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RESEARCH ON FACTORS INFLUENCING ON GROUNDWATER RECHARGE FROM RAINFALL FOR QUATERNARY SEDIMENTS IN RED RIVER DELTA PLAIN

SUMMARY OF DISSERTATION ON GEOLOGY

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INTRODUCTION

1. Rationale of the thesis

The Red River Delta Plain (RRDP) – one of the largest economic, political, social and cultural centers of the country, with an area of over 21,260 km2, is home to about 22.9 million inhabitants. Groundwater in the Red River Delta Plain is exploited and used for daily life and for production. Groundwater is mainly exploited in Quaternary sedimentary aquifers and used for production and daily life. However, some areas have shown signs of over-exploitation such as Hanoi and 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.

Studies on groundwater recharge in the RRDP often determine only one point or a local area, but there are no studies on the whole region. On the other hand, the previous studies have not mapped the groundwater recharge potential zone, mainly estimating groundwater recharge sources from rivers, bedrock or from other aquifers. So, the thesis "**Research on factors influencing groundwater recharge from rainfall in Quaternary sediments in the Red River Delta Plain**" has scientific and practical significance.

2. Research objectives of the thesis

Identify the influencing factors and the groundwater recharge from rainfall in Quaternary sedimentary aquifers in the Red River Delta Plain.

Assess the role of recharge from rainfall in the formation of groundwater reserves in the RRDP.

3. The main research content of the thesis

Overview of the study area and studies on groundwater recharge from rainfall in the world and Vietnam.

Further elucidate the geology, geomorphology and hydrogeology of the RRDP.

Study of influencing factors, potential zoning and determination of groundwater recharge in the RRDP.

Study on the role of groundwater recharge from rainfall in the formation of groundwater reserves in the RRD.

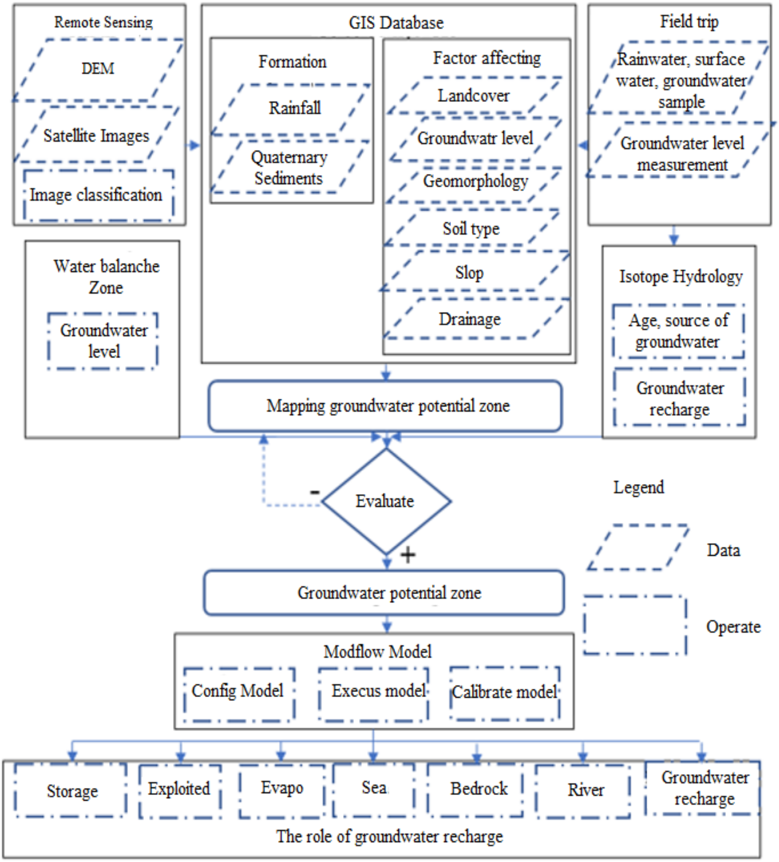


Figure 1. Schema of research

CHAPTER 1. OVERVIEW OF THE STUDY AREA AND RESEARCH ON GROUNDWATER RECHARGE FROM RAINFALL

1.1. Overview of the study area

The study area covers an area of over 14,860 km², located in the RRDP, carried out in the following range: in the north, bounded by Tam Dao - Yen Tu mountain range; in the south, bounded by Ba Vi – Vien Nam mountain range; in the east, bounded by the coastline. The study area is located in the tropical humid monsoon climate zone: dry season (from November to April of the next year, accounting for 15% of annual rainfall) and rainy season (from May to October, accounting for 85% of annual rainfall). The relative humidity is very high throughout the year, with an annual mean value of 84.5%.

The RRDP is a very complex hydrological network that has two main branches which are the Red river system and the Thai Binh river system with a drainage system density from 0.4 to 0.7 km/km^2.

1.2. Overview of research on groundwater recharge from rainfall

1.2.1. Researchs in the world

By using the water table fluctuation method, *Delin and partners (2007)* estimated that the groundwater recharge from rainfall accounts for 21% of precipitation in Minnesota. In Carolina, *Coes and partners (2007)* calculated this recharge accounts for 56% of precipitation.

By using 1D Hydrus modeling and GIS technology, *L. Bertrand and M. Dirk (2011)* estimated that the groundwater recharge from rainfall will decrease by 9% (in 2100) according to IPCC climate change scenario in Net basin, Belgium. *A.K. Mustafa, E.N. Ali (2013)*, by using MODFLOW modeling and GIS technology, determined that the groundwater recharge accounts for 5% of precipitation in summer and 95% in winter in Jafr basin, Jordan.

By using the stable isotopes in water (δ 2H, δ 18O) and modeling, *D. Adomako and all (2010)* estimated that the groundwater recharge from rainfall in the aquifers of Densu basin, Ghana is 94 ÷ 182 mm/year, equivalent to 6 - 14% of the precipitation (according with modeling method) and is 110 ÷ 250 mm/year, equivalent to 11- 14% of the precipitation (according with peak-shift method). *J. Parlov and partners (2019)* used the model of 2 or 3 components to determine the groundwater recharge in Quaternary aquifers in Zagreb (Croatia).

