Spatial decline distribution of groundwater levels of confined aquifer in the whole Red River Delta, Vietnam

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ABSTRACT

Monitoring and interpreting changes in groundwater levels are essential for groundwater management. However, a fairly wide groundwater monitoring network over the Red River Delta, Vietnam was not set up until 1995. This paper investigated trends and their slopes in groundwater level series (1995- 2009) in 63 observation wells for confined aquifer by the non-parametric Mann-Kendall trend test and Sen's slope estimator. The analyses revealed that groundwater levels experienced significant downward trends almost all wells and time series. Spatial distribution of different trend slope was clarified over the delta in which central and coastal areas showed more serious downward trend slopes than other areas. Trend results for 18 different time series (e.g. monthly, seasonal, annual means and so on) were quite similar regardless to time series to be studied. While annual cycle in groundwater levels were strongly associated with those in rainfall and river water levels, long-term downward trends could result from increasing groundwater withdrawal.

INTRODUCTION

Groundwater plays a very significant role in the supply of water for human activities. Sustainable management of groundwater resources is one of the essential objectives for the future a country, especially when the rising demand for clean drinking water is considered (Mende et al., 2007). Obviously, excessive groundwater abstraction causes serious groundwater level decline in many areas over the world. Groundwater level declines likely have a number of adverse impacts on the environment. Most directly, groundwater level decline is no doubt an indicator of groundwater depletion and aquifer degradation, which threatens aquifer sustainable development (Akther et al., 2009). Other obvious impacts are land subsidence resulting from the compaction of materials (Konikow and Kendy, 2005), and groundwater contamination partly due to the intrusion of undesirable materials (Hoque et al, 2007; Berg et al., 2007). Likewise, surface waters are also affected through reducing groundwater discharges to surface water bodies (Konikow and Kendy, 2005), and then ecosystems might be affected adversely (Zektser et al, 2005).

In the Red River Delta (RRD), Vietnam, people depend mainly on groundwater for their domestic water use, while quite a few groundwater-related studies for the Delta have been investigated in literature. Most of them were concerned about the origin, evolution, and development of the deltas, surface water and groundwater pollution, and aquifer system identification. Duong et al., (2003), for example, considered the groundwater quality and monitoring system design. 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. Even though an ability to understand and interpret changes in groundwater levels is essential for sound management of groundwater resources (Ferdowsian and Pannell, 2009; Hoque et al., 2007), there has not been any analysis on trend and variability of groundwater levels. In fact, detection long-term trends in groundwater levels is a difficult issue because underground data commonly have short record length, limited spatial coverage, and high uncertainty.

As the result of growth concerns in global warming and climate changes, numerous trend detection studies have been carried out in many parts over the world for many climate and surface hydrological variables such as: temperatures (Boyles and Raman, 2003; Sharma et al., 2000); precipitation (Boyles and Raman, 2003; Delgado et al., 2010); humidity (Abu-Taleb et al., 2007; Paltridge et al., 2007); surface water variables (Hamed, 2008; Delgado et al., 2010); snowmelt runoff (Burn, 1994; Mccabe and Clark, 2005); water quality (Antonopoulos et al., 2001; Johnsona et al., 2009) to name but a few. In contrast, there have been few trend studies for groundwater due to unavailability of long time series. Almedeij and Al-Ruwaih (2006), for example, investigated periodic behavior of groundwater level fluctuations in residential areas of Kuwait. In Bangladesh, Hoque et al. (2007) and Akther et al. (2009) clarified causes and quantification of declining trends as well as spatio-temporal pattern of groundwater levels in Dhaka, while Shamsudduha et al. (2009) identified recent trends in groundwater levels in the Ganges-Brahmaputra-Meghna Delta. Another case explored trends in groundwater level graphs in Esperance, Australia (Ferdowsian and Pannell, 2009). In these groundwater trend studies, however, the non-parametric Mann–Kendall (MK) test has not yet been tested even though it has been continually highlighted as an excellent trend detection tool (Esterby, 1998; Kundzewicz and Robson, 2004; Delgado et al., 2010).

At present, a fairly wide groundwater monitoring network of 82 observation wells for Pleistocene unconfined aquifer (PCA) in the Delta has been operated since around 1995 and then we have constructed and maintained a costly groundwater monitoring database (GMD) to gather all the observed groundwater data since 2000. To utilize our internally-available data sets, and to understand groundwater behaviors of the Delta's aquifer systems which were identified by our earlier study (Bui et al., 2010), This paper present an analysis of the trends and variability in groundwater levels of PCA for the period of (1995-2009). Before detecting the trends in groundwater level by the MK test, series of graphs of groundwater levels at every observation well were established to get the initial impression of seasonality and trends in the groundwater levels. The analysis was conducted for 18 time series of useful features of groundwater levels (e.g. monthly and annual data, dry and rainy seasonal data; annual maximum and minimum data; and the data for each of twelve months of a year) to provide insights into the trends and their slopes. In addition, the spatial distribution of trends and their slopes were clarified by using GIS methods.

