Zoning groundwater potential recharge using remote sensing and GIS technique in the Red river delta plain

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Abstract. The Red River delta plain is the second largest delta in Vietnam and is located in the North of the country with an area of 14,860 km² and residing more than 22.5 million inhabitants. Groundwater is mainly exploited in Quaternary sedimentary aquifers with a total discharge of about 3 million m³/day. Some localities have shown signs of over-exploitation such as in Hanoi and in Nam Dinh, which may lead to related problems such as depletion, subsidence, saltwater intrusion, and water pollution. In order to be able to sustainably exploit groundwater, the groundwater potential recharge needs to be estimated. There have been many studies using different methods to estimate the groundwater recharge and to zone potential recharge. In the study area, there are several studies for groundwater recharge, but some are still uncertain because of using indirect methods, some are locally estimated in specific areas. Therefore, the objective of this study is to apply remote sensing and GIS to zone the groundwater potential recharge and its verification by using radioactive isotope ³H analysis in the Red River delta plain. Various types of satellite images have been used and interpreted to detect the different thematic layers which concern the groundwater potential recharge. GIS has been applied as a platform for analysis and integration of thematic layers for zonation, finally. Field trip and water sampling for chemical and radioactive ³H analysis were also conducted. Zones with low, moderate, and high groundwater potential recharge have been delineated with good agreement from the direct estimation of groundwater recharge by radioactive isotopes ³H.

1. Introduction

The groundwater recharge of a certain area is a fundamental component of the balance of a certain catchment, which contributes to the sustainable exploitation of water resources in general and groundwater in particular. Lerner et al. [1] and Scanlon et al. [2] reviewed numerous methods have been used to estimate groundwater recharge. In recent years, many researchers have applied remote sensing methods and GIS techniques to assess potential groundwater [3, 4, 5, 6], groundwater recharge [7, 8, 9], potential areas for artificial recharge [7], and potential sites for groundwater exploration [10, 11]. This approach is based on the interpretation and integration of factors related to the influence of groundwater potential, groundwater recharge, conditions for artificial recharge, and the possibility of groundwater.
exploration. The limitation of this approach is that the methods are indirect with some uncertainties. To improve the reliability of these methods, it is very necessary to determine the weight of the relative importance of the relevant indicators objectively by analytical hierarchical process (AHP). Furthermore, verifying the evaluation results by the direct method is also very necessary. However, due to large uncertainties involved in the measurement of individual parameters of each method, a common recommendation is that recharge should be estimated by the use of multiple methods and the results compared [2, 12].

The Red River Delta Plain (RRDP) is the second largest delta in Vietnam with an area of over 14,860 km² accounting for about 4.5% of the total area of the country, residing 22.5 million people and the place with the largest population density in the country [13]. Groundwater is primary water supply source for the RRDP with a total exploitation discharge about 3 million m³/day [14]. However, long-term excesses groundwater exploitation in the delta has resulted in many problems such as ground subsidence, pollution, depletion, and saltwater intrusion related to groundwater have also occurred in this area [15].

There have been a number of studies to assess the amount of groundwater recharge in this area. For examples Pham [16] estimated the groundwater recharge in RRDP by using a modeling method. Tran [17] indicated that the groundwater recharge and the interaction between aquifers in Quaternary sediments in Thach That - Dan Phuong area, Hanoi were based on determining the average travel time by using stable isotope 18O/2H and radioactive isotope 3H. Pham et al [15] conducted isotope sampling to evaluate the interaction between river and groundwater. The authors showed that the water ratio from Red River recharged to well fields Ha Dinh, Mai Dich, Phap Van extracting from Pleistocene were 50%, 52% and 57%, respectively. Postma et al. [18] determined the recharge from the Red River to aquifers by Tritium/Helium dating in Nam Du area. Larsen et al. [19] using isotopes and modeling to determine the recharge from Red River and rainwater to Quaternary aquifers in Dan Phuong area. Although there have been several studies to evaluate groundwater recharge as mentioned above, either the reliability of the research results is limited, or the research results are just focused on specific areas in RRDP. The objective of this study is to apply remote sensing and GIS technique to zone groundwater recharge potential in the RRDP. In this study, we only focus on diffuse (direct) recharge derived from precipitation or irrigation, etc. that occurs fairly uniformly over large areas.

