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IMPACTS OF THE RED RIVER AND BEDROCKON GROUNDWATER RECHARGE IN QUATERNARY SEDIMENTS OF THE SOUTHWEST HANOI

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SUMMARY OF DISSERTATION IN GEOLOGY

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INTRODUCTION

1. Background and statement of the problem

Groundwater in Hanoi area is an important source for domestic water including potable and production of the capital and has been exploited since the late 19th century. However, the unreasonable exploitation of ground water in the area year by year have caused negative impacts such as water level decline, groundwater depletion, ground subsidence, groundwater pollution and salinization. To minimize negative impacts caused by water exploitation caused by ground water extraction in Hanoi city, it is necessary to develop riverside water plants, arrange a reasonable ground water exploitation scheme to maintain the ground water reserve during exploitation due to the additional recharge from the Red River and the southwest bedrock aquifer. One of the essential issues in the sustainable exploitation of groundwater resources is to identify additional sources for groundwater. Therefore, it is necessary to study and clarify the role of the Red River boundary and the southwestern bedrock boundary to exploit groundwater in Hanoi city sustainably.

2. The study objectives

- To identify and classify the types of boundary conditions of the Red River and of the bedrocks in Southwest Hanoi.
- To determine the roles of each section boundaries of the Red River and the bedrock on the groundwater recharge in the Quaternary sediments of Southwest Hanoi.
- To propose a rational plan of extracting groundwater to meet sustainable groundwater resources development.

3. The objects and scope of study

- *The objects of research:* Those aquifers in Quaternary sediments including (qp) and (qh) porous aquifers (Pleistocene to Holocene) age.
- *The scope of research:* The southern area of Hanoi city where the the Red River boundary is limited to the riverside area from Ba Vi to Phu Xuyen, and the bedrock boundary in the Southwest Hanoi is limited to the marginal zone, the interface between the qh aquifer and the qp aquifer with the fractured aquifers from Son Tay to My Duc.

4. Methodology

The main research methods that were used in this study involves: Data collection, inheriting and synthesizing documents; Geophysical survey; Hydrogeological drilling survey; Pumping test; Groundwater monitorrng; Numerical modeling; Professional solution.

5. Data and information

The collected documents and data obtained from the Governmental Project "Protection of groundwater in large urban areas - Hanoi" directly implemented by the doctoral candidate. The collected and processed documents include: hydrogeological stratigraphy of 514 boreholes; synthesis of hydrogeological parameters of 514 boreholes; monitoring data of groundwater and surface water of the Red River in the period 1995-2017 at 242 monitoring points; Cross section measuring data of the Red River at 95 sections. The documents directly involved in the author's implementation include: field survey data on groundwater resources at 18,166 points; Sounding Resistivity measurement at 556 points, Induced Polarization measurement at 160 points; hydrogeological drilling and pumping testing at 40 boreholes in the area along the Red River and along the Southwest’s bedrock edge; monitoring groundwater level at 40 boreholes; 11 isotopic samples (δ^2H, $\delta^{18}O$) of groundwater.

6. Main dissertation points of argument

- *Point of argument 1:*The hydrogeological structure along the Red River from Ba Vi to Phu Xuyen is divided into 9 regions with 3 types and 4 subtypes characterized by the total permeability resistance value varying from 50m to 836m. The amount of recharge from the Red River for groundwater in Quaternary sediments in the riverside is now from 424.086 m^3/day to 620.411 m^3/day.
- *Point of argument 2:* along the edge adjacent to bedrock in the Southwest Hanoi is divided into 4 regions with 3 types of structure, identified as second kind boundary (specified flux and changing over time). The amount of recharge from the bedrock for groundwater in Quaternary sediments in the southwest is now 19.815 - 20.349 m^3/day.

7. The contributions of study

- Applying the theory of scientific methods in hydrogeological calculations, combined with the results of pumping test from well cluster, the thesis has calculated the values of parameters on each section of the Red River and Southwest boundary, which helped to prove that the Southwest boundary is the time-varying specified flux.
- From the available data, for the first time, it is possible to determine quantitatively the values of groundwater recharge and

discharge through the divided boundary segments along the Red River and the bedrock boundary according to the hydrological structure, thence using it as a scientific basis for the rational adjustment of ground water exploitation plans for Hanoi city.

- The content of the thesis refreshes the ground water exploitation options in the Hanoi area to make it more reasonable by affirming the role of the Red River and the southwest bedrock boundary of Hanoi.

8. Scientific and pratical significance of the study

- *Scientific significance:*By a combination of research and inheritance methods, the thesis has contributed to clarifying the scientific method system in determining boundary conditions and determining additional sources for groundwater from the boundary. The Red River and the southwestern bedrock boundaries is one of the main sources of ground water exploitation in the Quaternary sediments. These research results are the basis for scientific solutions for exploitation, rational use and protection of ground water resources in Hanoi.

- *Practical significance*: The research results of the thesis have quantified the value of ground water recharge through each divided boundary segments and are a useful reference for managers in exploitation planning, protecting and developing ground water resources in Hanoi area.

9. The thesis' structur:

The thesis includes 5 chapters without Introduction and Conclusion.

CHAPTER 1. LITERATURE REVIEW

1.1. Study area

1.1.1. Geographical location

The study area is the entire administrative area of Hanoi city with the area of about 3,344 km^2. Hanoi is adjacent to Thai Nguyen and Vinh Phuc provinces in the North; to Ha Nam, HoaBinh in the South; to Bac Giang, Bac Ninh, Hung Yen in the East and to HoaBinh and PhuTho in the West.

1.1.2. Hydrogeological characteristics

The result of the study shows that the hydrogeological units in the area can be divided into 3 porous aquifer, 13 fissured aquifers and low permeability or impermeable formations.

- Vulnerable aquifers include:

+ Porous media in Holocene sediments (qh): mostly allocated throughout the study area, the lithology is mainly sand of all kinds, mixed sand, and sand with gravel and small gravel at the bottom of the layer. The thickness of this aquifer is of from 0.8m to 36.5m, the average of 13.14m.

+ Porous media in upper Pleistocene sediments (qp2): mostly allocated throughout the study area, the lithology is mainly sand of all kinds but mostly medium sand, coarse sand, the bottom part contains gravel. The thickness ranges from 1.3m to 39.0m, average 12.26m.

+ Porous media in lower Pleistocene sediments (qp1): This is the main quifer to supply water for the city's water use needs. The distribution area of quifer is almost all over the Quaternary sediment distribution area, extending from Ba Vi to Son Tay and then extending to almost cover Hanoi. The petrographic composition is mainly gravel, gravel, sand, belonging to river and flood sediments. This quifer has a thickness of 2m to 102.65m, with an average of 23.0m.