STUDY AREA AND GROUNDWATER MONITORING NETWORK

Study area

The Red River Delta with a surface area of about 13,000 km^2 in the north of Vietnam is one of two biggest and most developed deltas in Vietnam as shown in Fig. 1. The population is about 19 million in 2007, occupying 22% of the total population. Delta elevation is mainly below 12 m and considered as flood plain. The delta belongs to the tropical monsoonal area with two distinctive seasons: rainy (May to Oct) and dry (Nov till April) seasons. The annual rainfall is about 1,600 mm of which rainfall in the rainy season occupies about 75%. The tide range near the delta is about 4m. The river network is quite dense with the density of about 0.7 km/km^2. However, the water of the Red River is at high level of suspended load throughout the year. Surface water, especially in lakes, cities over the delta has been seriously polluted due to insufficiency of infrastructure and unwise management of dumping waste. Groundwater thus becomes a main source of water supply in the delta (Tong, 2007).

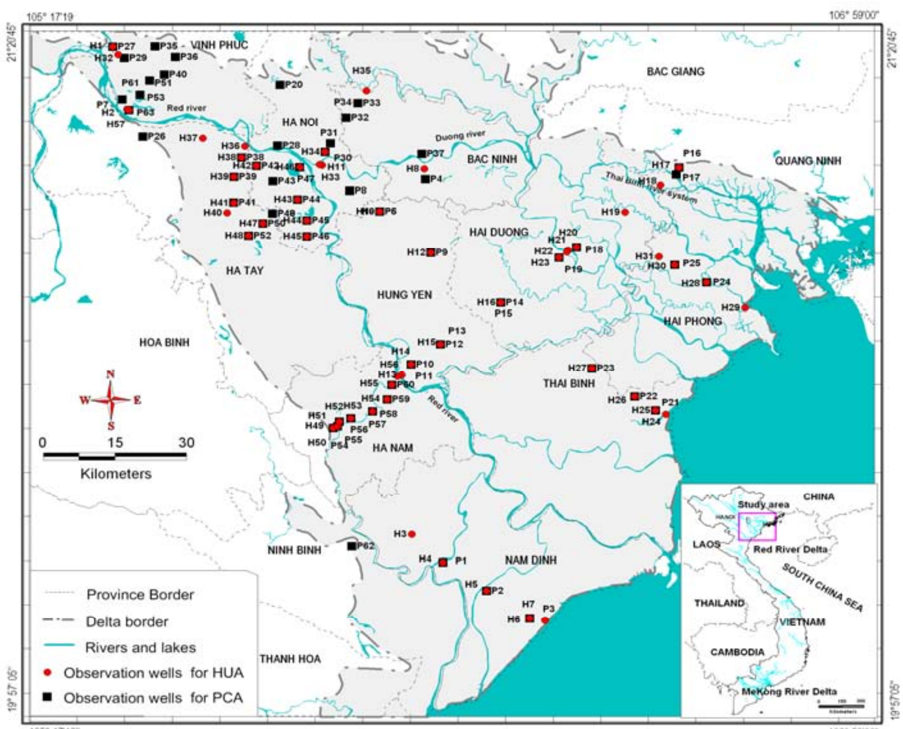

Figure 1. Study area and groundwater monitoring network.

Establishment of Groundwater Monitoring Network and Database

Data availability is also 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, which is an obstacle for groundwater management on a large basin scale. Since 1987, the Vietnamese government had begun investing to set up groundwater observation wells. However, it was not until

1995 that a fairly wide monitoring network was set up and has gone into operation. The monitored data are huge but not systematically organized. Thus, a costly project for better management and utilization of observed data was initiated in 2000, in which we constructed and have maintained a GIS-based groundwater monitoring database (GMD). So far, 82 wells have been installed for PCA of the delta. The basic data, such as groundwater level, temperature, and quality are being monitored. Record lengths and intervals vary depending on completion time, the intended uses of the 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. Up to now, the record lengths of about 15 years (1995-2009) basically satisfy the required length in utilizing the MK trend test (Maidment, 1993). Even though these data sets play a vital role in groundwater analyses, they are not yet open to the public, and only internally accessible by project-involved agencies and staff like us. Details about this project and the database were described in the project report (Tong, 2003).

