

# Characteristics of groundwater in karstic region in northeastern Vietnam

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**Abstract** The groundwater in the karst region of northeastern Vietnam is found in various structural zones such as the Ha Lang, Song Hien, Hon Gai, Song Lo, Song Gam, and Hoang Lien Son Zones, etc. Results from this study show that groundwater in this region is at different depths: ~120 m deep at Quang Ninh, ~100 m at Lang Son, ~80 m at Cao Bang (The most water-abundant depth observed at Cao Bang varies from 40 to 45 m) while it varies from 18–25 to 80 m deep at Quan Ba (Ha Giang), especially at Meo Vac (Ha Giang), where groundwater is observed at 700–800 m deep (equivalent to local base level of the Nho Que River). Overall, groundwater in the region is fresh with total minerals varying from 250 to 400 mg/l; except for the coastal area of Quang Ninh, where groundwater is characterized by much higher total minerals ( $M = 3\text{--}18\text{ g/l}$ ) due to the mixing with the saline sea water. The chemistry of water in the region demonstrates that the water is mainly bicarbonate with a  $[\text{HCO}_3^-]$  concentration varying from 150 to 265 mg/l, pH is of 6.5–8.1, and its hardness is of 3.7–6.0 meq/l.

**Keywords** Northeastern Vietnam · Groundwater · Carbonate rock

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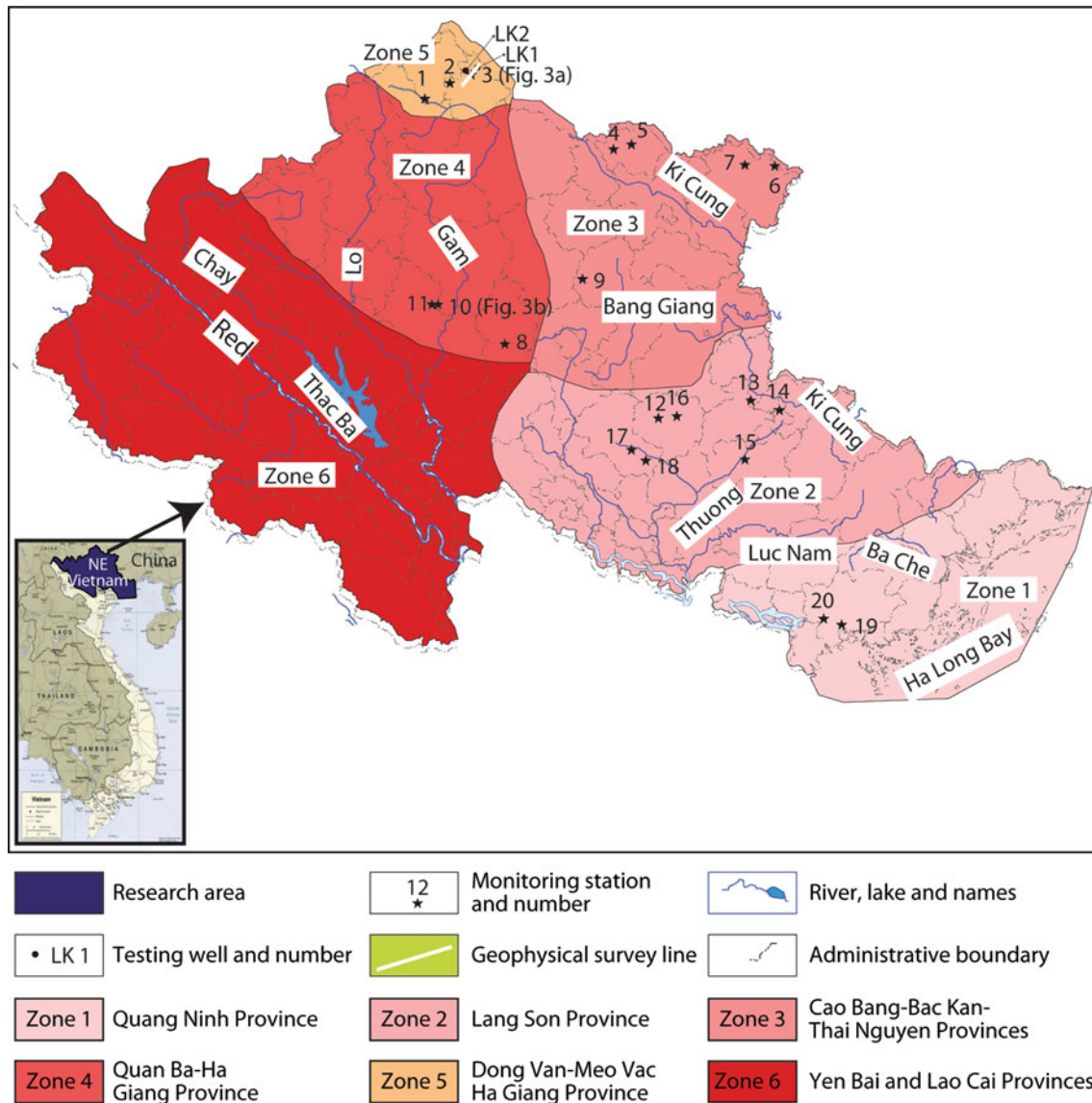
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## Introduction

Carbonate formations in northeastern Vietnam expose on an area of over 50,000 km<sup>2</sup>, which are widely observed in many provinces such as Phu Tho, Yen Bai, Lao Cai, Ha Giang, Tuyen Quang, Bac Giang, Thai Nguyen, Bac Kan, Cao Bang, Lang Son, and Quang Ninh, etc.

