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Research Article

Groundwater Potential Mapping at Highly Populated Sub-districts of Thimphu District Using Fuzzy Analytic Hierarchy Process

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Abstract

Groundwater is important when there is an insufficient spring water supply for daily needs. The population growth and expansion of the cities demand more water. Thimphu is the capital city of Bhutan and facing water shortage in recent times due to urban expansion and population growth. This study aims to find the potential area for groundwater using the Fuzzy Analytic Hierarchy Process. The factors used for this study are elevation, slope, curvature, topographic wetness index, drainage density, normalized difference vegetation index, distance from fault density, rainfall distribution map, soil texture map, and drainage density. The rating for the factors and classes of the factors were carried out with the help of field experts. As per the fuzzy weight, the highest contributing factor for the groundwater is rainfall with a fuzzy weight of 0.215. Only 1.19% of the study area falls under very high potential zone for groundwater and the area under the curve of the groundwater potential map is 70.37%. The groundwater potential map will help concerned officials to explore the subsurface groundwater using geophysical investigation using test drilling and borehole geophysical logging techniques.

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Introduction

Groundwater is defined as the water in the saturated subsurface zones filling the pore spaces between the particles of soil, root, mineral, and rock [1]. The groundwater is safe from evapotranspiration, pollution, and drought [2]. The increasing water requirement for human consumption and the associated developmental activities has imposed massive pressure on the limited freshwater resource [3]. It is important to identify groundwater stored in the subsurface geologic formation to meet the demand of the people and developmental activities in the urban area [1].

Traditional methods for preliminary groundwater exploration require extensive field survey which includes ground-based survey, exploratory drilling, geophysical methods, the geological and hydro-geological test which is uneconomical, time-consuming, and require large datasets [1]. Since the traditional methods are based on the trial-and-error approach, sometimes extensive field survey becomes useless when the site doesn't show any sign of groundwater. In recent times, the use of remote sensing data with geospatial tools in conjunction with appropriate models was used for preliminary identification of groundwater potential sites which is rapid, cost-effective, and requires minimum human resources for the groundwater potential studies [2]. The map generated from remote sensing and geographic information aystem (GIS) will help in avoiding the trial and error method of identifying potential groundwater sites.

There are several methods to assess groundwater potential mapping (GWPM) using GIS which is broadly classified into qualitative and quantitative methods [4].

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The qualitative methods are purely based on the judgement of the expert and these models are analytic hierarchy process (AHP), fuzzy set-based analysis, weighted linear combination, and ordered weighted average [4]. The quantitative methods are based on the input training data and some numerical relationships between the training data and factors. The quantitative methods are classified into statistical analysis, deterministic approach, probabilistic approach, and artificial intelligence(AI) [4]. Recently, most scholars used statistical analysis and AI for GWPM such as frequency ratio, weight of evidence, certainty factor, index of entropy, information value, artificial neural networks, random forests, support vector machines, decision trees, and so forth [3]. However, this method requires prior groundwater sites for training the datasets which is the main draw-back in Bhutan. Currently, none of the organizations explored the potential groundwater sites and there are no datasets available. Therefore, this study uses Fuzzy Analytic Hierarchy Process (FAHP) based on Chang Extent Analysis. The FAHP doesn't require prior groundwater data and it is based on experts' grading for individual factors and sub-classes of the factors. The FAHP method was developed by Van et al. [20] in 1983. The FAHP is a hybrid method that combines the traditional AHP method and the fuzzy set theory [10]. The fuzzy set theory is used to assign the weight and rank of each factor and their sub-classes for ground water potential mapping through judgement of the experts [17]. The main advantage of FAHP over AHP is that, fuzzy numbers achieve realistic and the most accurate results [17]. The study also found that the FAHP is more efficient to delineate groundwater potential zone compared to machine learning models [21].

A total of 78% of Bhutanese people have access to safe drinking water. However, the pressure on water resources is intensifying in urban areas due to the increase in the population [5]. The domestic water demand is increasing every year due to rapid socio-economic developmental activities. The shortage of safe drinking water is expected in the future due to rapid urbanization and rural-urban migration in Thimphu which is the capital city of Bhutan [5]. As per a report from WHO [7], more than 50% of the population has an intermittent water supply ranging from 6-12 hours per day in Thimphu. As per the 2017 Population and Housing Census of Bhutan (PHCB) report, the population in Thimphu increased from 79,200 in 2005 to 114,600 in 2017 which was an increase of 44.7% within 12 years [8]. As per National Statistics Bureau, Thimphu's population is projected to be 263,152 in 2047 which is an increase of 232.26% compared to the 2005 population [9]. The demand for safe drinking water will increase in the future. The government has to arrange an alternative source of water when the surface water becomes insufficient for all the people in the future.

Currently, the Bhutanese government never published a report on the feasibility study on the source of groundwater potential sites. With the increasing demand for freshwater, it becomes important to explore the groundwater potential sites to meet the demand of people in urban areas in the future. The GWPM is a very important tool for a preliminary investigation for the identification of potential groundwater sites. Therefore, the main objective of the study is to identify and map potential sites of the groundwater in Thimphu district of Bhutan using Fuzzy-AHP methods.

Materials and methods

1) Study area

The four sub-districts of Thimphu district were chosen as the study area (Figure 1) and it is chosen due to higher population density. The selected sub-districts of Thimphu districts are Kawang, Chang, Mewang, and Genye of Thimphu. The majority of the area falls under Thimphu City. The study area is located at 89.47°-89.78°E longitude and 27.26°N- 27.68°N latitude and it ranges from 2,000 m to 4,900 m above the mean sea level.

