Journal of Groundwater Science and Engineering
ISSN 2305-7068
Indexed by ESCI CABI CSA Scopus GeoRef AJ CNKI

Effects of urbanization on groundwater level in aquifers of Binh Duong Province, Vietnam

Luong Van Viet

Citation:
Luong Van Viet. Effects of urbanization on groundwater level in aquifers of Binh Duong Province, Vietnam[J]. *Journal of Groundwater Science and Engineering*, 2020, 9(1): 20-36.

View online: https://doi.org/10.19637/j.cnki.2305-7068.2021.01.003

DOI: 10.19637/j.cnki.2305-7068.2021.01.003

Effects of urbanization on groundwater level in aquifers of Binh Duong Province, Vietnam

Luong Van Viet*

Institute for Environmental Science, Engineering and Management, Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam.

Abstract: The purpose of this paper was to assess the impact of urbanization on the groundwater level (GWL) in aquifers of Binh Duong (BD) Province. The research method is to analyze the trend of GWL, the recharge capacity of surface over time and the relationship between them. The data of the GWL used in the study are the average values in the dry and rainy seasons of 35 observation wells from 2011 to 2018, which are in Pleistocene and Pliocene aquifers. The ability to recharge groundwater from the surface in this study was represented by the curve number (CN), a parameter used in hydrology for calculating direct runoff or infiltration from rainfall. The land use data to identify the CN was analyzed from the Landsat images. The results show that besides over-exploitation, the change of surface characteristic due to the urbanization development process is also the cause of the GWL decline. The analysis of seasonal GWL data shows that the increase in impervious surface area is the cause of GWL decline in the Pleistocene aquifer, which is more evident in the rainy season than in the dry season. The statistical results also show that in the rainy season and in shallow aquifers, a higher CN change can be found with the wells that had a remarkable GWL decline compared to the remaining wells.

Keywords: Urbanization; Land use change; Impervious surface; Curve number; Groundwater level

Received: 16 Jun 2020/ Accepted: 08 Aug 2020

Luong Van Viet. 2021. Effects of urbanization on groundwater level in aquifers of Binh Duong Province, Vietnam. Journal of Groundwater Science and Engineering, 9(1): 20-36.

Introduction

Groundwater depletion is a term often defined as long-term water level declines. If groundwater abstraction exceeds the natural groundwater recharge extensively and for a long time, over-exploitation or persistent groundwater depletion occurs.

Water use has been increasing worldwide by about 1% per year since the 1980s (WWAP, 2019). Many areas of the world are experiencing groundwater depletion. The main cause of GWL decline is over-exploitation (Marsh *et al*. 1983; Wada *et al*. 2010; Mishra *et al*. 2014; Bui *et al*. 2012).

The urban population of the world grew rapidly from 751 million in 1950 to 4.2 billion in 2018 (UN, 2018). Due to urbanization process, the changes in land use have occurred locally, regionally and globally. Land Use and Land Cover Change (LUCC) can significantly affect the groundwater recharge and quality (HUANG Tian-ming and PANG Zhong-he, 2010; Mishra *et al*. 2014; Khatri and Tyagi, 2015; Okotto *et al*. 2015; McGrane, 2016). Change of land surface characteristics is one of the major impacts of urbanization (Rahman *et al*. 2011; Bhatta, 2009; Jat *et al*. 2008; Dewan and Yamaguchi, 2009). In places with rapid urbanization, groundwater resources are severely affected quantitatively as well as qualitatively (Wakode *et al*. 2014). Therefore, groundwater abstraction and LUCC are the main

*Corresponding author. E-mail: vietvanluong@gmail.com

causes of groundwater degradation.

In the process of urbanization, the impermeable surface area is largely increased, which will increase surface flow (Arnold and Gibbons, 1996), reduce runoff lag time and increase flood return periods (Hollis 2010). Therefore urbanization can result in reduction in infiltration, which affects the groundwater recharge and storage (Pradeep *et al*. 2018; Aronica and Lanza, 2005a; Walsh *et al*. 2005; Hardison *et al*. 2009; O'Driscoll *et al*. 2010; McGrane, 2016). In a sample analysis, conversion of woodland to high-density residential and commercial area caused a loss of 11 to 100 percent of the natural groundwater recharge (Jonathan, 1994). Land use changes directly affect basin hydrology and many numerical models have been developed for the assessment (Fohrer *et al*. 2001; Tang *et al*. 2005; Dams *et al*. 2008; Aish *et al*. 2010; Fadil *et al*. 2011; Hamad *et al*. 2012; Eshtawi *et al*. 2016).

Binh Duong (BD) is a southern province of Vietnam with an area of 2 694 km^2. Most area of BD falls in the lower of the Be subbasin and the Sai Gon subbasin. These subbasins have a total area of 12 755 km^2 and are located in the upper of Dong Nai River basin.

BD has experienced the fastest urbanization and industrialization process. One of the clearest reflections of this process is its LUCC. According to the data from the BD Department of Natural Resources and Environment, in the period of 2000-2018, the agricultural land area in BD decreased rapidly from 228 thousand hectares (84.7% of the total area) to 207 thousand hectares (76.85% of the total area).

On the other hand, the non-agricultural land area increased from 28 thousand hectares (10.5% of the total area) to 62 thousand hectares (23.1% of the total area) in the same period from 2000 to 2018. In recent years from 2011 to 2018, BD's urbanization and industrialization rate was even faster. According to the data from the General Statistics Office of Vietnam, in 2011, the urban population was 1 064 thousand out of 1 659 thousand people as the total population, accounting for 64.1%. While in 2018, it increased to 1 691 thousand out of 2 164 thousand people, accounting for 78.2%. Also, from 2011 to 2018, the rural population decreased by 20.7% and the urban population increased by 59%, which indicates the rapid urbanization rate of BD.

Along with the rapid urbanization process, the growth of industrialization is also strong. By 2018, after more than 20 years of industrialization, BD had 29 industrial parks and 12 concentrated industrial clusters with a total area of over 13 600 hectares. Besides LUCC, groundwater abstraction has also increased remarkably, which may cause groundwater depletion.

Based on the above, urbanization has a negative impact on groundwater resource due to large scale pumping and decreased groundwater recharge caused by impervious surface. The rate and extent of GWL depletion depends on aquifer storage volume, hydraulic conductivity and long-term abstraction (Foster and MacDonald, 2014), therefore it is necessary to conduct a research to study the effects of urbanization on groundwater levels in BD.

