Vietnam Journal of Earth Sciences, 44(2), 286-300, https://doi.org/10.15625/2615-9783/17081

Vietnam Academy of Science and Technology
Vietnam Journal of Earth Sciences
http://www.vjs.ac.vn/index.php/jse

Rooftop rainwater harvesting and artificial groundwater recharge - a case study: Thanh Xuan district in south of Hanoi

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Received 14 July 2021; Received in revised form 22 September 2021; Accepted 21 April 2022

ABSTRACT

Groundwater over-exploitation in the south of Hanoi has formed depression cones and accelerated land subsidence. Thanh Xuan district is one of the most suffered areas in the south of Hanoi. Artificial groundwater recharge (AGR) is an effective solution to mitigate those negative impacts. This study aims to evaluate the potential of rooftop rainwater harvesting (RRH) for AGR in the Thanh Xuan district. The prospect of RRH for the study area is estimated based on the average annual rainfall for the period 2008-2018 and the total rooftop area of selected buildings. The rooftop area is determined by analyzing satellite images and using the built-in tool in Google Earth. Field site investigation and measurements confirmed this estimation. Rainwater samples were taken for quality assessment. This assessment was conducted by measuring pH, EC, TDS, turbidity of rainwater in the field and analyzing NO_3^-, NO_2^-, PO_4^{3-}, SO_4^{2-} and Cl^- contents in the laboratory. Moreover, to propose an effective AGR system, the maximum harvested rainwater and the recharge capacity of an injection well were estimated for the Golden Land building. The results show that 397 selected buildings can be used to collect rainwater. The total rooftop area of these 397 buildings is 262,645.8 m^2, and that can contain 385,930.5 m^3 of rainwater a year. The field measurement and analysis results indicate that rainwater quality meets the current standards appropriate for AGR. The AGR using rooftop rainwater will contribute to increasing groundwater level, reducing land subsidence, and mitigating urban flooding for Thanh Xuan and similar areas.

Keywords: artificial groundwater recharge, rooftop rainwater harvesting, injection well, Thanh Xuan district.

1. Introduction

Thanh Xuan district locates in the southern part of Hanoi city, where groundwater plays an essential role in water supply. However, groundwater overexploitation has had a great impact on the environment as it is forming a cone of depression (Nguyen Van Dan, Tong Ngoc Thanh, 2000; Pham Hoa Binh, 2018) and increasing land subsidence (Pham Huy Giao et al., 2020; Tran Manh Lieu, 2018). Being considered as one of the most effective solutions, AGR is widespread used by different construction methods such as bank infiltration, channel spreading, ditch and furrow, contour ridging for mountainous areas or slopes, recharge pit, and injection wells (Doan Van Canh, 2017; Malu, 2017; Indian Ministry of Water Resources, 2007). These

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solutions bring many benefits since it increases groundwater level, reduce land subsidence, mitigate urban flooding, and improve water quality. Selecting an adequate AGR method is based on the source of recharge water, natural condition, and infrastructure development status of a specific area. Remote sensing and GIS have been widely applied to determine appropriate AGR methods (Anbazhagan and Gupta, 2005; Alataway and Alfy, 2019; Hari et al., 2017).

The source of water used for AGR derives from rivers, lakes, treated wastewater, rainwater, or excessive water from regulation reservoirs. Rainwater is considered an essential renewable water resource in arid areas and populated cities (Adugna et al., 2018; Alataway and Alfy, 2019; Dwivedi et al., 2013; Misra, 2018). Rainwater can be harvested from the building's rooftop and stored in tanks or basins to use directly (Yan Zhang et al., 2009; Hussain et al., 2019). It is also collected in reservoirs or ditches for increasing natural recharge (Alataway and Alfy, 2019). In some of the populated cities, rooftop rainwater is directly used as an alternative source after UV treatment, for instance, in Malaysia (Ayob and Rahma, 2017), in Jordan (Abu-Zreig et al., 2019), or the United States (Thomas et al., 2014). However, in most cases, harvested rainwater is before use for AGR to increase groundwater levels and reduce environmental impacts. Rainwater can be recharged for shallow aquifers by recharge pits (Rao and Giridhar, 2014) or by injection wells (Hussain et al., 2019; Adugna et al., 2018; Moon et al., 2012). Some studies conducted a quality assessment for rainwater before it was injected into wells to confirm that rainwater would not contaminate the aquifers (Moon et al., 2012; Pham Hoa Binh, 2018).

In Vietnam, many studies evaluated the groundwater recharge potential for different areas and proposed sustainable solutions for groundwater resources (Nguyen Thi Kim Thoa, 2007; Dang Hoang Thanh, 2016; Hoang Ngo Tu Do, 2004; Nguyen Van Dan, Tong Ngoc Thanh, 2000; Pham Hoa Binh, 2018; Hoang Van Hoan, 2021). Groundwater can be naturally recharged (Hoang Van Hoan, 2021) or artificially recharged by several techniques in specific areas of Vietnam (Pham Hoa Binh, 2018; Nguyen Van Dan & Tong Ngoc Thanh; Huynh Phu, 2012; Nguyen Viet Ky & Nguyen Dinh Tu, 2009). Bank infiltration is considered a suitable method for riverside areas. Groundwater recharge occurs when groundwater level drops below river water level (Pham Hoa Binh, 2018; Nguyen Van Dan & Tong Ngoc Thanh, 2000; Doan Van Canh, 2017). Dang Hoang Thanh (2016) researched the recharge capacity for fractured basalt aquifers for the Central Highland of Vietnam. This study used injection wells and excessive water from regulating reservoirs for groundwater recharge. The study conducted a quality assessment for recharge water before injection (Dang Hoang Thanh, 2016). The study results revealed a high groundwater recharge capacity of 168.3 -219 m^3 /well/day. Ninh Thuan province faces water scarcity; the contour ridges were applied to slow down the surface runoff. Therefore, rainwater had time to infiltrate and recharge groundwater (Huynh Phu, 2012). A remarkable increase in groundwater level shows that this method can effectively apply to similar areas.