2) Methodology

The methodology (Figure 2) is divided into three steps namely i) data preparation, ii) data analysis using Fuzzy-AHP, and iii) accuracy assessment. The detail of these three stages is explained in the following sections.

3) Data preparation

The data was collected based on the importance of the factors. The factors used for the study are elevation, slope, curvature, topographic wetness index (TWI), distance from drainage, normalized difference vegetation index (NDVI), distance from the fault, rainfall distribution map, flow accumulation, and soil texture map. The detail of the data sources and their derivatives are mentioned in Table 1. The map of the factors prepared is shown in Figure 3.

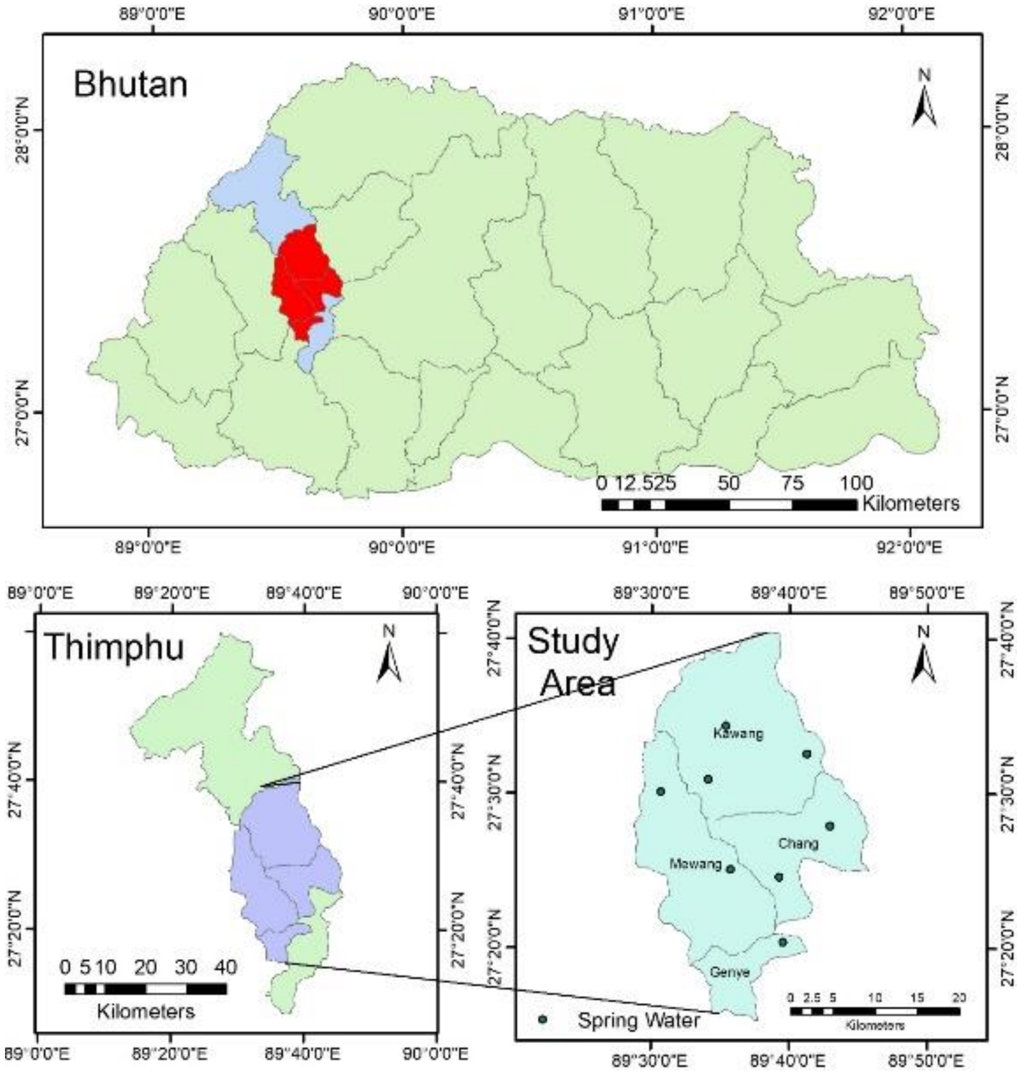

Figure 1 Study area for the research.

