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Simulation of the impact of managed aquifer recharge on the groundwater system in Hanoi, Vietnam

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Abstract

A transient numerical groundwater flow model using MODFLOW-NWT was set up and calibrated for Hanoi city, Vietnam, to understand the local groundwater flow system and to suggest solutions for sustainable water resource management. Urban development in Hanoi has caused a severe decline of groundwater levels. The present study evaluates the actual situation and investigates the suitability of managed aquifer recharge (MAR) to stop further depletion of groundwater resources. The results suggest that groundwater is being overexploited, as vast cones of depression exist in parts of the study area. Suitable locations to implement two MAR techniques—riverbank filtration and injection wells—were identified using multi-criteria decision analysis based on geographic information system (GIS). Three predictive scenarios were simulated. The relocation of pumping wells towards the Red River to induce riverbank filtration (first scenario) demonstrates that groundwater levels can be increased, especially in the depression cones. Groundwater levels can also be improved locally by the infiltration of surplus water into the upper aquifer (Holocene) via injection wells during the rainy season (second scenario), but this is not effective to raise the water table in the depression cones. Compared to the first scenario, the combination of riverbank filtration and injection wells (third scenario) shows a slightly raised overall water table. Groundwater flow modeling suggests that local overexploitation can be stopped by a smart relocation of wells from the main depression cones and the expansion of riverbank filtration. This could also avoid further land subsidence while the city's water demand is met.

Keywords Numerical modeling · Artificial recharge · Groundwater management · Site selection · Vietnam

Introduction

Global change, including urbanization, population growth and climate change, poses increasing risk to water resources especially in urban areas (Bouwer 2002). In urban cities, socio-economic development also results in increasing pressure on the limited water resources. As water demand is rising rapidly, securing a safe drinking water supply becomes a challenge.

Hanoi, the capital of Vietnam, is a major economic and political center of the country, both of which have caused fast population growth and greater urbanization, leading to increasing pressure on the infrastructure and the water supply system. The water demand of the city, which was already 1.05 M m^3 d^{-1} in 2010, is projected to increase further (Le Van Duc 2012; Stefan 2014; Phi and Strokova 2015). The water demand is mainly covered by groundwater, either pumped in a centralized regime by high-capacity wells operated by the public water supply company or decentralized by industrial wells and various illegal private wells (Le Van Duc 2012; Dang et al. 2014). As a result, groundwater levels are declining all over Hanoi and drawdown has already reached as much as 35 m in some parts of the city (Nguyen and Helm 1995; Fischer et al. 2011). The magnitude of groundwater-level decline is about 0.30 m $year^{-1}$ in the urban metropolitan area of Hanoi (Bui et al. 2012a).

Due to the fast urbanization, impervious areas are further increasing, leading to frequent flooding of the city, since the drainage system is often not able to cope with the high load (Stefan et al. 2012). As the rainwater and domestic wastewater drainage system is designed for a quick disposal, natural recharge is reduced further preventing natural replenishment of

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the groundwater resource (Stefan et al. 2012). In addition, most of the urban wastewater is directly discharged to lakes and rivers resulting in deterioration of groundwater quality (Montangero et al. 2007; Dang et al. 2014).

Land subsidence has been observed in various districts of Hanoi caused by groundwater exploitation and compression of the Quaternary soils (Nguyen and Helm 1995; Thu and Fredlund 2000; Le Van Duc 2012). Subsidence rates vary in different districts of the city and yearly subsidence rates have reached 6.8 cm in some areas causing damages to buildings (Le Van Duc 2012). In the old city center of Hanoi, total land subsidence reached as much as 100 cm in 2013 and will increase further if groundwater exploitation continues (Phi and Strokova 2015).

Furthermore, the mobilization of geogenic arsenic (As) leads to elevated drinking water concentrations often exceeding the WHO-guideline of 10 µg L^{-1} (Norrman et al. 2008). This poses a risk to the health of people drinking untreated groundwater from private wells (Berg et al. 2001). Due to the ongoing groundwater exploitation, further spread of As contamination is expected as the gradient and therefore also the leakage between the upper Holocene aquifer (containing reducing groundwater with high As concentrations) and the lower Pleistocene aquifer has increased (Norrman et al. 2008).

To overcome the quantitative and qualitative challenges related to water management in the city, mitigation and adaption measures are needed to compensate the effects of groundwater overexploitation. One solution as part of a sustainable water management strategy could be the implementation of managed aquifer recharge (MAR), which is the purposeful recharge of water into an aquifer for later recovery or environmental benefits (Dillon 2005). During times of high water availability or low demands, excess water is stored underground to use it later in times of water-shortage (Pyne 2005; Maliva et al. 2006). Although MAR is a well-established method worldwide (Stefan and Ansems 2017), it has only rarely been applied in Vietnam so far (Nguyen et al. 2008; Stefan and Ansems 2016). MAR techniques are manifold and include well, shaft and borehole recharge where water is directly infiltrated into the saturated zone or recharged by gravitation (Hannappel et al. 2014). Infiltration into the unsaturated zone is conducted by spreading methods through infiltration basins and ponds or drainage systems (Hannappel et al. 2014). The leakage from lakes and rivers is enhanced by well pumping through induced bank filtration (Dillon 2005). Furthermore, MAR also comprises in-channel modifications such as recharge or check dams and rainwater and runoff harvesting (Gale 2005). The suitability of a MAR method depends on the site-specific conditions such as hydrogeology, land use, the source of the recharged water and the intended use of the recovered water (Dillon et al. 2009). Each site needs to be investigated in detail to minimize the risk of failure at a MAR facility (Dillon et al. 2009).

A first site-screening can be conducted using a geographic information system (GIS) and widely available surface and subsurface spatial data (Russo et al. 2015). The identification of suitable MAR sites using GIS has already been done in catchments worldwide (Russo et al. 2015; Bonilla et al. 2016). Physical, economic and social factors that are included in the study can be adapted site-specifically, depending on available data and the proposed MAR method, making the approach very flexible. For the GIS-based selection of possible riverbank filtration sites, factors such as land use, geology, slope and stream network have been integrated (Patwal 2015). Grischek et al. 2003 identified the flow path length, aquifer thickness and the infiltration area in the river as key aspects to consider when selecting riverbank filtration sites. Especially the flow path length and thereby the residence time affects the extracted water quality and determines the attenuation and removal of suspended solids and particles, and biodegradable organic compounds as well as bacteria and viruses (Grischek et al. 2003). High transmissivity and low heterogeneity of the aquifer and low concentrations of total dissolved solids are key factors influencing the site suitability for infiltration wells (Brown 2005).

Numerical models are often used for the assessment of MAR schemes (Ringleb et al. 2016). Groundwater flow and transport models are applied to plan and optimize MAR facilities, to quantify the impact on the local groundwater, and to determine geochemical processes and the resulting recovery efficiency, as well as to investigate the feasibility of a MAR method at a proposed site (Kloppmann et al. 2012; Maliva 2015; Ringleb et al. 2016). The most widely applied groundwater flow model for MAR assessment is MODFLOW (Ringleb et al. 2016), which has been used, e.g. in Central and Western Asia (Karimov et al. 2012; Ebrahim et al. 2015), as well as in Vietnam (Stefan et al. 2012), to evaluate the feasibility of MAR at a suggested site. The combination of a GIS-based MAR suitability study with numerical modeling can provide an appropriate tool to identify possible locations for MAR and evaluate easily different placement and operational scenarios (Rahman et al. 2012; Patwal 2015; Russo et al. 2015).

This study evaluates the feasibility of MAR as a remediation technique to restore the aquifer system in the urban area of Hanoi by: (1) using the widely-applied numerical finite difference code MODFLOW-NWT (Niswonger et al. 2011) to study the present groundwater flow system; (2) conducting a GIS-based multi-criteria decision analysis (MCDA) to restrict possible areas suitable for MAR; and (3) simulating the implementation of MAR measures into the transient groundwater flow model to study the potential effect on the groundwater. This study focuses on the influence of the location and operation of potential MAR facilities on the groundwater level as part of an overall sustainable groundwater management concept for Hanoi. In specific, the potential of MAR to reduce

depletion cones while keeping the total water withdrawal constant to stop the groundwater depletion trends and to compensate overexploitation by infiltrating additional water, was tested by the scenario simulations. Hence, only quantity aspects were regarded and water quality issues were omitted as no sufficient data were available.

Materials and methods

Study area

The Red River Delta comprises one of the most developed regions of Vietnam and includes the capital Hanoi. In 2008, surrounding provinces were merged into the metropolitan area of Hanoi, tripling its total area to 3,324 km^2 (Bui et al. 2012b). In this study only a part of the old city center of Hanoi with an area of 138 km^2, including seven urban districts, was chosen as the model area (Fig. 1). The area is especially prone to high groundwater exploitation mainly due to the very high population density. Although the study area covers only 5% of the total area of Hanoi, around 30% of Hanoi's population lives in the studied districts. In addition, data availability was sufficient to set up a numerical groundwater flow model.