In densely populated areas, rainwater can be collected from streets, pavement, unused land, and rooftops. However, recharge water quality is an essential factor for designing the AGR system (Nguyen Viet Ky & Nguyen Dinh Tu, 2009; Moon et al., 2012; Dang Hoang Thanh, Nguyen Huy Vuong 2016).

Thanh Xuan district locates far away from the Red River, the largest river in Northern Vietnam. That leads to low groundwater recovery in aquifers due to the low recharge rate from the river. Meanwhile, in the south of Hanoi in general and in the Thanh Xuan district, infrastructure development has resulted in a meager natural recharge rate to groundwater. As a result, groundwater over-exploitation has formed a cone of depression in the south of Hanoi (Pham Hoa Binh, 2018; National Center for Planning and Investigation of Water Resources - NAWAPI, 2021). The groundwater is mainly abstracted from the Pleistocene aquifer, which underlies right beneath a soft clay layer of Hai Hung formation. This clay layer is more sensitive to land subsidence when this aquifer intensively exploits groundwater (Pham Huy Giao et al., 2020). In addition, infrastructure development is also a reason for urban flooding after heavy rain. Most precipitation becomes surface runoff and is then lost to drainage systems. With the high building density in Thanh Xuan district, collecting quality rainwater from high-rise building rooftops and using it for AGR will minimize the environmental impacts caused by groundwater exploitation and urbanization. Based on the above issues, this study aims to assess the potential of AGR using rooftops rainwater and propose appropriate solutions to mitigate the mentioned impacts for Thanh Xuan district as well as for other similar areas.

2. Materials and methodology

2.1. Materials

2.1.1. Study area

Thanh Xuan district is a flat area with an average elevation of 5-6 m. The elevation in the North and the West is slightly higher than those in the South and the East. There are a few small ponds, lakes, and low-lying areas with an elevation of about 3.0-3.5 m. This topographical condition is convenient for infrastructure development for the study area. However, this condition contributes to urban flooding due to slow water drainage, especially after heavy rain.

2.1.2. Rainfall

The study area is characterized by a tropical monsoon climate with average annual rainfall. The rainfall distribution is uneven during the year. About 80% of the rainfall is concentrated in the summer season. The yearly rainfall in Hanoi ranges from 1520 to 2268 mm from 2008 to 2018 (Fig. 2) (General Statistics office of Vietnam, 2021). These annual rainfall data were used to estimate the total rainwater harvested from rooftops in the Thanh Xuan area. Heavy rain events may cause urban flooding and impacts daily lives.

2.1.3. Hydrology

The Red River and Thanh Xuan district is more than 4 km, and it is not convenient for natural groundwater recharge. Other smaller rivers flow through the study area, including To Lich, Lu, and Set rivers. These three rivers are used for water drainage. In addition, there are some small lakes in the Thanh Xuan area, but they are not meant for water usage.

2.1.4. Hydrogeology

Groundwater resource is mainly abstracted from Holocene (qh) and Pleistocene (qp) aquifers in the Hanoi area. In Thanh Xuan district, the qh aquifer distributes from 4m below the ground surface with an average thickness of 22 m. This aquifer is composed of fine to coarse sands. The transmissivity of the qh aquifer is from 200 m^2/day to 800 m^2/day (Pham Huy Giao et al., 2020; Flemming Larsen et al., 2008). This transmissivity is equivalent to the value determined in the North-west area of Hanoi (Dang Tran Trung et al., 2020). Meanwhile, the Pleistocene confined aquifer consists of sand, pebbles, and gravel with a transmissivity of around 1600 m^2/d (Pham Huy Giao et al., 2020; Flemming Larsen et al., 2008). In the study area, the qp aquifer is distributed from the depth of 30 to 70 m with an average thickness of around 34.7 m (Fig. 3). The qh aquifer is interbedded with the qp aquifer by a low permeable layer of clay and organic matter as shown in Fig. 3.

2.1.5. Status of groundwater abstraction in Thanh Xuan district

The water supply for the Hanoi area in general and the Thanh Xuan district, in particular, is based on groundwater and surface water. Groundwater from the qp aquifer is abstracted at different wellfields in the Hanoi area. Ha Dinh is one of some wellfields located in the deep depression cone and in the center of Thanh Xuan district (Fig. 1 and Fig. 4).

Thanh Xuan district's water supply depends on groundwater from Ha Dinh wellfield and surface water from Duong and Da river water treatment plants. Previously, Ha Dinh wellfield operated at a 20,904 m^3/day design capacity under dynamic groundwater levels of -30 to -40 m above mean sea level. Intensive groundwater exploitation has formed a cone of depression. This is one of the main causes of land subsidence in the center part of Hanoi city (Tran Manh Lieu, 2018; Pham Huy Giao et al., 2020).

