Trend analysis of groundwater levels of Holocene unconfined aquifer in the whole Red River Delta, Vietnam

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Abstract

The Red River Delta is one of two biggest deltas in Vietnam. People living in the delta depend heavily on groundwater for their domestic water. However, a fairly wide groundwater monitoring network in the Delta was not set up until 1995, and then we have created and maintained its groundwater monitoring database (GMD). This paper investigated trends and their slopes in 15-year groundwater level series (1995- 2009) in 57 wells for Holocene unconfined aquifer (HUA) available in the delta obtained from the GMD by utilizing the non-parametric Mann-Kendall trend test and Sen's slope estimator. At each well, 17 time series encompassing important groundwater level components (i.e. annual average, rainy and dry season average, annual maximum and minimum, and 12 time series for each month across years) computed from the original data were analyzed for trends. In addition, efforts were made to clarify their spatial patterns. Analyses for annual data revealed that 35% of the wells for HUA showed downward trends, while about 21% showed upward trends. Spatial distributions of different trend slopes were elucidated over the delta using geographic information system (GIS) and Kriging interpolation method. Analyses have highlighted that strong downward trends are mainly in Hanoi with slopes of about 0.3 m/year, whereas upward trends are found in the coastal region, Hungyen province, and northern parts of the delta with slopes of around 0.1 m/year. Although the trend results for the 17 time series at a given well were quite similar, different trend patterns were detected in several time series. The findings about the trends in this paper provide useful references for further groundwater analyses required to ensure sustainable groundwater development in the delta.

Keywords: Monitoring database, Groundwater level trend, Mann-Kendall test, Holocene unconfined aquifer, The Red River Delta, Vietnam

1. Introduction

Groundwater plays a very significant role in the supply of water for human activities. Sustainable management of groundwater resources is one of the essential objectives for the future of a country, especially when the rising demand for clean drinking water is considered (Mende et al. 2007). The amount of groundwater abstraction has been rapidly and continuously increasing worldwide. Obviously, excessive groundwater abstraction causes serious groundwater level decline in many areas over the world. Groundwater level declines have a number of adverse impacts on the environment. Most directly, groundwater level decline is an indicator of groundwater depletion and aquifer degradation, which threatens aquifer sustainable development. Other obvious impacts are land subsidence resulting from the compaction of materials (Konikow and Kendy 2005) and groundwater pollution partly due to the contamination of undesirable materials (Hoque et al. 2007; Berg et al. 2007). Likewise, surface waters are also affected by reduced groundwater discharges (Konikow and Kendy 2005), and then ecosystems might be affected adversely (Zektser et al. 2005).

In the Red River Delta, Vietnam, people depend greatly on groundwater for their domestic water use because of the uneven distribution and unfavorable quality of surface water resources. However, just a few groundwater-related studies for some parts of the delta have been investigated. Most of these targeted the capital of Hanoi, and were concerned about groundwater pollution, land subsidence, and aquifer system identification. Duong et al. (2003), for example, considered the groundwater pollution in water supplies of Hanoi. Groundwater arsenic contamination was identified in some parts of Hanoi (Berg et al. 2007). Trinh and Fredlund (2000) investigated the land subsidence due to excessive groundwater exploitation in Hanoi. Even though an understanding of changes and behaviors of groundwater levels is essential for sound management of groundwater resources (Hoque et al. 2007), there has not yet been any analysis of trends or variability of groundwater levels in the delta.

At present, a fairly wide groundwater monitoring network of 78 observation wells for Holocene unconfined aquifer (HUA) in the Red River Delta has been operated since 1995. This paper presents a spatio-temporal analysis of the trends and variability of HUA groundwater levels for the longest period of 1995-2009 over the delta in order to understand groundwater behaviors of the Delta's aquifer systems which were identified by our earlier study (Bui et al. 2010).