The climate in Hanoi is characterized by tropical monsoon featuring two distinctive seasons: the wet (May–October) and the dry (November–April) season. About 75% of the annual precipitation, which is on average 1,600 mm, falls in the rainy season (Nguyen et al. 2014). The average temperature is 24 °C and the average evaporation is 900 mm year^{-1} (Nguyen et al. 2014).

The study area is located in the floodplain of the Red River which also represents a natural boundary towards the north and east of the investigated area. The Red River has an average discharge of 1,160 m^3 s^{-1} during the dry period and 3,970 m^3 s^{-1} during the wet period (Nguyen et al. 2014). The topography of the floodplain is quite homogeneous ranging between 3 and 17 m a.s.l.

The soil is mainly comprised of unconsolidated alluvial Quaternary deposits above metamorphosed consolidated Neocene bedrock (Nguyen and Helm 1995; Jusseret et al. 2009). Two main aquifers exist, the upper Holocene
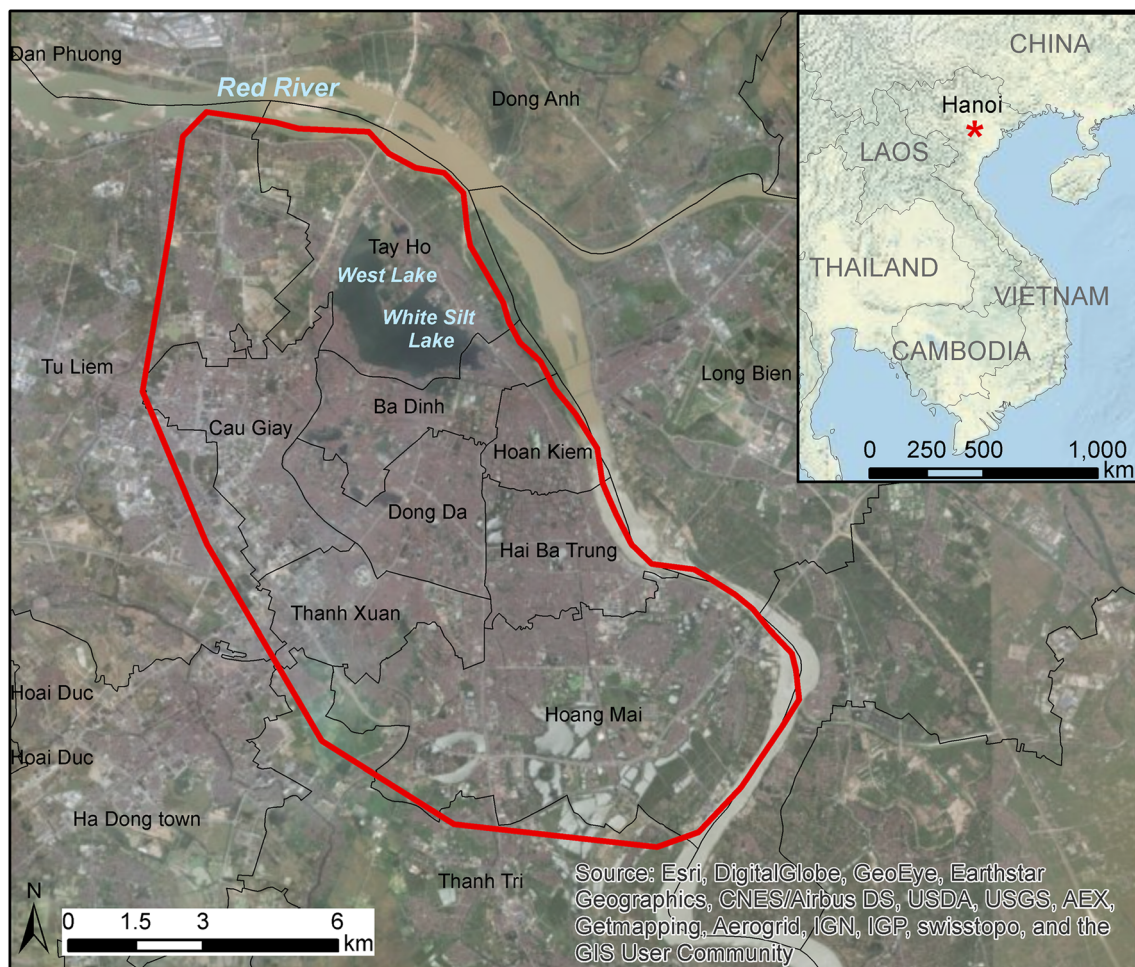

Fig. 1 Satellite image of Hanoi urban region with location of district boundaries (black lines) and extent of study area (red line)

unconfined aquifer (HUA) and the lower Pleistocene confined aquifer (PCA), which are in many parts separated by a silt-clay layer with low permeability (Jusseret et al. 2010). The majority of the city's water demand is met by the PCA through nine large pumping stations. Industrial wells pump additional water from the PCA and shallow private wells pump water mainly uncontrolled from the HUA.

The city has faced rapid and extensive land use changes, as several ponds and lowlands have been replaced by construction and buildings leading to a reduction of the natural groundwater replenishment (World Bank 2008). Furthermore, the surface-water bodies have been severely polluted by direct dumping of waste and discharge of wastewater (Bui et al. 2012b). Consequently, the main source for water supply in Hanoi is groundwater but the high pumping rates have caused groundwater level decline, groundwater pollution and land subsidence (Nguyen and Helm 1995; Fischer et al. 2011; Bui et al. 2012b; Le Van Duc 2012; Phi and Strokova 2015).

Groundwater flow model

A conceptual groundwater flow model was developed to study the groundwater flow system and to assess the feasibility of implementing MAR as a solution for sustainable water resource management. A numerical transient flow model was built using MODFLOW-NWT and calibrated for the years 2005–2007.

In contrast to an earlier study by Jusseret et al. 2009, the model was divided into four layers with varying thickness (Table 1; Fig. 2), whereby the HUA follows under a surface layer. The HUA and the PCA are separated by a low-permeability layer whose thickness varyies between 1 and 31 m. Below the PCA, the Neogene sediments were assigned as a no-flow boundary due to the low permeability. The thickness of each layer, the saturated hydraulic conductivity K, the specific yield S_y and the specific storage S_s were determined with the help of data from 90 boreholes (Table 1; Center for Water Resources Warning and Forecastings, Hanoi, unpublished data, 2015; National University of Civil Engineering, Hanoi, unpublished data, 2015). The layer limits were interpolated using the borehole strata data. For cells,

where the interpolation resulted in negative layer thicknesses, the layer boundaries were adjusted by hand to create continuous layers as required by MODFLOW. Homogeneous zones were generated to define the hydraulic parameters. Sharp boundaries with high gradients between adjacent parameter zones were smoothened via the integration of transition cells. The grid size of the study area with a size of 138 km^2 was set to 100×100 m (Fig. 2). Daily water level stages measured between 2005 and 2007 by three gauging stations (PSH2, PSH3 and PSH4) in the Red River were used to define the northern and eastern boundaries of the model area as head-dependent flux (Fig. 2). The southern and western boundaries of the study area were derived from the urban development of Hanoi as well as the availability of hydraulic head observations (HPT_4, Q_62, Q_68, H9) and were defined as time-variant-specified-head-boundary conditions. Previous studies (Fatkhutdinov 2013) showed that only 5% of precipitation is recharging the groundwater in the Long Bien district of Hanoi, which is adjacent to the east of the study area (Fig. 1). This value was taken as recharge for the green areas such as parks, pasture and agricultural land as well as the lakes (West Lake, White Silt Lake) and the Red River, while the rest of the area was assumed impervious due to roads and buildings (Fig. 2).

Pumping wells can be classified into three categories. The first category corresponds to public high-capacity wells, 157 distributed among nine different stations covering the major part of the water demand of the city from the PCA (Fig. 2; Table 2). The second category covers industrial low-capacity wells which pump mainly from the PCA. Monthly pumping rates were available for these first two categories (Table 2; Center for Water Resources Warning and Forecastings, Hanoi, unpublished data, 2015). The third category corresponds to private or unofficial wells from which no formal information about the location and the pumping rates is available; therefore, 100 private wells were distributed randomly in the urban area and a pumping rate of 150 m^3 d^{-1} per well was assumed (Fig. 2). As private wells are shallow, they pump only from the upper aquifer (HUA). All wells were defined using the MODFLOW Well Package to simulate the specified flux.

