RECENT TRENDS AND VARIATION IN GROUNDWATER LEVELS OF HOLOCENE UNCONFINED AQUIFERS IN HANOI, VIETNAM

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ABSTRACT: Excessive exploitation of groundwater causes groundwater level decline, but statistical significance and spatio-temporal patterns of groundwater level trends in Hanoi, Vietnam still remain poorly understood. A fairly wide groundwater monitoring network was not set up until 1995, and we have created and maintained a groundwater monitoring database (GMD). Using the longest monthly records to date (1995-2009) at a dense network of 21 observation wells available in Hanoi obtained from our GMD, this paper explored trends and their slopes in groundwater levels of Holocene unconfined aquifers (HUA) by utilizing the non-parametric Mann-Kendall trend test and Sen's slope estimator. At each well, 17 other time series encompassing important components (e.g. seasonal mean, annual mean, and so on) were analyzed to provide further insights into the trends. A brief interpretation of possible causes and impacts of the identified trends, and comparisons to other Asian cities were also done. Analyses for monthly data revealed that half the points showed downward trends while, about 10% of the points showed upward trends. The spatial patterns of different trend and their slopes were also identified. The results of trends and trend slopes in the other time series were quite similar to those in monthly time series. While annual cycles in groundwater levels were primarily caused by rainfall and river water levels, downward trends could be explained by increasing groundwater pumping. The findings are indispensable for further groundwater analyses required to ensure sustainable groundwater development.

INTRODUCTION

Sustainable management of groundwater resources is one of the essential objectives for the future of developing countries like Vietnam, especially when the rising demand for clean drinking water is considered (Mende et al., 2007). The Vietnamese capital, Hanoi, is particularly in this regard because: (1) Clean water demand has become rather urgent and water supply mostly depends on groundwater resources; and (2) Undue groundwater exploitation without proper management and adequate understanding of the groundwater behaviors have caused serious groundwater depletion and land subsidence (Bui et al., 2010).

In Vietnam, there have been quite a few groundwater related studies for Hanoi reported in literature. Gupta and Truong (1999) and Duong et al., (2003), for example, considered groundwater quality, pollution and monitoring system design. Groundwater arsenic contamination was identified in some parts of Hanoi (Berg et al., 2001, 2007; Larsen et al., 2008). Nguyen and Helm (1996) and Trinh and Fredlund (2000) investigated on land subsidence due to excessive groundwater exploitation. However, there has not been any analysis on trend and variability of groundwater levels, which is one of the most important parameters of groundwater system and influences the practical groundwater pumping and management strategies. An ability to understand and interpret changes in groundwater levels and groundwater behaviors is essential for sound management of groundwater resources (Ferdowsian and Pannell, 2009; Hoque et al., 2007). In fact, detection of changes in long time series of hydrological data is a difficult issue (Kundzewicz and Robson, 2004). It becomes much more difficult for groundwater because underground data commonly have shorter record length, less spatial coverage, and more uncertainty than climate and surface water data.

Increasing interests in global warming and climate changes have led to numerous trend detection studies over the world. The vast majority of these studies have been carried out in developed countries and focused on trends in climate and surface hydrological variables, such as: temperatures (Kadioglu, 1997; Boyles and Raman, 2003; Sharma et al., 2000); precipitation (Sharma et al., 2000; Boyles and Raman, 2003; Delgado et al., 2010); humidity (Abu-Taleb et al., 2007; Paltridge et al., 2007); surface water variables (Yue et al., 2003; Svensson et al., 2005; Aziz and Burn, 2006; Hamed, 2008; Delgado et al., 2010); snowmelt runoff (Burn, 1994a; Mccabe and Clark, 2005);

water quality (Antonopoulos et al., 2001; Johnsona et al., 2009; Esterby, 1998); and many others.