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 (Figure 1). Contiguous to the North and Northeast is the Northeast region, to the West and Southwest is the Northwest region, the East is the Gulf of Tonkin and the South is the North central region. 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 to 100 m. RRDP belongs to a humid tropical monsoon climate with two distinct seasons, the dry season and the rainy season. The rainy season is from May to October and the dry season is from November to April next year. The characteristics of rainfall, evaporation, and sunshine hours have markedly changed according to the seasons of the year and for different areas in the whole region. The average annual rainfall for the whole delta is from 1033 to 2338.7 mm and the amount of evaporation is from 828.2mm to 1057.1mm. The highest air temperature is 39°C and average is 23.5°C. The daily temperature difference is relatively large 8°C-15°C in summer and 4°C-13°C in winter season. 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. Research documents as well as satellite maps show that the Red River bed has moved and as a result formed a system of oxbow lakes as well as affecting the distribution of sedimentary facies in the RRDP. The coast is located in the
East and South East of the RRDP running from Quang Ninh to Thanh Hoa with a total length of about 200 km. 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, but also affects the shallow aquifers in the vicinity [18, 20].

![Figure 1. Location of study area. Modified from Tran [21]](image)

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 Paleogene, Neogene and Quaternary deposits [20]. The RRDP is surrounded by mountain ranges composed of crystalline rocks from Paleozoic and Mesozoic sedimentary rocks [22, 23]. According to Tran [24], the sediments were deposited in five fining-upward sedimentation cycles. The first two of these cycles are of lower to middle Pleistocene age and are composed of coarse-grained alluvial/fluvial deposits, followed by the upper Pleistocene cycle of fluvial deposits which grading upwards into deltaic-lacustrine swamp environment sediments. The fourth cycle has a lower to middle Holocene age and is composed of fine-grained sand and clay that formed in a deltaic environment; The top fifth cycle from the upper Holocene is dominated by coarse-grained sediments that form in delta plain and delta front environments. The deeper Pleistocene aquifers are recharged by the surrounding mountain range and the average annual recharge to the aquifers is in the range of 100-400 mm. 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 [19].

3. Methods and Materials
3.1. Data collection

The data on the groundwater monitoring network in the RRDP were collected, including data on the structure of the monitoring boreholes, the arrangement of screen at the aquifer. Monitoring data on rainfall and evaporation at 6 meteorological stations, 7 rivers, water levels at hydrological stations and groundwater level data at 128 groundwater monitoring boreholes were also collected. These data were included in the computation, assessment of groundwater recharge on the basis of data of stable isotopes and radioactive isotopes.

3.2. Delineation of groundwater recharge potential zones

Delineation of groundwater recharge potential zones was conducted by integrating different thematic maps obtained from satellite interpretation and field data analysis on GIS platform. The satellite images selected for interpretation depend on their application and are shown in the table below:

| Satellite Images | Resolution | Number of scenes | Time | Applications |
|------------------|------------|------------------|------|--------------|
| Multi-temporal PALSAR-/ScanSAR | 50 m | 450 (1° x 1°) | 2016 | Land use and land cover, topography, geology, climat and hydrology |
| ALOS-2 /PALSAR-2 | 25m | 60 (1° x 1°) | 2016 | Land coverage observation, disaster monitoring and resource surveying and elevation data |
| AW3D30 | 30m | 60 (1°x 1°) | 2006-2011 | Digital surface models |
| Multi-temporal Sentinel-1 SAR GRD C-band | 10m | 480 (1° x 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 | 30m | 480 (1° x 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° x 1°) | 2016 | Urban land cover and urban extent mapping |

The thematic maps as the factors of groundwater recharge influence were established on the same scale as i) Lithology map ii) Geomorphological map iii) Topographic slope map iv) Drainage system map v) Soil classification map vi) Land use map vii) Rainfall map and viii) Groundwater level map. The above maps were built on the same coordinate system and projection zone so that they can be integrated by the ArcGIS 10.5. Total value was applied to develop the groundwater recharge potential index of the area using the equation proposed by Malczewski, 1999 [25]

\[
GRI = \sum_{w=1}^{m} \sum_{j=1}^{n} W_j X_i \quad (1)
\]

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.
The analytic hierarchy process (AHP), developed by Saaty [26] 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; $\lambda_{\text{max}}$ 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 [26].