1 Data and methods

1.1 Data

The data used in this study is from 2011 to 2018, including GWL of aquifers and LUCC data Year 2011 is the time when the groundwater observation wells in BD started to operate.

There are four main aquifers in the study area: Middle-upper Pleistocene (qp_{2-3}), Lower Pleistocene (qp_1), Middle Pliocene (n_2^2) and Lower Pliocene (n_2^1). Table 1 shows the characteristics of the main aquifers in BD.

Table 1 Characteristics of the main aquifers in BD

Series	Subseries	Aquifer	Mean thickness (m)	Depth from surface (m)	Lithology	Storage capacity
Pleistocene	Upper	qp_3			Sand, pebble, gravel and clay powder	Very low
	Middle	qp_{2-3}	13.2	15~30	Pebble, gravel, sand and clay	Low
	Lower	qp_1	20.1	30~50	Sand, pebble and gravel	Medium
Pliocene	Middle	n_2^2	16.1	50~80	Fine sand and pebble, sand and clay powder	Medium to high
	Lower	n_2^1	43.6	>80	Sand, pebble, gravel, sand mixed with clay powder	High

BD's groundwater observation wells used in the study are located in these aquifers. The location of the wells is shown in Fig. 1, in which the ID is used to identify the well. In this study area, there are 35 observation wells, in which 3 wells are in the aquifer $qp_{2\text{-}3}$ with ID from 1 to 3. Eight wells are in the aquifer qp1 with ID from 4 to 11. Fourteen wells are in the aquifer n_2^2 with ID from 12 to 25. Ten wells are in the aquifer n_2^1 ID from 26 to 35.

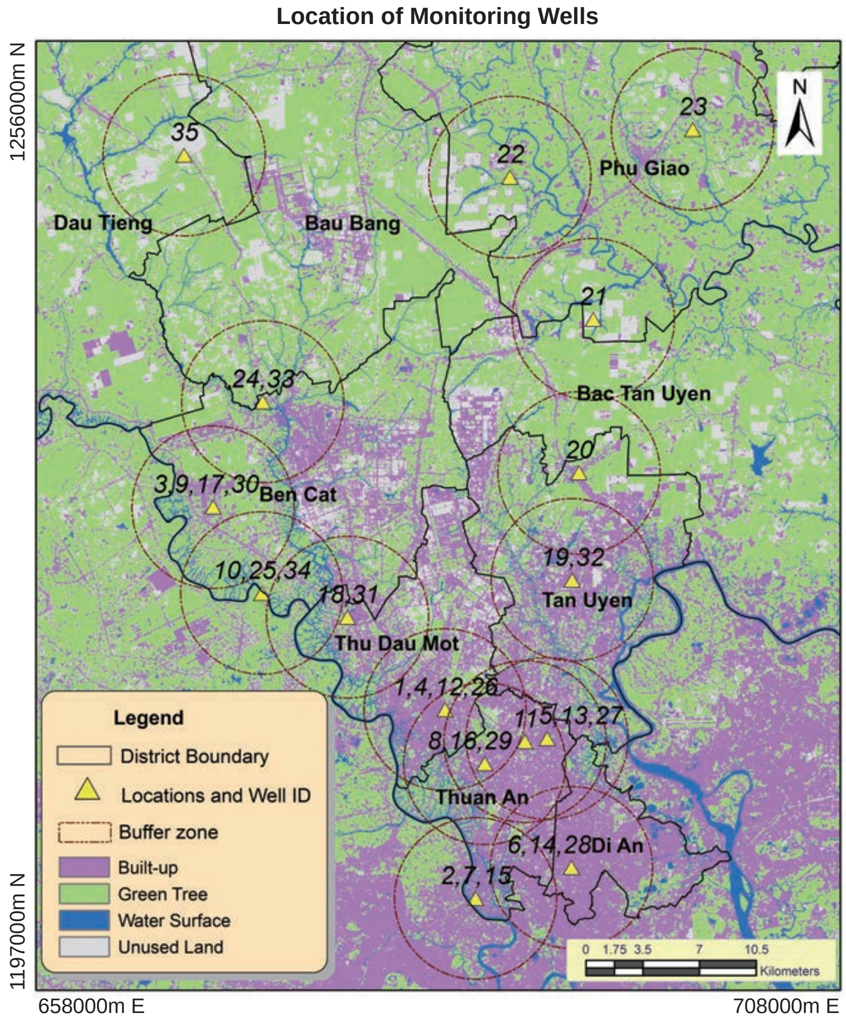

Fig. 1 Location of observation wells

Layer of land use type was interpreted and classified from Landsat image (https://ear-the-xplorer.usgs.gov). These imageries were selected in the dry season and the transition period from the rainy season to the dry season, in which the image quality is usually quite good due to less clouds and low humidity. Remote sensing images were taken at the beginning and the end of the analysis period. The 2011 image was from Landsat 5 on January 29 (LT05_125052_20110129). The 2018 image was from Landsat 8 on October 31 (LC08_125052_20181031). The image bands used in the study were visible spectral bands, from which multispectral images were built and used for image classification.

1.2 Methodology

To assess the effect of urbanization and industrialization on GWL change, the main contents of this study include: Classifying remote sensing images and creating CN grid in the research area; identifying the trend of GWL and rainfall at the observation sites; conducting CN statistics by buffer zone of wells with default radius and analyzing the relationship of CN change with GWL. To achieve these goals, the following methods were used:

(1) Classify remote sensing images

The purpose of the classification of remote sensing images is to identify land use types.

ENVI software was used in this study to analyze the images. The steps of image classification include: Geo-referencing, creating composite images, classifying and evaluating the results of classification. There was no mosaicking step because the study area was completely located in row 125 and path 52 in the Landsat imagery.

Four land use types have been classified as follows: Built-up, green trees, water surface and unused land. The method of supervised classification MLC (Maximum Likelihood Classifier) was used based on background sample dataset collected from field survey in 2018. Sample dataset was added and adjusted for 2011 based on the background sample dataset of 2018. The quality of image classification was evaluated using Kappa coefficient. The classification results then used as input files in ArcGIS to analyze land-use change and to create CN grid.