2. Study area and groundwater monitoring network

2.1. Study area

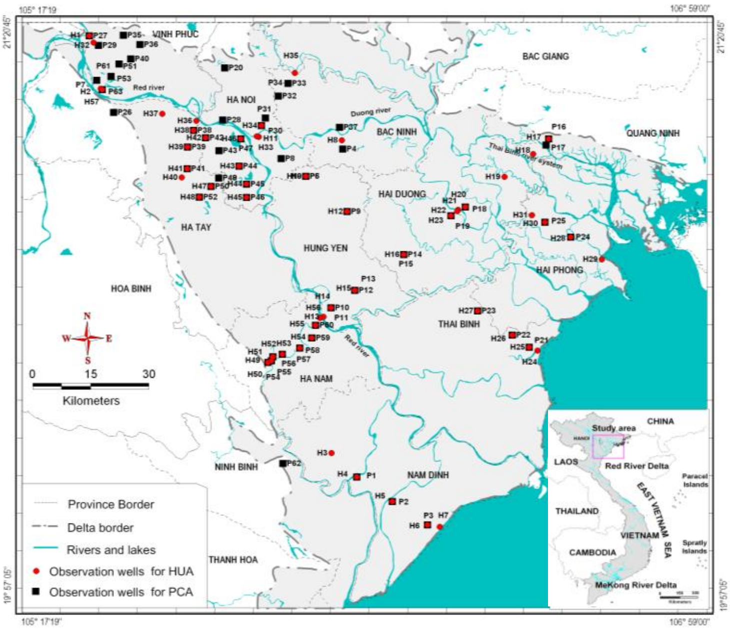

Figure 1 Study area and observation wells

The Red River Delta with a surface area of about 13,000 km^2 in the north of Vietnam is one of two biggest and most developed deltas in Vietnam as shown in Fig. 1. The population is about 19 million in 2007, occupying 22% of the total population. Delta elevation is mainly below 12 m and considered as flood plain. The delta belongs to the tropical monsoonal area with two distinctive seasons: rainy (May to Oct) and dry (Nov till April) seasons. The annual rainfall is about 1,600 mm of which rainfall in the rainy season occupies about 75%. The tide range near the delta is about 4m. The river network is quite dense with the density of about 0.7 km/km^2. However, the water of the Red River is at high level of suspended load throughout the year. Surface water, especially in lakes, over the delta has been seriously polluted due to insufficiency of infrastructure and unwise management of dumping waste. Groundwater thus becomes a main source of water supply in the delta (Tong, 2007).

2.2. Establishment of Groundwater Monitoring Network and Database

The reliability and validity of groundwater analysis strongly depend on the availability of a large volume of high-quality data. In Vietnam, however, detailed information and long term observation data were rare, which is an obstacle for the application of integrated groundwater management on a large basin scale.

Motivated by these necessities, since 1989, the Vietnamese government had been investing much money in setting up groundwater observation wells. However, it was not until 1995 when a fairly wide groundwater monitoring network was set up in the delta and was put into operation. The groundwater data monitored by that network is huge, but not systematically organized. Therefore, a time-consuming and costly project for better management and utilization of the observed data was initiated in 2000, in which we constructed and have maintained a GIS-based groundwater monitoring database (GMD). So far, 160 observation wells have been installed in the delta. Basic groundwater variables such as groundwater level, temperature, and quality are being monitored. Basically, the groundwater levels are recorded at three types of intervals: every day, once per three days, and once per six days. Details about this project and the database were described in the final report of the project (Tong 2003). Up to now, the record lengths are about 15 years (1995-2009) that satisfy the required length in utilizing the Mann–Kendall trend test (Maidment 1993).

3. Data used and methodology

3.1. Data used

In this paper, groundwater level was used, as it is a direct indicator of groundwater systems and contains less measurement uncertainty than other groundwater variables.. To take advantage of the data from our GMD as much as possible, groundwater levels at 57 out of 78 observation wells (Fig. 1) were selected based on the following criteria: (1) there are at least 15 years of recorded data; (2) there is no more than 5% missing data (Endo et al. 2009); and (3) data are observed for HUA, not for other aquifers. As shown in Fig. 1, the selected observation wells are widely distributed over the study area. From the original records as explained earlier, the monthly average groundwater levels were calculated and then used as the basic data set, from which 17 time series (e.g. annual, rainy and dry season average, annual maximum and minimum, and 12 time series for each month across years) were computed for each well. This re-sampling process is a commonly-used way to solve problems of serial correlation inherent in hydrological time series prior to adopting the non-parametric Mann–Kendall test (Burn and Elnur 2002; Serrano et al. 1999). Since there is a time lag of one year between consecutive data for the 17 time series, it is not necessary to include adjustments for seasonality and serial correlation when applying the Mann–Kendall test (Hirsch et al. 1982).