Table 1 Layer description for the study area (after (Jusseret et al. 2010) and borehole information (National University of Civil Engineering, Hanoi, unpublished data, 2015)

Layer	Name	Layer type	Description	Average thickness [m]	K [m d^{-1}]	S_y [−]	S_s [−]
1	Surface layer	–	Silt, silty clay, loam	7.8	1–20	0.2	–
2	HUA	Unconfined aquifer	Silt, silty clay, clay, fine sand	19.1	1–80	0.2–0.3	–
3	Low-permeability layer	Aquitard	Clay, silt	8.1	0.001–0.2	0.03	–
4	PCA	Confined aquifer	Gravel, coarse and middle sand, lenses of silt and clay	40.3	7–80	–	0.0004

HUA Holocene unconfined aquifer, *PCA* Pleistocene confined aquifer, *K* saturated hydraulic conductivity, S_y specific yield, S_s specific storage
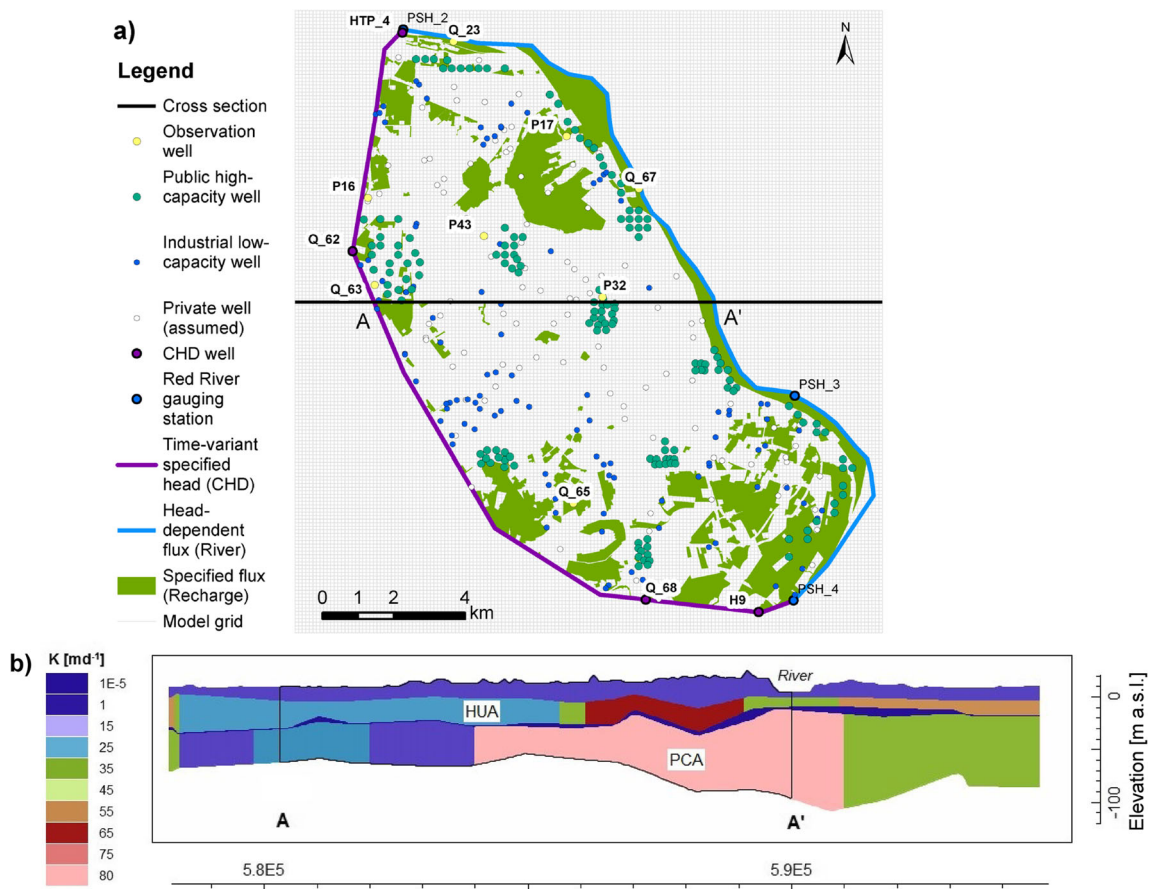
Fig. 2 Model setup. a Model grid including the boundary conditions: time-variant specified head, defined by observation well heads (CHD wells); head-dependent flux, defined by gauging stations of the Red River; and recharge (specified flux) assigned to vegetated areas and surface-water bodies. Pumping wells are categorized into public high-capacity wells, industrial low-capacity wells and private pumping wells (locations by random and number (100) assumed). Observation wells are used for calibration (Center for Water Resources Warning and Forecastings, Hanoi, unpublished data, 2015). b Cross-sectional view of hydraulic conductivity K [m d^{-1}] including the boundary of the active model area (black line). Vertical exaggeration: 20

A quasi-steady-state simulation covering a transient simulation with a single month-long stress period and 1,000 time steps helped to obtain the initial water-table head for the model area. The transient simulation included 36 monthly stress periods with daily time steps for 3 years (2005–2007). The calibration was done manually by trial and error using monthly measured observation heads in the PCA at eight wells spread throughout the study area (Fig. 2). The lack of additional data such as flow measurements or observations heads in the HUA constrains the model calibration and hence also the model results. Hydrogeological parameters including hydraulic conductivities and specific yield were adjusted individually for subsections of the model

Table 2 Categories for pumping wells including the exploited aquifer, the total number of wells within the study area and the average total pumping rate for the years 2005–2007 (Center for Water Resources Warning and Forecastings, Hanoi, unpublished data, 2015)

Category	Aquifer	Total number of wells	Average pumping rate [m^3 d^{-1}]
Public high-capacity wells	PCA	157	509,528
Industrial low-capacity wells	PCA	106	56,074
Private low-capacity wells	HUA	100[a]	15,000[a]
Total	–	639	580,602

[a] Estimated (each well pumps 150 m^3 d^{-1})

during the calibration procedure. The parameters were kept in the range provided in Table 1. By comparing observed and simulated hydraulic heads (y_{obs} and y_{sim}, respectively), the goodness of fit of the model was calculated using the root mean square error (RMSE) and the normalized root mean square error (NRMSE) with the help of Eqs. (1) and (2), with y_{max} as the maximum and y_{min} the minimum observed groundwater head, respectively, in the study area.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_{sim}-y_{obs})2}{n}} \qquad (1)$$

$$NRMSE = \frac{RMSE}{y_{max}-y_{min}} \qquad (2)$$

The calibration was regarded acceptable with an overall RMSE of less than 2 m and an NRMSE <10% (Waterloo Hydrogeologic Inc. 2006). For calibration results see section 'Setup and calibration of the groundwater flow model'. As a post-processor for the simulation results, ZONEBUDGET (Harbaugh 1990) was used to calculate subregional water budgets in order to study the connectivity between the two aquifers as well as the river–aquifer interaction.

GIS-based MAR suitability mapping

Suitable locations to apply MAR in the city of Hanoi were determined using the GIS-based multi-criteria decision analysis (MCDA) method (Rahman et al. 2012). According to specified decision rules, the approach involves the use of geographical data, the decision-maker's preferences and the manipulation of data (Malczewski 2004). By combining GIS with MCDA, GIS capabilities such as data acquisition, analysis, storage and manipulation as well as MCDA features, like the combination of geographical data and the users preference into unidimensional values, are optimally used (Malczewski 2004; Rahman et al. 2012). The approach integrates important user-defined factors, including possible project sites and MAR techniques as wells as limiting geological, political, social and environmental characteristics (Rahman et al. 2012). In that way, the chances of missing important information which could lead to a poor decision are reduced (Rahman et al. 2012). The overall workflow consists of three main steps: problem definition, constraint mapping and suitability mapping (Rahman et al. 2012).

Two MAR methods were considered (problem definition): riverbank filtration along the Red River induced by wells located in the PCA and injection wells to infiltrate storm water in the HUA. Spreading methods such as infiltration basins and ponds were not considered

feasible, as large surface areas would be needed which are not available in the urban center of Hanoi.

A constraint map, which serves as a mask for the suitability map, was generated to eliminate areas where riverbank filtration and injection wells are not feasible. For riverbank filtration, the distance to the Red River was taken as a constraint (Table 3). Areas further than 1,500 m from the Red River were excluded as the influence of the seasonal river discharge fluctuations on the groundwater head was smaller than 1.5 m (not shown). Areas too close to public high-capacity wells and industrial wells were also regarded as not feasible to implement injection wells and riverbank filtration schemes. A 200-m buffer around already existing official high-capacity wells and a 100-m buffer around industrial pumping wells were chosen to avoid negative interference among pumping wells. Additionally, the buffer was extended perpendicular from the wells towards the river. For well injection, a buffer zone of 500 m around already existing public and 250 m around industrial pumping wells was chosen to guarantee a sufficient residence time within the aquifer before the recharged water is recovered and thus to avoid contamination risks. In this theoretical study, it is assumed that the storm water is sufficiently treated before it is recharged to the aquifer to minimize clogging and contamination risks of the groundwater.

