Interactions between the surface water and groundwater of the Red River in Hanoi, Vietnam

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ABSTRACT

Understanding the interactions between surface water and groundwater is critical for effective water management and conjunctive water use planning as these are intimately linked in the hydrologic cycle. This study is the first attempt to determine the spatio-temporal patterns of the interactions between the surface water of the Red River in Hanoi, Vietnam and the groundwater of two main adjacent aquifers, the Holocene unconfined aquifer (HUA) and Pleistocene confined aquifer (PCA). In this study, an integrated surface-groundwater model was developed by coupling two commercial modeling packages: the river flow routing model (MIKE 11) and the ground flow model (MODFLOW). As for the results, this study revealed that there was very high correlation between the river water levels and HUA groundwater levels. The correlation was found decreasing not only with the distance from the river, but also from the upstream to downstream along the river. Upper parts of the river exhibited seasonal interactions of recharge and discharge between the river and aquifer, while the lower parts of the river recharged groundwater almost throughout the year.

INTRODUCTION

Domestic and industrial water supply in Hanoi is mainly from groundwater. Groundwater has been pumped in Hanoi since 1909 with an initial pumping rate of some 20,000 m^3/day. The groundwater abstraction has rapidly increased to over 500,000m^3/day in 2010 (Nguyen 2008). Rapid growth of population and urbanization in Hanoi has put more pressures on water supply. As a consequence of insufficiency of infrastructure, surface water, especially river and lake water has been seriously polluted. As groundwater is the most important sources of water supply in Hanoi, a great deal of groundwater related studies has been carried out. Most of these studies focused on the identification of aquifer system, land subsidence due to over withdrawal, and groundwater pollution. For example, Bui et al. (2011a) identified aquifer system not only for Hanoi but also for the entire Red River Delta. Modelling subsidence in the Hanoi City area, Vietnam was also conducted by Trinh and Delwyn (2000). However, there are very limited understandings on groundwater and surface water interactions in Hanoi, which is critical for effective water management and conjunctive water use planning.

Interaction between surface water and groundwater is an integral process in watershed, governed by climate, geology, surface topology and ecological factors. A watershed should be envisaged as a combination of both the surface drainage area and the parcel of subsurface solid and geologic formations that underlie it (Freeze and Cherry 1979). However, hydrologic components, such as surface water and groundwater, have historically been treated as separate units and modeled accordingly (Allison 2008). This has made inadequate estimates of the interaction between surface and groundwater, leading to unreasonable use of water resources. As such, water managers need a tool that is able to simulate both the physical processes of flow and management issues in order to meet the demands. To fulfill this need, a linkage between two modeling tools, a surface water model and a groundwater model has been proven as a promising approach. Many authors, for example, have studied the coupling between a surface water model and a groundwater model. BRANCH-MODFLOW coupling system has been used in several applications, most notably to examine the effects of raising groundwater levels on a neighboring residential community in the Florida (Swain and Wexler 1996). FHM-MODFLOW was developed to evaluate the water budget in the Big Lost River Basin in Idaho (Said et al. 2005). SWAT- MODFLOW (Jinggang et al. 2010) has been applied to several sites in Kansas including Rattle Snake Creek and the Lower Republican River Basin (Kim 2008). SWMM was linked to MODFLOW to characterize existing hydrology in New Jersey Turnpike (Steven 2010).

Specific objectives of this study were to: (1) increase the understanding of the dynamics of the surface water/ground water interaction along the Red river in Hanoi, Vietnam, (2) quantify the recharge between the Red River and groundwater of two main aquifers in Hanoi, (3) investigate temporal variations of groundwater level in two main aquifers in response to fluctuating water level of the Red River. While the coupled models above are successful for modeling the interactions of surface water in watershed, urban drainage and pipe system with groundwater, they are more complicated to quantify localized groundwater/surface water interaction between rivers and aquifers. Thus Mike 11 is enough to achieve these purposes. According to the technical description of this commercial modeling package, the coupled model could be ideally suited for a number of studies such as: analyzing the hydraulic connection between rivers, streams, and aquifer systems, determining groundwater base-flow and potential impacts to ecologically sensitive areas, calculating infiltration rates from surface water to groundwater during rainfall events, developing comprehensive watershed management plans and many others. However there has been no researches aim at testing its application capacity for actual sites so far.

