Spatio-temporal analysis of recent groundwater-level trends in the Red River Delta, Vietnam

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Abstract A groundwater-monitoring network has been in operation in the Red River Delta, Vietnam, since 1995. Trends in groundwater level (1995–2009) in 57 wells in the Holocene unconfined aquifer and 63 wells in the Pleistocene confined aquifer were determined by applying the non-parametric Mann-Kendall trend test and Sen's slope estimator. At each well, 17 time series (e.g. annual, seasonal, monthly), computed from the original data, were analyzed. Analysis of the annual groundwater-level means revealed that 35% of the wells in the unconfined aquifer showed downward trends, while about 21% showed upward trends. On the other hand, confined-aquifer groundwater levels experienced downward trends in almost all locations. Spatial distributions of trends indicated that the strongly declining trends (>0.3m/year) were mainly found in urban areas around Hanoi where there is intensive abstraction of groundwater. Although the trend results for most of the 17 time series at a given well were quite similar, different trend patterns were detected in several. The findings reflect unsustainable groundwater development and the importance of maintaining groundwater monitoring and a database in the Delta, particularly in urban areas.

Keywords Groundwater monitoring · Groundwater-level trend · Geographic information systems · Mann-Kendall · Vietnam

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Introduction

Groundwater plays a very significant role in public water supply in many places around the world. Sustainable management of groundwater resources is one of the essential objectives for the future development of a country, especially when the rising demand for clean drinking water is considered (Mende et al. 2007). The amount of groundwater abstraction has been rapidly and continuously increasing worldwide (Van et al. 2010) and excessive groundwater abstraction has caused serious groundwater-level declines in many areas (Vietnam 2001; Phien-wej et al. 2006; Shamsudduha et al. 2009). Declining groundwater levels have a number of adverse impacts on the environment. Most directly, groundwater-level decline is an indicator of groundwater depletion, which threatens aquifer sustainable development (Akther et al. 2009). Other obvious impacts are land subsidence resulting from compaction of aquifer materials (Konikow and Kendy 2005) and groundwater pollution due to additional recharge from leaking sewers and other wastewater sources (Hoque et al. 2007; Berg et al. 2007). Likewise, surface waters are also affected by reduced groundwater discharges (Konikow and Kendy 2005) that can adversely affect ecosystems (Zektser et al. 2005).

In the Red River Delta, Vietnam, people depend greatly on groundwater for their domestic water use because of the uneven distribution and contaminated quality of surface-water resources. Only a few studies have been conducted on groundwater related issues and these studies covered a small part of the delta. Most of these studies targeted the capital of Hanoi, and were concerned about groundwater pollution, land subsidence, and aquifer system identification. Duong et al. (2003), for example, considered the groundwater pollution in water supplies of Hanoi. Groundwater arsenic contamination was identified in some parts of Hanoi (Berg et al. 2007). Trinh and Fredlund (2000) investigated the land subsidence due to excessive groundwater exploitation in Hanoi. Even though an understanding of spatio-temporal changes in groundwater levels is essential for sound management of groundwater resources (Ferdowsian and Pannell 2009; Hoque et al. 2007), no analysis of trends or variability in groundwater levels has been conducted in the Red River Delta. Detection of spatio-temporal trends in groundwater levels in the Delta has long been a difficult issue because of the lack of in situ observational records of sufficient length, spatial coverage and quality.

Globally, very few studies have looked at spatio-temporal changes in groundwater variables because of the lack of a network of groundwater-level-monitoring systems. Almedeij and Al-Ruwaih (2006) investigated the periodic behavior of groundwater-level fluctuations in residential areas of Kuwait. In Bangladesh, the spatio-temporal patterns of groundwater-level fluctuation and trends in Dhaka and the Ganges-Brahmaputra-Meghna Delta were identified by Hoque et al. (2007), Akther et al. (2009), and Shamsudduha et al. (2009). Ferdowsian and Pannell (2009) studied trends in groundwater levels in Esperance, Australia. In these studies, several methods such as the graphical description, linear regression, and seasonal-trend decomposition were applied to detect trends in groundwater levels. The non-parametric Mann–Kendall test, the most commonly used method for detecting trends in environmental and hydrological variables (Esterby 1998; Kundzewicz and Robson 2004; Delgado et al. 2010) was also used for preliminarily testing groundwater-level time series in Orissa, India (Panda et al. 2007); in the Hillsborough River Basin, Florida, USA (Weber and Perry 2006); and Wisconsin, USA (Ghanbari and Bravo 2011). In this study, the Mann-Kendall test was applied, for the first time, to in situ groundwater-level data for a considerable period (1995–2009) to detect trends in water levels in the Red River Delta.

Currently, a dense network of groundwater-level monitoring stations, including 160 observation wells, exists for the Holocene unconfined aquifer (HUA) and the Pleistocene confined aquifer (PCA) in the Red River Delta. This monitoring network was established in 1995 and a systematic groundwater-level-monitoring database (GMD) has been maintained since 2000. This report presents a spatio-temporal analysis of the trends and variability of both HUA and PCA groundwater levels for the period of 1995–2009 in order to understand groundwater-level changes in aquifer systems. The Mann-Kendall method was applied to detect trends in groundwater-level time-series data while the Sen's slope estimator was used to estimate the magnitude of the trend. Geostatistical and geographic information systems (GIS) techniques were applied to map spatial trends in observed groundwater levels in the Red River Delta.

Study area and groundwater-monitoring network

Study area

The Red River Delta (Fig. 1) has a surface area of about 13,000 km^2 in the northern part of Vietnam, covering 4.5 % of the total Vietnam area. It is the most developed region of Vietnam, comprised of 13 provinces and cities as shown in Fig. 1. The population was about 19 million in 2007, occupying 22 % of Vietnam's total population. Many important centers of economy in Vietnam such as Hanoi and Haiphong, are located there. The major type of topography is flood plains with an elevation mainly below 12 m.

The delta belongs to the tropical monsoonal area with two distinctive seasons: the rainy season (May to October) and the dry season (November to April). The annual rainfall is about 1,600 mm; 75 % of the rainfall is during the rainy season. The annual average humidity is about 80 %, and the average temperature is around 24 °C. Evaporation is quite high with an annual average of 900 mm (Tong 2007).

The natural river network (i.e. excluding artificial irrigation channel systems) in the delta is quite dense with a density of about 0.7 km/km^2 (Tong 2007). The average discharge of the Red River at the Hanoi station is 385 m^3/s in the dry season and 14,800 m^3/s in the rainy season. The water of the Red River is at a high level of suspended load throughout the year. The tidal range along the coast is approximately 4 m. Surface water, especially in lakes, in some cities has been seriously polluted due to infrastructure insufficiency and unwise management of municipal waste (Tong 2007).

Groundwater is the main source of domestic water supply (Tong 2007; Bui et al. 2003, 2011, 2012). The amount of groundwater abstraction has been rapidly increasing each year. Using field data from well logs (e.g. thickness, materials and geological ages of each soil layer) and pumping tests (e.g. specific capacity, and hydraulic conductivity, storage coefficient, etc.), the hydrogeological architecture of the aquifer system (i.e. aquifers and aquitards) in the entire delta was identified (Bui et al. 2003, 2011, 2012). According to these studies, groundwater in the Red River Delta mainly exists in Quaternary unconsolidated sediments (i.e. clay sands, sands, gravels, cobbles) forming the topmost HUA and the shallow Pleistocene confined aquifer (PCA), sandwiching the Holocene-Pleistocene aquitard. The depth to the bottom of the aquifer system of the delta varies greatly, up to 100 m in the coastal areas, and it shows an increasing tendency from the northwest to the southeast of the delta (Bui et al. 2003, 2011, 2012). The topmost aquifer (HUA) and the shallow confined aquifer (PCA) are two important aquifers as they have the highest potential of groundwater resources (Bui et al. 2011, 2012). Concentrations of ammonia, arsenic, and other heavy metals in groundwater of the delta have increased over the years (Agusa et al. 2005; Berg et al. 2001, 2007; Bui et al. 2007; UNICEF Vietnam 2001).

