterion A is extremely more important than criterion B	9
6	Use even numbers for intermediate judgements	2, 4, 6, 8

$$Consistency\ Ratio\ (CR) = \frac{CI}{RI} \tag{1}$$

where CI is consistency index and RI is random index.

$$Consistency\ Index\ (CI) = \frac{\lambda_{max} - 1}{n - 1} \tag{2}$$

Applying Eqs. 1 and 2, the consistency ratio (CR) calculated is 0.049 which is within the permissible limit of 0.01. Thus, it reflects a good accuracy in pairwise comparison of different thematic layers, i.e., GWP conditioning parameters.

After evaluating weights using AHP model, the classes of each GWP conditioning parameters have been assigned a rank ranging from 1 to 9. Higher rank has been assigned to the class which is expected to have high GWP (Table 5).

Mapping of groundwater potential (GWP) zones

Weighted overlay analysis tool in ArcGIS software has been used to integrate the different thematic layers, i.e., GWP conditioning parameters. The GWPI has been evaluated after the integration of all the parameters using Eq. (3) (Malczewski, 1999).

$$GWPI = \sum_{w=1}^m \sum_{j=1}^n (W_j * X_i) \tag{3}$$

where W_j is the normalized weight of the jth parameter and X_i is the normalized weight of ith feature of the parameter.

Then, the computed GWPI values have been classified into four categories, viz., high, moderate, low, and very low. Based on these classes, the map of GWP zones of Tawi River basin has been developed.

Table 3 Pairwise comparison matrix

GM geomorphology, GL geology, LULC land use/land cover, SL soil, RF rainfall, RG roughness, DD drainage density, EL elevation LD lineament density, SP slope, CR curvature, TWI topographic wetness index, SM sum, NW normalized weight, % IF % influence

	GM	GL	RF	SL	EL	SP	LD	DD	TWI	CR	RG	LULC	SM	NW	%IF
GM	1	2	4	5	8	2	5	3	7	9	9	6	61.00	0.19	18.83
GL	½	1	3	4	7	1	4	2	6	8	8	5	49.50	0.15	15.28
RF	¼	1/3	1	2	6	1/3	3	1/2	5	6	7	4	35.42	0.11	10.93
SL	1/5	¼	½	1	5	¼	2	1/3	4	6	6	3	28.53	0.09	8.81
EL	1/8	1/7	1/6	1/5	1	1/6	¼	1/6	½	2	2	1/3	7.05	0.02	2.18
SP	½	1	3	4	6	1	3	2	5	7	7	4	43.50	0.13	13.43
LD	1/5	¼	1/3	½	4	1/3	1	1/3	4	5	5	3	23.95	0.07	7.39
DD	1/3	½	2	3	6	½	3	1	5	7	7	4	39.33	0.12	12.14
TWI	1/7	1/6	1/5	¼	2	1/5	¼	1/5	1	3	3	1/3	10.74	0.03	3.32
CR	1/9	1/8	1/6	1/6	½	1/7	1/5	1/7	1/3	1	1	1/4	4.14	0.01	1.28
RG	1/9	1/8	1/7	1/6	½	1/7	1/5	1/7	1/3	1	1	1/4	4.11	0.01	1.27
LULC	1/6	1/5	1/7	1/3	3	¼	1/3	1/4	3	4	4	1	16.68	0.05	5.15

Validation of GWP zones

The GWP zone map was validated using groundwater depth data from monitoring wells collected from the Central Ground Water Board. There are about 94 monitoring wells in Jammu district out of which 25 monitoring wells lie in the study area. Groundwater depths of pre-monsoon and post-monsoon months of 2018 and 2019 have been used for calculating the overall groundwater depth of these monitoring wells and classified into three classes, i.e., low depth, moderate depth, and high depth. Average groundwater depth classes of monitoring wells were represented using triangle of various size for each class in ArcGIS software and compared with GWP zones for the validation.

Results

Description of the GWP conditioning parameters

Geomorphology

Geomorphology is defined as the study of topographic features of the earth's surface (Britannica, 2021). In our study area, seven geomorphic features are identified which are alluvial plain, flood plain, highly dissected hills and valleys, low dissected hills and valleys, moderately dissected hills and valleys, river, and other water bodies (Fig. 3a). Higher rank was given to water bodies, alluvial land, and flood plain, while lower rank was assigned to dissected hills and valleys. Hussein et al. (2017), Soumen (2014), and Arulbalaji et al. (2019) also indicated that water body, alluvial plain, and flood plain have more impact in groundwater occurrence whereas mountains and dissected hills and valleys have less impact in controlling groundwater.

Geology

Geology plays an important role in the GWP as the percolation of water is directly controlled by the permeability of underlying rocks (Charon, 1974; Nampak et al., 2014). In our study area, two types of sediments were identified which are tertiary sediments and quaternary sediments. Tertiary sediments

are found in the hilly areas while Quaternary deposits were found in outer plains (Fig. 3b). Water infiltration capacity is more as in quaternary sediments as compared to tertiary sediments. Arulbalaji et al. (2019) also indicated that quaternary deposits have more contribution in increasing the GWP as compared to tertiary deposits.

Drainage density

Drainage density is the ratio between the total length of all the river in a drainage basin and the total area of that drainage basin (Suganthi et al., 2013). Drainage density has inverse relation with permeability of aquifers. Areas having high drainage density depict low water infiltration whereas high water infiltration is found in the areas having low drainage density. The obtained results have been categorized into five classes (Fig. 3c). Higher ranks were assigned to the areas having low drainage density while areas having high drainage density are assigned low ranks.

Land use/land cover (LU/LC)

LU/LC is an important factor in the recharge of groundwater. Rate of percolation and water runoff largely depends upon the type of land use (Ibrahim & Ahmed, 2016; Saranya & Saravanan, 2020). Low infiltration rate occurs in the built-up area due to lack of impermeable spaces, while agricultural land, forest, and water body have higher rate of water percolation (Arulbalaji et al., 2019; Celik, 2019). LU/LC map has been prepared according to NRSC scheme of LU/LC classification into six classes which were forest, agricultural land, water body, riverbed, built-up area, and scrub forest (Fig. 3d). Higher ranks were assigned to water body, riverbed, agricultural land, and forest whereas lower ranks were assigned to built-up area and scrub forest.

Slope

Slope is an important factor influencing the infiltration of water to the ground. Areas having higher slope gradient have relatively lower water infiltration owing to higher runoff. On the other hand,