- Fractured aquifers in the Vinh Bao formation (n2vb), Tien Hung formation (n1th), Phan Luong formation (n1pl), Song Boi formation (t2-3¬sb), Na Khuat formation (t2nk), Nam Tham formation (t2nt), Khon Lang formation (t2kl), Dong Giao formation (t2ad), Tan Lac formation (t1tl), Vien Nam formation (t1vn), Na Vang formation (p2nv), Si Phay formation (p1-2sp) and Proterozoic complex (pr).

Besides the above-mentioned aquifers, there are also other geological formations that poor in water to aquicluded sediments in Quaternary. These formations belong to the Thai Binh, Hai Hung, Vinh Phuc and Hanoi formations. They are layered, interspersed between the porous aquifers qh, qp_2 and qp_1.

1.2. Literature reviews on groundwater recharge from boundaries

1.2.1. In the world

Synthesizing and analyzing scientific published researches on groundwater boundary conditions and determining recharge from the boundary show that all of it use a combination of different meaures to solve the issue of groundwater reserves. Depending on the characteristics of hydrogeological conditions in the study area, the author use different research methods.

- For river and lake borders, the author often use the following groups of methods: Group of methods to determine the amount of recharge from the boundary by direct measurement; Group of methods to determine the amount of recharge from the boundary by heat indicator; Group of methods to determine the amount of addition from the boundary by analysis; Group of methods to determine the amount of recharge from the boundary by mass balance method; Group of methods to determine the amount of recharge from the boundary by numerical model method.

- For the boundary which is the interface between two aquifers, the boundary is always a second kind boundary if the flow rate across the boundary remains unchanged or a third kind boundary if the cross-border flow rate is a function of the water level in the respective aquifer. Thus, this type of boundary is similar to the boundary between aquifers and rivers or lakes. Therefore, all the methods used in the calculation to determine the seepage supply from the river to the aquifer can be used for the boundary between two aquifers. Perhaps that is one of the reasons why there is almost no research on this boundary alone. Only very few works have mentioned the determination of this boundary value.

1.2.2. In Vietnam

The study of recharge for groundwater from the boundary in Hanoi city has been mentioned by many researchers such as Nguyen Van Dan (1997), Pham Quy Nhan (2000), Tong Ngoc Thanh (2006), Tran Thi Viet Nga (2015),... Most of the research works mainly use methods such as: monitoring of groundwater and surface water dynamics; study the hydrogeological structure to determine this relationship; Some works using isotope technique to study the formation of groundwater recharge from surface water sources such as Trinh Van Giap (2005), Vu Kim Tuyen (1995),... One of the current ad popular methods studied by many author is the application of hydrogeological numerical modeling methods using Visual Modflow, Feflow, GMS software... such as Pham Quy Nhan (2000), Tong Ngoc Thanh (2006) to determine the amount of groundwater recharge from different formations.

There are not enough data to prove in detail and reliability the role of the Red River and the southwest bedrock boundary of Hanoi city in the research up to now. The bedrock boundary at the southwest area is often argued and determined with the constant discharge boundary condition, most of which is considered as the water boundary. As for the Red River boundary, most studies consider that the Red River is a boundary with a specified head but did not divide the boundary sections in detail according to the hydrogeological structure. The interpretation and determination of the role of the Red River and the bedrock boundary at the southwest edge of the groundwater recharge in Quaternary sediments in Hanoi city area has not been mentioned or is not reliable enough.

CHAPTER 2. IDENTIFICATION AND CLASSIFICATION OF BOUNDARY CONDITIONS OF THE RED RIVER IN HANOI

2.1. Scientific basis

2.1.1. Classificaiton of boundary conditions

To identify and classify the boundary conditions of the Red River for aquifers in the study area, the author relies on the hydrogeological structure and the spatial relationship between the Red River and aquifers.

a) Determination of hydrogeological structure

To determine the hydrogeological structure of the study area, the author proceeds in the following order of steps:

- Analysis of hydrogeological stratigraphic columns at boreholes along the Red River and adjacent areas to divide into aquifers, weakly permeable layers or water insulators;
- Building hydrogeological cross-sections in the direction perpendicular to the Red River and hydrogeological cross-sections along the river in the direction of the flow of the study area to clarify the distribution of aquifers and low permeable layers at the bottom of the river;
- On the basis of hydrogeological structure along the Red River along the flow direction of the study area, analyze and clarify the following main information: Existence of aquifers and water-insulating layers; Distribution depth and thickness of each aquifer, aquitard or aquiclude.

b) Determine the spatial relationship between the Red River and the aquifers

To determine the spatial relationship between the Red River and the aquifers in the study area, based on the documentation on hydrogeology and morphological characteristics of the Red River, the author proceeds in the following order:

- Building topographic cross-sections of the Red river bed at river sections in the study area;
- Superposition of the topographic profiles of the Red River bed onto the built hydrogeological cross-sections;

- Analyze the spatial relationship between the Red River and the aquifers in the study area to identify and clarify the following main information: The existence and distribution of aquifers and water-insulating layers in the area above the riverbed on both sides of the river; The existence and distribution of aquifers and water-insulating layers on the river bottom; The degree of river cutting into aquifers, the water-insulating layer includes: cutting width, cutting depth, cutting area, cutting percentage.

2.1.2. Determination of boundary conditions'parameters

To determine the values of parameters on the Red River boundary in the study area, the author used a combination of the following methods: 1) Determine the values of the parameters on the boundary according to the data of pumping test in the cluster test; 2) Determine the value of parameters on the boundary by spatial relationship between river and aquifers; 3) Determine the values of parameters on the boundary according to the water level monitoring data; 4) Determine the values of the parameters on the boundary according to the equilibrium method.

2.2. Practical basis

2.2.1. Classification of the Red River's boundary conditions

The author has synthesized and accumulated hydrogeological stratigraphy at the boreholes along the river and the results of the survey and measurement of the Red River section (95 river sections), built 16 hydrogeological cross-section lines across the river and a hydrogeological cross-section along the Red River from Ba Vi to Phu Xuyen. The basis of documents used to analyze the structure and classify the boundary conditions of the Red River involves: stratification results of 259 boreholes; survey results, measuring 95 river sections

2.2.2. Determination of boundary conditions'parameters of the Red river

To determine the values of parameters on the Red River boundary in the study area, the author relies on the results of drilling, surveying, stratigraphic exploration and pumping tests of water treatment plants along the Red River in the study area, including: : Son Tay, Thuong Cat, Bac Thang Long, Cao Dinh, Yen Phu, Luong Yen, Gia Lam, Nam Du water plants. In addition, the research results of cluster test along the Red River of the project "Protection of groundwater in Hanoi urban areas" are also used.

