UTILIZATION OF STABLE ISOTOPES FOR INVESTIGATING SURFACE WATER AND GROUNDWATER INTERACTION: A CASE STUDY IN THE THACH HAN RIVER REGION

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Abstract: *Investigation of GW-SW is crucial in hydrology and water resource management, employing diverse methodologies. This study integrates hydrogeological measurements and isotopic techniques to assess water sources, using δ^2H and $\delta^{18}O$ values. In the Thach Han River region of central Viet Nam, challenges like declining groundwater levels and salinization persist. During the dry season, groundwater recharge mainly comes from reservoir water for about 7 months. Base flow contributes 80-85% to streamflow in the rainy season, rising to 100% in the dry season, with an average travel time estimated at 120 ± 10 days.*

Keywords: *Stable Isotopes, δ^2H và $\delta^{18}O$, Surface water and groundwater interaction, Thach Han river's region.*

1. Introduction

The groundwater-surface water (GW-SW) interaction is a process between the two main components in the water cycle. Understanding the interaction between GW-SW assists in comprehending their interdependence and level of engagement in water resources management. The application of isotope technique to study this interaction has been mentioned by many publications. Environmental tracers are very commonly employed in determining different phenomenon of human interest, out of which the GW-SW interactions is one. The traces generally used for this purpose are stable isotopes like deuterium (2H) and oxygen-18 (18O), along with radioactive isotopes like 3H and 14C and chemical indices such as ion concentrations and electrical conductivity.For the last decades, stable isotopic signatures (δ^2H, $\delta^{18}O$) of water were used as conservative tracers for identifying the origin of groundwater, GW-SW interaction, possible connections between different aquifers or characterizing flows in streams [2-6]. However, to our understanding there were not many researches worldwide in which water stable isotopes signatures were used to verify recursive filtering models applied in the hydrograph separation.

In the Thach Han River region, the local community relies solely on groundwater as their source of clean water, while surface water is used for irrigation and other purposes. However, empirical evidence supporting this claim remains lacking. An observation on the groundwater abstraction in the Gio Linh Water Supply Work indicated a water table lowering rate of 0.53 m/year between 2003 and 2017 [7]. This groundwater overexploitation raises concerns about salt intrusion in the coastal aquifers [7].

This research aims to investigate GW-SW interaction in the Thach Han River region. The study employs isotopic techniques combined with hydrogeological measurements to explore the interaction between groundwater and surface water in the study area.

2. Hydro-geological settings in the study region

The study site encompasses the Thach Han River region, situated between latitude 16°9' - 17°N and longitude 106°52'40" - 107°10' [8]. This plain is bounded by the marine coast of the

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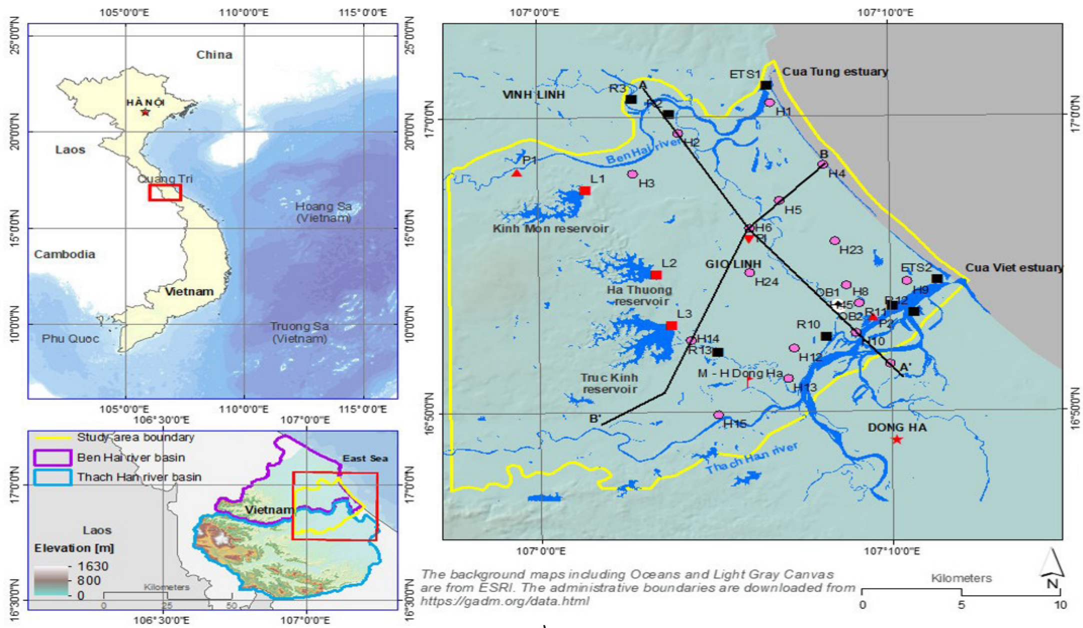
East Sea to the East, 50-144 m high mountains and hills to the West, the Ben Hai River to the North. Figures 1 depicted a map of the study site and sampling locations. The hydrogeological characteristics of the study area, as illustrated in Figures 1b and c for the east-west (W-E) and Northeast-Southwest (N-S) oriented cross-sections AA’ and BB’ respectively, delineate the sedimentary composition within the region.

