APPLICATION OF ANALYTICAL HIERARCHICAL PROCESS (AHP) METHOD FOR DELINEATION OF GROUNDWATER RECHARGES POTENTIAL ZONES IN THE RED RIVER DELTA PLAIN

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Abstract

The Red river delta plain is the second - largest delta in Vietnam with an area of over 14,860 km², residing 22.5 million people and the place with the largest population density in the country. Groundwater is a valuable resource that has been exploited but some problems such as ground subsidence, pollution, depletion and saltwater intrusion related to groundwater have also occurred in this area. In order to sustain groundwater exploitation, groundwater recharge needs to be clarified with an assessment of less subjective involvement. AHP method was applied to determine the weights based on their impact rating on groundwater recharge potential. The verification of overlay integration is also made and implied that the model made is reliable.

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1. Introduction

With population growth, development of the economy, the impacts of climate change, the increase of water demand for the domestic, irrigation and industrial sectors has created increasing pressure on water resources caused these natural resources to be facility vulnerable, declining in quantity and quality. Groundwater has limited pollution and is less affected than surface water, so groundwater is considered a priority water resource provide for living and production. Most of the authors assume that the groundwater exploited accounts for a part of the groundwater reserve; however, the groundwater level still tends to decrease in any location due to the less groundwater recharge. Therefore, identifying and zoning groundwater recharge potential from rainfall and surface infiltrating through unsaturated zone is essential for the sustainable use of this resource. Many researchers have used different techniques to quantify the rate of natural groundwater recharge such as empirical methods, groundwater level fluctuation method, the groundwater balance method, isotope and solute profile techniques,… With that, many methods

globally have been implemented to identify potential groundwater recharge zones as well as frequency ratio (FR), certainty factor (CF), logic index models and multi-influencing factors (MIF).

Constant Chuma et al., 2013 [6], Mustafa Al Kuisi and Ali El - Naqa, 2013 [19], Ha Quang Khai, 2014 [9], Bertrand Leterme, Dirk Mallants, 2011 [5], Batelaan và D Smith, 2001 [2], Batelaan and De Smedt, 2007 [3], Beekman, H.E et al, 1999 [4], have used the approach of Remote Sensing (RS) interpretation and Geographic Informatical System (GIS) technique to estimate groundwater recharge and to delineate groundwater recharge potential zones. The integrated approach of RS, statistical analysis and groundwater model techniques have been used for estimation of groundwater recharge such as Kishan Singh Rawat et al., 2012 [10], Anderson, J. R et al., 1976 [1], Haijing Wang, 2008 [7], Mehdi Zarei and all, 2016 [15]. The above - mentioned approach is to use index techniques and overlay based on spatial mapping but the weight of each indicator assigned for each layer is often subjective. Some researchers have integrated remote sensing (RS), overlay analysis provided by geographical information system (GIS) platform (ArcGIS) with Analytic Hierarchy Process (AHP) method, multi-criteria analysis (MCA) techniques for the groundwater recharge potential and sustainable exploitation zoning (Mohanavelu Senthilkumar et al., 2019 [16], Shivaji Govind Patil et al., 2014 [28], Preeja et al., 2011 [24]). AHP developed by Thomas L. Saaty, 1980 [25] is a GIS - based multi - criteria decision - analysis (MCDA) technique (Saaty,1986) [26] for pairwise comparison of spatial parameters by assigning weights based

on expert opinion. This method is rapid, precise and cost - effective by significantly reducing the mathematical complexity. This method is widely used in many majors such as agriculture, flood management, landslide, water security, forestry, etc even in Vietnam.