3.2. Methodology

Before conducting the Mann–Kendall test for trends, it is necessary to perform some preliminary analyses to get an initial understanding of the data, such as mean, gaps in record, monotonic trend or jumps, seasonality, independence, distribution, etc.

The non-parametric Mann–Kendall test is highly appropriate for trend detection because it allows minimal assumptions about the data, and is therefore particularly suited to hydrological series, which are often abnormally distributed and serially correlated (Kundzewicz and Robson 2004; Serrano et al. 1999). Furthermore, it is necessary to determine the slope (β) of the detected trends that indicates the direction and magnitude of the trend. The non-parametric robust Sen's slope estimator was adopted herein to estimate β, since it is an unbiased estimator of trend slopes and has considerably higher precision than a regression estimator where data are highly skewed (Hirsch et al. 1982).

After that, spatial patterns of trends and their slopes were determined by GIS and geostatistical techniques.

4. Results and discussion

4.1. General characteristics of groundwater levels

As for preliminary analyses, this paper plotted monthly time series of groundwater levels throughout the 15 years and their box-whisker plots at all 57 observation wells. Next, contour maps for annual groundwater levels of each year were established to get a bird's-eye view of the trends and spatio-temporal variation in groundwater levels.

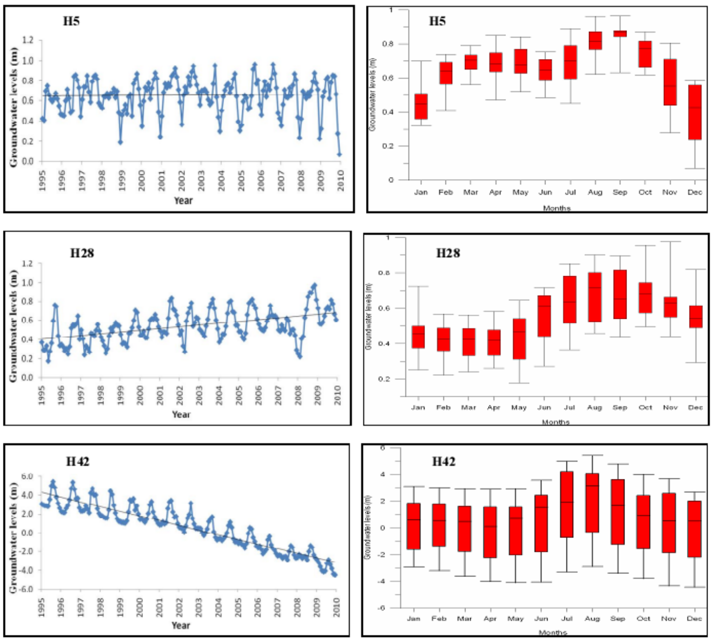

Figure 2 Monthly groundwater levels at three selected wells

Fig. 2 shows selected monthly groundwater levels (1995-2009) in 3 out of 57 HUA wells along with box-plots of their monthly variation. It is apparent from Fig. 2 that the annual cycle of groundwater levels is highly pronounced. Our earlier study indicated that this behavior is closely associated with the annual cycles of rainfall and river water levels (Tong 2007). The three time series graphs reveal three typical long-term trend patterns for HUA groundwater levels. The time series of H5 show an obvious annual cycle with an ambiguous long-term trends that is found widely in the delta. The H28 time series reveal another distinct pattern consisting of a slightly rising trend with an obvious annual cycle that is mainly located in the northern and coastal parts. The H42 time series show a representation of a clear declining trend with an obvious annual cycle of slightly decreasing amplitude which is generally observed in the highly-urbanized areas in the south of Hanoi. Their box-whisker plots in Fig. 2 indicate the observation of seasonal variability. Although there are great differences in monthly water levels among three wells, the highest water levels were measured in around August.

