GROUND WATER POTENTIAL ZONING USING GIS AND AHP: CASE STUDY OF BAGMATI RIVER BASIN, NEPAL

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ABSTRACT

Groundwater supplies around the world are under tremendous pressure due to overuse and noticeable climatic changes over time. The requirement to assess groundwater potential and aquifer productivity rise along with the global need for potable water for human consumption, agriculture, industrial applications and to maintain the ecological balance. GIS based techniques are being widely used to determine the potential zones for ground water as it provides quick and first-hand information for further decision making. In this study, factors affecting the potential of groundwater availability such as material factors like geology, near surface and sub-surface soil features, structure, and drainage patterns and replenishment factors like rainfall, land use type, slope and lineament density were used in the GIS platform to perform the Multi Criteria Decision Analysis (MCDA) and weight allocation for each thematic layer was determined by AHP method . Bagmati river basin of Nepal having the area of 4337 sq.km was delineated in five categories namely Very Low, Low, Moderate, High and Very High as the potential of ground water availability. The result showed that 1 % of study area falls in the Very Low zone, 25 % in the Low zone, 45 % in the Moderate zone, 17 % in the High and 12% in the Very High zone of ground water potential. Also ground water potential zones were cross validated with reference to the available groundwater sources in the study region. Most of the available ground water sources lie in the high and very high zone of ground water potential within the basin.

KEYWORDS: Groundwater Potential, Bagmati River Basin, GIS, AHP, MCDA

1. INTRODUTION

Water present beneath Earth's surface in rock and soil pore spaces and in the fractures of rock formations. About 30 percent of all readily available freshwater in the world is groundwater. So, it's the most important and vital natural resource of water for domestic, industrial, agricultural and many other development works. Groundwater is a significant source of water for agricultural and drinking purposes in Nepal also. Approximately twenty percent of irrigated agriculture, mostly in the Terai, uses groundwater and over fifty percent of people in the Kathmandu Valley use groundwater, frequently through shallow wells, as do eighty percent of people in Siwalik (USAID, 2021). according to the country report of UNICEF,2020, more than one third of the total population of Nepal don't have the access to the improved sanitation and furthermore more than ten percent of the total population don't even have the access to the basic water facilities. However, only ten percent of the total potential renewable ground water is being extracted annually (USAID, 2021). So, these facts infer that although Nepal couldn't have used all the potential of ground water resource to manage the basic water and improved sanitation facilities, there is unbalanced extraction of groundwater which is affecting the natural recharge cycle and the ecology.

Exploration and effective management of groundwater, a valuable natural resource, are crucial to choosing the best places for groundwater recharge, monitoring wells, water supply, and groundwater quality (Jha et al., 2010). The presence of groundwater is influenced by several physio-climatic and hydrogeological factors, including lithological structures, primary and secondary porosity, slope angle, geomorphological landforms, land use/land cover, drainage pattern, distribution and intensity of rainfall, and other physio-climatic conditions, which aid in identifying groundwater potential zones (Melese et al., 2021).

The groundwater potential varies spatially because of the large regional variation in the processes governing groundwater occurrence. However, the development of geospatial and remote sensing technologies to collect and analyse spatial data has made them effective tools in hydrogeology, notably for the assessment of ground water potential zones (Arnous, 2016; Dadgar et al., 2017). Traditionally, expensive and time-consuming ground surveys using geological, geophysical and hydrogeological tools and techniques have been used to identify, delineate and map the groundwater potential zones (Israil et al., 2006). Literatures reveal that several researchers have been using GIS to delineate groundwater potential zones with the integration of statistical approach such as simple additive weight (SAW) and analytic hierarchy process (AHP) (Israil, et al., 2006; Jaafarzadeh et al., 2011; Jha et al., 2010; Karki et al., 2021) and, machine learning (Kumar P. et al., 2016, Kumar R. et al., 2021; Machiwal et al., 2011). AHP is the most popular and widely used of Multi-Criteria Decision Analysis (MCDA) techniques to delineate groundwater prospecting zones. Hence, this research work will focus on the identification and classification of ground water potential zone in Bagmati river basin (BRB) using the integrated approach of AHP and GIS. The output of this research will provide valuable information to develop sustainable groundwater resource in BRB area. Also, this research will also create a suitable model to be implemented in other river basins of Nepal to delineate the ground water potential and ultimately sustainable groundwater management of the whole country.

2. METHODOLOGY

2.1 Study Area

The BRB encompasses 4337 sq. km and has an elevation range of 55 to 2903 m. It is physically bound between 85° 1′ E to 85° 57′ E longitude and 26° 45′ N to 27° 49′ N latitude (Figure 1(b)). The Bagmati River has six tributaries: Bishnumati, Dhobikhola, Manahara, Nakkhu, Balkhu, and Tukucha. The Bagmati River finds its source in the northern mountain highlands of Kathmandu, Baghdwar (at an altitude of 2690 m) and flows through Nepal's 196 km long section before merging with the Ganges in India.