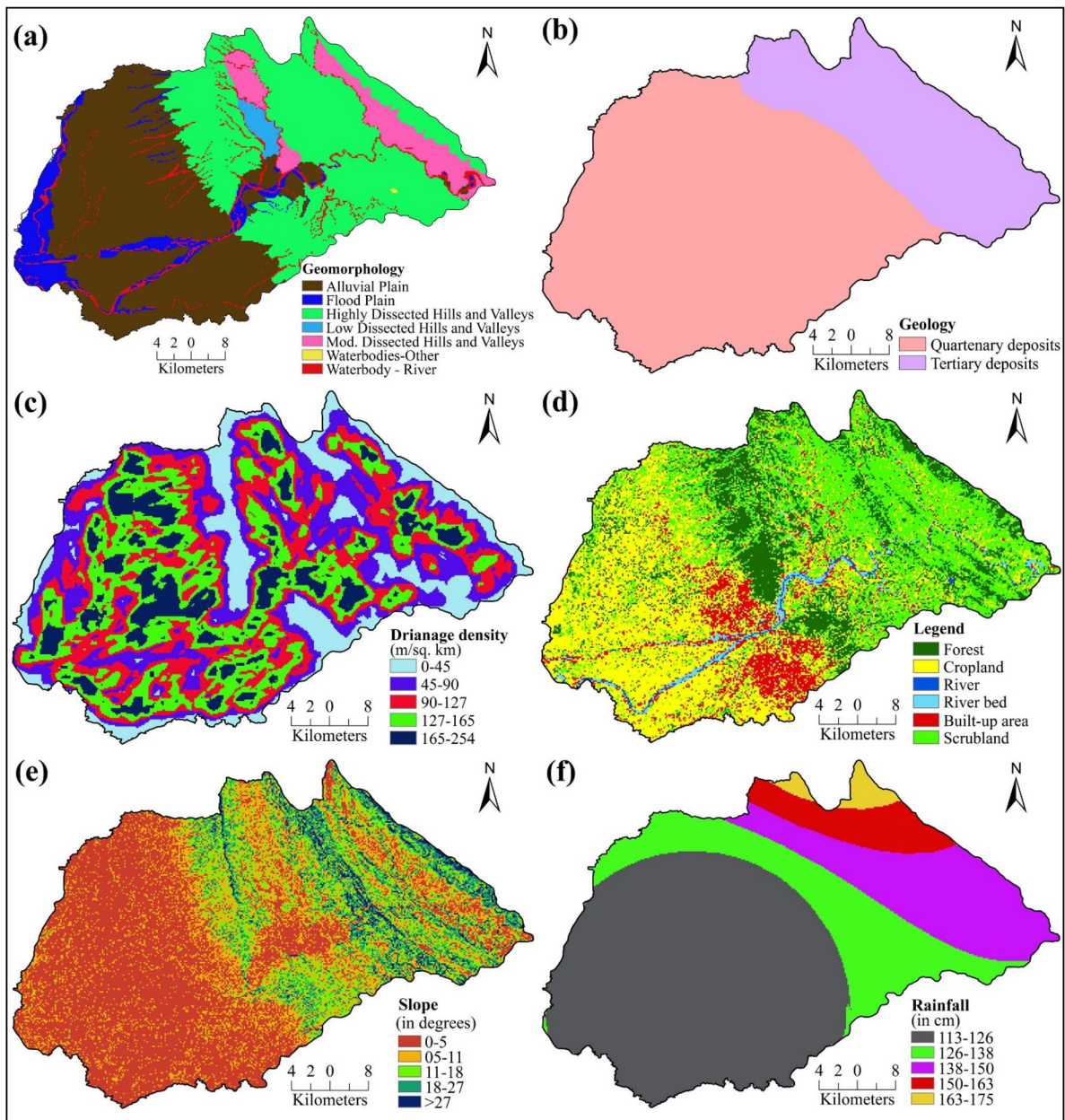


Fig. 3 Groundwater controlling factors thematic map; **a** geomorphology, **b** geology, **c** drainage density, **d** land use land cover, **e** slope, **f** rainfall

higher infiltration is found in the areas having lower slope gradient (Singh et al., 2013). The slope has been classified into five categories ranging from 0 to 5°, 5 to 11°, 11 to 18°, 18 to 27°, and >27°. Higher rank was assigned to the areas having gentle slope, while lower weight was given to the areas having relatively steep slope (Fig. 3e).

Rainfall

Rainfall is an essential factor that influences the groundwater recharge as it is the primary source of water available for percolation in the study area. Rate of water recharge depends upon the intensity and rainfall duration (Ibrahim & Ahmed, 2016).

Average annual rainfall is classified into five classes ranging from 113 to 125 cm, 125 to 138 cm, 138 to 150 cm, 150 to 163 cm, and 163 to 175 cm (Fig. 3f). Higher weight has been assigned to the areas having high rainfall, whereas areas receiving lesser rainfall are given lower weight.

Lineament density

Lineament density is defined as linear property which shows the characteristics of underlying structural features such as faults, fractures, cleavages, and discontinuity surfaces (Leary et al., 1976). It is an important

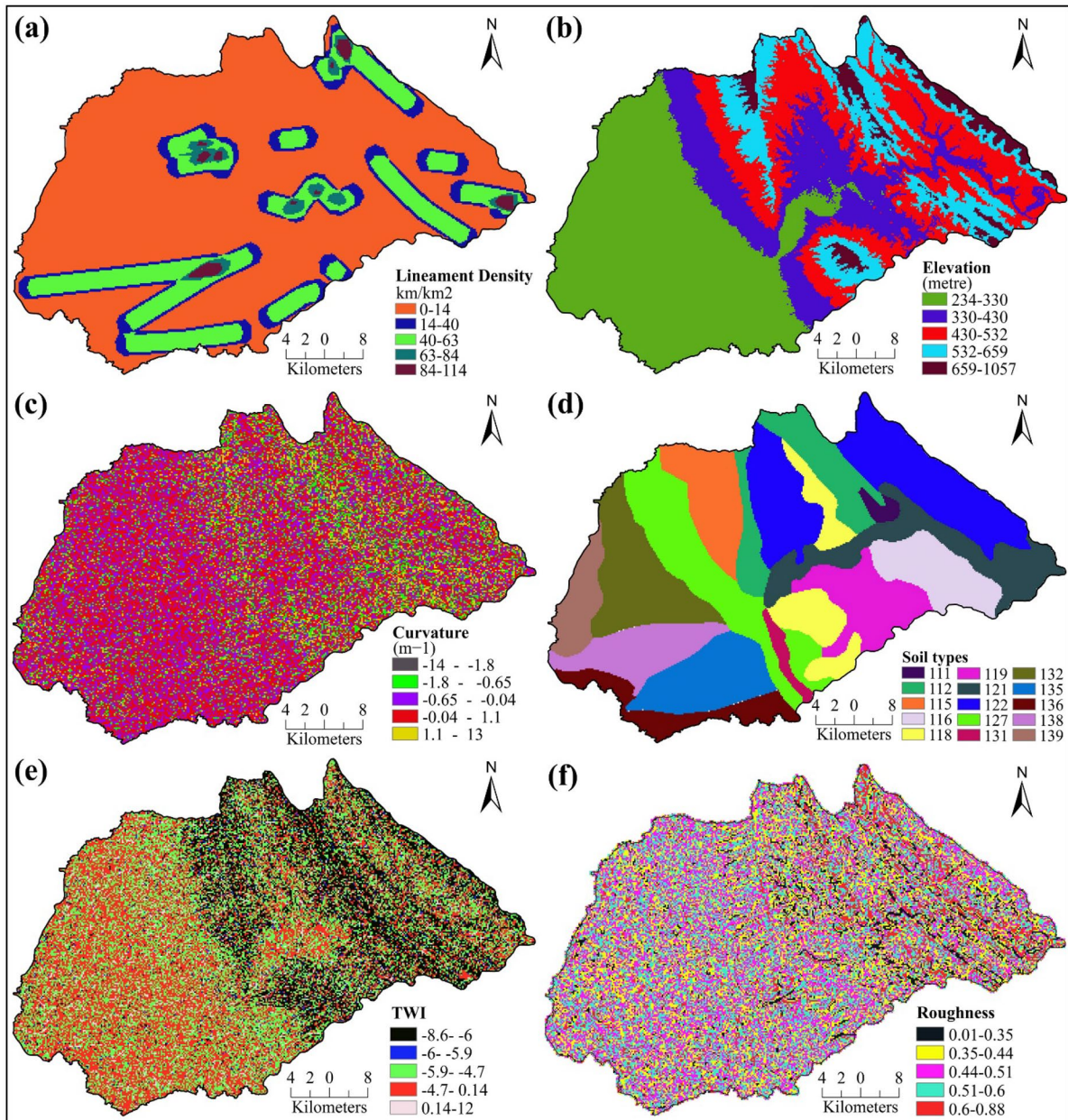


Fig. 4 Groundwater controlling factors thematic map; **a** lineament density, **b** elevation, **c** curvature, **d** soil, **e** TWI, **f** roughness

indicator that contributes in water infiltration to the ground. Areas having high lineament density have high water infiltration, while low water infiltration was shown by the areas having lower lineament density (Koch & Mather, 1997; Shekhara & Pandey, 2014; Sreedevi et al., 2001). In our study, lineament density has been classified into five classes, which are 0–14 km⁻¹, 14–40 km⁻¹, 40–63 km⁻¹, 63–84 km⁻¹, and 84–114 km⁻¹ (Fig. 4a). Higher rank was given to areas having high lineament density, while lower weight was given to the areas having lower lineament density.

