Trend Detection in Groundwater Levels of Holocene Unconfined Aquifer in Hanoi, Vietnam by Non-Parametric Approaches

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ABSTRACT

Using the longest records (1995-2009) at a dense network of 21 observation wells available for Holocene unconfined aquifer (HUA) in Hanoi, this paper explored trends and their slopes in groundwater levels by utilizing the non-parametric Mann-Kendall trend test and Sen's slope estimator. At each well, 18 time series encompassing important groundwater level components (e.g. monthly, seasonal, annual means and so on) were analyzed to provide insights into the trends. This study highlighted that nonparametric approach is particularly suited to hydrological series in general and to groundwater level series in particular. Analyses for monthly data revealed that 12 out of 21 wells showed downward trends, while 4 wells showed upward trends. The spatial patterns of different trend slopes were also identified over HUA area. Although the trend results for other time series at a given well were quite similar, different trend patterns were detected in several time series. The findings provide useful references to sustainable groundwater development in Hanoi.

INTRODUCTION

Achieving the 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 needs this because: (1) The demand for clean water has become rather urgent and the water supply mostly depends on groundwater resources; and (2) Undue groundwater exploitation without proper management and an 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. Duong et al., (2003), for example, considered the groundwater quality, pollution and monitoring system design. Groundwater arsenic contamination was identified in some parts of Hanoi (Berg et al., 2001, 2007). Nguyen and Helm (1996) and Trinh and Fredlund (2000) investigated the land subsidence due to excessive groundwater exploitation. However, there has not been any analysis on the trend and variability of groundwater levels, which is one of the most important parameters of the groundwater system and influences the practical groundwater pumping and management strategies.

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 (Boyles and Raman, 2003; Sharma et al., 2000); precipitation (Boyles and Raman, 2003; Delgado et al., 2010); humidity (Abu-Taleb et al., 2007; Paltridge et al., 2007); surface water variables (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); and many others. In contrast, there have been few trend studies on groundwater due to the 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 the periodic behavior of groundwater level fluctuations in residential areas of Kuwait. In Bangladesh, Hoque et al. (2007) clarified causes and the quantification of declining trends, and then Akther et al. (2009) analyzed the 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 the graphical description, linear regression, and seasonal-trend decomposition have been preliminarily tested. The methodologies for trend detection in hydrology and the environment have been comprehensively reviewed (Esterby, 1998; Kundzewicz and Robson, 2004) and the non-parametric Mann–Kendall (MK) test has been highlighted as an excellent tool. Even though, the test has been effectively and widely utilized for detecting trends for many regions by many researchers over the world, 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 of the observed groundwater data (Tong, 2003). To take advantage of our internally-available data sets, the main objective of this paper is to identify the trends and variability in groundwater levels over Hanoi quantitatively for Holocene unconfined aquifer (HUA) which was identified by our earlier study (Bui et al., 2010). To achieve the expected goals, this work first has focused on acquiring the longest original records (1995-2009) from the densest network of observation wells available in the region, and then computed 18 time series concerning the 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). Next, the MK test was adopted to statistically detect trends based on two statistical significant levels and then Sen's slope estimator was utilized to calculate the slopes of trends detected. Furthermore, 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