2.3. Results and discussion

2.3.1. Classification of the Red River's boundary conditions

The results have determined that along the Red River from Ba Vi to the end of Phu Xuyen district, it is divided into 9 regions with 3 main types and 4 subtypes of different hydrogeological structures. In which, subtype IA groundwater has close hydraulic relationship with the Red River, characterized by the hydrogeological structure of the Red River bottom including 3 Holocene aquifer (qh), Upper Pleistocene (qp_2) and Lower Pleistocene aquifer (qp_1) forms a hydraulic system. Sub-type I-B is characterized by hydrogeological structure on the bottom of the Red River, including the Vinh Phuc Formation watershed and two aquifers qp2 and qp1¬ forming a hydraulic system. Sub-type II-A is characterized by the Red River cutting into the qh aquifer, between the qh and qp2 aquifers, there is no water-insulating layer, thus forming a hydraulic system, the qp1 aquifer is separated by a water-insulating layer. Sub-type II-B is characterized by the Red River cutting into the qh aquifer, between qh and qp_2 aquifers, there is a aquiclude between qp2 and qp1 aquifers, there is no waterproof layer so a hydraulic system is formed.Type III is characterized by the full presence of aquifers and water-insulating layers separating them, so the degree of hydraulic relationship between the Red River and aquifer qp2 and qp1 is poorer.

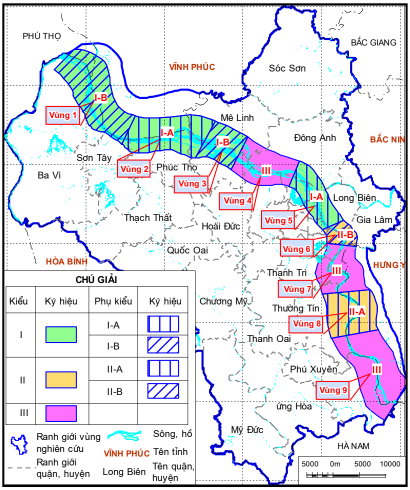

Figure 1. Zoning diagram of the Red Rive's structurer

2.3.2. Determination of boundary conditions of the Red River

Summarizing the results of calculations by different methods, the values of parameters on each section of the Red River boundary have been determined for each aquifer in the study area, specifically as follows:

- The value of ΔL on the Red River boundary of the qh aquifer ranges from 9m to 67m, with an average of 30m. The smallest marginal L value is distributed in zone 2 (from Le Loi, Son Tay town to Tho An, Dan Phuong district) in subtype IA, the largest in zone 7 (from Linh Nam, Hoang Mai district to Ninh So, Thuong Tin district) of type III.

- The value of ΔL on the Red River boundary of the qp_2 aquifer ranges from 23m to 151m, with an average of 96m. The smallest L on the boundary is distributed in zone 2 (from Le Loi, Son Tay town to Tho An, Dan Phuong district) in subtype IA, the largest in zone 6 (from Thanh Luong, Hai Ba Trung district to Linh Nam, Hoang district). Mai) is subtype II-B.

- The value of ΔL on the Red River boundary of the qp_1 aquifer ranges from 50m to 836m, with an average of 359m. The smallest L on the boundary is distributed in zone 2 (from Le Loi to Tho An, Dan Phuong district) under type IA, the largest in zone 8 (from Hong Van to Le Loi, Thuong Tin district) is dependent on type II-A.

CHAPTER 3. IDENTIFICATION AND CLASSIFICATION OF BOUNDARY CONDITIONS OF BEDROCK IN THE SOUTHWEST HANOI

3.1. Scientific basis

3.1.1. Classificaiton of boundary conditions

To identify and classify bedrock boundary conditions at the Southwestern edge of Hanoi, the author relies on the hydrogeological structure and spatial relationship between the porous aquifers in Quaternary sediments and the aquifers. Pre-Quaternary fractured reservoirs have different water levels. The order of execution includes:

- Analysis of hydrogeological stratigraphic columns at hydrogeological boreholes at the edge of bedrock and adjacent areas to divide into aquifers, aquitard layers or aquiclude layers;

- Building hydrogeological cross-section lines in the direction perpendicular to the interface between porous aquifers in Quaternary sediments with pre-Quaternary fractured aquifers and hydrogeological cross-sections along the interface between these aquifers to clarify the distribution of aquifers and water-insulating layers.

- On the basis of analysis of hydrogeological structure along the interface between porous aquifers in Quaternary sediments with pre-Quaternary fractured aquifers, conduct analysis to clarify information following: Existence and distribution of porous aquifers in Quaternary sediments and pre-Quaternary fractured aquifers; Distribution depth of roof, bottom, thickness, permeability and water conductivity of porous aquifers in Quaternary sediments; Soil composition, permeability, water conduction of pre-Quaternary fractured aquifers at the place of contact with porous aquifers in Quaternary sediments.

3.1.2. Determination of boundary conditions'parametersof the bedrock in the Southwest

To determine the values of the parameters on the bedrock boundary at the Southwestern edge of Hanoi, the author determines the values of the hydrogeological parameters, the location of the bedrock boundary, thereby determining the classification of boundary conditions and values of the parameters on the boundary according to the pumping test results. In addition, the author also determines the values of parameters on the boundary in natural conditions.

a) Determine the value of hydrogeological parameters and position of bedrock boundary

At the Southwestern edge of Hanoi city, the porous aquifer directly covers the fractured aquifers or is in contact with the fractured - karst aquifer so there is a boundary with different permeability coefficients between the porous and the fractured aquifer. In order to determine the value of hydrogeological parameters and the position of the bedrock boundary, thereby determining the type of bedrock boundary condition, the author diagrams a semi-limited aquifer with a water boundary (no-flow boundary) and analytical calculations are carried out by current addition using virtual boreholes as in the case of infinite aquifers. In case the boundary is in contact with the aquifer then different permeability coefficient boundary conditions apply. The schema illustrating hydrogeological conditions for the area described above is shown in Figures 2 and 3.

b) Determination of *the values of parameters on the boundary under natural conditions*

Determining the values of the parameters on the boundary in natural conditions can use the Darcy method to calculate when there are long-term water level monitoring data at the cross-section across two wells on the line perpendicular to the boundary. The amount of inflow water through the boundary to the aquifer per unit length of the boundary is determined by Darcy's formula as follows:

$$q_{(t)} = \frac{H_{1(t)} - H_{2(t)}}{L_{1-2}} T \qquad (3.1)$$

Where: q(t) is the inflow into the aquifer through the boundary per unit length of the boundary at time t (m3/day/m); H1(t) and H2(t) are the water level at borehole 1 and borehole 2 at time t, respectively, in the direction perpendicular to the boundary (m); L1-2 is the distance between bore holes 1 and 2 (m); T is the conductivity coefficient of the aquifer (m^2/day).