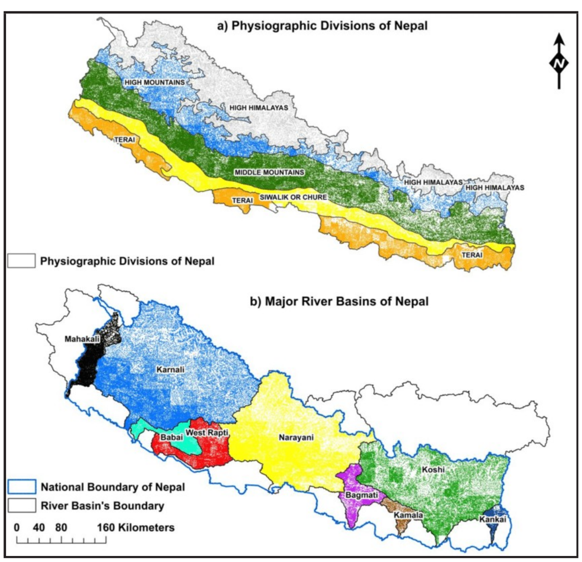
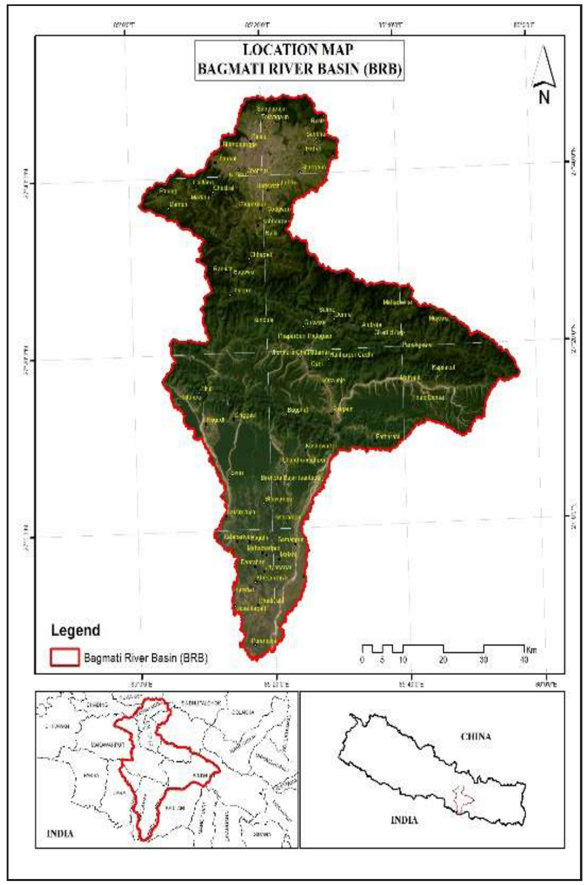


Figure 1(a) Physiographic (above) and Major River watershed basins (below) of Nepal (Karki et al., 2021)



Among nine watershed of Nepal, Bagmati river basin is the small river basin lies on the southern part of the country, and it consists of Middle Mountain, Siwalik region and Terai region as shown in Figure 1(a).

Although aquifers are frequently transboundary and can be damaged by groundwater pumping in India, lowland parts in the Terai have extremely productive alluvial aquifers (250 m deep) and robust recharging. Hard rock aquifers in the Siwalik have erratic groundwater availability, and productivity and recharge are average. Only few studies of groundwater potential in the Bagmati River Basin which is responsible for the water supply of countries' big cities, capital Kathmandu, Bhaktapur, Lalitpur, Chitwan etc…

2.2 Methodological flowchart

Geospatial multi-criteria decision analysis was carried out in the GIS environment to delineate the ground water potential of the BRB using the seven criteria's namely geology, soil, annual rainfall, slope, drainage density, lineage density, land use/land cover. Overall methodological flow diagram is shown in Figure 2.

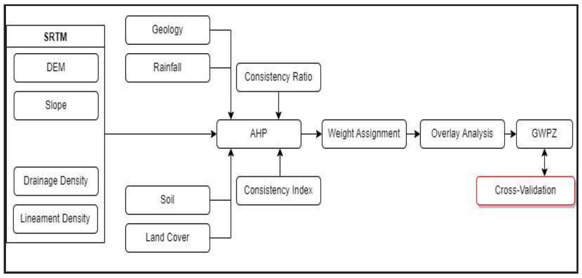


Figure 2. Flow chart of overall methodology

2.3 Data

Data required to prepare such layers was collected from various sources and formats as shown in Table 1.

Table 1. Data properties (Source, resolution, and format)

Data layer	Agency	Portal	Resolution
Global digital elevation model	NASA and JSS	https://www.earthdata.nasa.gov/	30m
Land use land cover	ICIMOD	http://rds.icimod.org/	30m
Geology	U.S. Geological Survey, Central Energy Resources Team	http://energy.cr.usgs.gov	
Soil	FAO-UNESCO World soil map	https://data.apps.fao.org/	
Annual rainfall	ICIMOD	http://rds.icimod.org/	100m

2.4 Data preparation

Pre-processing of each layer was performed to prepare the above mentioned seven layers using ArcGIS v10.8. First, BRB extent and boundary were delineated using DEM and hydrology tool and used as the study area. All data layers were clipped to the extent of study area and resampled to the raster of 30m resolution. WGS 1984 spheroid with UTM 45 N projection was used as the coordinate reference system.

Seven thematic influencing parameters such as slope, soil, geology, LULC, drainage density, lineage density and rainfall were prepared using the data collected as mentioned above.

2.4.1 Drainage Density: Drainage density indicates the closeness of the streams channel and can be calculated as the total length of streams and waters in the watershed divided by the total area of the drainage watershed. DEM was used to extract the drainage lines in the watershed and kernel density function available in ArcGIS was used to calculate the drainage density as shown in Figure 2. The drainage density has the inverse relationship with groundwater potential. Higher the drainage density, there is less probability of ground water potential (Choudhari et al., 2014). So, drainage density map of the watershed was categorized into five class as per the natural break classification method and rank was assigned from 1-9 such that lower density gets the higher rank and vice versa (Table 5) and drainage density map is shown in Figure 3.