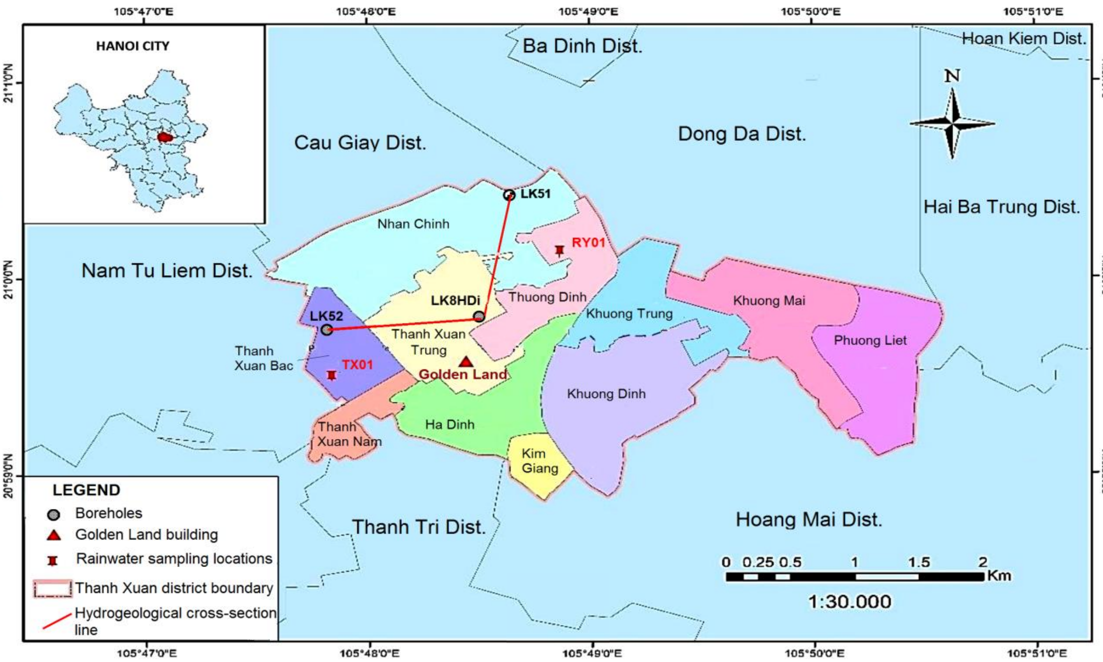

Figure 1. Study area and rainwater sampling locations

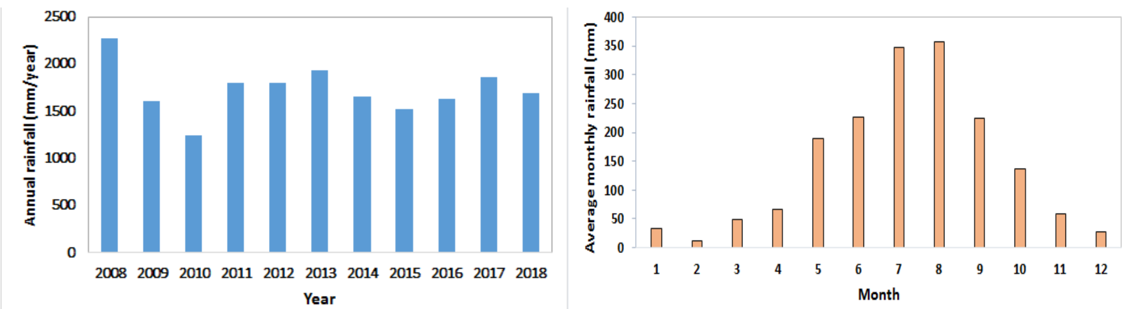

Figure 2. Annual (a) and seasonal (b) rainfall variability for the period of 2008-2018 at Lang station in Hanoi

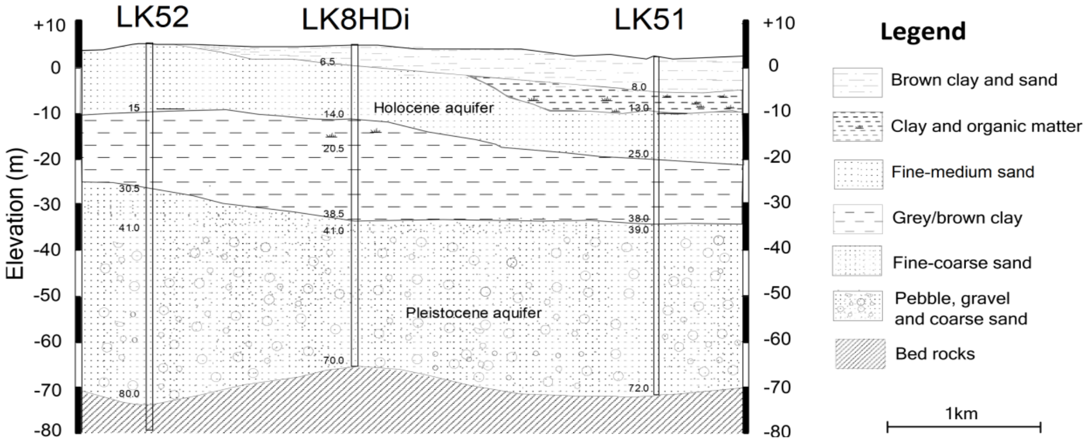

Figure 3. Hydrogeological cross-section of the study area
(see Figure 1 for borehole locations- Modified from drilling data of Tran Minh et al., 1979)