Within northeastern Vietnam, carbonate rocks are of different periods of geological time, but the most common deposits are the Bac Son formation (C-P<sub>bs</sub>). In addition, the older carbonate formations, for example, the Cam Duong Formation (C<sub>cd</sub>), Ha Giang Formation (C<sub>hg</sub>) (C<sub>hg</sub>) Phu Ngu Formation (O<sub>3</sub>-S<sub>1pn</sub>), Mia Le Formation (D<sub>2ml</sub>), Phia Phuong Formation (D<sub>1pp</sub>), Na Quang Formation (D<sub>1-2nq</sub>), and less common Triassic carbonate such as the Lang Son Formation (T<sub>1ls</sub>) can be observed in many areas (Tran 1962; Nguyen et al. 1994; Do 1998). Geomorphology of the region develops on these carbonate formations is characterized by arc-shaped form, strong incision and tendency of lowering from the east to the west. Groundwater resources in the region are much dependent on the geological settings of each specific geological zone (Nguyen 2003). Vu et al. (1985) showed that groundwater in northeastern Vietnam occurs in six different geological zones: (1) Quang Ninh (coastal area), (2) Bac Son (Lang Son), (3) Cao Bang-Bac Kan-Thai Nguyen, (4) Quan Ba (Ha Giang), (5) Dong Van-Meo Vac (Ha Giang), and (6) Lao Cai-Yen Bai zones (Fig. 1).

The local inhabitants in northeastern region of Vietnam are minority of the Muong, Dao, San Diu, H'Mong, and other groups of people have been living in substandard conditions. One of the reasons for the low living standard of those people is the shortage of freshwater for living and production. Besides, surface water is strongly dependent on seasonal climate and it is seriously degraded due to the consequence of deforestation and industrial pollution.



**Fig. 1** Locations of research area, hydrogeological zones, and monitoring stations

Therefore, exploration and exploitation of groundwater sources, especially groundwater, are crucial tasks for socio-economic development of the region.

Unfortunately, investigation of the potential of groundwater in the region has not been well conducted due to a number of reasons such as limited finance, complicated geological settings, lack of advanced equipments, etc. This study is a part of a Project funded by the Vietnamese Government, lasting for 5 years (2006–1010), encoded KC.08.19/06-10, that aims at defining the quality, potential as well as investigating the distribution pattern of groundwater resources in northeastern Vietnam in order to advise the Government to determine an appropriate exploitation and protection plan of the groundwater. As mentioned above, no detailed study or documentation on groundwater in northeastern Vietnam has been made previously. Some new study results are presented

in this paper based on a combination of various field geological, geophysical surveys, and drilling, together with data derived from sample analyses, which have been carried out during the last 4 years.

## Methodology

### Field survey

Geophysical measurement and drilling were used together with detailed geological mapping, and on-site observations to evaluate potential of groundwater resources as well as to define their spatial distribution patterns within the study area. Below is a brief description of each method applied in this study.

Detailed geological mapping

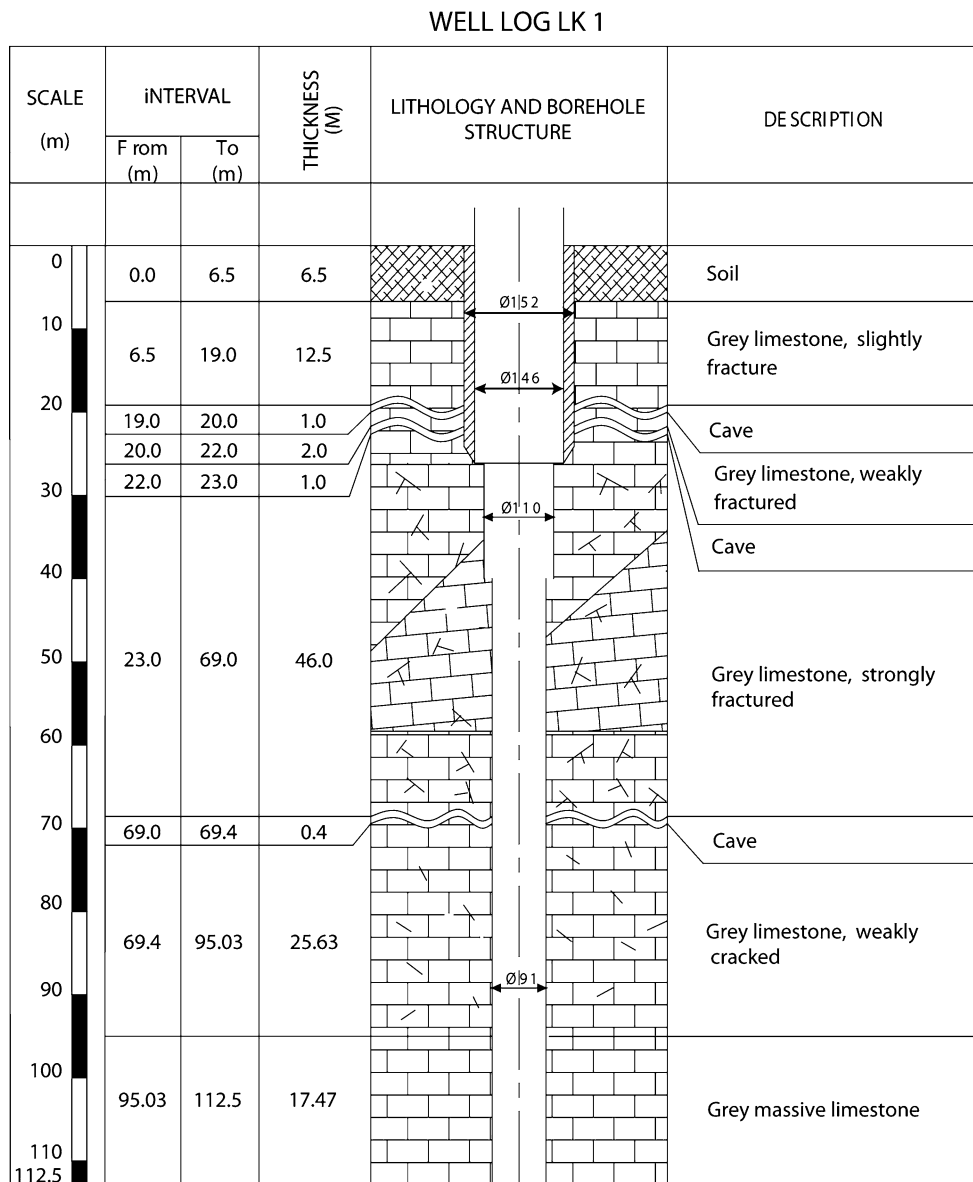
The main objective of this task is defining potential rock formations and structures, which are favorable for karstic development. The research focused on some specific areas, where limestone deposited and there are strongly broken zones. Simplified geological structures derived from testing wells (LK1 and LK2) are presented in Figs. 2 and 3.