In contrast, there have been few trend studies for groundwater due to unavailability of long time series. Recently more researches have begun paying attention to trends and variability in groundwater levels. Almedeij and Al-Ruwaih (2006), for example, investigated periodic behavior of groundwater level fluctuations in residential areas of Kuwait. In Bangladesh, Hoque et al. (2007) clarified causes and quantification of declining trends, and then Akther et al. (2009) analyzed spatio-temporal pattern of groundwater levels in Dhaka, while Shamsudduha et al. (2009) identified recent trends in groundwater levels in the Ganges-Brahmaputra-Meghna Delta. Another case tried to explain long-term trends in groundwater level graphs in Esperance, Australia (Ferdowsian and Pannell, 2009). In these studies, several methods such as graphical description, linear regression, and seasonal-trend decomposition have been preliminarily tested. The methodologies for conducting trend analysis studies in hydrological records have been comprehensively reviewed by Esterby (1998) and further reviewed by Kundzewicz and Robson (2004). These numerous trend studies and many others have continually highlighted the non-parametric Mann–Kendall test as an excellent tool for detecting trends in hydrology and environment. The test has been effectively and widely utilized for detecting trends for many regions by many researchers over the world, but it, as far as the authors know, has not yet been tested for any environmental and hydrological time series in Vietnam.

Motivated by the aforementioned necessities, since 2000, we have constructed and maintained a costly groundwater monitoring database (GMD) to gather all the observed groundwater data. To take advantages of our internally-available data sets as much as possible, and to understand groundwater behaviors of the Hanoi aquifer systems which were identified by our earlier study (Bui et al., 2010), the main objective of this paper is to identify the trends and variability in groundwater levels over Hanoi quantitatively for Holocene unconfined aquifer (HUA). To achieve the expected goals, this work first has focused on acquiring the longest original observed groundwater levels (1995-2009) from the densest network of observation wells available in the region, and then computed 18 time series of useful features of groundwater levels (e.g. monthly and annual data, dry and rainy seasonal data; annual maximum and minimum data; and the data for each of twelve months of a year). After that, we established series of graphs of groundwater levels at every observation well so as to get the initial impression of seasonality and trends in the groundwater levels. Next, the non-parametric Mann–Kendall test was adopted to statistically detect trends for the aquifers based on two statistical significant levels. Furthermore, Sen's slope estimator was utilized to calculate the slopes of trends detected. In addition, efforts have been made to clarify the spatial distribution of trends and their slopes by using geo-statistical and GIS methods.

DATA USED AND METHODOLOGY

Data used

Data are essential of any attempt to detect trend or other change in hydrological records, and so it is important to properly prepare and understand the data to be used. To that end, data should be quality-controlled before commencing an analysis of change (Kundzewicz and Robson, 2004). Currently, with the best record lengths of around 15 years (1995-2009), the time series satisfies the required length in utilizing Mann-Kendall test for identifying trends in hydrological data (Maidment, 1993). In trend detection, an important step is to choose the stations to be investigated. The primary factors of station selection were the record length and the quality of data. Therefore, to take advantages of the data from our GMD as much as possible, groundwater levels at 21 out of 60 observation wells in Hanoi and its neighboring regions (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; Ampitiyawatta and Guo, 2009); and (3) data are observed for HUA. The 15-year-long records from selected wells were analyzed in order to be consistent in data with majority of observation wells. As shown in Fig. 1, the selected observation points are well distributed over the study area. The advantage of this data selection is that it is less influenced by data quality problems, and provides a good spatial coverage and a reasonable record length.

Another important step in trend detection is the choice of which variables to be studied. In this paper, groundwater level was used, as it is a direct indicator of the aquifer and contains less measurement uncertainty than other groundwater variables. From original records as explained earlier, monthly average groundwater levels were calculated and then used as the basic data set, from which other 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 individual wells. This re-sampling process is a commonly-used way to solve problems of serial correlation inherent in hydrological time series prior to adopting non-parametric Mann–Kendall test (Boyles and Raman, 2003; Burn and Elnur, 2002; Serrano et al., 1999)

Since there is a time lag of one year between consecutive data for 17 time series, it is not necessary to include adjustments for seasonality and serial correlation when applying Mann–Kendall test (Hirsch and Slack, 1982; Helsel and Hirsch, 2002). Additionally, the data of monthly rainfall at Lang station and monthly Red River water levels at QHSH1 station as shown in Fig. 1 were also examined for their linkages with groundwater levels.