(2) Create CN grid

Urbanization increases the impervious surface area and reduces the groundwater recharge capacity, leading to changes in the GWL. In this study, the effects of urbanization on GWLs were analyzed by CN changes. CN is a parameter of the Soil Conservation Service Curve Number loss model (SCS CN model). This model estimates precipitation excess as a function of cumulative precipitation and CN. SCS CN is one of the popular models to investigate the impact of more realistic developmental scenarios on infiltration losses and rainfall excess (Hong and Adler *et al*. 2008; Sahu *et al*. 2012; Abushandi and Merkel *et al*. 2013; Laouacheria and Mansouri *et al*. 2015; Dwarakish and Ganasri, 2015).

The value of CN depends on antecedent moisture conditions, land use and soil type, which can be estimated by using tables published by the SCS (USACE, 2000). CN ranges from 30 to 100 with lower numbers indicating lower runoff (higher infiltration) potential and higher numbers representing higher runoff potential. SCS CN grid has been used in many hydrologic models. The software of HEC-GeoHMS and ArcGIS 10 was used to extract the CN grid.

(3) Analyze trend of GWL and rainfall

Mann-Kendall (MK) non-parametric test (Mann, 1945; Kendall, 1975) was used to identify the trends of an ordered time series data. This method can effectively avoid the biased trend caused by some extreme values when using the linear trend method by ordinary least squares. With an ordered time series data (x_1, x_2, ..., x_n).

Where: x_i represents the data at time i, the MK test statistic is given by:

$$S=\sum_{k=1}^{n-1}\sum_{j=k+1}^{n} sign(x_j - x_k) \tag{1}$$

$$sign(x_j - x_k)=\begin{cases}1 \; if \; x_j - x_k>0\\ 0 \; if \; x_j - x_k = 0\\ -1 \; if \; x_j - x_k<0\end{cases} \tag{2}$$

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{Var(S)}} & if \; S>0\\ 0 & if \; S=0\\ \dfrac{S+1}{\sqrt{Var(S)}} & if \; S<0\end{cases} , \tag{3}$$

Where: *Var(S)* is the variance of S, calculated by the following Equation (4):

$$Var(S)=\frac{1}{18}\left[n(n-1)(2n+5)+\sum_{p=1}^{g} t_p(1-t_p)(2t_p+5)\right] \tag{4}$$

In Equation (4), g is the number of tied groups in the dataset and t_p is the number of data points in the p^{th} tied group.

Since Z has a normal distribution, it is easy to test whether there is a trend or not in the dataset. In the test, if the null hypothesis is rejected, there is no trend in the dataset. It is depending on the calculated Z statistics is more than or less than the critical value of Z (Z_{crit}) obtained from the normal distribution table.

Sen's Slope was used to determine the slope of the trend line. Slope β is defined as the median of the series consisting of n(n-1)/2 elements { ($x_j - x_k$)/(j – k), with k = 1, 2, …, n-1; j>k}. With such definition, β has the same sign as Z. In this study, trend values were assessed at significance levels from 0.3 to 0.001, corresponding to confidence levels from 70% to 99.9%, depending on its responsiveness.

(4) Analyze the relationship between CN change and GWL trend

CN included in the analysis are the average values from the buffer zone of the well. The buffer zones are circles centered on wells and have radius of 1 km, 3 km and 7 km, corresponding to an area of about 3 km^2, 28 km^2, 79 km^2 and 154 km^2. The determination of the average value of the CN was based on the statistical tool in ArcGIS software.

The effects of land use change on GWLs were analyzed using statistical methods. The analysis was conducted in the dry and rainy seasons. Factors in this analysis are CN change and GWL trend over the period of 2011-2018.

2 Results and discussion

2.1 Land use change over the period of 2011-2018

The image classification results from the Landsat images are shown in Fig. 2. The Kappa index for the 2018 image is 0.88. Thus, the image classification results were reliable.

Based on classification images, the statistical results of built-up areas by administrative units of districts, towns and city are presented in Table 2. From this table, it shows that towns and city in the south of BD had faster urbanization rate. In 2011, the built-up areas of Thu Dau Mot City, Thuan An, Di An and Tan Uyen towns only accounted for 12.3% to 46.5%, then in 2018 these figures were 45.2% to 79.0%. Thus, in only 7 years, from 2011 to 2018, the increased percentages of built-up areas in these four administrative units are in the range of 26.4% to 32.8%.