3. Methods

This study utilized a comprehensive approach, combining conventional hydrogeological measurements, isotopic techniques, and chemical analyses of ionic contents in various water sources, including local precipitation, surface water from the Thach Han Rivers, reservoirs, and groundwater samples. Furthermore, the determination of baseflow in the river, based on δ^2H and $\delta^{18}O$ values, was employed to assess the reciprocal influence of river water on groundwater and their interaction.



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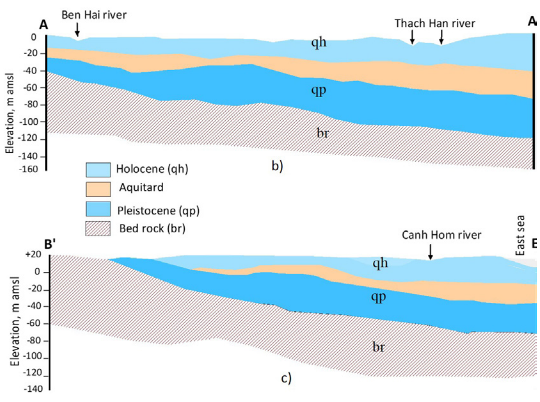


Figure 1. (a) The Thach Han River region and sampling locations: ▲’P): precipitation station; ■: samples from rivers (R) and estuaries (EST); ● (H-15): samples from Holocene aquifer with a sequence number (15); ▼ (Pl): samples from Pleistocene aquifer; ■ (L): reservoir water; • (OB): observation wells installed into Holocene (OB1) and Pleistocene (OB2) aquifers. (b) and (c): The hydrogeological settings and the cross-section lines AA' and BB' were illustrated in Figure 1a. The colors blue, brown, and dark blue indicate the Holocene aquifer (qh), the aquitard, and the Pleistocene aquifer (qp), respectively. The presence of bedrock is represented by diagonal stripes

A total of 34 samples of local precipitation, 21 groundwater samples from the Holocene aquifer at depths ranging from 2.5 to 25 m below the ground surface (bgs), 7 samples from the Pleistocene aquifer at depths ranging from 70 m to 80 m bgs, 30 surface water samples from the Ben Hai and Thach Han rivers and 5 samples from Truc Kinh, Ha Thuong, and Kinh

Mon reservoirs, and 1 sample from the mouth of the Thach Han river were systematically collected during the period of 2017-2018 (Figure 1a). Surface waters from rivers and reservoirs were collected at the same day for groundwater sampling. Precipitation was collected bi-monthly for the 2017-2018 years using a device constructed following an IAEA's recommendation [9] which was installed on the roof of the premises of Hydro-Meteorological Station (Figure 1a).

