Trend detection in groundwater levels in Hanoi, Vietnam by the Mann-Kendall test

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Abstract
The excessive exploitation of groundwater causes the groundwater level to decline, but the spatio-temporal patterns of groundwater level trends in Hanoi, Vietnam still remain poorly understood. Using the longest records (1995-2009) of a dense network of 47 observation wells (21 for Holocene unconfined aquifer (HUA) and 26 for Pleistocene confined aquifer (PCA)) available in Hanoi, this paper explored trends and their slopes in groundwater levels of both HUA and PCA 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 (e.g. annual average, rainy and dry season average, etc) computed from the original data were analyzed for trends. Analyses for monthly data revealed that 52% of the wells for HUA showed downward trends, while about 14% of the points showed upward trends. On the other hand, PCA groundwater levels seriously decreased at almost all observation wells over Hanoi. Although the trend results for other time series at a given well were quite similar, there were different trend patterns in several time series. In addition, the spatial patterns of different trend slopes were identified for both HUA and PCA.

Keywords: Groundwater level, database, Mann-Kendall test, trend detection, Hanoi

1. Introduction

Achieving sustainable groundwater management is one of the essential objectives for the future of the Vietnamese capital, Hanoi, because: (1) the water supply mostly depends on groundwater resources; and (2) undue groundwater exploitation without proper management have caused many groundwater related problems (Bui et al., 2011b). So far, there have been quite a few groundwater studies for Hanoi. For example, groundwater arsenic contamination was identified by Berg et al. (2007). Trinh and Fredlund (2000) investigated land subsidence due to excessive pumpings. However, there has not been any trend analysis in groundwater levels, which is one of the most important parameters of the groundwater system.

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 focused on trends in climate and surface hydrological variables, such as: temperatures, precipitation, humidity, surface water variables; water quality (Aziz and Burn, 2006; Abu-Taleb et al., 2007; Delgado et al., 2010). In contrast, there have been few trend studies on groundwater due to the unavailability of data. Furthermore, the non-parametric Mann–Kendall test has not been tested for groundwater levels even though it has been highlighted as an excellent tool for detecting trends in environmental data (Esterby, 1998).

In order to understand the groundwater behaviors of the Hanoi aquifer systems which were identified by our earlier study (Bui et al., 2011b), the main objective of this paper is to identify the trends in groundwater levels over Hanoi for both Holocene unconfined aquifer (HUA) and Pleistocene confined aquifer (PCA). To achieve the expected goals, this work first has focused on acquiring the longest observed groundwater levels (1995-2009) from the densest network of 47 wells available in the region, and then computed 17 time series concerning the useful features of groundwater levels (e.g. annual data, dry and rainy seasonal data, etc). After that, the non-parametric Mann–Kendall test was adopted to detect trends. Furthermore, Sen’s slope estimator was utilized to calculate the slopes of trends detected. In addition, spatial distribution of trends and their slopes were clarified by using geo-statistical and GIS methods.

2. Materials and methods

2.1 Study area and data source

Hanoi stretches from near the center to the northeast of the Red River Delta. The area is around 920 km^2 as shown in Figure 1 with the population of about 3.1 million habitants (Tong, 2008). Hanoi belongs to the tropical monsoonal area with two distinct seasons in the year: the rainy season (May to Oct.) and the dry season (Nov. till Apr.). Hanoi receives an average of about 1,550 mm rainfall per year in which 75% is in the rainy season. The annual humidity, temperature, and evaporation are about 80%, 24^{o}C, 933 mm, respectively. The river network is quite dense with an average slope of about 0.03 m/km. Due to poor infrastructure and management, the surface water in Hanoi has been seriously polluted (Tong, 2008). Groundwater thus becomes a main water supply source. The topmost HUA and shallow PCA are important aquifers from which groundwater are being abstracted (Bui et al., 2011b).