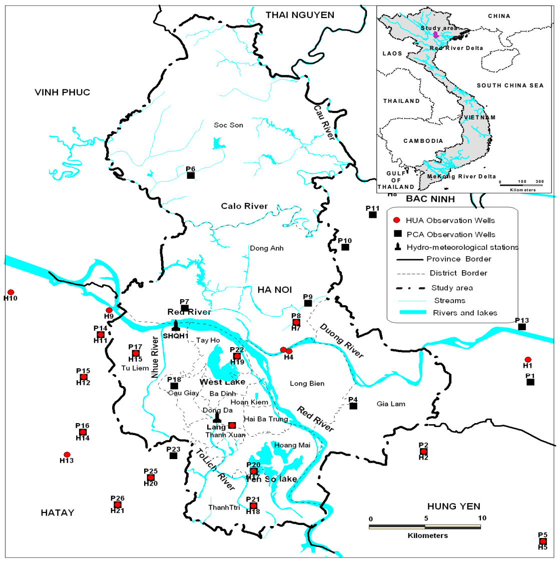

Figure 1 Study area and groundwater monitoring network

Methodology

Before conducting a formal test for trends, it is necessary to perform preliminary analyses to get an initial visual understanding of the data, such as data problems (mean, gaps in record, etc.), basic temporal and spatial patterns (monotonic trend or jumps, seasonality), test assumptions (independence, distribution), and so on. The conclusions of this step are fundamental to choosing suitable methods for formal trend detection.

The non-parametric Mann–Kendall test is highly appropriate 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) while being as good as their parametric competitors (Serrano et al., 1999). The test was originally developed by Mann (1945) and after further developed by Kendall (1948). The Mann–Kendall test is given by (1):

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \operatorname{sgn}(x_j - x_i)$$

$$\operatorname{sgn}(\theta) = \begin{cases} 1, \theta > 0 \\ 0, \theta = 0 \\ -1, \theta < 0 \end{cases} \qquad (1)$$

Kendall (1955) showed that the distribution of S approaches the normal distribution as the number of observations becomes large. The significance of a trend can thus be tested by using the standardized variable u as given in (2):

$$u = \frac{(S+m)}{\sqrt{V(S)}} \qquad m = \begin{cases} -1, S > 0 \\ 0, S = 0 \\ 1, S < 0 \end{cases} \qquad (2)$$

$$V(S) = \frac{1}{18}\left\{ N(N-1)(2N+5) - \sum_{i=1}^{n} e_i(e_i-1)(2e_i+5) \right\} \qquad (3)$$

Where x_i and x_j are the sequential data values, N is the record length, n is the number of tied groups, e_i is the number of data in the ith (tied) group (i = 1 ~ n) (Maidment, 1993). The important parameter of the test is the significance level α that indicates the trend's strength. In a two-sided test for trend, the null hypothesis is rejected at the α significance level if $|u| > u_{(1-\alpha/2)}$, where $u_{(1-\alpha/2)}$ is the 1-α/2 quantile of the standard normal distribution.

Furthermore, it is necessary to determine the slope (β) of the detected trends that indicates the direction and the 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 the trend slopes and has considerably higher precision than a regression estimator where data are highly skewed (Hirsch et al, 1982). The Sen's slope estimator is given by (4):

$$\beta = Median\left[(x_j - x_i)/(j-i)\right] \text{ for all } i<j \qquad (4)$$

After that, spatial patterns of trends and their slopes were determined by GIS and geostatistical techniques and then the results were interpreted considering other related knowledge.

RESULTS AND DISCUSSION

General characteristics of groundwater levels

Preliminary analysis, an initial visual examination of the data, is an essential component of any statistical analysis (Kundzewicz and Robson, 2004). In this paper, we therefore plotted the 18 time series of groundwater levels at all observation wells, and roughly calculated trend slope in groundwater levels by the ordinary least square method, and then established contour maps for seasonal and annual groundwater levels of each year, as to get a bird's-eye view of the trends and spatio-temporal variation in groundwater levels.