M. Senthilkumar (2019), Shivaji Govind Patil and all (2014), Preeja and all (2011) used the remote sensing and GIS data to build the map layers of factors influencing the groundwater recharge and map the groundwater recharge in the corresponding areas in Tamil Nadu, Maharashtra and Kerala, India, with potential recharge areas from the highest to the lowest.

1.2.2. Researchs in Vietnam

By using the water table fluctuation method, *Nguyen Duc Roi (2014)* estimated that the groundwater recharge from rainfall is 427mm/year, accounts for 34.1% of precipitation, in Van Lam and 547mm/year, accounts for 38.1% of precipitation, in Hung Yen city, Tien Lu. *Phan Van Truong (2011)* identified the main source of groundwater recharge in Quang Binh is rainfall and is equivalent to 15 - 16% of annual rainfall, about 77% appear in rainy season.

Pham Quy Nhan (2000) used the MODFLOW model and estimated the groundwater recharge in Quaternary sedimentary aquifers of the RRDP accounts for 56.28% in dry season and 84.11% in rainy season. *Hoang Minh Tuyen and all (2017)* used the SWAT model to estimate the groundwater recharge from rainfall in Dong Nai basin varies from 2% to 30% of precipitation depending on the land use of basin.

By using the isotope hydrology method, *Tran Thanh Le (2011)* estimed that the rainfall recharge for Holocene aquifers in Dan Phuong, Hanoi in the rainy season accounts for 88% of annual rainfall (by ^{18}O) and 85% of annual rainfall (by ^{2}H); in dry season, the groundwater of Holocene aquifers discharging to the Red river is 74% of annual rainfall (by ^{18}O) and 72% of annual rainfall (by ^{2}H). *Larsen, Pham Quy Nhan (2008)* calculated the groundwater recharge at Nam Du is 60 - 100mm/year (by Modflow model) and 195mm/year (by $^{3}H/^{3}He$).

From the researchs shown above, the author notices that, firstly, it is necessary to use different methods to determine the amount of recharge from rainwater to groundwater and then compare and evaluate the results with each other and with previous studies. Secondly, these researchs on the groundwater recharge in the RRDP only focus on a point or a local area, there is no research on the whole region of the RRDP (Fig 1.6). Thirdly, combining the isotope hydrology methods, remote sensing and GIS to map the groundwater recharge potential zone and estimate the groundwater recharge from rainfall is new method and feasible. Fourthly, the Modflow model is efficient in the determination of the role of rainfall in the infiltration supply component for the formation of groundwater reserve of Quaternary sedimentary aquifers in the RRDP.

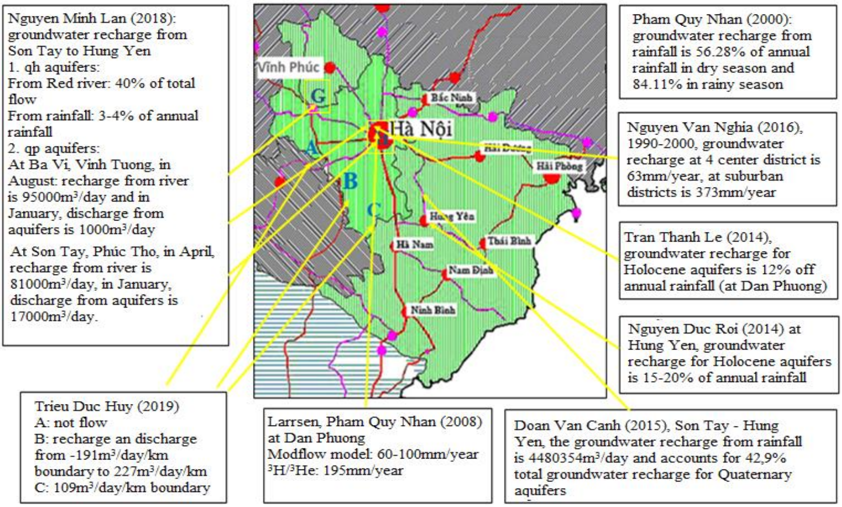


Figure 1.6. Groundwater recharge research in RRDP

CHAPTER 2. GEOLOGICAL, GEOMORPHOLOGICAL AND HYDROGEOLOGICAL FEATURES OF THE STUDY AREA

2.1 Geological features

In addition to the bedrocks forming the bottom of the delta, the Quaternary sediments inclure i) the Pleistocene formations (the Le Chi, Hanoi, Vinh Phuc formations) with the coarse-grained structures including gravel, pebble located at the bottom, upward transition is coarse grained sand, medium grained sands and the top of parts are usually clay, clay silt and sandy silt. ii) the Holocene formations (the Hai Hung and Thai Binh formations) with medium to fine-grained sand of aluvi origin and clay, clay silt components mainly of sea, lake and marsh origin.

2.2 Geogeomorphological features

The RRDP is characterized by different high and low terrains: i) the coastal areas with the altitude lower than 1m, ii) the terrace river with the altitude from 7 - 8m to 15m, iii) the hills with the altitude from 50 - 100m in the middle of the plain and iv) the high mountains with the altitude of 900m in the western and northwestern edges. The topography of the area is divided into many cells characterized by i) the Northwest-Southeast fault system (which controls and divides the RRDP into zones with different tectonic activity regimes) and ii) the Northeast-Southwest and sub-meridian fault systems (plays the role of gradation, dividing the plain).