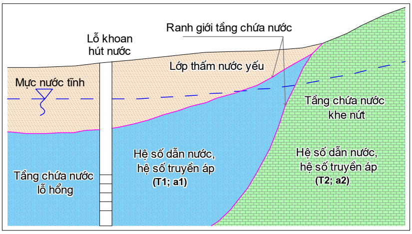

Figure 2. Hydrogeological cross-section in an area with semi-infinite heterogeneous aquifers

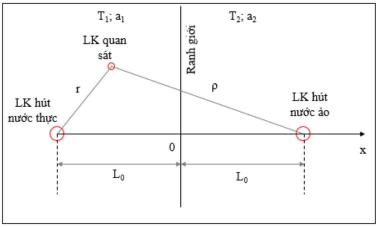

Figure 3. Calculation diagram of borehole in semi-infinite heterogeneous aquifer

Thus, at the monitoring line perpendicular to the boundary we have the data of monitoring the water level over time at the two boreholes and the distance between them. When knowing the water conductivity coefficient of the aquifer at the monitoring route area, we can determine the variation of the supply (or discharge) flow across the boundary over time according to formula (3.1).

In case the boundary segment needs to calculate the inflow (or outflow) across the boundary without water level monitoring documents at 2 boreholes on the line perpendicular to the boundary, we determine the approximate value based on the following assumptions: The groundwater level movement at the boundary without linear monitoring data is the same as the groundwater level movement on the boundary with the water level monitoring data. Therefore, it can be assumed that the water level dynamics on the boundary segments in the region are the same and depend mainly on the conductivity coefficient of the aquifer. Thus, for the boundary section without water level monitoring documents, the unit flow of recharge (or discharge) across the boundary is determined according to the following formula:

$$q'_{(t)} = q_{(t)} \frac{T'}{T} \qquad (3.2)$$

Where: q'(t) is the unit seepage flow at time t on the boundary without monitoring data (m3/day/m); q(t) is the unit at time t on the boundary with monitoring documents (m3/day/m); T' is the conductivity coefficient of the aquifer on the boundary without monitoring data (m^2/day); T is the conductivity coefficient of the aquifer on the boundary with the monitoring data (m^2/day). Thus, for the boundary segment without monitoring documents, it is necessary to determine the average conductivity coefficient of the aquifer.

3.2. Practical basis

3.2.1. Classification of hydrogeological structure in the Southwest

The author has synthesized and analyzed stratigraphic at 165 hydrogeological wells, conducted additional research drilling for 3 drill holes including: C1 cluster (in Sai Son commune, Quoc Oai district, including 7 drill holes); C2 cluster (in Hoang Dieu commune, Chuong My district, including 4 drill holes) and C3 cluster (in Phu Luu Te commune, My Duc district, including 5 drill holes). On the basis of the above hydrogeological drilling documents, the author established 19 hydrogeological sections in the direction perpendicular to the interface between Quaternary aquifers and fractured aquifers of pre-Quaternary, 1 hydrogeological cross-section along the boundary of the qp aquifer in the Southwestern area of Hanoi city

3.2.2. Determination of boundary conditions'parametersof the bedrock in the Southwest

In order to determine the values of parameters on the boundary for the Southwestern bedrock boundary of Hanoi city, it is necessary to determine the coefficient of water conductivity, the water level at the two boreholes and the distance between them on the perpendicular (or nearly square) with the boundary. The permeability coefficient of aquifers has been collected, synthesized and processed by the author of the experimental results of pumping tests at 497 hydrogeological wells, including 485 holes studied in the previous phase and 4 clusters experiments conducted directly by the author. The groundwater level in aquifers has been collected and processed by the author, processing groundwater monitoring documents at 4 monitoring points of the national monitoring network of groundwater dynamics; 8 works in 4 experimental clusters.

3.3. Results and discussion

3.3.1. Classification of hydrogeological structure in the Southwest

The results have divided the hydrogeological structure of the bedrock margin in the Southwest of Hanoi city into regions with 3 different types of structures and determined that the type of bedrock boundary condition is second kind boundary water flow across the defined boundary, specifically as follows:

- Type I: the area of aquifer qp in contact with sandstone, siltstone, and claystone without water of Phan Luong Formation. This type is allocated in the area of Son Tay to PhucTho with a length of 19km. The qp aquifer is in contact with the cobblestone, grit, sandstone, intercalated siltstone, black coal-containing clay without water of the Phan Luong Formation. The interface between the aquifer qp and bedrock is a second kind boundary, with zero crossflow, i.e. a no-flow boundary.

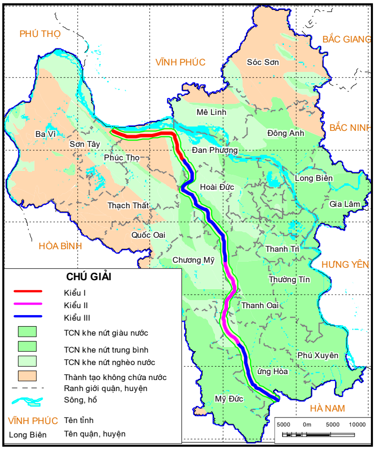

Figure4. Zoning schema of the Southwest Hanoi's structurer in the study area (over bedrock geological structure)

- Type II: the area of qp aquifer in contact with siltstone interspersed with shale with poor water content of the Nam Tham Formation. This type is allocates in the area from Cao Vien, Chuong My district to Truong Thinh, Ung Hoa district with a length of 19km. The qp aquifer is in contact with siltstone formations interspersed with shale, water-poor lime shale of the Nam Tham Formation. The interface between aquifer qp and bedrock is a second kind boundary, the discharge flows across a defined boundary or a boundary with different permeability coefficients but with small to very small water holding levels.

- Type III: the area where the qp aquifer is in contact with limestone with rich water content of the Na Vang formation and the Dong Giao formation. This is allocates in the area from PhucTho to Cao Vien, Chuong My district with a length of 26km and from Truong Thinh to Doi Binh, Ung Hoa district with a length of 15km. The qp aquifer in contact with the limestone of the Na Vang Formation and the Dong Giao Formation has a moderate to rich water content. The interface between the aquifer qp and bedrock is a second kind boundary, the discharge flows across a defined boundary or a boundary with different permeability coefficients with a large to very large water holding level.

