Sustainable water resources management in the Long Bien district of Hanoi, Vietnam
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ABSTRACT
The accelerated industrialization of Hanoi, Vietnam, coupled with a high population growth rate and changing climatic conditions create increasing pressure on the local water balance. Despite abundant precipitations, overexploitation endangers the groundwater resources, which are not able to sustain an adequate water supply. The present paper presents a sustainable approach for balancing the lowering of groundwater levels by increasing the rainwater percolation rates through enhanced infiltration. The efficiency of the method was assessed by a scenario analysis based on hydrological and hydrogeological models. Multi-criteria simulations revealed the optimum infiltration sites by considering technical and site-specific aspects and the positive impact of artificial recharge on seasonal groundwater budget.

Key words | drainage, groundwater recharge, Hanoi, stormwater, sustainable, Vietnam

INTRODUCTION
Motivation and challenges
The management of water resources in Hanoi, Vietnam, is endangered by two main factors. On one side, the population growth rates reached recently record levels of 3.5% (VIETNAMNET 2008) with densities of about 3,490 inhabitants per km² (VIETNAMNET 2007). At the same time, the country’s industrialization accelerated dramatically with insufficient protective measures for the environment. The downside of this rash development is the difficulty to provide a safe water supply and sustainable urban sanitation. In addition, the expansion of residential areas by merging adjacent provinces and districts into the metropolitan zone increases the challenges posed by the infrastructure-related works. On the other side, the extreme regional weather conditions, with high precipitations in a rather short time, lead to high loads of the existing urban drainage system which is often unable to work properly and flooding events inevitably occur. And since the system is mainly designed for a quick disposal of rainwater and domestic wastewater, the natural water resources located in the city’s subsurface are not sufficiently replenished naturally and tend to decrease in volume at worrying rates (Nguyen & Helm 1995; Nguyen & Nguyen 2002).

Description of the study area
Long Bien district is situated on the western side of Hanoi, Vietnam, between Red River and Duong River (20°57’56” N21°05’00” N and 105°49’05” E–105°57’45” E). With a total surface of about 60 km² (Figure 1), Long Bien is a new model district which is expected to become one of the city’s centres for trade, services and transportation that will connect Hanoi with other provinces in the north of Vietnam.
In 2008, the district’s population was about 200,000 inhabitants with predicted 350,000 inhabitants by 2020. Over the years, both rivers brought fine alluvial sediments such as clay, silt, sandy clay and fine sand into the study area, making the subsurface of Long Bien poorly permeable. As a flood prevention measure, the district was almost completely surrounded by a dike system along both riverbanks that also divides the area into three distinct zones: flat area inside the dike system, area outside the dikes and the alluvial terrain along the riverbanks.

The study area is also characterized by numerous irrigation and drainage ditches that are diverting the waters in the Cau Bay River which then flows into the Red River in the south of the district. During heavy rain events, the district’s drainage is impeded by Red River overflow and channelling the water out of the district is almost impossible. This leads to severe flooding events not only in the areas near the riverbanks but also in areas inside the dike system, as the district does not possess sufficient surface storage facilities to attenuate the high flow peaks.

Despite large volumes of water resulting from precipitations, the groundwater levels in the district decrease considerably (Fischer et al. 2011). The lowering rate of piezometric heads in Long Bien is yet not as alarming as in other districts of Hanoi (e.g. Thanh Cong) but this is considered to be the major cause for an average land subsidence of about 15 mm per year (HTA 2003).

**Objectives**

To overcome these challenges, a sustainable concept oriented mainly at naturally occurring processes was developed for the optimization of the existing master plan for the urban drainage system (Stefan & Werner 2009; Werner et al. 2011). The concept was tailored to match the hydrological, hydrogeological and socio-economic conditions of Long Bien district. The specific objective of this concept is the establishment of adequate water retention spaces (above surface and subsurface) in the Long Bien urban landscape. The approach includes measures for the delay of surface drainage in order to allow the decrease of flow peaks and to improve the subsurface reservoirs’ replenishment rate.

**METHODS**

A conceptual hydrologic model was combined with a groundwater model to assess the natural and enhanced
infiltration potential of rainwater in Long Bien. The hydrological rainfall-runoff model KOSIM 7.3 (Itwh 2006) was used for the simulation of the system load in the catchment area and its general drainage behaviour.

For the runoff calculations, Hanoi’s yearly precipitation (1,682 mm) and evaporation (1,262 mm) rates were extended by their monthly distribution and supplemented by hourly precipitation values for 2009 collected from Lang Weather Station (Long Bien, Hanoi). Additionally, daily precipitation data from 1961–2004 were obtained from Aphrodite’s Water Resources Project (2010). The degree of soil surface sealing was calculated for existing constructed areas as well as for residential and industrial zones included in the Master Plan of the district by land use analysis of available city plans. For the infiltration calculations, the average water percolation rate through the upper soil layer was estimated from the sedimentological data at $1 \times 10^{-6}$ m/s.