Geophysical survey

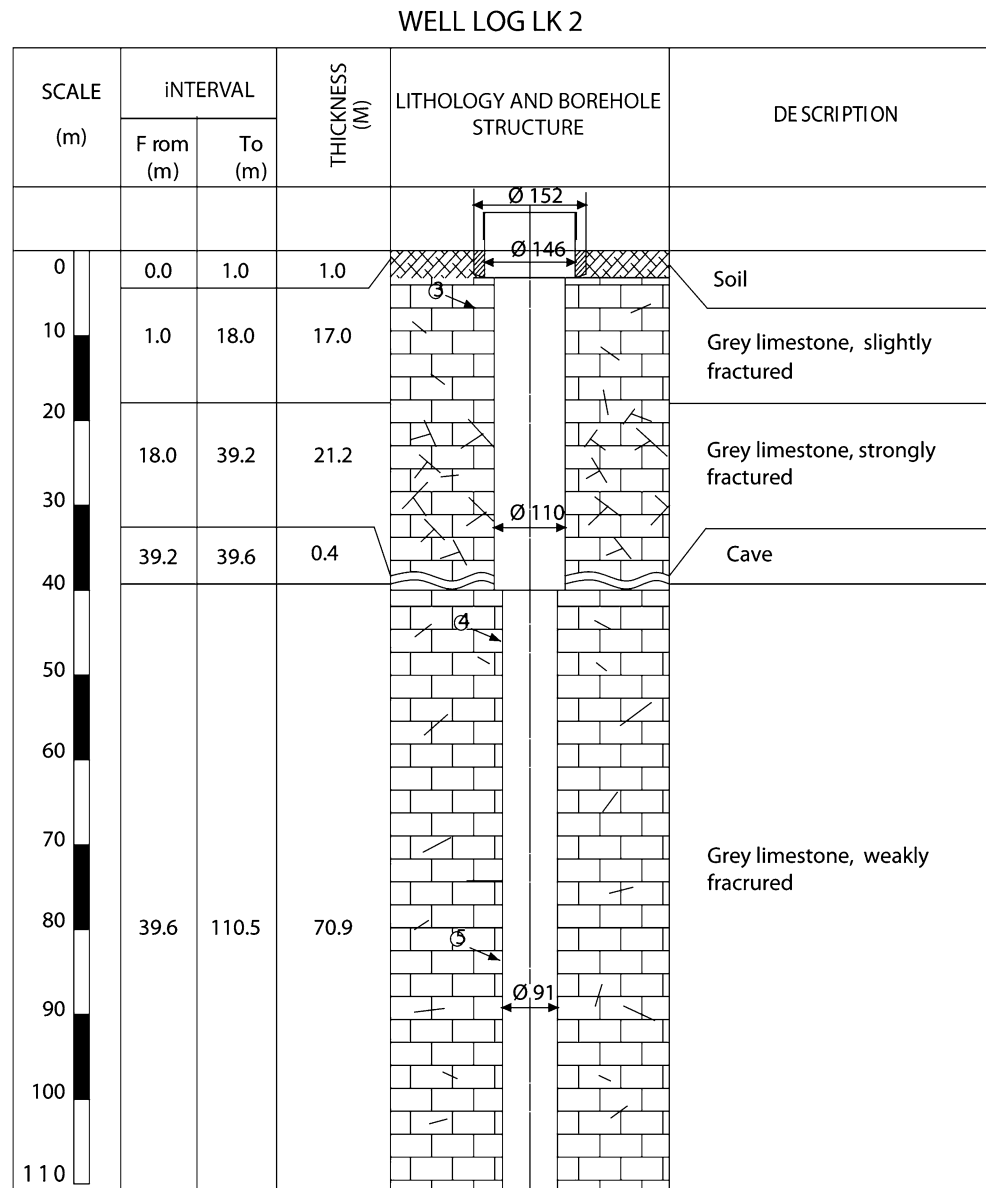
Due to the fact that karstic groundwater in northern Vietnam is situated at various depths, which developed under highly differentiated terrains, many geophysical methods such as gravitational or electrical cross-section survey do not demonstrate their effectiveness in such

regions (Sen 1995; Do 1998; Duong 2001; Le 2003; Waltham and Fookes 2003). In this study, the vertical electrical sounding (VES) method is an effective technique, which can be applied (Fig. 4). This work was conducted by using an ABEM device (provided by ABEM Instrument AB—Sweden), which measures resistivity of rocks through different rock units with different physical properties. The obtained results were subsequently processed and interpreted by using Res2Dinv software (Landviser) to simulate the ground resistivity and to link the presence of groundwater to the resistivity anomalies on geophysical sections. This software is designed to interpolate and interpret field data of electrical resistivity (conductivity) and induced polarization (IP). The inversion of the resistivity and IP data is conducted by least-square method involving finite-element and finite-difference

**Fig. 2** Well-log of the borehole LK1 showing simplified geological structure in Quan Ba, Ha Giang (Zone 5) (refer to Fig. 1 for its location)



**Fig. 3** Well-log of the borehole LK2 showing simplified geological structure in Quan Ba, Ha Giang (Zone 5) (refer to Fig. 1 for its location)