3.3.2. Determination of boundary conditions'parametersof the bedrock in the Southwest

a) Determine the value of hydrogeological parameters and position of bedrock boundary

Calculation is applied to cluster test C1 at the contiguous boundary between aquifers in Quaternary sediments with bedrock (p2nv) at Sai Son commune, Quoc Oai district, Hanoi city. The layout schema of testing borehole cluster is shown in detail in Figure 5. Testing borehole cluster C1 includes:

- Wells C1-A and C1-B are located 100m from the boundary between aquifer qp and bedrock (p2nv);
- Observation holes QS-1A and QS-1B are located 50m from the boundary between qp aquifer and bedrock (p2nv).
- The observation hole QS-1C is located 150m from the boundary between the qp aquifer and the bedrock (p2nv).

Calculation results through the data of pumping test of borehole C1-A in the aquifer of the Na Vang formation (p2nv) to determine the hydrogeological parameters and position of the bedrock boundary as follows: zone I (Eastern region) Transmissivity is equal to 480m2/day, the Diffusivity is 4.01x106m2/day. Zone II (Western region) Transmissivity is 190m2/day, Diffusivity is 2.4x106m2/day. The distance to the virtual well is 360m.

From calculation results through the data of pumping test of borehole C1-B in aquifer qp we can determine hydrogeological parameters and position of bedrock boundary: Transmissivity of zone I (Eastern region) 450m^2/day, the Diffusivity is equal to 6x106m^2/day. Zone II (Western region) Transmissivity is 205m^2/day, Diffusivity is 2x106m^2/day. Distance to virtual well is 450m.

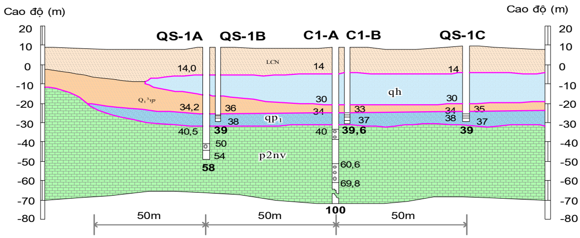

Figure5. Layout diagram of borehole cluster C1 in Sai Son commune, Quoc Oai district, Hanoi city

With the results of calculation of hydrogeological parameters and the position of the bedrock boundary according to the aquifer data in the qp aquifer and the fractured aquifer (p2nv), the conductivity coefficients of the two zones are quite similar with a relative error of 3% to 4% and the distance from the virtual well to the observation well with a relative error is of about 11%. This shows that the calculation results are acceptable. Thereby it can be seen that in this area, the interface between the qp aquifer and the fractured aquifer (p2nv) is the boundary with different permeability, or the boundary with a specified flux (second kind boundary) with the inflow from virtual wells to the aquifer when sucking water is 421 m^3/day.

b) Determine the values of parameters on the boundary under natural conditions

The results have determined the values of parameters on each boundary segment for each aquifer in the Southwestern edge of Hanoi city. In which the area from Sơn Tay to Phuc Tho is of type I, the cross-border flow is zero (no-flow boundary). The area from Cao Vien, Chuong My district to Truong Thinh, Ung Hoa district belongs to type II, groundwater in aquifers both drains across the border and is recharged through the border over time. The recharged and drainage flows through the boundary of the aquifer qh ranges from -190 m^3/day/km boundary length to 1.010 m^3/day/km boundary length, with an average of 295 m^3/day/km boundary length. The flow of recharged and drainage across the boundary of the qp aquifer ranges from -76 m^3/day/km boundary to 450 m^3/day/km boundary length, with an average of 285 m^3/day/km boundary length. The hard rock aquifer of the Nam Tham Formation, the inflow (or drainage flow) through the boundary of the aquifer is very small, nearly zero.

The area from PhucTho to Cao Vien, Chuong My district belongs to type III, groundwater in aquifers is both drains and rechaged across the border over time. The rechage and drainage flow across the boundary of the aquifer qh ranges from -30 to 83 m^3/day/km boundary, with an average of 7 m^3/day/km boundary. The rechaged and drainage flow across the boundary of the aquifer qp ranges from -1.103 to 262 m^3/day/km boundary, averaging -517 m^3/day/km boundary. The rechaged and drainage flow through the boundary of the Na Vang bedrock aquifer (p2nv) ranges from -4.779 to 1.782 m^3/day/km boundary, with an average of -2.091 m^3/day/km boundary.

The area from Truong Thinh to Doi Binh in Ung Hoa district belongs to type III, groundwater in aquifers is both drains and rechaged across the border over time. The rechaged and drainage flow across the boundary of the aquifer qh ranges from -261 to 968 m^3/day/km boundary, with an average of 401 m^3/day/km boundary. The rechaged and drainage flow across the boundary of the aquifer qp ranges from -127 to 751 m^3/day/km boundary, with an average of 476 m^3/day/km boundary. The rechaged and drainage flow through the boundary of the hard rock aquifer of the Dong Giao Formation (t2đg) ranges from -3.400 to 1.410 m^3/day/km boundary, with an average of -116 m^3/day/km boundary.

CHAPTER 4. IMPACTS OF THE RED RIVER AND BEDROCK ON GROUNDWATER RECHARGE OF QUATERNARY SEDIMENTS IN THE SOUTHWEST HANOI

4.1. Development of a model to identfy the impacts of the Red River and bedrock in groundwater recharge in Quaternary sediments

The groundwater model in the study area was developed with GMS software version 10.0 to study and determine the amount of recharge for groundwater in Quaternary sediments from the Red River and the Southwestern bedrock boundary of Hanoi. The structure of groundwater flow model consists of 5 layers as follows: Layer 1 corresponds to uncover aquitard layer in Holocene sediments; Layer 2 corresponds to porous aquifers in Holocene sediments; Layer 3 corresponds to the aquiclude layer Pleistocene - Holocene; Layer 4 corresponds to porous aquifers in Pleistocene sediments; Layer 5 corresponds to the pre-Quaternary fractured bedrock aquifer.

The model grid step is divided equally with the grid cell size of 500x500m. The block diagram of the layer structure in the groundwater flow model is shown in Figure 6.

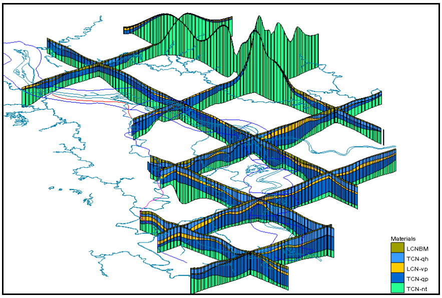

Figure 6. Schema of the structural layers

Values of parameters entered and model included

- Average monthly recharge and evaporation in the period 1995-2017 of meteorological stations Lang, Thanh Oai, Hung Yen, Dong Anh, Vinh Yen.
- The parameters of permeability, water release of layers in the model (5 layers)
- Flow of groundwater extraction over time of wells.
- Boundary conditions: the Red River boundary is as the one with the values determined for each segment by the author. For the Southwest boundary of the aquifers is considered as the time-varying specified flux determined by the author for each section. Other rivers and lakes such as Duong river, Ca Lo river, Day river, Nhue river are inherited from previous studies of the author when building groundwater models in Hanoi area.