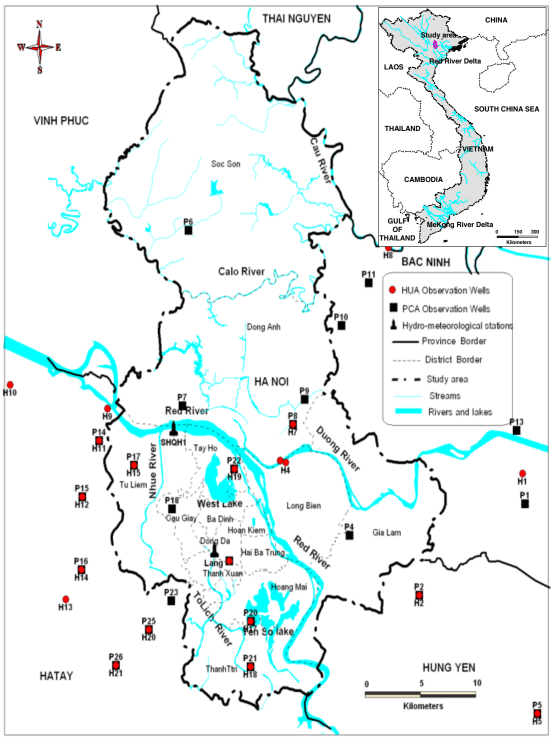

Fig. 1: Study area and groundwater monitoring wells

Currently, with the best record lengths of around 15 years (1995-2009), the groundwater levels data satisfy the required length in utilizing the Mann-Kendall test (Maidment, 1993). In this paper, groundwater levels at 47 out of 60 wells in Hanoi (Figure 1) were selected based on the criteria: (1) there are at least 15 years of recorded; (2) there is no more than 5% missing data; and (3) data are observed for either HUA or PCA. The numbers of wells are 21 for HUA and 26 for PCA. Regarding observation intervals, the numbers of wells which observe water levels at intervals every day, once per three days, and once per six days are 8, 23, and 16, respectively. From the original records, 17 time series (e.g. annual, rainy and dry season, annual maximum and minimum, and 12 monthly time series across years) were computed for every wells. 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 (Helsel and Hirsch, 2002).

2.2. Methods

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, while being as good as their parametric competitors. It was originally developed by Mann (1945) and later further developed by Kendall (1955). Furthermore, the non-parametric robust Sen's slope estimator was adopted to estimate the slope of the detected trends by the Mann–Kendall test, because 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). Regarding the specific formualtion of Mann–Kendall test and Sen's slope estimator, refer to our former study (Kawamura, et al, 2011). After that, spatial patterns of trends and their slopes were determined by GIS and geostatistical techniques. The contour maps of the trend slopes for each time series were created by utilizing GIS and Kriging interpolation methods. Creating sensible contour maps was a difficult task because monitorig wells are very small features on the scale of the heterogeneities of groundwater level. In this paper, Kriging interpolation only served as intitial basis which is used for reference when drawing the counter maps by hand (Bui et al., 2011a)

3. Results and discussion

In this paper, trend results were analyzed using two significance levels (α) of 5% and 1%. In other words, trend results were classified into five trend groups based on the u values: 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 were marked as (▼), (●), (×), (○), and (△), respectively in the following tables and maps.

3.1. Holocene Unconfined Aquifer (HUA)

Table 1 summarizes the trend results for the 17 time series of HUA groundwater levels at 21 wells during the period of 1995-2009. 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 the major portion of the wells (14 out of 21 wells), while no significant trends were found at the seven remaining wells. Although different number of significant trends are observed in the annual maximum and minimum than in the annual time series, the seasonal time series show quite similar trend results to the annual time series. Furthermore, a comparison among the results for the different months indicated that the highest number of significant trends was found in February (17 wells), while the lowest one was observed in November (11 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. To examine the spatial distribution of the detected trends, the maps showing the well locations of five trend groups for the annual time series is shown in Figure 2a. As seen in this figure, there are noticeable spatial groupings of wells with strong downward trends which are widely observed over Hanoi, while the upward and insignificant trends are sparsely located near rivers or lakes.

Table 1: Results of Mann-Kendall test for trends in HUA groundwater levels

Wells	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	△	○	△	×	△	△	△	△	△	△	○	×	×	○	△	△	△
H9	×	×	○	×	△	×	△	○	×	×	×	×	×	×	×	×	×
H10	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	●	●	●
H11	×	×	×	×	●	×	●	●	●	×	×	×	×	×	×	×	●
H12	△	△	△	△	△	△	△	△	△	△	△	△	△	△	△	△	△
H13	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
H14	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	●	▼
H15	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H16	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H17	△	△	△	△	△	△	△	△	△	△	△	△	△	△	△	△	△
H18	×	×	×	×	×	×	×	×	×	●	×	×	●	×	×	×	×
H19	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	●	▼	▼	▼	▼
H20	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H21	×	●	×	×	▼	●	▼	●	▼	×	●	●	×	×	×	×	×
Number of ▼	10	10	9	10	10	9	11	9	11	8	9	10	8	8	6	5	8
Number of ●	1	1	1	0	2	1	2	3	1	3	1	1	3	1	4	3	2
Number of ×	7	7	7	9	5	8	4	5	6	7	8	8	8	8	8	10	8
Number of ○	0	1	1	0	0	0	0	1	0	0	1	0	0	2	0	0	0
Number of △	3	2	3	2	4	3	4	3	3	3	2	2	2	2	3	3	3