The hydrological model was coupled with a transient groundwater hydraulic model run with Visual MODFLOW 4.2 software (Waterloo Hydrogeologic Inc. 2006). The model assessed the seasonal variations of groundwater piezometric levels of the water-bearing layer of Pleistocene origin considering both natural and anthropogenic factors (lateral recharge and withdrawal for above-surface use). The following data were used for the setup of the model: 30 drillings up to 150 m deep, daily water level stages measured from 1996 to 2003 by three gauging stations located on Red River (two stations) and Duong River (one station), monthly piezometric heads collected from 13 observation wells (1996–2003) and 23 municipal and private pumping wells (Figure 2). Three more boreholes were drilled in the study area for verification of the data set and for the calculation of hydrogeological coefficients. The Red River was chosen as model hydraulic boundary and the area on the eastern side (city centre) was considered as ‘no flow’ region.

Figure 2 | Location of observation wells, pumping wells and geological cross-section.
A scenario analysis was done for the assessment of the impact of rainwater infiltration on the local groundwater budget, the potential infiltration sites being selected using a multi-criteria analysis. Two infiltration approaches were considered for the simulation of deep-wells injection of rainwater into the deep aquifer as compensation of the groundwater withdrawal.

RESULTS AND DISCUSSION

Under natural conditions, the water balance is rather stable and sustainable. Man-made structures influence this equilibrium by changing the hydraulic conditions, i.e. reduce the natural percolation rates and increase the surface drainage by sealing more and more pervious surfaces. In addition, the increase in water demand worsens the fragile balance even more by increasing almost simultaneously the groundwater abstraction rates and the introduction of pollutants into the subsurface. However, the situation can be restored. For this it is only necessary to learn from and reproduce naturally occurring processes such as the creation of natural retention facilities, green spaces, avoid sealed surfaces, etc. The concept presented in this paper reflects the impact of a nature-oriented approach of the drainage system on the local water cycle. The approach is based on the increase and sustainable exploitation of infiltration potential of rainwater and it is shown from two complementary perspectives: (a) the impact of decentralized rainwater management systems on the surface rainwater drainage and (b) the subsurface rainwater infiltration and storage.

Surface rainwater drainage

Precipitation and evaporation are the guiding principles for the design and determination of the basic conditions for the planning of rainwater management systems. The study started with the classification and characterization of precipitation events (intensity-duration-frequency analysis) and preparation of data as input for the simulation of the rainfall-runoff process. Recurrence intervals for the daily precipitation rates were calculated for 2009 data using Cunnane plotting formula (Cunnane 1978), several 1-hour values enabling a detailed analysis in terms of total amount, length, change in intensity, flow peaks, etc. Additionally, hourly precipitation rates for 2009 were used for measuring rainwater management units (Figure 3).

Figure 3 | Precipitation hydrograph for Hanoi, Vietnam (2009).
The next step in data preparation was the soil and land use characterization. The degree of soil surface sealing was necessary to be estimated for the calculation of the runoff resulting from precipitations. Representative land use types were selected among the existing areas together with new areas from the master plan. For each type of construction, building and streets’ surface data were collected and contrasted with the total land surface. The water system was divided into various catchment areas whose shape was determined by the structure of the drainage system. The simulated hydrograph was then analysed using simple statistical methods. Beside the various total sum and average calculations, the overflow events at the discharge facilities in particular were examined in terms of amounts and frequency and their monthly distribution was represented. As expected, the percolation percentage increases with the decrease of impervious areas (an inflow of 5 $\text{l/(s} \times \text{ha)}$ would be the safeguarding limit for rainwater treatment when about 10% from the total land is occupied by decentralized rainwater management facilities while still providing a high percolation percentage) and with the increase in the degree of soil sealing.

Based on the previous estimations, it was assumed that, given the existing soil characteristics in Long Bien, 20% of the total pervious area can be made available for decentralized rainwater management measures. For this, the area flow restriction level was set at 10 $\text{l/(s} \times \text{ha)}$. Under these conditions, approximately 11% of rainwater can percolate via decentralized facilities (e.g. rainwater retention ponds). Up to 50% of impervious surfaces can be connected to decentralized facilities without overloading them (estimation using precipitation data from 2009). The other 50% shall, however, be channelled unchecked into the municipal central collection system. Overall, it is estimated that the implementation of decentralized rainwater management units would reduce the daily flow peak in case of a system load of 200 mm/day by almost 50%.