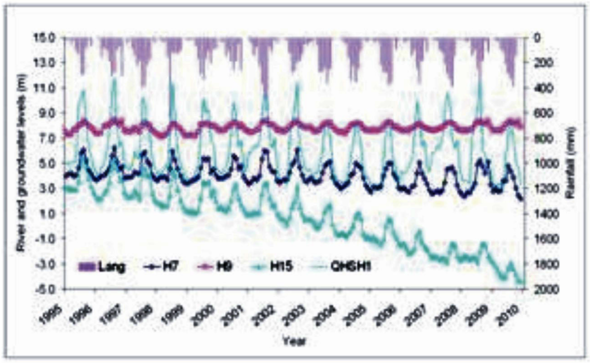

Figure 2 Monthly groundwater levels at three selected wells along with monthly rainfall and monthly Red River water levels

Fig. 2 shows selected monthly groundwater levels (1995-2009) at 3 out of 21 observation wells (H15, H7, and H9) for HUA, along with monthly rainfall and monthly Red River water levels. It is apparent from Fig. 2 that annual cycle in groundwater levels is highly associated with the annual cycles of rainfall and river water level because of almost no seasonal change in groundwater pumping rate within a year. Three groundwater level plots in Fig. 2 reveal three typical long-term trend patterns. Time series of H15 show a representative of clear declining trend with obvious annual cycle of slightly decreasing amplitude which is generally observed in the south of the Red River. H7 time series show an obvious annual cycle of steady amplitude without any clear long-term trend that is commonly found at the wells located near the rivers. H9 time series reveal another distinct pattern consisting of a slightly rising trend with obvious annual cycle of smaller amplitude that is commonly located in local areas of irrigation fields.

Table 1 shows the basic statistics of HUA groundwater levels including the annual means in 1995 and 2009, slope of anual means for 1995-2009 (m/year), average amplitude of annual cycle, and average differences between rainy and dry seasonal means at 21 wells with their mean value and standard deviation. On the average, Table 1 revealed that HUA groundwater levels have decreased from 4.10 to 3.10 m with a slope of -0.07 m/year. An average amplitude of annual cycles are 1.90 m. HUA groundwater levels in the rainy season are 0.94 m higher than in dry season. To visualize the spatial pattern of the HUA groundwater levels, countour maps showing annual mean of each year were created by utilizing the commonly-used GIS and Kriging interpolation methods. Fig. 3a and Fig. 3b show the two selected maps for 1995 and 2009, respectively. It is clear from these maps that the groundwater flow pattern has remarkably changed over the the south of Hanoi during the past 15 years. The groundwater generally flowed from the north to the south in 1995 but mostly from the east to the west in 2009. These figures also demonstrate the appearance of a cone of depression in the southeast during the study period. The contour maps of the other years, which were not presented here, showed gradual change in the groundwater flow pattern year by year.

Wells	Annual mean of groundwater levels (m) In 1995	In 2009	Slope by least square method (m/year)	Average amplitude of annual fluctuations (m)	Average differences between rainy and dry season (m)
H1	2.78	0.65	-0.15	0.75	0.72
H2	2.93	2.83	-0.01	1.52	0.33
H3	3.42	3.03	-0.03	5.00	0.84
H4	5.76	5.41	-0.03	0.80	2.94
H5	1.75	1.58	-0.01	4.76	0.21
H6	5.28	4.14	-0.08	2.33	2.69
H7	4.54	3.26	-0.09	2.53	1.24
H8	3.40	4.72	0.09	0.84	1.24
H9	7.79	7.95	0.01	2.72	0.47
H10	8.68	7.28	-0.10	1.23	1.38
H11	5.48	5.34	-0.01	0.45	0.56
H12	5.50	6.16	0.05	1.41	0.18
H13	3.00	2.95	0.00	1.32	0.71
H14	3.74	2.45	-0.09	2.36	0.59
H15	3.59	-3.66	-0.52	0.58	1.13
H16	2.06	-0.45	-0.18	0.73	0.09
H17	4.29	5.73	0.10	1.07	0.08
H18	4.23	4.23	0.00	5.15	0.46
H19	4.50	1.85	-0.19	0.39	2.87
H20	0.77	-2.77	-0.25	1.99	0.03
H21	2.57	2.44	-0.01	1.88	0.92
Mean	4.10	3.10	-0.07	1.90	0.94
Std. Dev.	1.89	2.97	0.14	1.46	0.89

Table 1 Basic statistics of groundwater levels (1995-2009)