Establishment of the groundwater-monitoring network and database

In Vietnam, detailed information and long-term observation data on groundwater levels were rare, which has been an obstacle for the application of integrated groundwater management on a large basin scale. Motivated by these necessities, since 1989, the Vietnamese government had

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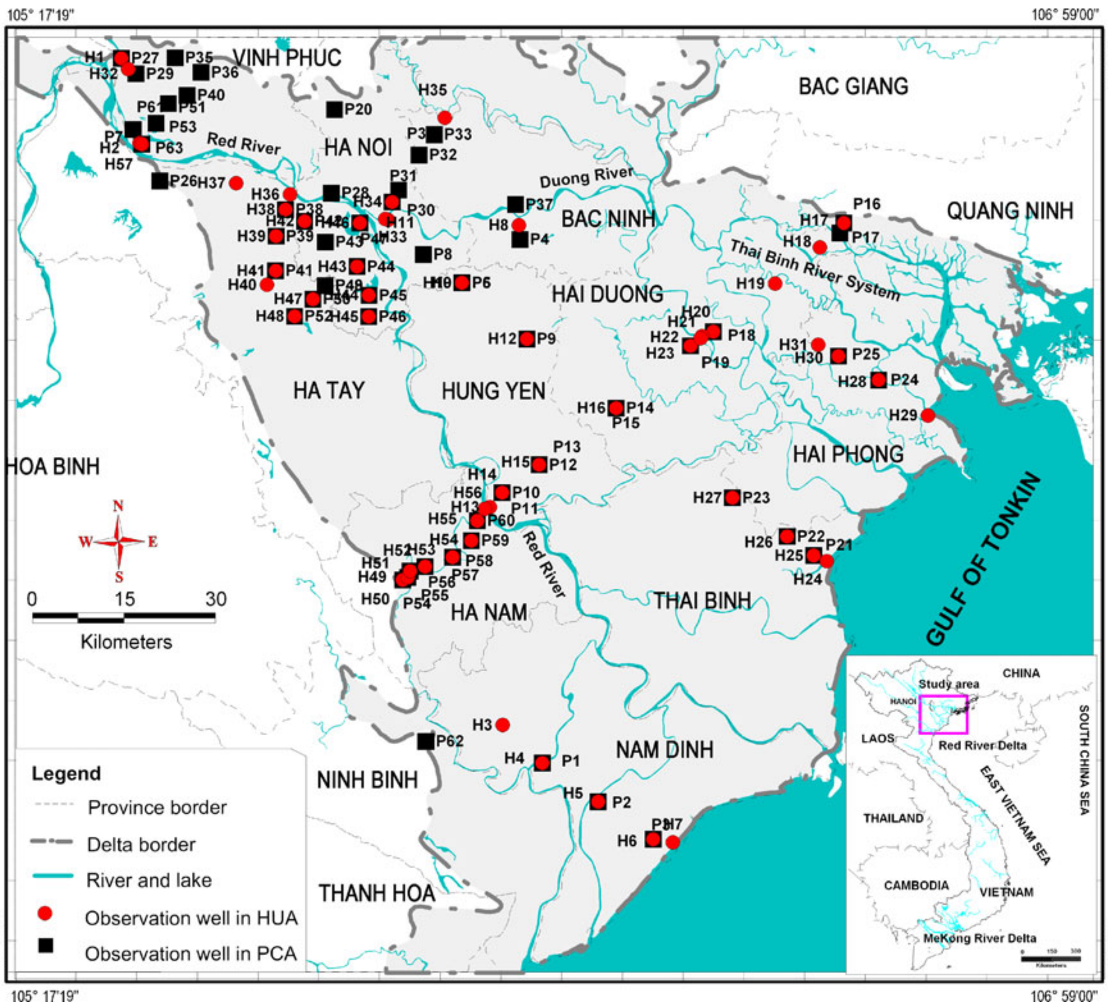

Fig. 1 Study area and groundwater-monitoring network

been investing funds in setting up groundwater observation wells. However, it was not until 1995 when a fairly wide groundwater-monitoring network was set up in the delta and was put into operation. The groundwater-level data monitored by that network is huge, but not systematically organized, and accessible only to a very limited number of users. These primary data sets came from various sources and have large differences in data format, quality, and storage media. Therefore, a time-consuming and costly project for better management and utilization of the observed data was initiated in 2000 under the support and nomination of the Vietnam Department of Geology and Minerals, in which a GIS-based groundwater-monitoring database (GMD) was constructed and maintained. The common advantages of a GIS-based database approach are the reduction in data redundancy, maintenance of data integrity, and security restrictions. Once monitoring wells were successfully constructed, only information about the height of monitoring well heads above the ground, elevation of ground surface and locations of wells (latitude and longitude) was documented and maintained. Other data and information during the construction period such as the drilling method, borehole diameter, annular space, borehole alignment, total depth of the hole, selection of backfill materials, the length of the screen/filter, and other borehole construction notes were not included in the GMD.

So far, 160 observation wells have been installed and maintained in the delta. Basic groundwater variables such as groundwater level, temperature, and quality are being monitored. Groundwater levels are measured either manually or automatically. Recognizing the importance of proper well maintenance, a visual inspection of the exterior of every well is conducted every 3 months to identify such problems as: (1) cracked or corroded well casing; (2) broken or missing well cap or locks; (3) damage to protective casing; and (4) settling and cracking of surface seals. If any of these problems are found, the well should immediately be repaired or abandoned. Furthermore, observers have to carefully check and process all monitoring data before sending them to the central office for updating into the GMD. From this database, general information about groundwater-level fluctuation such as average, max and min, are to be assessed and presented to the public once every year. Prior to the construction of the GMD in 2004, all monitoring data had been mainly stored in paper formats. Now they are stored in digital formats and managed by a GIS-based

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database, and thus the quality of monitoring data is controlled. In order to find out the direction of groundwater movement, it is necessary to determine the elevation (i.e. the height above a datum plane) of the water level in the wells. In this study, groundwater levels (water table) above the mean sea level (amsl) were determined by subtracting the depth of the water from the surface elevation at each observation well. After the water-table data were calculated and validated, they were inputted into the GMD. The record lengths and intervals vary greatly depending on the completion time and the intended usage of the observation wells, as well as the aquifers and variables to be monitored. The groundwater levels are recorded at three types of time interval: every day, once per 3 days, and once per 6 days. Up to now, the record lengths have been about 15 years (1995–2009), which satisfies the required length for utilizing the Mann–Kendall trend test (Maidment 1993). Even though these observed data sets play a vital role in groundwater analyses, so far they are not yet open to the public and only internally accessible by those who are involved in implementing the database project. In addition, the groundwater-monitoring network was installed for groundwater management purposes, and therefore, the recorded data are for internal uses only, not for research purposes. This report is the first to utilize groundwater-level data from the authors' established database. These data sets will be available to the public in the next stage, so that further analyses based on groundwater levels can be performed by scientists in Vietnam and elsewhere to ensure a sustainable development of groundwater resources in the Red River Delta. Details about this project and the database were described in the final report of the project (Tong 2003).

Data used and methodology

Data used

In trend detection studies, the choice of the number of stations is important in order to have a sufficiently high spatial coverage. Stations were selected primarily based on the record length and the quality of data. For the trend analysis groundwater-level data from 120 out of 160 observation wells (Fig. 1) was selected based on the following criteria: (1) a data span of 15 years (1995–2009); (2) there are no more than 5 % missing data; and (3) data are observed for either HUA or PCA, not for other minor aquifers. Among the 120 observation wells selected, there are 57 for HUA and 63 for PCA. The data frequencies of groundwater-level observations are daily, once per 3 days and once per 6 days for 20, 59 and 41 monitoring wells, respectively. The selected observation points well represent the study area.

From the original records, the monthly average groundwater levels were calculated and a total of 17 time series (e.g. annual, rainy and dry season average, annual maximum and minimum, and 12 time series for each month across years) were computed for each well. This resampling process is a commonly used way to solve problems of serial correlation inherent in hydrological time series prior to adopting the non-parametric Mann–Kendall test (Boyles and Raman 2003; Burn and Elnur 2002; Serrano et al. 1999). Observational data were averaged over each season or month in order to remove the seasonal component from the time series, and thus it is not necessary to include adjustments for seasonality and serial correlation when applying the Mann–Kendall test (Hirsch et al. 1982; Helsel and Hirsch 2002).

First, the focus was on detecting trends in the annual time series by applying the Mann–Kendall test since it represents the overall trend among others. Next, the other 16 time series were examined for their trends in more detail by using the same method. While the dry and rainy seasons were investigated to explore trends in seasons, the possible trends in annual maximum and minimum time series were also checked. The 12 time series for the different months of a year were examined to provide insights into groundwater-level trends for each month over the period of 1995–2009.

Methodology

Before detecting the trends in groundwater levels by the non-parametric Mann–Kendall test, a series of graphs of groundwater levels, together with their monthly box plots and linear trends using the parametric regression method, were conducted to get the initial impression of seasonality and trends in groundwater levels at every well. At this step, basic statistics of groundwater levels such as mean, maximum, minimum, coefficient of variation, standard deviation, skewness, etc., were also calculated and summarized into tables. After that, at each well, 17 time series encompassing important groundwater-level components (e.g. annual, dry and rainy seasons, annual maximum and minimum, and the data for each of the 12 months of a year) calculated from the original data were analyzed to detect their trends by utilizing the Mann–Kendall test.