The Red river delta plain (RRDP) is the second-largest delta in Vietnam with an area of over 14,860 km², residing 22.5 million people and the place with the largest population density in the country (MPI, 2020) [18]. Groundwater is a valuable resource that has been exploited quite a lot in this region with total exploitation discharges of about 3,000,000 m³/day (MONRE, 2015) [17]. Some problems such as ground subsidence, pollution, depletion and saltwater intrusion related to groundwater have also occurred in this area (Q.N. Pham et al., 2019) [22]. There have been a number of studies to assess the amount of groundwater recharge in this area. However, either the reliability of the research results is limited, or the research results are still local. Q. N. Pham, 2000 [21] estimated the groundwater recharge in RRDP by using a modeling method. Due to the lack of input data to build the model, the evaluation results have some uncertainty. Therefore, the objective of this study is to apply the AHP method with index technique for delineation of groundwater recharges potential zones in the Red River Delta Plain (RRDP).

2. Study area

The RRDP is located between latitude 21°34′ to 19°5′N and longitude 105°17′ to 107°7′10'E as its extremities. The overall area of the plain is approximately 14,860 km² (Fig. 1) (Q. N. Pham, 2019) [22]. The delta gradually lowers from the Northwest to the Southeast, from the

ancient alluvial shelves with an elevation of 10 - 15 m down to the alluvial flats of 2 - 4 m in the center where the tidal flats are still flooded every day. In the center of the delta, terrain elevation varies from 8 - 10 m, flat terrain. In the North, the delta is limited by the Tam Dao - Yen Tu mountain range, the South is limited by the Ba Vi - Vien Nam mountain range, in the East is limited by the coastline. In the middle of the plain, there are round top hills with gentle slopes and elevations from 25 - 45 to 100 m. The rainy season is from May to October and the dry season is from November to April next year. The average annual rainfall for the whole delta is from 1033.1 mm to 2338.7 mm and the amount of evaporation is from 828.2 mm to 1057.1 mm. RRDP has a dense network of rivers with an average density of 0.7 to 1 km/km². The whole region has two main river systems: The Red river system and the Thai Binh river system. Due to the impact of waves, tides and river systems, the surface water has been significantly saline intrusion in the estuaries. This saline intrusion in the river system not only affects the coastal ecosystem, irrigation water supply, etc. but also affects the shallow aquifers in the vicinity (Nielsen LH et al., 1999) [20].

The Geo - hydrogeology of the study area in the RRDP makes up the Northwest part of the Red River sedimentary basin; a basin filled with Paleocene, Neogene and Quaternary deposits (Nielsen LH et al., 1999) [20]. The RRDP is surrounded by mountain ranges composed of crystalline rocks from Paleozoic and Mesozoic sedimentary rocks (Mathers SJ et al., 1999) [14]. According to Tran N et al., 1991 [31], the sediments were deposited in five fining-upward sedimentation cycles. Hydraulic gradients in the range of 0.05 - 0.15 % are typical and groundwater flow velocities in the Holocene aquifers are a few tens of meters per year (Larsen F et al., 2008) [11].
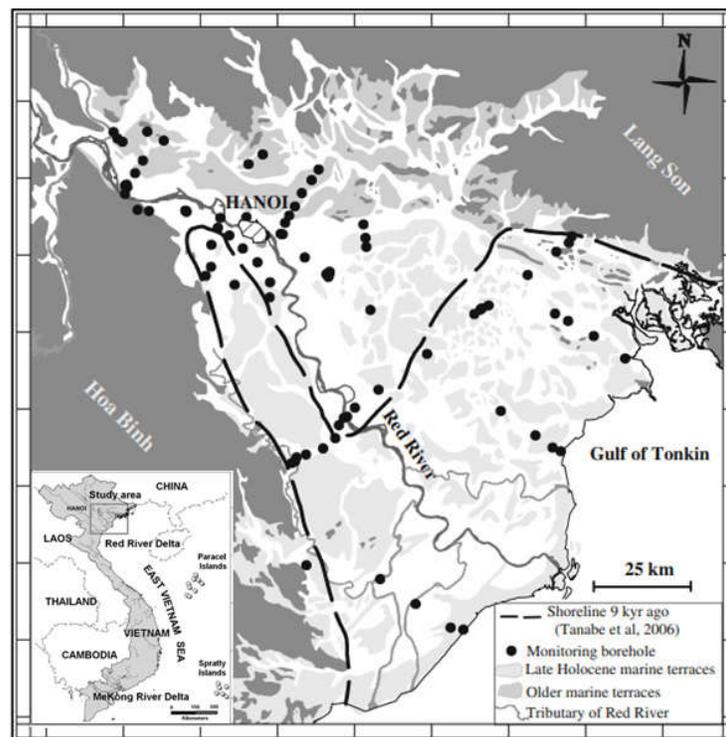