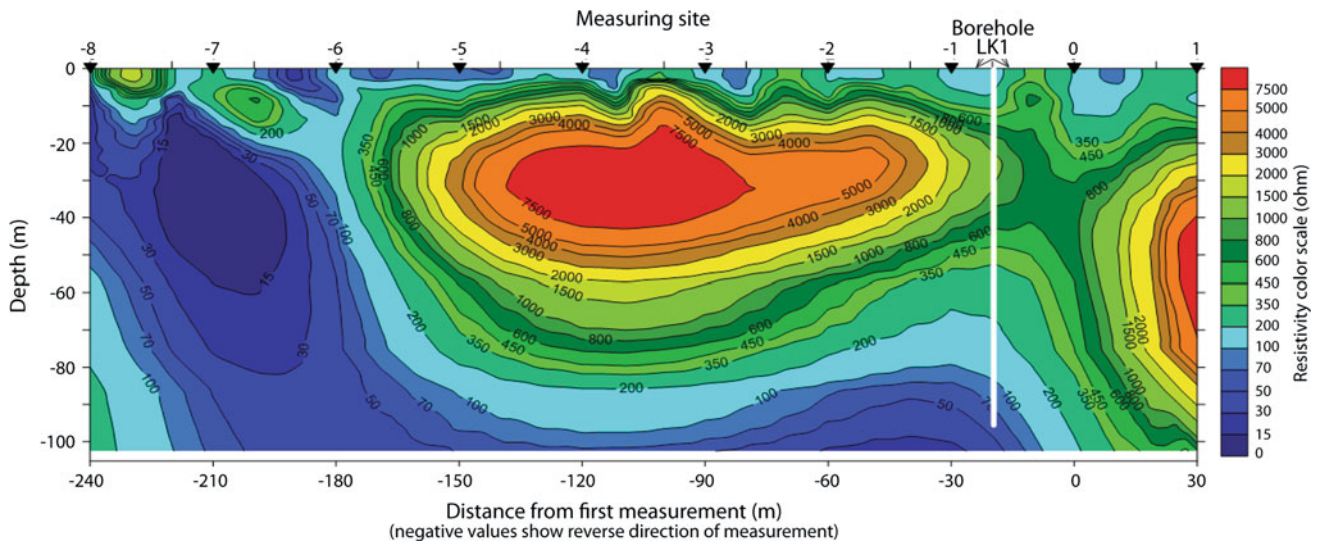


methods. This method inverts the entire data set and model at a single time to produce a continuous and seamless model (Landviser). Figure 4 is an example of resistivity profile processed by using Res2Dinv software. In general, massive carbonate rocks demonstrate very low conductivity and hence very high resistivity. However, if the rocks are strongly fractured and/or broken, water and other conductive materials can fill in empty spaces. As a result, total resistivity through the water-contained rock units decreased rapidly compared to surrounding areas. It is noteworthy to say that the very low resistivity anomalies are not only caused by water but also by other conductive media, for example, ore veins. It means that very low resistivity anomalies are indirect indicators of the presence of groundwater for the early stage of exploration, prior to wildcat drilling being commenced. These low resistivity

values demonstrate relative abundance of the groundwater below the earth surface. Therefore, quantifying the total amount of groundwater is hard to resolve by using this single method.

#### Drilling

Two drill holes of 80 and 120 m deep (LK1 and LK2) were drilled in Quan Ba (Ha Giang) (Figs. 2, 3) to examine characteristics and discharge of groundwater in the region. The drill sites were defined at a junction of different faulting/broken zones, which usually demonstrate high geophysical anomalies. Coring was done through the whole drilling section under geological supervision in order to track the change in rock properties, water loss/gain, depth of karstic zone, etc.



**Fig. 4** Resistivity profile measure in Quan Ba, Ha Giang (Zone 3). The very low resistivity anomaly below LK1 demonstrates high potential of groundwater (refer to Fig. 1 for its location)

*On-site measurement*

Figure 1 and Supplementary Table show locations of the water quality monitoring stations within the study areas. Physio-chemical properties of groundwater such as pH, temperature, EC, and salinity were measured at the middle of day each month using water quality checker (WQC) provided by the TOA Electronics Ltd. (Japan) with appropriate sensors. The alkalinity of groundwater was determined on-site by titration technique using 0.2 M H<sub>2</sub>SO<sub>4</sub> and a digital Titrator (HACH, USA).

Laboratory analysis

*Geological map and remote sensing image interpretation*

Interpretation of geological maps and remote sensing images were done during the early stage of the project and after field mapping was completed. This work was done to determine the most potential areas and/or geological structures, where karstic development is expected to occur so that geophysical survey line and drilling sites can be arranged properly in the subsequent steps.

*Water sample preparation and analysis*

Five hundred and eighty-six (586) water samples have been collected from the main rivers, their tributaries and water springs. Each 300-ml water sample collected from monitoring stations was bottled at the middle of every day. The samples were kept in a freezer at 4°C and left until the next day. They were later packed in a chest with ice and sent to the laboratory in Hanoi for analysis. All samples were

analyzed at the Geological Lab, Department of Geology and Mineral Resources of Vietnam. Concentrations of K<sup>+</sup>, Na<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, Cl<sup>-</sup>, and SO<sub>4</sub><sup>2-</sup> ions in the water were analyzed using a DIONEX 600 ion chromatographer, IC technique. Details of this analysis technique were described in Creed et al. (1996). The accuracy of the analysis was ensured by the balance of the electrical charge of ions present in the water samples and by cross-checking protocol proposed by the Global Environmental Monitoring System (GEMS Water), the United Nations Environmental Program (UNEP). Usually, the accuracy of the IC analysis is better than ±3%.