For suitability mapping, the influencing factors of the respective MAR methods were chosen depending on data availability and whether those were already applied in other published case studies (Table 4). The following factors were included to identify suitable locations for riverbank filtration: distance to Red River, hydraulic conductivity and aquifer thickness of the PCA. Influencing factors to identify suitable locations for injection wells comprise the hydraulic conductivity, the aquifer thickness and the minimum storage capacity of the HUA as well as the local hydraulic gradient. The minimum storage capacity was calculated using the difference in elevation between the top of the HUA and the maximum simulated water table, multiplied by the specific yield.

As a next step, the minor and major effects for the modified multi-influence factor method (MIF) are defined (Fig. 3) and from that the relative weights can be determined (Table 4). Weights were assigned by a modified version of the MIF method (Shaban et al. 2005; Magesh et al. 2012). Interrelationships between influencing factors were divided into major and minor effects. In contrast to Shaban et al. 2005 and Magesh et al. 2012, the objective to be analyzed (here the MAR method) was included in the scheme. After Shaban et al. 2005, a value of 1 is assigned to major effects and a value of 0.5 to minor effects. The absolute weight of each influencing factor is the sum of minor and major effects of that factor. The relative weight of each influencing factor is calculated by dividing the absolute weight of the factor by the sum of all absolute weights (Table 4).

Table 3 Constraint criteria considered for GIS-based MCDA to select sites for the MAR methods riverbank filtration and injection wells

Constraint criteria	Riverbank filtration	Injection wells
Proximity to high-capacity pumping wells	>200 m, flow path vertical towards river	>500 m
Proximity to industrial wells	>100 m, flow path vertical towards river	>250 m
Distance to Red River	<1,500 m	–

The thematic maps have to be standardized (value between 0 and 1) before the overlay using linear combination technique can be performed (Fig. 4). The standardization for the distance to the Red River is described as an example. At a distance to the river between 1,000 and 1,500 m the standardized value decreases linearly from 1 to 0 because the seasonal influence of the Red River diminishes from 2-m-seasonal-groundwater-head fluctuation at a distance of 1,000 m to less than 1.5-m fluctuation at distance 1,500 m. A standardized value of 1 was dedicated to distances less than 1,000 m. The relative weights were used to overlay the standardized thematic maps using the weighted linear combination technique to receive the resulting suitability map for the study area dependent on the MAR method (Rahman et al. 2012).

Scenario analysis

The calibrated transient flow model was used to estimate the influence of MAR on the groundwater flow system by developing three scenarios. The first scenario relocates ten wells from the main depression cones towards the Red River to induce bank filtration, keeping the pumping rates constant.

The high urbanization rate in combination with the fast-disposing discharge system led to a decrease of natural recharge rates. Injection wells which infiltrate water directly into the Holocene aquifer could store excess water during the wet season and increase the groundwater levels especially locally. In that way, more water could be pumped without further decreasing the groundwater resources.

As a second scenario, two well galleries consisting of ten injection wells each were implemented into the base model. Each well infiltrates 500 m^3 d^{-1} into the HUA during the rainy season when water availability is high (from May–October each year), corresponding to a total infiltration rate of 1.84 Mm^3 $year^{-1}$. The two well galleries were located in areas identified via GIS-MCDA as very suitable to recharge the aquifer via injection wells. Another point to consider was the proximity to the next surface-water body, which should be low so that the distance between source water and injection location is small. As the PCA is the main aquifer used for drinking water supply, injection of water into that aquifer was not considered feasible as only highly treated water meeting drinking water guidelines could be recharged. The third scenario combines the two aforementioned scenarios. For the scenarios, the hydrogeological and climatic parameters as well as the exterior boundary conditions were kept constant.

Results

Setup and calibration of the groundwater flow model

After conceptualization and setting up of the numerical groundwater flow model, the initial water table was obtained using a quasi-steady-state simulation. The groundwater head fluctuation over time is simulated well for most observation wells (e.g. Q_23, P_17; Fig. 5). However, for some observation wells, e.g. Q_65 and P_32, the seasonal fluctuations with time are not reproduced well by the model but the general trends are in agreement with the observations. The seasonal fluctuations could be caused by unaccounted leakages of the drainage system, recharging water mainly during the wet season or by additional pumping through unknown private wells during the dry season.

Table 4 Suitability criteria considered for GIS-based MCDA to select sites for the MAR methods riverbank filtration and injection wells. Relative and absolute weights were defined according to the interaction between influencing factors (Fig. 3)

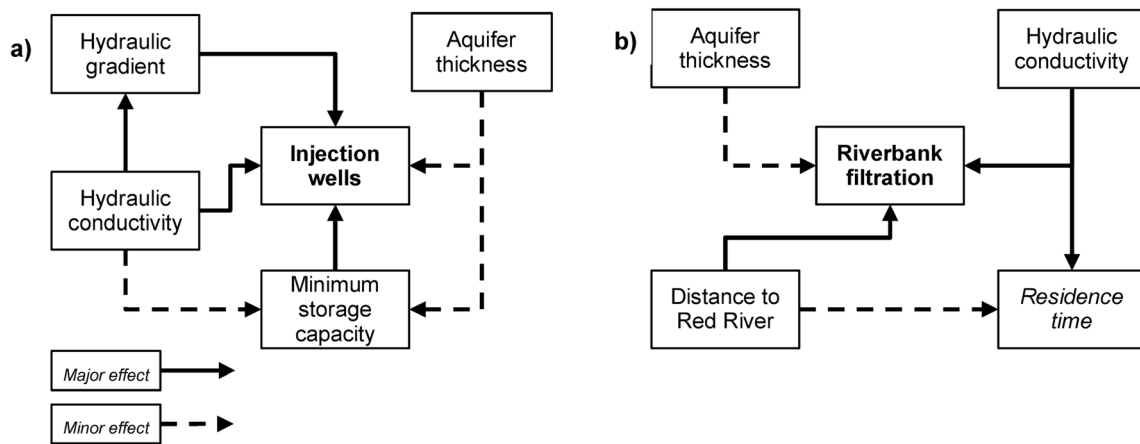| Suitability criteria	Riverbank filtration		Injection wells	
	Absolute weight	Relative weight [%]	Absolute weight	Relative weight [%]
Distance to Red River	1.5	37.5	–	–
Hydraulic conductivity of the aquifers	2	50	2.5	45.5
Aquifer thickness	0.5	12.5	1	18.2
Hydraulic gradient	–	–	1	18.2
Minimum storage capacity	–	–	1	18.2
Sum	4	100	5.5	100

Fig. 3 Influencing factors including major and minor effects for **a** injection wells and **b** riverbank filtration to determine weights for overlaying suitability maps

The analysis of residuals showed that most are smaller than 2 m. The maximum difference between the simulated and observed head was 3.32 m (well Q_67) and the absolute mean difference was 0.84 m. Considering the size of the model domain, the data available for calibration and the assumptions that had to be made, the resulting overall RMSE of 1.03 m and the overall NRMSE of 3.8% were regarded sufficient for the purpose of scenario analysis.