The non-parametric Mann–Kendall test is highly appropriate for trend detection in hydrological variables for several reasons: (1) it does not require data to be normally distributed, (2) it supports multiple observations per time period, (3) it allows missing values and censored observations in the time series (Helsel and Hirsch 2002; Kundzewicz and Robson 2004). This method is, however, not appropriate for time-series data where observations are highly seasonal and serially correlated. The test was originally developed by Mann (1945) and later further developed by Kendall (1948). The Mann–Kendall statistic (S) is given by Eq. (1):

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

x_i and x_j are the sequential data values, and N is the record length.

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 Eq. (2):

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

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

in which $V(S)$ is the variance of S; n is the number of tied groups; and 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 the 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, which provides 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 trends 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 Eq. (4):

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

The monthly time series, which were used for exploratory analysis, were not used for trend analysis at this stage since the presence of serial correlation and seasonality increases the probability of detecting pseudo-trends using the Mann-Kendall test even though no obvious trend exists (Gouglas et al. 2000; Yue et al. 2002; Burn and Hesch 2007). Computer programs were coded using FORTRAN to calculate the procedures of the Mann-Kendall trend test and the Sen's slope estimator. Finally, spatial patterns of trends and their magnitudes were mapped at the regional scale using GIS and Kriging geostatistical techniques. Kriging applies weighted functions according to a mathematical model of the variogram. Kriging has several variograms and in this study, a simple linear variogram was used as the fitting model since it usually generates acceptable grids (Nas and Ali 2010).

Results

General characteristics of groundwater levels

For the exploratory analysis, monthly time series of groundwater levels were plotted for the period of 1995–2009 along with monthly average values on box-whisker plots at 120 monitoring stations in the Red River Delta.

Holocene unconfined aquifer (HUA)

Figure 2 shows hydrographs of selected monthly groundwater levels (1995–2009) in 3 out of 57 HUA wells along with box-plots to show averaged monthly variations. It is apparent from Fig. 2 that the seasonality in groundwater levels is highly pronounced. The three time-series graphs reveal three typical long-term trend patterns for HUA groundwater levels among all 57 wells. The time series of well H5 show an obvious annual cycle with an ambiguous long-term trend, which is found widely in the delta. The H28 time series reveal another distinct pattern consisting of a slightly rising trend with an obvious annual cycle, which is mainly found in the northern and coastal parts. The H42 time series show a representation of a clearly declining trend with an annual cycle of slightly decreasing amplitude, which is generally observed in the highly urbanized areas in the south of Hanoi. The box-whisker plots in Fig. 2 show median, quartiles of 25 and 75 %, and the maximum and minimum values of the monthly groundwater levels. These plots indicate the observation of seasonal variability. Although there are great differences in the monthly water levels among the three wells, the highest water levels were all measured around August. The box-whisker plot revealed that August and December show the smallest and greatest spread (variation) in groundwater-level observations, respectively, for well H5. As the clear long-term trends are included in the box-whisker plots for wells H28 and H42, information on monthly variation of groundwater levels observed from the box-whisker plots for these wells has less accuracy than for well H5.

Table 1 shows the basic statistics for groundwater levels in all 57 wells in the HUA, including the annual water levels in 1995 and 2009, trends in annual water levels during 1995–2009 (m/year), 15-year average of annual cycle amplitude, and 15-year average of differences between rainy and dry seasons. As an average (mean) result of the 57 wells, Table 1 reveals that HUA water levels have decreased from 3.01 m asml—standard deviation (SD) 2.74 m—to 2.60 m amsl (SD 2.96 m) with a trend of 0.03 m/year (SD 0.10 m). The 15-year mean of the annual cycle amplitude was 1.54 m (SD 1.31 m), and the mean water level in the rainy season was 0.74 m (SD 0.76 m) higher than in the dry season.

Gravity is the dominant driving force in groundwater movement, so groundwater usually moves from higher to lower elevations or in the downward direction of the hydraulic head gradient. To visualize the spatial pattern of the water levels, contour maps of the annual mean water levels of each year were generated using the ordinary Kriging interpolation method within the ArcGIS environment. Figure 3a and b show the two selected maps for the water levels in 1995 and 2009, respectively. It is clear from the maps that a cone of depression had formed in Hanoi, while the regional head gradient pattern still

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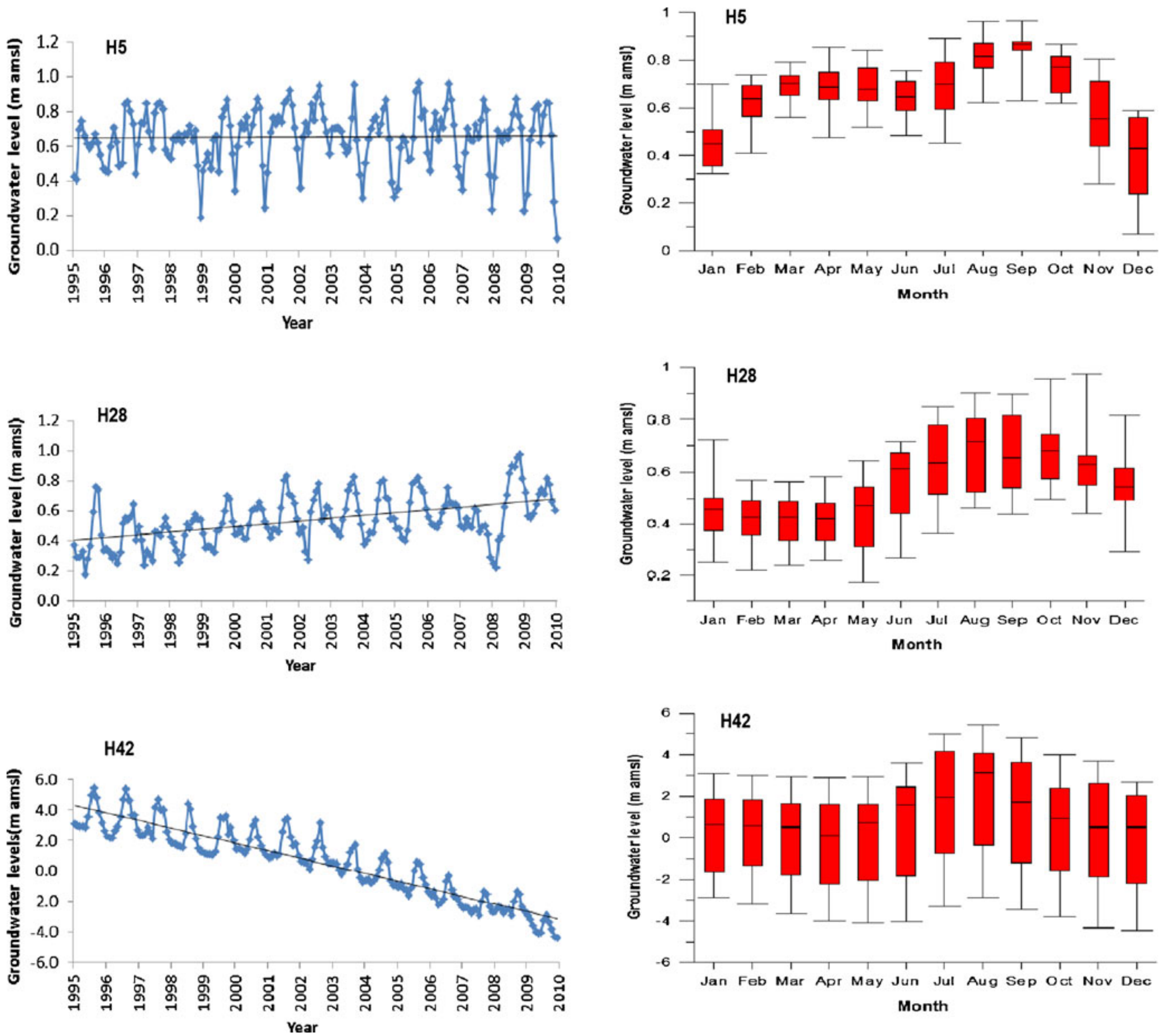

Fig. 2 Monthly groundwater levels (left panel) at three selected HUA wells (*H5*, *H28*, *H42*) along with box-plots of their monthly variation (*right panel*). The *straight line* on the hydrographs indicate linear trends in groundwater levels

remained from northwest to southeast during the past 15 years. The contour maps of the other years, which are not presented here, show gradual change in spatial patterns in groundwater levels in each year.