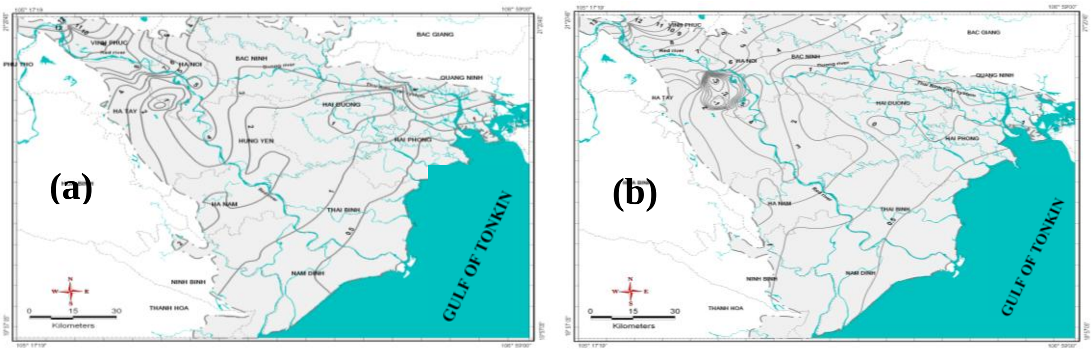

Figure 3 Contour map of annual HUA groundwater levels (a) in 1995 and (b) in 2009

To visualize the spatial pattern of the water levels, countour maps showing the annual water levels of each year were created by utilizing the commonly-used GIS and Kriging interpolation methods. Even though those methods were used, creating sensible contour maps was a difficult task because the information from the wells are very small features on the scale of the heterogeneities of an aquifer. We, therefore, not only utilized the methods but also interpreted and compared their results to observational data to draw realistic contour maps. Fig. 3a and Fig. 3b show the two selected maps for the water levels in 1995 and 2009, respectively. It is clear from the maps that a cone of depression has been formed in Hanoi, while the overall flow pattern still remained from northwest to southeast during the past 15 years. The contour maps of the other years, which are not presented here, show gradual change in the flow pattern year by year.

4.2. Spatio-temporal patterns of recent trends

In this paper, trend results were analyzed using two significance levels (α) of 5% and 1%. Referring to the common classifications used for the standard normal distribution (Jin et al. 2005), trend results were classified into five trend groups based on the values of Mann-Kendall statistic (u): strong downward trend ($u < u_{0.005}$), weak downward trend ($u_{0.005} \leq u < u_{0.025}$), no significant trend ($u_{0.025} \leq u \leq u_{0.975}$), weak upward trend ($u_{0.975} < u \leq u_{0.995}$), and strong upward trend ($u_{0.995} < u$

), where $|u_{0.025}| = u_{0.975} = 1.96$ and $|u_{0.005}| = u_{0.995} = 2.58$. The five trend groups are marked as (▼), (●), (×), (○), and (△), respectively, in the following tables and maps.

4.2.1. Holocene Unconfined Aquifer (HUA)

Table 1 summarizes the trend results for the 17 time series (1995-2009) of 57 HUA wells along with the details for five selected wells. It is apparent from the number of trends for the annual time series in Table 1 that statistically significant trends at 5% were identified in 32 wells (56%), while no significant trends were found in the 25 remaining wells. Among 32 wells of significant trends detected, 20 wells (62%) show downward trends. The number of trends for each trend group among the dry and rainy seasons and annual maximum and minimum time series is quite similar to the annual time series. The trend results of the 12 months (January to December) indicate a bigger variation of trends for every trend group. Detailed results of the five selected wells reveal that each of the five wells exhibits similar trend results regardless of the 17 time series. In the case of well H42, exactly the same results were obtained.

Table 2 shows the trend slopes by Sen's slope in meter per year for the 17 time series of five selected wells. As shown in Table 2, the trend slopes vary in a wide range, from -0.50 to 0.02 m/year by mean values, and they are much more different among wells than among time series. The upward slopes calculated for H28 (about 0.02 m/year) are much less than the downward slopes of H42 (around 0.5 m/year), even though the equal significance level of 1% was applied in both wells. In other words, the trend slopes calculated are not proportional to the significant levels of detected trends. Considering the detailed results of trend slopes of all 57 HUA wells, similar results of spatial heterogeneity among wells were observed.