Figure 1: Location of study area, modified from Luu T. Tran et al., 2012 [12]

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3. Methods and materials

3.1. Data requirement

Groundwater recharge potential depends on many elements of the study area which are clarified by data collection, remote sensing interpretation and field works. Some previous publications are reported concerning indexes for zoning groundwater recharge potential such as Q.N. Pham, 2000 [21], Luu T. Tran et al., 2012 [12], Le Viet Hung et al, 2021 [8]. Below is a summarized the main RS application which has been done by Le Viet Hung et al., 2021 [8]. Thematic maps such as rainfall, lithology, geomorphology, slope, drainage system, soil, land use/land and groundwater level which are most widely used for estimation of groundwater recharge are also formed at results and discussion.

Table 1. Type of satllite images, their parameters and application

Satellite Images	Resolution	Number of scenes	Time	Applications
Multi-temporal PALSAR-/ScanSAR	50 m	450 (1° × 1°)	2016	Land use and land cover, topography, geology, climate and hydrology
ALOS-2 /PALSAR-2	25 m	60 (1° × 1°)	2016	Land coverage observation, disaster monitoring and resource surveying and elevation data
AW3D30	30 m	60 (1° × 1°)	2006 - 2011	Digital surface models
Multi-temporal Sentinel-1 SAR GRD C-band	10 m	480 (1° × 1°)	2016	Not hindered by atmospheric effects and are capable of imaging through tropical clouds and rain showers to maritime monitoring, land monitoring
Multi-temporal Landsat 8 OLI Surface Reflectance Tier 1	30 m	480 (1° × 1°)	2016	To create higher-level science data such as surface temperature, surface water, land change and use analysis.
Multi-temporal Sentinel-2 MSI, MultiSpectral Instrument, Level-1C	10m	480 (1° × 1°)	2016	Urban land cover and urban extent mapping

3.2. AHP method

The analytic hierarchy process (AHP), developed by Saaty, 1980 [25] is one of the most popular and widely employed multi - criteria methods. In this technique, the processes of rating alternatives and aggregating to find the most relevant alternatives are integrated. The technique is employed for ranking a set of alternatives or for the selection of the best in a set of alternatives. The ranking/selection is done with respect to an overall goal, which is broken down into a set of criteria. The application of the methodology consists of establishing the importance weights to be associated with the criteria in defining the overall goal. This is done by comparing the criteria pairwise. Let us consider two criteria, C_j and C_k. The comparative judgment is captured on a semantic

scale (equally important/moderately more important/strongly important and so on) and is converted into a numerical integer value a_{jk}. The relative importance of C_k over C_j is defined as its reciprocal, i.e., $a_{kj} = 1/a_{jk}$. A reciprocal pairwise comparison matrix A is then formed using a_{jk}, for all j and k. Note that $a_{jj} = 1$. It has been generally agreed that the weights of criteria can be estimated by finding the principal eigenvector w of matrix A. When the vector w is normalized, it becomes the vector of priorities of the criteria with respect to the goal; λ_{max} is the largest eigenvalue of the matrix A and the corresponding eigenvector w contains only positive entries. The methodology also incorporates established procedures for checking the consistency of the judgments provided by the decision - maker. Using similar procedures, the weights of alternatives with respect to each criterion are computed. Then, the overall weights of alternatives are computed using the weighted summation. A method developed by structuring a decision-making problem as a hierarchy in the form of an upside-down tree where the main goal is placed on top. Partial objectives that meet the main objective are placed at the second level. Each partial objective at the second level can be decomposed into third - level objectives and each set at each level meets the objective of the level to which they are subordinate. These partial objectives are treated as criteria in this text. At a lower level, the alternatives are listed and then compared pairwise according to their contribution to reaching each objective, or criterion, from the lower level (Saaty, 1980) [25]