The stable isotopic signatures of hydrogen and oxygen (δ^2H, $\delta^{18}O$) in water were analyzed at the Hanoi University of Natural Resources and Environment (HUNRE) on a Picarro's cavity ring-down spectrometer, CRDS L2130-I, which works based on the principle of absorption spectroscopy. The working principle of the CRDS can be found in the Operation Manual of Picarro [10]. The precision of the method was as high as 1.5 ‰ and 0.15 ‰ for δ^2H and $\delta^{18}O$, respectively.

Quantification of surface water influence on groundwater through water isotopic signatures (δ^2H and $\delta^{18}O$) has been done. Initially, we establish a δ^2H vs. $\delta^{18}O$ relationship for the groundwater samples under study and then compare this pattern with that observed for precipitation in the region [2], [3], [4]. Baseflow in the Thach Han river's stream (Figure 1a) was separated and quantified. It is assumed that streamflow in the river comprises two components: Baseflow coming from aquifers and surface runoff of precipitation. The contribution of baseflow, i.e., groundwater into the total stream was determined based on $\delta^{18}O$ in the water samples as follows [11]:

$$BF\delta = \frac{Q_{BF}}{Q_{st}} = \frac{\delta^{18}O_{st} - \delta^{18}O_P}{\delta^{18}O_{BF} - \delta^{18}O_P} \qquad (1)$$

Where: $BF\delta$: Baseflow index by stable isotope method; Q_{BF} and Q_{st} are flow rate of baseflow and river, respectively; $\delta^{18}O_{st}$, $\delta^{18}O_P$, *and* $\delta^{18}O_{BF}$ are the content of *18O* isotope in river, precipitation and baseflow, respectively. Similarly, the Q_{BF} to Q_{st} ratio can also be determined if δ^2H in water samples were used.

In this study, Eckhardt's recursive digital filtering (RDF) method [1] was also applied for baseflow separation for hydrographs. The model of Eckhardt's filter [1] is the following equation:

$$Q_{Bf(i)} = \frac{(1 - BFI_{max}) x\alpha\ x\ Q_{Bf(i-1)} + (1-\alpha) x\ BFI_{max} x\ Q_i}{(1 - \alpha x BFI_{max})} \qquad (2)$$

Where $Q_{Bf(i)}$ and $Q_{Bf(i-1)}$ are calculated baseflow at ith and (i-1)th days, respectively; Q_i is total (observed) discharge at ith day; α is recession constant, and BFI_{max} is the maximum baseflow index. Eckhardt suggested the values of α and BFImax to be 0.96 and 0.81 [1], respectively. Mean travel time is the average duration required for a water patial to traverse a catchment, spanning from its entry point to its exit point. The MTT can also be equated to turn over time, where it is expressed as the ratio of mobile catchment storage to discharge. The value of tBF was estimated based on the sine curve method [12], [13]. The method relies on the sinuous pattern of seasonal variation of $\delta^{18}O$ or δ^2H in precipitation and river water following a model developed by Rodgers et al. [12]. For the case of using $\delta^{18}O$ the model was as follows:

$$\delta^{18}O_{t,P} = mean\ \delta^{18}O_P + A_P * \sin(\frac{2\pi}{365} * t + \emptyset_P) \qquad (3)$$

$$\delta^{18}O_{t,R} = mean\ \delta^{18}O_R + A_R * \sin(\frac{2\pi}{365} * t + \emptyset_R) \qquad (4)$$

Where: $\delta^{18}O_{t,P}$ and $\delta^{18}O_{t,R}$ are, respectively, oxygen 18 signature in precipitation and river's water on the day t elapsed since the beginning of sampling (days); mean $\delta^{18}O_P$ and mean $\delta^{18}O_R$ are, respectively, the mean value of $\delta^{18}O$ in precipitation and river's water derived from its time series that was determined for the entire sampling campaign; AP, ϕP, A_R and ϕR are, respectively, arbitrary amplitude and phase lag of the $\delta^{18}O$ functions (Equations 5, 6) for precipitation and river's water in radians that modeler would adjust to minimize the square root of the mean squared error (RMSE) between observations and model for precipitation or river's water [12], [13]; (2/365 = 0.017205 radian/day) is the radial frequency of annual fluctuation.