Pleistocene confined aquifer (PCA)

Figure 4 shows hydrographs of selected time series of 3 out of 63 wells for PCA along with their monthly box-whisker plots. The well P2 time series show a strong downward trend with an ambiguous annual cycle, which is generally observed in highly urbanized areas like Hanoi, Haiphong, Namdinh. The P20 time series present a slight downward trend with an annual cycle, which is commonly found in less urbanized areas. The P53 time series reveal an ambiguous trend with an obvious annual cycle, which is commonly found in groundwater recharge areas (in the margins of the delta). The three box-whisker plots shown in Fig. 4 verify the different levels of seasonality among the three wells. The P20 and P53, but not P2, show the highest water levels in August. The strong declining trend in P2 might diminish the seasonality. The box-whisker plot for the well showing the smallest long-term trends (P53) revealed that the smallest and greatest spread (variation) in groundwater-level observations were found in May and June, respectively.

Futhermore, Table 2 presents basic statistics for all 63 PCA wells during the study period. The mean values of 63 wells reveal that PCA groundwater levels have seriously decreased from 2.54 m amsl (SD 4.66 m) to –0.38 m amsl (SD 6.58 m) with a downward trend of 0.21 m/year (SD 0.18 m), which is much more serious than that of HUA. The 15-year averages of the annual cycle amplitudes and differences between two seasons are 1.35 and 0.51 m,

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Table 1 Basic groundwater-level statistics for all 57 wells in the HUA

Statistics	Annual groundwater levels			15-year average of annual cycle amplitudes (m)	15-year average of differences between rainy and dry seasons (m)
	1995 (m amsl)	2009 (m amsl)	Trends by least square method (m/year)		
Mean	3.01	2.60	–0.03	1.54	0.74
Maximum	12.45	13.35	0.11	5.19	2.94
Minimum	0.29	–3.66	–0.52	0.27	0.03
Median	2.12	1.93	–0.01	0.94	0.46
Coefficient of Vvariation	7.52	8.77	0.01	1.70	0.58
Standard deviation	2.74	2.96	0.10	1.31	0.76
Skewness	1.55	1.26	–2.77	1.51	1.55

respectively, which are smaller than for the HUA. Higher standard deviations indicate that PCA water levels vary in a larger range than HUA. It is interesting that a negative value appeared in the minimum value of the 15-year average of differences between dry and rainy seasons. Figure 5a and b show the two selected contour maps for PCA groundwater levels in 1995 and 2009, respectively. As shown in these figures, the regional head patterns are quite similar to each other, in which the regional head gradient generally runs from northwest to southeast (from inland to the sea) following the general topography of the delta. Large cones of depression had already existed in 1995 in urban areas (Hanoi, Haiphong, and Namdinh) and they were greatly expanded in 2009.

Spatio-temporal patterns of recent trends

Non-parametric 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, b), 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 ($u_{0.025}\leq u\leq u_{0.975}$), 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 $|u_{0.005}| = u_{0.995} = 2.58$.

Holocene unconfined aquifer (HUA)

Table 3 summarizes the trend results for the 17 time series (1995–2009) of 57 HUA wells along with the details for five selected wells. Each selected well is a typical example of each trend group. Table 3 shows statistically significant trends at 5 % in 32 wells (56 %), while no significant trends were found in the remaining 25 wells. Among the 32 wells with significant trends, 20 wells (62 %) show declining trends. The nature of trends for each trend group for the dry and rainy seasons, and annual maximum and minimum time series is quite similar to the trends in the annual time series. Trend results of the 12 months (January to December) show a bigger variation in trends for every trend group. Fewer strong declining trends were found in mostly October, November, and December. Detailed results of the five selected wells reveal that each of the five wells exhibits similar trend results regardless of the 17 time series. In the case of well H42, exactly the same results were obtained.

To examine the spatial distribution of the detected trends, maps showing the locations of 57 wells of the five

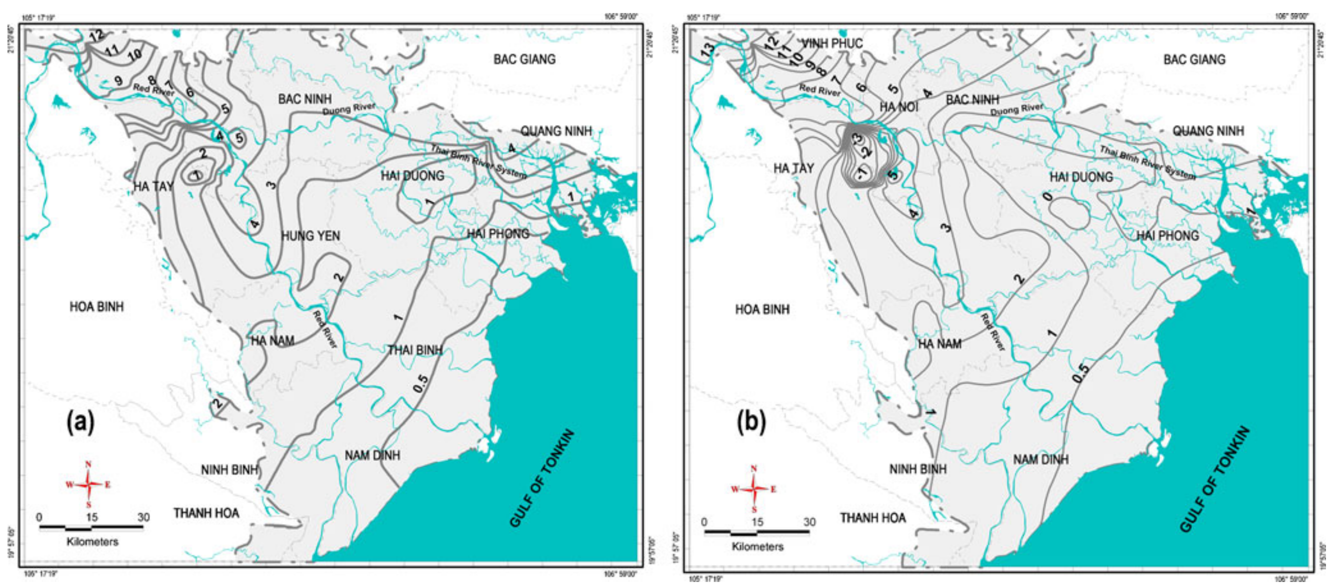

Fig. 3 Contour maps of annual mean of HUA groundwater levels (m asl) in **a** 1995 and **b** 2009

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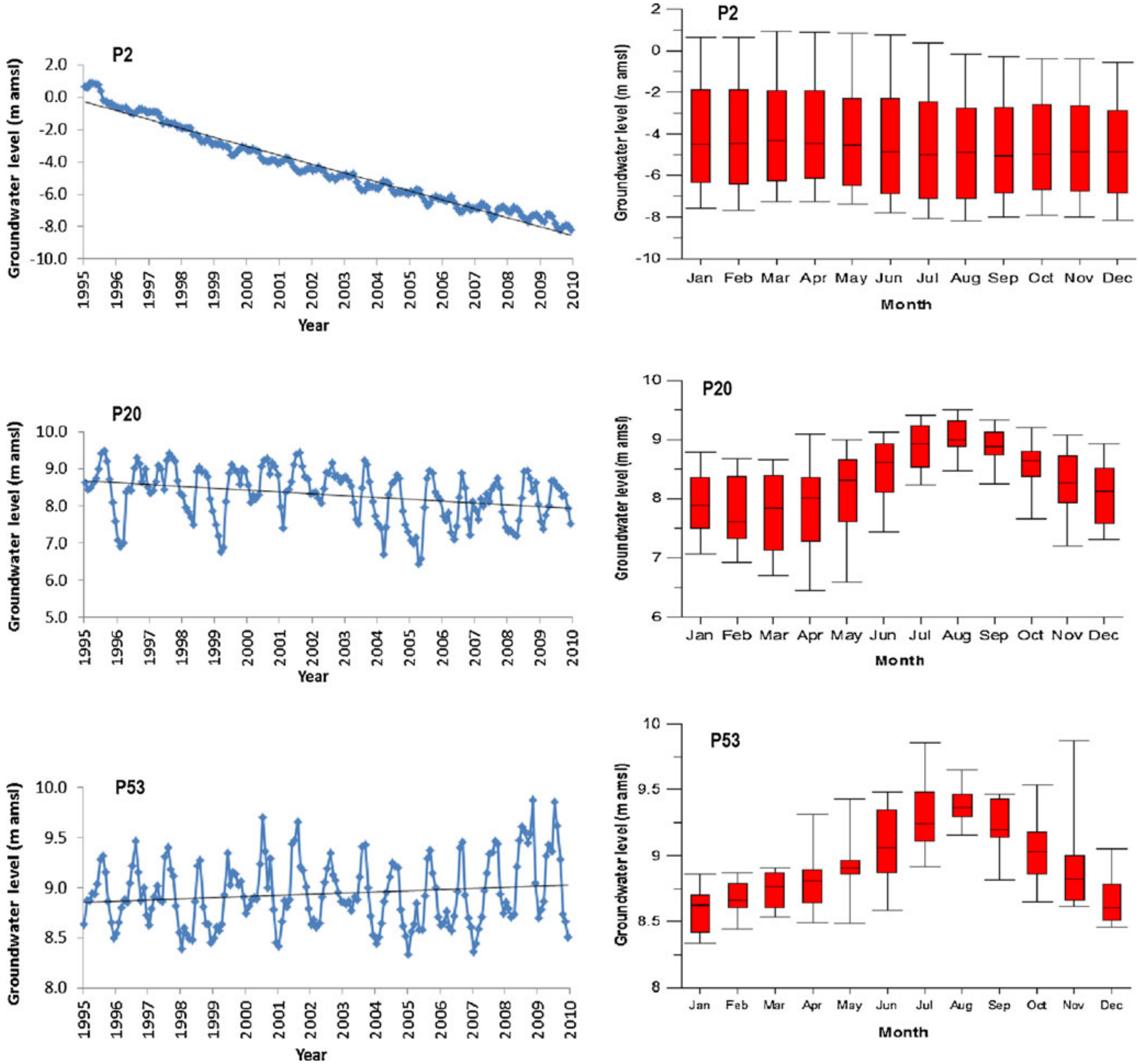

