Investigation of groundwater recharge mechanism for sustainable urban water system planning and management in Hanoi city

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Abstract. Seasonal variation of water levels and water quality of groundwaters and ponds was investigated to illustrate the recharge mechanism and seasonal effects of groundwater in Hanoi suburbs. Water level monitoring data showed that the upper aquifer had a fluctuating water level (variation: 2.0 m) corresponding to heavy rains, representing a substantial impact by infiltration of rainwater from the surface and perhaps pond water. In the area with less permeable surface, there was small response to rainy events, suggesting that the ground water levels were governed by a regional scale groundwater flow. The stable isotope ratios in pond waters had a clear seasonal change, in which isotopes were enriched throughout the dry season. In groundwater, isotope signatures indicated that the dominant sources had evaporation process. In studied areas, the isotope ratios in groundwaters and pore waters in the shallow soil (<25 m depth) were clearly heavier than that in the deep soil. Isotope results suggested that groundwaters close to the Red River are largely recharged by the river itself. In areas far from the river, surface waters having evaporation process (e.g., ponds and paddy fields) and the rainwater directly infiltrating from the surface mainly recharges the upper aquifer. The lower aquifer in inland locations would be recharged by lateral inflow, either from the Red River or surrounding mountains. The results revealed the recharge mechanism for groundwater budget which could contribute for the planning and sustainable development of urban water system in Hanoi City.

1. Introduction
In Hanoi city, Vietnam, groundwater is currently the major source of drinking water, either provided by public water supply or obtained by households using tubewells [4]. The population of Hanoi city is expected to increase by 43% in 2030, and by 68% in 2050 (PPJ-VIAP-HUPI, 2011). While public water supply using surface water is being extended in order to meet the additional water demand in urban areas, groundwater remains the important source of drinking water in Hanoi city (PPJ-VIAP-HUPI, 2011). In particular, the residents in suburban and rural areas of Hanoi city the in urban and suburban areas may need to use groundwater as a main source of water (An et al., 2012).
As many studies have shown, elevated level of As in groundwater is a major health threat in Hanoi city (Berg et al., 2001, Nga et al., 2003). High level of groundwater As is typically related to highly reductive aquifers in young Quaternary deltaic and alluvial sediments (Berg et al., 2008). However, As levels have highly diverse spatial distribution, the reasons of which are not yet fully understood. The general geochemical mechanisms involving mobilization of As under reducing condition is widely attributed to microbial and/or chemical reductive dissolution of As-bearing iron (Fe) minerals in the aquifer sediments (Fendorf et al., 2010). Others suggest that As may be released from soil minerals at oxic-anoxic boundaries and could subsequently be drawn down from the near-surface through the aquifer to well-depths (Polizzotto et al., 2008). Studies have shown that the availability of labile organic carbon as a driver of microbial reduction of Fe and As is an important factor affecting As release in subsurface. Elevated groundwater As concentrations broadly correspond with increased level of metabolic by-products in groundwater including inorganic carbon, ammonium, and methane (Nga, 2003; Fendorf et al., 2010). Therefore, the migration of organic matter contained in water or sediments of ponds needs to be further investigated, because it potentially enhances As mobilization from the soil minerals in the aquifers.

The recharge and the flow of groundwater in Hanoi are also considered as important factors affecting groundwater As. It was considered that both the Pleistocene aquifers (the lower aquifers) and Holocene aquifers (the shallow aquifers) along the Red River are mainly recharged by water from the river itself, at least in part because of the large withdrawals supplying the city of Hanoi (Berg et al., 2007, Berg et al., 2008). According to the modeling study by Water Master Plan of Hanoi for the period to 2030 (Hanoi PC, 2016), recharge of the lower aquifer in the areas where groundwater was pumped excessively was attributed 60–65% to vertical percolation, 30–35% to surface water bodies, and 2–3% to lateral inflow, stating “at a distance of 5 km from the Red River, the Pleistocene aquifer is largely replenished by vertical percolation from Holocene aquifer”. On the contrary, a few literatures (Norman et al., 2008, Berg et al., 2008) and our recent study (Hayashi et al., 2012) on stable isotopes showed that the groundwater in Hanoi partly had sources that have evaporation process (e.g., ponds and paddy fields; not the Red River), which suggests that a detailed study is required on the recharge of both upper and lower aquifers from surface waters other than rivers (e.g., ponds, paddy fields) because such surface waters are prevalent in suburban area of Hanoi city.