Groundwater flow model: base-case scenario

The calibrated groundwater head distribution for January 2005 (start of simulation period) and December 2007 (end of simulation period) show that two main groundwater depletion cones exist in the study area caused by intensive pumping (Fig. 6). Six locations in the study area were chosen for further analysis (Fig. 6). In the upper aquifer, groundwater heads are
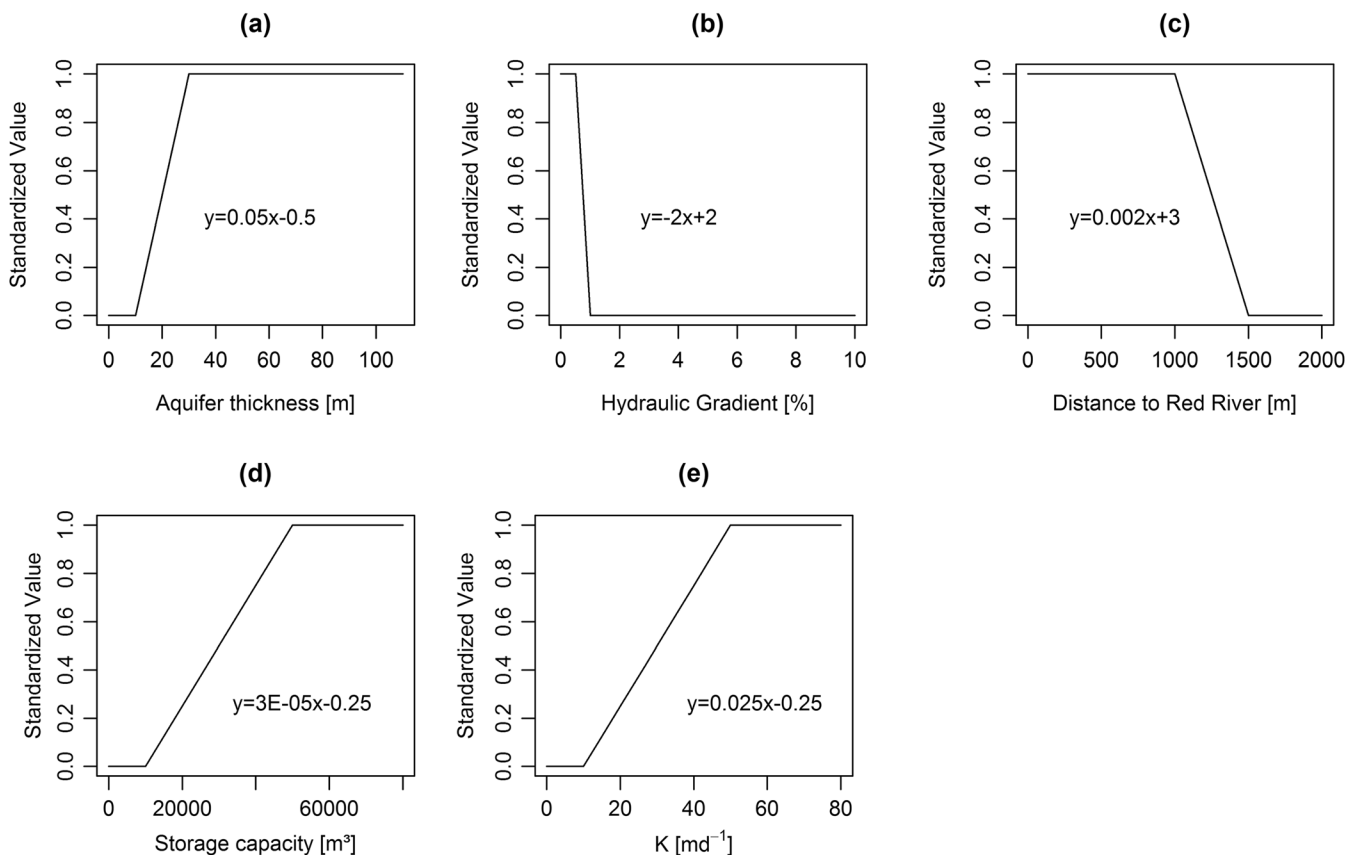

Fig. 4 Standardization used for MCDA including the slope equation for the influencing factors: **a** aquifer thickness [m], **b** hydraulic gradient [%], **c** distance to Red River [m], **d** storage capacity [m^3], and **e** saturated hydraulic conductivity K [m d^{-1}]
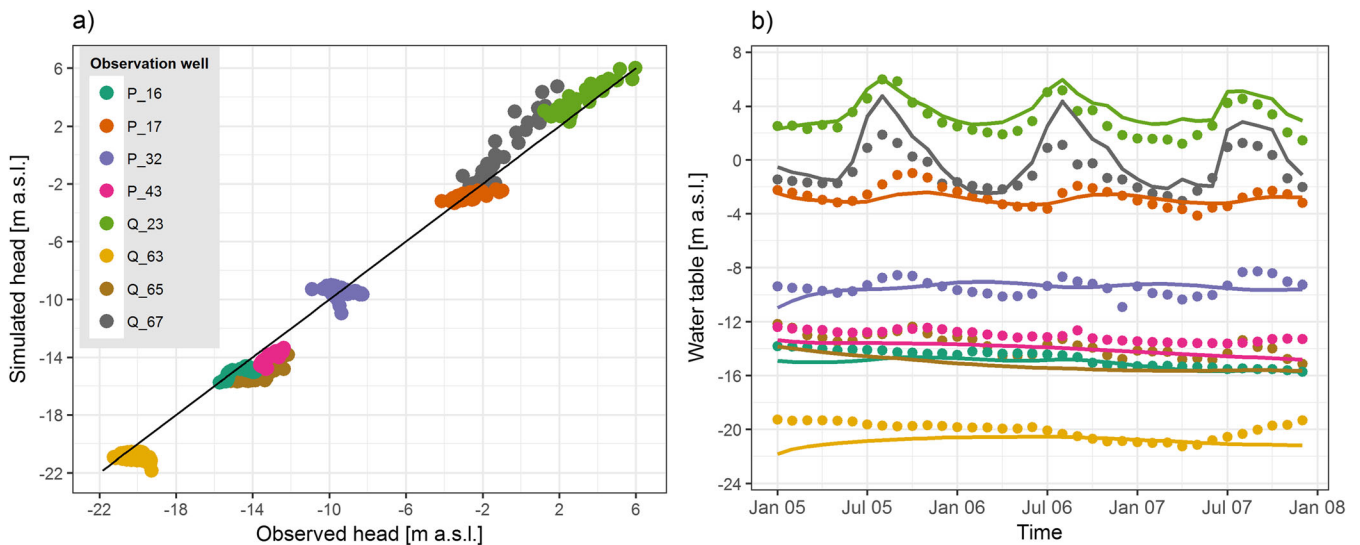
Fig. 5 **a** Simulated versus observed hydraulic groundwater heads [m a.s.l.] for the groundwater model during the study period 2005–2007. **b** Water-table elevation [m a.s.l.] during the study period (colored points) for groundwater observation wells and the corresponding simulated heads (colored lines) obtained via trial-and-error calibration

declining with a mean of 1 m during the study period. Nevertheless, the overall decline cannot be generalized for the whole study area. Especially along the Red River and in the southern part of the study area (location 4) groundwater levels increase locally by up to 8.3 m during the simulated 3 years. In contrast, groundwater heads are decreasing by up to 7.4 m in the center of the study area (e.g. around location 5 and northeast of location 4).

In the lower aquifer, groundwater heads are declining by a mean of −2.2 m between January 2005 and December 2007 (Fig. 6). An exception is the depression cone around location 1, where groundwater levels increase by up to 8.7 m due to the reduction of pumping rates by the local water supply company for that pumping station during the study period. The lowest groundwater head is, despite the pumping rate reduction, −31 m a.s.l. in that area. As in the HUA, groundwater levels decline especially in the central part of the study area around location 5 (by up to 8.1 m) and northeast of location 4 (by up to 7.4 m). The lowest groundwater levels still exist in the southwest of the study area, reaching −49 m a.s.l. at location 2. Simulations indicate that despite the local rise of groundwater levels in the depression cones (location 1, 2, 4), groundwater levels are declining regionally in the study area (e.g. around location 5, north of location 4).

The head difference patterns in the PCA and HUA are comparable, indicating that these aquifers are hydraulically connected although they are divided by the aquitard. ZONEBUDGET results show that water mainly flows from the top layer to the HUA and from there to the PCA. The reason for that could be the varying aquitard thickness across the study area which is partly in the range of 1 m. The increased gradient between both aquifers caused by the decreased groundwater levels furthermore facilitates the high

leakage from the HUA to the PCA. This situation causes cells to fall dry in the HUA. As no observation wells exist in the HUA, the location and extent of the dry cells cannot be verified.

Groundwater levels in the PCA close to the Red River are the result of confined conditions; in general, the groundwater levels are high and correspond to the seasonal discharge fluctuations of the river. This indicates that not only the HUA but also the PCA is hydraulically connected to the Red River. ZONEBUDGET results show that the seasonal river fluctuations are reflected in the river leakage rates and as a consequence in the leakage rates to the HUA as well as PCA. The high connectivity between both aquifers and the Red River suggests that groundwater withdrawals close to the Red River could be increased further by inducing more bank filtration.

Multi-criteria site selection

The GIS-based MCDA depicts the suitable locations to implement induced bank filtration in the PCA and injection wells in the HUA in the city of Hanoi. Identifying suitable sites for riverbank filtration is mainly dependent on the defined constraints (Fig. 7). As already a lot of wells exist along the Red River, most of the areas are excluded. Through constraint mapping, 85% of the study area was excluded from suitability mapping. The remaining sites are mainly classified as suitable (0.6–0.8, 7.8%) or very suitable (0.8–1.0, 4.5%) for riverbank filtration with respect to the used criteria. The suitability for riverbank filtration decreases with distance to the Red River and some areas further than 1,000 m from the river are classified as moderate (0.4–0.6, 1.9%) or poorly suitable (0.2–0.4, 0.6%).