4.2. Results on identification of impacts of the Red River and bedrock in groundwater recharge in Quaternary sediments

To identify the impacts of the Red River and the Southwest Hanoi's bedrock on groundwater recharge in Quaternary sediments, the author uses the built-in zoning map module in GMS software. For the Red River border, it is divided into 9 zones with different types and subtypes (for 2 aquifers qh and qp). Each zone is assigned a different zone number corresponding to each zone for each aquifer, in Figure7.

4.2.1. Groundwater recharge in Quaternary sediments from the Red River boundary

The calculation results of the groundwater balance study have been determined with the total groundwater reserves being extracted from the Quaternary aquifers in the southern part of Hanoi nowaday is about 846.530 m^3/day, of which groundwater exploitation in the Red River riparian area is about 462.014 m^3/day, in the inner city districts is about

382.569 m^3/day, about 1.947 m^3/day from bedrock in the Southwestern. The amount of groundwater recharged by the Red River ranges from 424.086 m^3/day to 620.411 m^3/day, with an average of 484.461 m^3/day, accounting for 50% to 73%, and an average of 57% of the total groundwater exploitation in the southern part of the Hanoi.

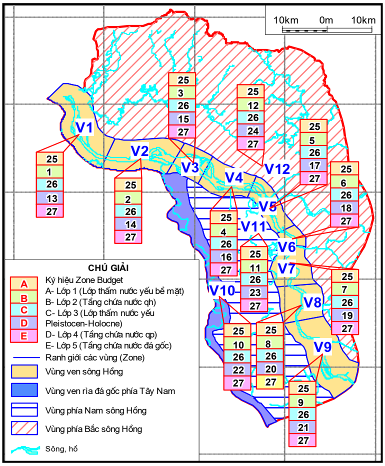

Figure 7. Map of zoning

In zones 4, 5, 6, 7, the big water treatment plants such as Thuong Cat, Cao Dinh, Yen Phu, Luong Yen, Nam Du, North Thang Long, Gia Lam, etc., are concentrated, thus forming significant derived flow, supplying most of the water wells. In addition, it also provides a part for the downtown area where a funnel has been formed to lower the water level. In order to ensure sustainable exploitation of groundwater in the study area, it is necessary to have a plan to adjust the exploitation flow of wells in the central area, even adjust additional large-scale water exploitation wells in the riverside areas, where abundant recharged sources to promote the capacity of aquifers and the role of the Red River. In the areas 1,2,3,8,9 the water level is hardly not affected by exploitation heavily so the Red River supply the quite small amount for groundwater and mainly naturally.

With the total groundwater exploitation reserves in both qh aquifers and qp aquifers in the Red River riparian zones is of about 462.014 m^3/day, the role of the Red River provides an average of 105% of the groundwater reserve. In which, for the aquifer qh, the Red River provides 100% of the exploited water (196 m^3/day), for the aquifer of the Red River, 89% of the exploited water (461.814 m3 exploited).

/day). For areas where large-scale water exploitation is concentrated such as areas 2, 4, 5, 6, 7 the Red River provides 69% (zone 5) to 86% (zone 4), even exceeding 100% (zone 6, zone 7) groundwater reserves are being exploited in the qp aquifer in the areas along the Red River.

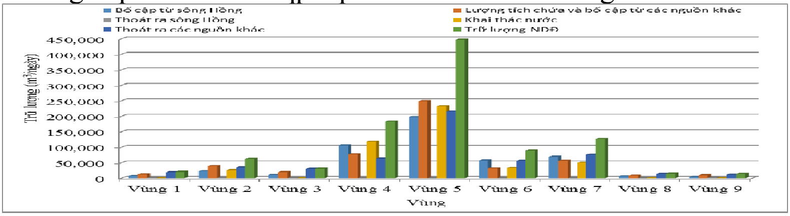

Figure8. Groundwater recharge volume from the Red River in Quaternary sediments in the study area

The above research results shows that the role of the Red River in replenishing groundwater in the riparian areas is quite clear and significant. The arrangement of groundwater exploitation works in the riverside area makes the most of the recharge from the Red River, so the exploitation flow and groundwater level there are always stable. Meanwhile, with thousands of groundwater wells currently in the city center, far from the recharge source from the Red River, the groundwater level is deeply lowered, the exploitation flow is not stable. Therefore, it is necessary to have reasonable plans for groundwater exploitation, in which it is necessary to pay attention to the arrangement of exploitation wells in the areas along the Red River with favorable conditions in order to make the most of the recharge from the river for groundwater, minimizing the negative impacts caused by groundwater extraction.

4.2.2. Groundwater recharge in the Southwest Quaternary sediments of Hanoi from the bedrock boundary

The groundwater reserve recharged across the Southwestern edge of Hanoi city ranges from 19.815 m^3/day to 20.349 m^3/day, with an average of 19.860 m^3/day. In which, the flow of water recharged across the boundary of the aquifer qh ranges from 9.063 m^3/day to 9.867 m^3/day, an average of 9.800 m^3/day; recharge across the border qp aquifer with flow from 9.948 m^3/day to 11.287 m^3/day, average 10.060 m^3/day. The amount of groundwater being exploited at the edge of bedrock only accounts for 10% of the recharge from the Southwestern edge. Therefore, the recharge from the Southwest border, in addition to completely meeting the amount of groundwater being exploited in the fringe area, also flows to supply the inner city. The amount of groundwater draining across the boundary is insignificant with the flow from 6.490 m^3/day to 10.156 m^3/day, averaging 6.795 m^3/day, accounting for 6% of the total groundwater reserve, of which mainly drains through the boundary layer qp.

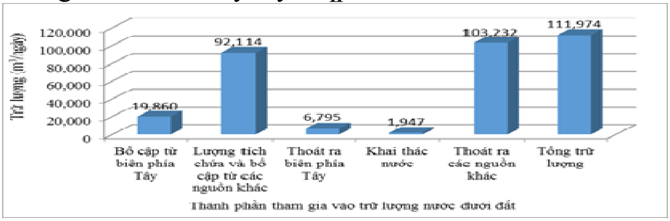

Figure9. In- and outflow to the Southwest of the study area over aquifers qh and qp

CHAPTER 5. PROPOSED PLAN OF RATIONAL GROUNDWATER EXPLOITATION AND USE TOWARDS SUSTAINABLE GROUNDWATER RESOURCES DEVELOPMENT

5.1. Basis

The results of the above studies show that:

- The Pleistocene aquifer in the study area has rich reserves, is a large-scale exploited water source and has a close hydraulic relationship with the Red River.