4. Results and discussion

### 4.1. Thematic map preparation

As above mentioned, eight thematic maps concerning the estimation of groundwater recharge potential are formed such as slope, soil texture, drainage density, land use/land cover, lithology, geomorphology, groundwater level and rainfall. All the thematic maps' corresponding layers were allocated ranks and weights based on their impact on groundwater recharge potential which is referenced from concerned studies such as Mohanavelu Senthilkumar, 2019 [16], Shivaji Govind Patil, 2014 [28], Preeja et al, 2011 [24], I.P. Senanayake et al., [27], Tesfa G.A, Girum G.D [29]

*Table 2. Weight assignment criteria of thematic maps [29])*

| No	Theme	Basic of categorization	Assigned Weight
1	Lithology Rock type	Weathering character, joints, fractures	7
2	Slope	Slope percentage	5
3	Geomorphology	Landform type	4.5
4	Lineament density	Lineament value	4
5	Land cover	Land cover type, Status and condition	3.5
6	Drainage density	Drainage density value	3
7	Soil type	Permeability, porosity and texture	2.5

(a)

(b)
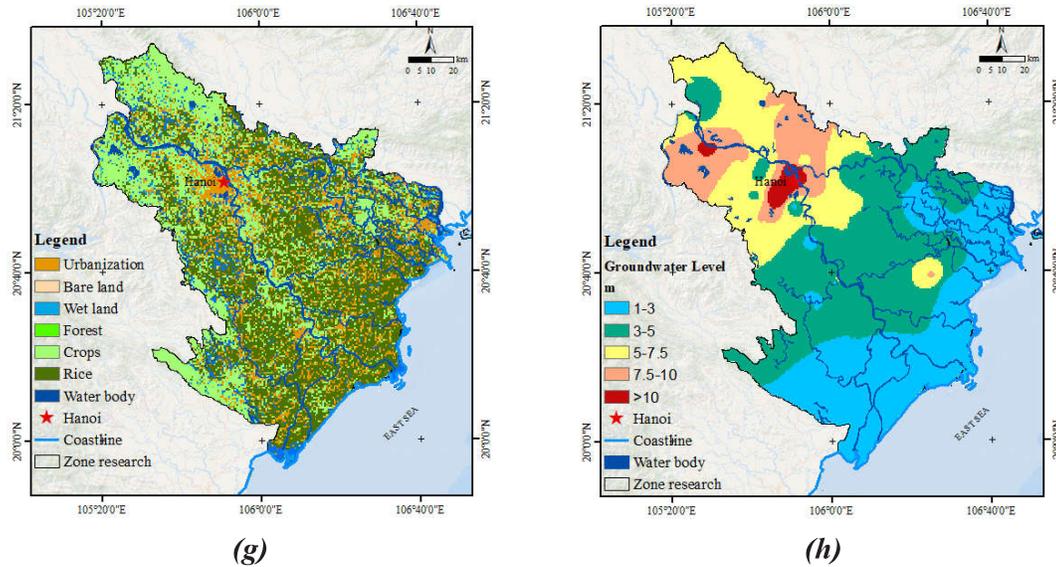
(c)

(d)

(e)

(f)