STUDY AREA

Hanoi is the capital of Vietnam with a total area of about 3,344 km^2 in the northern part of Vietnam (Fig.1.). The population was about 6.5 million in 2009, occupying 7.5% of the Vietnam’s population. The Hanoi belongs to the tropical monsoonal region with two distinctive seasons. The rainy season is from May to

October and the dry season lasts from November till April. The annual rainfall is about 1,600 mm of which rainfall in the rainy season occupies about 75%. The annual average humidity is about 90% and the average temperature is around 24^{o}C. Evaporation is quite high with an annual average of 900 mm . The river network is quite dense with the density of about 0.7km/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 concentration of suspended alluvials at any time (Bui et al. 2011b).

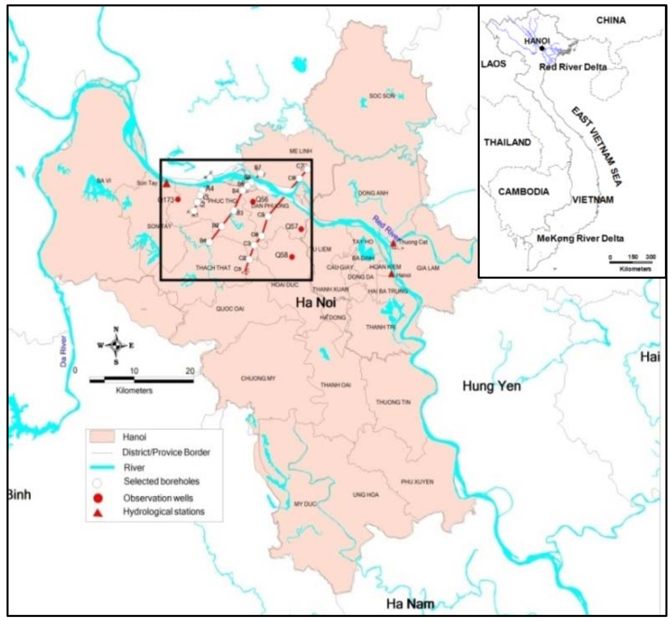

Figure 1. Study area, locations of hydrological stations, observation wells and three typical hydrological cross sections.

Our previous studies show that Hanoi has two main aquifers: Holocene unconfined aquifer (HUA) and Pleistocene confined aquifer (PCA). HUA is mainly composed of silty clay and various kinds of sands mixed with gravels. Thickness of this layer varies greatly, up to more than 35m with an average of about 15m. The transmissivity for HUA is form 20 to 1,788 m^2/day. The specific yield is between 0.01-0.17. The water level is 3-4m below the surface however in the south of the Red River the water level is lower due to the groundwater pumping. HUA is sufficient for small-scale water supply. (Bui et al. 2011b)

PCA or lower aquifer is situated lower in the stratigraphic sequence. The depth is only less than 10m in the North of the Soc Son District, but around 20m in Dong Anh district, and up to 40m in the south of the Red River. The PCA is made up of sand mixed with cobbles and pebbles. The thickness of the PCA also fluctuates over a large range, up to 50m with the average of about 35m and has an increasing tendency from the North to the South. The transmissivity ranging from 700 to 2,900m^2/day indicates a very high potential of groundwater resources. The specific storativity ranges from 0.00004 to 0.066. The specific capacity in the all tested wells in most cases is over 1L/sm. An impermeable layer (HPA) between the two aquifers is an aquitard preventing vertical flow from the two aquifers. (Bui et al. 2011b).

The study area is a rectangle which of 400 km^2 encompassing districts of the Dan Phuong and the Phuc Tho as shown in Fig.1. The study area selected is a typical area for hydro-geological condition in Hanoi which covers three types of interactions between aquifers and the Red River bed: (1) the Red River contacts to PCA directly; (2) the Red River connects to PCA through hydro-geological windows; and (3) the Red river connects to PCA through an impermeable layer (Bui et al. 2011b). Figure 2 shows the typical hydrogeological cross-sections A-A’, B-B’ and C-C’ as shown in Fig. 1 which were selected considering the location of boreholes.

METHODOLOGY

As mentioned above, the method used in this study is coupling MIKE 11 with MODFLOW. MIKE 11, developed by DHI, is a world-recognized surface water modeling package designed for simulating the hydrodynamic conditions found in rivers, lakes, reservoirs, and irrigation canals. MIKE 11 can be applied on applications ranging from simple design investigations to large forecasting projects including complex hydraulic structure operation policies. Through dynamic couplings to other DHI software products MIKE 11 allows to integrate rivers and floodplain modeling with models for watershed processes, detailed floodplain representation, sewer systems and coastal processes (DHI 2004).