The climate of Hanoi is characterized by a hot and humid rainy season (April–October) and a mild dry season (November–March). The water level of the Red River has a large seasonal variation (9 m), which may facilitate As dissolution in groundwater through repeating rises and drops of oxic-anoxic boundary in subsurface (Berg et al., 2008). In suburban inland groundwater, where the Red River might have a minor contribution in recharge, it is of a great interest whether such an As pollution mechanism by fluctuating water levels takes place or not. In terms of water resource management and urban planning, if infiltration from ponds is appreciable for groundwater recharge, and if that infiltration does not cause significant groundwater pollution by As, preservation of ponds in suburban areas would contribute to mitigate groundwater pollution by As, because infiltration from ponds may be a more stabilized source of recharge, with smaller water level fluctuation than direct recharge from the ground surface or paddy fields which should have a seasonal variation.

The study aims at illustrating the recharge mechanism of groundwater in Hanoi suburbs by investigating the seasonal variation of water levels and stable isotopes of groundwater and nearby ponds, based on continuous monitoring of water levels and regular sampling of waters.
2. Materials and methods

2.1 Site description.
Hanoi City is located in the upstream part of the Red River basin. Figure 1 shows the geological cross-section in Hanoi City (Berg et al., 2008). The geology of Red River basin is typically characterized by the alluvial sand and gravel layers, covered with thick clay sediments, which were formed during the succession of transgressions and regressions, bringing sediments of marine origin. Due to the multitude of sedimentation processing occurring in the Red River delta, the lithology of the delta sediments is highly complex and sediment sequences vary considerably within short distances (Tanabe et al., 2006). The upper aquifer is the Holocene layer (formed ten thousand years ago to present), typically from the surface to 10–20 m depth. The lower aquifer is the Pleistocene layer (formed 2.5 million to ten thousand years ago), lying underneath the Holocene layers. Holocene sediments are present in the larger Hanoi area (Trafford, 1996). Peat layers, which is rich in organic matter, are abundant in the area, sometimes with >10 m thick (Trafford, 1996).

2.2 Water level monitoring.
In sites Linh Dam (LD) and Tay Mo (TM), the water levels of the upper aquifer, the lower aquifer and nearby ponds were monitored by water level loggers (Diver®, Eijkelkamp, The Netherlands) and monitoring wells. The 30 minutes-interval pressure data was corrected with atmospheric pressure measured by a barometer (Barodiver®, Eijkelkamp, The Netherlands). The major land use of site LD was bare land, ponds and paddy fields. The major land use of site TM was residential area and ponds.

Figure 1. The geological cross-section in Hanoi City (Berg et al., 2008).
2.3 Water sampling and analysis
In series of sampling campaigns from March 2018 to November 2018, 89 groundwater samples and 37 pond water samples were taken in six villages shown in Figure 2. Some samples were taken more than two times at the same locations. In addition, a regular sampling campaign was conducted in 17 sites (9 groundwaters, 5 ponds, 2 paddy fields, and the Red River) in every month between August to November 2017. In sites LD and TM, pore water samples were taken by the Rhizon soil moisture sampler (Eijkelkamp, The Netherlands) from undisturbed soils that were obtained during the construction of monitoring wells.

All the water samples excluding pore water were filtered with 0.45 μm PTFE membrane on-site. Pore water was filtered through 0.2 μm membrane attached with the Rhizon sampler. Anions were measured with ion chromatography. Heavy metals were measured with ICP-MS (ICP-MS7500cx; Agilent, US) after sample acidification with nitric acid (1% (v/v)). Stable isotopes (δ¹⁸O, δD) were measured in limited number of samples with near-infrared laser spectrometer by Geo Science Laboratory, Japan. The isotope ratios are expressed as ‰ enrichments relative to Vienna standard mean ocean water (VSMOW). For example, δ¹⁸O isotope ratio is expressed as belows:

\[ \delta^{18}O (\text{‰}) = \left( \frac{^{18}O^{(16)O}^{-1} \text{sample} - ^{18}O^{(16)O}^{-1} \text{standard}}{^{18}O^{(16)O}^{-1} \text{standard}} \right) \times 1000 \]

3. Results and discussions

3.1 Seasonal changes of stable isotope ratios in pond water and groundwater
Most pond waters showed an enrichment of δ¹⁸O and δD compared to rainwater and the Red River waters (Figure 3). The local meteoric water line (LMWL) was calculated from the rainwater data of Hanoi (WISER database, IAEA). The Red River had a similar isotopic composition to rainwater, as was already reported (Berg et al., 2008): the slope of the Red River data was close to that of LMWL,
and the Red River water data were distributed around the weighted average of rain water (shown in Figures 4 and 5; data obtained from WISER database, IAEA).