**Subsurface rainwater infiltration and storage**

If the runoff is higher than the area restriction level, the above-ground decentralized systems for rainwater management (retention ponds) may get overloaded and fail. Moreover, in case of heavy rain during the monsoon season, the units must be emptied within a very short time (maximum 12 hours). Under the given soil characteristics, about 400 $\text{m}^3$ of retained precipitation requires approximately 1 ha and 12 hours for percolation into soil. Additional measures were sought for increasing the percolation rates and the one selected was the use of subsurface storage by means of managed groundwater recharge. This will not only reduce the load on the rainwater management system but also replenish the groundwater reservoir and compensate the subsidence of groundwater levels (Fischer et al. 2011).

**Characterization of local stratigraphy**

Stratigraphic and sedimentological data indicate a heterogeneous sedimentary architecture with two main types of deposits: the medium – coarse sands with rather high specific yields form aquifer layers and the alluvial silts and clays form low-permeable units between aquifers. The spatial distribution shows that upper permeable layers of Holocene origins are scattered only along the two rivers and are partially overlapping with the area of the district that is exposed to frequent flooding events. The layers are locally about 15–20 m deep, they are unconfined and consist of sandy sediments. Because of their local distribution, the Holocene layers were neglected in the groundwater model and their water permeability value was estimated as fitting parameter. The next water-bearing layers underlying the Holocene aquifer have Pleistocene origin and could be differentiated in: $q_{p2}$ – upper Pleistocene (semi-confined layer, 20–40 m deep, medium sands) and $q_{p1}$ – lower Pleistocene (confined, 30–40 m deep, coarse sand mixed with clay and gravel). The layers are separated from the Holocene aquifer by low-permeable clay and silt lenses (aquitard-type formations) that also inherit the direct recharge from the Red River during the dry season. Figure 4 shows the simplified sedimentological cross-section used in the groundwater model.

After model calibration, the water permeability values for the lower Pleistocene layer were set to values from $6 \times 10^{-5}$ to $5.5 \times 10^{-3} \text{m/s}$ and for the upper Pleistocene layer from $2.5 \times 10^{-4}$ to $5.5 \times 10^{-3} \text{m/s}$. The specific storage and specific yield of both layers were estimated at values from $1 \times 10^{-2}$ to $1 \times 10^{-4} \text{m/s}$ and the soil’s effective porosity has values from 0.1 to 0.2.
Seasonal variations of piezometric heads and groundwater infiltration characteristics

The next step is the simulation of natural variations of piezometric heads in order to set the optimum infiltration schedule (Figure 5).

The depression cones in the centre of the district correspond to the well fields of Hanoi Water Company and had the lowest variations in depth during the season change. This can be explained by the little lateral recharge due to the long distance to both adjacent rivers. The difference between the piezometric heads in dry and rainy seasons can reach up to 7 m. However, many authors reported a severe decline in piezometric heads of Hanoi’s groundwater over the past years (Nguyen & Helm 1995; Thu & Fredlund 2000; Nguyen & Nguyen 2002; HTA 2003). This drawdown of piezometric heads produced an increasing stress in the underlying aquifers caused by the decrease of pore water pressure from an unbalanced recharge–discharge mechanism. This stress has been coupled with the weak geological structure of the upper layers (mud, clay, peat, silt) and, as a direct consequence, land subsidence cases occurred and were reported in the literature (Nguyen & Helm 1995; Thu & Fredlund 2000; Nguyen & Nguyen 2002; Luu & Pham 2008; Go et al. 2010).
Selection of infiltration site

GIS-based multi-criteria decision analysis (MCDA) is frequently used for the selection of potential sites for managed groundwater recharge (Masciopinto et al. 1991; Kallali et al. 2007). MCDA was used in the present study for the identification of the most suitable locations of groundwater infiltration wells in Long Bien district. The analysis included environmental, geological, hydrogeological, and urban criteria, which are assumed to be constraints of the same weight. The acceptability ranges were determined by a critical threshold value (Table 1).

Based on these acceptability ranges, the results were graphically expressed for each criterion individually using a simple Boolean mapping system, where the excluded areas are represented in white and the areas considered for infiltration in black (Figure 6).

The MCDA was done by abstracting the acceptable ranges from the overlaid Boolean maps (Figure 6(a)–(d)). After overlaying, it was concluded that about 30% of the district’s surface (about 18 km²) is suitable for the installation of managed groundwater recharge units (Figure 6(e)). The potential infiltration sites are mostly located in the centre-east of the district, with smaller areas scattered in the southwest.