Fig. 4 Monthly groundwater levels (*left panel*) at three selected PCA wells (*P2*, *P20*, *P53*) along with box-plots of their monthly variation (*right panel*). The *straight line* on the hydrographs indicate linear trends in groundwater levels

trend groups were created for the 17 time series. Among these maps, the one for the annual time series is shown in Fig. 6. As seen in this figure, there are noticeable spatial groupings of wells with significant trends. The downward

Table 2 Basic groundwater-level statistics for all 63 wells in the Pleistocene confined aquifer (PCA)

Statistics	Annual groundwater levels			15-year average of annual cycle amplitudes (m)	15-year average of differences between rainy and dry seasons (m)
	1995 (m amsl)	2009 (m amsl)	Trends by least square method (m/year)		
Mean	2.54	–0.38	–0.21	1.35	0.51
Maximum	11.43	9.11	0.07	5.04	2.68
Minimum	–15.35	–21.41	–0.66	0.21	–0.43
Median	2.09	0.34	–0.16	1.09	0.43
Coefficient of variation	21.73	43.25	0.03	0.97	0.42
Standard deviation	4.66	6.58	0.18	0.99	0.65
Skewness	–1.05	–1.09	–0.99	1.79	1.43

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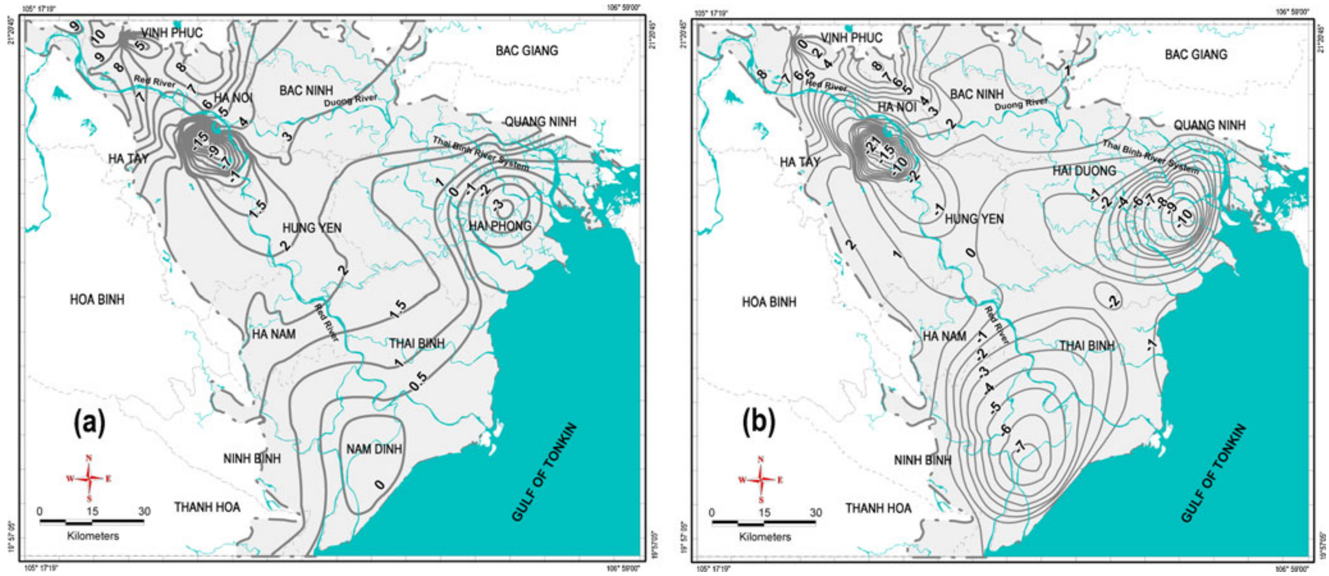

Fig. 5 Contour maps of annual mean of PCA groundwater levels (m amsl) in **a** 1995 and **b** 2009

trends are widely observed in the upper parts of the delta, especially in Hanoi and Hanam, while the upward and insignificant trends are mainly located in the coastal areas.

Table 4 shows trends (m/year) for the 17 time series of five selected wells. The positive and negative signs of trend present rising and declining water levels, respectively. As shown in Table 4, the mean of the trends varies from –0.50 to 0.02 m/year, and they are different between the wells. The rising trend calculated for H28 (~ 0.02 m/year) is in contrast to the declining trend of H42 (–0.5 m/year) at the same significance level of 1 %. Considering the detailed results of the trends of all 57 HUA wells, similar results of spatial heterogeneity were observed.

To visualize the spatial pattern of trends, contour maps of the trends for each time series were created by utilizing GIS and Kriging interpolation methods as mentioned earlier. Figure 7 shows a selected map for the annual time series where distinct regional slope patterns are highlighted. Declining slope trends are distributed in a major portion of the delta, while three zones of upward trends are identified in the coastal region, Hungyen province, and northern parts of the delta. As shown in Fig. 7, downward trends are mainly less than 0.2 m/year except for around 60 km^2 in the south of Hanoi where severe downward trends of more than 0.3 m/year are observed. On the other hand, the upward trends are rather small, less than 0.1 m/year.

Pleistocene confined aquifer (PCA)

Similar to Table 3, Table 5 presents a summary of the trend results of 63 PCA wells along with the details for three typical wells. The number of trends for the annual time series in Table 5 indicates that statistically significant downward trends were identified in almost all the wells (57 strong and 3 weak downward trends out of 63 wells).

Table 3 Results of Mann-Kendall test for trends in 57 HUA groundwater levels along with the details for five selected wells

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

UU strong upward trend, U weak upward trend, X no significant trend, D downward trend, and DD strong downward trend

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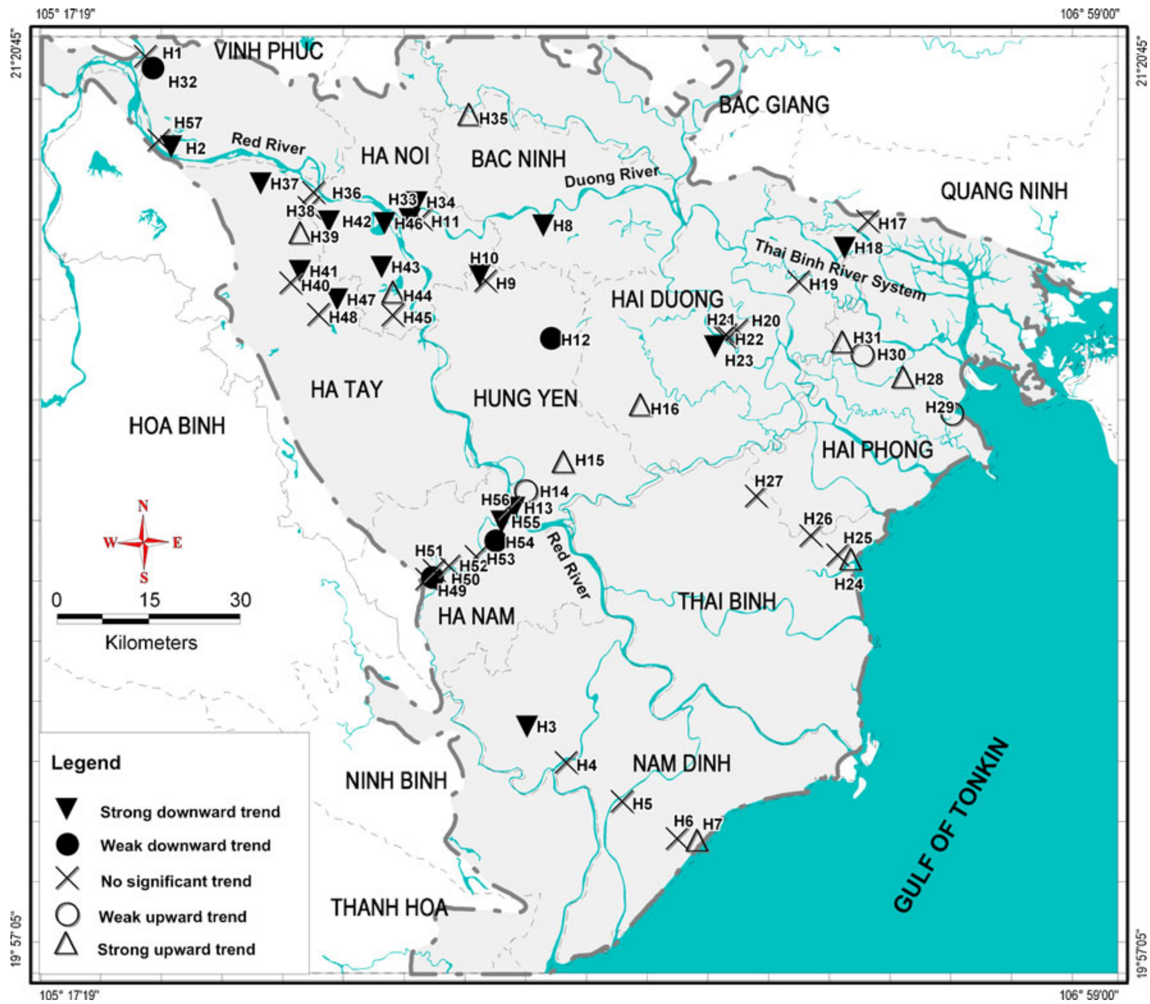

