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# Identification of Groundwater Potential Zones: A Case Study in Bagmati River Basin

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***Abstract***
*The availability of clean and reliable groundwater is essential for the sustainment of human and environmental health. Groundwater is a crucial resource that contributes significantly to the total annual supply. However, over-exploitation has depleted groundwater availability considerably and led to some land subsidence. Determining the potential zone of groundwater is vital for protecting water quality and managing groundwater systems. Groundwater potential zones are marked with the assistance of Geographic Information System techniques. During the study, a standard methodology was proposed to determine groundwater potential using an integration of GIS and AHP techniques. When choosing the prospective groundwater zone, accurate information was generated to get parameters such as geology, slope, soil, temperature, rainfall, drainage density and lineament density. However, identifying and mapping potential groundwater zones remains challenging due to aquifer systems' complex and dynamic nature. Then, ArcGIS was incorporated with a weighted overlay and appropriate ranks were assigned to each parameter group. Through data analysis, MCDA was applied to weigh and prioritize the different parameters based on their relative impact on groundwater potential. There were three probable groundwater zones: low potential, moderate potential, and high potential. Our analysis showed that the central and lower parts of the Bagmati River Basin have the highest potential, i.e., 7.20% of the total area. In contrast, the northern and eastern parts have lower potential. The identified potential zones can be used to guide future groundwater exploration and management strategies in the region.*
***Keywords:*** *Groundwater, Geographic Information System, Analytic Hierarchy Processes, Multi-Criteria Decision Analysis, Bagmati*

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## I. Introduction

Groundwater, found underground in soil pores and fractures, is a crucial resource for domestic and agricultural purposes (Jena, 2015). However, groundwater availability and quality can vary significantly depending on the location and geology of an area. Identifying and prioritizing potential groundwater zones is vital for sustainable resource management and development in this context. This study aims to use geospatial technologies and analytical tools, namely GIS (Geographic Information Systems) and AHP (Analytical Hierarchy Process), to identify and prioritize areas with the highest potential for groundwater development. GIS allows for the integration, visualization, and analysis of various data layers in a spatial context, such as geology, topography, and land use. AHP is a decision-making tool that helps to prioritize and rank the different factors based on their importance and influence on the overall objective.

Given the increasing demand for water for various purposes like agricultural, domestic, industrial etc., a greater emphasis is being laid on a planned and optimal utilization of water resources. It has resulted in an increased focus on the development of groundwater resources. Groundwater is one of the most natural resources supporting human health and ecology. Under the water table, the pore space and geological structure are filled with subsurface water. The water travels through the aquifer and is discharged into wells, lakes, oceans, and other bodies of water. Because of its intrinsic properties, groundwater has emerged as a crucial and dependable source of water supply in all climatic regions, including urban and rural areas of established and emerging nations (Alireza Arabameri, 2019).

Groundwater is a dynamic system and a replenishable resource of the Earth's surface). Its flow rate is controlled by the rock's properties: porosity and permeability. Steep slopes convey higher runoff, while topographical depressions increase infiltration. The primary sources of groundwater recharge are precipitation and flow and discharge, including seepage into the streams and lakes, springs, evaporation and pumping It is estimated that around 34% of the world's population uses groundwater for drinking,80% of rural areas use groundwater for domestic purposes, and 50% of urban regions use groundwater for domestic purposes. More dependent on the usage of groundwater for domestic purposes and irrigation and other sectors may result in the exploitation of groundwater resources. The developments of GIS technologies coupled with Multi-Criteria Decision Analysis (MCDA) provide a new scientific inquiry in hydrogeological studies. MCDA using Analytic Hierarchy Process (AHP) is the most common and well-known method for delineating groundwater potential based on multi-parameters. It is a technique used to simplify the problems of applying multiple parameters by decision-makers. Using satellite imageries and GIS-based MCDA to extract detailed drainage, slope, and geomorphic features in parts of the Bagmati river catchment area suggests appropriate methods for groundwater potential zone studies.

**Table 1** Ranking in order of Importance

| Rank | Description |
|---|---|
| 1 | Very Low Potential |
| 2 | Low Potential |
| 3 | Moderate Potential |
| 4 | High Potential |
| 5 | Very High Potential |

Several studies have combined GIS and MCDA to identify and map potential groundwater zones e.g., (M. T. Mahdavi, 2015) (Jena, 2015). These studies have demonstrated the usefulness of combining these two approaches for the integration and analysis of complex spatial data and have provided valuable insights and guidance for the sustainable management and protection of groundwater resources.