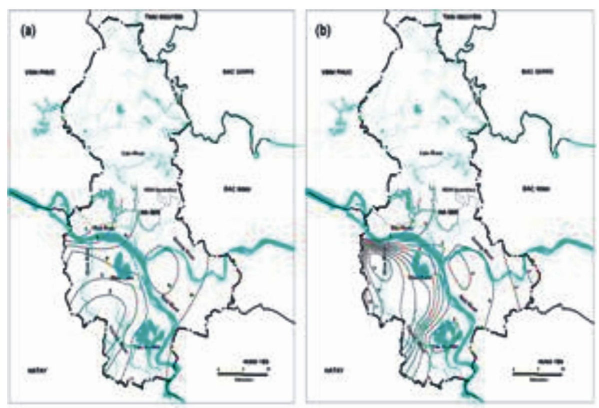

Figure 3 Contour map of annual HUA groundwater level mean in 1995 (a) and in 2009 (b)

Spatio-temporal patterns of recent trends

As aforementioned, the trends in groundwater levels in Hanoi generally are monotonic (no jumps), so non-parametric Mann-Kendall test is a suitable method for a formal trend detection (Kundzewicz and Robson, 2004). A small program for calculating the Mann-Kendall test procedures was coded using the programming language FORTRAN. 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., 2005a; 2005b), trend results were classified into five trend groups based on the u values by Eq. (2): strong downward trend ($u < u_{0.005}$), weak downward trend ($u_{0.005} \leq u < u_{0.025}$), no significant trend ($u_{0.025} \le u \le u_{0.975}$), weak upward trend ($u_{0.975} < u \le u_{0.995}$), 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 were marked as (&), (#), **(3), ()),** and (+), respectively in the following tables and maps.

Table 2 summarizes the trend results from the Mann-Kendall test for 18 time series of HUA groundwater levels at 21 observation wells for the period of 1995-2009. The number of wells of five trend groups was also presented. It is apparent from the number of trends for monthly time series in Table 2 that statistically significant trends (both upward and downward) at 5% were identified in the major portion of the wells (16 out of 21 wells), while no significant trends were found at the five remaining wells. The strong downward and upward trends have been found in 9 and 3 wells, respectively. Although annual, seasonal (rainy and dry), and annual minimum time series show quite similar trend results to monthly data, annual maximum are observed less number of significant trends than others. Furthermore, comparison among the results for the different months (January to December) indicated that the highest number of significant trends was found in February (17 out of 21 wells), while the lowest ones was observed in November (11 out of 21 wells). Well H6 shows downward trends in all time series except for November which shows no significant trend. Most of the 21 wells showed quite similar trend results regardless of the time series to be studied, especially 8 wells were observed exactly the same results. Furthermore, to examine the spatial distribution of the observed trends, 18 maps for each time series were created to display the well locations of five trend groups. Among these maps, the trend results for monthly time series was selected and shown in Fig. 4 since they have the best sample size among others. As shown in Fig. 4, there are noticeable spatial groupings of wells with strong downward trends. The downward trends are widely observed over Hanoi while upward and insignificant trends are sparsely located near rivers or lakes.

Table 3 shows the trend slopes in meter per year of 21 wells for the 18 time series that were identified by Eq. (4) at 5% significant level. The average slopes of the upward and downward wells are also presented at the bottom of the table. The time series, which show no significant trend in Table 3, are also marked as **(3)** in Table 3. Positive and negative values indicate increasing and decreasing trends, respectively. As shown in Table 3, the mean downward slope in monthly time series is about -0.15 m/year. Although, trend slope results from all 18 time series are quite similar with continuous downward tendency, February exhibits the lowest slope (-0.14 m/year) that could be explained by irrigation schedule that rice fields are commonly irrigated around February. It is noted in more details that trend slopes are also different from well to well depending on its locations that provides great motivation to investigate the spatial pattern of the trend slopes. For this reason, 18 contour maps of trend slopes for each time series were created by utilizing GIS and Kriging interpolation methods as mentioned earlier. Fig. 5 shows a selected map presenting the trend slope of monthly data where distinct regional patterns are highlighted. From this figure, decreasing trends dominated over the area except for an area near the Yenso Lake. HUA groundwater levels show slight downward in the north of the Red River, while the more southerly regions show more serious downward trend slopes, particularly in the areas near the Nhue River.

