TREND ANALYSIS OF GROUNDWATER LEVELS OF CONFINED AQUIFER IN HANOI, VIETNAM BY THE MANN-KENDALL TEST

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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 did not exist until 1995, and then we have created and maintained a groundwater monitoring database (GMD). Using the longest records (1995-2009) at a dense network of 26 observation wells for Pleistocene confined aquifer (PCA) available in Hanoi obtained from the GMD, this paper explored trends and their slopes in PCA groundwater levels, the most important aquifer, by utilizing the non-parametric Mann-Kendall (MK) trend test and Sen's slope estimator. At each well, 18 time series encompassing important groundwater level components (e.g. monthly, seasonal, and annual means and so on) were analyzed to provide insights into the trends. In addition, efforts were made to clarify the spatial patterns of the trends and trend slopes. Analyses for monthly data revealed that PCA groundwater levels seriously decreased at almost all observation points over Hanoi. The areas which showed the serious downward trend slope of less than -0.3 m per year have occupied up to almost 370 km^2 in the south (about 50% of PCA surface area). In general, the groundwater levels of southern parts showed more serious trend slope than northern ones. Trend and slope results for other time series were also identified. The findings provide useful references for further groundwater analyses required to ensure sustainable groundwater development in Hanoi.

1 INTRODUCTION

The Vietnamese capital, Hanoi, is particularly in the regard of sustainable groundwater development because clean water demand has become rather urgent and water supply mostly depends on groundwater resources (Bui *et al*., 2010). Although there have been some groundwater resource studies reported in literature for Hanoi, most of them were concerned about the potential of groundwater, aquifer framework, groundwater pollution, and land subsidence (Duong *et al.*, 2003; Trinh and Fredlund, 2000, Agusa, *et al*., 2005; Larsen *et al*., 2008; Bui *et al* 2010). 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 practical groundwater pumping and management strategies.

Increasing interests in 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 (Sharma *et al*., 2000; Boyles and Raman, 2003); precipitation (Sharma *et al*., 2000; Boyles and Raman, 2003; Delgado *et al*., 2010); humidity (Abu-Taleb *et al*., 2007; Paltridge *et al*., 2009); surface water variables (Aziz and Burn, 2006; Delgado *et al*., 2010); water quality (Esterby, 1998; Johnsona *et al*., 2009); and many others. In contrast, there have been few trend studies for groundwater levels. Recently more researches have begun paying attentions to trends and variability in groundwater levels. (Almedeij and Al-Ruwaih, 2006; Hoque *et al*., 2007; Akther *et al*., 2009; Shamsudduha *et al*., 2009). In the studies for groundwater, the non-parametric Mann–Kendall (MK) test has not been tested, although it has been proven as an excellent tool for detecting trends in environmental data for many regions by many researchers over the world.

Since 2000, we have constructed and maintained a valuable groundwater monitoring database (GMD) to gather all the observed groundwater data. To take advantages of our internally-available data sets as much as possible, the main objective of this paper is to identify the trends and trend slopes in groundwater levels quantitatively for Pleistocene confined aquifer (PCA) over Hanoi. 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 to date, and then 18 useful time series of groundwater levels (e.g. mean, max, min, and so on) were computed. Next, the non-parametric MK trend test and Sen's slope estimator were adopted to statistically determine trends and their slopes in the 18 time series based on five statistical significance categories. In addition, efforts have been made to clarify the spatial preterm of trends and their slopes by using GIS. The findings obtained from this study could provide basic references for sustainable groundwater development in Hanoi.

2 STUDY AREA AND GROUNDWATER MONITORING DATABASE

Hanoi (old Hanoi before its being merged) has the area of around 920 km^2 with 14 districts as shown in Figure 1. Hanoi's topography is mainly below 12 m. Hanoi belongs to the tropical monsoonal area with two distinct seasons in a year: rainy and dry seasons. Hanoi receives an average rainfall of about 1,550 mm per year in which rainfall in the rainy season occupies about 75%. The river network is quite dense with the density of about 0.7 km/km^2. There are also more than 100 lakes with a total surface area of more than 2,180 hectares. However, the water of the Red River has a high level of suspended deposits at any one time. Due to poor infrastructure and management of dumping waste, surface water in Hanoi has been seriously polluted (Tong, 2008). Therefore, groundwater is a main source of water supply. (Bui *et al*, 2010).