**Results**

By applying a combination of various investigation methods, including either field survey and laboratory work, the results obtained are important contributions to define fundamental characteristics and distribution patterns of groundwater in northeastern Vietnam. In this section, some of the most important issues are as follows:

Quality and distribution of the groundwater in northeastern Vietnam

Table 1 shows average chemical composition of the groundwater in northeastern Vietnam while detailed analytical results are presented in Supplementary Table. It is clearly demonstrated that chemical composition of groundwater varies from region to region. General trend of variation shows that water is fresh with total minerals (M) ranging from 242 mg/l (in Tuyen Quang (Table 1) to



**Table 1** Major chemical compositions of groundwater in NE Vietnam

| Zone number | Location    | Major chemical compositions   |                 |                               |                  |                  |                                  |        |          |     |
|-------------|-------------|-------------------------------|-----------------|-------------------------------|------------------|------------------|----------------------------------|--------|----------|-----|
|             |             | HCO <sub>3</sub> <sup>-</sup> | Cl <sup>-</sup> | SO <sub>4</sub> <sup>2-</sup> | Ca <sup>2+</sup> | Mg <sup>2+</sup> | Na <sup>+</sup> + K <sup>+</sup> | M      | Hardness | pH  |
| 6           | Lao Cai     | 263.6                         | 5.8             | 0.2                           | 55.7             | 20.7             | 1.6                              | 350.0  | 37.0     | 6.5 |
| 5           | Ha Giang    | 168.5                         | 17.8            | 14.0                          | 33.8             | 9.6              | 27.1                             | 273.0  | 4.3      | 7.4 |
| 4           | Tuyen Quang | 161.1                         | 13.4            | 1.8                           | 28.1             | 2.8              | 31.5                             | 242.0  | 5.1      | 7.9 |
| 3           | Cao Bang    | 189.2                         | 12.7            | 3.8                           | 37.6             | 8.4              | 23.2                             | 276.0  | 3.8      | 7.7 |
| 3           | Bac Kan     | 180.7                         | 6.9             | 6.9                           | 43.5             | 3.0              | 22.1                             | 282.0  | 5.5      | 6.7 |
| 6           | Thai Nguyen | 212.7                         | 9.3             | 8.7                           | 48.1             | 10.7             | 19.9                             | 301.0  | 6.0      | 6.5 |
| 2           | Lang Son    | 227.4                         | 17.2            | 7.4                           | 45.1             | 5.3              | 52.1                             | 362.0  | 4.8      | 8.0 |
| 1           | Quang Ninh  | 157.7                         | 3564.0          | 154.0                         | 138.0            | 64.9             | 2154.0                           | 6218.0 | 3.8      | 8.1 |

**Table 2** Total minerals in groundwater in different rock ages

| Geological age      | Sampling location | Total minerals (M), mg/l |             |               |                 |            |
|---------------------|-------------------|--------------------------|-------------|---------------|-----------------|------------|
|                     |                   | <200 (%)                 | 200–500 (%) | 500–1,000 (%) | 1,000–3,000 (%) | >3,000 (%) |
| Permo-Carboniferous | Well              | 30.5                     | 59.5        | 5.8           | 1.6             | 2.5        |
|                     | Spring            | 38.1                     | 62.9        | 0.0           | 0.0             | 0.0        |
| Devonian            | Well              | 36.0                     | 59.3        | 4.8           | 0.0             | 0.0        |
|                     | Spring            | 26.0                     | 67.5        | 6.5           | 0.0             | 0.0        |
| Cambrian            | Well              | 44.0                     | 56.0        | 0.0           | 0.0             | 0.0        |

382 mg/l (in Lang Son and Bac Kan) (Table 1), except for the coastal area of Quang Ninh (Fig. 1; Table 1 and Supplementary Table), where the water mostly is saline with an average M of 6,200 mg/l. While groundwater in most regions is characterized by the bicarbonate type with a concentration of [HCO<sub>3</sub><sup>-</sup>] varying between 157.7 and 263.6 mg/l (Table 1), the groundwater in Quang Ninh (Fig. 1) is bicarbonate-chloride type. However, groundwater in some particular locations like Quang Hanh (Fig. 1) is chloride type (Table 1 and Supplementary Table). The hardness and pH of all water samples vary from 3 to 6 meq/l and from 6.5 to 8.0, respectively (Supplementary Table). It is clearly suggested that high alkalinity could be attributed to the contribution of bicarbonate, [HCO<sub>3</sub><sup>-</sup>] only while concentration of hydrated carbon dioxide (CO<sub>2,hyd</sub>) was suggested to be negligible compared with the bicarbonate content in water (Postma and Appelo 2005). It is interesting that only groundwater accumulating in the C–P carbonates has total minerals greater than 1,000 mg/l (Table 2) while the water existing in the older formation demonstrates much lower total mineral values (Table 2). In this study, the karstic region was subdivided into six different zones based on their locations, geological characteristics, chemical properties, flow regimes, etc. as follow:

- *Zone 1, Coastal area of Quang Ninh* (Fig. 1): Groundwater in this zone mainly accumulates in the C–P and