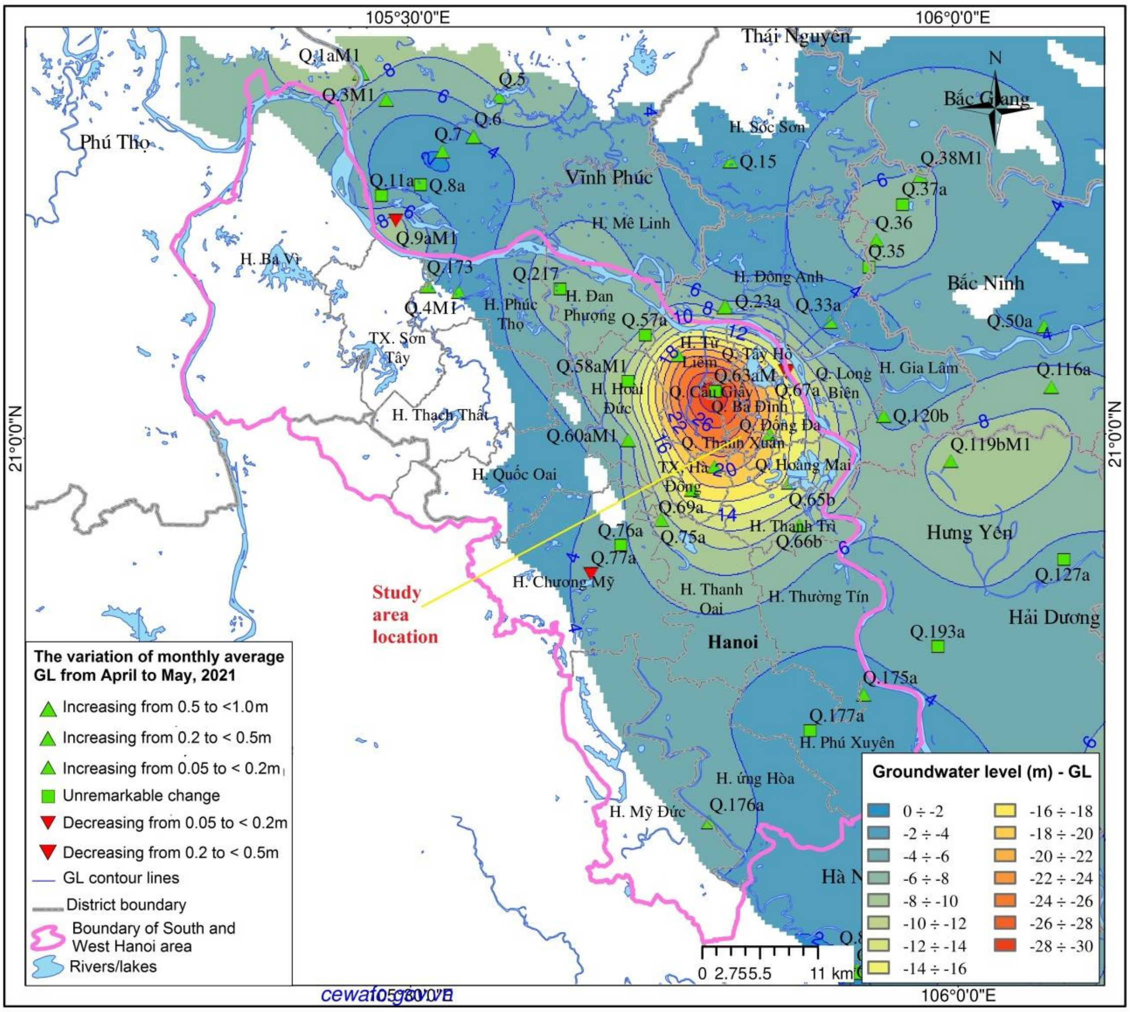

Figure 4. Location of depression cone surrounding study area (NAWAPI, 2021)

The Vietnamese Government has approved the adjustment of water supply planning for Hanoi city up to 2050 in Decision No. 554/QD. According to this Decision, Ha Dinh wellfield will reduce almost half of the designed abstraction capacity from 2025 and close by 2050. Meanwhile, the river water treatment plants will increase their ability to adapt to the increasing water demand. In contrast, the other groundwater wellfields maintain a high exploitation capacity. It means the total groundwater abstraction from the Pleistocene aquifer in the Hanoi area is approximately unchanged, and it will continue to impact the Thanh Xuan area.

2.2. Methodology

2.2.1. Determining and estimating the total rooftop area using Google Earth

This study focuses on RRH from high-rise building rooftops. As regulated in Vietnam construction standard No.94:2006, a high-rise building must have nine floors, excluding the foundation and basements. Selecting high-rise buildings for harvesting rainwater will minimize the pollutant from the surrounding environment. Therefore, it’s essential to define the appropriate structures before estimating the rooftop’s area. The rooftop area is calculated using satellite images and built-in tools on Google Earth (Fig. 5). The total rooftop area is the sum of all suitable rooftops in the study area. The selected buildings will be confirmed by field site investigation for checking the heights and surrounding accessible space areas.

2.2.2. Field site investigation

A field investigation was carried out to verify the appropriateness of the buildings for RRH. The building’s height was measured to ensure it was high enough to limit pollution. Otherwise, some random buildings were selected for checking the estimation of the rooftop area in Google Earth. Besides, some measurements were done in the field to calculate the free space area around the selected building. This was done to confirm enough space for setting up the AGR systems (Fig. 6).

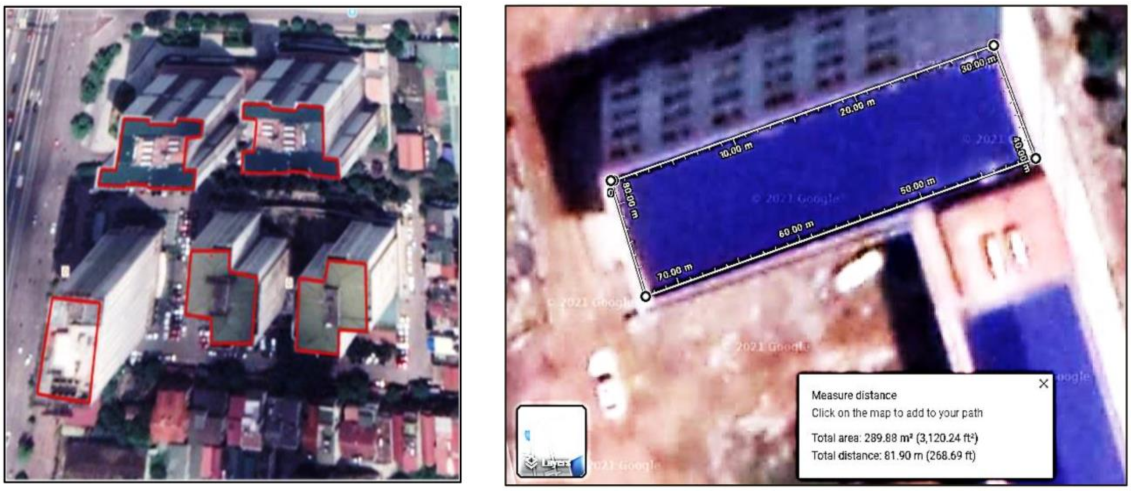

Figure 5. Determining and estimating roof top’s area using Google Earth

Figure 6. Golden Land building on Google Earth (a) and investigation in the field (b)