Data availability is essential to develop complicated, integrated approaches for groundwater management (Rossetto *et al*., 2007) and enable decision-makers to make appropriate decisions (William, 2004). In Vietnam, however, detailed information and long term data were rare that is an obstacle to the application of integrated groundwater management on a large basin scale. Motivated by these necessities, since 1987, Vietnam government had begun investing to set up groundwater observation wells, yet, it was not until 1995 that a fairly wide groundwater monitoring network was set up and went into operation. The groundwater monitored data are huge but they were not systematically organized. Therefore, one time-consuming and costly project was initiated in 2000 under nomination of the Vietnam Department of Geology and Minerals, in which we constructed and maintained a GIS-based GMD since then. So far, 60 observation wells have been installed in Hanoi. The basic data about groundwater, such as groundwater level, temperature, and quality are being monitored. Record lengths and intervals are different depending on completion time, the intended uses of observation wells, and variables to be monitored. Basically, groundwater levels are recorded at three types of intervals: every day, once per three days, and once per six days. So far, the record lengths have been about 15 years that satisfies the minimum data length requirement of trend detection. Details about this project and the database were described in the final report of the project (Tong, 2003).

3 DATA USED AND METHODOLOGY

3.1 Data used

The primary factors of station selection were the record length and the quality of data. Therefore, groundwater levels at 26 out of 60 observation wells in study area (Figure 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) wells are observed for PCA. Records at the length of 15-year (1995-2009) were analyzed in order to be consistent in data with majority of observation wells. As shown in Figure 1, the selected observation wells are distributed over the study area. In this paper, groundwater level was used, as it is a direct indicator of groundwater system. From the original records as explained earlier, monthly average groundwater levels were calculated and then used as the basic data set, from

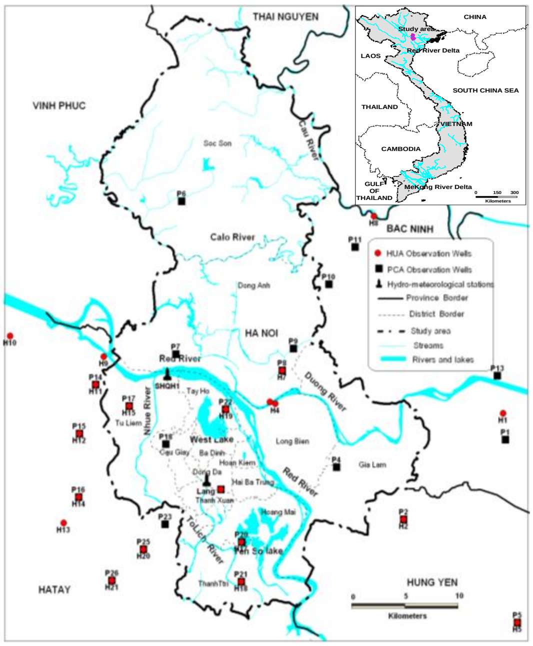


Figure 1. Study area and observation network

which other time series (e.g. monthly time series for each month across years; annual, rainy and dry season average, annual maximum and minimum) were computed for individual wells. A comprehensive trend analysis for various groundwater level time series was conducted so as not only to resolve problems of serial correlation inherent in hydroclimatic time series (Serrano *et al.*, 1999; Burn and Elnur, 2002) but also to provide detailed and better understandings on trends in groundwater levels. First, the focus was on detecting trends in monthly average time series throughout the years since they have the best sample-size among the time series. Next, in addition to annual average data, monthly time series for each month across years were examined for trends to provide insight into groundwater level trends for different months of a year. While seasonal average groundwater levels were investigated to explore seasonal patterns of the trends, annual maximum and minimum groundwater levels were checked to identify trends in two extremes of groundwater levels. Additionally, monthly rainfall at Lang station and monthly Red River water levels at SHQH1 station as shown in Figure 1 were examined for their linkages with groundwater levels.