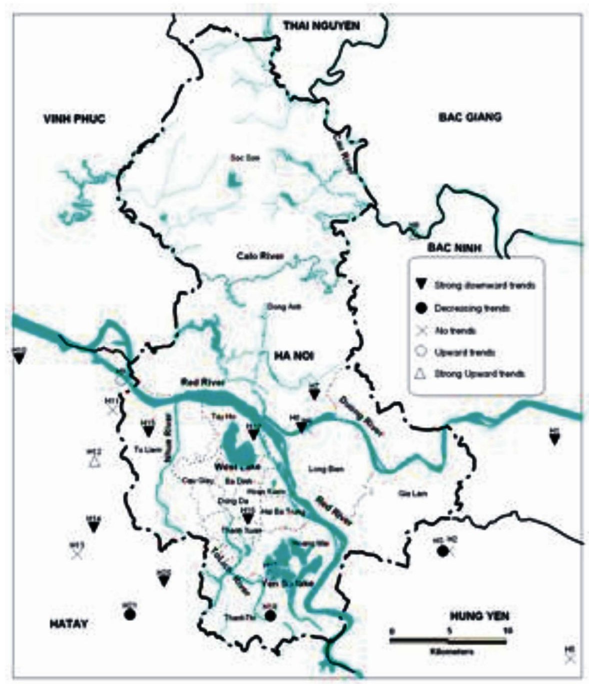

Figure 4 Spatial distribution of trend results for monthly groundwater level of HUA

Fig. 5 also indicates an area of around 55 km^2 with the downward trend slopes of less than -0.3 m/year. Increasing trends observed around the Yenso Lake have rather small slope of around 0.1 m/year. These behaviors mainly result from the fact that recently many private and household wells in this area have been stopped by the local government, and the groundwater levels have been gradually recovered to their previous stages. The trend slopes estimated herein could be useful reference to estimate HUA water levels in the future.

This paper revealed several interesting features of groundwater level regime in Hanoi. From the analysis, it is concluded that long-term downward trends in groundwater levels were primarily governed by increasing groundwater abstraction. Referring to the information about locations of current well-fields quoted in survey's report (Tong, 2007). Locations of the well-fields are well matched with the areas of serious declining trends.

Both upward and downward trends in groundwater levels likely have a number of adverse impacts on the environment. Most directly, groundwater level decline is no doubt an indicator of groundwater depletion and aquifer degradation, which threat aquifer sustainable development (Akther et al., 2009). Other obvious impacts are land subsidence resulting from compaction of materials (Koninow and Kendy, 2005), and groundwater contamination partly due to intrusion of undesirable materials (Hoque et al, 2007; Berg et al., 2008). Likewise, surface waters are also affected by falling groundwater levels through reducing groundwater discharges to springs, streams, lake, and wetlands (Konikow and Kendy, 2005), and then ecosystems might be affected adversely (Zektser et al, 2005). On the other hand, considerable groundwater level rise might lead to flooding and deterioration of construction materials (Almedeij and Al-Ruwaih, 2006).

It should be noted that trend detection in groundwater variables is of concerns just recently. The approach in this study provides meaningful procedures for other similar researches. The findings herein certainly provide valuable information about groundwater dynamics and long-term responses to climate and urbanization in other Asian areas where topographical and hydrogeological conditions are similar.

Annual cycles in groundwater and its strong linkages to rainfall and surface water in Hanoi are similar to other Asian areas (Almedeij and Al-Ruwaih, 2006, Shamsudduha et al., 2009). Increasing groundwater abstractions have also been widely documented for other Asian urban areas such as Dhaka, Bangkok, (Phien-wej et al., 2006; Shamsudduha et al., 2009). Sustainable groundwater development strategies in these cities certainly need to consider the trends in groundwater levels and their environmental impacts.