Elevation

It refers to the altitude of a place above the mean sea level. It is one of the most important factors that influence the GWP. Lower topography is more favorable for water storage than higher topography (Ramu & Vinay, 2014). The elevation map has been classified into five classes which are 234–330 m, 330–430 m, 430–532 m, 532–659 m, and 659–1057 m (Fig. 4b).

The higher rank has been assigned to the areas having low altitude, while lower weight was assigned to the areas having high altitude.

Curvature

Curvature is a numerical representation of the presence of a surface profile, which might be concave or convex upwards. In a convex and concave contour, water tends to slow down and gather (Nair et al., 2017). Curvature map has been prepared from ASTER DEM and the obtained values are categorized into four classes, which are –14 to –1.8, –1.8 to –0.65, –0.65 to 0.037, 0.037 to 1.1, and 1.1 to 13 (Fig. 4c). High ranks were assigned to areas having high curvature, while low ranks are given to the areas having low curvature.

Soil

Soil is a significant component influencing groundwater, because the rate of water penetration is determined

Table 4 Characteristics of different soil types

Soil code	Soil type	Soil characteristics		
		Drainage class	Groundwater depth	Erosion class
111	Entisols, Typic Udorthents, fine loamy	Excessive	Deep	Severe
112	Inceptisols, Dystric Eutrochrepts, coarse loamy	Well drained	Deep (> 5 m)	Moderate
115	Inceptisols, Typic Udorthents, clayey skeletal	Excessive	Deep (> 10 m)	Moderate
116	Entisols, Typic Udorthents, sandy skeletal	Very well drained	Deep (> 5 m)	Moderate
118	Inceptisols, Dystric Eutrochrepts, clayey skeletal	Well drained	Deep (> 5 m)	Moderate
119	Inceptisols, Typic Udorthents, loamy skeletal	Well drained	Deep (> 5 m)	Moderate
121	Inceptisols, Dystric Eutrochrepts, fine loamy	Well drained	Deep (> 5 m)	Slight erosion
122	Entisols, Typic Udorthents, coarse loamy	Well drained	Deep (> 5 m)	Moderate
127	Inceptisols, Udic Ustochrepts, coarse loamy calcareous	Well drained	Deep (> 5 m)	Moderate
131	Inceptisols, Fluventic Ustochrepts, coarse loamy	Well drained	Moderate deep (< 5 m)	Slight erosion
132	Entisols, Typic Ustifluvents, fine silty	Well drained	Moderate deep (2–5 m)	Moderate erosion
135	Inceptisols, Udic Ustochrepts, fine loamy	Moderately well drained	Moderate deep (2–5 m)	Slight erosion
136	Inceptisols, Udic Ustochrepts, coarse loamy calcareous	Well drained	Moderate deep (2.5 m)	Slight erosion
138	Inceptisols, Fluventic Ustochrepts, coarse loamy skeletal	Well drained	Moderate shallow (1–2 m)	Slight erosion
139	Entisols, Typic Ustifluvents, coarse loamy	Well drained	Moderate shallow (1–2 m)	Slight erosion

Department of Soil Survey, Jammu and Kashmir

by the soil's water holding capacity and permeability (Gupta et al., 2018; Saranaya, & Sarwanan, 2020). In our study area, soil has been classified into fifteen types based on drainage class, groundwater depth, and level of erosion which are shown in Fig. 4d and Table 4.

Topographic wetness index (TWI)

The TWI is an index or measure of impact on flow and accumulation of water because of local topography (Ballerine, 2017). It is widely used to measure the topographic influence on surface and sub-surface

Table 5 Assigned weight and ranks to different thematic layers

Layers	Normalized weight	Domain of effect	Ranks	Layers	Normalized weight	Domain of effect	Ranks
Geomorphology	18.8	Alluvial plains	7	Elevation	2.2	234–330	8
		Flood plains	7			330–430	7
		Highly dissected hills and valleys	3			430–532	6
		Low dissected hills and valleys	5			532–659	5
		Moderately dissected hills and valleys	4			659–1057	4
		Water bodies (river)	9	Curvature	1.3	–14 to –1.8	3
Water bodies (others)	9	–1.8 to –0.65	4				
Geology	15.3	Quaternary deposits	7	TWI	3.3	–0.65 to –0.037	5
		Tertiary deposits	4			–0.037 to 1.1	6
Drainage density	12.1	0–45	5			1.1–13	7
		45–90	4			–8.6 to –6	2
		90–127	3			–6 to –5.9	3
		127–165	2	–5.9 to –4.7	4		
		165–254	1	–4.72 to –0.14	5		
LULC	5.2	Forest	7	Soil	8.8	–0.14 to 12	6
		Agricultural land	6			111	5
		Waterbody	9			112	3
		Scrubland	4			115	5
		Settlement	2			116	5
		River bed	7			118	5
Lineament density	7.4	0–14	2			119	5
		14–40	4			121	5
		40–63	6			122	5
		63–84	8			127	5
		84–114	9			131	6
Slope	13.4	0–5	8	132	7		
		5–11	6	135	7		
		11–18	4	136	7		
		18–27	3	138	8		
		> 27	2	139	9		
Roughness	1.3	0.1–0.35	7	Rainfall	10.9	113–126	3
		0.35–0.44	6			126–138	4
		0.44–0.51	5			138–150	5
		0.51–0.6	4			150–163	6
		0.6–0.88	3			163–175	7

hydrology and reflects the potential for water infiltration caused by topographic effects (Arulbalaji et al., 2019; Mokarram et al., 2015). TWI has been classified into five classes which are -8.62 to -6 , -6 to -5.9 , -5.9 to -4.7 , -4.7 to -0.14 , and -0.14 to 12 (Fig. 4e).

Roughness

Roughness index depicts the difference in elevation of the adjacent cells of digital elevation model (Riley, 1999). It measures the undulation in the topography. Areas having higher roughness index have more undulation in the topography and vice versa (Nair et al., 2017; Arulbalaji et al., 2019). Roughness index of the study area has been classified into five classes which are $0.01-0.35$, $0.35-0.44$, $0.44-0.51$, $0.51-0.6$, and $0.6-0.88$ (Fig. 4f).

Analysis of the GWP zones

The total of 12 GWP conditioning parameters has been prepared using ArcGIS. Normalized weight for each thematic layer has been calculated through AHP method and ranks to sub-parameters of each conditioning parameter have been assigned based on their

relative importance in GWP (Table 5). Subsequently, overlay analysis tool in ArcGIS 10.5 has been used for the delineation of GWP zones. The derived result has been categorized into 4 categories, viz., high, moderate, low, and very low (Fig. 5).

The high GWP zone covers 204.19 km^2 accounting for 21.98% of the total land area (Table 6). High GWP lies in the western part of the study area mostly comprising of flood plain and alluvium plains. Areas having high lineament density, gentle slope, and areas in the vicinity of water bodies also have high GWP. The moderate GWP zone covers 376.58 km^2 , accounting for 40.54% of the total land area. Moderate GWP was found mainly in the area of alluvium plain and moderately dissected hills and valleys. Areas having low lineament density, gentle slope, and areas having coarse loamy and clayey skeletal type of soil coincide with moderate GWP. Low and very low GWP zones were spread in the area of 324.31 km^2 and 23.86 km^2 which accounts for 34.91% and 2.57% of the total area, respectively. Low and very low GWP zones were found in the central and eastern part of the study area comprising mostly of highly dissected hills and valleys. Areas having high drainage density, high altitude, low lineament density, and steep slope also coincide with low and very low GWP zones.