3. 2 Methodology

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

The methodologies for conducting trend analysis studies in hydroclimatic records have been comprehensively reviewed by Esterby (1998) and further reviewed by Kundzewicz and Robson (2004). Numerous trend studies referred to earlier and many others have continually highlighted the non-parametric MK test as an excellent tool for detecting trends in hydrology and environment. This method is highly appropriate because they allow minimal assumptions about the data, and are 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). In this study, the test was also applied to determine trends in various time series of groundwater levels. Furthermore, the non-parametric robust Sen's slope estimator was adopted to estimate the slope (β) of the detected trends, 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). 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 (e.g. groundwater abstraction, rainfall, and surface water levels).

4 RESULTS AND DISCUSSION

4.1 General characteristics of groundwater levels

Preliminary analysis, an initial examination of the data, is an essential component of a statistical analysis. Thus, we plotted the 18 time series of groundwater levels at each wells, 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 shows selected monthly groundwater levels at 3 out of 26 observation wells, along with monthly rainfall and monthly Red River water levels. It is apparent from Figure 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. In addition, three groundwater level plots in Figure 2 reveal three typical long-term trend patterns. P23 time series show a clear downward trend with an ambiguous annual cycles which is generally observed in the south of, and far from the Red River. P14 time series show clear downward trend with an obvious annual cycle that is commonly located in the south, and near the Red River. P6 time series reveal an unclear long-term trend with the annual cycle that is commonly found in northern Hanoi. Futhermore, to visualize the spatial pattern of the groundwater levels, countour maps showing annual mean of each year were created by utilizing the commonly-used GIS and Kriging interpolation methods. Figure 3 (a) and (b) show the two selected maps in 1995 and 2009, respectively. As shown in these Figures, the groundwater flow partems are quite similar to each others, in which flow direction is generally from north to south corresponding to Hanoi topography. A large cone of depression already existed in 1995 in the south of the Red River and it continuously expanded and deepend during the past 15 years. The contour maps for the other years, which were not presented here, indicated an annual expansions of the cone.

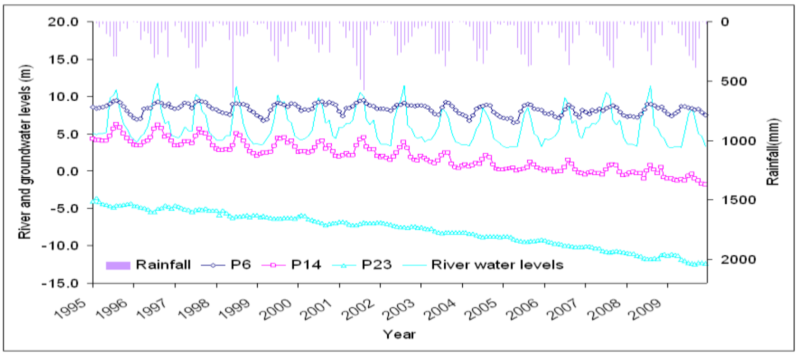
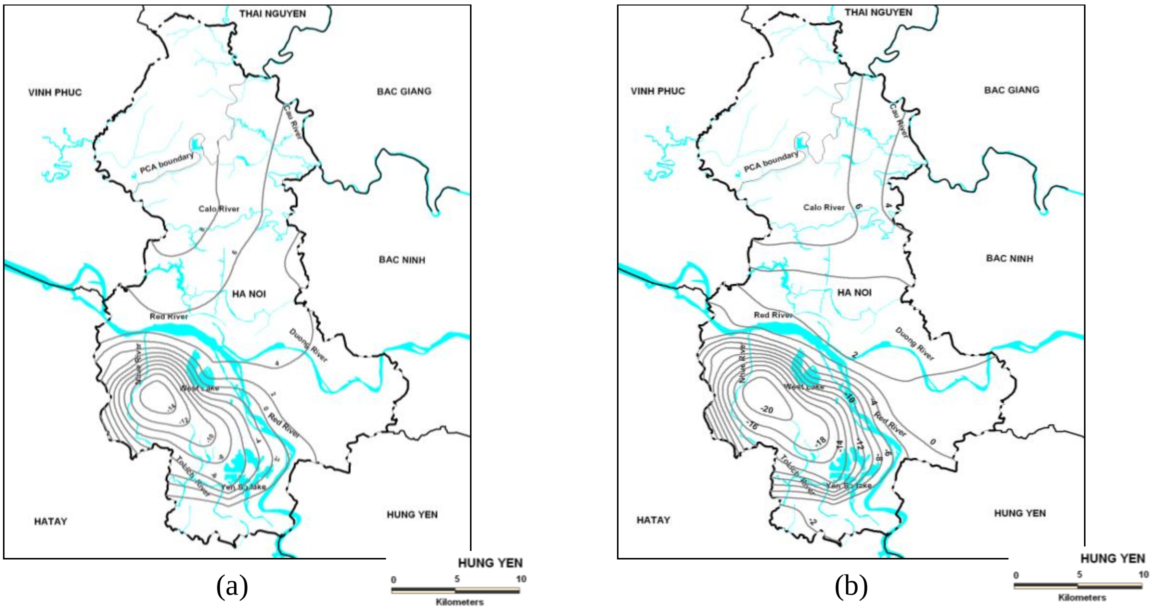