The modular finite-difference groundwater flow model MODFLOW (Waterloo Hydrogeologic Inc.) was selected to simulate the behavior of groundwater flow in the study area because it is a well-documented and extensively tested model.

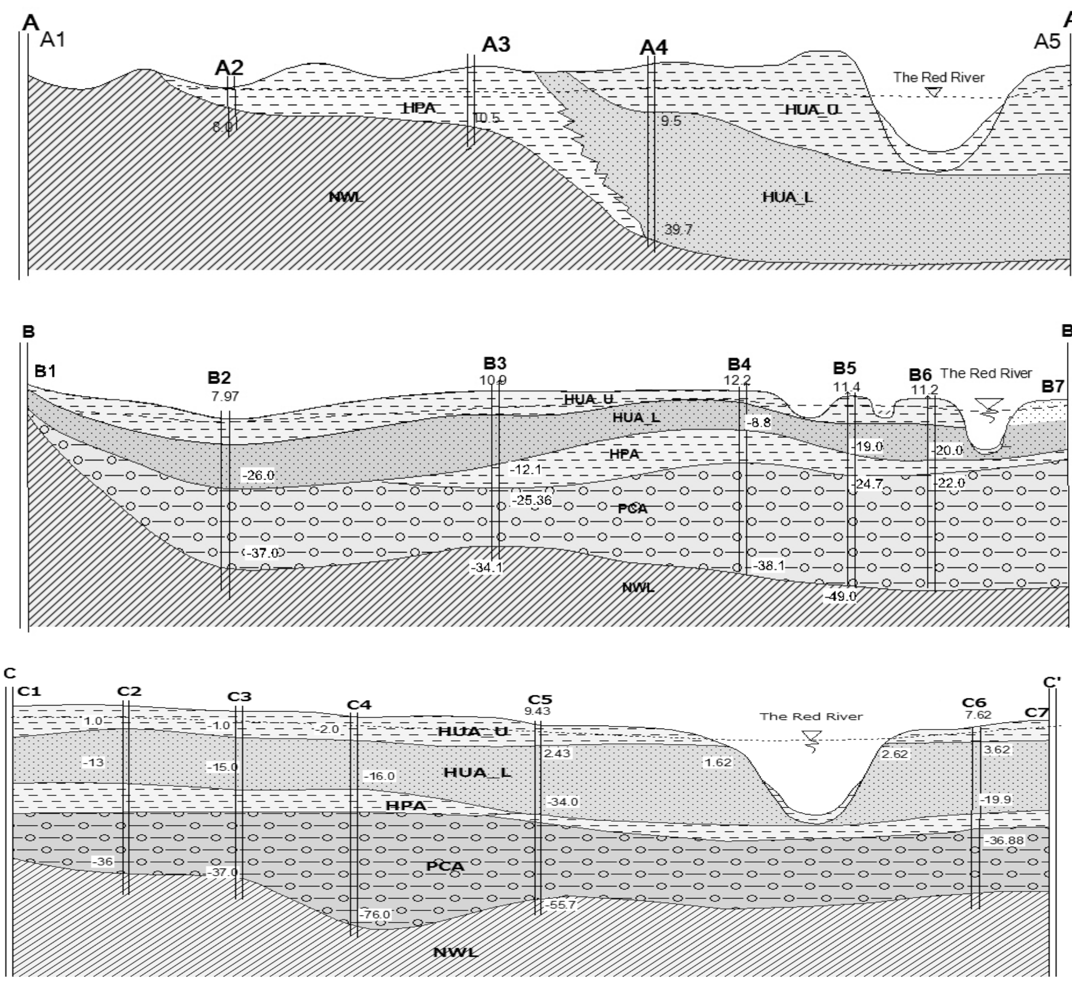

Figure 2. The typical hydrological cross-sections A-A’, B-B’ and C-C’.

MODFLOW is a three-dimensional, numeric, finite difference, porous medium flow model (Harbaugh et al. 2000).

MODFLOW is the de facto standard in groundwater modeling. However, MODFLOW is strictly a saturated groundwater model, typically with boundary conditions defined by surface water bodies, such as lakes, rivers and streams. In the case of Rivers and Streams, MODFLOW requires a time series of river levels for every cell in the model that intersects a river. (Harbaugh et al. 2000). Therefore, output from Mike 11 that is shared with MODFLOW replaces data that is input by the user in the River package of MODFLOW.