The MTT of baseflow then was determined by the formula [12], [13]:

$$MTT_{BF} = \frac{1}{0.017205}[\left(\frac{A_P}{A_R}\right)^{0.5} - 1], days \qquad (5)$$

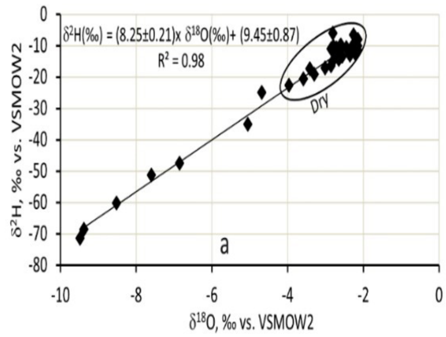
Where: A_P and A_R are the amplitudes of the sine curve of $\delta^{18}O$ in precipitation and river water (Equations 5, 6), respectively.

4. Results and discussion

4.1. Isotopic signatures of precipitation, surface water and groundwater

The isotopic signatures (δ^2H and $\delta^{18}O$) of local precipitation, surface water, and groundwater in the Thach Han River region were presented in Figure 2a, b, c.

Figure 2a depicts local meteoric water line and for surface water of Truc Kinh, Ha Thuong and Kinh Mon reservoirs along with the LMWL. Figure 2c presents relationship of δ^2H vs. $\delta^{18}O$ for water of Thach Han river.



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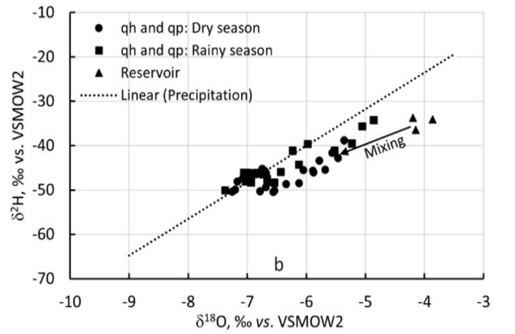

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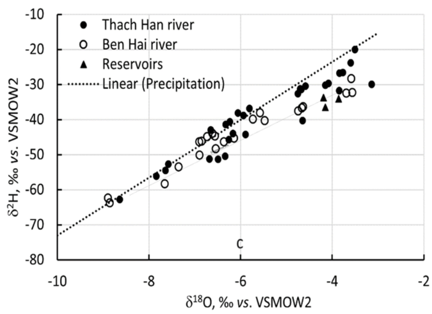

c)

Figure 2. (a) Local meteoric water line (LMWL); (b) isotopic compositions of groundwater in Holocene (qh) and Pleistocene (qp) aquifers and that of Truc Kinh, Ha Thuong and Kinh Mon reservoirs along with the LMWL; and (c) isotopic compositions of surface water from Thach Han river and the three reservoirs along with the LMWL

4.2. Baseflow separation

Table 1 presents results of estimated (Equation 3) contribution of baseflow to the total streamflow of the Thach Han river in rainy and dry seasons.

In Table 2, the variables $\delta^{18}OSt$, $\delta^{18}OP$, and $\delta^{18}OBF$ denote the average oxygen-18 isotopic compositions observed in river water, precipitation, and groundwater sourced from the Pleistocene aquifer, respectively, across different seasons.