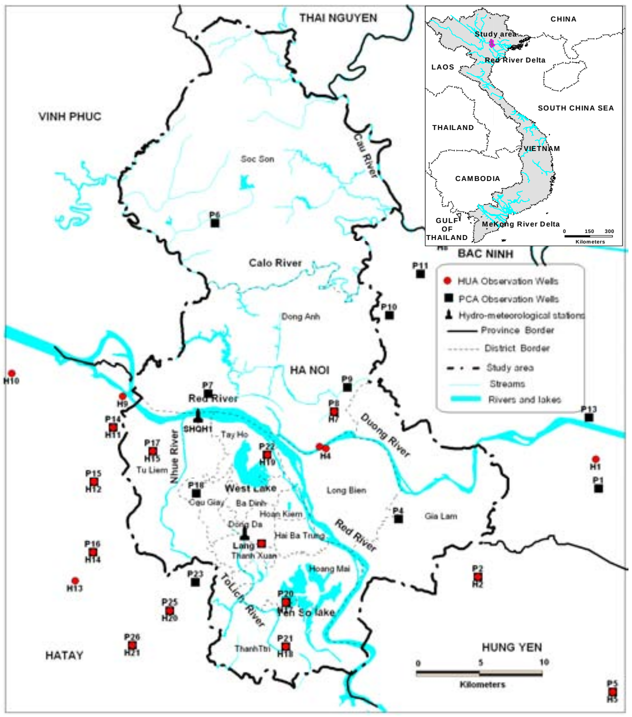

Figure 1. Study area and groundwater monitoring network.

Data are essential of any attempt to detect trends or other changes in hydrological records, and so it is important to properly prepare and understand the data to be used. Likewise, data should be quality-controlled before commencing an analysis of change (Kundzewicz and Robson, 2004). Therefore, to take advantage 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 to satisfy the required length in utilizing the MK test; (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 the majority of observation wells. As shown in Fig. 1, the selected wells are distributed over the study area. The advantage of this data selection is that it is less influenced by data quality problems, and provides 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, and 18 time series as explained earlier were computed for the 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 MK test (Boyles and Raman, 2003; Burn and Elnur, 2002; Serrano et al., 1999). It thus is not necessary to include adjustments for seasonality and serial correlation when applying the MK test for those 18 time series (Hirsch and Slack, 1982; Helsel and Hirsch, 2002).

Methodology

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 later further developed by Kendall (1948). The Mann–Kendall test is given by (1):

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \operatorname{sgn}(x_j - x_i) \quad \operatorname{sgn}(\theta) = \begin{cases} 1, \theta > 0 \\ 0, \theta = 0 \\ -1, \theta < 0 \end{cases} \tag{1}$$

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):

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

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

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 $1-\alpha/2$ 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):

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

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

RESULTS AND DISCUSSION

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 ($u_{0.005} \le u < u_{0.025}$), 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 $|u_{0.025}|$ =

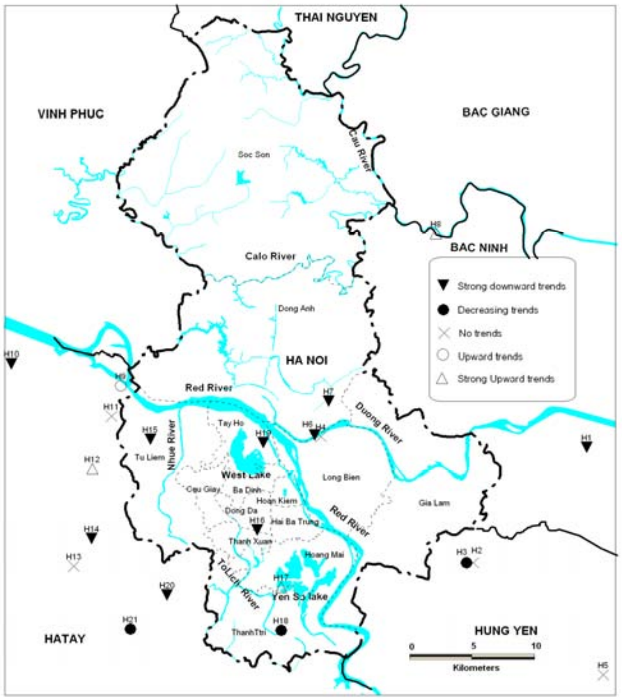

Figure 2. Spatial distribution of trend results for monthly groundwater level.