2.2.3. Estimating the total rooftop rainwater

The formula (1) is widely used for estimating the potential rainwater harvested from rooftops (Adugna et al., 2018; Anchan and Prasad, 2021). In this study, we applied this formula using actual data to evaluate the total rooftop rainwater for adequate buildings in the Thanh Xuan district.

$$Q_{rain} = I \times A \times C \quad (1)$$

Here,

- Q_{rain}: represents total rooftop rainwater (m^3)
- I: denotes average annual rainfall (m/year)
- A: indicates total rooftop area (m^2)
- C: indicates runoff coefficient (%).

This study used the rainfall data from 2008 to 2018 at Lang meteorological station for calculating annual rainfall. This meteorological station is close to the study area. The total rooftop area was estimated and validated. In addition, the value of the runoff coefficient was referred from similar works (Adugna et al., 2018; Anchan and Prasad, 2021) with considering the actual conditions of the study area. Based on the real situation, the runoff coefficient C for the study area is 0.85.

2.2.4. Estimating the recharge capacity of injection well

An appropriate ARG system is defined based on specific conditions and recharges water sources of each area. Thanh Xuan district is a flat area characterized by high infrastructure density while it locates far away from the Red River. With this specific condition of the study area, ARG using injection wells and rooftop rainwater is an appropriate method. To clarify the most effective design for the ARG system, it is necessary to define the number of recharge wells. The recharge well is estimated based on the RRH for the heaviest rainy day and the recharge capacity of an injection. The recharge capacity of an injection well is calculated by using the formula (2). This formula was proposed by Duiput (Todd & May 2004) and applied for confined aquifers under steady-state conditions. In the case of the Thanh Xuan district, the Pleistocene confined aquifer is selected for using ARG to mitigate environmental impacts due to urbanization and groundwater abstraction.

$$Q_{rc} = -\frac{2\pi.m.K.(h_e - H_o)}{\ln\frac{R}{r_o}} \quad (2)$$

(Subtraction indicates the reverse flow comparing to the case of pumping well)

Here,

- Q_{rc}: Recharge capacity (m^3/day)
- h_e: Static groundwater level (m)
- K: Hydraulic conductivity (m/day)
- m: Aquifer's thickness (m)
- H_o: Groundwater level when rainwater recharged to injection well (m)
- R: Radius of influence (m)

$S_o = h_e - H_o$: The changing of groundwater level in injection well (m)

The static groundwater level of the Pleistocene aquifer for the study area is referred to from the reports of monitoring groundwater level (NAWAPI, 2021). When rainwater is injected into the well, the groundwater level will increase and reach the value of Ho (Fig. 7). The value of Ho is defined as shown in Fig. 7, which will be clarified in section 3.3. The average thickness m of the Pleistocene aquifer was determined based on the hydrogeological cross-section (Fig. 3). This cross-section is established based on the drilling data from the works of Tran Minh, 1979, and Tran Man Lieu, 2018. Hydraulic conductivity, the K value, is induced from other related studies (Pham Huy Giao et al., 2020; Larsen et al., 2008). The radius of influence R is calculated using equation (3) applied for steady-state conditions (Pham Quy Nhan, 2000).

$$R = 10.S_o.\sqrt{K} \quad (3)$$

2.2.5. Rainwater sampling and analysis

Rooftop rainwater may be affected by pollutants from transportation activities, garbage, construction smoke, or materials from the surrounding environment. Therefore, to get an effective design for the ARG system, it is also necessary to conduct a quality assessment for rooftop rainwater. In this study, two rainwater samples were collected at the thirty-five-floor building (sample RY01) and at the five-floor building (sample TX01) (sampling locations in Fig. 1). These two buildings were selected to examine the effect of the building height on rainwater quality. The conductivity (EC), pH, turbidity, and total dissolved solids (TDS) were measured in the field using portable multi-parameter water quality measurement Horiba U51. Main anions Cl^-, NO_2^-, NO_3^-, and SO_4^- were determined by ion chromatography using Shimadzu HIC 20A-super instrument. Particularly, PO_4^{3-} content was determined by molecular absorption spectroscopy using Shimadzu UV-1800 equipment.