In this case, the weights which got from expert opinions and from Tesfa and Girum [6], Senanayake et al. [9], Jaiswal et al. [11], Magesh et al. [18] and Chuma et al. [3]) were assigned to each factor. Pairwise comparisons between this each thematic factor obtained based on methods used by Machiwal et al. [4] and Sahoo et al. [10], Chowdhury et al. [5], and Chowdhury et al. [7] were presented in Table 2. The normalized weights were determined by dividing each geometric mean by the its total column. This ratio reflects a reasonable level of consistency in the pair-wise comparison phase. Similarity, each of the thematic factor has been divided into different features based on indicators which got references from Tesfa and Girum [6] and Senanayake et al. [9]. Nomanlized weights were also calculated by the AHP method as described above.

3.3. Water sampling and analysis

Groundwater was taken using a Grundfos MP1 submersible pump for main ion and tritium ($^3$H) samples. Before taking samples, static water level in each sampling borehole was measured. The samples were taken once pH and electrical conductivity (EC) in water became unchanged. For $^3$H analysis, the water samples were first subjected to distillation to remove the minerals dissolved until the electric conductivity was less than 10 mS cm$^{-1}$. Around 500 ml of the distilled water samples were then subjected to the electrolytic enrichment for tritium at 4°C till around 10 ml was attained [27]. These samples were analysed at Institute of Nuclear Science and Technology, Hanoi (INST). Sixteen of $^3$H samples and major ions samples were collected from national monitoring network of groundwater with different screen depth in Holocene aquifer. Based on the analysed results groundwater recharge rate can be estimated and also validated for zoning groundwater potential recharge.

3.4. Estimation of groundwater recharge using isotopes technique

According to David [28] the groundwater recharge calculated on the basis of radioactive isotope 3H is determined by the following formula:
Where:

\[ W \geq \frac{CD - (EL - WT)}{A} \]

4. Results and discussion

4.1. Building the related factors to groundwater potential recharge

i. Rainfall

Rainfall distribution in the delta also directly affects the groundwater recharge. Heavy rainfall increases the groundwater recharge rate and vice versa. Using CHIRPS: Rainfall Estimates from Rain Guage and satellite Observation data with 08 meteorological stations’ data in the RRDP and associated with Multi-temporal Sentinel-1 SAR GRD C-band interpreted data supported to divide the RRDP into 5 areas with different rating presented at Table 4 and Figure 2 a. The heavy rainfall were located in the edges and near coastal areas.

ii. Lithology

The aquifer properties vary from one rock type to another rock type. The lithology influences both the permeability of aquifers while the distribution of weathered regolith is also known to be important for groundwater yields in crystalline rocks as described by Wright [29]; McFarlane et al. [30]. The weathered regolith may extend to greater depths in a highly fractured terrain like in RRDP margin. By using Multi-temporal PALSAR-ScanSAR images interpretation associated with collected data from previous studies [31-34] the lithology was divided into 06 areas and presented in Table 4 and Figure 2b. The RRDP consists of metamorphic rocks of khondalitic group (Fig. 2) which include garnetiferous biotite gneiss (48.03%), garnet biotite gneiss of migmatite complex (41.34%)

iii. Geomorphology

The identification and characteristics of various landforms and structural features in the study area was very important from geomorphological study point of view. Many of these features are favourable for occurrence and recharge of groundwater and are classified in terms of groundwater recharge potentiality. The geomorphic imprints can be considered as surface indicators for identification of subsurface water conditions. This information provides a reliable base for effective planning, development and management of groundwater resources of an area. By using Digital Elevation, Shuttle Radar Topography Mission (SRTM) 1 Arc-second Global and Multi-temporal PALSAR-ScanSAR data the geomorphology were founded and were divided into 04 areas and presented in Table 4 and Figure 2c. The study area are covered with plain terrain and high gradient hill in edge North-Western and South-Western of the deltas.