Table 1. Results of estimated contribution of baseflow (Equation 1) to the total streamflow of Thach Han and Ben Hai Rivers during the rainy (August - December) and dry seasons (January - July)

River	Rainy season				Dry season			
	δ^{18}OSt ‰	δ^{18}OP ‰	δ^{18}OBF ‰	BFδ	δ^{18}OSt ‰	δ^{18}OP ‰	δ^{18}OBF ‰	BFδ
Thach Han	-6.32	-8.74	-5.73	0.804	-6.33		-6.15	1.0

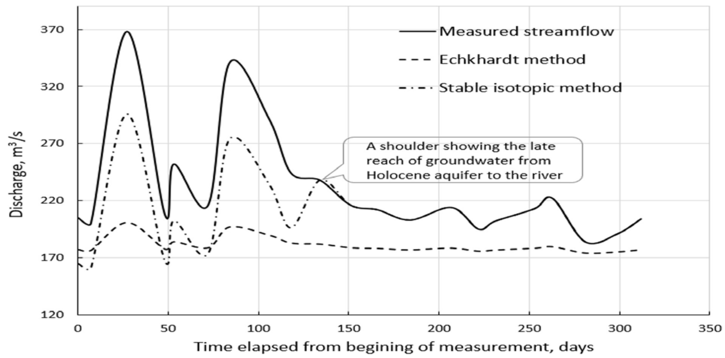

Figure 3. A visualization of baseflow separation from streamflow (solid line) of the Thach Han River during a time period from Jul 15, 2017 to 15 Jun, 2018 using isotopic method and by Eckhardt's RDF method (BFImax = 0.81, α = 0.96) that gave contribution of baseflow to stream to be of (0.85 ± 0.11)

In this study, varying BFImax and α in the Eckhardt's model (Equation 2) resulted in a quite different pattern of the baseflow curve and if BFImax and α accepted to be, respectively, 0.81 and 0.96 then the baseflow tended to look like that drawn in Figure 3 (dash line). With these values for the parameters, the contribution of baseflow derived from the Eckhadt's method was in the range of those derived from the stable isotopic method, it was (0.85 ± 0.11) for the entire experimental period.

The only difference between the two methods observed was that during precipitation events baseflow separated by isotopic method seems to be higher than that separated by the RDF method. It could be understood because in the RDF method not necessarily separate surface run off and groundwater as the two-component separations as in isotopic method, but usually the fast and slow responses. Therefore, we believed that the result of baseflow separation based on the water isotopic signature is more reliable as it was mentioned by David et al. [14]. It is important to note that, due to the infrequent isotopic sampling, the base flow value reflects only the annual average or the period during which the stable isotope samples were collected. For a more detailed analysis, especially during the flood season, the sampling frequency should be increased.

4.3. Mean travel time (MTT) of baseflow

Figure 4 depicts the seasonal variation of δ^{18}O measured in local precipitation and the Thach Han River water along with those that were simulated using Equations (1, 2).

The seasonal variation of δ^{18}O in local precipitation follows a best fitted model:

$$\delta^{18}OP = -5.64 - 7.94 \times \sin(0.0172 \times t + 405.8), ‰ \quad (6)$$

for which AP value was derived as -7.94 ‰; and the model for river's water was:

$$\delta^{18}OR = -6.40 - 1.58 \times \sin(0.0172 \times t + 405.4), ‰ \quad (7)$$

With *AR = -1.58 ‰*

Based on the known AP and AR, the mean travel time of baseflow was estimated (Equation 5) as long as 120 ± 10 days.

This could be a result of mixing recent precipitation with those from previous season which retained in aquifer sediment pores made the isotopic signatures in groundwater discharging to the river's stream as base flow to be homogeneous by seasons. As groundwater is a major contributor to the river's flow, thus simulated values of $\delta^{18}O$ in river water were close to measured ones. The total error in the determination of mean $\delta^{18}OP$, mean $\delta^{18}OR$, AP and AR (Equations 3, 4) were estimated as large as 8.6%. To our opinion the simulation results were good enough and could be accepted for estimating the base flow MTTBF (Equation 5), and it was as long as 120 ± 10 days. It should be noted that the information of MTTBF of base flow in the Thach Han Rivers region was the first time derived in this study.

Additionally, Table 2 provides the age estimations of groundwater at various depths using the $^3H/^3He$ method. Utilizing the data from Table 3, a graphical representation of groundwater ages plotted against depth was generated and is presented in Figure 5.