2.3 Hydrogeolgical features

The RRDP has two main aquifers: i) Holocene aquifer, which is composed of medium to fine-grained sand deposits of the Thai Binh formation and the upper part of the Hai Hung formation and is the first aquifer from the ground with the youngest age; ii) Pleistocene aquifer, which is distributed widely across the plain, exposed mainly at the top of the plain and mostly covered by younger Holocene deposits. The aquifer is composed of coarse-grained to median-grained deposits. Between two main aquifers, there is the sediments that are weakly permeable dated Early Holocene and Middle Holocene (Hai Hung formation, Q_2^{1-2}hh) and the impermeable sediments dated Late Pleistocene (Vinh Phuc formation, Q_1^3vp).

CHAPTER 3. RESEARCH DATA AND METHODOLOGY

3.1 Research data

The author and his colleagues had directly took 128 groundwater samples, 30 surface water samples, 72 rainwater samples for stable isotope analysis, 16 groundwater samples for radioisotope analysis (according to the framework of NUFIC Project phase 3, OKP Project phase 2, Netherlands).

The satellite image data, DEM data and groundwater exploitation data... have been collected and inherited from the Earth Observation Research Center (EORC, JAXA), United States Geological Survey (USGS, USA), and National Centre for Water resource Planning and Investigation (NAWAPI, MONRE).

The stable isotope was analyzed at the Water Resources Laboratory, HUNRE by the author and colleagues. The radioisotope result was analysed at the Laboratory of Isotope Hydrology, Institute of Nuclear Science and Technology.

3.2 Research methodology

The author uses the collecting and analyzing documents method to determine the content, the research methodology of the thesis. The expert questionnaire and AHP method: determine the influencing factors and their importance. Remote sensing and spatial analysis in geographic information systems (GIS) method: to establish influencing maps as well as additional potential zoning. Isotop hydrology method, water table fluctuation method: to build local meteorological water lines and isotopic distribution lines of surface water and groundwater in the area, there by determining the age as well as the amount of recharge from rainfall to the groundwater. MODFLOW modeling method and the "Zone Budget" module: to evaluate role and distribution of the recharge from rainfall to the groundwater.

CHAPTER 4. FACTORS INFLUENCING, MAPPING POTENTIAL ZONE AND ESTIMATION OF RECHARGE IN HOLOCENE AQUIFER OF THE RRDP

4.1 Basis to determine factors affecting on the groundwater recharge from rainfall

4.1.1 Permeability properties of soil

Surface groundwater recharge from rainfall or irrigation water is defined as the downward movement of water from the unsaturated (vadose) zone of soil or rock and into the groundwater saturated (phreatic) zone. Permeability is the movement of water from the surface into a hole or fissure environment in the soil under the action of gravity. Permeability is one of the components of hydrological processes and is important in water balance (*Horton, 1933*).

4.1.2 Research on soil permeability

The studies show that the infiltration rate and water permeability of soil not only depend on rainfall, the time of rain but also depend on the characteristics and slope of the terrain, the mechanical composition, the thickness, the moisture and the permeability characteristics of the soil, the land cover and land use (*Bouma and Dekker, 1978; Dune and all, 1991; Onda and Yukawa, 1995; Hille, 1982; Pham Van Dien, 2006, 2009; Bui Huy Hien, 2012*).

4.1.3 Consult experts

The expert method is used with 30 questionnaires as a scientific basis to determine the factors affecting the groundwater recharge from rainfall, from there, the AHP method is applied to build the impact of weight and the influence level of each consulted factor on the groundwater recharge from rainfall.

4.2 Factors influencing on the groundwater recharge from rainfall to the Holocene aquifer of the Red River Delta Plain

4.2.1 Rainfall

The rainfall of the RRDP accounts for 80-85% of the annual rainfall, therefore, the groundwater recharge is very high in this season. In the rainy season, the groundwater level of the Holocene aquifer has a proportional relationship with the rainfall. The rainfall increases as the groundwater level increases but not at the same time. This linear relationship is highly dependent on the groundwater depth, geological conditions, topography and land cover.

4.2.2 Land cover, land use

The RRDP is divided into areas with different land cover, land use such as land for rice and crops, forests, wetlands, bare land, urban land and water. Most of the area of the RRDP is land for cultivation and crops (more than 40%) distributed mainly in Thai Binh, Nam Dinh, Ninh Binh, Ha Nam… The primary forest areas and planted forests can be observed at the edge of the delta such as Tam Dao, Ninh Binh, Ha Nam... These are types of land cover, land use that are very good for retaining rainwater and groundwater recharge. The impermeable surfaces are urban areas (about 15%) is located in Ha Noi and in cities that are centers of provinces or towns, districts… After each rain, the rainwater will create surface runoff and the groundwater recharge is poor.

4.2.3 Soil type

Characteristics and composition of soil have a significant role in water permeability and transportation. The top area of the RRDP is composed of sandy soil, mixed sandy soil, so it has good water permeability. About 45% of the area of the RRDP is composed of alluvial and fertile clay soils with good average water permeability. Feralite soil located on the northwestern and southwestern edges of the plain (about 7%) and acidic, saline soils distributed in the coastal strip from Hai Phong to Ninh Binh (about 28%) are characterized by poor to moderate permeability.

4.2.4 Quaternary sediments and bedrocks

In the RRDP, from the middle plain to the coastal area, the sediments are mainly upper Holocene sedimentary origin alluvial (aQ_2^3), composed of medium grain sand, mixed sand, sandy clay, and upper Holocene sedimentary origin river-sea (amQ_2^3) composed of clay, sand powder with moderate to poor water permeability. The aluvi-ptoluvi Pleistocene sediment (apQ_1^{1-2}) is exposed in Hanoi, Vinh Phuc and at the Northwestern and North edges of the delta, composed of grit, medium-grained sand, silt sand with good water permeability.

4.2.5 Groundwater level

The groundwater level is shallow in the coastal zone (0.5m from the ground). Further towards the top of the delta, the groundwater level is deep to deeper, especially in urban areas (> 10m). The groundwater level of the Holocene aquifer in the areas near the sea such as Nam Dinh, Hai Duong, Thai Binh… is closely related to the rainfall. In the rainy season, after each rain, the groundwater level rises, the aquifer is almost saturated, and the water level in drilled wells is almost equal to the ground.