Holocene unconfined aquifer (HUA)
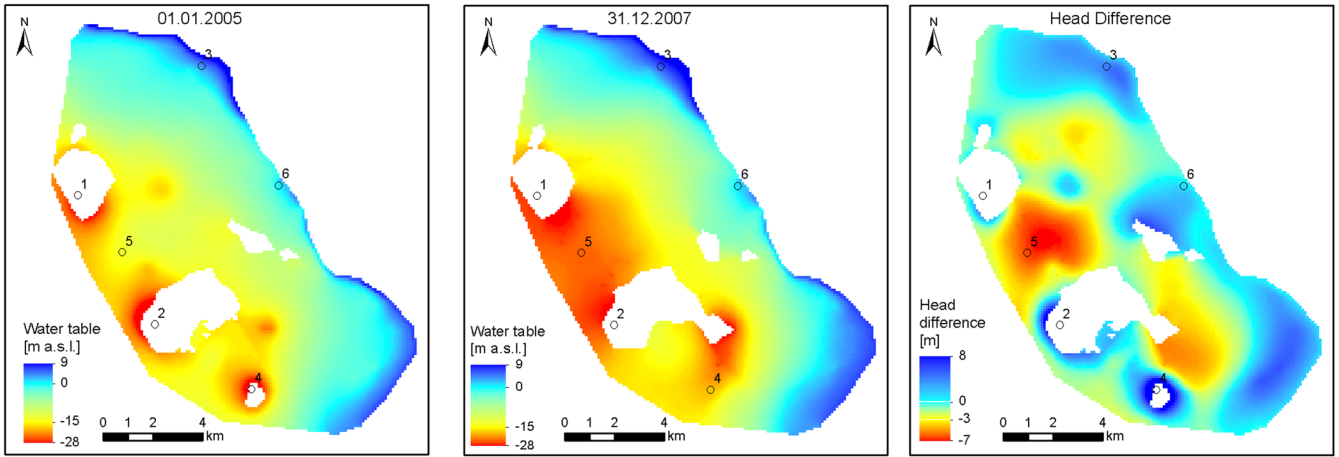
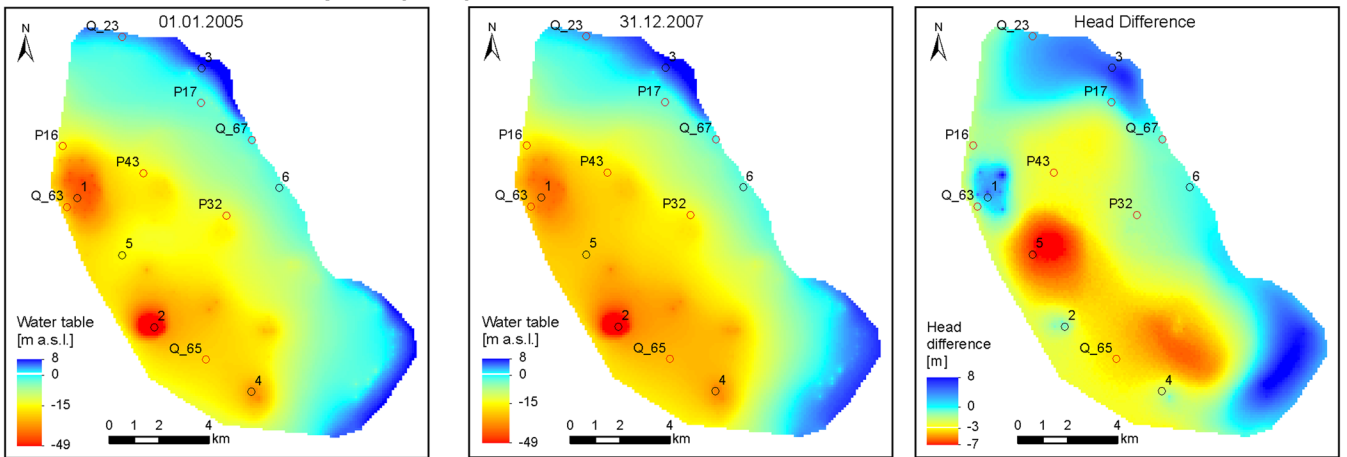## Pleistocene confined aquifer (PCA)

Fig. 6 Distribution of water-table elevation [m a.s.l.] at the beginning (1 January 2005, left panel) and end of simulation period (31 December 2007, middle panel) for the HUA (top row) and PCA (bottom row) as well as groundwater head difference [m] between the two time steps (right panel). Locations for groundwater head analysis are numbered (black circles), observations wells in the PCA are named and located with red circles, and the white areas represent dry cells
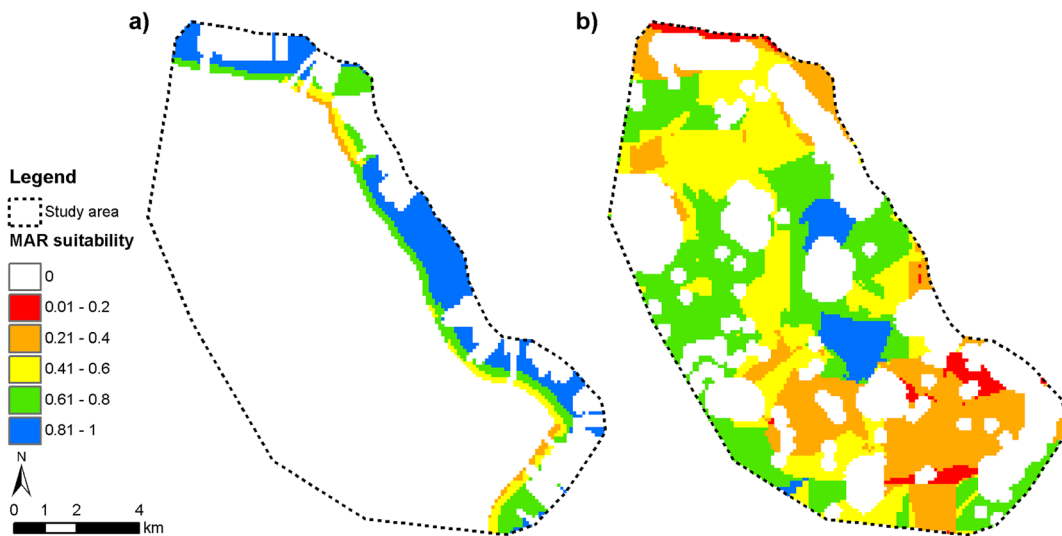

Fig. 7 Suitability maps for **a** riverbank filtration in the PCA and **b** infiltration wells in the HUA. A score of 1 means that the area is very suitable to implement MAR, and a score of 0 means that it is unsuitable depending on the influencing factors and constraints identified in this study

For the other considered MAR method, well recharge in the HUA, 35% of the study area was excluded by constraint mapping due to the proximity to existing pumping wells. Around 26% of the study area can be classified as suitable or very suitable for the implementation of injection wells. The highest potential for injecting water into the HUA exists in the south-central part of the study area (Fig. 7). Almost one fifth of the study area (19.6%) has a moderate suitability (0.4–0.6) and another fifth of the study area (19.1%) is unsuitable (0.0–0.2) or has a poor suitability (0.2–0.4).

Scenario analysis

Three scenarios were built to demonstrate alternative management options in the urban center of Hanoi based on the results of the calibrated groundwater flow model, referred to as the base-case scenario. The first scenario covers the relocation of public high-capacity wells towards the Red River to induce riverbank filtration (Fig. 8). The second scenario encompasses the infiltration of water via injection wells in the HUA, and the third scenario combines the previous described two scenarios (Fig. 8).
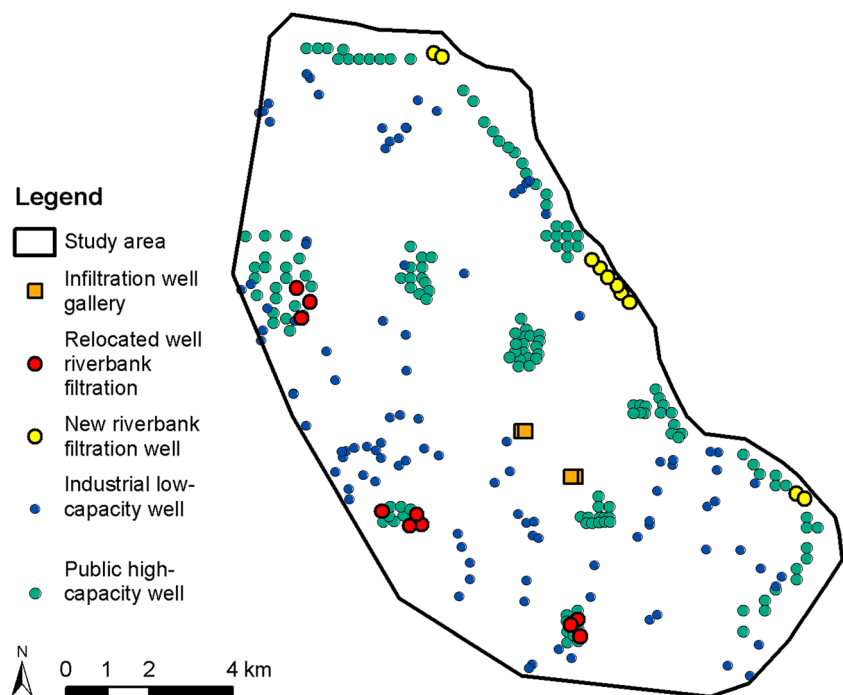
Scenario 1: riverbank filtration

Groundwater flow modeling showed that the Red River is the main recharge source in the study area; therefore, the relocation of wells towards the river can induce bank filtration and decrease the prominent depression cones in the southwest of the study area. The distribution of public high-capacity wells

in the study area suggests that riverbank filtration is already applied as a water supply technique in the city of Hanoi. Further wells along the river could help to manage the aquifer more efficiently, while the ecological sustainability of the river is not threatened as the mean discharge is 1,160 m^3 s^{-1} during the dry season (Nguyen et al. 2014).