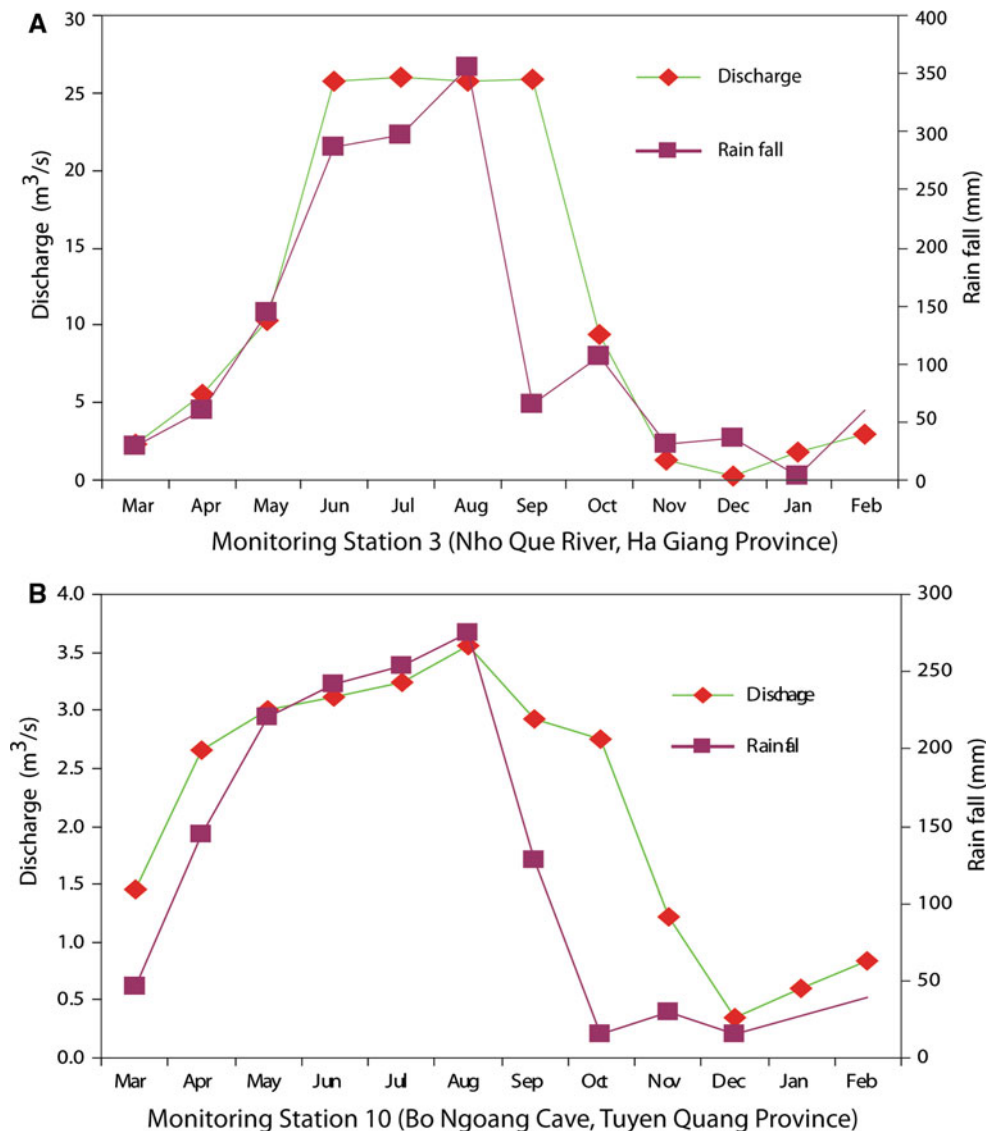
D<sub>2</sub> carbonate rocks. Karstification strongly develops when flow rate of streams is as high as 0.01 up to 10 l/s. However, water from most boreholes is saline. The maximum depth of karstic water in this area can reach up to 120 m.

- *Zone 2, Lang Son* (Fig. 1): Groundwater in this zone is abundant in the C–P carbonate rocks. The flow rate of stream in this zone varies from 0.1 to 100 l/s. The maximum recognizable depth of karstic development in this zone is of ~100 m.
- *Zone 3, Cao Bang-Bac Kan-Thai Nguyen* (Fig. 1): Zone 3 is characterized by karstic development in the C–P, P<sub>2</sub> carbonate rocks. There are some streams demonstrating high flow rates, which can reach hundreds of liters/s such as Dragon Eye Stream in Thai Nguyen or Lenin Stream in Cao Bang. The recognizable depth of karstic development is down to 80 m below surface, but the interval from 40 to 50 m shows the most abundant karstic water.
- *Zone 4, Quan Ba (Ha Giang)* (Fig. 1): This zone mainly consists of the C–P and D<sub>2</sub> limestone formations. Flow rate of streams in this area varies from 0.1 to a few liters/s. In some boreholes, the flow rate becomes very high as of 2–10 l/s. Results of geophysical measurements and exploration drilling conducted in this zone indicate that karstification develops from the surface, where it gives rise to formation of >80 m depth sinkholes.

**Table 3** Discharge of groundwater at different monitoring stations in NE Vietnam

| Station number | Name of station            | Location   | Coordinates               | Discharge (m <sup>3</sup> /s) |                         | Seasonal difference      |
|----------------|----------------------------|--|---------------------------|-------------------------------|-------------------------|--------------------------|
|                |                            |  |                           | Wet season                    | Dry season              |                          |
| 1              | Ban Vang Stream            | Ban Vang hamlet, Huu Vinh commune, Yen Minh district, Ha Giang province          | 20°58.92' N 107°12.15' E  | 4.45                          | 1.9                     | 2.55                     |
| 2              | Dong Van small Tributary   | Quyet Tien hamlet, Dong Van commune, Dong Van district, Ha Giang province        | 23°16.85' N 105°21.45' E  | 1.28                          | 0.51                    | 0.77                     |
| 3              | Nho Que River              | Hamlet Hau Chua, Chu Giang commune, Meo Vac district, Ha Giang province          | 23°13.12' N 105°25.17' E  | 18.37 × 10 <sup>-3</sup>      | 1.75 × 10 <sup>-3</sup> | 16.62 × 10 <sup>-3</sup> |
| 4              | Pac Po Cave                | Ha Quang district, Cao Bang province   | 22°59.04' N 106°02.91' E  | 4.97                          | 2.75                    | 2.22                     |
| 5              | Lenin Stream               | Ha Quang district, Cao Bang province   | 22°58.63' N 106°02.95' E  | 5.87                          | 4.06                    | 1.81                     |
| 6              | Nguom Ngao Stream (site 1) | Khuoi Ky hamlet, Dam Thuy commune, Trung Khanh district, Cao Bang                | 22°51.22' N 106°42.10' E  | 2.5                           | 1.53                    | 0.97                     |
| 7              | Nguom Ngao Stream (site 2) | Khuoi Ky hamlet, Dam Thuy commune, Trung Khanh district, Cao Bang                | 22°51.47' N 106°42.29' E  | 1.33                          | 0.29                    | 1.04                     |
| 8              | Na Pang Stream             | Na Tum village, Ngoc Phai, Cho Don, Bac Kan                                      | 22°10.34' N 105°34.74' E  | 0.64                          | 0.4                     | 0.24                     |
| 9              | Khuoi Duong Stream         | Khuoi Duong hamlet, Ban moi villages, Ha Hieu, Ba Be district, Bac Kan province. | 22°26.50' N 105°50.96' E  | 2.12                          | 0.55                    | 1.57                     |
| 10             | Bo Ngoang Cave             | Ban Cam hamlet, Phuc Son village, Chiem Hoa district, Tuyen Quang province       | 22°19.05' N 105°12.34' E  | 3.04                          | 0.89                    | 2.15                     |
| 11             | Bo Ngoang Stream           | Ban Cam hamlet, Phuc Son village, Chiem Hoa district, Tuyen Quang province       | 22°19.05' N 105°12.34' E  | 3.89                          | 1.57                    | 2.32                     |
| 12             | Po Sang Cave               | Bac Son town, Bac Son district, Lang Son province.                               | 21°54.43' N 106°19.65' E  | 9.52 × 10 <sup>-3</sup>       | 9.52 × 10 <sup>-3</sup> | 0                        |
| 13             | Ky Cung River (site 1)     | Thac Tra Spillway, Lang Son province   | 21°50.80' N 106°44.40' E  | 33.17                         | 13.92                   | 19.25                    |
| 14             | Ky Cung River (site 2)     | Mai Pha Commune, Lang Son City   | 21°49.61' N 106°46.50' E  | 37.66                         | 20.09                   | 17.57                    |
| 15             | Thuong River               | Under a bridge across the Thuong river in 3 km apart from the Dong Mo hamlet     | 21°37.97' N 106°33.25' E  | 4.04                          | 2.95                    | 1.09                     |
| 16             | Mo Nghe Cave               | Na Gheo village, Bac Son district, Lang Son province                             | 21°53.01' N 106°12.85' E  | 2.25                          | 0.86                    | 1.39                     |
| 17             | Mo Ga Cave                 | Phu Thuong commune, Vo Nhai district, Thai Nguyen                                | 106°46.49' N 106°07.18' E | 3.07                          | 0.94                    | 2.13                     |
| 18             | Mo Ga Stream               | Dong Mo hamlet, Phu Thuong Vo Nhai district, Thai Nguyen                         | 21°46.18' N 106°06.62' E  | 3.52                          | 1.57                    | 1.95                     |
| 19             | Troi River                 | At Troi Bridge, Hoanh Bo district, Quang Ninh                                    | 106°01.47' N 106°59.36' E | 92.61                         | 82.95                   | 9.66                     |
| 20             | Cai Dam Stream             | Hamlet 2, La Quang commune, Hoanh Bo district, Quang Ninh                        | 21°05.79' N 106°53.79' E  | 0.49                          | 0.37                    | 0.12                     |