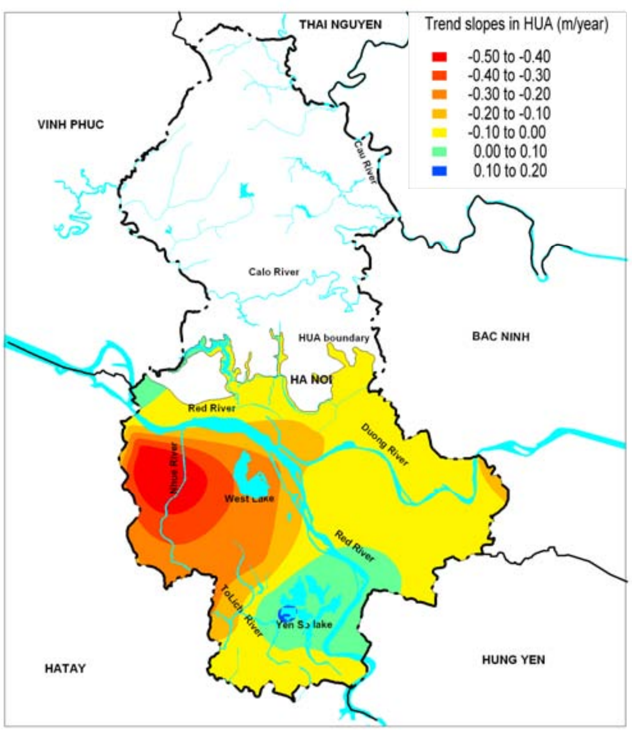

Figure 3. Spatial distribution of trend slope in monthly groundwater levels.

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

Table 1 summarizes the trend results from the Mann-Kendall test for the 18 time series (1995-2009) groundwater levels at 21 observation wells. The number of wells of five trend groups was also presented. It is apparent from the number of trends for the monthly time series in Table 1 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 the annual, seasonal (rainy and dry), and annual minimum time series show quite similar trend results to monthly data, annual maximum are observed less in the 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 one was observed in November (11 out of 21 wells). 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, Fig. 2 was created to display the well locations of five trend groups for monthly time series as a representative since they have the best sample size among other time series. As shown in Fig. 2, there are noticeable spatial groupings of wells with strong downward trends. The downward trends are widely observed over Hanoi while the upward and insignificant trends are sparsely located near rivers or lakes.

Table 2 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 1, are also marked as (✕) in Table 2. Positive and negative values indicate increasing and decreasing trends, respectively. As shown in Table 2, the mean downward and upward slopes in the monthly time series are -0.15 and 0.08 m/year. Although the slopes of the downward trends from all 18 time series are quite similar, February exhibits the smallest slope of -0.14 m/year that could be explained by the irrigation schedule because rice fields are usually irrigated in February. It is noted in more details that trend slopes are also different from well to well depending on its location that provides great motivation to investigate the spatial pattern of the trend slopes. For this reason, contour map of the trend slopes for monthly time series was created by utilizing GIS and Kriging interpolation methods and shown in Fig. 5 where distinct regional patterns are highlighted. From this figure, decreasing trends dominated over the area except for an area near Yenso Lake where increasing trends with small slope of around 0.1 m/year were observed. These increasing 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 gradually recovered to their previous stages. 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. Fig. 5 also indicates an area of around 55 km^2 with the downward trend slopes of less than -0.3 m/year. The trend slopes estimated herein could be useful reference to estimate HUA water levels in the future. Referring to the information about locations of current well-fields quoted in survey's report (Tong, 2007). It is concluded that long-term downward trends in groundwater levels were primarily governed by increasing groundwater abstraction since the locations of the well-fields are well matched with the areas of serious declining trends.

It should be further noted that the trend detection in groundwater variables is of concerns just recently. The approach in this research provides meaningful procedures for other similarstudies. 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. Increasing groundwater abstraction and its strong linkages to groundwater level decline 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.

Table 1. Results of Mann-Kendall test for trends in 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 2. Results of trend slopes (m/year) in groundwater levels by Sen method.

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 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. As for the results, about 12 out of 21 wells for HUA showed downward trends, while about 4 cases showed upward trends. Analyses have highlighted that downward trends are mainly in southwestern areas with slopes of about -0.3 m/year, whereas upward trends are found in the southeast (around the Yenso Lake) with smaller slopes of around 0.1 m/year. The 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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