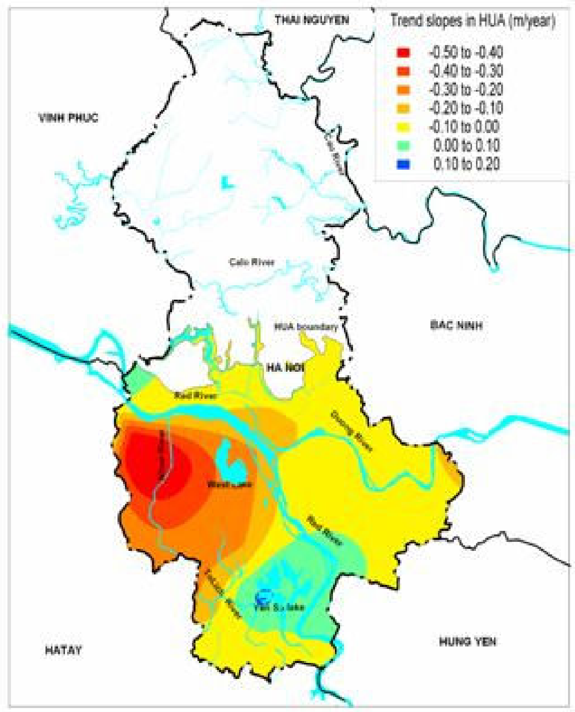

Figure 5 Spatial distribution of mean trend slope in HUA groundwater levels.

Table 2 Results of Mann-Kendall test for trends in HUA groundwater levels

Wells	Monthly	Annual	Rainy	Dry	Max	Min	Jan	Feb	Mar	Arp	May	Jun	July	Aug	Sep	Oct	Nov	Dec
H1	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H2	×	×	×	●	×	●	×	▼	●	▼	●	×	×	×	○	×	×	×
H3	●	▼	▼	×	▼	×	×	×	×	×	×	×	▼	▼	▼	●	×	×
H4	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
H5	×	●	×	×	×	×	×	●	×	×	×	×	×	×	×	×	×	×
H6	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	●	▼	▼	●	●	●	×	▼
H7	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	×	●	●	▼
H8	Δ	Δ	○	Δ	×	Δ	Δ	Δ	Δ	Δ	Δ	○	×	×	○	Δ	Δ	Δ
H9	○	×	×	○	×	Δ	×	Δ	○	×	×	×	×	×	×	×	×	×
H10	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	●	●	●
H11	×	×	×	×	×	●	×	●	●	●	×	×	×	×	×	×	×	●
H12	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ
H13	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
H14	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	●	▼
H15	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H16	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H17	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ
H18	●	×	×	×	×	×	×	×	×	×	●	×	×	●	×	×	×	×
H19	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	●	▼	▼	▼	▼
H20	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H21	●	×	●	×	×	▼	●	▼	●	▼	×	●	●	×	×	×	×	×
Number of ▼	9	10	10	9	10	10	9	11	9	11	8	9	10	8	8	6	5	8
Number of ●	3	1	1	1	0	2	1	2	3	1	3	1	1	3	1	4	3	2
Number of ×	5	7	7	7	9	5	8	4	5	6	7	8	8	8	8	8	10	8
Number of ○	1	0	1	1	0	0	0	0	1	0	0	1	0	0	2	0	0	0
Number of Δ	3	3	2	3	2	4	3	4	3	3	3	2	2	2	2	3	3	3

Table 3 Results of Sen's estimator for trend slopes in HUA groundwater levels (m/year)