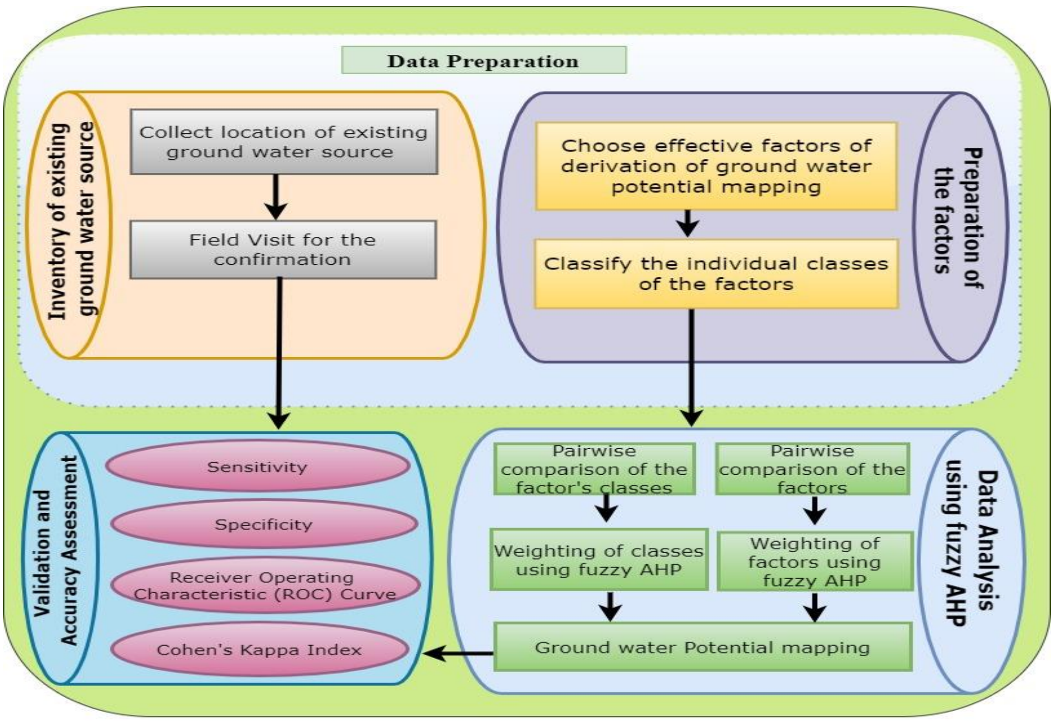

Figure 2 Overall workflow of the research.

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Table 1 Data acquisition and its derivatives

Source	Website/ Agencies	Data derived
SRTM DEM	https://www.gislounge.com/	Elevation, Slope map, curvature map, topographic wetness index, flow accumulation, and density
Landsat 8 OLI	https://earthexplorer.usgs.gov/	Normalized difference vegetation index
Geological map of Bhutan	Department of Geology and Mine, Bhutan	Fault map
Rainfall data	National Center for Hydrology and Meteorology, Bhutan	Rainfall distribution map
Soil map	FAO	Soil texture

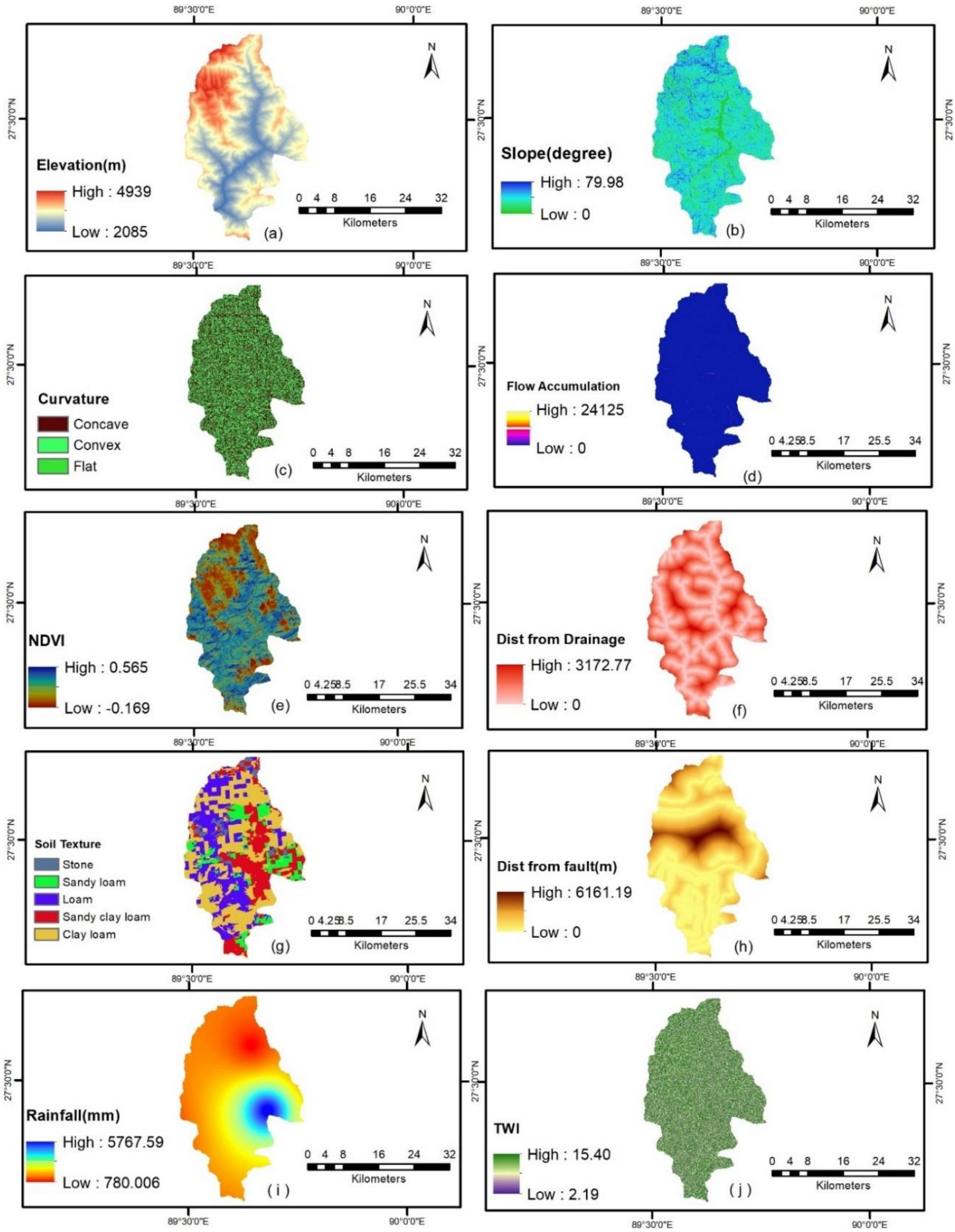

Figure 3 Factors for preparation of ground water potential map (a) elevation, (b) slope, (c) curvature, (d) flow accumulation, (e) NDVI, (f) distance from drainage, (g) soil texture, (h) distance from fault, (i) rainfall map, and (j)TWI map.