2.4.2 Slope: Slope is one of the important factors for the ground water potential as slope determines the amount of water available for recharge and the ruggedness in the terrain of any watershed. Terrain having lower slope prevents the runoff and allows higher infiltration of water to recharge the ground water (Singh et al., 2018). The slope for this study was generated from the SRTM DEM and classified into five class. Rank for each class was assigned from 1-9 inversely with the slope value as shown in Table 5 and slope map is shown in Figure 4.

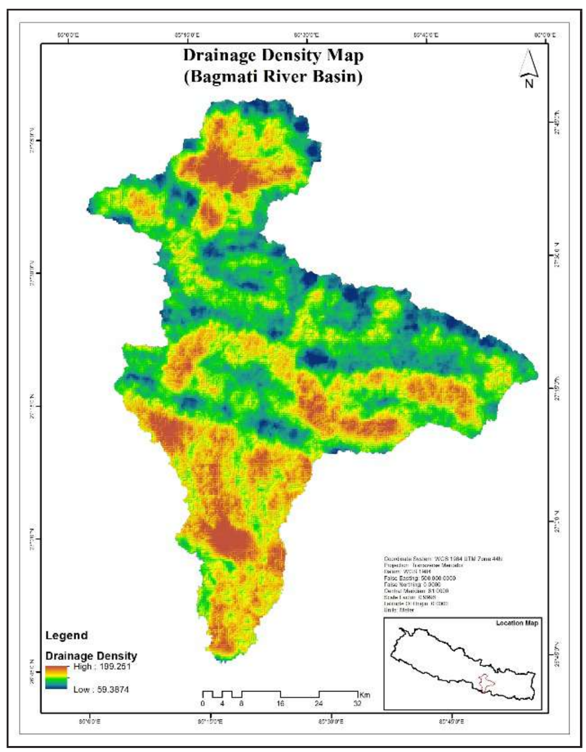


Figure 3. Drainage density map

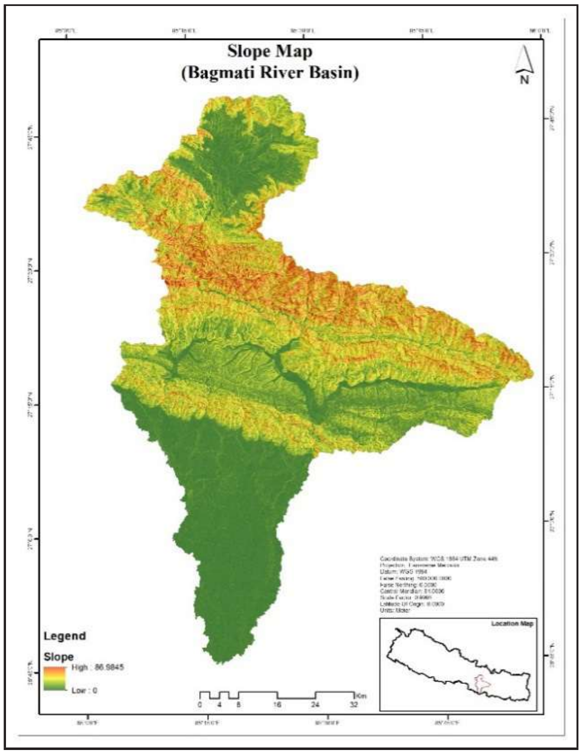


Figure 4. Slope map

2.4.3 Soil: Types of soil of the basin plays an important role for ground recharge and water holding capacity of the area as well. So, it is considered as the one of the important factors for ground water potential zonation (Kumar et al., 2016). There is major three types of soils in the study area namely Dystric Cambisols, Dystric Regosols and Eutric Fluvisols. Maximum portion of the area i.e 79% contains the cambisols , 7% by Regosols and rest 14% by Fluvisols soil type (Figure 5). Among them Cambisols are formed in materials with a medium to fine texture that come from a variety of rocks, primarily in alluvial, colluvial, and aeolian deposits and have medium capacity to recharge the ground water. Whereas Regoslos are weakly developed soils classified as Leptosols (very shallow soils), Arenosols (sandy soils), or Fluvisols are not included in the Regosols (in recent alluvial deposits) and have low infiltration and recharge capacity for ground water. On all continents and in all climate zones, fluvisols are found on alluvial plains, river fans, valleys, and tidal marshes. Periodic flooding is rather typical under natural conditions. The stratification of the soils is seen in the soils and very good recharge and infiltration capacity. Detail soil classification map is shown in Figure 6.

2.4.4 Geology: Lithology or say geology influence ground water potential significantly (Melese et al., 2021). The geology of the study area is made up of Mesozoic and Paleozoic intrusive and metamorphic rocks Neogene sedimentary rocks, undivided Paleozoic rocks, Quaternary sediments and undivided Precambrian rocks. Among these Quaternary sediments and Mesozoic and Paleozoic intrusive rocks mostly favours the infiltration and ground water recharge. Ranking of each geology class is presented in Table 5 and geological map of study area is shown in Figure 7.

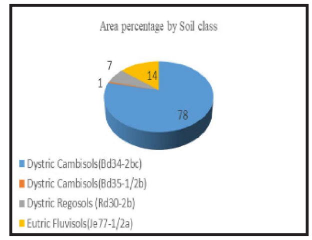


Figure 5 Soil Classification area

2.4.5 Rainfall: Rainfall is a crucial factor in determining the potential of groundwater and the main hydrological sources of groundwater storage (Arulbalaji et al., 2019). Rainfall is maximum across the central part of the study area and decreases towards the north and south region as shown in Figure 8. Ranking of the rainfall class was directly proportional to the amount of rainfall as shown in Table 5.