Fig. 5 Groundwater potential zones of Tawi River basin

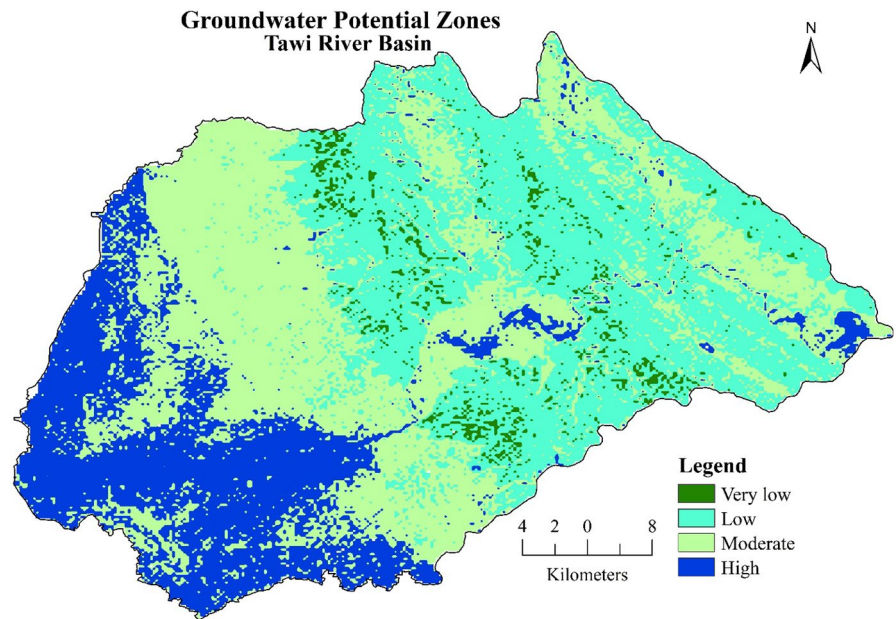


Table 6 Area under groundwater potential zones

S no	Zone	Area (in km ²)	Area (in %)
1	High	204.19	21.98
2	Moderate	376.58	40.53
3	Low	324.31	34.91
4	Very low	23.86	2.56

Validation of the GWP zones

The GWP zone map was validated using the existing average groundwater depth data from 25 monitoring dug wells collected from CGWB Jammu (Fig. 6). Groundwater depths of the monitoring dug wells have been classified into 3 classes, i.e., low depth (0 to 4 m), moderate depth (4 to 8 m), and high depth (> 8 m), as depicted in Table 6.

Table 7 and Fig. 7 illustrate that monitoring wells of low depth coincide with high GWP zone except monitoring dug well of Muthi which lies within the moderate GWP zone. Similarly, monitoring dug wells of moderate depth calibrate with moderate water potential zone except Miran Sahib and Chatha and lastly monitoring wells of high depth coincide with low GWP zone except Purkhoo and Patta khu. No monitoring well was found in very low GWP zone.

Hence, groundwater depth classes of 20 monitoring wells out of 25 coincide with their respective GWP zones, which show that the obtained results have a good correlation with 80% accuracy after comparing with actual field data. The average depths of monitoring wells which coincide with high GWP zone, moderate GWP zone, and low GWP zones are 2.45 m, 6.81 m, and 13.93 m, respectively. Thus, there is an indirect correlation between the average groundwater depth and GWP.

Discussion

GIS-based multi-criteria decision-making is a strong tool for decision makers to detect GWP. Pal, Ghosh, et al. (2020), Pal, Kundu, et al. (2020)) used geospatial techniques and the MCDA method to investigate GWP in the Purba Bardhaman area of West Bengal. Owolabi et al. (2020) in a similar study used AHP technique for analyzing GWP for semi-arid environment region of South Africa. Similarly, we applied the AHP technique with pair-wise comparison in our study and then combined the data using overlay analysis. This method is particularly effective for establishing outcome consistency and decreasing decision bias. In the current study, agricultural land, forests, and water bodies were given higher rankings

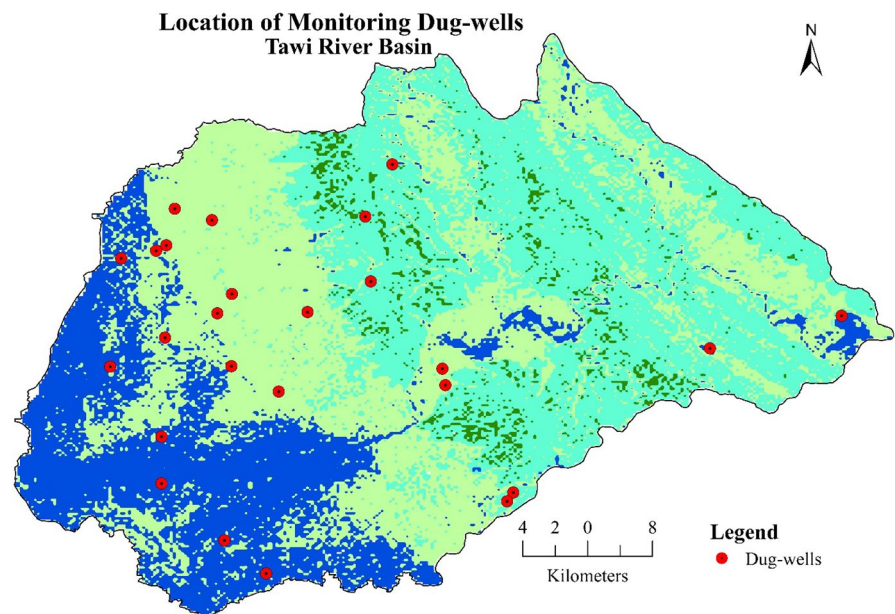
Fig. 6 Location of monitoring dug wells

Table 7 Water depth of monitoring wells and their respective level of potential

Level of potential	Location of monitoring wells	Average water depth in meters	Zonal average water depth in meters
High potential zone	Gajansoo	2.71	2.45
	Gho-Manhasan	2.31	
	Katcha-PindDansal	1.94	
	KotkaSwal	0.93	
	Marh	2.51	
	Muthi	1.89	
	Nagbani	3.19	
	Surinsar	0.56	
	Sohanjana	3.45	
	Lalyal	3.45	
	Kana Chak	2.87	
	Khairi (Raipur)	3.72	
	Sidhra	3.29	
	Rangoora	1.51	
Medium potential zone	Shame Chak	5.39	6.81
	Batera	7.79	
	Garhi (Jammu)	7.40	
	Miran Sahib	7.40	
	KarnaileChak	7.40	
	Chatha	6.22	
	Jhiri	6.05	
Low potential zone	Kangar	8.99	13.93
	Purkhoo	15.2	
	PataKhu	21.79	
	Greater Kailash	9.77	

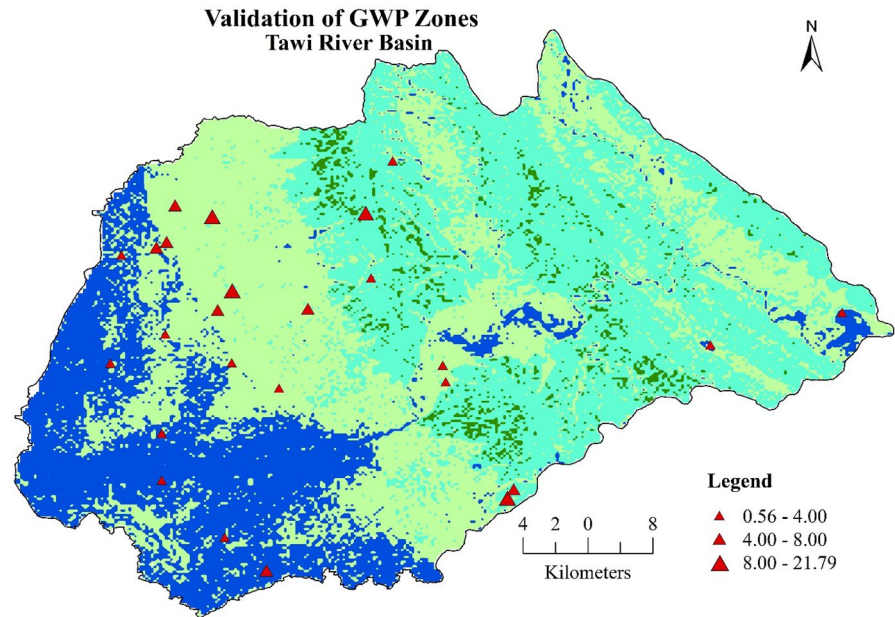
CGWB, Jammu

than scrub forest and built-up areas. These areas aid in groundwater recharge because they have a higher rate of water percolation (Rajaveni et al., 2017). In contrast, built-up areas have low infiltration rates and capacities due to the dominance of impermeable surface in this type of land use (Jat et al., 2009). The study area has moderate to high drainage density, implying a negative impact on GWP. Since the permeability of aquifers is inversely proportional to the density of drainage. Water infiltration is minimal in areas having high drainage density, whereas areas having water low drainage density have high water infiltration (Allafta et al., 2021). Kumar et al. (2020) reported that areas with high lineament density depict high permeability of water and thus his results coincide with our study. Tesfaye (2010) shows in his research that soil qualities impact the link between runoff and infiltration rates, which in turn regulates

the degree of permeability, which determines GWP. Similarly, in our study, areas having coarse loamy and clayey skeletal type of soil have shown moderate GWP.