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(g)   *(h)*
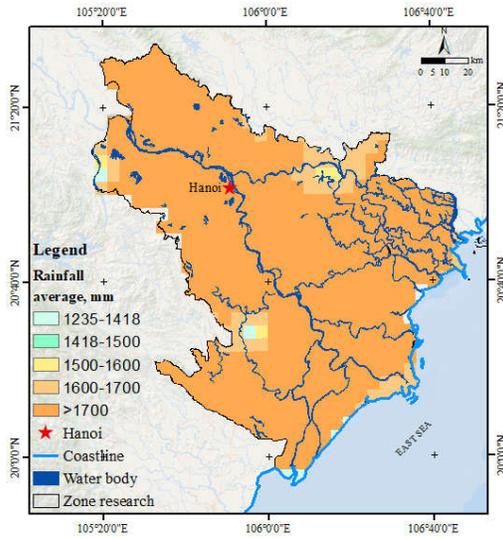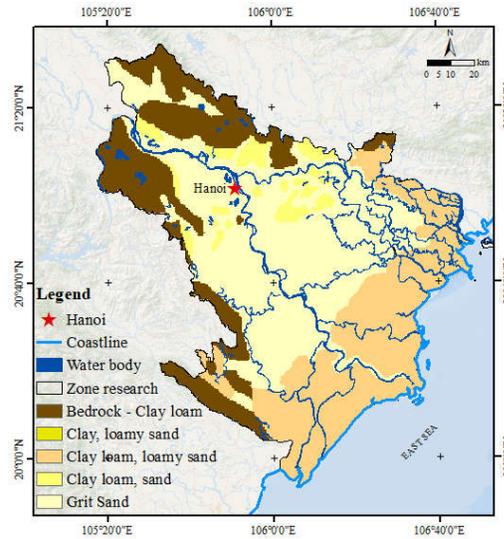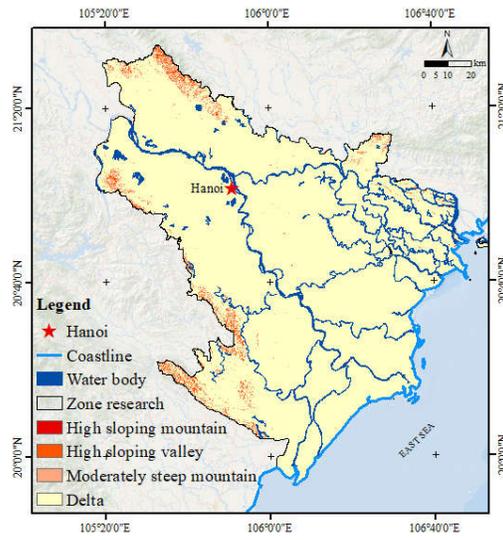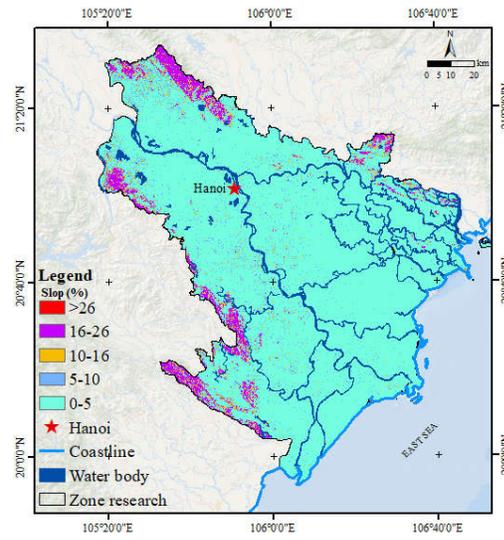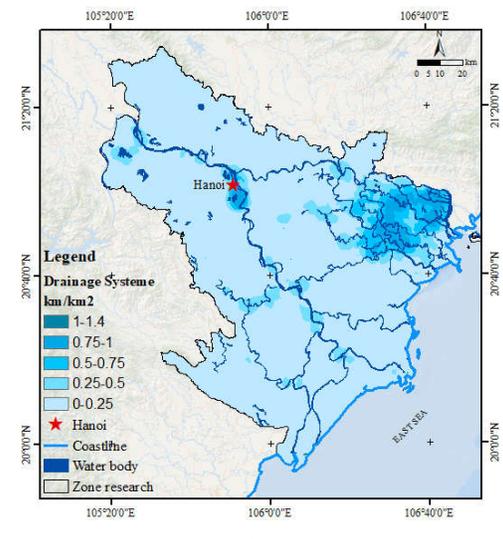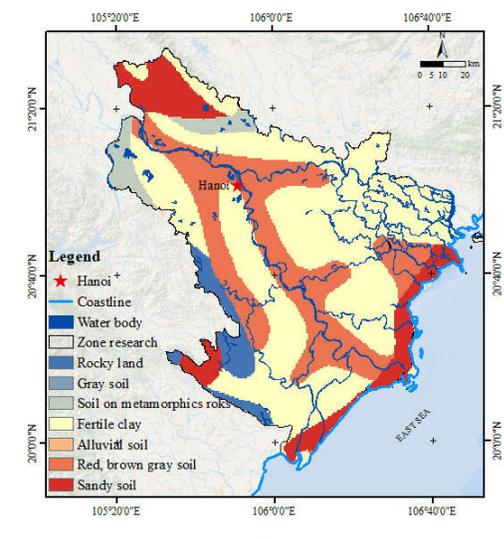
***Figure 2: Thematic maps a) Rainfail b) Lithology map c) Geomorphology map
d) Slop map e) Drainage system map f) Soil map g) Land use/land cover map
h) Groundwater level map [8]***