4.2.6 Geomorphology

The RRDP has nearly 70% of the topographic area on the delta with relatively low elevation. The average elevation is from less than 1m in some coastal places, from 5-7m to 15m in terrace river (Ba Vi, Chuong My, Vinh Yen, Chi Linh, Bac Ninh…). More than 30% of the remaining area is topography of erosion origine with an altitude of 50m to 900m. The plain terrain has a shallow groundwater level, so rainwater easily recharges to the aquifer. Hilly and high mountainous terrain is the opposite, the recharge from rainwater is difficult.

4.2.7 Slope

The terrain of the RRDP is from flat to moderately sloping with the slope varying from 0% to more than 26%, in which, from 0% to 5% accounting for 70% of the area, more than 26% accounting for only 5% of the area. The slope is proportional to the runoff, so these areas with high slope often have a small groundwater recharge.

4.2.8 Drainage

The recharge capacity of a river and stream network depends on sediment conditions and slope of topography. The average drainage of the RRDP is about 0.45-0.7 km/km^2, which is a favorable condition for groundwater recharge from rainfall.

4.3 Mapping groundwater recharge potential zone of the RRDP

Based on expert questionnaire and previous researche by *M. Senthilkuma (2019), S.G Patil (2014), Preeja et al (2011), Bhave et al (2019)*, the author estimates the score of each factor influencing according to the assessment of Shaaty (1980) (table 4.16) and builds maps of factors affecting the groundwater recharge from rainfall (figure 4.9 to figure 4.11, figure 4.13 to figure 4.17). The high weight means that the factor has high influence and vice versa.

Table 4.16. The score and weight of influencing factors

TT	**Factor**	**Sign**	**Score**	**Normalized weights**
1	Rainfall	RF	9,5	0,204301
2	Land cover, land use	LC	8	0,172043
3	Soil type	SC	7,5	0,161289
4	Quaternary sediment, bedrock	LG	6,5	0,139786
5	Groundwater level	GL	6	0,129033
6	Geomorphology	GG	4	0,086021
7	Ground slope	SG	3	0,064516
8	Drainage system	DS	2	0,043010