2.4.6 Land use Land cover (LULC): Land use land cover plays an important role in recharge, occurrence and availability of groundwater (Selvam et. al., 2015). Land use land cover data used in this study was well prepared by ICIMOD using remote sensing techniques into eleven classes namely, waterbody, glacier, snow, forest, riverbed, built-up area, cropland, bare soil, bare rock, grassland and other wooden land. Ranking for each class is as per the Table 5 and land use land cover map is shown in Figure 9.

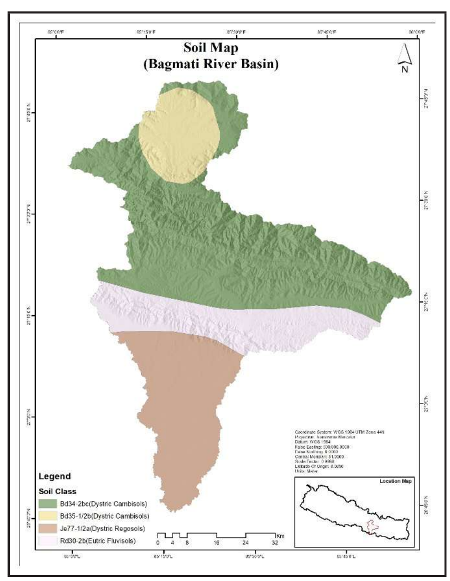


Figure 6. Soil map

2.4.7 Lineage density: Lineament is a linear geographical feature that represents underlying lithology in a landscape and is defined as the total length of the lineament per area of consideration and created using the hill shades of the study area at various angle of azimuth and altitudes. As lineament density is directly proportional to the ground recharge zone directly as with more lineament, more fracture will be in the area for water infiltration and mobility.

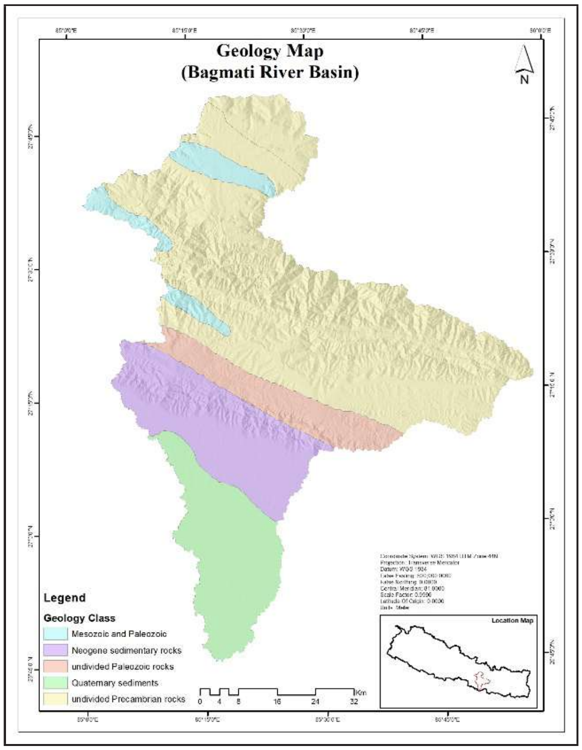


Figure 7. Geology map

2.5 Analytical Hierarchical Processing (AHP)

One of the best approaches to make the complex decision-making problems is Analytical Hierarchical Process (AHP) based multi-criteria decision analysis (MCDA) making. AHP is the widely accepted model used to define the weight of each criterion associated in the MCDA. (Saaty, 1980) defined AHP is a structured method for analysing and solving complex decision problems by decomposition, comparative judgments and synthesis of priorities. A problem's fundamental components are