4.2. Normalized weight and groundwater recharge potential

Groundwater recharge zones were evaluated based on the groundwater potential index (GRI) calculated from the integration of all factors affecting groundwater recharge by thematic indicator (Malczewski, 1999) [13]

$$GRI = \sum_{w=1}^{m} \sum_{j=1}^{n} W_j X_i \qquad (1)$$

Where GRI is groundwater recharge index, W_j is normalized weight of the jth thematic factor, X_i is the normalized weight of the ith feature of the thematic factor, m is the total number of thematic factors and n is the total number of features of a given factor.

Normalized weights are calculated by AHP methods which the assigned weights were referenced from previous studies, local expert opinions and the results of each indicator and variables presented in Table 3, Table 4 and Table 5. Table 4 is the normalized weight that is the result of AHP's calculation for each factor affected on groundwater recharge. Table 5 is the normalized weight of the sub - criteria of factors listed in Table 2. Each sub - criteria was also assigned weight - based theirs impacts on groundwater recharge and based on expert knowledge and literature review listed above.

Table 3. Weight assignment criteria of thematic maps

No	Factor	Basis of categorization	Assigned weight
1	Rainfall	Amount of rain	8
2	Lithology	Rock type, weathering character	7
3	Geomorphology	Landform type	4.5
4	Slop	Slope percentage	5
5	Groundwater level	Level of underground water	5
6	Drainage system	Drainage density value	3.5
7	Land use/land cover	Land cover type, Status	3
8	Soil	Soil type, texture	2.5

Table 4. Normalizer weight of factors

Factor*	RF	LG	GG	SP	GL	DS	LC	SL	Arime-thic mean	Normali-zed weight
RF	8/8	8/7	8/4.5	8/5	8/5	8/3	8/3.5	8/2.5	1.6618	0.2077
LG	7/8	7/7	7/4.5	7/5	7/5	7/3	7/3.5	7/2.5	1.4549	0.1819
GG	4.5/8	4.5/7	4.5/4.5	4.5/5	4.5/5	4.5/3	4.5/3.5	4.5/2.5	0.9338	0.1167
SP	5/8	5/7	5/4.5	5/5	5/5	5/3	5/3.5	5/2.5	1.0388	0.1299
GL	5/8	5/7	5/4.5	5/5	5/5	5/3	5/3.5	5/2.5	1.0388	0.1299
DS	3/8	3/7	3/4.5	3/5	3/5	3/3	3/3.5	3/2.5	0.6249	0.0781
LC	3.5/8	3.5/7	3.5/4.5	3.5/5	3.5/5	3.5/3	3.5/3.5	3.5/2.5	0.7279	0.0910
SL	2.5/8	2.5/7	2.5/4.5	2.5/5	2.5/5	2.5/3	2.5/3.5	2.5/2.5	0.5191	0.0649
Total									8.00	1.00

RF: Rainfall, LG: Lithology, GG: Geomorphology, SP: Slope, GL: Groundwater level, DS: Drainage system, LC: Land cover, SL: Soil

According to Saaty 1986, in the AHP technique, it is necessary to consider the consistency ratio. If consistency ratio CR ≤ 0.1 (10 %) the result is acceptable because the expert judgment is relatively consistent. Conversely, if CR > 0.1, this assessment is inconsistent, the judgments are somewhat random and should be re - evaluated.