As a first scenario, ten high capacity pumping wells which pump about 32,000 m^3 d^{-1} from the PCA were relocated from the three depression cones towards the very suitable sites identified with the GIS-based MCDA (Fig. 8). The results indicate that groundwater heads in the HUA change only slightly (Fig. 9). The riverbank-filtration well gallery around location 6 causes a head decline of up to 2 m in the HUA. In the areas where wells are relocated from, groundwater heads are slightly increasing caused by the decreasing abstraction rates in the PCA. Especially in the south of the study area (location 4) groundwater heads are increasing about 1.5 m. Overall, the relocation of wells towards the river causes a mean decrease of groundwater heads in the HUA of 0.12 m.

The water table difference in December 2007 between the base case and the riverbank filtration scenario for the PCA shows an increase of almost 13 m for the depression cone at location 2 and up to 5 m at location 4 in the southwest of the study area (Figs. 9 and 10). By relocating two wells from the northwest depression cone, the groundwater head increased by up to 2 m. On the other hand, groundwater heads decreased by up to 2.7 m at the riverbank filtration sites around location 6 in the PCA. Overall, groundwater heads increased on average by 0.1 m in the PCA at the end of the study period. ZONEBUDGET showed that the river leakage along the Red River is increased by 1.4%

Fig. 8 Scenario setup: relocation of existing public high-capacity wells (red circles) towards locations close to the Red River (yellow circles) to induce riverbank filtration, and infiltration well galleries (orange squares) in the HUA

Legend

☐ Study area

🟧 Infiltration well gallery

🔴 Relocated well riverbank filtration

🟡 New riverbank filtration well

🔵 Industrial low-capacity well

🟢 Public high-capacity well

N   0 1 2   4 km

a) Holocene unconfined aquifer (HUA)
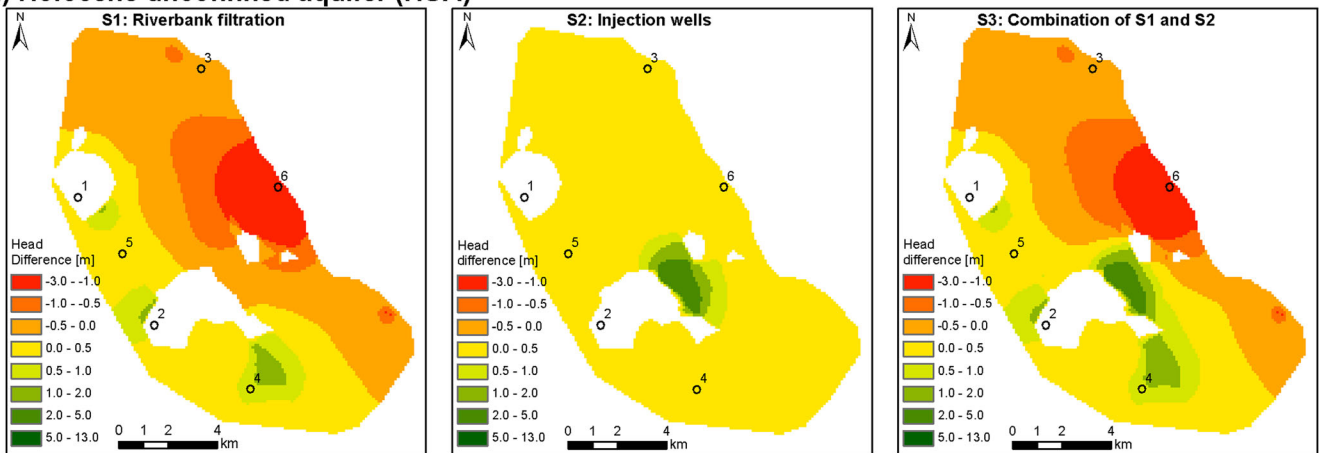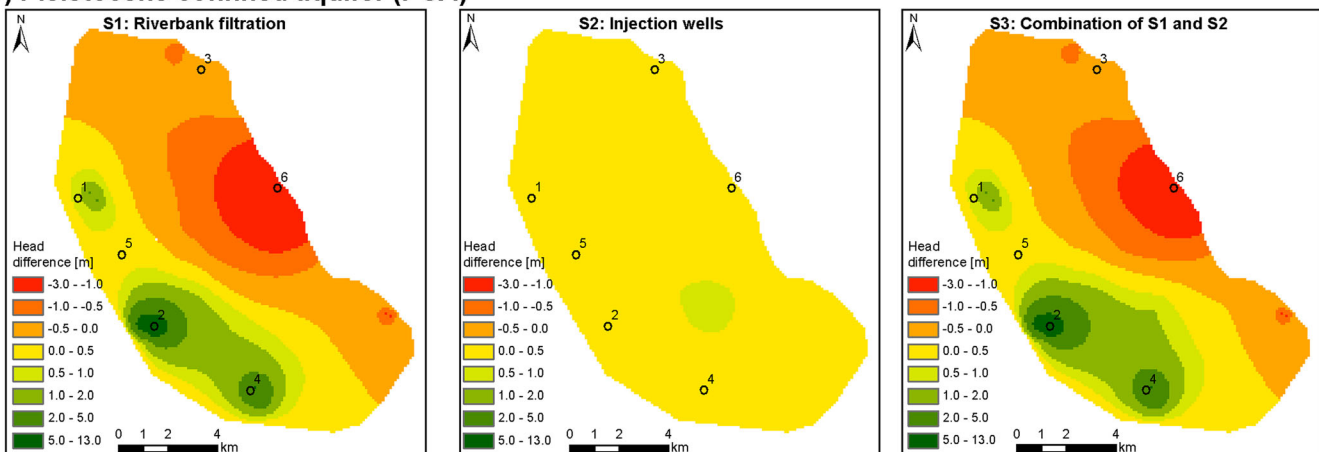

b) Pleistocene confined aquifer (PCA)

Fig. 9 Groundwater head difference [m] for December 2007 in **a** HUA and **b** PCA between the base-case scenario and scenario 1 (S1, riverbank filtration), scenario 2 (S2, injection wells), and scenario 3 (S3, combination of riverbank filtration and injection wells). Locations for groundwater head analysis are marked and numbered. White areas indicate cells with no head change

for scenario 1 compared to the base-case scenario, proving that riverbank filtration was induced by the relocation of wells. This also causes increasing leakage between the HUA and the PCA, which rose overall by 3.6%.

Scenario 2: injection wells

As a result of scenario 2, groundwater mounding is visible in the HUA aquifer where water is recharged (Fig. 9). Groundwater heads rise locally by up to 3.8 m. Overall, the infiltration of surplus water results in a mean increase in the HUA of 0.13 m.

The mean groundwater head in the PCA increases by 0.11 m compared to the base-case scenario at the end of the study period (Fig. 9). Underneath the infiltration galleries, the groundwater heads in the PCA increase up to 0.9 m. The infiltration of surplus water into the HUA has only a small influence on the PCA groundwater heads in large parts of the study area and in particular on the depression cones (Fig. 10). The latter is not surprising as water was infiltrated far away

from that area. The leakage between both aquifers stays almost constant compared to the base-case simulation.

When doubling the recharged water amount, e.g. by installing 20 injection wells per infiltration gallery instead of 10, the influence of the recharged water on the groundwater levels can, of course, be increased. The twofold recharge amount results in a mean rise of groundwater heads in the HUA of 0.25 m and in the PCA of 0.23 m and the maximum head increase accounts for 6.00 m in the HUA and 1.68 m in the PCA (not shown). Nevertheless, this requires more injection wells to be drilled and the additional surface water also needs to be treated before it can be recharged to the aquifer, resulting in higher costs.