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4) Data analysis using Fuzzy-AHP process

The question of pairwise comparison between factors and sub-classes was distributed through an online google form to multiple relevant professionals such as geologists, water resource engineers, civil engineers, environmental engineers, irrigation engineers, and GIS specialists from Bhutan and abroad. A total of 14 experts performed a fuzzy pairwise comparison between the different factors as shown in Table 3. The experts also performed pair-wise comparisons between the different classes of factors as shown in Table 4. The comparison was done based on the relative importance scale using the triangular fuzzy numbers (TFNs) as shown in Table 2. The concept of TFNs is shown in Figure 4. lij, mij and uij are the lower, middle, and upper points of the pairwise comparisons for the factor i with respect to the factor j, respectively.

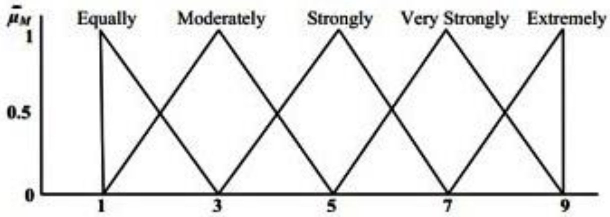

Figure 4 Membership function of triangular fuzzy number.

This study used Chang's extent analysis method. According to Chang [11], X = (x1, x2, x3, …., xn) is an object set, and U = (u1, u2, u3, …, um) is a goal set. Each object is taken and extent analysis is applied for each goal, gi, respectively. Thus, m extent analysis values are obtained for each object and these values are shown as: M_gi^1, M_gi^2, M_gi^3, ….M_gi^m, i=1, 2, …, n where all the M_gi^j (j =1, 2, …, m) are TFN. A pairwise comparison matrix based on the fuzzy process can be created following Eq. 1.

Table 2 Triangular fuzzy scale

Linguistic variable	Triangular Fuzzy scale (l_{ij}, m_{ij}, u_{ij})	Triangular Fuzzy reciprocal scale ($1/u_{ij}$, $1/m_{ij}$, $1/l_{ij}$)
Extremely strong	(9, 9, 9)	(1/9, 1/9, 1/9)
Very strong	(6, 7, 8)	(1/8, 1/7, 1/6)
Strong	(4, 5, 6)	(1/6, 1/5, 1/4)
Moderately strong	(2, 3, 4)	(1/4, 1/3, 2)
Equally strong	(1, 1, 1)	(1,1,1)
Intermediate values	(7, 8, 9)	(1/9, 1/8, 1/7)
	(5, 6, 7)	(1/7, 1/6, 1/5)
	(3, 4, 5)	(1/5, j, 1/3)
	(1, 2, 3)	(1/3, S, 1)

$$(M_{gi}^{m})_{nxm} = \begin{bmatrix} (1,1,1) & (l_{12}, m_{12}, u_{12}) & \cdots & (l_{1n}, m_{1n}, u_{1n}) \\ (\frac{1}{u_{12}}, \frac{1}{m_{12}}, \frac{1}{l_{12}}) & (1,1,1) & \cdots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & \vdots & \vdots & \vdots \\ (\frac{1}{u_{1n}}, \frac{1}{m_{1n}}, \frac{1}{l_{1n}}) & (\frac{1}{u_{2n}}, \frac{1}{m_{2n}}, \frac{1}{l_{2n}}) & \cdots & (1,1,1) \end{bmatrix} \quad \text{(Eq. 1)}$$

The calculation of Fuzzy synthetic extent can be done by using Eq. 2.

$$\boldsymbol{S_i = \sum_{j=1}^{m} M_{gi}^{j} \times \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}\right]^{-1}} \quad \text{(Eq. 2)}$$

Where, Si is the synthetic extent value of the pair-wise comparison. The ∑_(j=1)^m M_gi^j and [∑_(i=1)^n ∑_(j=1)^m M_gi^j]^(-1) are calculated as using Eq. 3 and Eq. 4.

$$\sum_{j=1}^{m} M_{gi}^{j} = \sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \quad \text{(Eq. 3)}$$

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{j=1}^{m} l_j}, \frac{1}{\sum_{j=1}^{m} m_j}, \frac{1}{\sum_{j=1}^{m} u_j}\right) \quad \text{(Eq. 4)}$$

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The concept of degree possibility degree is shown in the Figure 5. Let $S_i = (l_i, m_i, u_i)$ and $S_j = (l_j, m_j, u_j)$ are the triangular fuzzy members and $S_i \neq S_j$. If $S_i \geq S_j$, the PD is expressed using Eq. 5.

Calculate the degree of possibility of a convex fuzzy number to be greater than n fuzzy number and weight vector and normalized weight from Eq. 6 - 8. The final calculated normalized weight of the factors and classes of the factors are given in Table 3 and Table 4 respectively.