Fig. 6 Spatial distribution of Mann-Kendall trends in annual mean of HUA groundwater level

Only three wells show no significant trend and there is no upward trend at all. Regarding the other time series, upward trends were also not detected at all, while the numbers of no significant, strong and weak downward trends were different among time series. The annual and dry season time series show the highest number (60) of

Table 4 Results of Sen's estimator for trends in groundwater levels in five typical HUA wells (m/year). SD standard deviation

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

[a] Indicates trends at 5 % significance

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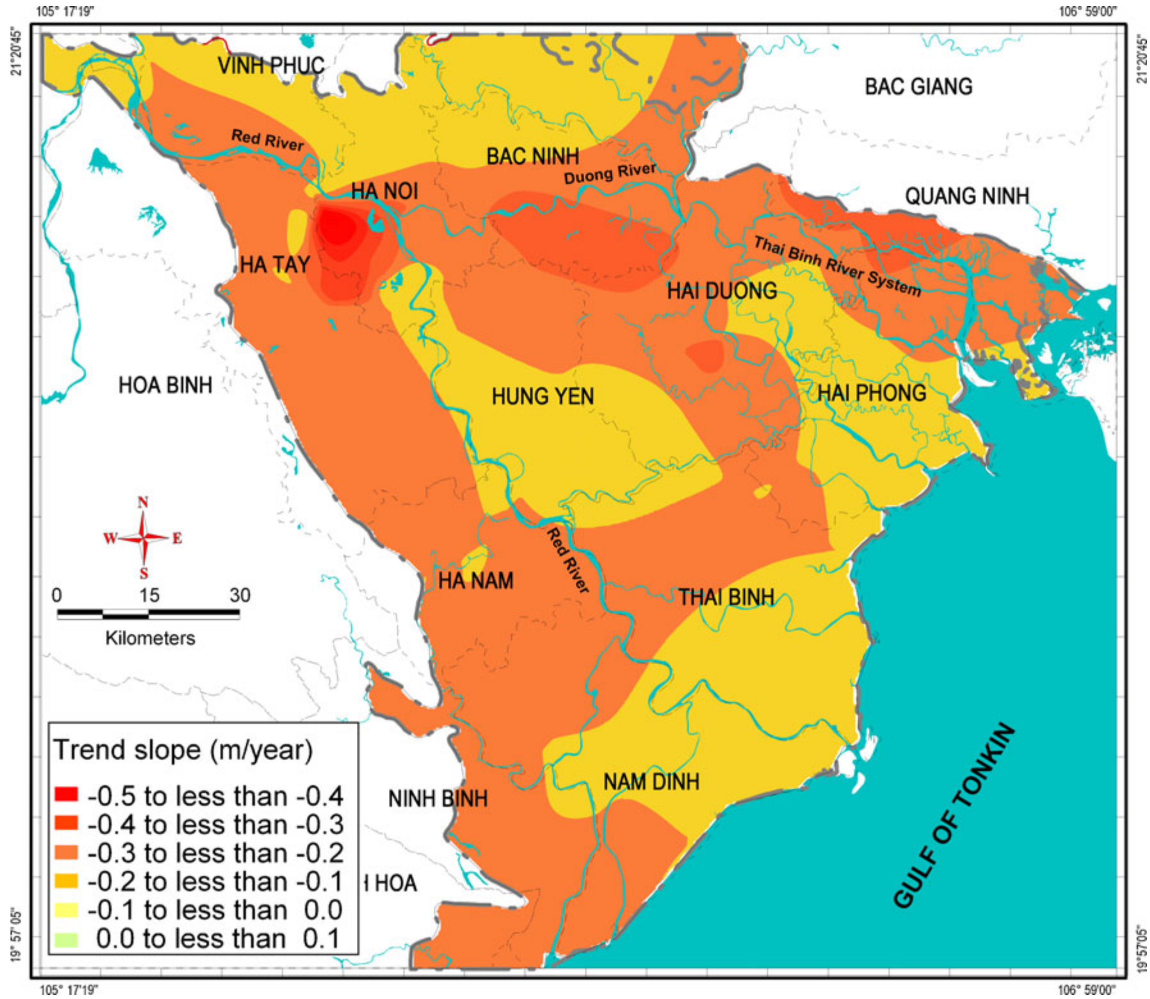

Fig. 7 Spatial distribution of trends in annual mean of HUA groundwater levels. *Negative values* represent downward trend and positive values represent upward trend

downward trends (both strong and weak downward trends), while only 52 cases are found in November. The detailed results of three selected wells reveal that wells P2 and P53 show exactly the same trend results regardless of the 17 time series. The trend results with different trends in several time series like P20 are only observed in a few

Table 5 Results of Mann-Kendall test for trends in 63 PCA groundwater levels along with the details for three selected wells

Time series	Number of trends in 63 wells					Trend details of three selected wells		
	DD	D	X	U	UU	P2	P20	P53
Annual	57	3	3	0	0	DD	D	X
Rainy season	56	3	4	0	0	DD	DD	X
Dry season	57	3	3	0	0	DD	D	X
Maximum	54	4	5	0	0	DD	DD	X
Minimum	56	2	5	0	0	DD	X	X
January	52	7	4	0	0	DD	X	X
February	55	3	5	0	0	DD	X	X
March	56	2	5	0	0	DD	X	X
April	57	1	5	0	0	DD	D	X
May	53	5	5	0	0	DD	X	X
June	51	5	7	0	0	DD	X	X
July	55	4	4	0	0	DD	DD	X
August	55	3	5	0	0	DD	DD	X
September	51	4	8	0	0	DD	DD	X
October	50	6	7	0	0	DD	D	X
November	45	7	11	0	0	DD	X	X
December	53	5	5	0	0	DD	X	X

UU strong upward trend, U weak upward trend, X no significant trend, D downward trend, and DD strong downward trend

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of the 63 wells. Compared to HUA, it is clear that the trend results for the PCA are quite different from those for HUA. Both PCA and HUA show the highest number of insignificant trends in November. Furthermore, Fig. 8 shows the locations of 63 PCA wells with the symbols of the five trend groups for the annual time series. As shown in this figure, strong downward trends widely occur over the study area. Only three wells (P32, P53, and P54), located in the margins of the delta, show no significant trend.

Table 6 presents the trends (m/year) for the 17 time series of 3 selected wells for PCA. Similar to HUA, Table 6 reveals that the mean of the trends varies from –0.53 to 0.01 m/year, and they are quite similar among time series. P2 exhibited the most severe downward trends, with more than 0.50 m/year, in all time series. Upward trends of about 0.01 m/year were observed in P53, even though it has the same significance level of 5 % as P2.

In order to examine the spatial distribution of the trends, the 17 contour maps of the trends for all time series were created. Figure 9 shows a selected map for the annual time series where distinct patterns of trends are clarified. An extensive decreasing tendency was dominant almost all over the study area. Serious downward trends occurred in the central and coastal regions of the delta, particularly in main cities such as Hanoi, Hatay, Haiphong and Namdinh. Figure 9 indicates three areas, of around 3,400 km^2 in total, with serious downward trends of more than 0.30 m/year. These areas occupy almost 25 % of the delta, and are much larger than those of the same downward trends occurring in HUA.