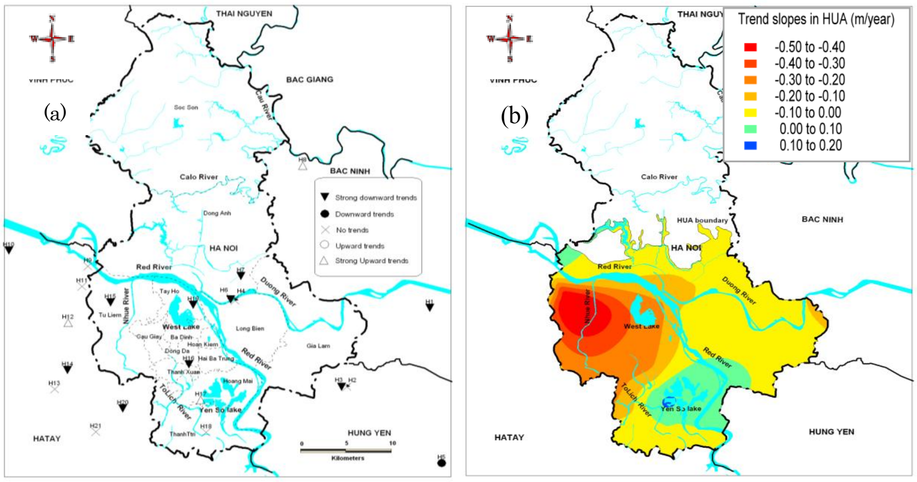

Fig. 2: Spatial distribution of (a) trends and (b) trend slopes for annual HUA groundwater levels

Table 2 shows the trend slopes in meter per year of 21 wells for the 17 time series. The time series, which show no significant trend, 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 annual data are -0.18 and 0.07 m/yr. Although the slopes of the downward trends from all 17 time series are quite similar, February exhibits the smallest slope of -0.14 m/year that could be explained by the irrigation schedule in February. Futhermore, Figure 2b shows a selected map presenting trend slope of annual time series where distinct regional patterns are highlighted. From this figure, decreasing trends dominated over the study area except near Yenso Lake. Southeast areas show slight downward, while the westerly regions show greater downward. Figure 2b also indicates an area of around 55 km^2 with downward trend slopes of less than -0.3 m/yr. Increasing trends observed around Yenso Lake have small slopes of around 0.1 m/year.

Table 2: Results of Sen's estimator for trend slopes in HUA groundwater levels (m/yr)

Well	Annual	Rainy	Dry	Max	Min	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H1	-0.16	-0.13	-0.19	-0.1	-0.2	-0.19	-0.18	-0.2	-0.22	-0.17	-0.12	-0.11	-0.11	-0.12	-0.16	-0.19	-0.2
H2	×	×	-0.02	×	-0.01	×	-0.02	-0.03	-0.03	-0.01	×	×	×	×	×	×	×
H3	-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	-0.11	-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	-0.08	-0.1	-0.1	-0.12	-0.1	-0.1	-0.11	-0.12	-0.08	-0.09	-0.11	-0.1	×	-0.07	-0.09	-0.09
H8	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	×	0.02	1	0.02	0.02	×	×	×	×	×	×	×	×	×
H10	-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	-0.1	-0.1
H11	×	×	×	×	-0.04	×	-0.04	-0.03	-0.03	×	×	×	×	×	×	×	-0.05
H12	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	-0.11	-0.12	-0.09	-0.1	-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	-0.5	-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	-0.5	-0.51	-0.48
H16	-0.21	-0.22	-0.2	-0.24	-0.2	-0.21	-0.21	-0.19	-0.2	-0.2	-0.2	-0.21	-0.24	-0.23	-0.22	-0.21	-0.2
H17	0.11	0.12	0.1	0.08	0.16	0.09	0.11	0.13	0.11	0.12	0.13	0.12	0.11	0.1	0.09	0.09	0.08
H18	×	×	×	×	×	×	×	×	×	-0.02	×	×	-0.03	×	×	×	×
H19	-0.22	-0.21	-0.23	-0.2	-0.24	-0.2	-0.22	-0.23	-0.25	-0.19	-0.2	-0.26	-0.21	-0.19	-0.15	-0.2	-0.21
H20	-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	×	-0.03	×	×	-0.03	-0.02	-0.03	-0.01	-0.05	×	-0.04	-0.06	×	×	×	×	×
Downward mean	-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	0.07	0.08	0.08	0.06	0.11	0.08	0.09	0.1	0.15	0.12	0.1	0.08	0.08	0.07	0.08	0.09	0.09