Geology is important in GWP because the permeability of underlying rocks directly controls water percolation. The flow of water is aided by unconsolidated and fractured rocks (Balamurugan et al., 2020). According to Arulbalaji et al. (2019), quaternary deposits contribute more to increasing GWP than tertiary deposits. Similarly, in our study, quaternary sediments were found to be more favorable for groundwater prospect than tertiary sediments. Because of the longer stagnation period for water to percolate, GWP rises with gentle slope and low topographic elevation locations (Mogaji et al., 2016). Hence, in the study area, higher rank was assigned to the areas having gentle slope, while lower weight was given to the

Fig. 7 Validation of groundwater potential zone with water depth of monitoring dug wells



areas having relatively steep slope (Fig. 3e). Thapa et al. (2017) as well as Maity and Mandal (2017) reported that waterbody, alluvial plain, and flood plain have a greater impact on groundwater occurrence, while mountains, dissected hills, and valleys have a lesser impact on groundwater control and thus assigned higher and lower ranks, respectively. The intensity and duration of rainfall determine the rate of water recharge (Katchoni et al., 2019). In our study, areas with high rainfall lie in higher elevation leading to higher runoff and low GWP, while areas with low rainfall lie in Kandi belt. Curvature, roughness, and TWI add significant impact on the groundwater recharge. Previous studies suggested areas having convex and concave profile, higher roughness, and TWI showed greater accumulation of water (Nair et al., 2017; Mokarram et al., 2015; Arulbalaji et al., 2019). Likewise, in the current study, roughness, curvature, and TWI showed similar results.

The findings of the present study show that high GWP zone accounts for 21.98% of the entire study area. This zone is particularly noticeable in the areas with high lineament density, alluvial plain, mild slope, flood plain, and places near water bodies in the study area. The findings of the current study are consistent with similar studies conducted in the Himalayan regions. Qadir et al. (2020) found that alluvial plain and flood plains have higher GWP. Similarly, Jasrotia

et al. (2016) found that moderate GWP zones were confined in residual hills and valley fill deposits with moderate to moderately steep slopes in Devak and Rui watersheds of Jammu. The results of the study also show similar results for Tawi basin where moderate GWP zones are concentrated in areas with low lineament density, gentle slopes, and moderately dissected hills. The areas with high drainage density, high elevation, highly dissected hills, and valleys with steep slopes were found to have low GWP in the study area. Singh et al. (2018) show that lower GWP is found along Shiwalik ridge and along steeper slopes.

The final GWP map was validated using CGWB data related to depth of 25 monitoring dug wells which were classified into 3 categories, viz., high depth (0.56–4 m), moderate depth (4–8 m), and low depth (8–22 m). Similar approach has been used by Jasrotia et al. (2016) and Yildirim (2021) in their studies for the validation of GWP. Variation in the water depth of different monitoring dug wells is due to the number of conditioning factors. For example, monitoring wells of high water depth lie in the areas of high elevation, high drainage density, highly dissected hills, and valleys and steep slopes. Similarly, areas of high lineament density, alluvium plains, gentle slope, flood plains, and places near water bodies have monitoring dug wells with low water depth. Our results are consistent with the results

of similar studies done by Qadir et al. (2020) and Singh et al. (2018) in Jammu region.

The MCDM approach was utilized to analyze GWP, which is purely logical and beneficial for determining the GWP of large-scale basins, since conventional methods of drilling observational wells are expensive and time consuming. The GWP zone map prepared in this study provides insights to planners and decision makers that can be used for watershed management and planning. Planning is to be done in such a way that in low GWP zones, groundwater usage should be limited to household purposes, whereas in high GWP zones, where water availability is enormous, groundwater could be used for large-scale agricultural and commercial purposes.

Conclusion

Depletion of groundwater is a serious threat for sustainability of hydrological cycle. Therefore, it is the need of the hour to estimate the available groundwater for better planning and management of this precious resource. In the present, an attempt has been made for the mapping of GWP zones in the Tawi River basin of Jammu district, which is characterized of having both hilly and plain topographies. Geospatial techniques and the analytical hierarchy process were proven to be a cost-effective tool for defining GWP zones. Based on the study, the GWP in the region is being controlled by combination of many factors among which lineament, topography, slope, rainfall, LU/LC, and soil condition were the most important ones. The main findings of the present study show that high GWP zone is located in the southwestern and western part of the study area. The high GWP zone accounts for 21.98% of the study area and is characterized by plain terrain and gentle slope in the flood plain and alluvial plain. Around 40.54% of the land area is found to be lying under moderate GWP zone, characterized by alluvial and moderately dissected hills and valleys. Thus, it is very important to use the available groundwater judiciously with proper planning by constructing dams and check dams for proper recharge in this zone so that this zone may not slip towards low GWP zone. Low and very low GWP zones cover around 37.48% of the total area and were associated with highly dissected hills and valleys governed by steep mountainous slopes which were found

predominantly in the central and eastern parts of the study area. Approximately 78% of the land is classified as having moderate to very low GWP, indicating that there is lack of favorable condition for high GWP. The observed results have been validated with groundwater depth of monitoring dug wells with 80% field validity. The outcome of the present study will be helpful for planner and decision makers for proper management of available groundwater in a judicious manner. Similar studies could be carried out for better planning especially in the hilly and foothill regions where the groundwater is crucial for sustainable development.

Acknowledgements The authors would like to thank the Department of Geography at the University of Jammu for providing laboratory space and the Department of Science and Technology (DST) of the Government of India for providing GIS software under the FIST Program. The authors are also thankful to Central Ground Water Board (CGWB), Jammu, Geological Survey of India (GSI), United States Geological Survey (USGS), and National Remote Sensing Centre (NRSC) for providing necessary data to carry out this research work. Beside this, the authors are also indebted to the University Grant Commission (UGC), India, for providing doctoral fellowship as Junior Research Fellowship (JRF) during this research work.

Data availability The data associated with this research are available on request from the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

References

- Allafta, H., Opp, C., & Patra, S. (2021). Identification of Groundwater Potential Zones Using Remote Sensing and GIS Techniques: A Case Study of the Shatt Al-Arab Basin. *Remote Sensing*, 13, 112. <https://doi.org/10.3390/rs13010112>
- Anbazhagan, S., & Jothibas, A. (2016). Groundwater sustainability indicators in parts of Tiruppur and Coimbatore districts, Tamil Nadu. *Journal of the Geological Society of India*, 87, 161–168. <https://doi.org/10.1007/s12594-016-0384-y>
- Andualem, T. G., & Demeke, G. G. (2019). Groundwater potential assessment using GIS and remote sensing: A case study of Gunatana landscape, upper Blue Nile Basin. *Ethiopia. Journal of Hydrology: Regional Studies*, 24, 1–13. <https://doi.org/10.1016/j.ejrh.2019.100610>
- Arulbalaji, P., Padmalal, D., & Sreelash, K. (2019). GIS and AHP techniques based delineation of groundwater