DATA USED

Data used in MIKE 11 consist of: river network, 119 cross sections of the Red river, daily discharges recorded at Son Tay station, daily water levels at the watershed outlets, hydrodynamic model parameters (bed and floodplain resistance data for the river network), observed daily water levels at Hanoi, Thuong Cat, Hung Yen station. The daily data in 1996 was used for model calibration and the daily data in 2003 was used for model validation. After model calibration and validation, the daily data in 2006 was used for determining the interactions. Output data of Mike 11 is water levels at the cross sections used as input data for MODFLOW.

Data used for MODFLOW model setup consist of: available geological information (e.g. boreholes data and cross sections) and topographic maps used to determine the aquifer-system geometry; hydrological parameters including hydraulic conductivity, specific storage and specific yield; pumping volume; effective recharge; groundwater evaporation; groundwater heads at observation wells.

To simulate the recharge and the interaction between surface water and groundwater more accurately, HUA is divided into two layers: the upper layer is a low permeable layer (HUA_U) and the lower layer has higher permeability (HUA_L). Therefore, the aquifer system was discretized into four layers as shown in Fig. 2. Layer 3 represents the Holocene-Pleistocene aquitard (HPA), while layer 4 refers to PCA. The finite difference grid contained 94 columns, 70 rows, oriented north-south, with a regular grid size of 250m. Input data of cells in the first layer is effective recharge, evaporation, discharge into the under layer and recharge/discharge from/into other cells. Input data of cells in the under layers is recharge from the other cells/ river, discharge into the other cells/river, pumping volume. Groundwater head data from fours observation wells (Fig.1) were used for model calibration and validation using 1996 and 2003 data, respectively. The output of MODFLOW data are daily groundwater levels of each cell. However, in this study, daily groundwater levels in some nodes which are typical of hydrological conditions were analyzed to determine the interactions between surface water and groundwater in the study area.

RESULTS

Model Calibration and Validation

The parameters referring to the hydrodynamic parameters (MIKE 11), the hydraulic conductivity, specific yield, and recharge coefficient (MODFLOW) were calibrated through an iterative process. River level from three stations (i.e Son Tay, Hanoi, Thuong Cat) were used for MIKE 11 model calibration, and ground water levels from four observation wells (i.e. Q173, Q56, Q57, Q58) as shown in Fig 1 were used for MODFLOW model calibration. The calibration was performed for the period from January 1st 1996 to December 31st 1996. A trial and error method was used in the calibration process. The Nash was used as an indicator of goodness of fit (Moriasi *et.al.*, 2007). Fig. shows the calibration results of MIKE 11 at the three stations and Fig. 4a presents the calibration results of MODFLOW at the four observation wells. Both regressions show good agreements between measured and simulated river water level (Fig. 3a) and ground water level (Fig. 4a), with the Nash coefficients shown as Table 1.

The models were validated for the period from January 1st 2003 to December 31st 2003. The same stations and observation wells used for calibration were used for validation. All hydraulic parameters and empirical coefficients were the same as used for calibration. Fig. 3b indicates the results of validation of MIKE 11 at those stations and Fig. 4b shows the results of validation of MODFLOW at those observed wells. Comparision of observed and simulated data showed small errors of the estimate (Fig. 3b, 4b), and the high Nash index which are almost the same as calibration shown as Table 1, hence indicating that parameters were properly calibrated.

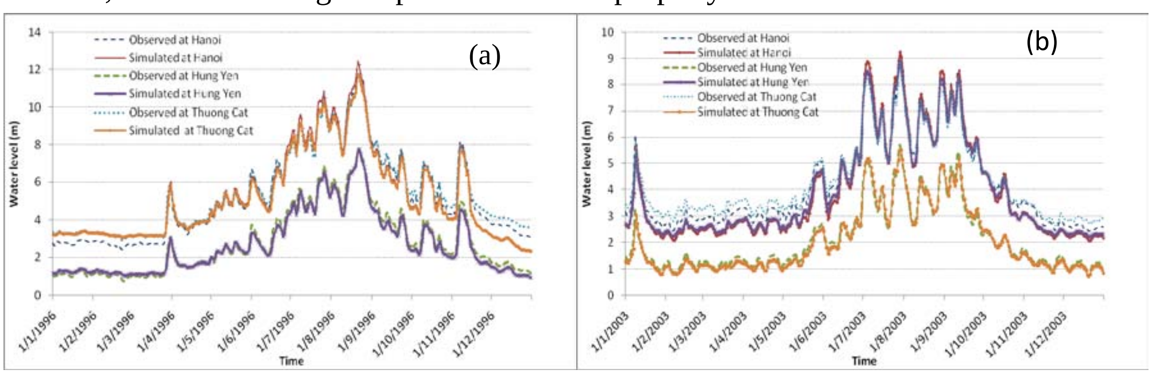

Figure 3. Comparision of observed and simulated water levels at observed stations for (a) calibration in 1996 and (b) valibration in 2003 of MIKE 11 model.