iv. Slope

The precipitous terrain causes rapid runoff and does not store water easily. Slope of any terrain is one of the factors allowing the infiltration of groundwater into subsurface or in other words groundwater recharge. In the gentle slope area the surface runoff is slow allowing more time for rainwater to percolate whereas steep slope area facilitates high runoff allowing less residence time for rainwater to percolate and hence comparatively less infiltration. Slope is the rate of change of elevation and considered as the principal factor of the superficial water flow since it determines the gravity effect on the water movement. The slope is directly proportional to runoff and groundwater recharge will be lesser in the areas with steep slope. The water flow over the gently undulating plains is slow and adequate time is available to enhance the infiltration rate of water to the underlying fractured aquifer. With the data from
Digital Elevation, Shuttle Radar Topography Mission (SRTM) 1 Arc- Second Global, the slope percentage map of zone research was created with 05 ranks from 0 to plus of 26% and presented in Table 4 and Figure 2d. The major deltas were found in class 1 (slope from 0 to 5 %) which covers 70% of the study area while the class 5 (slope plus 26%) covers only 5%.

v. **Groundwater level**

Groundwater level is related to the unsaturated zone thickness distribution in unconfined aquifers. Obviously, the shallower the groundwater level the greater the ability to groundwater recharge and vice versa. Groundwater levels at 128 monitoring boreholes were measured during sampling and divided in 05 areas and presented Table 4 and Figure 2e. Near the coastal areas, the groundwater level found from 1 to 3m from the ground covered 32% of areas. The zone deepest values were found in Ha Noi (> 10m), covers 1.5% zone research.

vi. **Drainage**

The drainage is dominated by the deeply incised, sand/clay filled seasonal streams. The development of stream segments is affected by slope and local relief and these may produce differences in drainage density from place to place. The spatial variation of drainage density was estimated by following the methodology adopted for calculating lineament density. Drainage data in the RRDP is available in annual statistic report for every province. The drainage density of Red River Delta Plain was prepared from Digital Elevation, Shuttle Radar Topography Mission (SRTM) 1 Arc- Second Global, the digital elevation AW3D30 (30 m x 30 m resolution) in ArcGIS 10.3.1 platform and presented in Table 4 and Figure 2e. About 56.6% and 20.2% of the area were found in very low (0-0.25 km/km²) and low (0.25-0.5 km/km²) drainage density classes, respectively.

vii. **Landuse/Land cover**

Land use/land cover features control the occurrence of groundwater and also causes for infiltration for recharge with variety of classes among itself. Standard visual interpretation methods were applied to identify and interpret the land use pattern of the area and various land use classes delineated includes agriculture, forest, waste land, built-up land and water body. With the data from Japan Aerospace Exploration Agency - Earth Observation Research Center and using Multi-temporal Sentinel-2, Landsat 8 imagery, we were interpreted land use, land cover map (see Table 4 and Figure 2e). The study area consists of seven types of land cover: rice, crop, forest, wetland, bare land, urbanization and water. The major parts of the deltas were dominated by agriculture covering with 32% of the study area.

viii. **Soil**

Soil characteristics have a considerable role on the infiltration of water. The rate of infiltration largely depends on the grain size of soils. Wetland hydromorphic soils are poorly drained with a depth and they are developed on fluvial sediments. The low land plains are differentiated by the presence of lateritic soils and riverine alluvium and moderately well drained nature with depth and texture varies from clay loam to clay texture. Soil maps are available in DONRE and FAO of every province. This soil types was divided into 08 areas and presented in Table 4 and Figure 2f. All of the most of deltas is the alluvial soil (45% of areas). The feralit soil located on the North-Western and South-Western edges of the plain (7%) and the acidic, salty soil distributed in a coastal strip from Hai Phong to Ninh Binh (28%). These soils are characterized by poor to moderate infiltration property.
Figure 2. Thematic maps a) Rainfall map b) Lithology map c) Geomorphology map d) Slope map e) Drainage system map f) Soil map g) Land use/land cover map h) Groundwater level map
4.2. Building the related factors to groundwater potential recharge

The groundwater recharge potential map is developed by overlaying thematic factors. 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 computed according to Formula 1. Results of pairwise comparisons between thematic factors and its normalized weights are presented in Table 2. Similarly, weights are assigned respectively from expert opinion and references to the indicator variables and the corresponding normalized weights are presented in Table 3.