Figure 2. Monthly groundwater levels at three selected wells for PCA along with monthly rainfall and monthly Red River water levels



(a) (b)

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

4.2 Spatio-temporal pattern 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 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 $|u_{0.025}| = u_{0.975} = 1.96$ 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 1 presents trend slope results for the period 1995–2009 for the 18 time series that were identified as being field significant. The time series, which show no significant trend, are marked (Γ). Positive and negative signs indicate upward and downward trends, respectively, while their values show the trend slope (meter per year). The number of wells exhibiting trend of the five trend groups were also presented in the five last lines of the table. From the number wells exhibiting trend in Table 1, statistically significant decreasing trends were identified in the almost all time series and wells. Only P6 and P10 observed no significant trend in several time series. There is no case observing upward trend at all. At each well the trend results are quite similar for 18 time series. 100% wells were observed as significant trends in rainy and dry season means, annual maximum, and September data. Regarding trend slopes, Table 1 reveals a range of slope values are quite similar among time series, around -0.3 meters per year (downward). The groundwater levels of July, August, and November exhibit the highest average slope of -0.32 meter per year, while February data exhibited the lowest average slope of -0.27 meter per year among other time series. It is noted that the slope is rather different from well to well than from time series to time series. Slope values of around -0.76 meter per year are typical for well P19 while values in the range of -0.05 meter per year are typical for station well P6.

Furthermore, it is very helpful to examine the spatial distribution of the trend results, 18 maps for 18 time series were created to display the locations of wells based on the five trend groups. Figure 4 (a) shows selected map for the monthly trend results. It reveals exact spatial patterns in the location of stations that exhibit a significant trend. As can be seen from the Figure 4 (a), downward trends widely occur over the study area. Well P10 showing no significant trend is close to the Calo River. In addition, to examine the spatial pattern of trend slopes in PCA groundwater levels, contour maps were created by utilyzing GIS and Kriging interpolation methods. Even though we used those methods, creating sensible contour maps was a difficult task because infomation from wells are very small features on the scale of the heterogeneities of an aquifer, and natural partern of PCA groundwater levels have been seriously broken due to excessive exploitation. We, therefore, not only utilized the methods but also interpreted and compared their results to observational data by ourselves to draw the realistic contour maps. Figure 4 (b) shows selected map presenting the trend slope from monthly data where distinct patterns of trend slope are highlighted. From this Figure, decreasing trends dominated in almost entire PCA areas. PCA groundwater levels show slight downward in the north of the Red River, while the more southerly regions show more serious decreasing trends, particularly the northern areas above Yenso Lake. Figure 4 (b) indicates an area of around 370 km^2 with the serious downward slope of less than -0.3 m/year. This area occupies almost 40% of Hanoi. Less serious downward slope observed around the Calo River likely results from greater groundwater recharge from the irrigation water nearby.

Table 1. Results of Sen's estimator for trend slopes in PCA groundwater levels (m/year)