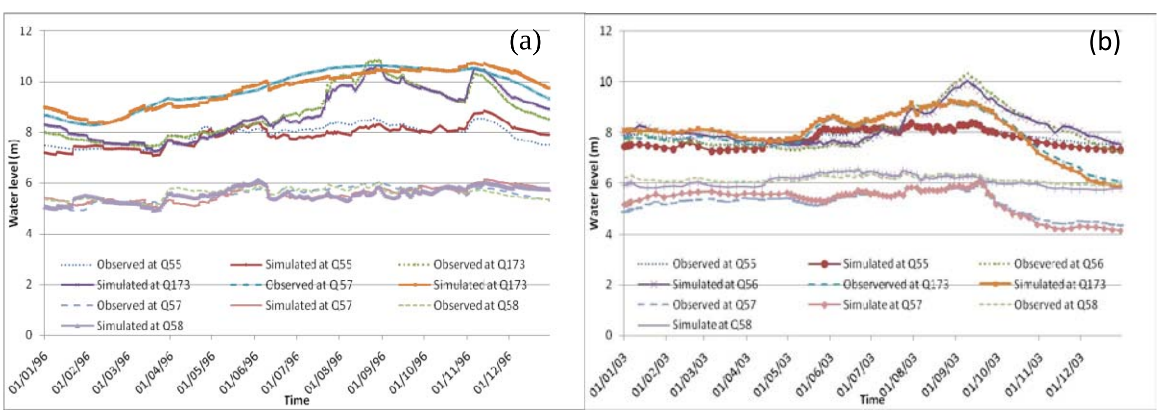

Figure 4. Comparision of observed and simulated water levels at observed stations for (a) calibration in 1996 and (b) valibration in 2003 of MODFLOW model.

Table 1. The results of calibration and validation.

No	Station/Well	Model	NASH	
			Calibration (1996)	Validation (2003)
1	Hanoi	MIKE	0.87	0.86
2	Hung Yen		0.82	0.81
3	Thuong Cat		0.85	0.83
4	Q173	MODFLOW	0.76	0.78
5	Q56		0.88	0.85
6	Q57		0.78	0.81
7	Q58		0.84	0.83

Estimating the recharge rate of the three zones by the water balance method

According to hydro-geological conditions in Hanoi (Bui et al. 2011b), the study area was divided into three zones in accordance with the three types of interconnections between aquifers and the Red River riverbed as shown in Fig. 5.

Figure 6 presents the recharge value between groundwater and the Red river in the three zones. From Fig. 6 in zone A, groundwater discharged into the river from January to May, September, November and December. In zone B, groundwater contributed to the flowing river in January, February, September, November and December 2006. On the contrary, in zone C, water seeped from the river down to the water table over the whole year.

Interactions between the Red River stages and groundwater levels in the Holocene unconfined aquifer

Table 2 shows distance to the riverside, correlation coefficient between groundwater level in and the river level in the selected nodes (i.e. NA1, NA2, NA3 in zone A; NB1, NB2, NB3 in zone B; NC1, NC2, NC3 in zone C) (Fig.5). It is noted that in node NC3, the HUA does not exist and NA1, NA2, NA3, the PCA does not exist. As shown from Table 2, the correlation coefficients in the HUA vary in a wide range, from 0.74 to 0.95 with a decreasing tendency with distance from the river.