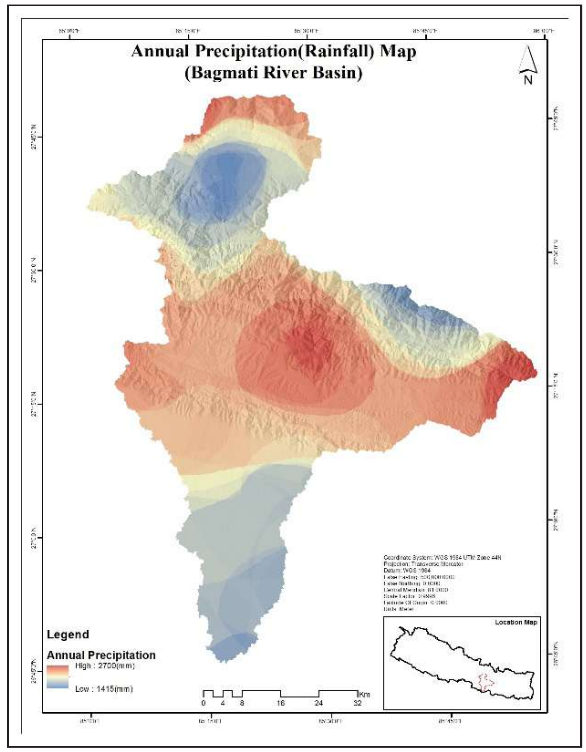


Figure 8. Annual precipitation (Rainfall) map

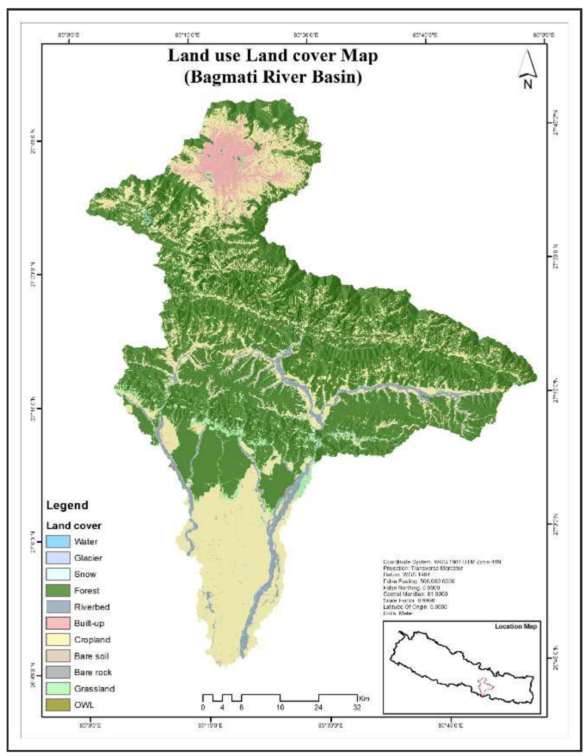
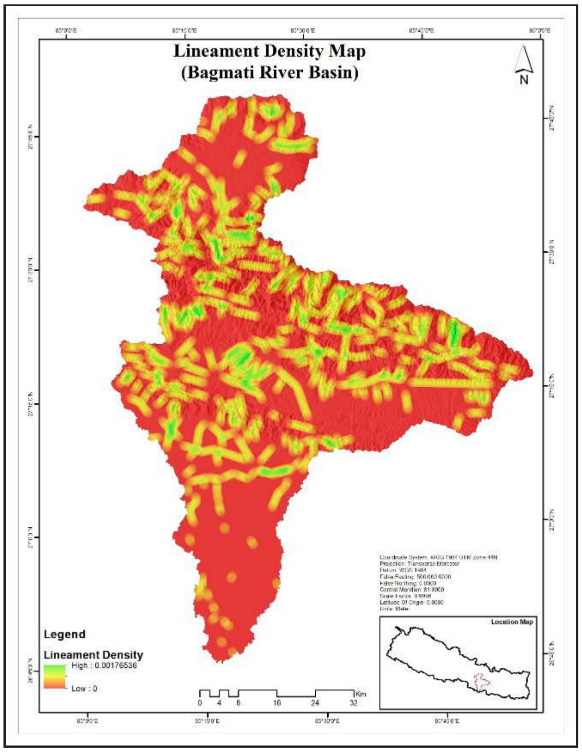


Figure 9. Land use land cover map



captured through its deconstruction, and a hierarchical structure is created by arranging the goal, objectives, attributes, and possibilities. By comparing two components at once, the pairwise comparison lowers the conceptual complexity of the issue. A comparison matrix is created to evaluate the relative relevance of each level's components in relation to those in the nearby high-level hierarchy, and expressed as

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & 1 & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & \cdots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & \cdots & 1 \end{bmatrix}$$

$$\text{where } a_{ij} = \frac{weight\ for\ attribute\ i}{weight\ for\ attribute\ j}$$

By normalizing the eigenvector of the pairwise comparison matrix that corresponds to the highest eigenvalue, the relative importance of each element is calculated. Based on the expert's opinion and review of pertinent literatures (Machiwal et al., 2011; Rahmati et al., 2015; Maheswaran et al., 2016; Arulbalaji et al.,2019; Ajay Kumar et al., 2022), influence level of each parameter for ground water potentiality was recognized and comparative weights for each factor was assigned. The AHP approach can be used to arrange both quantitative (objective) and qualitative (subjective) information concerning decision-making analysis. Each criterion was assigned a rank from 1 to 9 based on their relative importance as per Table 5 and pairwise comparison was matrix was prepared as shown in Table 3. While preparing pairwise comparison matrix, degree of preferences of one factor over another is analysed and ranked as per the Table 2 by the subject experts. Total of five expert's response was collected and averaged with one factor as per the literature as well (Machiwal et al., 2011; Rahmati et al., 2015; Maheswaran et al., 2016; Arulbalaji et al., 2019; Ajay Kumar et al., 2022).

The final weight of each prospect was calculated then by determining the principal Eigenvalue of the generated pairwise comparison matrix. The reliability of the weight assignment process was monitored by calculating the Consistency Index (CI) and Consistency Ratio (CR) values. One of the strengths of the AHP method is that it allows for inconsistent relationships while providing a CR as an indicator of the degree of consistency or inconsistency (Chen et al., 2010).

Table 2. Description of scales for pair comparison with AHP (source: Saaty 1990)

Scales	Degree of Preferences	Descriptions
1	Equally important	The contribution of the two factors is equally important.
3	Slightly important	Experiences and judgment slightly tend to a certain factor
5	Quite important	Experiences and judgment strongly tend to a certain factor.
7	Extremely important	Experiences and judgment extremely strongly tend to a certain factor
9	Absolutely important	There is sufficient evidence for absolutely tending to a certain factor
2,4,6,8	Intermediate values	There is sufficient evidence for absolutely tending to a certain factor

Table 3. Pairwise comparison matrix of seven parameters

Parameters	Geology	Soil	Slope	Rainfall	Lineage Density	LULC	Drainage Density	Geometric Mean	λ
Geology	1.00	1.13	1.20	1.58	1.58	1.88	2.40	0.20	7
Soil	0.88	1.00	1.06	1.39	1.39	1.66	2.12	0.18	7
Slope	0.83	0.94	1.00	1.32	1.32	1.56	2.00	0.17	7
Rainfall	0.63	0.72	0.76	1.00	1.00	1.19	1.52	0.13	7
Lineage Density	0.63	0.72	0.76	1.00	1.00	1.19	1.52	0.13	7
LULC	0.53	0.60	0.64	0.84	0.84	1.00	1.28	0.11	7
Drainage Density	0.42	0.47	0.50	0.66	0.66	0.78	1.00	0.08	7

(Saaty, 1990) recommended that, assigned weights are consistent only when the consistency ratio remains within 10% otherwise needs to be reconsidered to eliminate the irregularity. To calculate the Consistency Ratio, first Principal Eigen value (λ_{max}) is calculated as;

$$\lambda\text{max} = \frac{49}{7} = 7$$

Then, Consistency Index (CI) is calculated as.

$$CI = (\lambda\max - n)/(n - 1)$$

Where $\lambda_{max} = 7$ is the principal Eigen value and n = 7 is the number of factors used in the analysis.