Scenario 3: combination of riverbank filtration and injection wells

The third scenario combines the aforementioned two scenarios to evaluate the influence of the combined implementation of induced riverbank filtration and injection wells.
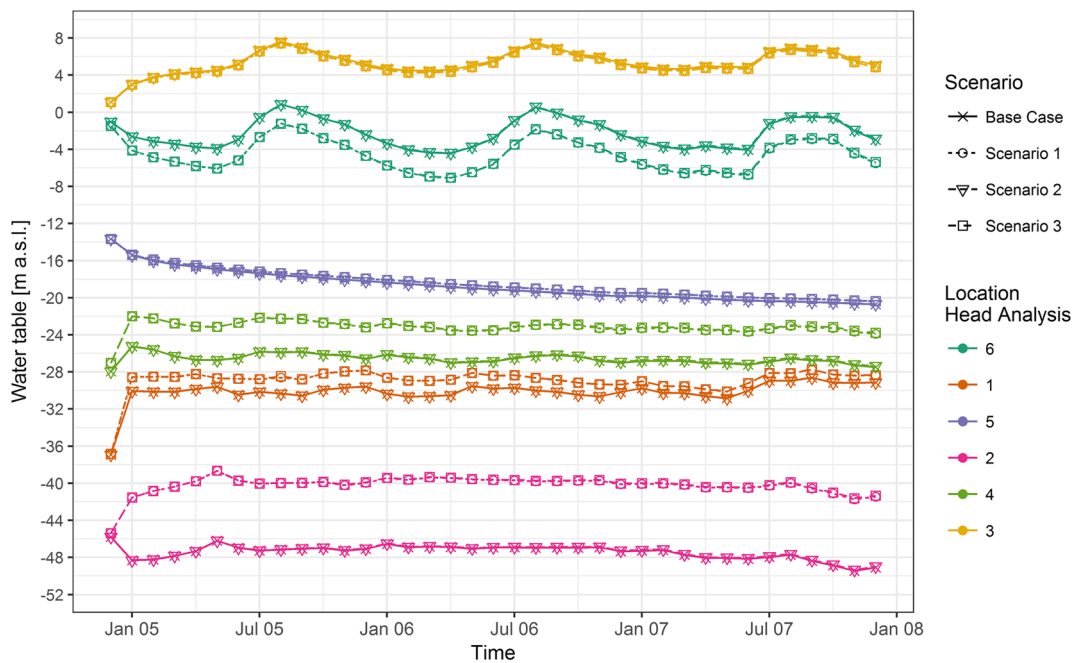
Fig. 10 Groundwater head fluctuation over time for the PCA at different locations defined in Fig. 9 for the base-case scenario, scenario 1 (riverbank filtration), scenario 2 (injection wells) and scenario 3 (combination of riverbank filtration and injection wells)

Groundwater mounding in the HUA, which was already detected for the second scenario, spread further (Fig. 9); however, the groundwater heads also decrease at the riverbank filtration sites (location 6) as in the first scenario. Overall, mean groundwater levels in the HUA are not changing compared to the base scenario.

In the PCA, mean groundwater levels increase by 0.2 m in December 2007 for the third scenario (Fig. 9). In the depression cone around location 2, groundwater levels rise by 13.1 m compared to the base-case scenario and around location 4 by 5.2 m. This is also a small improvement compared to the first scenario where groundwater levels rose by 13 m at location 2 and 5 m at location 4. At the main riverbank filtration site (location 6), groundwater levels decrease by up to 2.6 m compared to the base-case scenario, which is in accordance with the first scenario (2.7 m). Compared to the first scenario, river leakage is lower (rise of 1.3% compared to base-case scenario instead of 1.4% for scenario 1) but the overall leakage between the aquifers is slightly increased with 3.7% (scenario 1: 3.6%).

Discussion

With the help of a GIS-based MCDA, suitable locations to implement induced riverbank filtration and injection wells in the study area were identified. The suitability map for riverbank filtration clearly demonstrates that constraint mapping significantly influences the analysis. As a result, 84% of the study area is excluded by the defined constraints (maximum distance to the river, buffer around already existing wells). The remaining areas are mainly classified as suitable or very suitable for riverbank filtration in the PCA. Around two fifths of the study area is suitable or very suitable to implement the MAR-method well recharge in the HUA, while the highest potential exists in the south-central part of the study area. The suitability maps can only give a hint where the implementation of MAR is feasible, as social and economic criteria also have to be taken into account. The availability and the cost of land, and the quality of the pumped water including treatment costs, are only two examples which further influence the site selection and were not evaluated in this study.

The numerical groundwater flow model shows two main depression cones in the study area, which is in accordance with the groundwater head maps presented by Phi and Strokova 2015. The simulated scenarios indicate that the local overexploitation of the PCA can be decreased by the application of MAR. The first scenario covers the relocation of wells towards the river to induce bank filtration. As a consequence, the groundwater head in the PCA increases especially in the critical areas in the southwest of the study area, while groundwater heads along the river and the HUA only slightly decrease. Due to the higher permeability of the HUA in this area, the groundwater extraction affects a larger area and causes the less-deep groundwater extraction cones. Induced riverbank filtration can easily be implemented in the center of Hanoi, especially because it is already used as a water supply technique. Nevertheless, detailed hydrogeological characterization is necessary at the proposed locations. Furthermore, water quality needs to be investigated especially with regard to

elevated As concentrations already occurring in some parts of Hanoi along the riverbank (Berg et al. 2001; Norrman et al. 2008). The mobilization of geogenic As is probably caused by the highly reducing aquifer conditions generated by oxidation of buried peat material (Berg et al. 2001). The expansion of bank filtration could therefore cause a higher hydraulic gradient between the Red River and the aquifer and induce leakage of contaminated water towards the lower aquifer. Water quality concerns also with regard to other pollutants need to be eliminated by field investigations before the construction of riverbank filtration wells can be initiated.

Compared to the first scenario, the second scenario does not have such a big influence on the resulting groundwater heads and is not suitable to increase the water table in the depression cones. With regard to combating local overexploitation in the lower aquifer, the implementation of infiltration wells is thus not an effective measure but it can be useful to slow down overall groundwater depletion. Only high quality water can be recharged by injection wells to minimize chemical processes such as clogging and contamination risks of the underlying aquifer. As the present discharge system carries rainwater and wastewater at the same time, water has to be pretreated before it can be recharged, which is cost-intensive. Hence, the implementation of injection wells is not suitable in the city center of Hanoi.

The combination of the two MAR methods—induced riverbank filtration and injection wells—leads to the greatest simulated water-table rise. Compared to the first scenario, the third scenario only slightly increases the overall water table but the same disadvantages apply as previously discussed for the second scenario. Therefore, the first scenario is recommended to be considered for implementation as it is the most promising in terms of effort and the results achieved.

Land subsidence caused by the extensive groundwater exploitation in combination with the local geology is a major issue in the city center of Hanoi (Phi and Strokova 2015). The simulations indicate that the relocation of high-capacity wells can effectively increase the groundwater levels in the depression cones and stop further groundwater-level decline, while the groundwater yield can be kept at the same level. Hence, the smart relocation of pumping wells away from the main depression cones could be a management strategy to stop further land subsidence in those parts of the city. Nevertheless, it should be kept in mind that groundwater exploitation at the new pumping locations will also lead to new land subsidence, the extent of which is highly dependent on the local geology. As permeability in both the HUA and PCA is high along the central part of the Red River where most of the high-capacity wells were relocated to, groundwater pumping would cause shallower groundwater extraction cones but affect a larger area, which is favorable with regard to land subsidence. For areas with high thickness of easily compressible soft soil layers which are especially prone to land subsidence, future high groundwater-level decline should be, in general, avoided.

The scenario analysis indicates that MAR only has a small influence on the overall groundwater budget. The mean groundwater head and the river leakage are only slightly improved by the implementation of MAR. Nevertheless, the smart relocation of wells can have a positive impact on the local groundwater depression cones and, as a consequence, can avoid further land subsidence in those areas while meeting the groundwater demand. Also, in view of future predicted water demand rise (Phi and Strokova 2015), riverbank filtration and a smart relocation of wells can provide an option for further groundwater exploitation, avoiding further high land subsidence rates induced by decreasing groundwater levels in the already existing groundwater depression cones.

Conclusions

The simulations indicate that MAR can only have a small contribution to the overall water budget in the city of Hanoi. Nevertheless, the study suggests that the application of MAR can contribute to combating the existing large groundwater depression cones in the city through the smart relocation of wells towards the Red River to induce riverbank filtration. Groundwater simulations show that groundwater levels can be locally increased which, for instance, stops further land subsidence and secures sufficient water supply especially during the dry season. However, the presented modeling study should be recognized as merely a first step to quantify the feasibility of MAR as part of sustainable water-resource management in Hanoi, Vietnam. Detailed hydrogeological characterization of the study area, as well as field tests considering water quality aspects, are needed to implement MAR to meet future increasing water demand. The approach presented in this article is not limited to the city of Hanoi and can be replicated to study the feasibility and possible impacts of implementing MAR in an aquifer prone to exploitation caused by, e.g. climate change, population growth or the lack of a sustainable water management concept.

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