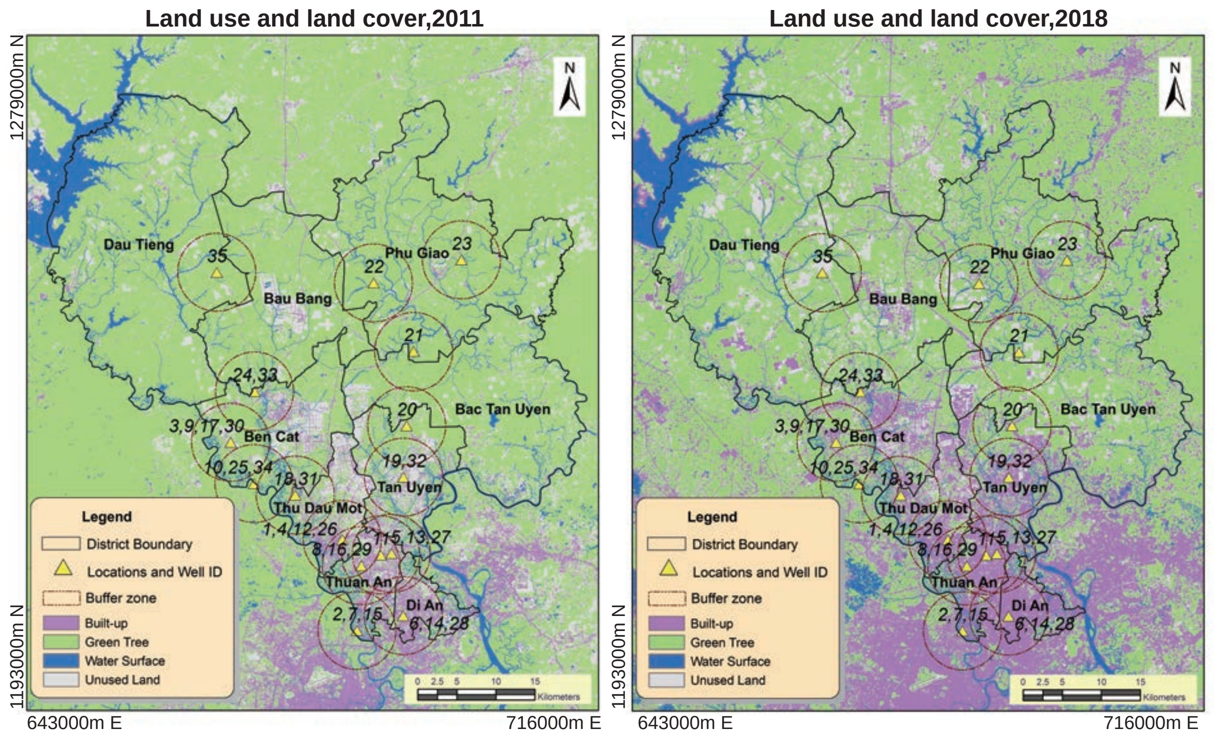

Fig. 2 Land use and land cover in 2011 and 2018

Considering all city and towns in the province, or the first five rows in Table 1, the increases of built-up areas are still high. From 2011 to 2018, the increased percentage of build-up areas are in the range of 21.1% to 32.8%. Thuan An and Di An towns had the highest percentage of built-up areas in 2018, *i.e.* 68.7% and 79%, respectively. For rural districts, the percentages of built-up areas in 2011 are quite low with values ranging from 1.2% to 2.3%. But in 2018, the percentages are in the range of 7.2% to 13.8% and the increased percentage of built-up areas are in the range of 6% to 11.4%.

2.2 CN changes in the period of 2011-2018

The CN grid was generated from land-use data based on the classification of remote sensing images and soil data. From CN grid, the average value of CN in each administrative unit is presented in Table 3, in which △CN, the difference between CN in 2018 and 2011 is also given. Table 3 shows that, the increase of CN is significant from 2011 to 2018. In 2011, for all administrative units, the average value of CN is from 67.4 to 80.4, while in 2018 this value is from

69.7 to 85.0. The average increase of CN value is 2.3 from 2011 to 2018. Especially in Thu Dau Mot, Thuan An, Di An, Ben Cat and Tan Uyen, the increases of CN are very high, from 3.4 to 4.9. The increase of CN in this area could be attributed to the rapid urbanization and industrialization, which effectively reduce infiltration and groundwater recharge.

Table 2 Change of built-up areas over the 2011-2018 period

ID	Administrative units	Area (ha)	Built-up areas (ha)		Built-up areas (%)		Increase (%)
			2011	2018	2011	2018	
1	Tan uyen Town	18 363	2 265	8 292	12.3	45.2	32.8
2	Di An Town	6 010	2 794	4 745	46.5	79.0	32.5
3	Thuan An Town	8 373	3 116	5 748	37.2	68.7	31.4
4	Thu Dau Mot City	11 840	2 838	5 960	24.0	50.3	26.4
5	Ben Cat Town	23 486	2 210	7 159	9.4	30.5	21.1
6	Bac Tan Uyen District	40 824	950	5 617	2.3	13.8	11.4
7	Phu Giao District	54 370	781	6 021	1.4	11.1	9.6
8	Bau Bang District	34 047	786	3 731	2.3	11.0	8.7
9	Dau Tieng District	72 044	872	5 201	1.2	7.2	6.0

Table 3 The average of CN in administrative units

ID	Administrative units	CN mean		△ CN
		Year 2011	Year 2018	
1	Tan uyen Town	74.1	79.0	4.9
2	Di An Town	80.4	85.0	4.6
3	Thuan An Town	79.2	83.6	4.4
4	Thu Dau Mot City	76.8	80.5	3.7
5	Ben Cat Town	71.2	74.6	3.4
6	Bac Tan Uyen District	68.9	70.9	2
7	Phu Giao District	67.4	69.2	1.8
8	Bau Bang District	67.9	69.7	1.8
9	Dau Tieng District	69.2	70.5	1.3
10	Binh Duong Province	70.0	72.3	2.3

To determine the effect of increase of the built-up area on the GWL, the CN was calculated by the buffer zones with radius of 1 km, 3 km, 5 km and 7 km from CN grid for each well. Fig. 3 demonstrates the value of CN by the buffer zone with a radius of 5 km in 2011 and 2018. From the data on the average value of CN by the buffer zones, the increase of CN in each well is shown in Fig. 4. Statistical results of CN change are shown in Table 4, which shows that △CN has various increases among wells and by buffer zones, from 1.7 to 7.8. The average increase is from 4.5 to 4.9 by buffer zones. It is also found that the increase of CN is inversely proportional to the buffer radius. This significant increase of CN indicates the reduction in groundwater recharge and may affect the water level of the wells.

Table 4 The average of CN in the buffer zone of wells

		Buffer radius			
		1 km	3 km	5 km	7 km
CN 2011	Min	65.8	65.9	66.1	66.0
	Max	83.7	83.1	81.2	81.2
	Mean	76.0	74.2	73.6	73.1
CN 2018	Min	68.4	68.5	68.5	67.7
	Max	87.9	87.3	85.9	85.9
	Mean	80.9	79.0	78.2	77.6
△ CN	Min	2.2	2.5	2.4	1.7
	Max	7.8	7.7	6.2	6.6
	Mean	4.9	4.8	4.6	4.5