Therefore,

$$CI = \frac{7-7}{7-1} = 0$$

Now, Consistency ration (CR) is calculated as the ratio of Consistency Index (CI) and Random Consistency Index (RCI) obtained from Saaty's standard for 7th order of matrix (Table 5).

$$CR = \frac{CI}{RCI} = \frac{0}{1.32} = 0$$

According to (Saaty, 1990), CR of 0.10 or less is sufficient to continue the analysis. If the consistency value is larger than 0.10, the judgment needs to be reviewed to identify the underlying causes of the inconsistency and make the necessary corrections. CR of 0 indicates there is the perfect level of consistency in the pair-wise comparison matrix.

2.6 Ground Water Potential Zoning (GWPZ)

The groundwater recharge potential map was generated by considering the comparative importance of various thematic layers and their corresponding classes. GWPZ, a dimensionless quantitative approach was adopted to delineate groundwater potential zone.

$$GWPZ = \sum(r_{ij} * w_i)$$

Where, (w_i) is the weight for each parameter layer and (r_{ij}) is the rank for each layer classes. The result of the Ground Water Potential Zoning using MCDA using AHP is shown in Figure 12 and 13 and discussed in following section.

Table 5. Weighted parameters and ranked class parameters

Wt.	Parameter	Class	Rank
18	*Soil*	Bd35-1/2b(Dystric Cambisols)	7
		Bd34-2bc (Chromic Cambisols)	4
		Rd30-2b (Dystric Regosols)	2
		Je77-1/2a (Eutric Fluvisols)	9
13	*Lineament Density*	(0 - 0.1523)m per sq. m	1
		(0.1524 - 0.4223)m per sq. m	2
		(0.4224 - 0.6785)m per sq. m	3
		(0.6786 - 0.9623)m per sq. m	4
		(0.9624 - 1.7654)m per sq. m	5
20	*Geology*	Mesozoic and Paleozoic intrusive	8
		Neogene sedimentary rocks	3
		Paleozoic rocks	7
		Quaternary sediments	9
		Precambrian rocks	6
11	*Land use land cover*	Waterbody	9
		Snow	7
		Forest	8
		Riverbed	7
		Built-up area	3
		Cropland	6
		Bare soil	4
		Bare rock	2
		Grassland	3
		Other wooded land	4
17	*Slope*	0 - 10	8
		11-25	6
		26-40	4
		41-55	3
		56-90	2
13	*Rain Fall*	(1,415 - 1,717) mm	3
		(1,718 - 1,919) mm	4
		(1,920 - 2,115) mm	6
		(2,116 - 2,282) mm	8
		(2,283 - 2,700) mm	9
8	*Drainage Density*	(59.3874 - 91.1996)m per sq. m	8
		(91.1997 - 109.2996)m per sq. m	6
		(109.2997 - 127.3996)m per sq. m	4
		(127.3997 - 149.3391)m per sq. m	3
		(149.3392 - 199.2513)m per sq. m	2

3. RESULTS AND DISCUSSION

The result of the Ground Water Potential Zoning (GWPZ) of Bagmati River Basin (BRB) with Multi Criteria Decision Analysis (MCDA) using Analytical Hierarchical Process (AHP) and Geographic Information System (GIS) is shown in Figure 12 and 13. The resulted map is zoned into five categories of ground water potential namely, very low,

low, moderate, high, and very high. From the map, most of the central region and the upper region of the study area is in the moderate zone, mountainous region of the central and lower region are categorized as the low ground water potential zone, and some patches in Siwalik regions have very low ground water potential. Valley and Lower plane land of the study area in the southern part and northern part of the study area are zoned in high and very high category.

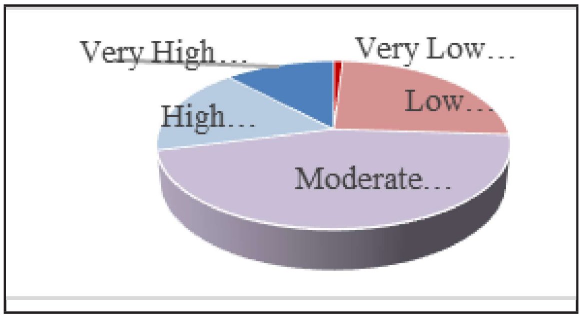


Figure 11. Aerial distribution of ground water potential zones of Bagmati river basin

As per figure 11, less than the half of the study area (45 %) is zoned in the moderate zone for ground water potential, 25 % and 1 % of the study area is in low and very low ground water potential zone respectively. Whereas 17 % of the study area shows the high potential of ground water potential and 12 % of the basin possess very high potential for ground water resource. From figure 13, it is seen that settlements are in the area with higher potential of ground water. Kathmandu Valley which comprises the valley of Kathmandu, Bhaktapur and Lalitpur districts has high potential of ground water. More than 50 % of people of Kathmandu valley uses groundwater frequently through sallow wells (USAID, 2021). Similarly, in the central region of Sindhuli district where there is the high potential of ground water, we can see the dense settlements. Moreover, in the low land area, there is very high dense settlements and has very high potential of ground water.