Discussion

Analyses of groundwater-level trends in this report revealed several interesting features of groundwater-level patterns in the Red River Delta. The seasonality in groundwater levels for both HUA and PCA is closely associated with the annual cycles of rainfall and river-water levels (Tong 2007). The smaller annual cycle amplitudes and less differences between two seasons found in PCA indicate that the influences of rainfall and river-water levels on PCA are less than those on HUA. Interestingly, the minimum values of the 15-year average of differences between dry and rainy seasons were found to be negative in some wells (as shown in Table 2), which indicates higher groundwater levels in the dry season than

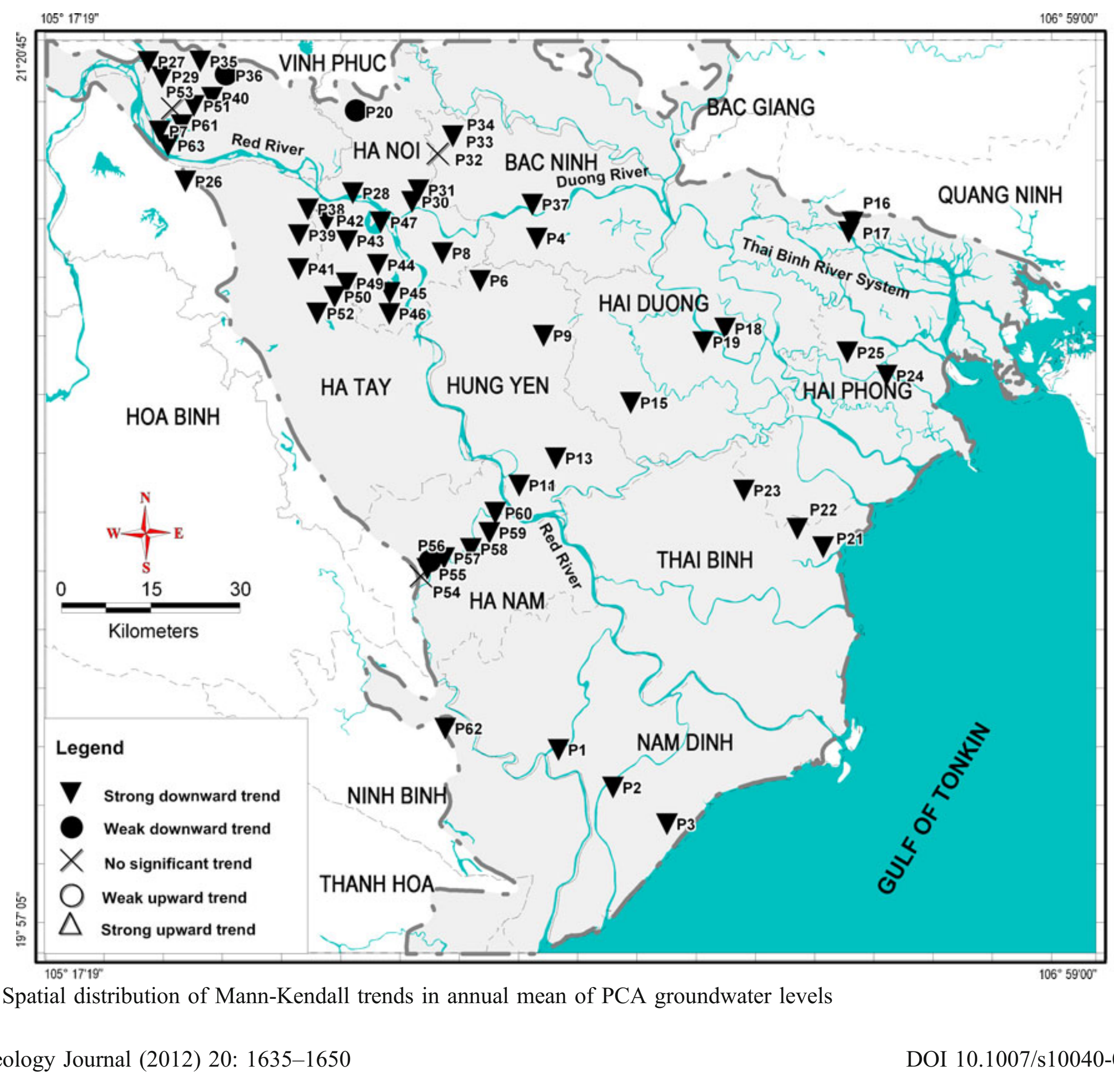

Fig. 8 Spatial distribution of Mann-Kendall trends in annual mean of PCA groundwater levels

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Table 6 Results of Sen's estimator for trends in groundwater level in three typical PCA wells (m/year). SD standard deviations

Time series	P2	P20	P53
Annual	–0.53[a]	–0.06	0.01
Rainy season	–0.54[a]	–0.05[a]	0.02
Dry season	–0.53[a]	–0.06	0.00
Maximum	–0.50[a]	–0.05[a]	0.02
Minimum	–0.53[a]	–0.03	0.00
January	–0.55[a]	–0.06	0.00
February	–0.54[a]	–0.04	–0.01
March	–0.52[a]	–0.04	0.00
April	–0.50[a]	–0.06	–0.01
May	–0.52[a]	–0.05	0.01
June	–0.55[a]	–0.04	0.01
July	–0.55[a]	–0.06[a]	0.01
August	–0.54[a]	–0.05[a]	0.01
September	–0.53[a]	–0.05[a]	0.03
October	–0.53[a]	–0.06	0.02
November	–0.53[a]	–0.07	0.00
December	–0.52[a]	–0.04	0.01
Mean	–0.53	–0.05	0.01
SD	0.02	0.01	0.01

[a] Indicates trends at 5 % significance

the rainy season. This phenomenon could be due to the lag time for rainwater to be infiltrated into the deeper aquifer (PCA). Both parametric and nonparametric procedures revealed long-term trends in groundwater levels throughout the delta. The trends estimated here could be a useful reference to estimate groundwater levels in both aquifers