DATA USED AND METHODOLOGY

Data used

Data are essential of trends or changes detection studies, and so they should be quality-controlled before commencing an analysis of change (Kundzewicz and Robson, 2004). Therefore, to take advantage of the data from our GMD as much as possible, groundwater levels at 63 out of 82 wells in the delta (Fig. 1) were selected based on the following criteria: (1) there are at least 15 years of recorded data; (2) there is no more than 5% missing data (Endo et al., 2009; Ampitiyawatta and Guo, 2009); and (3) data are observed for PCA. As shown in Fig. 1, the selected points are well distributed over the study area. The advantage of this data selection is that it is less influenced by data quality problems, and provides good spatial coverage and a reasonable record length. From the original records, 18 time series for each well were computed for detecting trends. Additionally, the monthly rainfall and Red River water level in Hanoi were also examined for their linkages with groundwater levels.

Methodology

Before conducting a formal test for trends, preliminary analyses were conducted to get an initial visual understanding of the data, such as data problems (mean, gaps in record, etc.), basic temporal and spatial patterns (monotonic trend or jumps, seasonality), test assumptions (independence, distribution), and so on. In this study, the non-parametric MK trend test is utilized since it is highly appropriate trend test for hydrological series. 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 (β) of the detected trends as 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.

RESULTS AND DISCUSSION

General characteristics of groundwater levels

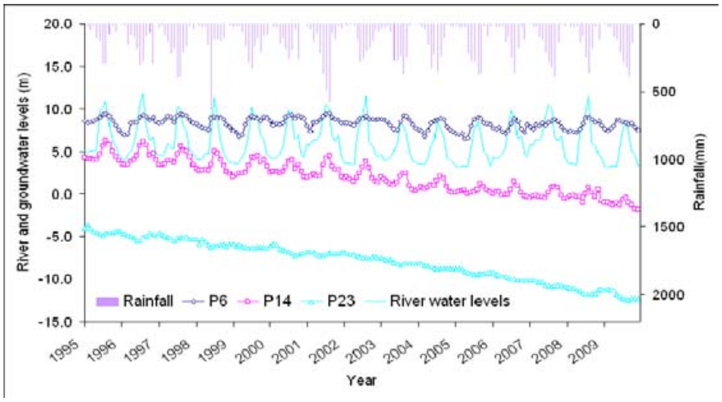

Figure 2. Monthly groundwater levels at three selected wells along with monthly rainfall and monthly Red River water levels

Preliminary analysis is conducted through plotting the 18 time series at each well, and then establishing 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. Fig. 2 shows selected monthly groundwater levels at 3 out of 63 wells, along with monthly rainfall and river water levels. It is apparent from Fig. 2 that annual cycle in groundwater levels is highly associated with those of rainfall and river water level because of almost no seasonal change in withdrawal rate within a year. In addition, Fig. 2 reveals three typical long-term trend patterns: a clear downward trend with an ambiguous annual cycle (P23); clear downward trend with an obvious annual cycle (P14); and unclear long-term trend with the annual cycle (P6). Futhermore, Fig. 3 (a,b), which were created by utilizing the GIS and Kriging methods to visualize the spatial pattern of groundwater levels, show two selected countour maps of the groundwater levels in 1995 and 2009, respectively. As shown in these figures, the groundwater flow patterns are quite similar to each others, in which flow direction is generally from northwest to southeast corresponding to the delta topography. Large cones of depression already existed in 1995 in urban areas (Hanoi, Haiphong, and Namdinh) and they are continuous to expand during the past 15 years. The maps for the other years, which were not presented here, indicated annual expansions of the cones.