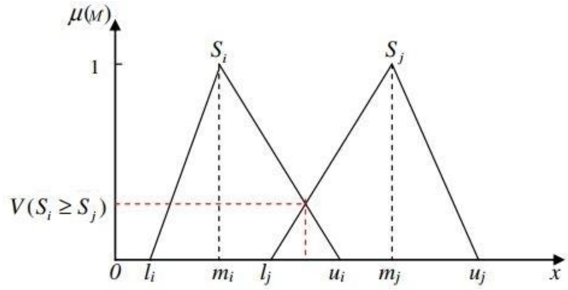

Figure 5 Definition of the degree of possibility of $V(S_i \geq S_j)$.

$$V(S_i \geq S_j) = \begin{cases} 1 & if\ m_i \geq m_j \\ 0 & if\ \ l_i \geq u_i \\ \frac{l_j - u_i}{(m_i - u_i)-(m_j - l_j)} & otherwise \end{cases} \quad \text{(Eq. 5)}$$

V(S   S1, S2, …, Sk)=min V(S   Sk), i=1,2,3,…k

Considering $d'(A_i)$=min $V(S_i \quad S_k)$ for k=1,2,….,n (Eq. 6)

$$\text{Weight vector } (W_i') = W_i' = \frac{d\prime(A_i)}{\sum_{i=1}^{n} d\prime(A_i)} \quad \text{(Eq. 7)}$$

Normalized weight vector $W=(W_1', W_2', W_3',\ldots W_n')^T$ (Eq. 8)

Table 3 Fuzzy pairwise comparison matrix and fuzzy weight of factors

	Drainage density	Flow accumulation	NDVI	Curvature	Slope	Soil Texture	Fault	Elevation	Rainfall	TWI	Fuzzy weight
Drainage density	1, 1, 1	2, 3, 4	1/4, 1/3, 1/2	2, 3, 4	2, 3, 4	2, 3, 4	4, 5, 6	2, 3, 4	1/4, 1/3, 1/2	4, 5, 6	0.147
Flow accumulation	1/4, 1/3, 1/2	1, 1, 1	1/4, 1/3, 1/2	2, 3, 4	4, 5, 6	2, 3, 4	4, 5, 6	4, 5, 6	1/4, 1/3, 1/2	6, 7, 8	0.135
NDVI	2, 3, 4	2, 3, 4	1, 1, 1	2, 3, 4	2, 3, 4	2, 3, 4	4, 5, 6	4, 5, 6	1, 1, 1	6, 7, 8	0.211
Curvature	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1, 1, 1	2, 3, 4	1, 1, 1	2, 3, 4	2, 3, 4	1/4, 1/3, 1/2	2, 3, 4	0.076
Slope	1/4, 1/3, 1/2	1/6, 1/5, 1/4	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1, 1, 1	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1/6, 1/5, 1/4	2, 3, 4	0.000
Soil texture	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1, 1, 1	2, 3, 4	1, 1, 1	2, 3, 4	2, 3, 4	1/4, 1/3, 1/2	2, 3, 4	0.076
Fault	1/6, 1/5, 1/4	1/6, 1/5, 1/4	1/6, 1/5, 1/4	1/4, 1/3, 1/2	2, 3, 4	1/4, 1/3, 1/2	1, 1, 1	2, 3, 4	1/6, 1/5, 1/4	2, 3, 4	0.040
Elevation	1/4, 1/3, 1/2	1/6, 1/5, 1/4	1/4, 1/3, 1/2	1/4, 1/3, 1/2	2, 3, 4	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1, 1, 1	1/6, 1/5, 1/4	2, 3, 4	0.040
Rainfall	2, 3, 4	2, 3, 4	1, 1, 1	2, 3, 4	4, 5, 6	2, 3, 4	4, 5, 6	4, 5, 6	1, 1, 1	2, 3, 4	0.215
TWI	1/6, 1/5, 1/4	1/8, 1/7, 1/6	1/8, 1/7, 1/6	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1, 1, 1	0.000

Table 4 Fuzzy pairwise comparison matrix and fuzzy weight for the classes of the factors

Factor	Class	2085 - 2688	2688 - 3095	3095 - 3499	3499 - 3980	3980 - 4939	Fuzzy weight
Elevation	2085 - 2688	1, 1, 1	2, 3, 4	4, 5, 6	6, 7, 8	6, 7, 8	0.457
	2688 - 3095	1/4, 1/3, 1/2	1, 1, 1	2, 3, 4	4, 5, 6	6, 7, 8	0.270
	3095 - 3499	1/6, 1/5, 1/4	1/4, 1/3, 1/2	1, 1, 1	2, 3, 4	4, 5, 6	0.123
	3499 - 3980	1/8, 1/7, 1/6	1/6, 1/5, 1/4	1/4, 1/3, 1/2	1, 1, 1	2, 3, 4	0.063
	3980 - 4939	1/8, 1/7, 1/6	1/8, 1/7, 1/6	1/6, 1/5, 1/4	1/4, 1/3, 1/2	1, 1, 1	0.000
		0 - 14.63	14.63 - 23.05	23.05 - 30.98	30.98 - 40.69	40.69 - 79.98	Fuzzy weight
Slope	0 - 14.63	1, 1, 1	2, 3, 4	2, 3, 4	4, 5, 6	6, 7, 8	0.443
	14.63 - 23.05	1/4, 1/3, 1/2	1, 1, 1	2, 3, 4	4, 5, 6	6, 7, 8	0.286
	23.05 - 30.98	1/4, 1/3, 1/2	1/4, 1/3, 1/2	1, 1, 1	2, 3, 4	4, 5, 6	0.156
	30.98 - 40.69	1/6, 1/5, 1/4	1/6, 1/5, 1/4	1/4, 1/3, 1/2	1, 1, 1	4, 5, 6	0.082
	40.69 - 79.98	1/8, 1/7, 1/6	1/8, 1/7, 1/6	1/6, 1/5, 1/4	1/6, 1/5, 1/4	1, 1, 1	0

Table 4 Fuzzy pairwise comparison matrix and fuzzy weight for the classes of the factors (*continued*)