The consistency index CI = 0.0148 and the consistency ratio CR = 0.0105 (<10 %), the result is acceptable because the expert judgment is relatively consistent.

Table 5. Normalized weights corresponding to indicator variables of each factor

Factors	Indicator variables	Assigned weight	Geometric mean	Normalized weight
Rainfall (RF)	1,700.01 - 2.026.00	9	1.73	0.35
(mm/years)	1,600.01 - 1.700.00	7	1.35	0.27
	1,500.01 - 1.600.00	5	0.96	0.19
	1,418.01 - 1,500.00	3	0.58	0.12
	1,235.00 - 1,418.00	2	0.38	0.08
Lithology (LG)	Grit sand	6	2.32	0.39
	Clay loam, sand	3	1.16	0.19
	Clay loam, loamy sand	2.5	0.97	0.16
	Clay, loamy sand	2	0.77	0.13
	Clay loam	1	0.39	0.06
	Bedrock	1	0.39	0.06
Geomorphology (GG)	Delta	8	2.13	0.53
	Moderately steep mountains	4	1.07	0.27
	High sloping valley	2	0.53	0.13
	High sloping mountain	1	0.27	0.07
Slope (SP), %	0.00 - 5.00	7	1.84	0.37
	5.01 - 10.00	5	1.32	0.26
	10.01 - 16.00	4	1.05	0.21
	16.01 - 26.00	2	0.53	0.11
	> 26.00	1	0.26	0.05

Factors	Indicator variables	Assigned weight	Geometric mean	Normalized weight
Groundwater level (GL) m bgs	>10	8	1.74	0.35
	7.51 - 10	6	1.30	0.26
	5.01 - 7.5	4	0.87	0.17
	3.01 - 5	3	0.65	0.13
	1 - 3	2	0.43	0.09
Drainage system (DS), km/km^2	0.00 - 0.25	8	2.1	0.41
	0.26 - 0.50	5	1.3	0.26
	0.51 - 0.75	3.5	0.9	0.18
	0.76 - 1.00	2	0.5	0.10
	1.01 - 1.40	1	0.3	0.05
Land cover (LC)	Water bodies	8	1.72	0.25
	Rice	7	1.51	0.22
	Crop	6	1.29	0.18
	Forest	4	0.86	0.12
	Wetland	3.5	0.75	0.11
	Bare land	3	0.65	0.09
	Urbanization	1	0.22	0.03
Soil (SL)	Sandy soil	7	2.04	0.25
	Red brown silver gray soil	5	1.45	0.18
	Fertile alluvial soil	4	1.16	0.15
	Salty brackish alluvial soil	4	1.16	0.15
	Rich in nutrients and fertile clay	3	0.87	0.11
	Discolored gray soil on sedimentary and metamorphic rocks	2	0.58	0.07
	Gray soil. silver color shale	1.5	0.44	0.05
	Rocky land	1	0.29	0.04

All the thematic maps were converted into raster format and superimposed by weight overlay method which consists of GRI and integration of them through GIS. Integration of thematic maps for carrying out multi - criteria or overlay analysis in the GIS environment was done using ArcGIS software. The GRI value of groundwater recharge potential was calculated as Formula 1 and got in the range from 0.14 to 0.34. It has been reclassified into 3 zones of groundwater recharge potential, namely low (zone I), moderate (zone II) and high (zone III). GRI value less than 0.22 was assigned for a low potential zone whereas from 0.22 to 0.27 and higher than 0.27 were assigned for moderate and high recharges, respectively (Fig. 3).

4.3. Verification

Groundwater recharge rates are estimated as 77 mm/year, 280 mm/year and 440 mm/year corresponding to 3 zones as low, moderate and high recharge, respectively (Le Viet Hung et al, 2021) [8] (Tab. 6).