Overall, the literature suggests that using GIS and MCDA is a promising approach for identifying and mapping potential groundwater zones and highlights the importance of considering both hydrogeological and land use factors in such analyses. However, further research is needed to refine and improve the accuracy and reliability of these methods and to explore their potential application in different regions and contexts

**Multi-criteria Decision Analysis (MCDA)**

MCDA is a family of techniques that aid decision-makers in formally structuring multi-faceted decisions and evaluating alternatives. (Rajesh Reghunath, April 2020). It has been used for about two decades with geographic information systems. The GIS-based multi-criteria assessment applies to define the rates of various classes in each layer. Weights of each thematic layer are allocated according to its influence on groundwater potential. In MCDA, weightage assignment for each influencing factor is applied by considering its practical role in a particular area (Alireza Arabameri, 2019). The AHP is a subjective approach in which subunit selection and its weightage allocation are based on comparing various criteria derived from the appropriate decision-making strategy. The AHP method is applied according to the calculation of weightage from a preference matrix representing map layers. The weightage is generated by comparing relevant criteria based on preference factors. The ability to manage a vast number of heterogeneous data for the required weightage, even for enormous data in a straightforward manner, has made the method popular within various GIS methods (Imran Ahmad, 2020).

**Weight Assignment and Normalization of Criteria Using AHP**

The AHP was first introduced by Saaty (Saaty, 1980). for solving a complex problem by splitting it into different categories and integrating each subsection to find out the big picture that has to be solved. AHP, developed by Saaty, is a decision support tool widely used in making complex decisions based on pairwise comparisons. In this study, twelve thematic layers have been formed, and their relationships are defined with the aid of the AHP. Choosing the primary criteria for the goal decision and developing a pairwise comparison matrix based on knowledgeable assessments of the standards chosen are the initial steps in the AHP technique. A pairwise comparison matrix (n * n) was generated based on the input factors. Each entry indicates the influence of the row relative to the column factor. A diagonal matrix was prepared by placing the values in the upper triangle, and their shared values were used to fill the triangular matrix.

The complex decision-making process between the criteria is simplified to a single level with the help of the pairwise comparison matrix indicated in Equation (1), and the relative relevance values of the requirements in relation to one another are obtained.

$$A = \begin{matrix} a11 & a12 & a13 \\ a21 & a22 & a23 \\ a31 & a32 & a33 \end{matrix} \quad (1)$$

The second step of the AHP calculations is to determine the normalized weights using the criteria geometric mean, as shown in Equation (2).

$$Wn = \frac{G}{\sum_{n-1}^{n} Gm} \quad (2)$$

Where W is the Eigenvector and Gm is the geometric mean of the $i^{th}$ row of the judgement. The eigenvector indicates the relative weights of each indicator and is computed by dividing column values by column sum.

The normalized criteria weights' consistency is examined in the final step of the AHP approach. Equation (3), which is shown below, is used to compute the consistency ratio (CR) in this case:

$$CR = \frac{CI}{RI} \quad (3)$$

where CR is the consistency ratio, CI is the consistency index calculated using Equation (4), and RI is the random consistency index. The Consistency Index (CI) is the ratio of the difference between λ max and the number of indicators involved, as shown in Equation (4).

$$CI = \frac{\lambda max - n}{n-1} \quad (4)$$

Where $\lambda_{max}$ is the maximum eigenvalue of the judgment matrix, calculated using Equation (5)

$$\lambda_{max} = \frac{1}{n \sum_{i=1}^{n} \frac{(Aw)i}{wi}} \quad (5)$$

The relative weights obtained from AHP were assigned to each thematic map to generate a cumulative weight of the respective thematic maps. Each map's weight value with the highest or lowest weight was set according to the actual field situation. The summary of the assigned and normalized weights of the features/classes of the different thematic layers and the consistency ratio of its thematic map were also computed and given for the respective thematic map. Then, the five other thematic maps were integrated as a summation of overall groundwater influencing factors to generate the study area's groundwater potential map (GPM).