It was indicated that the pond water underwent evaporation process. The pond data showed a shift from LMWL toward $d^{18}$O-enrichment, and were distributed around the so-called evaporation line (EL) in calculated from Hanoi groundwater (Berg et al., 2008).

Moreover, a seasonal trend of pond water isotopes was inferred: dry season samples (January, March) were close to EL, while rainy season samples (May, June, October) were rather close to LMWL. The isotope ratios in ponds were the smallest in the samples in the end of rainy season (October) and were the largest in the samples just before the rainy season (March). Figure 4 showed a seasonal change of isotope ratios in pond waters in a) LD and b) TM throughout the year, which is January–March (largest)–May–June–October (smallest).

**Figure 3.** The relationship between $d^{18}$O and $d^2$H values in pond waters, grouped by sampling months, and the Red River waters (WISER database by IAEA) in Hanoi city. The local meteoric water line (LMWL) was calculated using precipitation data from WISER database (IAEA) and was expressed as $d^2H=7.91\times d^{18}O+12.45$. The broken line shows the evaporation line (EL), which was the fitted line of isotopes in groundwater in HL area in Hanoi, with the slope of 5.6 (Berg et al., 2008).

**Figure 4.** The seasonal change of $d^{18}$O and $d^2$H values in pond waters in a) site LD and b) site TM. The local meteoric water line (LMWL) was calculated using precipitation data from WISER database (IAEA) and was expressed as $d^2H=7.91\times d^{18}O+12.45$. The broken line shows the evaporation line (EL), which was the fitted line of isotopes in groundwater in HL area in Hanoi, with the slope of 5.6 (Berg et al., 2008). Arrows show the presumed seasonal change of $d^{18}$O and $d^2$H values.
The relationship between $d^{18}$O and $d^2$H values in groundwater samples in different locations in Hanoi city. The local meteoric water line (LMWL) was calculated using precipitation data from WISER database (IAEA) and was expressed as $d^2$H=$7.91 \times d^{18}$O+12.45. The broken line shows the evaporation line (EL), which was the fitted line of isotopes in groundwater in HL area in Hanoi, with the slope of 5.6 (Berg et al., 2008).

The seasonal change in isotope ratio would reflect the seasonal changes in isotopic signatures of rainwater and in the degree of evaporation process of pond waters. In Hanoi, rainwater isotopes were the heaviest in February and the lightest in August (Larsen et al., 2008). Similar seasonal change of isotopes was also found in Canada (Maule et al., 1994). In Hanoi, pond water samples were positioned close to LMWL during the rainy season, probably because pond waters were largely and frequently recharged by rainwater, thereby having little isotope fractionation by evaporation. During the dry season, isotope signatures approached toward EL, because effect of evaporation would be significant due to less rain.

The isotope data in groundwater showed that the dominant sources of groundwater undergo evaporation process. Therefore, the indispensable contribution of surface water other than the Red River (e.g., ponds, paddy fields) to groundwater recharge was indicated. Similar to ponds, isotope ratios in groundwater were in larger than the weighted average of rain water (Figure 8). Groundwater data were plotted in between LMWL and EL, but more closely to EL side. Compared with the location of the villages (Figure 2), inland villages (TM, LD and NH) had larger isotope ratios (t-test, $P<0.001$) than riverine villages (SM, TC and VP). To our knowledge, these spatial differences in isotope ratios in groundwater have not been reported in the literature.

3.2 Recharge of groundwater
The source and the mechanism of groundwater recharge were considered to be different between the upper aquifer and the lower aquifer. Figure 6 shows a) the $d^{18}$O-$dD$ diagram and b) the depth profile of $d^{18}$O isotope ratio of pore water samples in sites LD and TM. The pore water data were plotted closely along EL, which is in accordance with groundwater samples. However, the depth profiles of pore waters showed a clear difference in isotope ratios between the shallow soil and the deep soil, where $d^{18}$O was more enriched in the shallow soil. In TM, $d^{18}$O decreased at 25 m, where impermeable silt and clay layers began toward the deeper depth. The groundwater samples from the upper aquifer and the lower aquifer in the two sites had similar isotope signatures of pore waters from respective depths. Furthermore, groundwaters and pore waters from the shallow soil had similar isotope ratios in inland
groundwater, while isotope ratios of those from the deep soil layer were close to that in riverine groundwater. The distinct difference in isotope ratios between the upper aquifers and the lower aquifers have not been clearly seen in the reported comparison of groundwater from the two aquifers (Norrman et al., 2008, Berg et al., 2008).