Infiltration scenarios

The lower Pleistocene layer (up to 80 m deep) consists of coarse sand and gravel and offers good conditions for use as a primary source of drinking water. With a good specific yield, this was also the layer selected for the managed infiltration with filters installed at about 50 m below mean sea level. In this case, it was estimated that the direct input by precipitation is very low and therefore the natural groundwater recharge rates from precipitation were neglected.

Four scenarios were simulated taking into consideration the best-case locations and the objectives above (Figure 7). The base-line scenario (‘S-0’) simulates the natural fluctuations of piezometric levels in the complete absence of any anthropogenic influence (neither extraction, nor managed infiltration). In this case, the piezometric heads reach 7–8 m above mean sea level during the rainy season and 3–4 m during the dry season. In case of ‘Sn’ scenario, the lateral recharge has been neglected and only the effect of groundwater extraction is represented. In this case, the piezometric heads were following the same time profile but they reach only 4–6 m above mean sea level during the rainy season and 1–2 m during the dry season. The aim of the infiltration is therefore ‘to lift’ the piezometric heads as close as possible to the 3–4 m lower boundary during the dry season without passing the upper limit of 7–8 m above mean sea level.

### Table 1 | Criteria for the selection of groundwater infiltration wells

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Acceptability range</th>
<th>Comments</th>
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<tbody>
<tr>
<td>A. Environmental</td>
<td>500 m around main groundwater extraction wells</td>
<td>Sanitary protective area</td>
</tr>
<tr>
<td>B. Geological</td>
<td>Thickness of poorly permeable soil layer below ground surface less than 10 m</td>
<td>Land subsidence can be influenced by the thickness of the alluvial material right below surface</td>
</tr>
<tr>
<td>C. Hydrogeological</td>
<td>Groundwater levels higher than 2 m below surface</td>
<td>Infiltration potential increases with groundwater drawdown</td>
</tr>
<tr>
<td>D. Urban/land use</td>
<td>Outside residential and densely constructed areas</td>
<td>Available open spaces (no constructions)</td>
</tr>
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Figure 6 | The Boolean mapping system used for assessment of optimum infiltration sites using selection criteria from Table 1.
Two approaches were used for the infiltration: (1) Scenario ‘S1’ implies the infiltration of rainwater through five infiltration fields, each well field located in the vicinity of the main groundwater extraction sites (but not closer than 1,000 m due to sanitary reasons). Choosing this location can provide a fast compensation of local groundwater depletion and helps avoid major land subsidence issues but with strong qualitative considerations for the infiltration water; (2) Scenario ‘S2’ implies the infiltration of rainwater using only three well fields that are located in the vicinity of the future wastewater treatment plants. This scenario takes into account the planned drainage infrastructure, e.g. the construction of wastewater treatment units that can be partially adapted to handle only rainwater. The optimum number of wells for each scenario was estimated iteratively by running the simulation of groundwater recharge for arbitrary values and comparing the resulting piezometric heads with the values from scenarios S-0 and Sn.

The best results were obtained for the scenario S1, where the calculated piezometric heads reproduce the conditions of the base-line scenario S-0. In this case, the enhanced rainwater infiltration may compensate almost 100% of the whole groundwater extraction in Long Bien and therefore provides sustainable groundwater replenishment in Long Bien district. The scenario S2 also promotes a significant increase of piezometric heads but mostly during the dry season, a fact which makes this approach suitable as a flood mitigation measure by providing subsurface storage space for peak flow reduction.

**CONCLUSIONS**

The objective of the present paper is to provide a nature-oriented concept for the sustainable urban drainage in Long Bien district, Hanoi, Vietnam. The example presented aims at strengthening the city’s identity by urban...
development on and around the water and the integration of water bodies into the city’s social life. The decentralized rainwater management measures will be integrated into the urban landscape tackling the problems at origins while it will relive the drainage system and improve the general aspect of the area. In the meantime, the measures for managed groundwater recharge will reap two rewards: taking over partial load from the drainage system and by counter-balancing the lowering of piezometric heads caused by groundwater overexploitation. The two scenarios were simulated using a groundwater model and showed that infiltration of rainwater is also possible during the rainy season but without significant increase of groundwater piezometric heads. The first method allows additional infiltration of rainwater during the whole year and represents a sustainable solution for the management of rainwater in fast developing areas such as Hanoi, Vietnam.

For the sake of simplification, it was assumed that all the water required for direct infiltration into the subsurface is collected and provided to the infiltration sites either by decentralized rainwater management units or by other storage and delivery means. The quantitative approach presented in this paper assumes therefore that rainwater meets the quality criteria at the time and site of infiltration requested by national regulations. Further work is necessary to elucidate the exact qualitative criteria imposed by the implementation of enhanced rainwater infiltration with consideration to groundwater protection and sustainable management.

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**REFERENCES**


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