**Random Index (RI)**

RI is the random consistency index given by (Saaty, 1980)

**Table 2:** RI ratio of the different values of n

| **n** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0.00 | 0.00 | 0.58 | 0.9 | 1.12 | 1.24 | 1.41 | 1.4 | 1.45 | 1.49 | 1.51 | 1.48 |

**Factors Influencing Groundwater**

- **Slope**

The identification of groundwater potential zones depends on slope. A higher degree of slope means a faster rate of runoff and erosion, with comparably less possibility for recharging (Prince, 2012). It is also believed that slope and water storage potential are inversely related. A 30 m x 30 m SRTM Digital Elevation Model (DEM) and the spatial analysis tool included into the GIS program were used to create the slope map. Five slope classifications were used to categorize the research area (Table 3).

- **Drainage Density**

The availability and pollution of groundwater are highly dependent on drainage density (Ganapuram, 2009). The drainage system is lithology-dependent and serves as a significant gauge of infiltration rate. Permeability has an opposite relationship with drainage density. As a result, it plays a crucial role in defining the groundwater potential zone. A drainage basin's drainage density is calculated by dividing the sum of the lengths of its rivers by the area of the drainage basin (eh, 2016). Low infiltration due to high drainage density makes the area's potential for groundwater less favorable. Low drainage density translates to high infiltration, which raises the groundwater potential more. The drainage density was reclassified and categorized into five classes the value ranges from 0-2.24.

- **Precipitation**

The primary water source in the hydrological cycle and the most important determining factor for a region's groundwater is rainfall. The rainfall data from 2011-2019 was used in this investigation. Using the IDW interpolation approach, a map of the spatial distribution of rainfall was created. Rainfall varies from 1695 mm to 2123 mm every year. The classification of the rainfall has been changed to five categories based on the maximum and minimum values. The amount and length of rainfall have an impact on infiltration. Low intensity and long duration rain impacts higher infiltration than runoff, while high intensity and short duration rain influence less infiltration and more surface runoff (Ibrahim-Bathis, 2016). High rainfall receives high weights, and vice versa.

- **LULC**

In addition to offering guidance on groundwater needs, LULC provided crucial information on infiltration, soil moisture, groundwater, surface water, etc. (Imran Ahmad, 2020). The Bagmati river basin has a variety of land use types, including agricultural land, aquatic bodies, evergreen forests, forest plantations, scrub forests, built-up land, and barren area. Based on Esri- LULC categorization, the LULC types in the region were identified. The obtained domains of LULC were water bodies, forest, agriculture, build-up area, barren and pasture land. Agriculture land is the most common class among the several classifications. These classes were classified on the basis of their influence in absorption and in-filtration of the water.

- **Lineament Density**

A lineament is a linear feature in a landscape that expresses a fault or other underlying geological structure (Jena, 2015). In the examination of fractures or structures, lines of reference are typically used. Within the project area, the densities were categorized in 5 classes, from lowest to highest, ranging from 0-99.6; the highest rank was assigned to higher value.

- **Curvature**

Concave upward or convex upward profiles can both be described using curvature, which is a quantitative description of the nature of the surface profile (Nair, 2017). Water has a tendency to slow down and to build up in convex and concave profiles, respectively. The research area's curvature ranged from negative to positive. The values are redistributed and grouped into five categories. High curvature values are paired with positive value, and vice versa.

- **Temperature**

Temperature was the factors that determine precipitation; hence they are crucial when evaluating a certain area's groundwater potential. Increased surface temperatures could affect the amount of subsurface water (Jannis, 2021)whereas decreased humidity over a longer period of time could cause prolonged periods of draught, which could result in excessive groundwater extraction or a lack of it. Therefore, for this study, lower temperatures received higher weights and vice versa. The temperature value of our study area ranges from 13-26 degrees, which was the average of last 10 years data obtained from Open Data Nepal.

- **Soil**

The soil maps collected from NARC and, the delineated study area map of the Bagmati sub- basin was overlaid on the soil map. Finally, a soil map of the study area was thus extracted in a GIS environment. Soils are described by geology, physiography, and climate, which also plays a big part in runoff and groundwater recharge (Das, 2017). In the area under research, there are five different types of soils: Colluvial, Fluvial non-calcareous, Fluvial calcareous, Quartzite and Sandstone. For this factor the CR value was assigned 0.013. (Table 3)

- **Geology**

Groundwater might be accessible under water table circumstances. The existence of joints and fractures in the various rock types may allow for the presence of water. A geological map was prepared from the vector data collected from USGS, which contains information about the types of rocks. The types of rocks and its values are assigned (in Table 3)