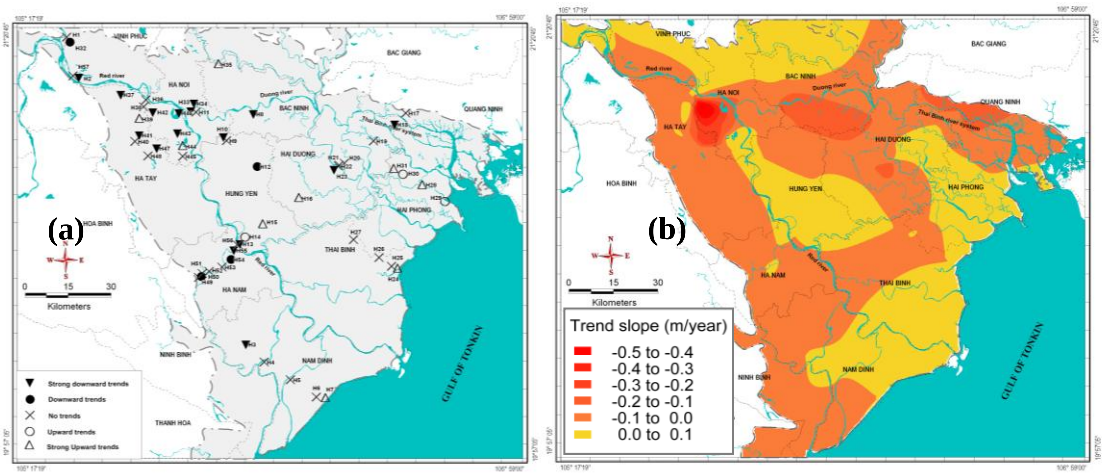

Figure 4 Spatial distribution of (a) trends and (b) trend slopes in annual data

Table 1 Results of Mann-Kendall test for trends
in 57 HUA groundwater levels along with the details for five selected wells

Time series	Number of trends in 57 wells					Trend details of five selected wells				
	▼	●	×	○	△	H42	H50	H5	H29	H28
Annual	16	4	25	3	9	▼	●	×	○	△
Rainy season	15	6	22	5	9	▼	●	×	△	△
Dry season	15	5	24	4	9	▼	●	×	○	△
Maximum	16	6	24	5	6	▼	●	×	○	○
Minimum	14	5	25	5	8	▼	●	●	○	△
January	12	3	32	4	6	▼	●	×	×	○
February	15	3	27	3	9	▼	×	×	×	△
March	13	4	27	4	9	▼	×	×	△	△
April	17	5	26	3	6	▼	●	×	○	△
May	11	6	31	3	6	▼	×	×	○	△
June	11	3	34	3	6	▼	×	×	○	△
July	15	8	26	3	5	▼	●	×	○	△
August	11	12	26	2	6	▼	●	×	○	○
September	12	4	31	2	8	▼	●	×	△	○
October	9	7	29	4	8	▼	×	×	△	○
November	7	6	35	1	8	▼	×	×	△	○
December	10	5	31	5	6	▼	×	×	○	△

Table 2 Results of Sen's estimator for trend slopes
in five typical HUA groundwater levels (m/year) among 57 wells

Time series	H42	H50	H5	H29	H28
Annual	**-0.50**[a]	-0.05	0.00	0.04	**0.02**
Rainy season	**-0.55**	-0.06	0.01	**0.03**	**0.02**
Dry season	**-0.46**	-0.04	0.00	0.05	**0.02**
Maximum	**-0.57**	-0.05	0.01	0.02	0.02
Minimum	**-0.46**	-0.05	-0.02	0.06	**0.02**
January	**-0.43**	-0.04	-0.01	0.04	0.01
February	**-0.42**	-0.04	0.01	0.04	**0.01**
March	**-0.44**	-0.04	0.00	**0.05**	**0.02**
April	**-0.48**	-0.06	-0.01	0.02	**0.02**
May	**-0.47**	-0.05	0.01	0.03	**0.03**
June	**-0.53**	-0.04	0.01	0.03	**0.03**
July	**-0.61**	-0.07	0.01	0.02	**0.03**
August	**-0.61**	-0.09	0.01	0.02	0.02
September	**-0.51**	-0.10	0.01	**0.02**	0.02
October	**-0.50**	-0.06	0.00	**0.04**	0.01
November	**-0.51**	-0.06	-0.01	**0.05**	0.01
December	**-0.48**	-0.05	-0.02	0.05	**0.02**
Mean	-0.50	-0.06	0.00	0.04	0.02
Standard Deviation	0.06	0.02	0.01	0.01	0.01