**Fig. 5** Seasonal variation in discharge and rainfall measured at monitoring stations No. 3 and No. 10 (refer to Fig. 1 for their locations)



- *Zone 5, Dong Van-Meo Vac (Ha Giang)* (Fig. 1): The Dong Van-Meo Vac karstic zone is mainly exposed by the C–P and D<sub>2</sub> limestone. The flow rate of most streams is generally low. Development depth of karstification is greater than 150 m. In some particular areas, karst was found at a depth of ~700–800 m, which is close to the local base level of the Nho Que River.
- *Zone 6, Lao Cai-Yen Bai* (Fig. 1): Groundwater in this zone is primarily found in the Cambrian carbonate-rich metamorphic rocks. The flow rate of streams varies from 1 to 2 up to 20 l/s. Maximum depth of karstic development in this zone can be ~120 m below surface.

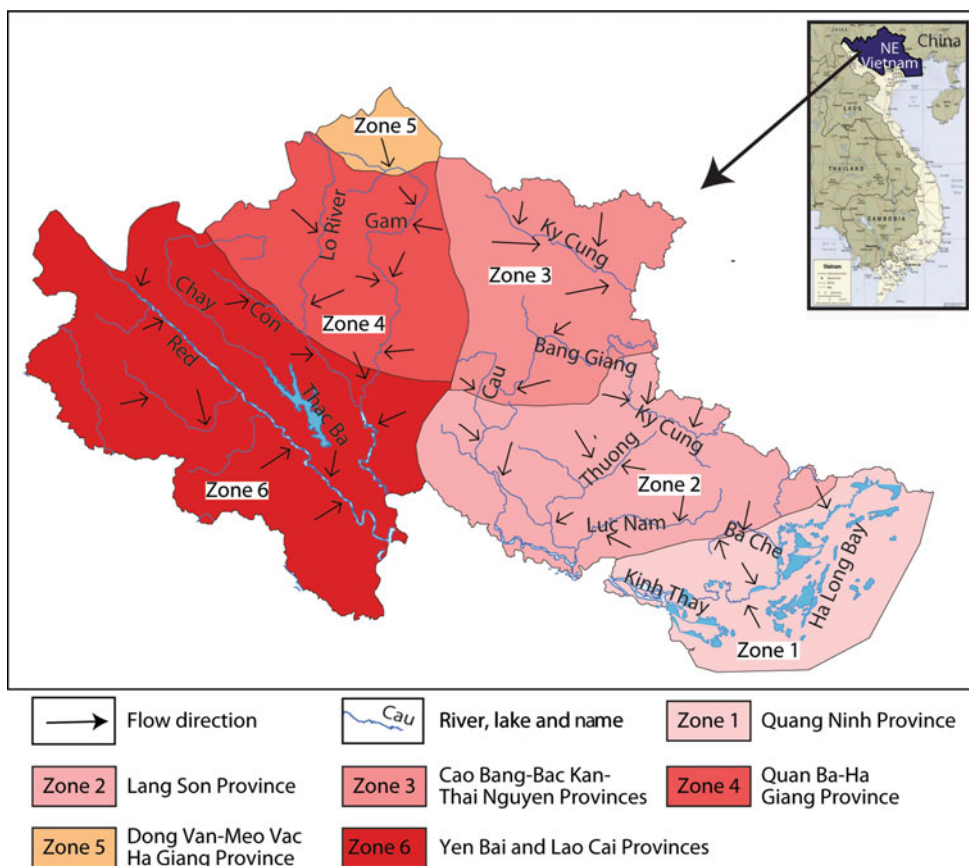
#### Discharge of groundwater in Northeastern Vietnam

Figure 1 shows the location of 20 stations numbered from 1 to 20 (refer to Table 3 for the name of monitoring station)

monitoring the dynamics of groundwater in northeastern region of Vietnam. The monitoring locations were chosen based on the specific hydrogeological structures within the region. The monitoring was conducted consecutively for 3 years from 2007 to 2009. Table 3 represents variation in discharges of groundwater during the dry and rainy seasons in northeastern Vietnam. Results obtained during this monitoring show that dynamics of groundwater in the region is much dependent on the weather conditions (Fig. 5). Many streams dried out during the dry season, but in the rainy season their discharges are as high as up to 100 l/s. Figure 5a and b describes the seasonal variation in discharge of the groundwater observed in Meo Vac Town, Ha Giang Province (Zone 5) (Fig. 1), and in Chiem Hoa District, Tuyen Quang Province (Zone 4) (Fig. 1). Similar variation tendency between the rainfall and discharge in Fig. 5a and b clearly demonstrates that groundwater in the



**Fig. 6** Flow directions of groundwater in different zones in NE Vietnam



region is closely related to the local precipitation. As the result, discharge of streams during the wet season is 1–10 times higher than that in the dry season (Table 3).