- **Topographic Wetness Index**

The Topographic Wetness Index (TWI) was first introduced by (K.J. Beven, 1979). Generally, TWI refers to the measurement of water availability in a region which is affected by the impact of water accumulation caused by topography (Biswas et al., 2020). The TWI distribution map has been prepared in ArcGIS 10.8.1 using the following formula: -

$$TWI = \frac{\ln A}{TanB} \qquad (6)$$

Here, A refers to the specific catchment while tan$\beta$represents the slope angle of the particular grid. It is proved that high TWI is characterized by high water availability than low TWI. The TWI of the study area varies from 0-15 and is classifies into 5 classes. The high weight has been assigned for the high TWI value and vice versa.

- **Topographic Position Index**

TPI (Topographic Position Index) is widely used for automating landform categorization and measuring topographic slope locations (De Reu *et al.* 2013). TPI comes in handy to explain physical processes (hill, ridges, valley, flat plains, etc.) (Jenness 2006). TPI value close to zero stands for flat ground surface (Nair *et al.* 2017, Arulbalaji *et al.* 2019). The TPI ranges varied from -62 to 248 (Table 3), the high weight is assigned for low TPI value and vice versa.

- **Roughness**

The roughness index represents the topographic surface's undulation by comparing the elevation difference among the adjacent raster cells in the Digital Elevation Model (DEM) (Riley *et al.* 1999, Nair *et al.* 2017). Higher weights were given for lower values of roughness and vice versa. The higher and lowest value were 0.07 and 0.84 (Table 3). The Roughness map was prepared from the DEM data.

## II. Study Area

Considering the high population density, excessively dense settlement and scarcity of daily drinking water, the suitable study area for this project was the Bagmati river basin. Bagmati river lies in central Nepal. It originates in Bagdwar at an altitude of 2690 m and flows south through the Kathmandu valley. The river basin includes eight districts of Nepal, i.e., Kathmandu, Lalitpur, Bhaktapur, Makwanpur, Kavre, Sindhuli, Rautahat, and Sarlahi of Bagmati and Madhesh province, with a total stretch of approximately 3640 sq. Km.

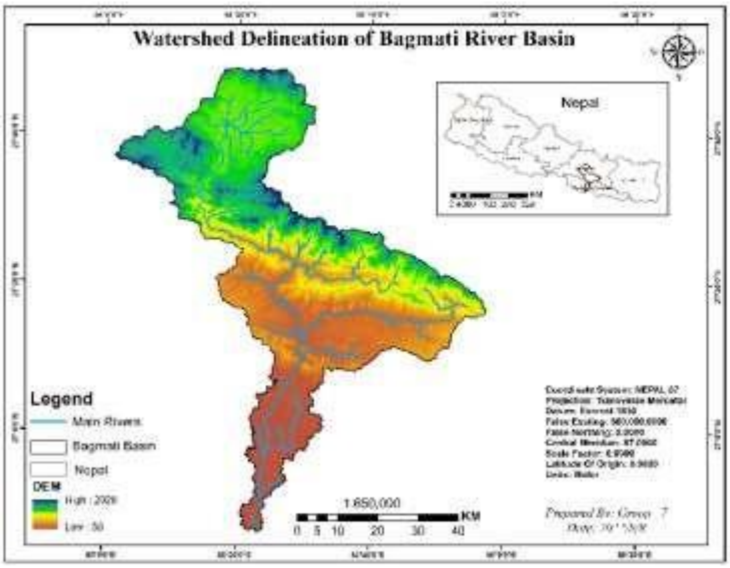


Figure 1 Study Area

## III. Study Workflow

The proposed methodology of study comprised various activities like preparation of base map and LULC map followed by digitization and image processing using different software. Initially, the watershed of the Bagmati river basin was delineated using DEM. In addition, with the use of GIS, required thematic maps concerning groundwater like stream length, drainage density, slope, contour, river length, Land use etc., were prepared.

The second stage involved preparing slope, aspect, flow accumulation and stream order maps using the Digital Elevation Model. The thematic layers will be prepared using standardized classification techniques. The relation of groundwater to cropping intensity was found to be inverse as agricultural production decreases with the increase in groundwater (Refat Nasherab, 2022).

Finally, all the prepared thematic maps were overlaid using GIS to rank the ultimate suitable groundwater potential zones. The analytical Hierarchical Process (AHP) provided a ranking based on influence, and the weighted overlay method will be used for final output preparation.