Factor							Fuzzy weight
Curvature		Concave	Flat	Convex			Fuzzy weight
	Concave	1, 1, 1	1/4, 1/3, 1/2	2, 3, 4			0.258
	Flat	2, 3, 4	1, 1, 1	4, 5, 6			0.637
	Convex	1/4, 1/3, 1/2	1/6, 1/5, 1/4	1, 1, 1			0.105
TWI		2.196 - 7.869	7.869 - 11.810	11.810 - 14.854	14.854 - 15.406		Fuzzy weight
	2.196 - 7.869	1, 1, 1	1/4, 1/3, 1/2	1/6, 1/5, 1/4	1/8, 1/7, 1/6		0.055
	7.869 - 11.810	2, 3, 4	1, 1, 1	1/4, 1/3, 1/2	1/6, 1/5, 1/4		0.118
	11.810 - 14.854	4, 5, 6	2, 3, 4	1, 1, 1	1/4, 1/3, 1/2		0.263
	14.854 - 15.406	6, 7, 8	4, 5, 6	2, 3, 4	1, 1, 1		0.564
NDVI		-0.263	0.094 - 0.183	0.183 - 0.263	0.263 - 0.332	0.332 - 0.565	Fuzzy weight
	-0.263	1, 1, 1	1/4, 1/3, 1/2	1/6, 1/5, 1/4	1/8, 1/7, 1/6	1/8, 1/7, 1/6	0
	0.094 - 0.183	2, 3, 4	1, 1, 1	1/4, 1/3, 1/2	1/6, 1/5, 1/4	1/8, 1/7, 1/6	0.065
	0.183 - 0.263	4, 5, 6	2, 3, 4	1, 1, 1	1/4, 1/3, 1/2	1/6, 1/5, 1/4	0.123
	0.263 - 0.332	6, 7, 8	4, 5, 6	2, 3, 4	1, 1, 1	1/4, 1/3, 1/2	0.27
	0.332 - 0.565	6, 7, 8	6, 7, 8	4, 5, 6	2, 3, 4	1, 1, 1	0.497
Drainage density		0-442.94	442.94-920.27	920.27- 1426.18	1426.18-1999.45	1999.45- 3172.77	Fuzzy weight
	0-442.94	1, 1, 1	1/8, 1/7, 1/6	1/6, 1/5, 1/4	1/4, 1/3, 1/2	1/4, 1/3, 1/2	0.049
	442.94-920.27	6, 7, 8	1, 1, 1	1/8, 1/7, 1/6	1/6, 1/5, 1/4	1/4, 1/3, 1/2	0.091
	920.27- 1426.18	4, 5, 6	6, 7, 8	1, 1, 1	1/6, 1/5, 1/4	1/4, 1/3, 1/2	0.185
	1426.18-1999.45	2, 3, 4	4, 5, 6	4, 5, 6	1, 1, 1	1/4, 1/3, 1/2	0.298
	1999.45- 3172.77	2, 3, 4	2, 3, 4	2, 3, 4	2, 3, 4	1, 1, 1	0.377
Distance from fault		0-500	500-1000	1000-1500	1500<		Fuzzy weight
	0-500	1, 1, 1	4, 5, 6	4, 5, 6	6, 7, 8		0.588
	500-1000	1/6, 1/5, 1/4	1, 1, 1	4, 5, 6	6, 7, 8		0.268
	1000-1500	1/6, 1/5, 1/4	1/6, 1/5, 1/4	1, 1, 1	4, 5, 6		0.108
	1500<	1/8, 1/7, 1/6	1/8, 1/7, 1/6	1/6, 1/5, 1/4	1, 1, 1		0.04
Rainfall		780.01 - 1637.25	1637.25 - 2319.14	2319.14 - 3195.87	3195.87 - 4325.87	4325.87 - 5767.59	Fuzzy weight
	780.01 - 1637.25	1, 1, 1	1/4, 1/3, 1/2	1/6, 1/5, 1/4	1/8, 1/7, 1/6	1/8, 1/7, 1/6	0
	1637.25 - 2319.14	2, 3, 4	1, 1, 1	1/4, 1/3, 1/2	1/6, 1/5, 1/4	1/8, 1/7, 1/6	0.061
	2319.14 - 3195.87	4, 5, 6	2, 3, 4	1, 1, 1	1/6, 1/5, 1/4	1/8, 1/7, 1/6	0.105
	3195.87 - 4325.87	6, 7, 8	4, 5, 6	4, 5, 6	1, 1, 1	1/6, 1/5, 1/4	0.252
	4325.87 - 5767.59	6, 7, 8	6, 7, 8	6, 7, 8	4, 5, 6	1, 1, 1	0.549
Flow accumulation		0 - 829	829 - 3509	3509 - 10746	10746 - 24125		Fuzzy weight
	0 - 829	1, 1, 1	1/4, 1/3, 1/2	1/6, 1/5, 1/4	1/8, 1/7, 1/6		0.055
	829 - 3509	2, 3, 4	1, 1, 1	1/4, 1/3, 1/2	1/6, 1/5, 1/4		0.118
	3509 - 10746	4, 5, 6	2, 3, 4	1, 1, 1	1/4, 1/3, 1/2		0.263
	10746 - 24125	6, 7, 8	4, 5, 6	2, 3, 4	1, 1, 1		0.564
Soil texture		Clay loam	Sandy clay loam	Loam	Sandy loam	Stone	Fuzzy weight
	Clay loam	1, 1, 1	2, 3, 4	4, 5, 6	4, 5, 6	6, 7, 8	0.476
	Sandy Clay Loam	1/4, 1/3, 1/2	1, 1, 1	2, 3, 4	4, 5, 6	6, 7, 8	0.277
	Loam	1/6, 1/5, 1/4	1/4, 1/3, 1/2	1, 1, 1	2, 3, 4	4, 5, 6	0.136
	Sandy loam	1/6, 1/5, 1/4	1/6, 1/5, 1/4	1/4, 1/3, 1/2	1, 1, 1	4, 5, 6	0.079
	Stone	1/8, 1/7, 1/6	1/8, 1/7, 1/6	1/6, 1/5, 1/4	1/6, 1/5, 1/4	1, 1, 1	0.000