- In the Red River area, groundwater is replenished quite a lot from river water with an average supply of 89% of groundwater exploitation reserves for qp aquifer. Large riverside water plants such as Son Tay, Thuong Cat, Bac Thang Long, Cao Dinh, Yen Phu, Luong Yen, Nam Du, Gia Lam are supplied by the Red River with a supply volume of 69% (region 5) up to 86% (Zone 4), even exceeding 100% (Zone 6 and 7) groundwater reserves being exploited in the qp aquifer in the areas along the Red River, the drawdawn in water level is not great and always stable.

- The Southwest area of Hanoi city is provided with a part of groundwater reserves from the border, partly meeting the demand for rural water use in the Southwest region. However, due to the small thickness of the aquifer, the complicated geological conditions, and the allocation of karst caves, it is vulnerable to ground subsidence. Therefore, it is necessary to limit the large-scale groundwater extraction and exploitation surface water from Da water plant for use.

- In the inner center of the city, due to the influence of water exploitation, which has been increasing for decades, combined with the unreasonable arrangement of water exploitation well fields, high density of wells, cited far from rechargeble sources. Rapid civlization have led to an increasing water level lowering than ever with the area is of hundreds of square kilometers, increasing negative impacts on the environment such as depletion, pollution, salty water intrusion that need to have solutions to limit the exploitation of groundwater.

- The groundwater quality of the Pleistocene aquifer is relatively good, completely guaranteed to be exploited for domestic;
- Demand for water for domestic and socio-economic development is increasing.

Stemming from the above practical characteristics, the author develops 3 plans for groundwater exploitation as follows:

- Option 1: Maintain the status quo of groundwater exploitation, do not develop more centralized and great single exploitating groundwater by 2030.
- Option 2: Keeping the current location and capacity of exploitation wells along the Red River; at the same time, adjust the flow of some large well yards in the city center and mining more wells along the river and alluvial glaciers in the River.
- Option 3: Stop all groundwater exploitation activities in the inner city that being exploited unreasonable and adjust the location and flow of some groundwater plants along the Red River, at the same time, adding new wells along the river like option 2.

5.2. Proposal of plan

Based on the results of the construction of the above 3 options, the author analyzes, argues and thinks that option 3 is a reasonable exploitation plan for groundwater resources that Hanoi city can choose into the planning socio-economic development in the coming years.

Calculation results of option 3 show that the groundwater level in the inner city will basically be restored, ranging from 0m to 3m high. Especially, the water level of the Holocene aquifer has been restored, and the depletion of aquifers is no longer developed at present. Adjusting the location and exploitation flow of river wells, and adding new wells as above will ensure water supply for the whole city until 2030. Under this option, the total Groundwater extraction amount in the study area is about 1.571.000 m^3/day, of which the exploitation flow of 8 existing water plants is about 951.000 m^3/day and the exploitation flow of 9 newly added wells along the river is about

620.000 m^3/day, the water level of both Holocene and Pleistocene aquifers in the inner city is basically restored. Calculation results of water balance in zones according to this option show that the amount of recharge from the Red River for groundwater in Quaternary sediments ranges from 865.614 m^3/day to 1.089.401 m^3/day, with an average of 965.607 m3 /day. In which, the Red River supplies the qh aquifer with the flow from 108.660 m^3/day to 144.841 m^3/day, an average of 122.871 m^3/day and supplies the qp aquifer with the flow from 756.954 m^3/day to 944.560 m^3/day, average 842,736 m^3/day.

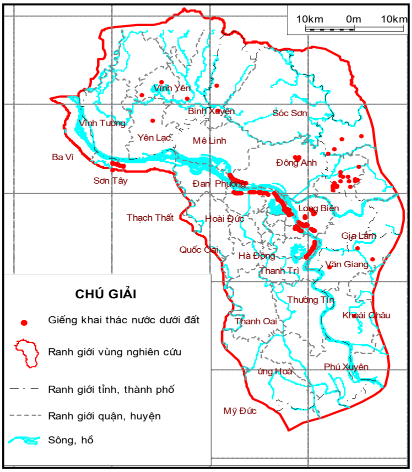

Figure 10. Map of wells in option 3

If the water exploitation is adjusted according to the option 3, the recharge amount of the Red River is 2 times larger than the current water exploitation plan and this is the plan for sustainable exploitation and use of groundwater resources for the future, the city in the long run, but resources are needed to stop the old wells in the inner city and develop new wells along the Red River. Figure 11 shows the recharge of Red River water to groundwater in both qh and qp aquifers in the study area.

The results of the options show that with the current plan, the volume of groundwater extraction can hardly meet the economic development needs of the city and there are many potential negative risks due to groundwater exploitation. Option 2 shows that if the position and flow of the wells are adjusted immediately, it will significantly reduce the negative impacts caused by groundwater exploitation and save investment resources, groundwater could meet the city's water supply demand for the current period and in the next 5 years. With option 3, it is possible to meet the long-term water supply needs and the problem of ensuring water security for the capital will be thoroughly solved. However, the adjustment, investment and demand need to ensure the harmony of resources as well as a feasible roadmap to ensure maximum use of resources but also ensure environmental and sustainable development goals.

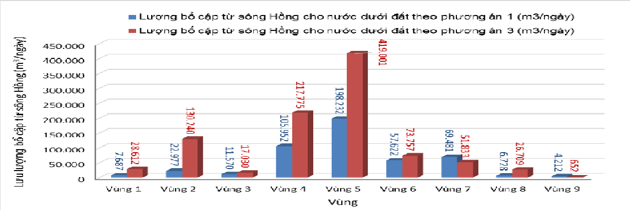

Figure11. Groundwater recharge volumes from the Red River with respect to different option plans

CONCLUSIONS AND RECOMMENDATION

Conclusion:

(1) On the basis of analysis results of hydrogeological structure characteristics, spatial relationship between the Red River and aquifers in the study area along the Red River from Ba Vi to Phu Xuyen divided into 9 regions with 3 main types and 4 subtypes of different hydrogeological structures characterized by the total permeability resistance value varying from 50m to 836m. The amount of recharge from the Red River for groundwater in Quaternary sediments in the riverside is now determined from 424.086 m^3/day to 620.411 m^3/day.

(2) The hydrogeological structure along the edge adjacent to the bedrock in the Southwest of Hanoi city is divided into 4 regions with 3 different types of structures, identified as type II boundary (boundary with specified flux and changing over time). The amount of recharge for groundwater in Quaternary sediments in the periphery of southwestern bedrock ranges from 19.815 m^3/day to 20.349 m^3/day.