3.2 Pleistocene Confined Aquifer (PCA)

Table 3 summarizes the trend results for 26 wells of PCA. It is apparent from the number of trends for annual time series in Table 3 that statistically significant downward trends were identified in almost all wells (25 out of 26 wells). Only P10 indicated no significant trend. There is no upward trend at all. Regarding the other time series, an upward trend is also not detected at all, while no significant, strong downward, and weak downward trends are slightly different among time series. Furthermore, Figure 3a shows the well locations of the five trend groups for the annual time series for PCA. As shown in Figure 3a, strong downward trends widely occur over the study area except for one well near the Calo River.

Table 4 presents the trend slope results for 26 PCA wells. Table 4 reveals that the mean downward slope for the PCA annual time series is -0.3 m/yr which is much larger than that of HUA. Although trend slopes from all 17 time series of PCA are all much bigger than those of HUA, the smallest slope is still found in February (-0.27 m/year) like HUA due to the irrigation schedule. The spatial patterns of the trend slopes in annual time series were examined through creating and analyzing the contour map as shown in Fig. 3b where distinct patterns of trend slopes are clarified. The decreasing tendency is dominated almost all over the study area.The north of the Red River show a slight downward trends, while southerly regions show more serious decreasing trends. Figure 3b indicates an area of around 370 km^2 with the serious downward slope of less than -0.3 m/yr around the southwest of the Red River. This area occupies almost 40% of Hanoi, and is 7 times larger than the area in HUA.

Table 3 Results of Mann-Kendall test for trends in annual PCA groundwater levels

Wells	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	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	●	▼	▼	●	▼	●	▼
H9	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	●	●	●	▼
H10	×	●	●	●	×	×	×	×	×	×	●	×	×	●	×	×	▼
H11	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H12	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H13	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	●	▼	▼	▼	●	●	▼
H14	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H15	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H16	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H17	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H18	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H19	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H20	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H21	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H22	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H23	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H24	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H25	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
H26	▼	▼	▼	●	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	●	▼
Number of ▼	24	25	24	24	24	24	24	24	24	24	22	25	25	23	22	20	25
Number of ●	1	1	2	2	0	0	0	0	1	0	3	0	0	3	3	4	0
Number of ×	1	0	0	0	2	2	2	2	1	2	1	1	1	0	1	2	1
Number of ○	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Number of △	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4: Results of Sen's estimator for trend slopes in PCA groundwater levels (m/yr)