Furthermore, we draw Fig.7 to show the visual presentation of the relationship between river water levels and groundwater levels over the time of a year in 2006. From Fig. 7, we found that fluctuation of water levels in all wells was similar to the water levels in the river. The water levels in nodes farther from the river appeared to follow the

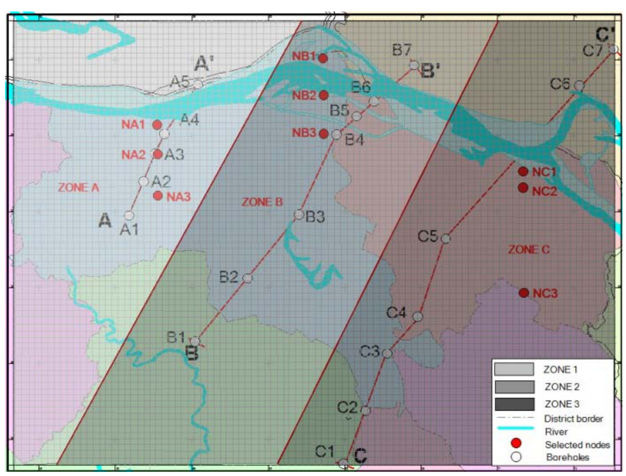

Figure 5. The division of the study area into three zones.

downward trend representative of the regional groundwater system. Water level in the Red river is lower than ground water levels in node NA1, NA2, NA3 almost of throughout the year (Fig. 7a). This means ground water recharged to the river during almost time of the year. In contract, water level in the river is higher than groundwater levels in node NC1, NC2 over almost the year (Fig. 7c) which indicates that water was flowing from the river into the aquifer. Fig. 7b shows that the ground water levels in node NB2, NB3 were higher than the Red river levels but ground water level in node NB1 was lower. Thus, the interactions between ground water and the river were highly varied depending on the distance from the river. Water levels in all nodes increased coincident with the high stream flow events from June to August, 2006 (Fig. 7). These groundwater level rises are consistent with increased recharge to the aquifer from river leakage.

Interactions between the Red river and groundwater in the Pleistocene confined aquifer

Table 2 reveals that the correlation coefficients in the PCA vary from 0.7 to 0.89, with an increasing tendency from far to near the river. Aside from this observation, Table 2 also indicates a decreasing tendency of the correlation coefficients from upstream to downstream along the river.

Like nodes in the HUA, water levels in nodes in the PCA which are near to river responded more rapidly to changes in river stage (Fig. 8). The rapid response to changes in stage in the near-river nodes is consistent with hydro-geological conditions at those locations. The difference in the magnitude of the response to river stage fluctuations among the near-river wells may result from differing hydraulic properties in the near-river aquifer and streambed material, and the resulting amount of leakage from the river. The observations of the spatio-temporal pattern of the interactions between river water levels in the Red River and groundwater levels of PCA are quite similar to those of HUA

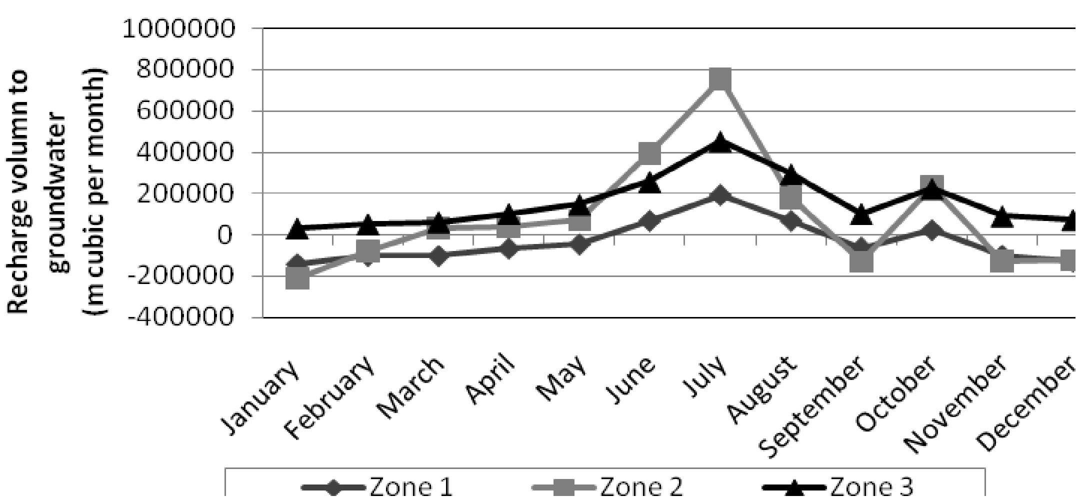

Figure 6. The recharge value between groundwater and Red River in the three zones.