Table 6. Goundwater's age is determined by the component ^3H (mbs: from ground)

Zone 1. Low GRI			Zone II: Moderate GRI			Zone III: Hight GRRI		
Borehole	H, mbs	^{3}H-Age, years	Borehole	H, mbs	^{3}H-Age, years	Borehole	H, mbs	^{3}H-Age, years
Q68a	-8	2.8	Q83	-7.7	0.0	Q109	-9	5.5
Q1	-9	6.4	Q89	-8.4	1.4	Q110	-9	3.5
Q67	-7	0.4	Q115	-14	22.0	Q159a	-7.5	3.0
Q66	-12	27.0				Q158	-7.4	1.7
						Q164	-9	3.5
						Q145	-9	3.5
						Q147	-9	2.5

These groundwater recharge rates imply that the classification by GIS and remote sensing as above mentioned and weight and rating which were assigned to each factor are reasonable. Postma et al., 2007 [23] estimated the recharge from the Red River to aquifers by Tritium/Helium dating in Dan Phuong where it is located in the North of Hanoi and in-between zone I and zone II. Water samples for Tritium/ Helium dating of the groundwater were taken from screens placed at different depths in the distance range from 64 to 75 m. The results suggest the groundwater to be less than 40 years old and a downward groundwater velocity of 0.5 m/yr. If formation porosity is 30% groundwater recharge rate could be about 150 mm/year. T. L. Tran, 2011 [30] used a water balance site with 05 boreholes and groundwater level measurements in the period 2008 - 2011 in Dan Phuong - Thach That area where is margin of the delta. Groundwater recharge rates were estimated as 175 mm/ year. These results also proved that zone delineation is fair enough for groundwater recharge potential in the RRDP.
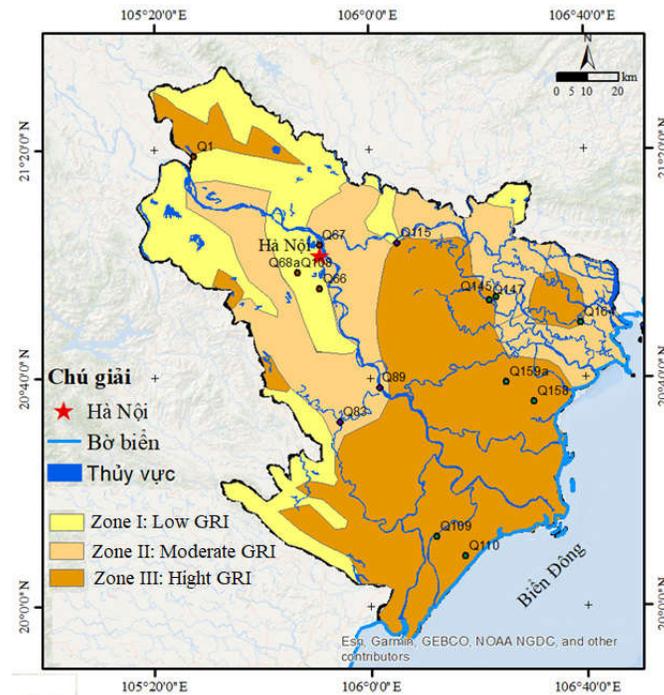

Figure 3: Map of groundwater recharge potential zones

5. Conclusions

The analytic hierarchy process (AHP) is one of the most popular and widely employed multi - criteria methods. Assessment of groundwater recharge potential in the RRDP based on eight thematic maps concerning the estimation of groundwater recharge potential is formed such as slope, soil texture, drainage density, land use/land cover, lithology, geomorphology, groundwater level and rainfall. All the thematic maps' corresponding layers were allocated ranks and weights based on their impact on groundwater recharge potential which is referenced from concerned studies and local expert opinions. Normalized weights of each indicator and its variables calculated were superimposed by the weight overlay method. Outcome GRI and delineation of groundwater zones are reliable.

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