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5) Accuracy assessment

This study uses area under the curve (AUC) of the receiver operating characteristics (ROC) curve for the validation of the GWPM. The existing spring water will be used to derive the AUC of the ROC. These AUC will be derived from the true positive (TP), false positive (FP), true negative (TN), and false negative (FN). These parameters will be used to calculate sensitivity and specificity. The sensitivity (Eq. 9) is the proportion of correctly classified groundwater potential pixels while specificity (Eq. 10) is the proportion of correctly classified non-ground water potential pixels.

The prediction capability of the GWPM is assessed based on the value of AUC of the ROC curve. The ROC curve is plotted using 1-specificity on the x-axis and sensitivity on the y-axis[1].

The AUC is calculated using Eq. 11 and its value ranges from 0.5-1. The AUC values are evaluated as follow: excellent (0.9–1), very good (0.8–0.9), good (0.7–0.8), moderate (0.6–0.7), and poor (0.5–0.6)[1].

$$\text{Sensitivity} = \frac{\text{TP}}{\text{TP+FN}} \quad \text{(Eq. 9)}$$

$$\text{Specificity} = \frac{\text{TN}}{\text{TN+FP}} \quad \text{(Eq. 10)}$$

$$\text{AUC} = \frac{\sum\text{TP}+\sum\text{TN}}{n} \quad \text{(Eq. 11)}$$

Where, TP, TN, FP, FN, n (ground water source pixel and equal number of non-ground water potential pixel).

Results and discussion

1) Relationship between factors and the groundwater using fuzzy AHP

The consistency ratio(CR) is necessary to check the consistency of the experts' pairwise comparisons. The value of the CR should be less than 0.1. If the CR is more than 0.1, it is necessary to re-evaluate the pairwise comparison of the factors [12]. The consistency ratio(CR) was calculated using Eq. 13.

$$CI = \frac{\lambda_{max}-n}{n-1} \quad \text{(Eq. 12)}$$

$$CR = \frac{CI}{RI} \quad \text{(Eq. 13)}$$

For this study, λ_{max} is 11.25 and it's calculated from AHP matrix, n is 10 which is the number of factors. The consistency index (CI) is calculated using equation 12 and its value is 0.146. The standard value of RI (random index) for 10 factors (n=10) is 1.49. Finally, the CR is 0.093 (<0.1) which is within the acceptable range.

The pairwise comparison between the factors and their fuzzy weight is given in Table 3. It is observed that the highest contributing factor to the feasibility of groundwater are rainfall with a fuzzy weight of 0.215, followed by distance from drainage (0.147), flow accumulation (0.135), NDVI (0.211). The least contributing factors are TWI and slope gradient with a fuzzy weight of zero. The slope gradient directly influences the infiltration of rainfall. The steeper slopes consume less recharge to the saturation zone. The steeper slope surface runoff flows rapidly during the rainfall making insufficient time to infiltrate to the sub-surface [22]. Bhutan is a mountainous country characterized by steep slopes in many parts of the country. Since the majority of the places in Thimphu have a steeper slope, the fuzzy weight is zero indicating the slope is not playing a crucial role in groundwater potentiality. Similarly, the TWI is a steady state wetness index. Since majority of Thimphu is not a flat area, it doesn't seem to hold groundwater and its fuzzy weight is zero.

2) Relationship between classes of the factors and the groundwater using fuzzy-AHP

The experts also conducted pairwise comparisons between the classes of the factors and their fuzzy weight of the classes is given in Table 4. Regarding the elevation and slope, the lowest elevation and lowest slope are favorable for the groundwater. The fuzzy weight decreases as the elevation and slope value increase indicating higher elevation and steeper slopes are not favorable for the groundwater. The result of elevation and slope follows a similar trend to the result of Adeyeye et al. [13].

Regarding the terrain curvature, the flat surface is more favorable for the groundwater, followed by the concave terrain with a fuzzy weight of 0.637 and 0.258 respectively.

The TWI shows the flow accumulation at a point in a catchment area and the capability of water to flow downstream [14]. It affects the distribution of soil moisture and groundwater flow [15]. In this study, the groundwater is more favorable in places having higher TWI.

NDVI indicates the health of vegetation coverage with a value ranging from -1 to 1 and the NDVI value closer to 1 indicate healthy vegetation coverage [23]. This study used Red and Near Infrared band of Landsat 8 for NDVI and it was calculated using the expression: NDVI=(NIR-R)/(NIR+R). As per Mallick et al. [24], the potentiality of groundwater is higher for higher fuzzy weight and higher vegetation coverage. This study also shows a similar result to Mallick et al. [24] indicating higher groundwater potentiality in the highly vegetated area.

The drainage density is the ratio of the length of all streams in a basin to its area [16]. The drainage density has a direct relation with maximum discharge in the basin. Generally, the higher value of drainage density shows a higher fuzzy weight. In this study, the drainage density and the fuzzy weights are directly proportional indicating there is high correlation relation between the drainage density and groundwater and the result is almost similar to the study of Sener et al. [17].