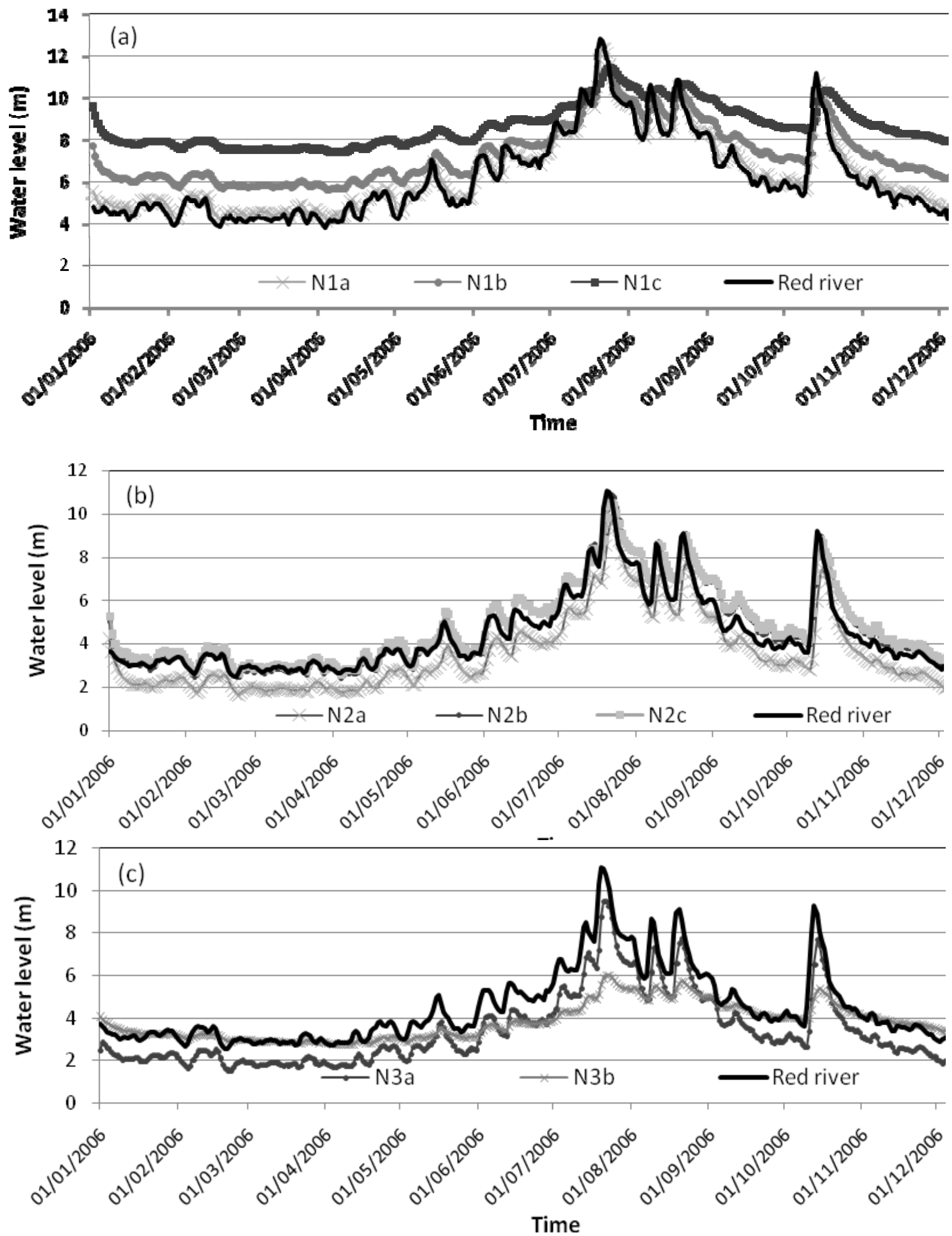

Figure 7. Fluctuation of water level in Red river and groundwater levels in the HUA at nodes: (a)N1a, N1b, N1c; (b) N2a, N2b, N2c; (c) N3a, N3b.

Table. 2. The hydraulic interactions between groundwater in the two main aquifers and the river.