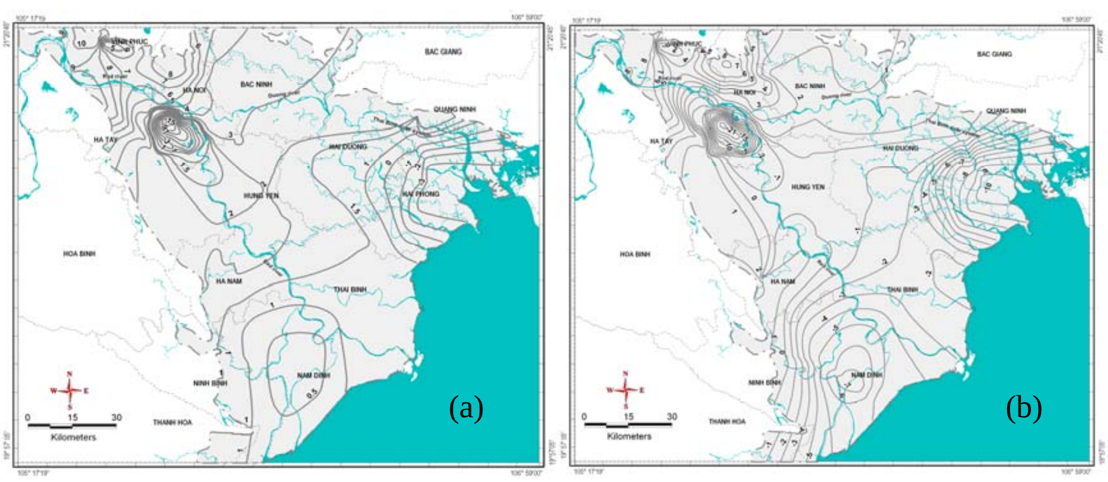

Figure 3. Contour map of annual groundwater level in (a) 1995 and (b) 2009

Spatio-temporal pattern of recent trends

In this paper, trend results were analyzed using two significance levels (α): 5% and 1%. Referring to the common classifications used for the standard normal distribution (Jin et al., 2005a; 2005b), trend results were classified into five trend groups based on the u values by Eq. (2): strong downward trend ($u < u_{0.005}$), weak downward trend ($u_{0.005} \le u < u_{0.025}$), no significant trend ($u_{0.025} \le u \le u_{0.975}$), weak upward trend ($u_{0.975} < u \le u_{0.995}$), and strong upward trend ($u_{0.995} < u$), where $|u_{0.025}| = u_{0.975}$ = 1.96 and $|u_{0.005}| = u_{0.995}$ =2.58. The five trend groups were marked as (▼), (●), **(×), (○),** and (△), respectively in the following tables and maps.

Table 1. Results of trend and trend slopes (m/year) in groundwater levels.

Time series	Number of trends					Mean slope (m/year)
	▼	●	×	○	△	
Monthly	57	3	3	0	0	-0.20
Annual	57	3	3	0	0	-0.21
Rainy season	56	3	4	0	0	-0.22
Dry season	57	3	3	0	0	-0.20
Maximum	54	4	5	0	0	-0.21
Minimum	56	2	5	0	0	-0.21
January	52	7	4	0	0	-0.19
February	55	3	5	0	0	-0.19
March	56	2	5	0	0	-0.20
April	57	1	5	0	0	-0.20
May	53	5	5	0	0	-0.19
June	51	5	7	0	0	-0.20
July	55	4	4	0	0	-0.21
August	55	3	5	0	0	-0.23
September	51	4	8	0	0	-0.24
October	50	6	7	0	0	-0.22
November	45	7	11	0	0	-0.21
December	53	5	5	0	0	-0.22

Table 1 summarizes the trend results of the five trend groups and average slope for the 18 time series (1995-2009) groundwater levels at 63 observation wells. The values in the last column show average trend slopes (m/year), while their positive and negative signs indicate upward and downward trends, respectively. It is apparent from the number of trends for monthly time series in Table 1 that statistically significant downward trends were identified in almost all wells (57 strong downward trends and 3 weak downward trends out of 63 wells). Only three wells 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 quite different among time series. Time series for monthly, annual, dry season, show the highest number of 60 downward trends, while only 45 cases are found in November. Compared to our earlier trend results for in Hanoi (Bui et al., 2010), it is clear that the trend results for the whole delta are quite different, and more complicated. This behavior could result from differences in withdrawal rates among provinces, climatic variations, and heterogeneous, anisotropic characteristics of the delta's aquifers. As for the trend slopes, Table 1 reveals the trend slopes are quite similar among time series, around -0.21 m/year (downward). The groundwater levels of Jan, Feb, and May exhibit the lowest average slope of -0.19 m/year, while Sep data exhibited the highest slope of -0.24 m/year among other time series. Although detailed slopes for each well are not presented here, it is noted that the slope is rather different among wells than among time series.