Wells	Monthly	Annual	Rainy	Dry	Max	Min	Jan	Feb	Mar	Arp	May	Jun	July	Aug	Sep	Oct	Nov	Dec
H1	-0.16	-0.16	-0.13	-0.19	-0.10	-0.20	-0.19	-0.18	-0.20	-0.22	-0.17	-0.12	-0.11	-0.11	-0.12	-0.16	-0.19	-0.20
H2	×	×	×	-0.02	×	-0.01	×	-0.02	-0.03	-0.03	-0.01	×	×	×	×	×	×	×
H3	-0.02	-0.03	-0.05	×	-0.05	×	×	×	×	×	×	×	-0.08	-0.05	-0.07	-0.05	-0.03	-0.02
H4	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
H5	×	-0.01	×	×	×	×	×	-0.01	×	×	×	×	×	×	×	×	×	×
H6	-0.10	-0.11	-0.14	-0.09	-0.18	-0.09	-0.11	-0.06	-0.09	-0.12	-0.12	-0.19	-0.17	-0.15	-0.12	-0.12	×	-0.11
H7	-0.09	-0.09	-0.08	-0.10	-0.10	-0.12	-0.10	-0.10	-0.11	-0.12	-0.08	-0.09	-0.11	-0.10	×	-0.07	-0.09	-0.09
H8	0.14	0.11	0.06	0.16	×	0.19	0.16	0.17	0.17	0.18	0.19	0.13	×	×	0.06	0.09	0.13	0.13
H9	0.01	×	×	0.01	×	0.02	1	0.02	0.02	×	×	×	×	×	×	×	×	×
H10	-0.11	-0.11	-0.12	-0.11	-0.11	-0.12	-0.09	-0.11	-0.11	-0.14	-0.13	-0.12	-0.16	-0.13	-0.09	-0.07	-0.10	-0.10
H11	×	×	×	×	×	-0.04	×	-0.04	-0.03	-0.03	×	×	×	×	×	×	×	-0.05
H12	0.05	0.05	0.05	0.06	0.04	0.07	0.06	0.07	0.07	0.05	0.06	0.04	0.04	0.05	0.05	0.05	0.05	0.05
H13	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
H14	-0.10	-0.11	-0.12	-0.09	-0.10	-0.09	-0.09	-0.08	-0.09	-0.11	-0.12	-0.13	-0.14	-0.13	-0.13	-0.11	-0.08	-0.07
H15	-0.50	-0.50	-0.55	-0.46	-0.57	-0.46	-0.43	-0.42	-0.44	-0.48	-0.47	-0.53	-0.61	-0.61	-0.51	-0.50	-0.51	-0.48
H16	-0.20	-0.21	-0.22	-0.20	-0.24	-0.20	-0.21	-0.21	-0.19	-0.20	-0.20	-0.20	-0.21	-0.24	-0.23	-0.22	-0.21	-0.20
H17	0.10	0.11	0.12	0.10	0.08	0.16	0.09	0.11	0.13	0.11	0.12	0.13	0.12	0.11	0.10	0.09	0.09	0.08
H18	-0.01	×	×	×	×	×	×	×	×	×	-0.02	×	×	-0.03	×	×	×	×
H19	-0.21	-0.22	-0.21	-0.23	-0.20	-0.24	-0.20	-0.22	-0.23	-0.25	-0.19	-0.20	-0.26	-0.21	-0.19	-0.15	-0.20	-0.21
H20	-0.23	-0.24	-0.23	-0.24	-0.22	-0.23	-0.21	-0.22	-0.22	-0.24	-0.25	-0.24	-0.23	-0.23	-0.22	-0.24	-0.24	-0.23
H21	-0.02	×	-0.03	×	×	-0.03	-0.02	-0.03	-0.01	-0.05	×	-0.04	-0.06	×	×	×	×	×
Downward mean	-0.15	-0.18	-0.17	-0.17	-0.19	-0.15	-0.17	-0.14	-0.15	-0.17	-0.16	-0.19	-0.19	-0.18	-0.19	-0.17	-0.18	-0.16
Upward mean	0.08	0.07	0.08	0.08	0.06	0.11	0.08	0.09	0.10	0.15	0.12	0.10	0.08	0.08	0.07	0.08	0.09	0.09

CONCLUSION

Taking advantages of our groundwater monitoring database, this paper explored statistical significances and spatio-temporal patterns of recent (1995-2009) trends in groundwater levels in Hanoi, Vietnam by utilizing the robust non-parametric Mann-Kendall trend test and Sen's slope estimator. Using the longest records at the densest monitoring network of 21 wells for Holocene unconfined aquifer (HUA) available in the region obtained from our database, at each well 18 time series encompassing important groundwater level components (e.g. monthly, seasonal, annual means and so on) were computed from the original data, and then were examined for their trends and slopes. This paper also briefly investigated possible causes of the indentified trends and variation, and their linkages with groundwater abtraction, rainfall, and river water levels. As for the results, half the wells of HUA showed downward trends, while about 10% showed upward trends. Analyses have highlighted that downward trends are observed mainly in southwestern areas with slopes of about -0.5 m/year, whereas upward trends are found in the southeast (around the Yenso Lake) with smaller slope of around 0.1 m/year. This study also indicated that annual cycles in HUA groundwater levels are primarily governed by rainfall and river water levels, while their long-term trends were strongly influenced by groundwater abstraction. These findings provide useful references for further groundwater analyses required to ensure sustainable groundwater development.

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