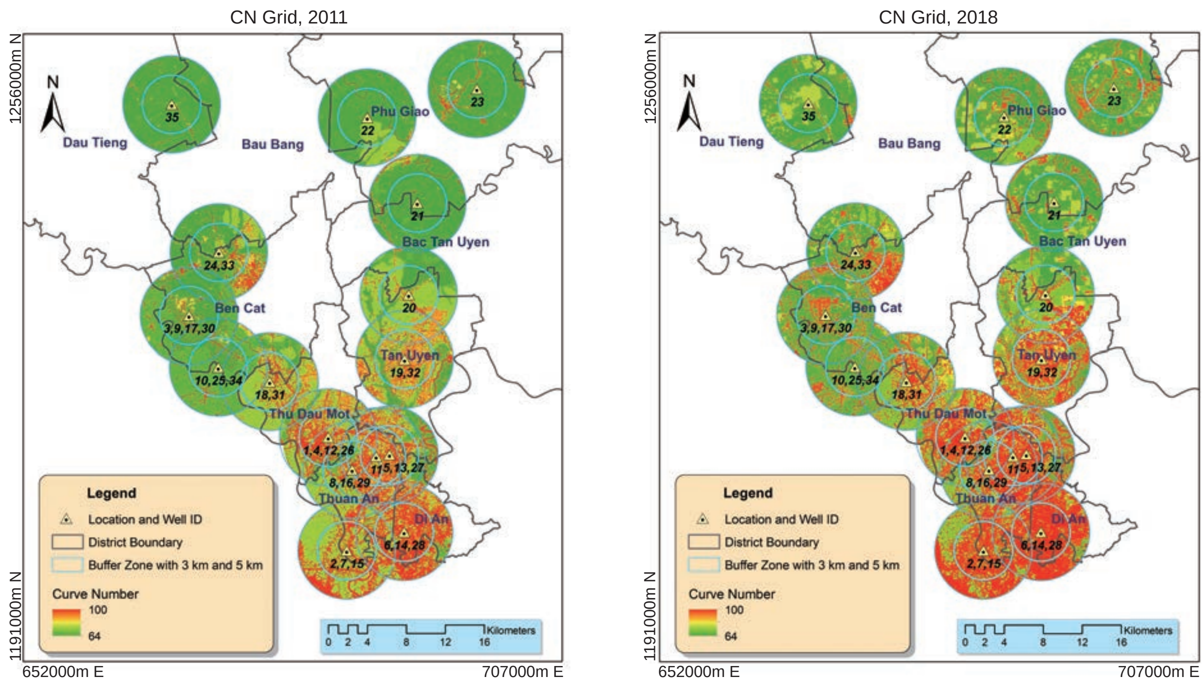

Fig. 3 CN grid around the observation wells in 2011 and 2018

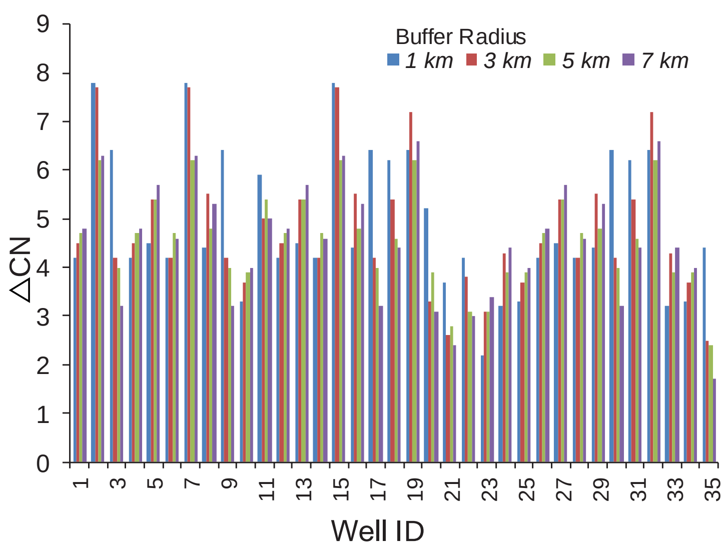

Fig. 4 Change of CN by buffer zones of wells

According to Fig. 4, except for wells with ID of 3, 9, 17, 20, 30 and 35, △CN does not show large variation by the buffer zones. In the wells with ID of 2, 7, 15, 19 and 32, △CN is prominent (>6) in all four buffer zones. These wells are located in the towns of Thuan An, Tan Uyen Di An, Ben Cat and Tp. Thu Dau Mot, which are also those administrative units with the fastest urbanization speed.

2.3 GWL trend

BD is located in the tropical monsoon region so its rainfall varies by the season. The climate in this area is divided into two seasons: Dry season and rainy season. The rainy season usually starts from early May to the end of November while the rest is dry season. The total rainfall during the rainy season accounts for about 92% of the annual rainfall. Rainfall is evenly distributed in the months of the rainy season.

2.3.1 Trend of GWL in dry season

In this section, the average GWL in the dry months, from December to April of next year, is analyzed. MK test results and Sen's Slope analysis are presented in Fig. 5. This figure shows:

In the aquifer qp_{2-3}, GWL in only 1 out of the 3 wells (33.33%) has the tendency to decrease with the rate of 0.33 m/a with the confidence level of 95%. Such trend has not been identified in the remaining 2 wells.

In the aquifer qp_1, GWL in only 3 out of 8 wells (37.5%) tends to decrease with the rate from 0.09 m/a to 0.34 m/a with the confidence level of 80%~95%. Such trend has not been identified in the remaining 5 wells.

In the aquifer n_2^2, GWL in 10 out of 14 wells (64.39%) tends to decrease with the rate from 0.12 m/a to 0.65 m/a, with the confidence level of 80%~95%. Such trend has not been identified in the remaining 4 wells.

In the aquifer n_2^1, GWL in 6 out of 10 wells (60%) tends to decrease with the rate from 0.14 m/a to 0.57 m/a. Except for one well with a confidence level of 70%, the remaining wells have the confidence level of 80% to 90%. GWL in 1 well tends to increase at a rate of 0.36 m/a with a confidence level of 90%. The trend of the remaining 3 wells cannot be identified.

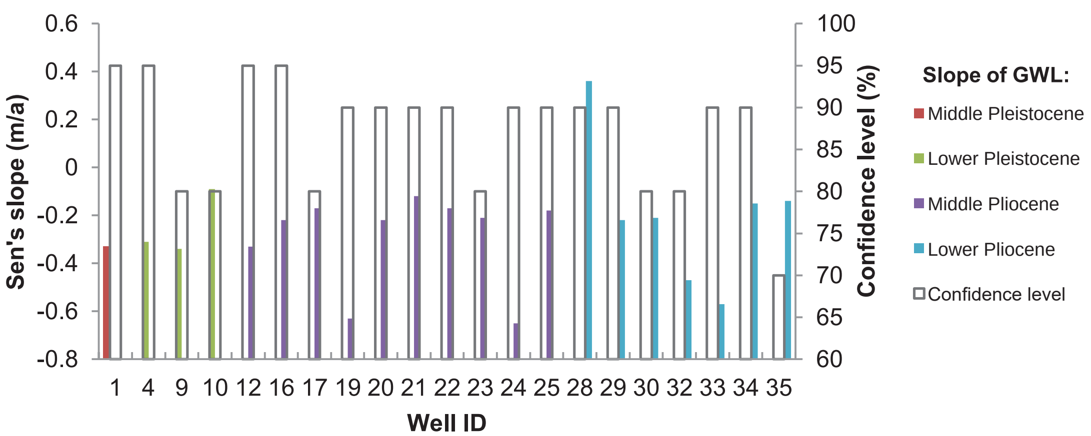

Fig. 5 Results of MK test and Sen's slope analysis of GWL at observation wells in dry seasons of 2011-2018