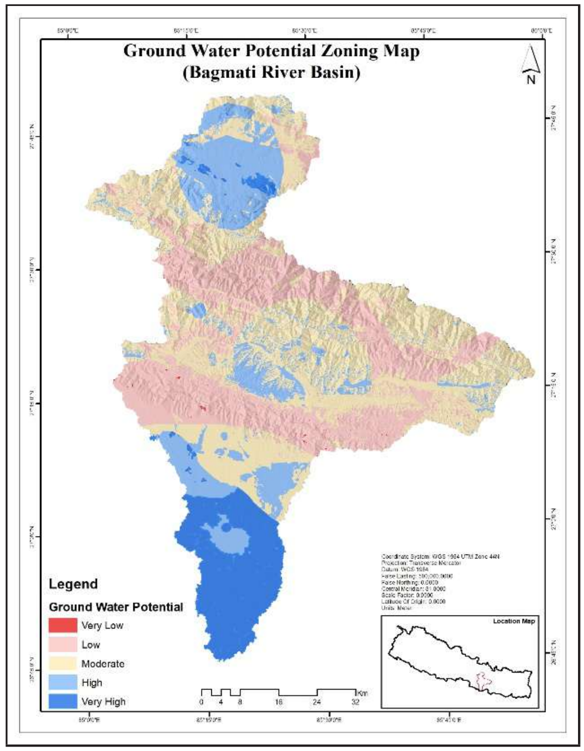


Figure 12. GWPZ and Administrative units and settlements in BRB

3.1 Cross-validation

The ground water potential zone map is further cross verified using the secondary data sources and comparing the result with the other research outputs. As water flows from aquifers into surface water bodies at seeps or springs, or infiltrates from rivers or lakes into aquifers, there is the strong relationship and dependency between the ground water level and waterbodies in the surface. Hence, the GWPZ map overlaid with the still water bodies such as lakes, ponds, reservoirs etc.... of the study area (Figure 14).

Almost 72 % of the waterbodies lie within the very high zone, approximately 20 % of the waterbodies lie on the high zone, 6% of it lie in the Moderate zone and the rest 2% of the water bodies lie in the low and very low zone of the ground water potential zone (Figure 15).

In figure 16, the relationship between the elevation and distance from river is shown with the ground water level,

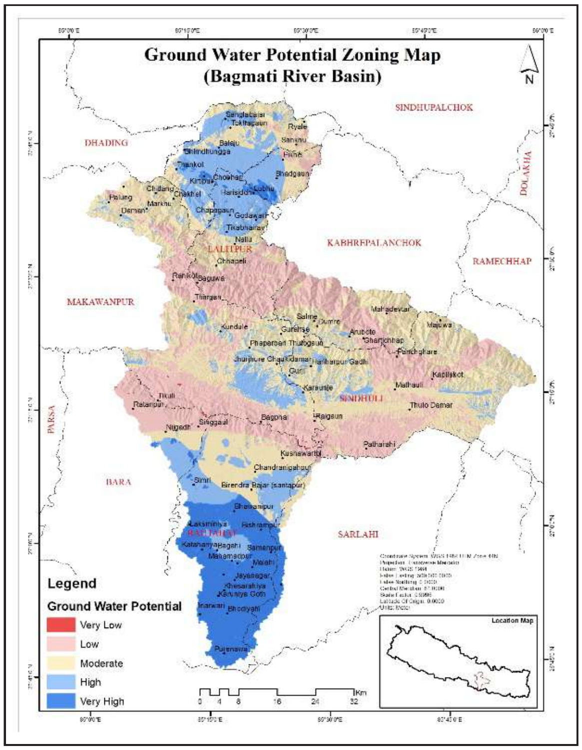


Figure 13. Ground water potential zoned map of Bagmati river basin

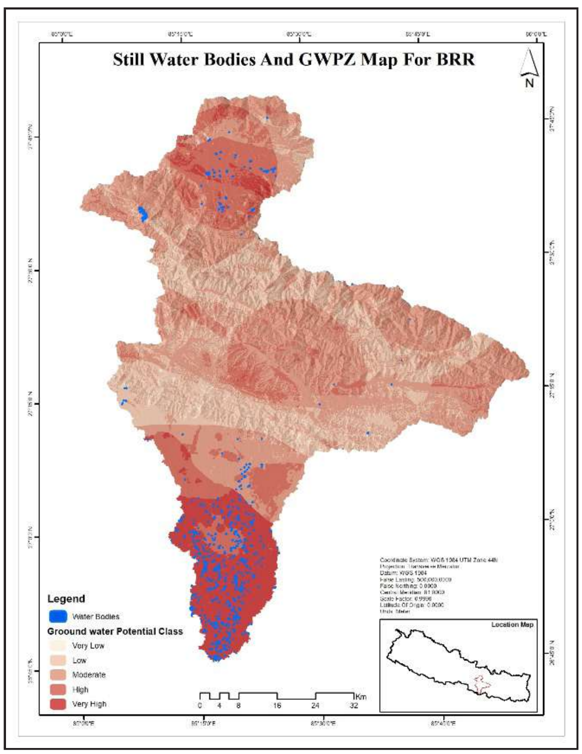


Figure 14. Still water bodies overlaid with GWPZ map

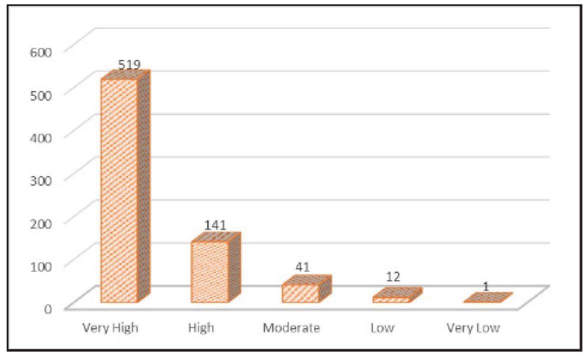


Figure 15. Number of Still water bodies in each zone of GWPZ map

and signifies that, near the distance from the river, near the ground water table from the surface i.e. more ground water potential (Akiyama et al.,2012). When overlaying the river area over the GWPZ map, figure 17 was obtained. In figure 17, most of the areas near the river possess higher potential of ground water and accumulation or amount of water in the river tends to increase the potential of ground water as well.