## IV. Standardization of Criteria

Table 3: Standardization of criteria

| Factor | Domain of Effect | Rank | CR |
|---|---|---|---|
| LULC | Water Bodies | 5 | 0.022 |
| | Forest | 4 | |
| | Agriculture | 3 | |
| | Built-Up Area | 1 | |
| | Barren | 2 | |
| | Pasture | 3 | |
| Lineament Density | 0-19.92 | 1 | 0.019 |
| | 19.92-39.84 | 2 | |
| | 39.84-5977 | 3 | |
| | 59.77-79.69 | 4 | |
| | 79.69-99.6 | 5 | |
| Slope | 0-4 | 5 | 0.02 |
| | 4-8 | 4 | |
| | 8-12 | 3 | |
| | 12-16 | 2 | |
| | 16+ | 1 | |
| Drainage Density | 0-0.24 | 5 | 0.018 |
| | 0.24-0.58 | 4 | |
| | 0.58-0.94 | 3 | |
| | 0.94-1.36 | 2 | |
| | 1.36-2.24 | 1 | |
| Soil Type | Colluvial | 3 | 0.013 |
| | Fluvial non-calcareous | 3 | |
| | Fluvial calcareous | 4 | |
| | Quartzite & Slate | 1 | |
| | Sandstone | 2 | |
| Rainfall | 1695-1780 | 1 | 0.02 |
| | 1781-1866 | 2 | |
| | 1867-1951 | 3 | |
| | 1952-2037 | 4 | |
| | 2038-2123 | 5 | |
| TWI | 0-3 | 1 | 0.019 |
| | 3-6 | 2 | |
| | 6-9 | 3 | |
| | 9-12 | 4 | |
| | 12-15 | 5 | |
| Temperature | 13-16 | 5 | 0.018 |
| | 16-18 | 4 | |
| | 18-20 | 3 | |
| | 20-22 | 2 | |
| | 22-26 | 1 | |
| TPI | <-62 | 5 | 0.02 |
| | (-62)-(-18) | 4 | |
| | (-18)-19 | 3 | |
| | 19-68 | 2 | |
| | 68-248 | 1 | |
| Roughness | 0.07-0.32 | 5 | 0.019 |
| | 0.32-0.41 | 4 | |
| | 0.41-0.48 | 3 | |
| | 0.48-0.55 | 2 | |
| | 0.55-0.84 | 1 | |
| Geology | Igneous | 4 | 0.036 |
| | Neogene Sedimentary | 2 | |
| | Quaternary Sediment | 2 | |
| | Undivided Paleozoic | 3 | |
| | Undivided Precambrian | 5 | |
| Curvature | <0 | 1 | |
| | 0-1 | 4 | 0.4 |
| | 1+ | 5 | |

A diagonal matrix was prepared by placing the values in the upper triangle and their reciprocal values were used to fill the triangular matrix. The expert's judgment was used for PCM (Rajendra Bhausaheb Zolekar, 2015). Besides, the relative weights were normalized. The normalized principal eigenvector is obtained by averaging the order to verify the consistency of the priority vector. The principal eigenvalue is acquired by adding the products among every component of the eigenvector and the summation of the columns of the mutual matrix. The calculation based on the AHP method in this study has been conducted by considering different factors, such as $n$ = number of factors involved (i.e., 12) and $\lambda$ = average value of the consistency vector.

$\lambda = 13.32$

$CI = 0.12$

RI = 1.48 (for n=12)

And $CR=0.08$ <0.10, is under the acceptable limit, indicating reliability in the pairwise comparison. Finalized weights for slope, geology, geomorphology, LULC, drainage density, slope, groundwater depth, soil texture, and rainfall were derived.