Wells	Monthly	Annual	Rainy	Dry	Max	Min	Jan	Feb	Mar	Arp	May	Jun	July	Aug	Sep	Oct	Nov	Dec
P1	-0.13	-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	-0.19	-0.17	-0.17	-0.18	-0.20	-0.20	-0.19	-0.21	-0.19	-0.18	-0.18	-0.21	-0.20
P3	-0.19	-0.19	-0.19	-0.19	-0.19	-0.20	-0.17	-0.17	-0.18	-0.20	-0.19	-0.20	-0.21	-0.19	-0.18	-0.18	-0.21	-0.20
P4	-0.15	-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	-0.15	-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	-0.05	-0.06	-0.05	-0.06	-0.05	Γ	Γ	Γ	Γ	-0.06	Γ	Γ	-0.06	-0.05	-0.05	-0.06	Γ	Γ
P7	-0.27	-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	-0.30	-0.29	-0.28
P8	-0.09	-0.09	-0.09	-0.10	-0.11	-0.11	-0.10	-0.09	-0.10	-0.12	-0.08	-0.10	-0.11	-0.11	-0.07	-0.07	-0.10	-0.10
P9	-0.08	-0.08	-0.07	-0.08	-0.09	-0.10	-0.10	-0.09	-0.10	-0.09	-0.06	-0.07	-0.09	-0.09	-0.05	-0.04	-0.07	-0.08
P10	Γ	Γ	-0.01	-0.01	-0.01	Γ	Γ	Γ	Γ	Γ	Γ	-0.02	Γ	Γ	-0.01	Γ	Γ	-0.02
P11	-0.12	-0.12	-0.13	-0.12	-0.11	-0.10	-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	-0.14	-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	-0.07	-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	-0.10	-0.08
P14	-0.40	-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	-0.38	-0.41	-0.37	-0.40	-0.39	-0.35	-0.33	-0.32	-0.37	-0.36	-0.39	-0.41	-0.44	-0.41	-0.40	-0.43	-0.42
P16	-0.09	-0.10	-0.12	-0.09	-0.11	-0.09	-0.07	-0.07	-0.08	-0.11	-0.10	-0.11	-0.12	-0.12	-0.13	-0.11	-0.11	-0.10
P17	-0.68	-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	-0.45	-0.44	-0.46	-0.46	-0.46	-0.46	-0.46	-0.45	-0.45	-0.39	-0.38	-0.40	-0.45	-0.48	-0.50	-0.51	-0.50
P19	-0.78	-0.77	-0.82	-0.75	-0.78	-0.79	-0.75	-0.73	-0.70	-0.74	-0.76	-0.75	-0.82	-0.83	-0.85	-0.89	-0.78	-0.75
P20	-0.64	-0.63	-0.68	-0.59	-0.69	-0.65	-0.56	-0.57	-0.55	-0.60	-0.60	-0.65	-0.68	-0.69	-0.70	-0.68	-0.65	-0.68
P21	-0.26	-0.28	-0.32	-0.25	-0.35	-0.25	-0.22	-0.22	-0.23	-0.25	-0.26	-0.30	-0.33	-0.35	-0.36	-0.26	-0.27	-0.26
P22	-0.36	-0.38	-0.40	-0.37	-0.46	-0.39	-0.35	-0.39	-0.37	-0.42	-0.37	-0.38	-0.42	-0.40	-0.34	-0.32	-0.32	-0.31
P23	-0.53	-0.53	-0.54	-0.52	-0.54	-0.53	-0.52	-0.53	-0.52	-0.50	-0.50	-0.50	-0.53	-0.55	-0.55	-0.56	-0.54	-0.53
P24	-0.60	-0.59	-0.60	-0.59	-0.60	-0.59	-0.59	-0.60	-0.59	-0.60	-0.57	-0.58	-0.61	-0.63	-0.61	-0.60	-0.60	-0.63
P25	-0.38	-0.38	-0.40	-0.37	-0.37	-0.38	-0.37	-0.37	-0.38	-0.38	-0.36	-0.39	-0.40	-0.41	-0.40	-0.39	-0.39	-0.38
P26	-0.10	-0.10	-0.12	-0.10	-0.10	-0.10	-0.08	-0.08	-0.08	-0.10	-0.10	-0.11	-0.12	-0.11	-0.14	-0.11	-0.12	-0.10
Mean	-0.29	-0.30	-0.30	-0.28	-0.29	-0.31	-0.28	-0.27	-0.28	-0.30	-0.29	-0.30	-0.32	-0.32	-0.30	-0.30	-0.32	-0.30
Number of 5	25	24	25	24	24	24	24	24	24	24	24	22	25	25	23	22	20	25
Number of)	0	1	1	2	2	0	0	0	0	1	0	3	0	0	3	3	4	0
Number of Γ	1	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	0
Number of 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Analyses of groundwater level trends in Hanoi in this paper revealed several interesting features of groundwater level regime. Annual cycle of groundwater levels are primarily governed by rainfall and river water levels, while long term trend groundwater levels are strongly impacted by groundwater abstraction. Although, there is no detailed time series of groundwater abstraction, survey as of 2005 showed that there were 21 public well-fields mainly taking about 500,000 m^3/day (almost double compared to 1990s) from PCA, The locations of these well-fields are well matched with the PCA areas of serious declining trends. The fact that annual irrigation water for the Calo River areas was equal to about 60% of annual rainfall (Tong, 2007) could be reasonable explanation for less serious decline in these areas, because groundwater here receives greater recharge from irrigation water than other areas. It should be further noted that trend detection in groundwater variables has taken the attentions of researchers just recently. The approach in this study provides meaningful procedures for similar researches. The findings in Hanoi certainly provide valuable information about groundwater dynamics and long-term responses to climate variation and rapid development in other Asian areas where topographical and hydrogeological conditions are similar. Seasonal fluctuation in groundwater levels and its strong linkages to rainfall and surface water factors in Hanoi are in similar to other Asian areas (Almedeij and Al-Ruwaih, 2006, Shamsudduha *et al*., 2009). Groundwater level declines due to over-exploitation have also been widely documented for other Asian urban areas such as Dhaka, Bangladesh; Bangkok, Thailand (Phien-wej *et al*., 2006; Shamsudduha *et al*., 2009).