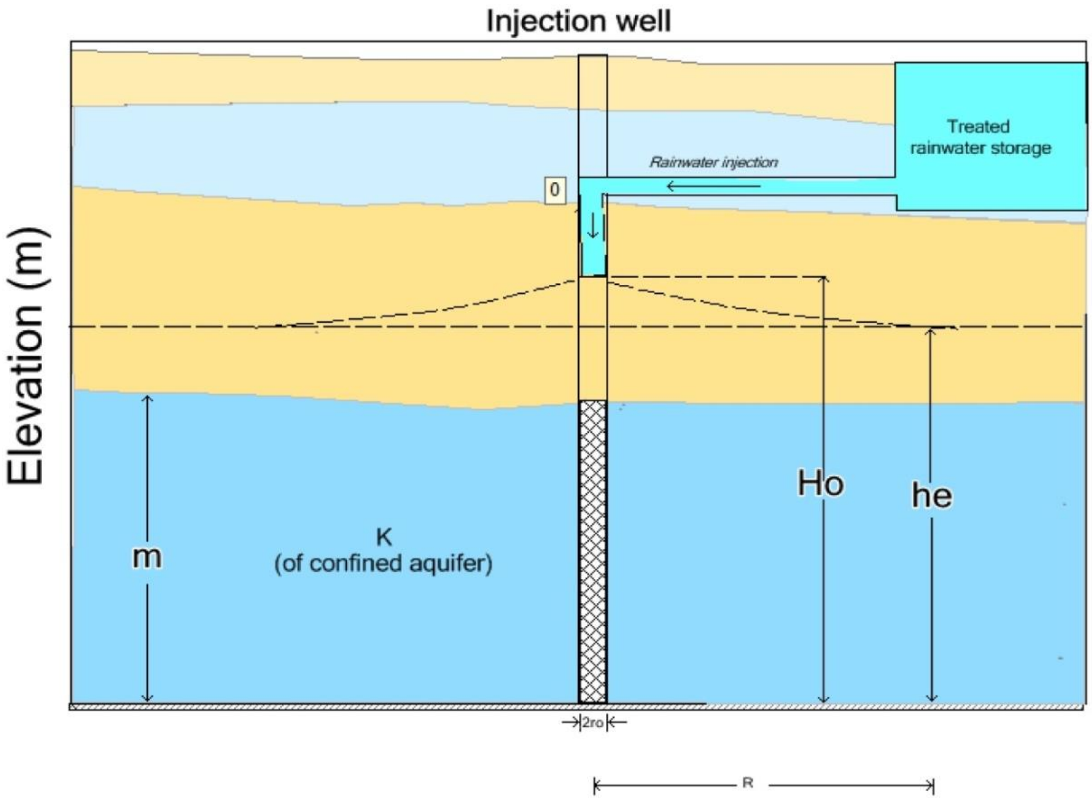

Figure 7. Injection well and calculating parameters

3. Results and discussions

3.1. The potential of rooftop rainwater harvesting in Thanh Xuan district

The appropriate buildings for rainwater harvesting were determined by Google Earth and confirmed after an investigation in the field. In the study area, 397 high-rise buildings meet the requirement for applying AGR systems. The total rooftop area of these 397 buildings is 262.645,8 m^2 which was estimated by built-in tools in Google Earth (Table 1). The rainfall data recorded at Lang meteorological station in Hanoi was used to evaluate the rainfall for the Thanh Xuan district. The average annual rainfall for 2008-2018 is 1728.6 mm/year. The runoff coefficient (C) is 0.85, referring to similar studies of Adugna et al., 2018 and Anchan, and Prasad, 2021.

Table 1 summarizes the data of the total rooftop area, annual rainfall, and the runoff coefficient. Based on these data, the potential of RRH for the Thanh Xuan district was estimated at a value of 385,930.5 m^3/year. This calculation is only applied to high-rise buildings. The potential RRH will be higher if rooftop rainwater quality and the nearby free space meet all requirements for constructing an AGR.

Table 1. The potential of rooftop rainwater harvesting in Thanh Xuan district

Number of high-rise buildings	Total rooftop area (m^2)	Average annual rainfall (mm/year)	Runoff coefficient (%)	The potential of rooftop rainwater harvesting (m^3/year)
	A	I	C	**Q_{rain} =A x I xC**
397	262,645.8	1728.7	85	**385,930.5**

3.2. Rainwater quality

The results of field measurement of two rainwater samples indicate that the pH values are within the standards mentioned in Vietnam's regulations QCVN 08-MT:2015 and QCVN 09-MT:2015. These two regulations are used for surface water and groundwater quality assessment, respectively (Table 2). The conductivity and TDS values are much lower than standards and show the low salinity of rainwater. The turbidity is not mentioned in the regulations. Still, the low turbidity values indicate that the rainwater is very high clarity, and there are no suspended solids in the water.

Besides, the rainwater analysis data indicate very low anion contents in the two rainwater samples. The concentrations of PO_4^{3-} range from almost zero in the TX01 sample to 0.021 mg/l in the RY01 sample. These values of PO_4^{3-} are much lower than the allowable limit in QCVN 08:2015 regulation (Fig. 8a). The PO_4^{3-} content is not regulated for groundwater. At the same time, the NO_2^- contents in rainwater samples are smaller than 0.1 mg/l and more than ten times lower than permitted limits (Fig. 8b). Similarly, the NO_3^- concentration in TX01 and RY01 samples are 0.8 mg/l and 2.87 mg/l, respectively, which are much lower than the standards (Fig. 8b). Finally, figure 8c shows the very small values of SO_4^{2-} and Cl^- contents in two samples compared to those in the regulations for water quality assessment.

The above results from field measurement and laboratory analysis reveal that both rainwater samples in the Thanh Xuan district meet surface and groundwater quality assessment standards. Especially, rainwater sample TX01 was taken at a five-floor building. It means that the potential of RRH may be higher for the Thanh Xuan district. The air quality index level in the study area is moderate to unhealthy for sensitive groups. These groups are characterized by low concentrations of sulfur dioxide and nitrogen dioxide but high in PM10 and PM2.5 contents (General agency of environment, 2020). The air quality assessment is appropriate to the rainwater quality since the pH values and the contents of NO_2^-, NO_3^-, SO_4^{2-} are within the standard limitations. With this rainwater quality assessment, the harvested rainwater is not necessary to have intensive treatment before recharging groundwater. However, in this study, it could be concluded that the rainwater quality from the rooftops is not quite sure for the low-rise buildings due to a small number of samples. A further study is good if the correlation between rooftop height and rainwater quality is set up. Besides, the injected rainwater may also affect the groundwater environment in changing redox conditions. Therefore, it is necessary to set up a reactive model and empirical experiment to monitor how the groundwater system changes when mixing groundwater, rainwater, and soil minerals occur.