Flow patterns of groundwater in northeastern Vietnam

The movement direction of the groundwater was defined by using Rhodamine B tracers, which are widely used in practice. Figure 6 represents a very complicated flow pattern of groundwater in the region. The most important factors affecting the flow direction of groundwater in the region are possibly linked to the local karstic development processes, meteorological conditions (e.g., temperature and rainfall), topographical gradient, and the local level. The movement of groundwater in certain places within the fractured/karstified carbonate rocks is possibly controlled by topographical gradient. Nonetheless, general movement pattern of groundwater shows a tendency of flow toward the river basins. Some general directions of groundwater in northeastern Vietnam are initially described as follows (Fig. 6).

- Quang Ninh Zone (Zone 1): groundwater discharges into the Bach Dang and Da Bac Rivers and Ha long Bay (Fig. 6).
- Lang Son Zone (Zone 2): groundwater from the northern part drains into the Ky Cung River, but in

the southern part the water discharges into the Thung River (Fig. 6).

- Cao Bang zone (Zone 3): groundwater drains into the Bang Giang River (Fig. 6).
- Yen Minh and Quan Ba Zone (Zone 4): groundwater drains into the Mien River (Fig. 6).
- Tuyen Quang-Bac Kan-Thai Nguyen Zone (Zone 4): groundwater primarily discharges into the Lo River (Fig. 6).
- Dong Van-Meo Vac Plateau (Zone 5): groundwater mainly fills into the Nho Que River (Fig. 6).
- Muong Khuong-Bac Ha-Simakai Plateau, Lao Cai Province (Zone 6): groundwater drains into the Chay River (Fig. 6).

Generally, movement pattern of groundwater in northeastern Vietnam is quite different from zone to zone, and it is affected by topography and geological settings of each particular area (Fig. 6).

**Discussions and conclusions**

The results obtained from the investigation allow some issues to be addressed as follows:

The distribution pattern and flow direction of groundwater in northeastern Vietnam are not uniform for the

whole region, and they depend on geological structures, topographical features, meteorological regime, and the local level of each specific zone. Six groundwater zones were identified based on their distribution location, abundance, physio-chemical properties, etc.

The groundwater is the most abundant in the C–P carbonate formation and karstification development within each geological structure of each zone changes with depth significantly. Although the depth of karstification development varies from place to place, it generally demonstrates that the most common depth of karstification is from ~40–50 m to ~120 m deep, except for Zone 5, where karstification can be found at a depth of ~700–800 m below the surface. It is noteworthy to show that the depth of karstification in higher regions is normally deeper than that in the lower region, where the local level and/or the water table is much shallower.

Chemical analysis shows that the quality of the groundwater in the study area generally is good, and the bicarbonate water is dominant over the other types of the groundwater in the region. Groundwater inland is fresh but it becomes more saline in the coastal zone due to the seawater contamination/invasion. Although groundwater found in some place of the C–P formation demonstrates total minerals greater than 1,000 mg/l, there is no clear linkage between total minerals and the age of rocks. The extremely high total mineral values in the groundwater found in some parts of the C–P carbonate formations is attributed to the fact that these formations are situated in coastal areas, which are close to the sea and/or linked to the sea via fracture and/or fault systems.

The identification/classification of six karstic zones and the understanding of their spatial/temporal distribution of groundwater as well as defining their physio-chemical properties are important contributions to the understanding of the groundwater resources in northeastern Vietnam. These new findings are crucial for orienting groundwater

exploration and/or exploitation in the karstic regions. These are also important scientific evidences for making effective plans of water resource management and exploitation for the local societies in the future.

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## References

- Creed JT, Magnuson ML, Pfaff JD, Carol B (1996) Determination of bromate in drinking waters by ion chromatography with inductively coupled plasma mass spectrometric detection. *J Chromatogr* 753(A):261–267
- Do T (1998) Overview on karst of Vietnam. International Conference on Groundwater. Beijing, pp 123–129
- Duong TTT (2001) Hydrogeological characteristics of the groundwater in the Lang Son City: suggestions for proper exploitation and management. *J Geol* 265:46–64 (In Vietnamese)
- Le TT (2003) Some problems in geoenvironment investigation in the karstic region. *J Geol* 272:123–135 (In Vietnamese)
- Nguyen KN (2003) Hydrogeology and groundwater resources in Vietnam. *J Geol* 53:12–21 (In Vietnamese)
- Nguyen XB, Tran ĐL, Huynh T (1994) Explanatory to the Geological map of Vietnam on 1: 500,000 scale. Geological Publishing House, Hanoi, p 31
- Postma D, Appelo CAJ (2005) Geochemistry, groundwater and pollution. Taylor & Francis Group, London, p 655
- Sen Z (1995) Applied hydrogeology for scientists and engineers. CRC-Press, New York, p 464
- Tran QT (1962) Limestone and applications. *J Geol* 15:23–28
- Vu NK, Nguyen KN, Nguyen VL (1985) Groundwater resources of Vietnam. Hanoi University of Mining and Geology, Hanoi, p 210
- Waltham AC, Fookes PG (2003) Engineering classification of karst ground conditions. *Eng Geol Hydrogeol* 36:125–133