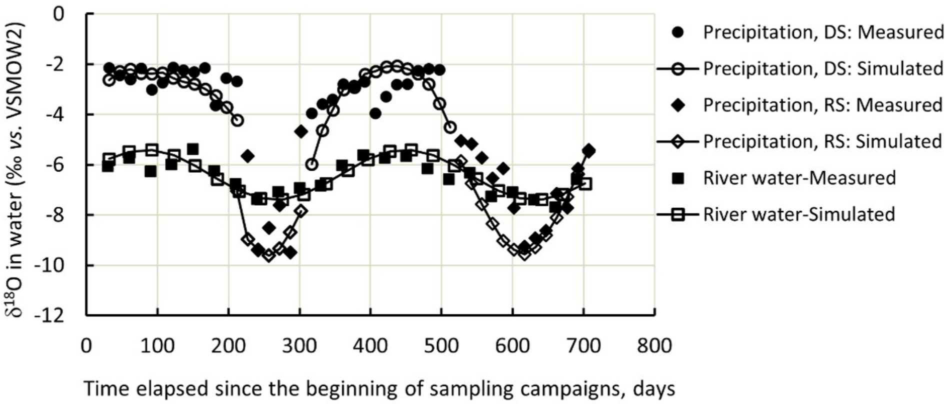

Figure 4. Seasonal variation of $\delta^{18}O$ values in precipitation and in the Thach Han river's water measured in the 2017-2019 and that for the simulated values using Equations (5,6). DS and RS stand for the dry and rainy seasons, respectively

Table 2. The $^3H/^3He$ age of groundwater at different depths in Gio Linh plain determined for the 2017-2018

No	Borehole	Coordinate		Depth, m, bgs*	Age, y
		X	Y		
1	BH 01	719,563.00	1,867,876.00	11.60	18.50
2	BH 03	719,973.84	1,869,307.44	13.40	50.80
3	BH 04	721,705.00	1,866,546.00	8.10	19.80
4	BH 05	723,026.00	1,872,667.00	5.10	15.30
5	BH 06	728,419.00	1,869,694.00	20.70	79.40
6	BH 08	719,286.89	1,880,890.81	10.10	28.90
7	BH 09	707,817.00	1,875,785.00	7.30	8.80
8	BH 12	733,114.00	1,871,038.00	5.70	4.10
9	BH 13	730,381.00	1,868,482.00	11.20	28.30
10	BH 14	730,214.00	1,870,932.00	22.50	64.80

**) bgs: below ground surface*

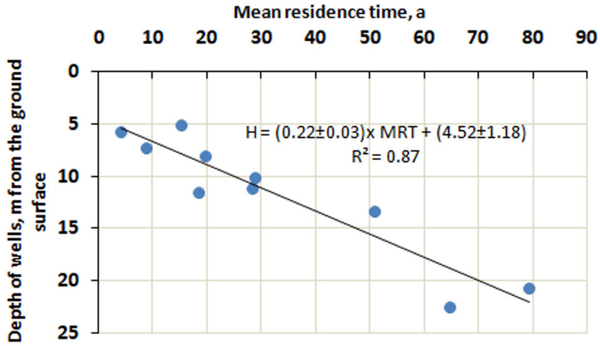

Figure 5. Relationship of boreholes depth H vs. mean residence time MRT (age) of groundwater in Gio Linh region

5. Conclusions and recommendations

The results of this study allow one to conclude as follows:

The Thach Han River region has 80 %-85 % groundwater recharge as baseflow during the rainy season, increasing to 100 % during the dry season. The mean traveling time (MTTBF) of the baseflow was found to be 120 ± 10 days. During the 7-month dry season, water from the reservoirs in the west serves as the sole source to recharge groundwater in the region. The insights gained from this study are anticipated to play a crucial role in the sustainable management and exploitation of water resources in the region.

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Competing interest statement: *The authors declare that this article was the work of theauthors, has not been published elsewhere, has not been copied from previous research; therewas no conflict of interest within the author group.*

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