Well	Annual	Rainy	Dry	Max	Min	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P1	-0.14	-0.14	-0.13	-0.15	-0.15	-0.13	-0.12	-0.12	-0.13	-0.13	-0.13	-0.14	-0.14	-0.14	-0.14	-0.14	-0.15
P2	-0.19	-0.19	-0.19	-0.19	-0.19	-0.17	-0.17	-0.18	-0.2	-0.2	-0.19	-0.21	-0.19	-0.18	-0.18	-0.21	-0.2
P3	-0.19	-0.19	-0.19	-0.19	-0.2	-0.17	-0.17	-0.18	-0.2	-0.19	-0.2	-0.21	-0.19	-0.18	-0.18	-0.21	-0.2
P4	-0.15	-0.14	-0.16	-0.11	-0.16	-0.15	-0.13	-0.15	-0.18	-0.18	-0.18	-0.18	-0.11	-0.11	-0.12	-0.17	-0.15
P5	-0.16	-0.16	-0.15	-0.16	-0.16	-0.16	-0.15	-0.15	-0.15	-0.16	-0.15	-0.16	-0.17	-0.16	-0.15	-0.16	-0.16
P6	-0.06	-0.05	-0.06	-0.05	×	×	×	×	-0.06	×	×	-0.06	-0.05	-0.05	-0.06	×	×
P7	-0.29	-0.32	-0.27	-0.33	-0.28	-0.25	-0.24	-0.26	-0.31	-0.25	-0.31	-0.34	-0.32	-0.27	-0.3	-0.29	-0.28
P8	-0.09	-0.09	-0.1	-0.11	-0.11	-0.1	-0.09	-0.1	-0.12	-0.08	-0.1	-0.11	-0.11	-0.07	-0.07	-0.1	-0.1
P9	-0.08	-0.07	-0.08	-0.09	-0.1	-0.1	-0.09	-0.1	-0.09	-0.06	-0.07	-0.09	-0.09	-0.05	-0.04	-0.07	-0.08
P10	×	-0.01	-0.01	-0.01	×	×	×	×	×	×	-0.02	×	×	-0.01	×	×	-0.02
P11	-0.12	-0.13	-0.12	-0.11	-0.1	-0.09	-0.09	-0.11	-0.14	-0.14	-0.14	-0.13	-0.12	-0.09	-0.11	-0.12	-0.12
P12	-0.14	-0.15	-0.14	-0.15	-0.13	-0.12	-0.12	-0.13	-0.16	-0.15	-0.16	-0.16	-0.15	-0.13	-0.15	-0.14	-0.14
P13	-0.07	-0.08	-0.07	-0.09	-0.08	-0.06	-0.05	-0.06	-0.09	-0.07	-0.06	-0.08	-0.09	-0.08	-0.07	-0.1	-0.08
P14	-0.42	-0.46	-0.39	-0.48	-0.39	-0.37	-0.34	-0.35	-0.39	-0.38	-0.44	-0.49	-0.47	-0.46	-0.45	-0.43	-0.41
P15	-0.38	-0.41	-0.37	-0.4	-0.39	-0.35	-0.33	-0.32	-0.37	-0.36	-0.39	-0.41	-0.44	-0.41	-0.4	-0.43	-0.42
P16	-0.1	-0.12	-0.09	-0.11	-0.09	-0.07	-0.07	-0.08	-0.11	-0.1	-0.11	-0.12	-0.12	-0.13	-0.11	-0.11	-0.1
P17	-0.69	-0.75	-0.64	-0.58	-0.69	-0.61	-0.42	-0.55	-0.67	-0.68	-0.74	-0.75	-0.74	-0.74	-0.73	-0.75	-0.72
P18	-0.45	-0.44	-0.46	-0.46	-0.46	-0.46	-0.46	-0.45	-0.45	-0.39	-0.38	-0.4	-0.45	-0.48	-0.5	-0.51	-0.5
P19	-0.77	-0.82	-0.75	-0.78	-0.79	-0.75	-0.73	-0.7	-0.74	-0.76	-0.75	-0.82	-0.83	-0.85	-0.89	-0.78	-0.75
P20	-0.63	-0.68	-0.59	-0.69	-0.65	-0.56	-0.57	-0.55	-0.6	-0.6	-0.65	-0.68	-0.69	-0.7	-0.68	-0.65	-0.68
P21	-0.28	-0.32	-0.25	-0.35	-0.25	-0.22	-0.22	-0.23	-0.25	-0.26	-0.3	-0.33	-0.35	-0.36	-0.26	-0.27	-0.26
P22	-0.38	-0.4	-0.37	-0.46	-0.39	-0.35	-0.39	-0.37	-0.42	-0.37	-0.38	-0.42	-0.4	-0.34	-0.32	-0.32	-0.31
P23	-0.53	-0.54	-0.52	-0.54	-0.53	-0.52	-0.53	-0.52	-0.5	-0.5	-0.5	-0.53	-0.55	-0.55	-0.56	-0.54	-0.53
P24	-0.59	-0.6	-0.59	-0.6	-0.59	-0.59	-0.6	-0.59	-0.6	-0.57	-0.58	-0.61	-0.63	-0.61	-0.6	-0.6	-0.63
P25	-0.38	-0.4	-0.37	-0.37	-0.38	-0.37	-0.37	-0.38	-0.38	-0.36	-0.39	-0.4	-0.41	-0.4	-0.39	-0.39	-0.38
P26	-0.1	-0.12	-0.1	-0.1	-0.1	-0.08	-0.08	-0.08	-0.1	-0.1	-0.11	-0.12	-0.11	-0.14	-0.11	-0.12	-0.1
Mean	-0.3	-0.3	-0.28	-0.29	-0.31	-0.28	-0.27	-0.28	-0.3	-0.29	-0.3	-0.32	-0.32	-0.3	-0.3	-0.32	-0.3