- potential zones: A case study from Southern Western Ghats. *India. Scientific Report*, 9, 2082. <https://doi.org/10.1038/s41598-019-38567-x>
- Balamurugan, P., Kumar, P. S., Shankar, K., Nagavinothini, R., & Vijayasurya, K. (2020). Non-carcinogenic risk assessment of groundwater in southern part of Salem district in Tamilnadu, India. *Journal of the Chilean Chemical Society*, 65(1), 4697–4707.
- Ballerine, C. (2017). *Topographic Wetness Index Urban Flooding Awareness Act Action Support Will and DuPage Counties, Illinois*. Illinois State Water Survey.
- Benjmel, K., Amraoui, F., Boutaleb, S., Ouchchen, M., Tahiri, A., Touab, A. (2020). Mapping of groundwater potential zones in crystalline terrain using remote sensing, GIS techniques, and multicriteria data analysis (case of the Ighrem Region, Western Anti-Atlas, Morocco). *Water*, 12(2), 471
- Bhattacharya, P., Mukherjee, A., Mukherjee, A. B. (2014). Groundwater arsenic in India: Source, distribution, effects and alternate safe drinking water sources. Reference Module in *Earth Systems and Environmental Sciences*. Elsevier. <https://doi.org/10.1016/B978-0-12-409548-9.09342-8>
- Bierkens, M. F. P., Wada, Y. (2019). Non-renewable groundwater use and groundwater depletion: A review. *Environmental Research Letters*, 14 (6), 063002.
- Britannica, E. (2021) Geomorphology. Retrieved from <https://www.britannica.com/science/geomorphology>
- Celik, R. (2019). Evaluation of groundwater potential by GIS-based multicriteria decision making as a spatial prediction tool: Case study in the Tigris River Batman-Hasankeyf Sub-Basin. *Turkey. Water*, 11(12), 1–16. <https://doi.org/10.3390/w11122630>
- CGWB. (2018–19). Groundwater Year Book: Jammu District, Jammu & Kashmir. Jammu.
- CGWR. (2017). National compilation on dynamic groundwater resources of India. Faridabad. India. <http://cgwb.gov.in/GW-Assessment/GWRA-2017-National-Compilation.pdf>
- Charon, J. E. (1974). Hydrogeological applications of ERTS satellite imagery. In: *Proc UN/FAO Regional Seminar on Remote Sensing of Earth Resources and Environment, Cairo*. Commonwealth Science Council, 439–456.
- Chen, Y., Yu, J., & Khan, S. (2013). The spatial framework for weight sensitivity analysis in AHP-based multi-criteria decision making. *Environmental Modelling & Software*, 48, 129–140.
- Duan, H., Deng, Z., Deng, F., Wang, D. (2016). Assessment of groundwater potential based on multicriteria decision making model and decision tree algorithms. *Mathematical Problems in Engineering*, 1-11. <https://doi.org/10.1155/2016/2064575>
- Farooq, M. (2016). Climate change & concerns of j&k. <https://doi.org/10.13140/RG.2.1.2683.8802>
- Ferrari, S., Caballero, Y., Perrin, J., Gascoïn, S., Dewandel, B., Aulong, S., Dazin, F., Ahmed, S., & Maréchal, J. C. (2014). Projected impacts of climate change on farmers' extraction of groundwater from crystalline aquifers in South India. *Scientific Reports*, 4, 3697.
- Gdoura, K., Anane, M., & Jellali, S. (2015). Geospatial and AHP-multicriteria analyses to locate and rank suitable sites for groundwater recharge with reclaimed water. *Resources, Conservation and Recycling*, 104, 19–30.
- Gleeson, T., & Richter, B. (2016). How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers. *River Research and Applications*, 34(1), 83–92.
- Greenbaum, D. (1985). Review of remote sensing applications to groundwater exploration in basement and regolith. British Geological Survey, Nicker Hill.
- GSI (2021). Bhukosh retrieved from <https://bhukosh.gsi.gov.in/>
- Gupta, D., Yadav, S., Tyagi, D., & Tomar, L. (2018). *Multi-Criteria Decision Analysis for Identifying of Groundwater Potential Sites in Haridwar*, 3, 9–15.
- Gupta, M., & Srivastava, P. K. (2010). Integrating GIS and remote sensing for identification of groundwater potential zones in the hilly terrain of Pavagarh, Gujarat. *India. Water International*, 35(2), 233–245. <https://doi.org/10.1080/02508061003664419>
- Hakhoo, S. (2019). State again stares at water scarcity, The Tribune. <https://www.tribuneindia.com/news/archive/j-k/state-again-stares-at-water-scarcity-779557>
- Helena, B., Pardo, R., Vega, M., Barrado, E., Fernandez, J. M., & Fernandez, L. (2000). Temporal evolution of groundwater composition in an alluvial aquifer (Pisuerga River, Spain) by principal component analysis. *Water Resources*, 34, 807–816. <https://doi.org/10.1016/j.jclepro.2020.120311>
- Hussein, A. A., Govindu, V., & Nigusse, A. G. M. (2017). Evaluation of groundwater potential using geospatial techniques. *Applied Water Science*, 7, 2447–2461. <https://doi.org/10.1007/s13201-016-0433-0>
- Ibrahim-Bathis, K., & Ahmed, S. A. (2016). Geospatial technology for delineating groundwater potential zones in Dodahalla watershed of Chitradurga district. *The Egyptian Journal of Remote Sensing and Space Science*, 19(2), 223–234. <https://doi.org/10.1016/j.erjs.2016.06.002>
- Jaiswal, R. K., Mukherjee, S., Krishnamurthy, J., & Saxena, R. (2003). Role of remote sensing and GIS techniques for generation of groundwater prospect zones towards rural development- An approach. *International Journal of Remote Sensing*, 24(5), 993–1008.
- Jasrotia, A. S., Kumar, A., & Singh, R. (2016). Integrated remote sensing and GIS approach for delineation of groundwater potential zones using aquifer parameters in Devak and Rui watershed of Jammu and Kashmir. *India. Arabian Journal of Geosciences*, 9(4), 304.
- Jat, M., Khare, D., & Garg, P. (2009). Urbanization, and its impact on groundwater: A remote sensing and GIS-based assessment approach. *The Environmentalist*, 29, 17–32.
- Jayarajan, S. K. P., & Kuriachan, L. (2021). Exposure and health risk assessment of nitrate contamination in groundwater in Coimbatore and Tirupur districts in Tamil Nadu, South India. *Environmental Science and Pollution Research*, 28, 10248–10261.
- Jha, M. K., Chowdhury, V. M., & Chowdhury, A. (2010). Groundwater assessment in Salboni Block, West Bengal (India) using remote sensing, geographical information system, and multi-criteria decision analysis techniques. *Hydrogeol. Journal*, 18, 1713–1728. <https://doi.org/10.1007/s10040-010-0631-z>