To sum up, in all the 35 observation wells, GWL tends to decrease in 20 wells; tends to increase in only 1 well; and cannot be identified in the remaining 14 wells. In the Pleistocene aquifers, GWL in 4 out of 11 wells tends to decrease, accounting for only about 36%, while no trend can be identified in the remaining 7 wells. In the Pliocene aquifers, GWL in 16 out of 24 wells tends to decrease, accounting for 67%, while GWL in one well tends to increase and no trend is identified in the remaining 7 wells.

2.3.2 Trend of GWL in rainy season

In this part, the average GWL in rainy season, from early May to end of November, is analyzed.

MK test results and Sen's Slope analysis are presented in Fig. 6. It shows:

In aquifer $qp_{2\text{-}3}$, GWL in all 3 wells tends to decrease with the rate from 0.12 m/a to 0.56 m/a with the confidence levels from 70% to 95%.

In aquifer qp_1, GWL in 5 out of 8 wells (63%) tends to decrease with the rate from 0.10 m/a to 0.61 m/a and an average of 0.28 m/a, while no such trend is identified in the remaining 3 wells. 2 wells have a confidence level of 70% and the remaining 3 wells have quite high confidence level from 80% to 90%.

GWL in 10 out of 14 wells (71%) in the n_2^2 aquifer tends to decrease with the rate from 0.07 m/a to 0.74 m/a and an average of 0.33 m/a, and the confidence level is from 70% to 95%. GWL in the remaining 4 wells does not show a clear trend.

In the lower Pliocene stratification, n_2^1, GWL in 5 out of 10 wells (50%) tends to decrease with rate of from 0.07 m/a to 0.62 m/a and an average of 0.29 m/a, The confidence level is from 70% to 95%. GWL in the remaining 5 wells does not show a clear trend.

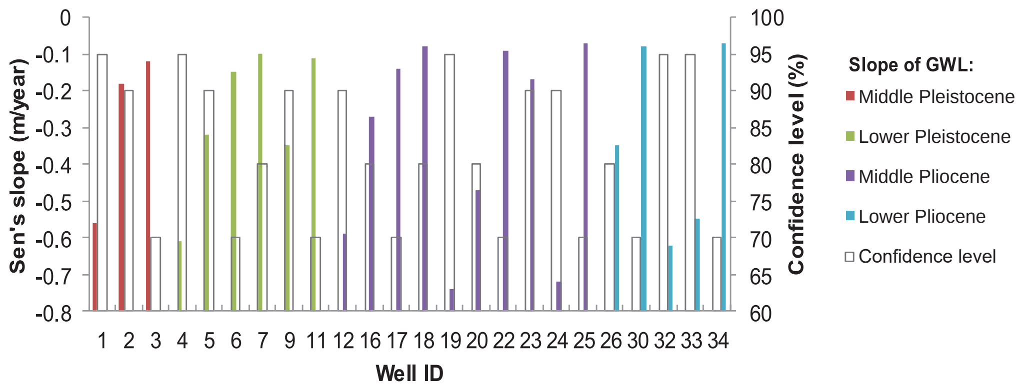

Fig. 6 Results of MK test and Sen's Slope analysis of GWL in observation wells in rainy seasons of 2011-2018

To sum up, GWL in 24 out of 35 wells (68.6%) tends to decrease during the rainy season, the percentage of which is more than that in the dry season. In particular, in the Pleistocene aquifers, GWL in 9 out of 11 wells (82%) tends to decrease, the percentage of which is two times higher when compared to that in the dry season. In the Pliocene aquifers, GWL in 15 out of 24 wells (62.5%) tends to decrease. No trend is identified in the remaining 11 wells.

Compared to the dry season, the tendency of GWL decline in the rainy season is more clear in the shallow aquifers. This may be due to the reduced recharge. The total rainfall and the number of rainy days in this area are very high and the terrain is quite flat, which provides an excellent natural condition for groundwater recharge. However, when the natural ground surface is replaced with urbanized artificial materials, the recharge capacity is significantly reduced, which may cause the continuous decline of GWL in shallow aquifers.

2.4 Analysis of changes in GWL

2.4.1 Effect of groundwater exploitation on GWL

Water supply for domestic and production activities of BD mainly relies on surface water from Dong Nai and Saigon rivers. In 2011, BD exploited around 10 500 m^3/h from surface water, meeting about 75% of water demand. The rest 25%, 3 500 m^3/h, was extracted from underground water. In 2018, surface water extraction was 24 000 m^3/h and groundwater extraction was 13 000 m^3/h, the percentage of which was increased to over 35%. Thus, compared to 2011, groundwater abstraction in 2018 increased nearly 4 times. Industrial wells are often exploiting the Pliocene aquifers. Households and small businesses usually extract water from the qp_1 and n_2^2 aquifers. This is the cause of the rapid decrease of GWL in most wells in the Pleistocene and Pliocene aquifers in both dry and rainy seasons.

The effect of groundwater extraction on

GWL is reflected in the relationship between the increase in groundwater extraction and the rate of GWL decline. The increase in groundwater extraction (dQ) in the period of 2011-2018 around the wells with radius of 1 km, 3 km and 5 km was calculated based on licensing data of groundwater exploitation. Fig. 7 illustrates dQ for aquifers n_2^2 and n_2^1. Among the aquifers, n_2^1 is the aquifer with the main exploitation.

The correlation coefficient (R) between dQ and the rate of GWL reduction is illustrated in Fig. 8 and showed in Table 5. Considering the mean value in Table 5, from qp_1, n_2^2 and to n_2^1, the highest absolute value of R decreases. Thus, in this area, the influence of groundwater extraction on the water level of the exploitation layer is more evident in the shallow aquifer. Also according to this table, in all three buffer zones with radius of 1 km, 3 km and 5 km, the effect of dQ on the rate of GWL decline have been clearly shown in the qp_1, n_2^2 and n_2^1 aquifers, with the mean value of R between -0.85 and -0.52.