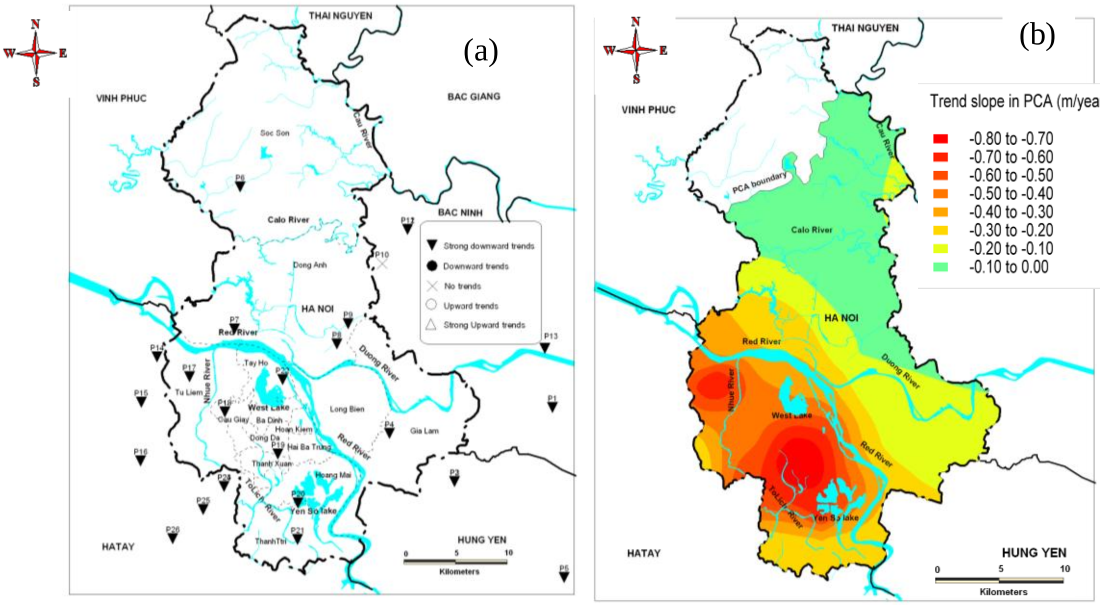


Figure 4. Spatial distribution of (a) trend results, and (b) trend slopes for monthly PCA groundwater levels

5 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 26 wells for PCA 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, this study revealed that PCA groundwater levels seriously decreased at almost all observation points over Hanoi. The area which showed the serious downward trend slope of less than -0.3 m per year has occupied almost 370 km^2 (about 50% of PCA surface area) in the south. In general, the groundwater levels of southern parts showed more serious trend slope than northern ones. Trend results for other time series were quite similar to monthly time series regardless to time series to be studied. This study also indicated that annual cycles in groundwater levels are primarily governed by rainfall and river water levels, while their long-term trends were strongly influenced by groundwater abstraction.

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