- Kadiyan, N., Chatterjee, R. S., Pranjali, P., et al. (2021). Assessment of groundwater depletion-induced land subsidence and characterisation of damaging cracks on houses: A case study in Mohali-Chandigarh area, India. *Bulletin of Engineering Geology and the Environment*, 80, 3217–3231.
- Karmakar, K. (2019). The Tawi River: Pure and toxic [Blog post]. Retrieved from <https://tushika.com/tawi-river-pure-and-toxic-part-1/>
- Koch, M., Mather, P.M. (1997). Lineament mapping for groundwater resource assessment: A comparison of digital Synthetic Aperture Radar (SAR) imagery and stereoscopic Large Format Camera (LFC) photographs in the Red Sea Hills, Sudan. *International Journal of Remote Sensing*, 18(14).
- Kolli, M., Opp, C., & Groll, M. (2020). Mapping of potential groundwater recharge zones in the Kolleru Lake catchment, India, by using remote sensing and GIS techniques. *Natural Resources*, 11, 127–145.
- Kotchoni, D., Vouillamoz, J., Lawson, F., Adjomayi, P., Boukari, M., & Taylor, R. (2019). Relationships between rainfall and groundwater recharge in seasonally humid Benin: A comparative analysis of long-term hydrographs in sedimentary and crystalline aquifers. *Hydrogeology Journal*, 27, 447–457.
- Kumar, P., Herath, S., Avtar, R., & Takeuchi, K. (2016). Mapping of groundwater potential zones in Killinochi area, Sri Lanka, using GIS and remote sensing techniques. *Sustainable Water Resources Management*, 2(4), 419–430.
- Kumar, V., Mondal, N., & Ahmed, S. (2020). Identification of groundwater potential zones using RS, GIS and AHP techniques: A case study in a part of Deccan Volcanic Province (DVP), Maharashtra, India. *Journal of Indian Soc. Remote Sens*, 48, 497–511.
- Kumar, V., Rai, S. P., Rathore, D. S. (2004). Land use mapping of Kandi belt of Jammu region. *Journal of The Indian Society of Remote Sensing*. 32(4):323–328. <https://doi.org/10.1007/BF03030857>
- Kumari, B., Shahfahad., Tayyab, M., Ahmed, I.A., Baig, M.R.I., Ali, M.A., Usmani, T.M., Rahman, A. (2021). Land use/land cover (LU/LC) change dynamics using indices overlay method in Gautam Buddha Nagar District-India. *Geology Journal*. <https://doi.org/10.1007/s10708-021-10374-w>
- Lakshmi, S. V., & Reddy, Y. V. K. (2018). Identification of groundwater potential zones using GIS and remote sensing. *International Journal of Pure and Applied Mathematics*, 119(17), 3195–3210.
- Leary, O., Friedman, J., & Pohn, H. (1976). Lineament, linear, lineation: Some proposed new standards for old terms. *Geological Society of America Bulletin*, 8, 1463–1469.
- Lee, S., Hyun, Y., Lee, S., & Lee, M. J. (2020). Groundwater potential mapping using remote sensing and GIS-based machine learning techniques. *Remote Sensing*, 12(7), 1200. <https://doi.org/10.3390/rs12071200>
- Machiwal, D., Jha, M. K., & Mal, B. C. (2011). Assessment of groundwater potential in a semi-arid region of India using remote sensing, GIS and MCDM techniques. *Water Resource Management*, 25, 1359–1386.
- Maity, D., & Mandal, S. (2017). Identification of groundwater potential zones of the Kumari river basin, India: An RS & GIS based semi-quantitative approach. *Environment, Development and Sustainability*, 21, 1013–1034.
- Malczewski, J. (1999). *GIS and multicriteria decision analysis*. John Wiley and Sons.
- Mallick, J., Talukdar, S., Alsubih, M., Ahmed, M., Islam, A. R. M. T., Shahfahad., Thanh, N. V. (2021). Proposing receiver operating characteristic-based sensitivity analysis with introducing swarm optimized ensemble learning algorithms for groundwater potentiality modelling in Asir region, Saudi Arabia. *Geocarto International*. <https://doi.org/10.1080/10106049.2021.1878291>
- Ministry of Home Affairs, Government of India. (2011). District Census Handbook. Retrieved from <http://censusindia.gov.in>
- Mogaji, K., Omosuyi, G., Adelusi, A., & Lim, H. (2016). Application of GIS-based evidential belief function model to regional groundwater recharge potential zones mapping in Hardrock Geologic Terrain. *Environ. Process*, 3, 93–123.
- Mokarram, M., Roshan, G., Negahban, S. (2015). Landform classification using topography position index (case study: salt dome of Korsia-Darab plain, Iran). *Model. Earth System Environment*, 1(40).
- Morote, Á. -F., & Hernández, M. (2016). Urban sprawl and its effects on water demand: A case study of Alicante, Spain. *Land Use Policy*, 50, 352–362.
- Mukherjee, A., Saha, D., Harvey, C. F., Taylor, R. G., Ahmed, K. M., Bhanja, S. N. (2015). Groundwater systems of the Indian Sub-Continent. *Journal of Hydrology: Regional Studies*, 4(A), 1–14. <https://doi.org/10.1016/j.ejrh.2015.03.005>
- Murtaza, B., Nazeer, H., Amjad, M., Imran, M., Shahid, M., Shah, N. S., Farooq, A. B. U., Amjad, M., & Murtaza, G. (2020). Hydrogeochemical investigation of arsenic in drinking water of schools and age dependent risk assessment in Vehari District, Punjab Pakistan: A multivariate analysis. *Environmental Science and Pollution Research*, 27, 30530–30541.
- Nabi, G., Ali, M., Khan, S., & Kumar, S. (2019). The crisis of water shortage and pollution in Pakistan: Risk to public health, biodiversity, and ecosystem. *Environmental Science and Pollution Research*, 26, 10443–10445.
- Naikoo, M. W., Islam, A. R. M. T., Mallick, J., & Rahman, A. (2022). Land use/land cover change and its impact on surface urban heat island and urban thermal comfort in a metropolitan city. *Urban Climate*, 41, 101052.
- Nair, H. C., Padmalal, D., Joseph, A., Vinod, P. G. (2017). Delineation of groundwater potential zones in river basins using geospatial tools- An example from Southern Western Ghats, Kerala, India. *Journal of Geovisualization and Spatial Analysis*, 1(1–2). <https://doi.org/10.1007/S41651-017-0003-5>
- Nampak, H., Pradhan, B., & Manap, M. P. (2014). Application of GIS based data driven evidential belief function model to predict groundwater potential zonation. *Journal of Hydrology*, 513, 283–300.
- Nowreen, S., Newton, I. H., Zzaman, R. U., Islam, A. S., Islam, G. T., & Alam, M. S. (2021). Development of potential map for groundwater abstraction in the northwest region of Bangladesh using RS-GIS-based weighted overlay analysis