Table 2. Results of field measurement and Regulations' limitations

Parameters / Sampling locations	pH	EC (mS/cm)	Turbidity (NTU)	TDS (mg/l)
TX 01 (5th floor)	6.47	0.009	0	0.006
RY 01 (35th floor)	7.43	0.024	0	0.016
Regulations				
QCVN 08-MT:2015	6.0-8.5	-	-	-
QCVN 09-MT:2015	5.5-8.5	-	-	1500

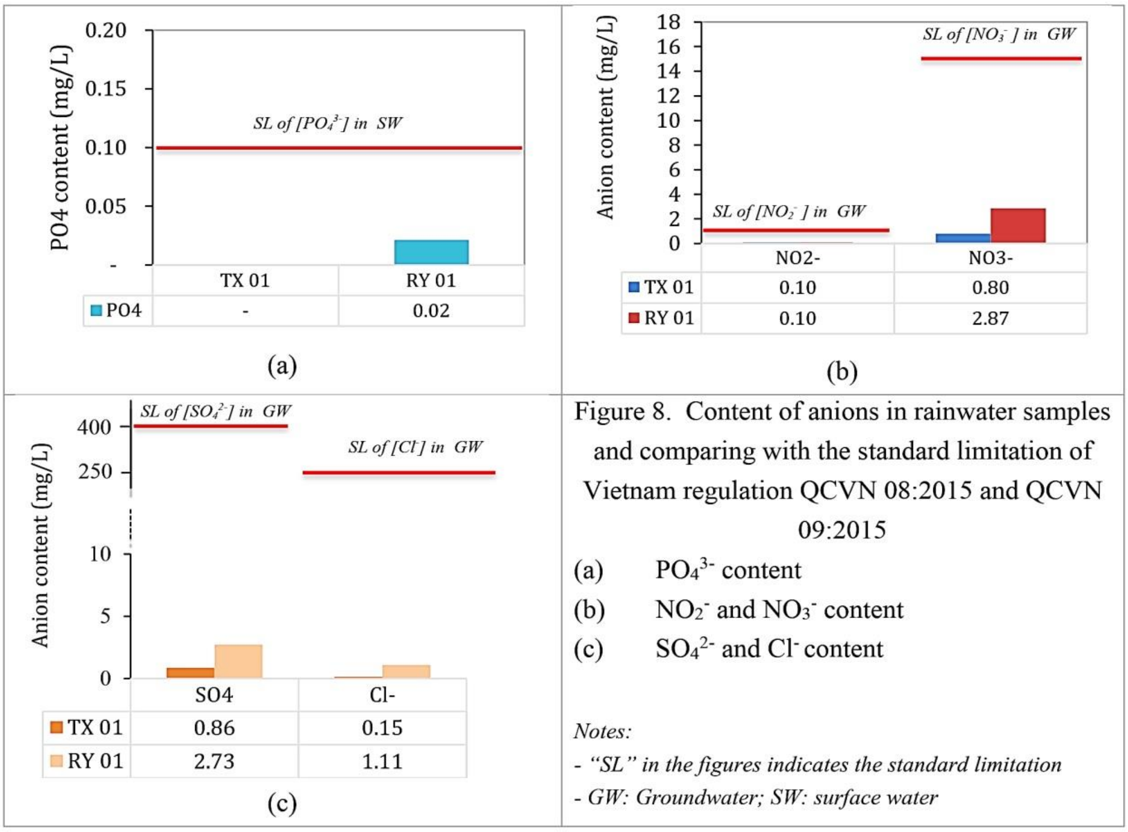

Figure 8. Content of anions in rainwater samples and comparing with the standard limitation of Vietnam regulation QCVN 08:2015 and QCVN 09:2015

(a) PO_4^{3-} content

(b) NO_2^- and NO_3^- content

(c) SO_4^{2-} and Cl^- content

Notes:

- "SL" in the figures indicates the standard limitation

- GW: Groundwater; SW: surface water

Figure 8. (Included in the Figure)

3.3. Proposing the artificial groundwater recharge system for Thanh Xuan area

Thanh Xuan is populated with very high infrastructure density and minimal unused land area. Urbanization has caused shallow natural infiltration to groundwater in this area. Besides that, the flat topography and the extended distance from Red River make Thanh Xuan unsuitable for applying bank infiltration, spreading, and ditch methods. However, Thanh Xuan has many high-rise buildings, which are very useful for RRH. Therefore, harvesting rainwater from rooftops will reduce surface flow and mitigate urban flooding. Moreover, using this rooftop rainwater for recharging groundwater through the injection well will increase groundwater level and mitigate land subsidence. In Thanh Xuan district, this rainwater will be recharged to the Pleistocene confined aquifer where groundwater is intensively exploited.

Field measurement and rainwater analysis data reveal that rainwater in Thanh Xuan district meets current regulation standards and can be used for ARG. However, to prevent the well from clogging by dirt, a sand filter will be applied to remove all unexpected material from rainwater before injecting it into the aquifer. Therefore, the ARG system includes four main components: a trough and pipeline system for collecting and transferring rainwater from the rooftop, a sand filter system, a treated rainwater storage tank, and injection well(s). It is necessary to define a good number of injection wells and the size of storage tanks to collect the maximum rainwater amount. That can be clarified by estimating the recharge capacity of the injection well, and the maximum harvested rainwater for the heaviest rain day in the period of 2008-2018.