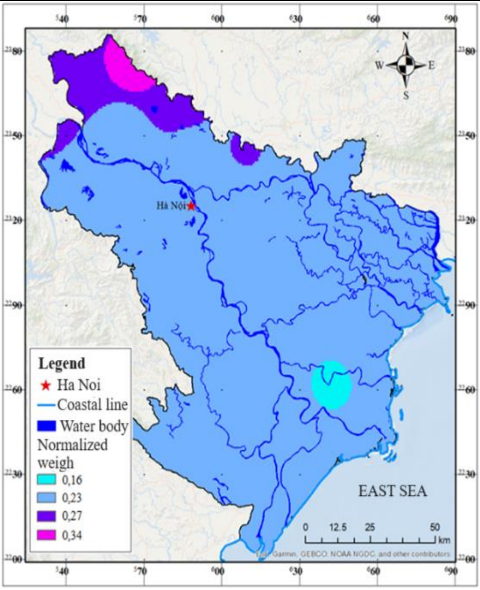


Figure 4.9. Rainfall influencing map

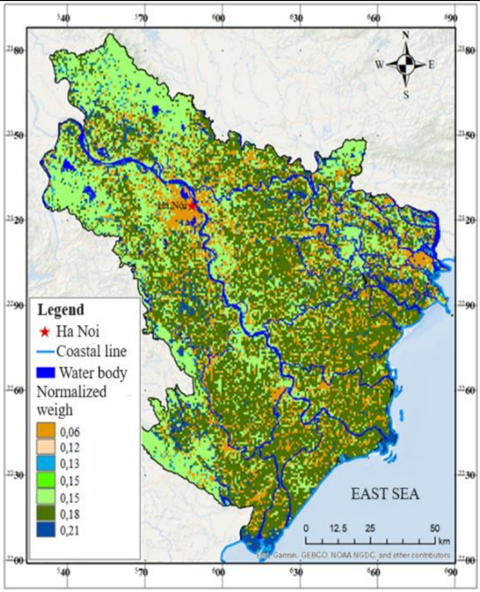


Figure 4.10. Land cover influencing map

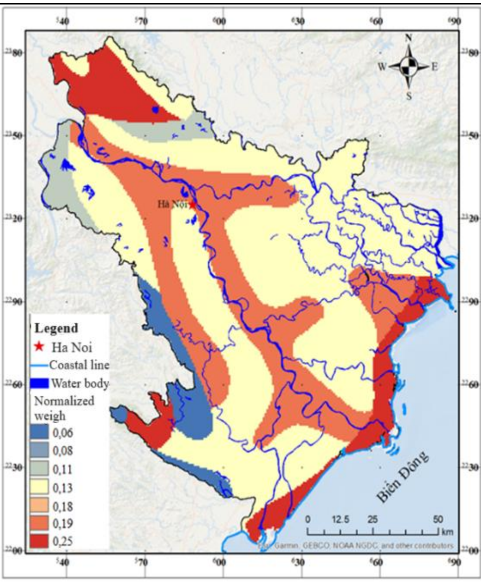


Figure 4.11. Soil type Rainfall influencing map

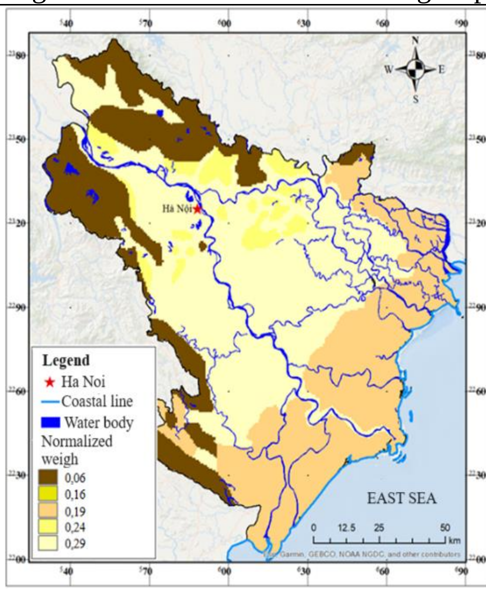


Figure 4.13. Quaternary sedimen influencing map

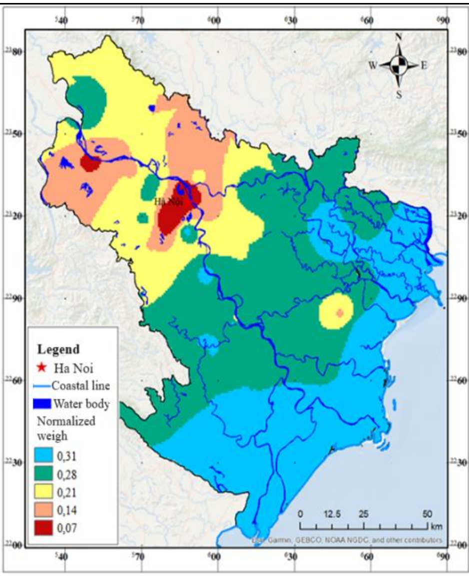


Figure 4.14. Groundwater level influencing map

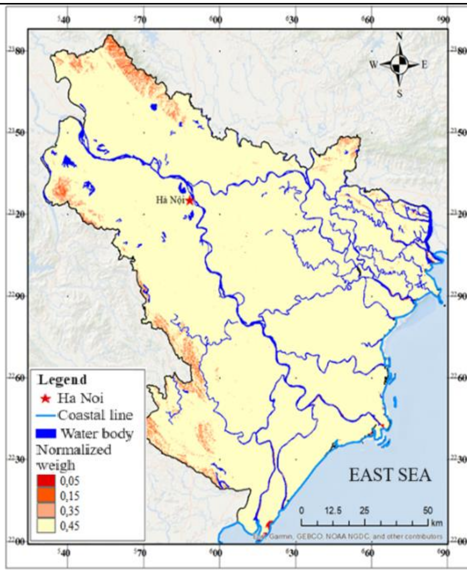


Figure 4.15. Geomorphology influencing map

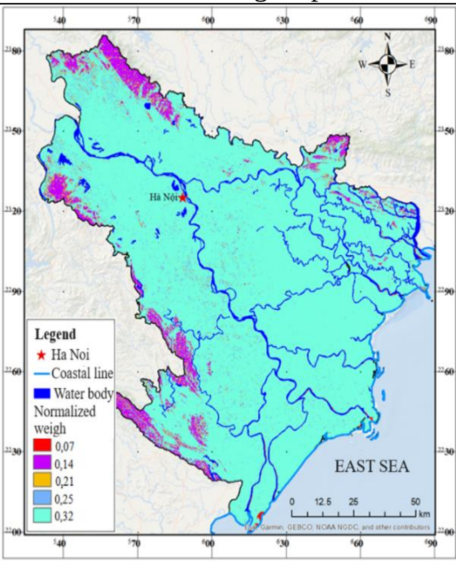


Figure 4.16. Slop influencing map

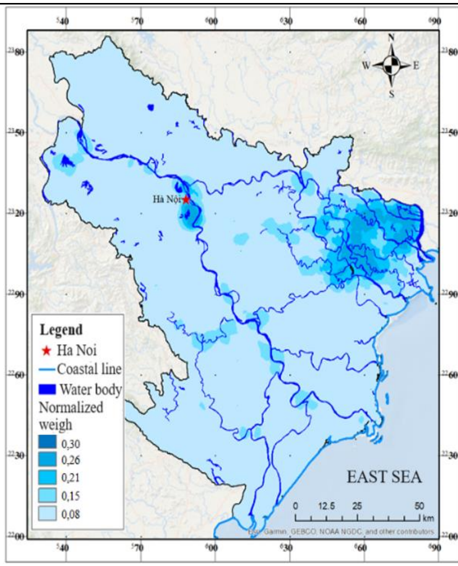


Figure 4.17. Drainage influencing map

Consistency index CI = 0.0066 and consistent index CR = 0.0043 (<10%) ensures requirements. Groundwater recharge index (GRI) estimate by formule 4.15 (Malczewski, 1999):

$$GRI = \sum_{i=1}^{m}\sum_{j=1}^{n} W_j X_i \qquad (4.15)$$

In which, the GRI is groundwater recharge index, W_j is the weight of the j^{th} characteristic in factor X, X_i is normalized weight of factor i; m is the total number of factors; n is the total number of characteristics of the factor.

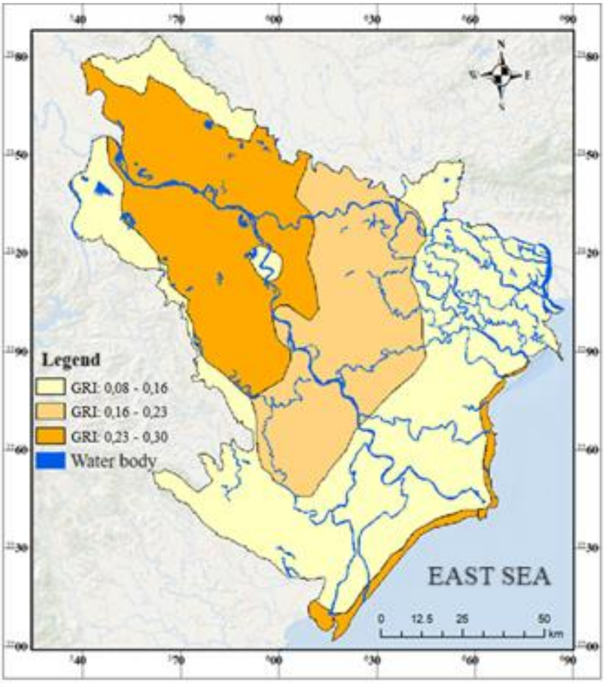


Figure 4.19. Groundwater potential zone map with GRI

GRI has a value from 0,08 to 0,30 and is diviđe into 03 zones: Zone I (0,08 ≤ GRI ≤ 0,16), Zone II (0,16 < GRI ≤0,23) và Zone III (0,23 < GRI ≤ 0,30) (Figure 4.19).