(3) From the classification and determination of the role of each boundary segment, reasonable plans for exploitation of groundwater resources have been proposed in the study area. With the adjustment of the location as well as the volume of groundwater exploitation and the addition of new wells along the Red River, the amount of groundwater that can be exploited reaches 1.146.700 m^3/day (option 2) to 1.571.000 m^3/day (option 3). Groundwater extraction according to options 2 and

3 shows that the groundwater level in the city center has been restored, contributing to minimizing the risk of ground subsidence. This result once again confirms that the role of the Red River in groundwater recharge in Quaternary sediments in Hanoi city is very important and very meaningful.

(4) When a reasonable water exploitation corridor is arranged until 2030, the total groundwater reserve will be recharged by the Red River to both qh and qp aquifers in the riverside with the flow from 865.614 m^3/day to 1.089.401 m^3/day, an average of 965.607 m^3/day. In which, the Red River recharges for the qh aquifer with the flow from 108.660 m^3/day to 144.841 m^3/day, an average of 122.871 m^3/day and recharges for the qp aquifer with the flow from 756.954 m^3/day to 944.560 m^3/day, average 842.736 m^3/day.

Recommendation:

(1) The results of research and classification of bedrock boundary conditions at the Southwestern edge of Hanoi are only the first step to complete in terms of methodology and approach. In order to monitor as well as have calculation data, it is necessary to complete the monitoring network in order to have a data base for monitoring and calculating the groundwater flow across the boundary.

(2) The results of the thesis have clearly shown the role of the Red River in recharge as well as exploitation capacity in each riverside area from Ba Vi to Phu Xuyen. To be able to exploit, protect and effectively use groundwater resources in these riparian areas, Hanoi city needs to soon implement solutions to protect water resources as well as regional spatial development planning along the Red River, water resources must be taken as the core for development.

(3) The choice of exploitation plan should be considered according to the route, resources as well as development goals of the city in each period. However, it must be based on the principle of sustainable development and must consider groundwater resources as a strategic resource of the city for the present and future period, especially in the upcoming context of the city's planning orientation developing urban areas along the Red River which are the areas that will greatly affect the ability to exploit and protect this valuable resource.

(4) It needs to carry out the specific studies on the impact of ground subsidence caused by groundwater extraction and the groudwater pollution issues caused by surface water quality of the Red river in Hanoi city.

LIST OF PUBLICATIONS

1. Nguyễn Văn Đản, Triệu Đức Huy, Phạm Bá Quyền, Trần Duy Hùng, Văn Thùy Linh, Phùng Anh Đào, Đào Văn Dũng (2015), "Đặc điểm địa chất thủy văn, thủy địa hóa và tính phân đới của chúng ở vùng ven biển Việt Nam", *Tạp chí Khoa học và Công nghệ Biển*, Tập 15, Số 4, tr. 334-340.
2. Đào Văn Dũng, Triệu Đức Huy, Phạm Bá Quyền, Hoàng Đại Phúc, Đặng Đình Phúc (2020), "Nghiên cứu, đánh giá khả năng lưu trữ nước ngọt khu vực nhiễm mặn vùng đồng bằng sông Hồng", *Tạp chí Tài nguyên & Môi trường*, số 9 (335), Kỳ 1 - Tháng 5/2020, tr. 36-38.
3. Đào Văn Dũng, Triệu Đức Huy, Phạm Bá Quyền, Hoàng Đại Phúc (2020), "Quy trình công nghệ lưu trữ nước ngọt trong khu vực nhiễm mặn tầng chứa nước pleistocene vùng đồng bằng sông Hồng", *Tạp chí Tài nguyên & Môi trường*, số 15 (341), Kỳ 1 - Tháng 8/2020, tr. 55-57.
4. Triệu Đức Huy, Đào Văn Dũng, Phạm Bá Quyền, Hoàng Đại Phúc, Đặng Đức Nhận (2020), "Bộ công cụ đánh giá hiệu quả mô hình lưu trữ nước ngọt trong các tầng chứa nước mặn vùng đồng bằng sông Hồng", *Tạp chí Tài nguyên & Môi trường*, số 18+19 (344+345), Kỳ 2 Tháng 9 + Kỳ 1 tháng 10, tr. 98-100.
5. Triệu Đức Huy, Nguyễn Văn Lâm, Tống Ngọc Thanh, Phạm Bá Quyền, Hoàng Đại Phúc (2020), "Vai trò của biên sông Hồng đối với lượng bổ cập cho nước dưới đất trong trầm tích Đệ tứ khu vực Hà Nội", *Hội nghị toàn quốc khoa học trái đất và tài nguyên với phát triển bền vững (ERSD 2020)*.
6. Trieu Duc Huy, Tong Ngoc Thanh, Nguyen Van Lam (2016), "Methods to determine groundwater flow through boundary to abstraction wells located near boundary", *International Conference on Geology and Georesources (GAG)-ESASGD 2016*, pp. 279-289.
7. Tong Ngoc Thanh, Trieu Duc Huy, Nguyen Van Kenh, Tong Thanh Tung, Pham Ba Quyen, Nguyen Van Hoang (2017), "Methodology of determining effective porosity and longitudinal dispersivity ofaquifer and the application to field tracer injection test in Southern Hanoi, Vietnam", *Vietnam Journal of Earth Sciences*, Vol39(1), pp. 58-75.
8. Nguyen Van Hoang, Tong Ngoc Thanh, Nguyen Duc Roi, Trieu Duc Huy & Tong Thanh Tung (2017), "Potential for the desalination of a brackish groundwater aquifer under a background of rising sea level via salt intrusion prevention river gates in the coastal area of the Red River Delta, Vietnam" *Environ Dev Sustain*, Vol20, ISSN: 1387-585X. 2747-2771. Doi 10.1007/s10668-017-0014-x.
9. Trieu Duc Huy, Tong Ngoc Thanh, Nguyen Van Lam, Nguyen Van Hoang (2018), "Inverse analysis for transmissivity and the Red river bed's leakage factor for Pleistocene aquifer in Sen Chieu, Hanoi by pumping test under the river water level fluctuation", *Vietnam Journal of Earth Sciences*, Vol40(1), pp. 26-38.
10. Trieu Duc Huy, Tong Ngọc Thanh, Nguyen Van Lam, Pham Ba Quyen, Hoang Dai Phuc, Trinh Hoai Thu (2021), "Classification of hydrogeological structure along the Red River in Hanoi area", *Vietnam Journal of Marine Science and Technology*, Vol21, No3, pp. 1-12.