## V. Result and Discussions:

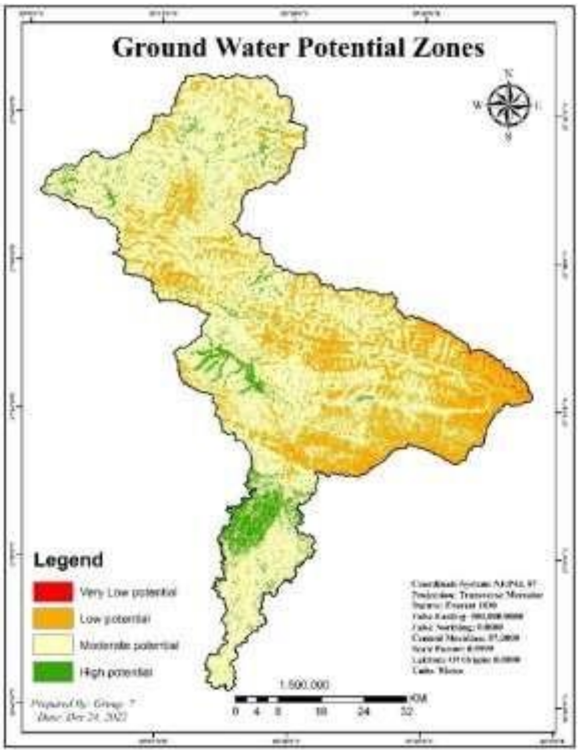


Figure 2 Groundwater Potential Zones

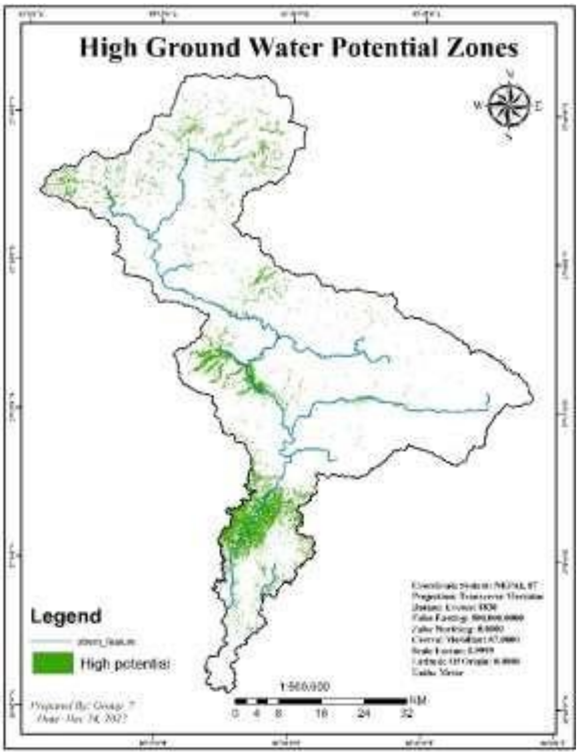


Figure 3 High Groundwater Potential Zones

The results project showed that the central and southern parts of the study area had the highest potential for groundwater development, while the northern and eastern parts had lower potential.

The results were generated by overlaying the various spatial layers representing the factors affecting groundwater potential and using the MCDA approach to integrate these layers and generate a composite map of the potential groundwater zones. The map showed that the northern and western parts of the study area had the highest potential, while the eastern and southern parts had lower potential. In terms of the factors affecting groundwater potential, the study found that geology and rainfall were the most important factors, followed by soil and land use. The results also showed that the higher the slope, the lower the groundwater potential, while areas with relatively flat terrain had higher potential.

**Table 3** Areas of Groundwater zones

| Zones | Area (%) |
|---|---|
| High Potential | 7.20 |
| Moderate Potential | 65.52 |
| Low Potential | 27.13 |
| Very Low Potential | 0.15 |

The above Table shows that most of the region contains moderate groundwater zones followed by high potential, but there are scarce regions with shallow groundwater.

## VI. Conclusion & Recommendation:

This research utilized a Geographic Information System (GIS) and Multi Criteria Decision Analysis (MCDA) to identify and map groundwater potential zones in the Bagmati River Basin. Multiple data sources, including topographic maps, geophysical surveys, hydrogeological investigations, and meteorological data, were collected and analyzed. Geographical layers representing various aspects of groundwater potential, such as soil type, slope, land use, and rainfall, were integrated using the MCDA method. The results indicated that the central and southern regions of the study area exhibited the highest potential for groundwater development, with 7.2% and 65% representing high and moderate potential, respectively. The eastern and northern regions showed lower potential. The study suggests that extraction of drinking water can be carried out in the identified areas, but considering potential negative environmental and hydrological impacts. The accuracy and reliability of the findings depend on data quality and availability, which should be regularly updated. High-resolution data and consideration of temporal variations in groundwater potential are recommended for future studies. Overall, the research demonstrated the effectiveness of GIS and MCDA methodologies for locating and mapping groundwater potential zones, emphasizing the need for comprehensive water resource management strategies in the Bagmati River Basin, taking multiple factors into account.

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