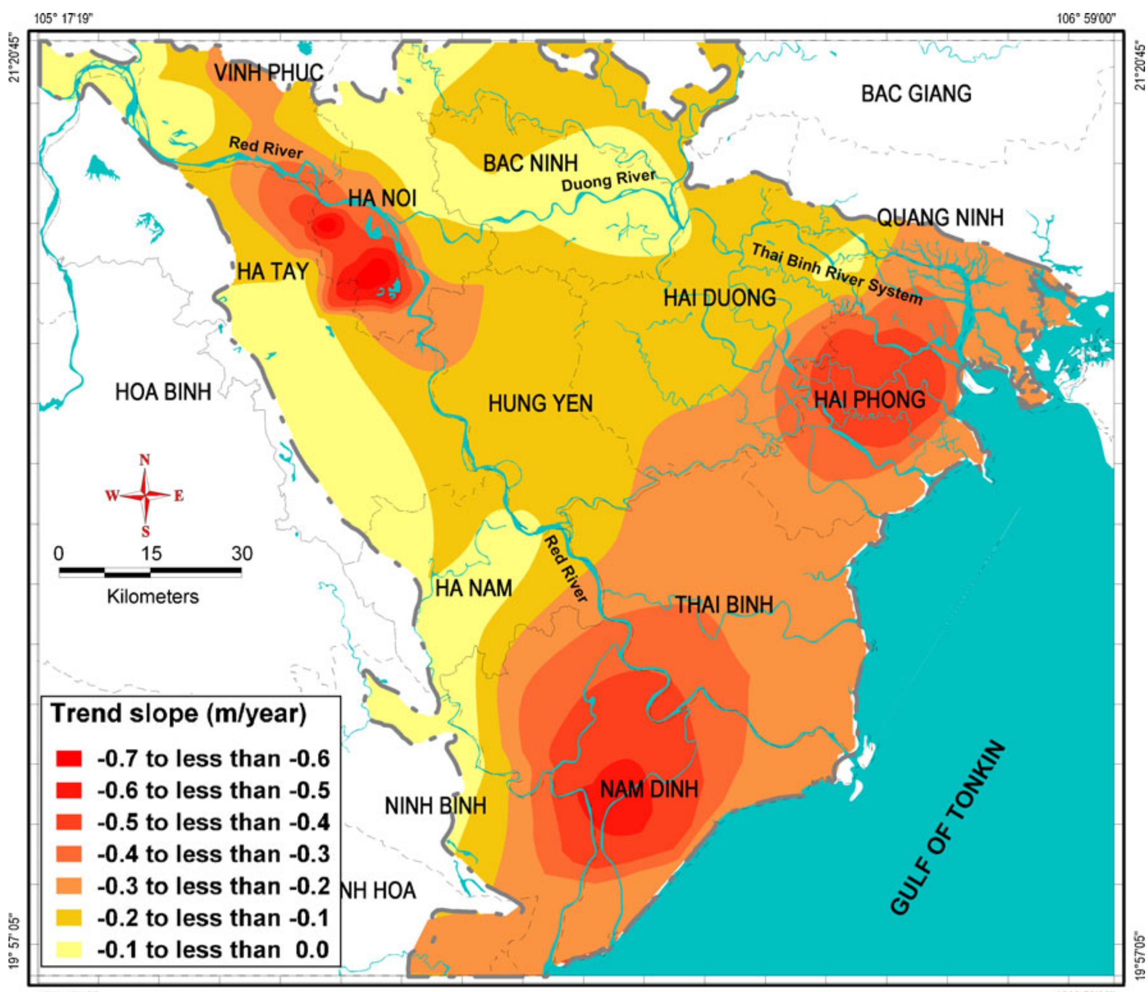

Fig. 9 Spatial distribution of trends in annual mean of PCA groundwater levels

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in the Red River Delta in the future. The trend results for the two aquifers in the delta are complicated and vary in wide ranges, which results from great heterogeneities of groundwater abstraction, climatic variations, and characteristics of the aquifers. The spatial distribution of groundwater pumping for each province within the delta quoted in the survey report (Tong 2007) illustrates that the urban areas with substantial abstractions (e.g. Hanoi, Hatay) are well matched with the areas of serious declining trends. In Hanoi, for example, almost 100 % of domestic water is from groundwater, and the amount of groundwater abstraction has been rapidly increasing from 200,000 m^3/day in the 1970s to about 400,000 m^3/day in 1990s and up to 800,000 m^3/day at present (Tong 2007). Although there have been no quantitative estimations of groundwater recharge in the delta, the aquifer framework identified by earlier studies (Bui et al. 2011, 2012) indicated that the recharge zones of the aquifers are mainly in the neighboring mountains around the border of the Delta. This fact could be one of the reasons for reduced downward trends (< 0.1 m/year) in water levels along the margin of the delta because the groundwater recharge in these areas is obviously higher than in other areas due to the exposures of aquifers on the ground surface. Regarding the trend results for HUA (Fig. 7), the cone of depression of the upper aquifer (HUA) in the south of Hanoi is partly due to a serious drop in groundwater levels of the deeper aquifer (PCA), because the thicknesses of the aquitard sandwiched by the HUA and PCA in Hanoi are much thinner than those in other areas (Bui et al. 2011, 2012) and groundwater levels of the two aquifers in Hanoi are highly interconnected (Tong 2007). As indicated in these studies, the confining layer between the HUA and the PCA is mainly composed of slightly permeable or impermeable materials like silty clay, clay sand and clay. It has an average thickness of about 10 m and low permeability, less than 0.1 m/day. However, in some minor places in Hanoi the confining layer has been thinned out and PCA is covered directly by HUA and they even share a unique hydraulic head. As for the PCA, this report identified the biggest cone of depression in Namdinh (Fig. 9), but total pumping from the PCA in Namdinh is only about 5 % of total abstraction in Hanoi (Tong 2007). This is not a contradiction because the earlier study (Bui et al. 2011, 2012) indicated that the PCA in Hanoi is shallow, highly permeable, and closely interconnected with the Red River. Therefore, groundwater in Hanoi receives more recharges from surface water than in Namdinh because shallow aquifers adjacent to rivers mostly experience greater groundwater recharge (Shamsudduha et al. 2011). In lower reaches of the river, groundwater levels are also mostly low, which is similar to the phenomena observed in other regions such as the Rivers Brahmaputra and Ganges (Shamsudduha et al. 2011) and the River Meghna (WMO and GWP 2003).

Serious water-level decline over the coastal areas of the PCA likely causes saltwater intrusion, which was proven by the high concentration of total dissolved solids (>1 g/L) in groundwater in these areas (Bui et al. 2011). Projected rises in sea level due to effects of global warming would accelerate the intrusion of saline water, thereby impairing groundwater quality and threatening sustainable development of coastal aquifers. The <0.1 cm/year rising trend observed from 1995–2009 in HUA groundwater levels mainly resulted from the changes in pumping strategy, whereby the local governments in those areas recently stopped pumping groundwater from the top most aquifer (HUA; Tong 2007), and thus the HUA groundwater levels have gradually recovered to their normal stages. Rising trends in groundwater levels in the estuary and coastal areas of HUA in the Red River Delta is also likely associated with rising sea levels. Observed sea levels from 1960–2005 in the adjacent sea (Gulf of Tonkin) revealed mean rates of sea level rise of around 0.4 cm/year (MONRE 2009). These rates are much higher than the average rate of global sea level rise of 0.18 cm/year for the twentieth century (IPCC 2007). Other studies have indicated that, as sea levels rise, shallow groundwater in coastal areas is elevated through an overall rise in the position of the freshwater-seawater interface (McCobb and Weiskel 2003; Barlow 2003). It is important to note that a rise in the groundwater level caused by sea level rise could impact river deltas up to 20–50 km inland (Barlow 2003), and coastal defenses (e.g., embankments, dykes) will not inhibit groundwater intrusion from seawater (Shamsudduha et al. 2011).

Furthermore, rising trends in HUA groundwater levels in lower parts of the delta could be associated with land subsidence. Even though there are no data on land subsidence in the lower part of the delta, evidence of land subsidence in other areas within the delta could provide valuable references for these processes. For example, Nguyen and Nguyen (2004) found that the land surface in Hanoi had subsided with an average rate of about 0.02 m/year. The highest land subsidence rate (0.04 m/year) was found in the central and southeastern parts of Hanoi where groundwater levels have seriously declined, and the soil strata are composed of thick, compressible soils. Similar land subsidence might take place in two coastal cities (i.e. Haiphong and Namdinh) in the lower deltaic region because similar cones of depression have occurred. Once land subsidence occurs, the tops of the wells might move down and then affect measurement of groundwater levels. The detected upward trends in groundwater levels might be overestimated and the downward trends could be underestimated. Thus, field observation of land subsidence in these regions needs to be implemented in the future so that contribution of land subsidence to the groundwater-level trends can be taken into account.

Furthermore, it is also noted that the observation wells in the delta (Fig. 1) are denser in urbanized areas, and thus the trend results for cities have higher accuracy than those for rural areas. The contour maps showing spatial pattern of annual groundwater levels (Figs. 3, 5) and trends (Figs. 7, 9) would provide more insights if there were more observation wells in rural areas. In addition, similar to the Red River Delta, the annual cycle in groundwater levels and its strong linkages to rainfall and surface water

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have been clarified in other countries. The strong seasonal variations in groundwater levels are closely associated with monsoon rainfall in the Ganges-Brahmaputra-Meghna Delta, Bangladesh (Shamsudduha et al. 2009), while direct relationships between groundwater storage and river-water levels (Sanz et al. 2011) as well as lake water levels (Ghanbari and Bravo 2011) were found in Spain and Wisconsin, USA, respectively. Groundwater-level declines due to over-exploitation have also been studied in other Asian cities such as Dhaka and Bangkok (Phien-wej et al. 2006; Shamsudduha et al. 2009, 2011). Current groundwater abstractions in other Asian Deltas such as the Chao Phraya Delta (Thailand) and Ganges-Brahmaputra-Meghna Delta are higher than in the Red River Delta but increasing groundwater abstraction in the Red River Delta, particularly in urban areas are likely to intensify groundwater-level declines. The findings of this project reflect unsustainable development of groundwater resources in the Red River Delta, particularly in urban areas, and the importance of maintaining groundwater-level monitoring and the database.

Conclusion

A groundwater-level database has been constructed consisting of 160 monitoring wells in the Red River Delta, Vietnam, and examined spatio-temporal patterns of recent (1995–2009) trends in groundwater levels using the robust non-parametric Mann-Kendall trend test and Sen's slope estimator. Estimated trends in annual, seasonal, maximum, minimum, and monthly groundwater-level time-series data at 120 monitoring locations are given. Results from the annual time series showed declining trends in 20 out of the 57 wells for the HUA, but rising trends were found in 12 wells. Analyses have highlighted that strong declining trends are mainly in Hanoi, with magnitudes of about 0.30 m/year, whereas rising trends are found in the coastal region, Hungyen province, and northern parts of the delta with magnitudes of around 0.10 m/year. On the other hand, the study revealed that groundwater levels of the PCA have decreased in 63 wells with an average trend of about 0.20 m/year. The areas which showed strongly declining trends of >0.30 m/year occupied an area of 3,400 km^2 (about 25 % of the delta). In general, the groundwater levels in the main cities such as Hanoi, Haiphong, and Namdinh showed greater declines in groundwater levels than other areas. Rapidly declining groundwater levels in coastal areas particularly threaten sustainable development of aquifers due to saltwater intrusion.

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