3.3.1. Estimating the maximum harvested rainwater

The maximum amount of rainwater was determined based on formula (1) using maximum daily rainfall from 2008 to 2018. The maximum daily rainfall of 347mm/day was recorded in October 2008 at Lang meteorological station. In this study, the Golden Land building, located close to Ha Dinh wellfields, is selected for calculation as a pilot site (Fig. 1). The total rooftop area of the building is 5596 m^2 which was estimated via Google Earth and field investigation.

The maximum RRH from Golden Land buildings is 1650.5 m^3/day, which was shown in Table 3. This value will be compared to the recharge capacity of an injection well. The comparison will help define the number of injection wells needed for the AGR system.

Table 3. Maximum rainwater harvested a day from Golden Land building

Golden Land building rooftop area (m^2)	Maximum daily rainfall (mm/day)	Runoff coefficient (%)	Maximum rainwater harvested a day (m^3/day)
A	I	C	$Q_m = A \times I \times C$
5596	374	85	**1650.5**

3.3.2. The recharge capacity of an injection well

The recharge capacity of an injection well is estimated based on Dupuit's formula which applies to the confined aquifers. The average aquifer thickness m of 34.7 m is derived from drilling data (Fig. 3). The hydraulic conductivity K = T/m was defined as 46.1 m/day by referring to the values of transmissivity (T) for qp aquifer (Pham Huy Giao et al., 2020; Larsen et al., 2008) and the average thickness (m). It is easy to see that Thanh Xuan district is located in the center of the depression cone with a groundwater level of -26 m as shown in Fig. 4. Therefore, the static groundwater level of the Pleistocene aquifer (he) was taken as -26 m. The value of Ho depends on the rising of groundwater in the well, in this case, the borehole LK8HDi, which locates near Ha Dinh wellfields, will be chosen to define the Ho value. Assuming that the treated rainwater reservoir is constructed to the depth of 10m below the ground. It means that the bottom of the treated rainwater reservoir locates at an elevation of around -5 m. In this case, the water level in the injection well is kept stable at the elevation of -10 m. The total head in the well equals 16 m in which well loss has been considered based on the similar study of Guttman et al., 2017. When rainwater is injected into the aquifer by the gravitational flow, assuming the rising of groundwater level in the aquifer (So) is equal to 1m when groundwater level rises to -25 m from -26 m. The radius of the well's screen, r is taken at a value of 0.15 m. Basing on the data listed in Table 4 and formula (3), the radius of influence is estimated as R = 10. So.√K =67.9 (m). The recharge capacity of the injection well (Qr) was calculated by using formula (2) with Qr = 1644.2 m^3/day. This value is as high as the maximum harvested rainwater calculated for the Golden Land building. It means that, for the Golden Land building, one injection well may be enough for collecting rainwater from rooftops. Therefore, the AGR system includes four main components: (1) trough and pipeline system for collecting and transferring rainwater from the rooftop, (2) sand filter system, (3) treated rainwater storage tank, and (4) at least one injection well with full penetration in design.

Table 4. Characterized values of aquifer and well parameters

Aquifer thickness	Hydraulic conductivity	Rising of groundwater level	The radius of the well's screen
m (m)	K(m/day)	S_0 (m)	r_o (m)
34.7	46,1	1	0.15

However, after a period, the recharge capacity of the well may be reduced due to clogging. This phenomenon can cause higher well loss. It may happen due to the material around the screen or the ion oxidation when oxidized water is injected into the well. To achieve better efficiency, it's important to clean the well regularly to prevent clogging. Another option for the system to work correctly is to use more than one injection well with a smaller radius. The number of wells and their radius can be defined based on the rooftop area of buildings.

4. Conclusions

Artificial groundwater recharge using RRH could be an effective solution for the Thanh Xuan district. The solution can bring many benefits, such as mitigating urban flooding, reducing land subsidence, and increasing the groundwater level. In this study area, the AGR method using injection well to recharge the Pleistocene aquifer will reduce the impacts of groundwater over-exploitation.

- 397 buildings are appropriate for harvesting rainwater. The total rooftop area is 262,645.8 m^2. With the runoff coefficient of 85% and the average annual rainfall for the period of 2008-2018 is 1728.7 mm/year, the potential rainwater collected in the Thanh Xuan district is 385,930.5 m^3/year.

- Rainwater quality at two locations, TX01, and RY01, meets the required standards. All parameters of pH, EC, TDS, turbidity, and contents of NO_3^-, NO_2^-, PO_4^{3-}, SO_4^{2-} and Cl^- are within the allowable limits of the current National Technical Regulations for surface and groundwater quality assessment. Therefore, the RRH can be used for AGR. However, with the small sample size, it could be concluded that the rainwater quality from the rooftops is not quite sure for the low-rise building in particular. Follow up study is good if the correlation between rooftop height and rainwater quality is set up. Moreover, injected rainwater may influence the underground environment; therefore, it is recommended that a reactive model and empirical experiment is necessary to be set up to monitor how the groundwater system changes when the mixing of groundwater, rainwater, and soil minerals occurs.

- The maximum harvested rainwater a day in the period 2008-2018 is similar to that of the recharge capacity of injection wells. From the study results, the AGR for the study area includes four main components: (1) trough and pipeline system, (2) sand filter system, (3) the treated water storage tank (4) and injection well(s). The number of wells for AGR is dependent on a specific building. For a better understanding of the AGR system, it is suggested that the recharge capacity of the injection well also needs to be tested at the site.

- To ensure that the system will work properly, it is proposed that the recharge be maintained regularly to prevent the well from clogged ng. Otherwise, it is necessary to monitor rainwater quality to ensure it will not contaminate the aquifer.

Acknowledgments

This research is funded by the VNU University of Science, Vietnam National University, Hanoi under project number TN.20.11.

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