Furthermore, to examine the spatial distribution of the detected trends and their slopes, the number of maps showing the well locations of five trend groups, and showing spatial pattern of slopes were created for the 18 time series. Among these maps, two maps for the monthly time series were selected and shown in Fig. 4 (a), (b) since they were calculated from the best sample size among others. Fig. 4 (a) reveals exact spatial patterns of the location of wells where downward trends widely occur over the study area. Three wells P32, P53, and P54 showing no significant trend are close to the margins of plain in Bacninh, Vinhphuc, and Hanam provinces, respectively. In addition, Fig. 4 (b) shows distinct patterns of trend slope from which domination of decreasing trends in almost the entire delta are highlighted. Groundwater levels show slight downward in the northern and southern margins of the delta, while the central and coastal regions show more serious decline, particularly in three main cities: Hanoi, Haiphong, Namdinh. Fig. 4 (b) indicates an area of around 3,400 km2 with the serious downward slope of less than -0.3 m/year. This area occupies almost 25% of the delta. Less serious downward slope observed around the margins of the plain likely results from greater groundwater recharge from the hills/mountains nearby, and from less pumping there than other areas.

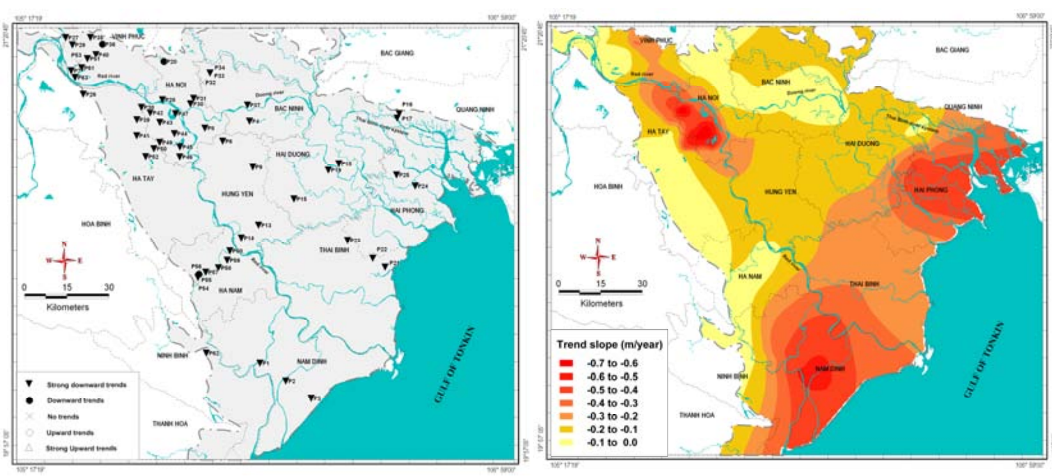

Figure 4. Spatial distribution of (a) trends and (b) slopes in monthly time series.

Analyses of groundwater level trends in delta in this paper revealed several interesting features of groundwater level regime. Referring to the information about spatial pattern of current pumping over the delta quoted in survey's report (Tong, 2007), the urban areas of substantial withdrawals such as Hanoi, Haiphong, and Namdinh are well matched with the areas of serious declining trends. The presence of irrigation systems (Tong, 2007) could be reasonable explanation for less serious groundwater decline in the Duong River areas and Hanam province, because groundwater here receives greater recharge from irrigation water than other areas. Serious decline in groundwater levels over the coastal areas is no doubt an indicator of groundwater depletion and aquifer degradation due to salt intrusion, which threatens sustainable development of coastal aquifers. The findings about the trends herein certainly provide valuable information for other delta where topographical and hydrogeological conditions are similar. Annual cycle in groundwater levels and its strong linkages to rainfall and surface water factors in this delta are in similar to other 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 cities such as Dhaka, Bangkok (Phien-wej et al., 2006; Shamsudduha et al., 2009).

CONCLUSION

Spatio-temporal analyses of most recent trends (1995-2009) in the longest groundwater level records available at 63 wells of Pleistocene confined aquifer over the Red River Delta of Vietnam have been carried out. At each well, 18 time series of important 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 by making use of non-parametric approaches. This paper also briefly investigated possible causes of the trends and variation, and their linkages to groundwater abstraction, rainfall, and river water level. Evidence from the study revealed that groundwater levels have decreased at almost all wells. An average trend slope is estimated at about -0.2 m/year, while the area which showed the serious downward trend of less than -0.3 m/year has occupied almost 3,400 km^2 (about 25% of the delta). In general, the groundwater levels in cities such as Hanoi, Haiphong, Namdinh showed more serious downward trend slope than others. Trend results for other time series were quite similar to monthly time series, while November data exhibit the highest number of statistically insignificant trends. Annual cycles in groundwater levels are primarily governed by rainfall and river water levels, while their long-term trends are mostly attributed to pumping. Serious declines in groundwater levels particularly threaten sustainable development of coastal aquifers due to salt intrusion.

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