[a] Bold values indicate the slopes of the trends at 5% significance

To examine the spatial distribution of the detected trends, the maps showing the locations of 57 wells of five trend groups were created for the 17 time series. Among these maps, the one for the annual time series is shown in Fig. 4a. As seen in this figure, there are noticeable spatial groupings of wells of significant trends. The downward trends are widely observed in upper parts of the delta, especially in Hanoi and Hanam, while the upward and insignificant trends are mainly located in the coastal areas. Moreover, the contour maps of the trend slopes for each of 17 time series were also created. Fig. 4b shows a selected map for the annual time series where distinct regional slope patterns are highlighted. Downward slopes are distributed in major portion of the delta, while three zones of upward trends are identified in the coastal region, Hungyen province, and northern parts of the delta. As shown in Fig. 4b, downward slopes are mainly less than 0.2 m/year except for around 60 km^2 in the south of Hanoi where severe downward slopes of more than 0.3 m/year are observed. On the other hand, upward trend slopes are rather small, less than 0.1 m/year. The trend slopes estimated here could be a useful reference to estimate HUA water levels in the future.

5. Conclusion

This paper explored the statistical significance and spatio-temporal patterns of recent (1995-2009) trends in groundwater levels of Holocene unconfined aquifer (HUA) in the Red River Delta, Vietnam by utilizing non-parametric approaches. Using the longest records at of 57 wells available in the region obtained from our database, 17 time series encompassing important groundwater level components (e.g. annual, dry and rainy seasons, etc.) at each well were computed from the original data, and then were examined for their trends and slopes. As for the results from the annual time series, 20 out of the 57 wells for HUA showed downward trends, while 12 wells showed upward trends. Analyses have highlighted that strong downward trends are mainly in Hanoi with slopes of about 0.30 m/year, whereas upward trends are found in the coastal region, Hungyen province, and northern parts of the delta with slopes of around 0.10 m/year.

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References

Berg M, Stengel C, Pham TKT et al (2007) Magnitude of arsenic pollution in the Mekong and Red River Deltas - Cambodia and Vietnam. Science of the Total Environment 372: 413–425

Bui DD, Kawamura A, Tong TN et al (2010) Identification of aquifer system in the whole Red River Delta, Vietnam. Geosciences Journal (Accepted)

Burn DH, Elnur MAH (2002) Detection of hydrologic trends and variability. Journal of Hydrology 255: 107-122

Duong HA, Berg M, Hoang MH et al (2003) Trihalomethane formation by chlorination of ammonium-and bromide-containing groundwater in water supplies of Hanoi, Vietnam. Water Research 37: 3242–3252

Endo N, Matsumoto J, Lwin T (2009) Trends in precipitation extremes over Southeast Asia. SOLA 5: 168-171

Hirsch RM, Slack JR, Smith RA (1982) Techniques of trend analysis for monthly water quality data. Water Resources Research 18: 107–121

Hoque MA, Hoque MM, Ahmed KM (2007) Declining groundwater level and aquifer dewatering in Dhaka metropolitan area, Bangladesh: causes and quantification. Hydrogeology Journal 15: 1523-1534

Jin YH, Kawamura A, Jinno K et al (2005) Detection of ENSO-influence on the monthly precipitation in South Korea. Hydrological Processes 19(20): 4081 – 4092

Kundzewicz ZW, Robson AJ (2004) Change detection in hydrological records- a review of the methodology. Hydrological Sciences–Journal–des Sciences Hydrologiques 49: 7-19

Konikow LF, Kendy E (2005) Groundwater depletion: A global problem. Hydrogeology Journal 13: 317- 320

Maidment DR (1993) Handbook of Hydrology. McGraw-Hill, Inc

Mende A, Astorga A, Neumann D (2007) Strategy for groundwater management in developing countries: A case study in northern Costa Rica. Journal of Hydrology 334: 109-124

Serrano A, Mateos VL, Garcia JA (1999) Trend analysis of monthly precipitation over the Iberian Peninsula for the period 1921-1995. Physics and Chemistry of the Earth (B) 24: 85-90

Tong TN (2003) National groundwater monitoring database program. Project technical report, Department of Geology and Minerals of Vietnam (In Vietnamese)

Tong TN (2007) Groundwater level variation in the Red River Delta. PhD Thesis, University of Geology and Mining, Hanoi, Vietnam (In Vietnamese)

Trinh MT, Fredlund DG (2000) Modeling subsidence in the Hanoi City area, Vietnam. Canadian Geotechnical Journal 37: 621–637

Zektser S, Loáiciga HA, Wolf JT (2005) Environmental impacts of groundwater overdraft: selected case studies in the southwestern United States. Enironmental Geology 47: 396-404