Node	Distance from the riverside	Correlation coefficient (2006)	
	(m)	HUA	PCA
NA1	100	0.95	NA
NA2	1200	0.91	NA
NA3	2800	0.81	NA
NB1	100	0.89	0.89
NB2	1400	0.92	0.88
NB3	3000	0.9	0.85
NC1	100	0.85	0.88
NC2	500	0.74	0.89
NC3	4800	NA	0.7

Note: NA- None aquifer

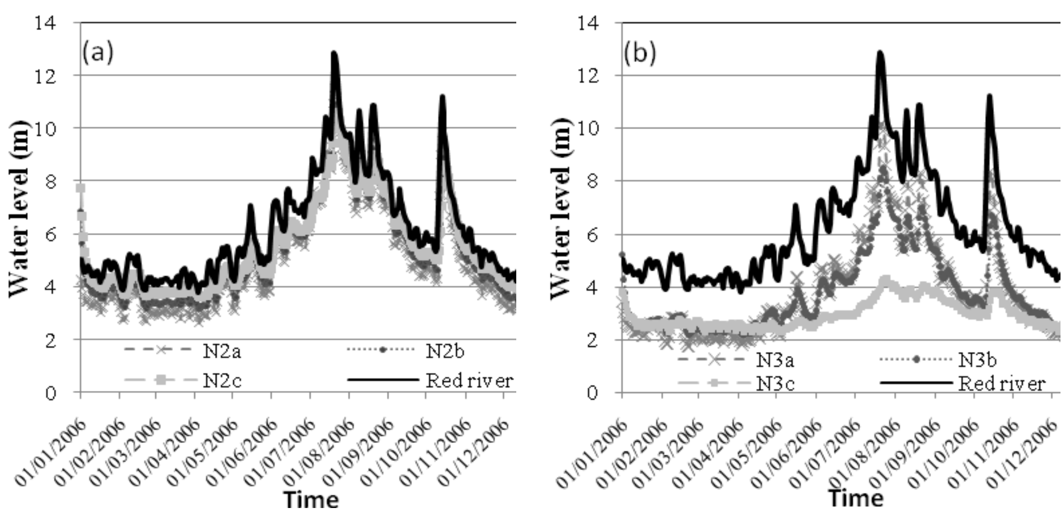

Figure 8. Fluctuation of water level in Red river and groundwater levels of the PCA at nodes: (a) N2a, N2b, N2c; and (b) N3a, N3b, N3c.

DISCUSSION

The result shows that the correlation coefficients between the river and groundwater in the HUA were higher than those in the PCA. The reason of this is that the HUA is the topmost aquifer which is affected directly by rainfall and the river water. Conceptually, groundwater in the shallow near-river aquifer has a steep gradient away from the river or is a mound of the water table underlying the river that exists only because of recharge from the river (Rodney et al. 2003). Therefore, water levels in the near-river aquifer are controlled by hydraulic properties of the aquifer material and the amount of local recharge from the river, in combination with water level fluctuations of the regional system.

Understanding the relationship between surface water and groundwater, we may reveal the possible causes leading to degradation of groundwater quality. That is because of decrease of the recharge sources to the aquifers. The recharge sources to the ground water for the study area are mostly from rainwater and surface water. In addition, the results of this study also help managers in the operation of reservoirs upstream.

One of the most severe consequences of excessive groundwater pumping in Hanoi is decline of groundwater level (Bui et al. 2011b). The close relationship between river water and groundwater found in this study area reveals a clear indication of reduction of water in river as the water flowing in rivers during low flow period mostly comes from seepage of groundwater into the streambed. Declines of groundwater level can alter intercept of groundwater flow that discharges into river. The ultimate effect is a loss of riparian vegetation and wildlife habitat.

Although the annual cycle in groundwater levels and its strong linkages to rainfall and surface water have been also clarified in Bangladesh (Shamsudduha et al. 2009), Spain (Sanz et al. 2011), and Wisconsin, USA (Ghanbari and Bravo 2011), the levels of correlation and the mechanism of interaction between surface water and groundwater somehow different from those in Hanoi. More interesting, the close interactions between surface water and groundwater were found not only in unconfined aquifer (HUA) but also in confined aquifer (PCA) that were rarely exist in other deltas in the world.

CONCLUSION

This study investigates the hydraulic relationship between the surface water of the Red River in Hanoi and the ground water of two main adjacent aquifers, the Holocene unconfined aquifer (HUA) and Pleistocene confined aquifer (PCA). The results show that in three selected cross-sections, that there are very high correlation between the river water levels and HUA groundwater levels. The correlation was highly influenced by not only the hydrogeological conditions of the aquifer and riverbed but also the distance from the river. It was also found that the correlation decreased along the river from upstream to downstream. More specifically, upper parts of the river exhibited seasonal interactions of recharge and discharge between the river and the aquifers, while the lower parts of the river recharged the groundwater almost throughout the year. Although the correlation between the river water and PCA groundwater levels was also high with the similar tendency to HUA, it was rather small due to the existence of a thin aquitard between the two aquifers in a major portion of Hanoi.

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