4.4 Evaluation of component and amount of the groundwater recharge from rainfall for Holocene aquifer

4.4.1 By the isotop hydrology method

4.4.1.1 Contribution of recharge components from rainwater and river water

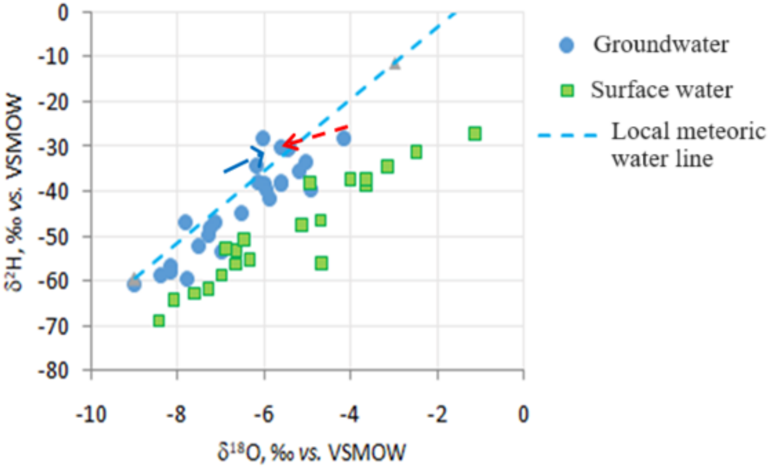


Figure 4.20. The isotope component of groundwater, surface water and local meteoric water of the RRDP

Figure 4.20 shows that, in dry seasons, the groundwater has been recharged by rainfall and surfacewater (blue arrow).

4.4.1.2 Estimation of groundwater recharge from rainfall for Holocene aquifer

Table 4.23 shows the result the results of determining the age of groundwater according to the 3H isotopic composition of groundwater samples and the corresponding recharge value according to the age of drill holes in the study area.

The author overlaid the ^3H borehole points on the GRI zoning map made above and noticed that, Zone I ($0,08 \leq GRI \leq 0,16$) correspond with the recharge 188mm/year, Zone II ($0,16 < GRI \leq 0,23$) correspond with the recharge 372mm/year và Zone III ($0,23 < GRI \leq 0,30$) correspond with the recharge 429mm/year. (Figure 4.25)

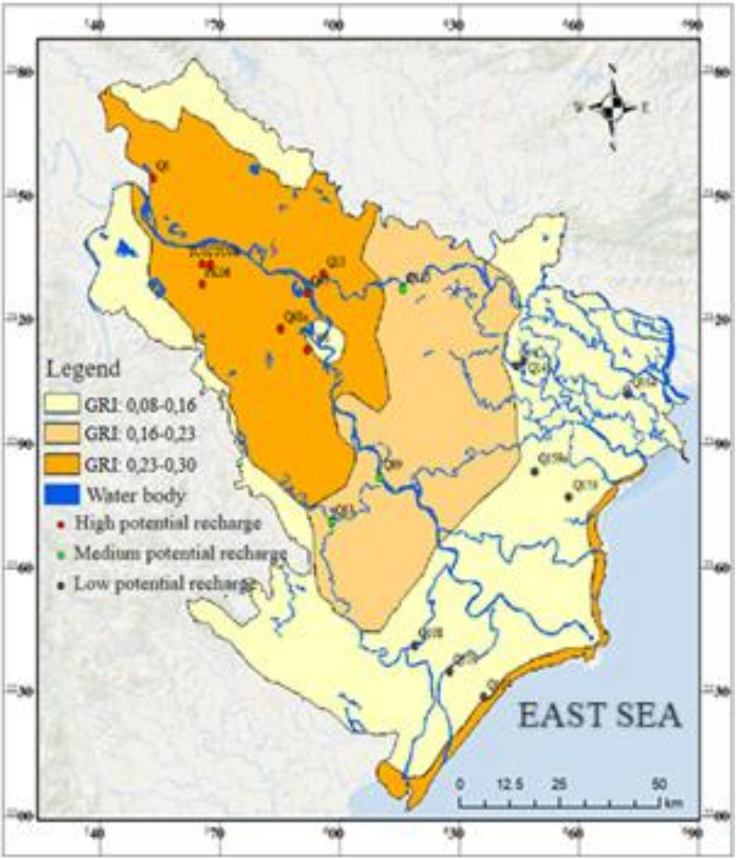


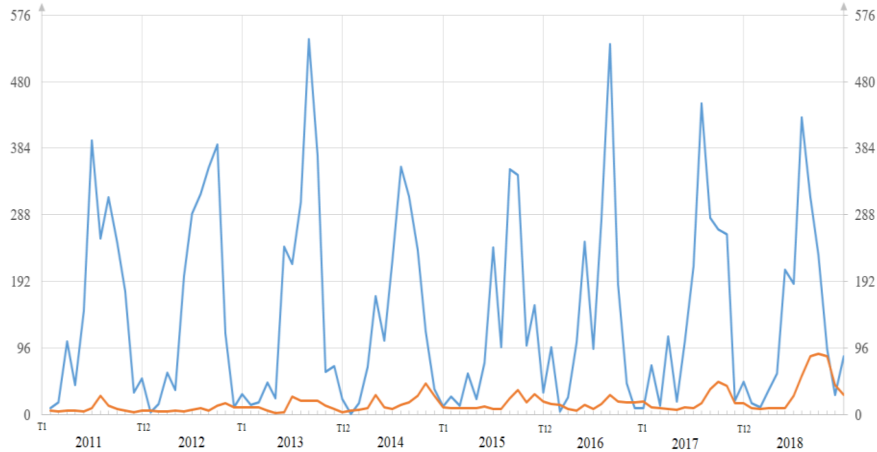
Figure 4.25. Groundwater recharge by Triti (^{3}H)