- and water-table-fluctuation technique. *Environmental Monitoring and Assessment*, 193(1), 1–17.
- NRSC. (1995). Natural Resource Census- Land use land cover database. Technical Report – Ver.1. Retrieved May 2021, from <https://bhuvan-app1.nrsc.gov.in/2dresources/thematic/2LULC/lulc1112.pdf>
- Owolabi, T. S., Madi, K., Kalumba, A. A., & Orimoloye, I. R. (2020). A groundwater potential zone mapping approach for semi-arid environments using remote sensing (RS) geographic information system (GIS) and analytical hierarchical process (AHP) techniques: A case study of Buffalo catchment, Eastern Cape. *South Africa. Arabian Journal of Geoscience*, 13, 1184. <https://doi.org/10.1007/s12517-020-06166-0>
- Pal, S. C., Ghosh, C., & Chowdhuri, I. (2020). Assessment of groundwater potentiality using geospatial techniques in Purba Bardhaman district. *West Bengal. Applied Water Science*, 10(10), 1–13.
- Pal, S., Kundu, S., Mahato, S. (2020). Groundwater potential zones for sustainable management plans in a river basin of India and Bangladesh. *Journal of Cleaner Production*, 257, 120311.
- Patel, R. J., Rank, H. D., Ajudiya, B. H., & Dhanani, N. V. (2014). An assessment of ground water recharge potential through tube well. *International Journal of Engineering and Technical Research*, 3, 155–160.
- Pham, B. T., Jaafari, A., Prakash, I., Singh, S. K., Quoc, N. K., & Bui, D. T. (2019). Hybrid computational intelligence models for groundwater potential mapping. *Catena*, 182, 104101. <https://doi.org/10.1016/j.catena.2019.104101>
- Phiri, D., & Morgenroth, J. (2017). Developments in landsat land cover classification methods: A review. *Remote Sens*, 9, 967.
- Prusty, P., & Farooq, S. H. (2020). Seawater intrusion in the coastal aquifers of India - A review. *Hydrology Research*, 3, 61–74.
- Qadir, J., Bhat, M. S., Alam, A., & Rashid, I. (2020). Mapping groundwater potential zones using remote sensing and GIS approach in Jammu Himalaya Jammu and Kashmir. *Geology Journal*, 85(2), 487–504.
- Rajaveni, S. P., Brindha, K., & Elango, L. (2017). Geological and geomorphological controls on groundwater occurrence in a hard rock region. *Applied Water Science*, 7(3), 1377–1389.
- Ramu, M. B., & Vinay, M. (2014). Identification of ground water potential zones using GIS and remote sensing techniques: A case study of Mysore taluk -Karnataka. *International Journal of Geomatics and Geosciences*, 5(3), 393–403.
- Razavi-Termeh, S. V., Sadeghi-Niaraki, A., & Choi, S. M. (2019). Groundwater potential mapping using an integrated ensemble of three bivariate statistical models with random forest and logistic model tree models. *Water*, 11(8), 1596. <https://doi.org/10.3390/w11081596>
- Riley, S. J. (1999). Index that quantifies topographic heterogeneity. *International Journal of Science*, 5, 23–27.
- Romshoo, S. A., Dar, R. A., Murtaza, K., & O., Rashid, I., & Dar, F. A. (2017). Hydrochemical characterization and pollution assessment of groundwater in Jammu Siwaliks. *India. Environmental Monitoring and Assessment*, 189, 122.
- Roy, S. S., Rahman, A., Ahmed, S., & Shahfahad, & Ahmad, I. A. (2020). Alarming groundwater depletion in the Delhi Metropolitan Region: A long-term assessment. *Environmental Monitoring and Assessment*, 192, 620.
- Saaty, R. W. (1987). The analytic hierarchy process—What it is and how it is used. *Mathematical Modelling*, 9(3–5), 161–176.
- Saaty, T. L. (1990). *Decision making for leaders: The analytic hierarchy process for decisions in a complex world*. RWS publications.
- Saaty, T.L. (1980). *The Analytic Hierarchy Process*; McGrawHill: New York, NY, USA.
- Saranya, T., Saravanan, S. (2020). Groundwater potential zone mapping using analytical hierarchy process (AHP) and GIS for Kancheepuram District, Tamilnadu, India. *Modeling Earth Systems and Environment*. <https://doi.org/10.1007/s40808-020-00744-7>
- Saranya, T., & Saravanan, S. (2020). Groundwater potential zone mapping using analytical hierarchy process (AHP) and GIS for Kancheepuram District, Tamilnadu, India. *Modeling Earth Systems and Environment*, 6(2), 1105–1122.
- Sarkar, S. K., Talukdar, S., Rahman, A., & Roy, S. K. (2021). Groundwater potentiality mapping using ensemble machine learning algorithms for sustainable groundwater management. *Frontiers in Engineering and Built Environment*. <https://doi.org/10.1108/FEBE-09-2021-0044>
- Shaji, E., Santosh, M., & Others. (2021). Arsenic contamination of groundwater: A global synopsis with focus on the Indian Peninsula. *Geoscience Frontiers*, 12(3), 101079.
- Sharma, V., & Arora, S. (2015). Land degradation processes and factors affecting crop production in Foothills of Jammu Shivaliks. *Journal of Soil and Water Conservation*, 14(4), 295–300.
- Shekhara, S., & Pandey, A. C. (2014). Delineation of groundwater potential zone in hard rock terrain of India using remote sensing, geographical information system (GIS) and analytic hierarchy process (AHP) techniques. *Geocarto International*. <https://doi.org/10.1080/10106049.2014.894584>
- Schneider, K. (2018). Circle of Blue, Groundwater scarcity pollution set India on perilous course. <https://www.circleofblue.org/2018/world/groundwater-scarcity-pollution-set-india-on-perilous-course/>. Accessed on 24/11/2021
- Singh, P., Thakur, J. K., & Kumar, S. (2013). Delineating groundwater potential zones in a hard-rock terrain using geospatial tool. *Hydrological Sciences Journal*, 58(1), 213–223.
- Singh, L., Khare, D., Mishra, N. (2018). Remote sensing and GIS for groundwater potential zones Ghagger Watershed, Himachal Pradesh. *Journal of Graphic Era University*, 80–93.
- Soumen, D. (2014). Delineation of ground water prospect zones using remote sensing, GIS techniques—A case study of Baghmundi development block of Puruliya district, West Bengal. *International Journal of Geology, Earth & Environmental Sciences*, 4(2) 62–72. ISSN: 2277–2081 (online). <http://www.cibtech.org/>
- Sreedevi, P. D., Srinivasulu, S., & Raju, K. K. (2001). Hydrogeomorphological and groundwater prospects of the Pageru river basin by using remote sensing data. *Environmental Geology*, 40, 1088–1094.

- Suganthi, S., Lakshmanan, E., & Subramanian, S. K. (2013). Groundwater potential zonation by remote sensing and GIS techniques and its relation to the groundwater level in the coastal part of the Arani and Koratalai River Basin. *Southern India. Earth Sciences Research Journal*, 17(2), 87–95.
- Sutanudjaja, E. (2020). Modeling falling groundwater head declines in major cities of the world: Current situation and future projection, EGU General Assembly 2020, EGU2020-12270. <https://doi.org/10.5194/egusphere-egu2020-12270>
- Talukdar, S., Singha, P., Mahato, S., Shahfahad, Pal, S., Liou, Y. A., Rahman, A. (2020). Land-use land-cover classification by machine learning classifiers for satellite observations— A review. *Remote Sensing*, 12(7), 1135
- Tesfaye, T. (2010). Ground water potential evaluation based on integrated GIS and RS techniques in Bilate river catchment, South rift valley of Ethiopia. *Am Sci Res J Eng Technol Sci (ASRJETS)*, 10(1), 85-120. ISSN (Print) 2313–4410, ISSN (Online) 2313–4402. Global Society of Scientific Research and Researchers. <http://asrjetsjournal.org>
- Thapa, R., Gupta, S., Guin, S., & Kaur, H. (2017). Assessment of groundwater potential zones using multi-influencing factor (MIF) and GIS: A case study from Birbhum district. *West Bengal. Applied Water Science*, 7, 4117–4131.
- The United Nations World Water Development Report. (2021). *Valuing Water*. UNESCO.
- Tolche, D. T. (2021). Groundwater potential mapping using geospatial techniques: A case study of Dhungeta-Ramis su3b-basin. *Ethiopia, Geology, Ecology, and Landscapes*, 5(1), 65–80.
- UN WWDR. (2018). <http://www.unwater.org/>
- UNESCO. (2021). Groundwater: The invisible resource. Retrieved from <https://en.unesco.org/news/groundwater-invisible-resource-0>
- Velis, M., Conti, K. I., & Biermann, F. (2017). Groundwater and human development: Synergies and trade-offs within the context of the sustainable development goals. *Sustainability Science*, 12, 1007–1017. <https://doi.org/10.1007/s11625-017-0490-9>
- Wen, C.F., Wuing, L.C. (2012). Estimation of the spatial rainfall distribution using inverse distance weighting (IDW) in the middle of Taiwan. *Paddy Water Environment*10(3). <https://doi.org/10.1007/s10333-012-0319-1>. ISSN 1611–2490 Vol. 10 No. 3.
- Wilopo, W., Putra, D. P. (2021a). Groundwater recharge estimation using groundwater level fluctuation patterns in unconfined aquifer of Yogyakarta City, Indonesia. *Kuwait Journal of Science*, 48(2).
- Wilopo, W., Putra, D. P. E., & Hendrayana, H. (2021b). Impacts of precipitation, land use change and urban wastewater on groundwater level fluctuation in the Yogyakarta-Sleman Groundwater Basin. *Indonesia. Environmental Monitoring and Assessment*, 193(2), 1–14.
- Yan, X., Zhu, Z., & Li, T. (2019). Pollution source localization in an urban water supply network based on dynamic water demand. *Environmental Science and Pollution Research*, 26, 17901–17910.
- Yildirim., U. (2021). Identification of Groundwater potential zones using GIS and Multi criteria decision making techniques: A case study of upper Coruh river basin (NE Turkey). *International Journal Geo Information*. 10(396).
- Zubaidi, S. L., Ortega-Martorell, S., Al-Bugharbee, H., Olier, I., Hashim, K. S., Gharghan, S. K., Kot, P., & Al-Khaddar, R. (2020). Urban water demand prediction for a city that suffers from climate change and population growth: Gauteng province case study. *Water*, 12(7), 1885.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.