(Thakur et al., 2016) calculated the Water Poverty Index (WPI) for the upper basin region of Bagmati river basin. WPI explains about the poverty of water based on resource, access, capacity, use, and environment (Thakur et al., 2016). As per the figure 18(b), eastern part, Lubhu has the higher WPI index, inferring the proper accessibility of water resources. This could be due to the abundant availability of ground water resources in the area, which is also supported by the GWPZ map of the area. But in the northern part of the Kathmandu valley, Sundarijal also has a higher WPI but does not fall in the high or very high GWPZ, this is because Sundarijal is the gateway of the Melamchi River drinking water project and has lots of infrastructure for water access. Whereas the red circle in figure 18(b) suggests the area with low WPI and the area with low GWPZ. So, the comparative analysis of WPI for upper Bagmati river basin also supports the obtained result of GWPZ map.

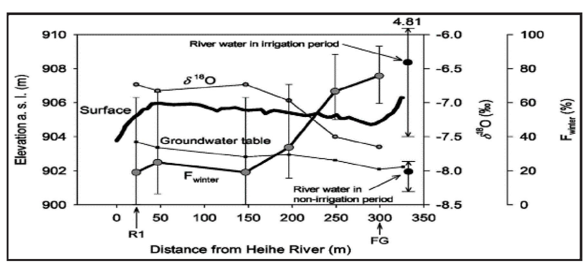


Figure 16. Relation between the distance from river and

ground water level (Akiyama et al., 2012)

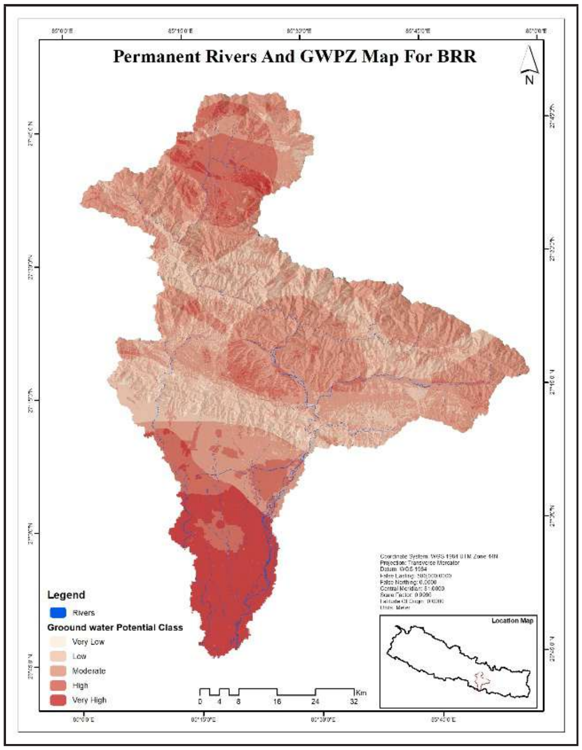


Figure 17. Rivers overlaid with GWPZ map of BRB

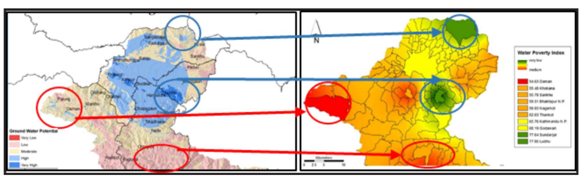


Figure 18. (a) GWPZ map of Upper BRB	Figure 18. (b) WPI map of Upper BRB (Thakur et al., 2016)

4. CONCLUSION

Ground water, yet being the important source of renewable water resource, has not been used and managed to fulfill the need of the drinking and sanitation need of the people. Identification and assessment of groundwater potential zone is the preliminary and vital step towards the use and management of ground water. MCDA techniques with the help of AHP in GIS platform has been proved to be the efficient way of modeling the ground water potential zones based on the various geomorphological, physiographical, lithological and climatic factors namely, Slope, Drainage density, Lineage density, Geology, Soil, Land use Land cover and Rainfall. Weight for each parameter was determined using the AHP process.

Weighted overlay of those seven variables was used to divide the study area into five zones namely, very low, low, moderate, high and very high zone for ground water potential, depending upon the value of each pixel. Plain lands and valley of the study area consist of high and very high potential zone for ground water and covers 17 % and 12% respectively of the Bagmati river basin. Siwalik region and higher mountainous regions tend to have very low and low potential for ground water with 25% and 1% of the study area. The rest of the region falls within the moderate zone for ground water potential. The map of ground water potential was cross verified using the still water bodies and past research in the similar study area and supports the obtained result.

So, Multi-criteria Decision Analysis (MCDA) using weighted overlay of various prospects of ground water using Analytical Hierarchical Process (AHP) in Geographic Information System (GIS) can be very useful for government bodies, policy makers, urban planners, infrastructure developers, environmentalist and any other enthusiasts about the ground water to get the basic insights regarding the ground water availability of the region and to develop the sustainable irrigation, drinking water and sanitation management system(model) by the optimum use of the renewable ground water.

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