Compairison with the results of Postma et all (2016) and Tran Thanh Le (2011), the results of this study may be acceptable. The gourndwater recharge estimated by Postma (2016) is 200-800mm/year in Nam Du, Ha Noi. The result of Tran Thanh Le is about 425- 605mm/year in Thach That, Ha Noi.

Table 4.23. Groundater recharge for Holocene aquifer (qh2)

No	Well	Deep (m)	Well Elevation (m)	Water level elevation (m)	Age (year)	Porosity n (%)	Groundwater Recharge (W) (mm/year)
1	Q1	10,28	15,867	13,04	5,14	0,32	0,46401037
2	Q33	12,7	6,534	2,39	21,54	0,32	0,12711417
3	Q66	20,7	5,742	3,85	7,68	0,32	0,78315862
4	Q83	7,95	4,495	1,11	2,68	0,25	0,42632584
5	Q89	9,69	7,043	1,42	2,74	0,25	0,3716181
6	Q115	17,2	4,452	1,66	11,32	0,25	0,31830171
7	Q108	14,65	1,617	1,29	15,76	0,2	0,18172745
8	Q109	11	1,4	0,97	19,91	0,2	0,10618006
9	Q110	9,05	1,243	0,23	11,32	0,2	0,1420428
10	Q145	10,65	1,865	1,27	22,59	0,2	0,08900686
11	Q147	12,53	2,41	0,36	12,30	0,2	0,17037032
12	Q158	6,9	1,334	0,80	5,14	0,2	0,24770982
13	Q159	9,1	2,474	1,09	5,69	0,2	0,27119915
14	Q164	11,3	2,921	0,76	6,26	0,2	0,29206028

4.4.2 Estimated the groundwater recharge by water table fluctuation method.



Hình 4.28. Rainfall (blue) and groundwater recharge (orange) at Tho An (2011-2018)

Figure 28 show that the rainfall and the groundwater recharge for qh aquifer have a relatively close relationship. In the rainy season, when the rainfall increases, the amount of recharge increases and vice versa, in the dry season, when the rainfall decreases, the amount of recharge decreases. However, the groundwater recharge and the rainfall diphase from 1 month to 3 months depending on the year. We see that, in Tho An, the average annual groundwater recharge is 197.4mm/year (2011-2018).

4.4.3 General assessment

Table 4.24 show that the result of groundwater resource from rainfall calculated by isotope hydrology method, Kamenski water table fluctuation method performed by PhD student and by other authors in Hanoi area.

Table 4.24. Groundwater recharge by the author and different researchers Ha Noi

TT	Author	Method	Groundwater recharge (mm/year)	Location
1	L.V Hung	Isotope	429	Hanoi
2	L.V Hung	Kamenxki	197.85	Dan Phuong
3	Postma et al (2016), N.T.H Mai et al (2014)	Isotope	200 - 800	Nam Du
4	T.T Le (2011)	Isotpe	425.37 - 605.38	Thạch Thất

With the above results, it is found that using the isotope method to determine the groundwater recharge for Quaternary aquifers in the RRDP is reasonable, the results are acceptable although there are still differences in values calculated between the studies.

CHAPTER 5. THE ROLE OF RAINWATER IN THE FORMATION OF GROUNDWATER RESERVES IN QUATERTARY SEDIMENTS IN THE RED RIVER DELTA

5.1 Config model

To be able to evaluate the role of natural recharge in the formation of Quaternary sedimentary groundwater reserves in the Red River Delta, a groundwater model is built on the basis of research and investigation data from the past to the present. The objective of model building is to update the latest research results on hydrogeological structure from the latest studies on urban areas in the delta, studies on the formation of the RRDP, on the recharge sources from rainwater, surface water, river water, from the edge of the delta, updating the current exploitation status and finally adjusting the model.

5.2 The role of rainfall in the formation of groundwater reserves in Quatertary sediments in the RRDP

Figure 5.25 illustrates variations in the components contributing to the groundwater water balance within the Quaternary aquifers system. Positive quantities signify contributions to the aquifer system, while negative quantities denote outflows. This analysis examines the role of groundwater recharge sources into Quaternary aquifer system within the Red River Delta Plain.

- Direct groundwater recharge into the Quaternary aquifer system occurs year-round, with the highest rates observed during the rainy season, accounting for 67,63% (equivalent to 5607868m3/day). In contrast, during the dry season, this recharge dwindles to approximately 9,75% (equivalent to 664326m3/day).

- Storage within the aquifer system and ground evaporation take place throughout the year, contributing between 13,94% and 59,74%, corresponding to a range of 705693 to 4085660m3/day.

- Recharge from rivers into the Quaternary aquifer system is primarily observed during the rainy season, accounting for 9,51% to 17,36%, ranging from 788378 to 1928548m3/day.

- Recharge from the bedrock boundaries along the delta's margins into the Quaternary aquifer system, as well as the outflow of groundwater to the sea from the same system, occurs consistently throughout the year but in comparatively smaller volumes.