Figure 3. Map of groundwater recharge potential zones
Table 2 Pairwise comparison between thematic factors

| Factor  | RF     | LG     | GG     | SP     | GL     | DS     | LC     | SL     | Assigned weight | Geometric mean | Normalized weight |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|-----------------|----------------|------------------|
| RF      | 8/8    | 8/7    | 8/4.5  | 8/5    | 8/5    | 8/3.5  | 8/2.5  | 8      | 1.66            | 0.21           |                  |
| LG      | 7/8    | 7/7    | 7/4.5  | 7/5    | 7/5    | 7/3    | 7/2.5  | 7      | 1.45            | 0.18           |                  |
| GG      | 4.5/8  | 4.5/7  | 4.5/4.5| 4.5/5  | 4.5/5  | 4.5/3.5| 4.5/2.5| 4.5    | 0.94            | 0.12           |                  |
| SP      | 5/8    | 5/7    | 5/4.5  | 5/5    | 5/5    | 5/3    | 5/2.5  | 5      | 1.04            | 0.13           |                  |
| GL      | 5/8    | 5/7    | 5/4.5  | 5/5    | 5/5    | 5/3    | 5/2.5  | 5      | 1.04            | 0.13           |                  |
| DS      | 3/8    | 3/7    | 3/4.5  | 3/5    | 3/5    | 3/3    | 3/2.5  | 3      | 0.62            | 0.08           |                  |
| LC      | 3.5/8  | 3.5/7  | 3.5/4.5| 3.5/5  | 3.5/5  | 3.5/3  | 3.5/2.5| 3.5    | 0.73            | 0.09           |                  |
| SL      | 2.5/8  | 2.5/7  | 2.5/4.5| 2.5/5  | 2.5/5  | 2.5/3  | 2.5/2.5| 2.5    | 0.52            | 0.06           |                  |
| Total   | 8.00   | 8.00   | 8.00   | 8.00   | 8.00   | 8.00   | 8.00   | 8.00   | 8.00            | 1.00           |                  |

*RF: rainfall, LG: Lithology, GG: Geology, SP: Slope, GL: Groundwater level, DS: Drainage system, LC: Land cover, SL: Soil

Table 3 Normalized weights corresponding to indicator variables of each factor

| Factors               | Indicator variables                  | Assigned weight | Geometric mean | Normalized weight |
|-----------------------|--------------------------------------|-----------------|----------------|------------------|
| Rainfall (RF) (mm/years) | 1,700.01 - 2,026.00 | 9               | 1.73           | 0.35             |
|                       | 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             |
| 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             |
Factors | Indicator variables | Assigned weight | Geometric mean | Normalized weight
---|---|---|---|---
Drainage system (DS), km/km² | 1 - 3 | 2 | 0.43 | 0.09
 | 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
Landcover (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 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 it from 0.22 to 0.27 and higher than 0.27 were assigned for moderate and high recharges, respectively.

4.3. Estimation of groundwater potential recharge using radioactive isotope \(^3\)H

Table 4 showed results of \(^3\)H-age of the groundwater samples under this study and these results were separated into 3 groups which attributed to 3 zones.

**Table 4** \(^3\)H-age of groundwater samples taken from boreholes with different water table elevation H (mbs: meter below the ground surface)

| Zone I: Low recharge | Zone II: Moderate recharge | Zone III: High recharge |
|---|---|---|
| **Borehole ID** | **H, mbs** | **\(^3\)H-Age, y** | **Borehole ID** | **H, mbs** | **\(^3\)H-Age, y** | **Borehole ID** | **H, mbs** | **\(^3\)H-Age, y** |
| Q68a | -8 | 2.8 | Q83 | -7.7 | 0.0 | Q108 | -12 | 11.0 |
| Q1 | -9 | 6.4 | Q89 | -8.4 | 1.4 | Q109 | -9 | 5.5 |
With results in Table 4 potential recharge rates for the three expected zones in the RRDP were estimated based on the relationship between the $^3$H-age of groundwater samples and the elevation of the water table in boreholes from where the samples were taken in this study. Figure 4 presents this relationship.