Given that the isotope depth profile in sites LD and TM represents that in inland Hanoi area, the recharge of groundwater in Hanoi city could be described as below. First, as literatures indicated, riverine groundwaters are largely recharged by the Red River itself. On the contrary, surface waters which have evaporation process (e.g., ponds and paddy fields) and direct infiltration of rainwater from the surface are the dominant sources of groundwater in the upper aquifers of the distant location from the Red River. The lower aquifers are predominantly recharged by lateral inflow, either from the Red River (riverine area) or surrounding mountains (inland area), as suggested by (Larsen et al., 2008). With more data on isotopes in pond waters, the time-averaged isotope ratios of ponds could be estimated, which will be used to estimate the respective contributions of rainwater infiltration and pond infiltrates to groundwater recharge. In addition, more detailed data analysis on isotopes in groundwater from the upper aquifers and the lower aquifers are needed to strengthen the discussion.

3.3 Temporal changes of water quality in regular monitoring sites

Figure 7 and 8 show the seasonal variation of chloride and As in 17 regular monitoring sites. For chloride and arsenic, ponds, paddy fields and the Red River showed a large fluctuation (±50% or more), and its concentration was seemingly higher in dry season. On the other hand, chloride in most groundwater had a very small temporal change. Interestingly, TM21, which was from the upper aquifer, had a large fluctuation, while the monitoring well of upper aquifer, TM1, did not show such a large change. The chloride level in TM22 (a neighboring well) and TM2 (monitoring well for lower aquifer), both from lower aquifer, did not change at all. On the other hand, fluctuation of As level was large in TM22 than in TM21. The Red River had rather stable concentrations of chloride and As despite large seasonal change of flow. The groundwaters in TC and SM, which were close to the river, showed similar chloride and As levels, probably because of the recharge from the river.

The variable chloride level but stable As level in TM21 might suggest a sporadic contamination by wastewater, rather than a dynamic change of recharge source. The small seasonal variation observed by water level monitoring in TM suggested a rather small groundwater recharge dynamics throughout the year. On the contrary, the comparatively large fluctuation of As despite the very stable chloride
level in TM22 might be caused by the frequent change of water level of lower aquifer by daily abstraction, which may facilitate As dissolution in groundwater through repeating rises and drops of oxic-anoxic boundary in subsurface (Berg et al., 2008).

Figure 7. Seasonal changes of Cl concentrations in regular sampling sites.

Figure 8. Seasonal changes of As concentrations in regular sampling sites.

Similar to surface water, major cations and anions in groundwater were often enriched in dry season (Schot and Pieber, 2012). On the other hand, fluctuations of groundwater As with no relationship with seasons were reported (Berg et al., 2008, Dhar et al., 2008). The large seasonal variation of chloride
and As in site TM despite the presumably small recharge dynamics needs to be studied further, by continuing monitoring of water quality and levels.

4. Conclusions

Seasonal variation of water levels and water quality of groundwaters and ponds was investigated to illustrate the recharge mechanism and seasonal effects of groundwater in Hanoi suburbs. In the area with large bare land, the upper aquifer had a fluctuating water level corresponding to heavy rains, showing a substantial impact by infiltration of rainwater from the surface and perhaps pond water. In the area with less permeable surface, there was small response to rainy events, suggesting that the water levels were governed by a regional scale groundwater flow. The stable isotope ratios in pond waters had a clear seasonal change, in which isotopes were enriched throughout the dry season. In groundwater, isotope signatures indicated that the dominant sources had evaporation process. The results revealed that groundwaters close to the Red River are largely recharged by the river itself. In areas far from the river, surface waters having evaporation process (e.g., ponds and paddy fields) and the rainwater directly infiltrating from the surface mainly recharges the upper aquifer. The lower aquifer in inland locations would be recharged by lateral inflow, either from the Red River or surrounding mountains. Chloride and arsenic had temporal variations at groundwater samples in TM, whereas the groundwater recharge dynamics seemed small, suggesting a need for further studies on the relationship between groundwater recharge and quality.

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