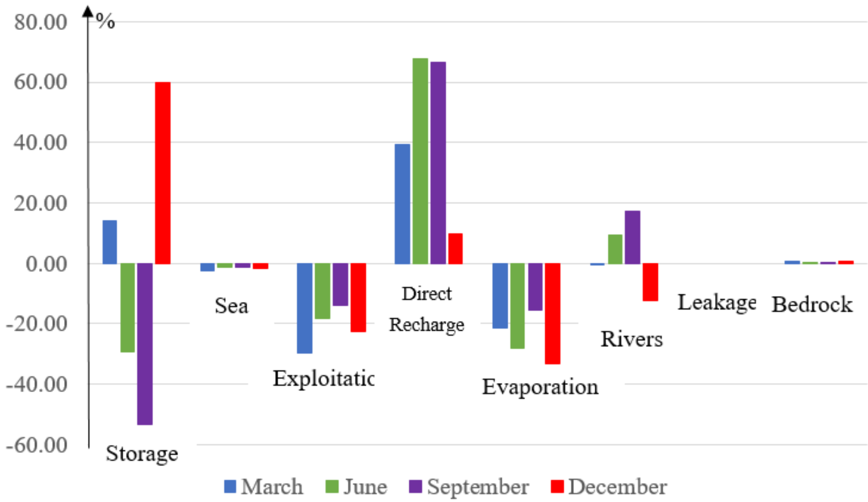


Figure 5.25. The recharge resource in Quaternary aquifer

CONCLUSIONS AND RECOMMENDATIONS

Conclusions:

The results of the thesis "**Research on factors influencing groundwater recharge from rainfall in Quaternary sediments in the Red River Delta Plain**" is mainly summerized in the following points:

1. Develop a system method to determine and evaluate the factors affecting the groundwater recharge from rainfall for Quaternary aquifers of the RRDP by combining the isotope hydrology method, remote sensing - GIS method and numerical modeling method. This combination of these methods can be used for other regions.

2. The factors influencing on the groundwater recharge from rainfall for Quaternary aquifers of RRDP, in order from most influential to least influential, include the rainfall, the land cover - land use, the soil type, the Quaternary sediments and bedrock, the groundwater level, geomorphology, ground slope and drainage system.

3. Mapping groundwater recharge potential zone according to the groundwater recharge index (GRI) with $0.08 \leq GRI \leq 0.30$.

4. Determine the amount of recharge from rainwater to groundwater according to the recharge potential zone: i) zone I, low groundwater recharge potential (the amount of groundwater recharge is 188mm/year corresponding with GRI = 0.08 ÷ 0.16); ii) zone II, medium groundwater recharge potential (the amount of groundwater recharge is 372mm/year corresponding with GRI = 0.16 ÷ 0.23); iii) zone 3, high groundwater recharge potential (the amount of groundwater recharge is 429mm/year corresponding with GRI =0.23 ÷ 0.30).

5. Assess the role of rainfall in the formation of groundwater reserves. The groundwater recharge from rainfall, surface water occurs in all seasons of the year. The recharge rate is highest in the rainy season, accounting for 67,63% (equivalent to 5607868 m3/day). In contrast, during the dry season, this recharge dwindles to approximately 9,75% (equivalent to 664326 m3/day).

- Storage within the aquifer system and ground evaporation take place throughout the year, contributing between 13,94% and 59,74%, corresponding to a range of 705693 m3/day to 4085660 m3/day.

- Recharge from rivers into the Quaternary aquifer system is primarily observed during the rainy season, accounting for 9,51% to 17,36%, ranging from 788378 m3/day to 1928548m3/day.

- Recharge from the bedrock boundaries along the delta's margins into the Quaternary aquifer system, as well as the outflow of groundwater to the sea from the same system, occurs consistently throughout the year but in comparatively smaller volumes.

Recommendations:

Due to limited conditions of the field trip, the isotope samples have been taken only in the dry season. It is necessary to take additional isotope samples in the rainy season. The radioisotope samples need to be supplemented to ensure that the number of samples is sufficient to reflect and represent each of the different recharge potential zones as well as to ensure different isotope sampling depths are evenly distributed throughout the upper Holocene aquifer.

It is necessary to additionally calculate the groundwater recharge from rainfall by using the water table fluctuations method throughout the study area. When the number of samples is large enough, it is necessary to evaluate the sensitivity of the normalized weights according to the ROC method, thereby strengthening the reliable basis for the method system to determine the groundwater recharge from rainfall.

The management of water resources, the sustainable exploitation and the protection of Quaternary aquifers in the Red River Delta Plain need more attention and consideration about the role of groundwater recharge from rainfall as well as other supply components that are provided comprehensive evaluation in this study.

LIST OF THE PUBLICATIONS RELATED TO THE DISSERTATION

Vietnamese

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English

1. V.H Le, Q.N Pham, T.L Tran, D.N Dang, *Using isotope technique to estimate groundwater recharge in the Red river delta plain*, Tạp chí Khoa học Thủy lợi và Môi trường, số 77, trang 88-95, 12/2021

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2. V.H Le, Q.N Pham, *Application of analytical hierarchical process (AHP) method for delineation of groundwater recharges potential zones in the Red River Delta Plain*, Tạp chí Khoa học Tài nguyên và Môi trường, số 39, trang 93-104, 2021.

3. Q.N Pham, V.H Le, T.L Tran, V.L.K Thi, D.N Dang, Q.C Tran, *Zoning groundwater potential recharge using remote sensing and GIS technique in the Red river delta plain*, IOP Conf. Ser.: Earth Environ. Sci. 964 012022

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4. V.H Le, V.L.K Thi, *Application of satellite - retrieved vegetation index and surface temperature in delineating potential agricultural drought risk areas,* International Conference "Technology in Natural disaster prevention and Risk reduction", Publishing house for Science and Technology, ISBN 9786043570700, 31/08/2022.

5. V.H Le, Q.N Pham, T.L Phung, V.C Doan, Q.C Tran, T.T Dang, A role of groundwater recharge to groundwater exploitation in the Red River Delta Plain, Vietnam Journal of Science, technology and engineering, P-ISSN 2525-2461, E-ISSN2615-9937.