| Zone | $^3$H-age | Elevation | Q67 | Q33 | Q66 |
|------|-----------|-----------|-----|-----|-----|
| I    | -7        | 0.4       | Q115| -14 | 22.0|
| II   | -8.94     | 20.0      |     |     |     |
| III  | -12       | 27.0      |     |     |     |
|      |           |           | Q110| -9  | 3.5 |
|      |           |           | Q159a| -7.5 | 3.0 |
|      |           |           | Q158| -7.4 | 1.7 |
|      |           |           | Q164| -9   | 3.5 |
|      |           |           | Q145| -9   | 3.5 |
|      |           |           | Q147| -9   | 2.5 |

Figure 4 A graph showing a relationship between groundwater table elevation and $^3$H age of groundwater samples taken from 3 zones with different potential recharge rates; mbs: meter below the surface; $^3$H-age: groundwater age estimated by the $^3$H method

As seen from Fig 4 in zone I, II, and III the relationships between groundwater table elevation and 3H-age followed three models as:

\[
\text{Zone I: } H = -0.077 \times \text{Age} - 7.66 \text{ (m) } (R^2 = 0.52) (3) \\
\text{Zone II: } H = -0.28 \times \text{Age} - 7.85 \text{ (m) } (R^2 = 0.998) (4) \\
\text{Zone III: } H = -0.44 \times \text{Age} - 7.12 \text{ (m) } (R^2 = 0.83) (5)
\]

This means that in zone I, II, and III the potential recharge rates could be as high as 77 mm/year, 280 mm/year and 440 mm/year, respectively.

4.4. Verification

The estimation of groundwater recharge rate by radioactive isotope $^3$H shows that the zonation of groundwater potential recharge based on remote sensing combined with GIS techniques and determining the weights for overlay analysis by mean of AHP is completely reliable and acceptable. However, due to the limited number of samples in the regions and the uneven distribution of screen depth of the boreholes, the correlation coefficient is not good enough, especially for zone I. The reason for the small correlation coefficient is large differences of the $^3$H isotope compositions of the groundwater samples at boreholes Q67 and Q33 where the screen depth of boreholes are almost located at the same depth in different locations. It may be the lithology of the unsaturated layer at borehole Q33, which is mainly clay so that the travel time of rainwater is also longer than borehole Q67.
Some previous studies of groundwater recharge in RRDP also verified the above mentioned zonation. Postma et al. [18] estimated the recharge from the Red River to aquifers by Tritium/Helium dating in Dan Phuong where it is located in Noth 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 ground waters 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 150mm/year. Tran [11] used water balance site with 05 boreholes and groundwater level measurements in period 2008-2011 in Dan Phuong - Thach That area where is margin of the delta. Groundwater recharge rate were estimated as 175 mm/year. These results also proved that delineation is fair enough for groundwater potential recharge in the RRDP.

5. Conclusions

The Quaternary aquifer system in the RRDP is recharged mainly from rainwater, river water, and surrounding bedrocks. The topmost Holocene aquifer is an unconfined and semi-unconfined aquifer and recharged from mainly rainwater and surface water bodies. In this case of a large area with a lack of related information for delineation of groundwater potential recharge, a holistic approach based on the factors by using remote sensing interpretation on conditions of groundwater recharge and overlay analysis by GIS technique. To improve the reliability of this technique, it is very necessary to determine the weight of the relative importance of the relevant factors objectively by AHP. Furthermore, verifying the evaluation results by the direct method of radioactive isotope $^3$H is also very effective. By this approach, groundwater potential recharge in the RRDP has been classified into 03 zones: low potential, moderate potential and high potential recharge. Using the results of $^3$H radioisotope analysis the groundwater recharge rate from high, moderate, and low potential zone were roughly estimated 77; 280; and 440 mm/year, respectively. However, $^3$H analysis samples are quite few and have only been conducted in the dry season, so they need to continue to be followed up in the near future. Weight value for thematic factors need to be improved if necessary when the data to estimate the groundwater recharge rate is large enough to have a more suitable.

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