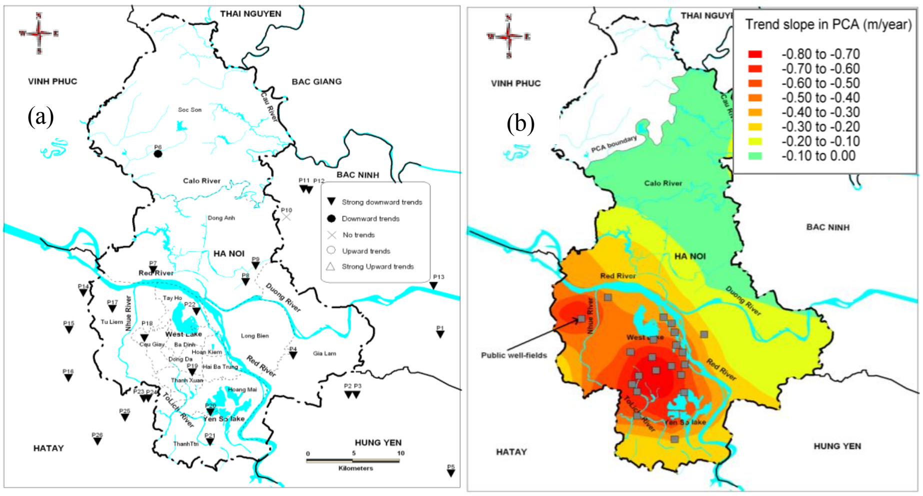

Fig. 3: Spatial distribution of (a) trends and (b) trend slopes for annual PCA groundwater levels

Long-term downward trends in groundwater levels are primarily governed by increasing groundwater abstraction. Although there is no detailed time series of groundwater abstraction, a survey in 2005 showed that there were 21 public well-fields as shown in Fig. 3b and many household wells in Hanoi. The public well-fields were mainly taking about 500,000 m^3/day from the PCA which was almost double the amount recorded in the 1990s. In addition, the PCA naturally receives less recharge from rainfall and surface water than the HUA, primarily because PCA is mostly located under HUA (Bui et al, 2011b). Hence, greater downward trends in groundwater levels are found more in PCA than in HUA. The locations of the well-fields as shown in Fig. 3b considerably match with the PCA areas that have serious declining trends. As declining trends of groundwater level depends not only on groundwater pumping but also on natural characteristics of aquifers, the order of abstraction in public well-fields is not always corresponding with rate of declining trends. The fact that the annual irrigation water for the Calo River areas was equal to about 60% of the annual rainfall (Tong, 2008) could be a reasonable explanation for the less serious decline in these areas. The progress of urbanization in the form of high density housing-land deveropment could contribute to the decrease of groundwater level to some extent because of the increased amount of impervious surface areas with less infiltration. Furthermore, it should be noted that the trend detection of groundwater variables has been of concern just recently. The approach in this research provides meaningful procedures for other similar studies. The findings herein provide valuable information about groundwater dynamics to climate and urbanization in other Asian areas where topographical, hydrogeological conditions and increasing pumping are similar.

4. Conclusions

This paper is the first attempt to explore the statistical significance 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 47 wells (21 for HUA and 26 for PCA) available in the region, at each well 17 time series encompassing important groundwater level components (e.g. 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 of annual time series, 52% of the wells for HUA showed downward trends, while about 14% showed upward trends. Analyses have highlighted that downward trends are mainly in southwestern areas with slopes of about -0.3 m/yr, whereas upward trends are found in the southeast with smaller slopes of around 0.1 m/yr. On the other hand, PCA groundwater levels seriously decreased at almost all wells over Hanoi. This paper has indentified areas of around 370 km^2 with serious downward slopes of less than -0.3 m/yr, which occupies almost 40% of Hanoi, and is 7 times larger than those in HUA. Although the trend results for other time series at a given well were quite similar, there were different trend patterns in several time series. These findings provide useful references for sustainable groundwater development in Hanoi.

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