Rainfall is one of the most important hydrological factors and the magnitude and duration of the rainfall are the main determinants of groundwater recharge [18]. Generally, the higher magnitude rainfall will have a higher groundwater potential in an area [18]. For this study, the fuzzy weight increases with an increase in rainfall magnitude indicating rainfall intensity is proportional to the groundwater storage.

The flow accumulation also increases the possibility of the groundwater indicating the accumulated water drains into the porous soil contributing to the groundwater. On contrary, the potentiality of the groundwater seems to be decreasing as the distance from the fault increases. This may be due to the storage of the groundwater in the faults.

In several literatures, the silt and silt loam is best for surface water infiltration and groundwater storage. However, there is no silt soil available in the study area. In this study, the clay loam soil contributes more to the groundwater, followed by sandy clay, and loamy soil. The least contributing soil texture is stone. The clay loam soil contributes more to the groundwater due to high infiltration by the loam soil and retention in the clay. The result is similar to the report published on the Noble Research Institute website. On the other hand, the stone doesn't contribute to groundwater due to the impermeability of the stones.

3) Groundwater potential map and validation

The groundwater potential map of the study area was prepared using GIS-based fuzzy-AHP using the overlay analyses of the selected factors. The fuzzy weight of the factors and the fuzzy weight of the sub-classes of the factors were assigned with the help of field experts. The sub-classes of the factors are reclassified using the fuzzy weight from Table 4. The reclassified factors were multiplied with individual fuzzy weights from Table 3 using Eq. 14 to generate a groundwater potential map (Figure 6). Only 1.19% of the total study area falls under a very-high potential zone for groundwater at selected sub-districts of Thimphu as per the natural break classification.

$$\text{GWPM}=\sum_{w=1}^{m}\sum_{i=1}^{n}(w_j x X_i) \quad \text{(Eq. 14)}$$

where GWPM = groundwater potential map, Xi = factors maps, and wj = normalized weight of the jth factor. m = total number of factor, and n = total number of classes in a factor.

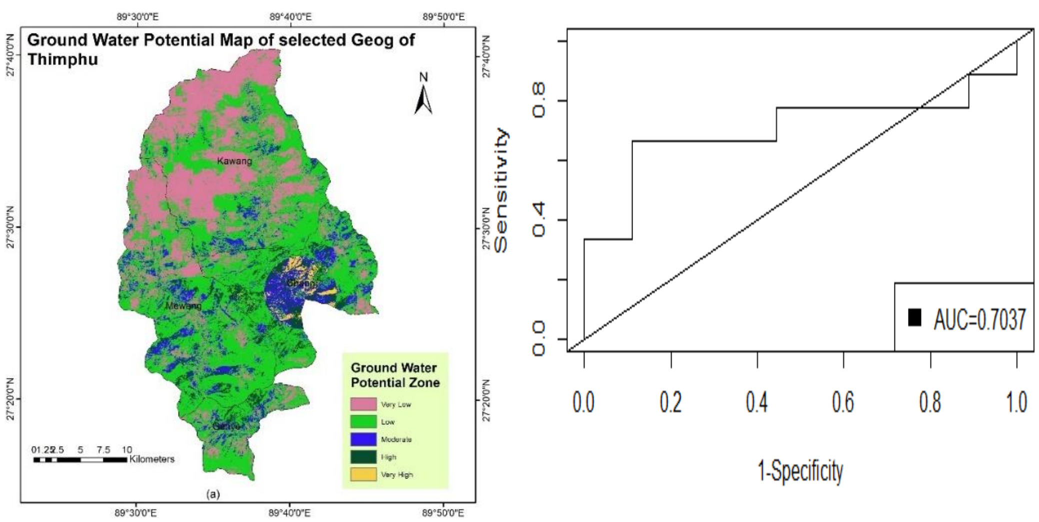

Figure 6 Pictures of (a) ground water potential map(GWPM) and (b) receiver operating characteristic curve (ROC).

Validation is one of the most important tasks of any scientific analysis. The AUC of the ROC curve has been used to determine the accuracy of the produced result. The AUC is calculated by comparing the observed value from the site and the generated predicted map. Spring water sources are highly associated with underground aquifers [19]. Therefore, the observed data were used from the existing spring discharged point as suggested

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by Sener et al. [17] which is finally digitized into point features using the GIS software. There were 9 spring discharge points for the study area. The predicted data were picked from the generated groundwater potential map (Figure 6). The AUC is calculated using Eq. 11 and its value is 70.37%. which fall under the good category indicating its within acceptable range.

Conclusion

In this study, FAHP techniques have been implemented with the use of remote sensing and GIS for the evaluation of groundwater potential zone in highly populated sub-districts of Thimphu, Bhutan. The methodology for identifying groundwater potential zone includes data preparation, data analysis, and validation. The data used for the study are elevation, slope, curvature, flow accumulation, NDVI, distance from drainage, soil texture, distance from the fault, rainfall map, and TWI map. The FAHP was used for data analysis to generate fuzzy weight. The weighted overlay analysis for the factors used to generate GWPM. The validation was conducted using the AUC with the use of an existing source of spring water. A total of 1.19% of the study area is highly feasible for the groundwater and the accuracy of the generated map is 70.37%. The majority of the 1.19% is located in the Chang sub-district of Thimphu City compared to other sub-districts. The advantage of the study is that it will help to identify the most feasible area for groundwater exploration.

However, the limitation of this study is that a geophysical investigation was not conducted for this study. Therefore, in the next phase of the study, the geophysical investigation such as performing drill boreholes and electrical resistivity will be conducted in high-potential zone to ascertain the potentiality of the groundwater.

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