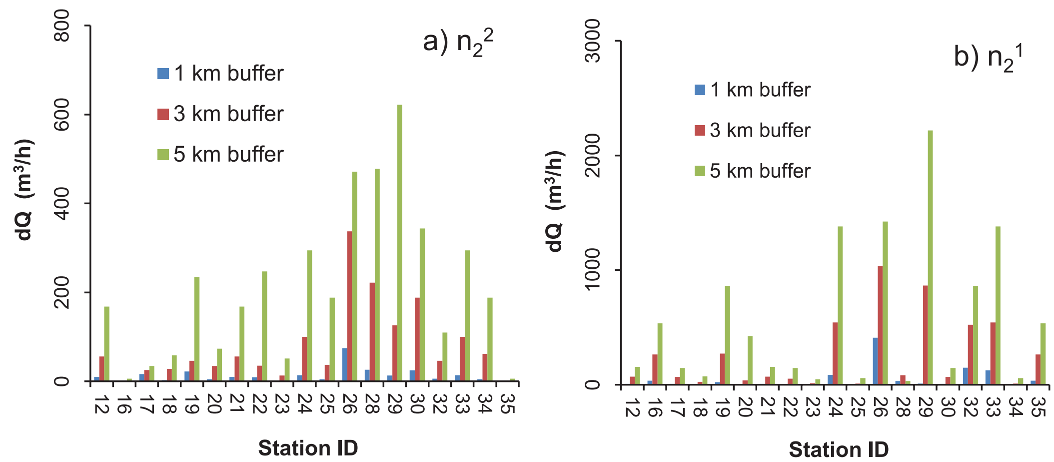

Fig. 7 The increase of groundwater extraction in the period of 2011-2018 in the aquifers: a) n_2^2 and b) n_2^1

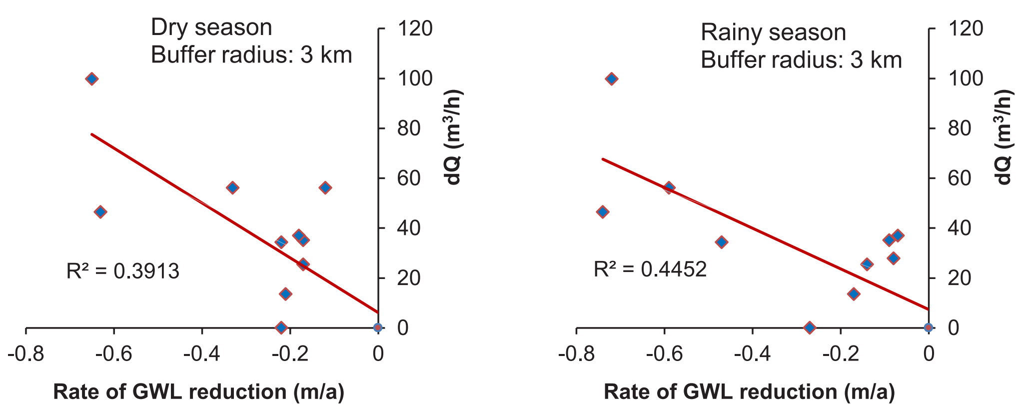

Fig. 8 The relation between the rate of GWL reduction and dQ in the aquifer n_2^2

Table 5 The correlation coefficient (R) between the rate of GWL reduction and dQ

	Dry season			Rainy season			Mean		
Buffer radius	1 km	3 km	5 km	1 km	3 km	5 km	1 km	3 km	5 km
qp_1	-0.71	-0.94	-0.87	-0.99	-0.67	-0.29	-0.85	-0.80	-0.58
n_2^2	-0.61	-0.63	-0.58	-0.57	-0.67	-0.49	-0.59	-0.65	-0.53
n_2^1	-0.54	-0.55	-0.59	-0.50	-0.62	-0.73	-0.52	-0.59	-0.66

2.4.2 The difference in the rate of GWL decline between the dry and rainy seasons

The number of observation wells, in which the water level tends to decrease, and the Sen's slope in both dry and rainy seasons are shown in Fig. 9 and Table 6. The following differences in GWL trends in the dry and rainy seasons have been observed:

In Pleistocene aquifers, the number of wells which have a decreasing trend of GWL in the dry season is less than that in the rainy season. Of all 13 observation wells in these aquifers, GWL in only 3 wells tends to decrease in the dry season but the number goes up to 9 in the rainy season. Table 6 shows that the highest rate of GWL decline occurs in the rainy season and it is almost twice higher than that in the dry season.

In the Pliocene aquifers, there is no significant difference in the number of wells in which GWL tends to decrease between the two seasons. In both the n_2^2 and n_2^1 aquifers, compared to the dry season, the number of wells in which GWL tends to decrease is increased by only 1 well in the rainy season. The mean and maximum rates of GWL decline in the same wells also show no significant difference between the two seasons.

Table 6 Comparison of GWL trends in rainy season and dry season

Series	Aquifer	The number of wells tends to decrease		Sen's slope (m/a)			
				Mean		Max	
		Dry season	Rainy season	Dry season	Rainy season	Dry season	Rainy season
Pleistocene	$qp_{2\text{-}3}$	1	3	-0.33	-0.29	-0.33	-0.56
	qp_1	2	6	-0.33	-0.27	-0.34	-0.61
Pliocene	n_2^2	9	10	-0.31	-0.33	-0.65	-0.74
	n_2^1	4	5	-0.35	-0.33	-0.57	-0.62

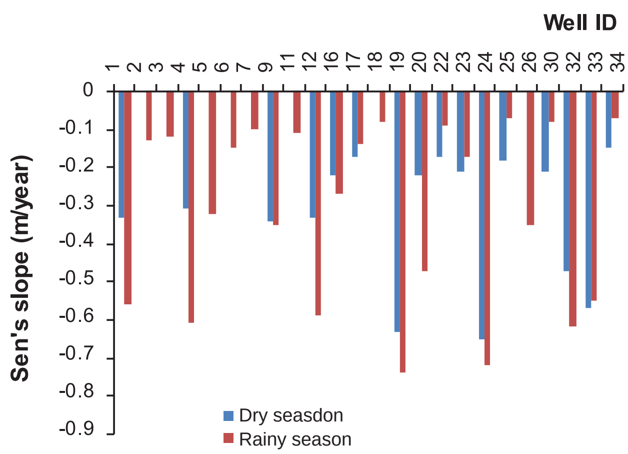

Fig. 9 The rate of GWL decline (Sen's slope) in observation wells

To sum up, GWL in the rainy season decreases more significantly than in the dry season, especially in the Pleistocene aquifers. Causes of this difference may be related to the following: (1) trend of seasonal rainfall; (2) more water is exploited in the rainy season than in the dry season; (3) the effect of an increase in impervious surface area. These possible causes are discussed below:

(1) Trend of seasonal rainfall

The locations of weather stations in and around the study area used for this analysis are shown in Fig. 10. The results of the seasonal rainfall trend analysis at these stations are presented in Table 7 and Table 8, in which Table 7 analyzes rainfall data in the same timeframe (2011 to 2018) with GWL data and Table 8 uses a longer timeframe (1988 to 2018) for more stable results.

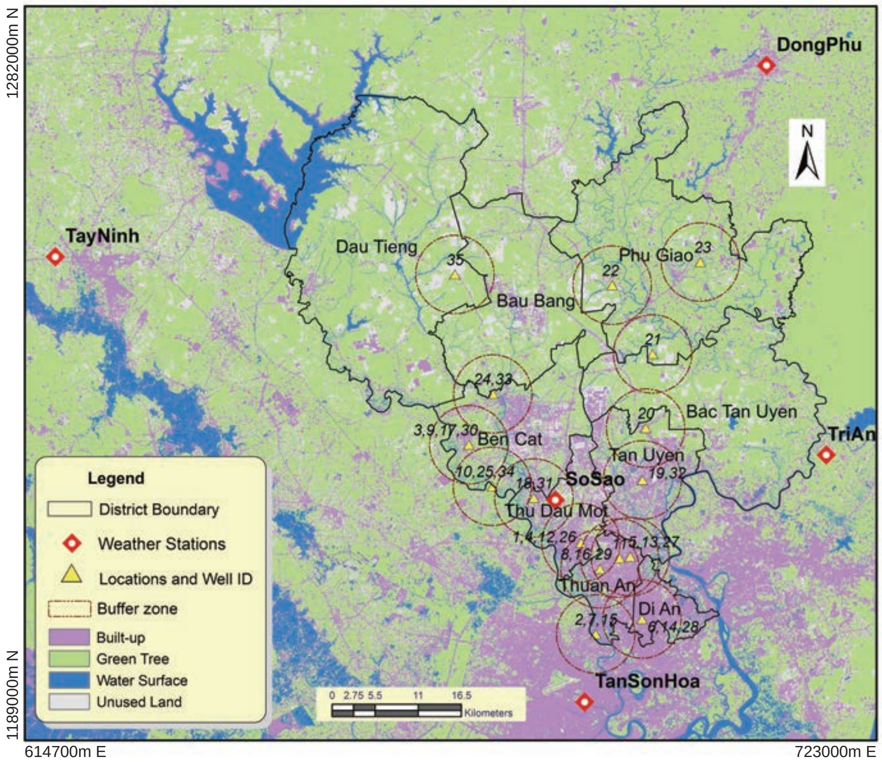

Fig. 10 Location of weather stations

In the 2011-2018 periods, Table 7 shows that the values of Sen's slope for all stations in both seasons are positive, while the values in the rainy season are significantly higher than that in the dry season. However, the testing results show that the trend is not clear in the dry season. During the rainy season, 3 out of 5 stations show the increasing trend, but the confidence levels are quite low, only from 60% to 80%.

Table 7 Results of MK test and Sen's Slope analysis of rainfall at weather stations in the 2011-2018 period

Season	Weather station	Sen's slope (mm/season)	Trend	Confidence level (%)
Dry season	Tay Ninh	5.7	Unknown	
	Dong Phu	3.1	Unknown	
	Tri An	2.5	Unknown	
	Tan Son Hoa	2.2	Unknown	
	So Sao	9.1	Unknown	
Rainy season	Tay Ninh	29.8	Increasing	60
	Dong Phu	42.0	Unknown	
	Tri An	24.3	Unknown	
	Tan Son Hoa	70.8	Increasing	70
	So Sao	50.0	Increasing	80

In the 1988-2018 periods, Table 8 shows that the values of Sen's slope for all stations and both seasons are positive. In the dry season, except for Tay Ninh station, there is a clear increasing trend in all other stations with the confidence levels between 80%~98%. However, the increase rate is quite small, only from 3.9 mm/a to 6.0 mm/a. In the rainy season, only one station, Tri An, shows a clear increase of 8.1 mm/a with the confidence level of 90%. The trend of the remaining stations is not clear.

Table 8 Results of MK test and Sen's Slope analysis of rainfall at weather stations in the 1988-2018 period

Season	Weather station	Sen's slope (mm/season)	Trend	Confidence level (%)
Dry season	Tay Ninh	2.1	Unknown	
	Dong Phu	4.6	Increasing	80
	Tri An	2.3	Increasing	90
	Tan Son Hoa	6.0	Increasing	98
	So Sao	3.9	Increasing	90
Rainy season	Tay Ninh	2.4	Unknown	
	Dong Phu	1.9	Unknown	
	Tri An	8.1	Increasing	90
	Tan Son Hoa	7.2	Unknown	
	So Sao	3.3	Unknown	

The total rainfall in the dry season is about 150~250 mm, accounting for only 8%~12% of the annual rainfall. During the dry season, the air humidity is low, the temperature is high, so the potential evapotranspiration (ETo) of these months is very high. The average value of ETo in the dry months is about 4.2~4.4 mm/d, while the average daily rainfall of these months is only about 1.0~1.7 mm/d, which can significantly reduce the recharge potential. With relatively low rainfall during the dry season, the above increase in rainfall over the years cannot effectively affect the GWL. If precipitation is a valid cause of the GWL decline in the area, the rainfall in the rainy season should have had a decreasing trend. However, the above analysis shows that no such trend can be identified. Thus, the cause of rainfall is excluded.

(2) Groundwater exploitation

Compared to the rainy season, this region has lower humidity and higher temperatures in the dry season, so the water demand for production and domestic activities is higher. In fact, groundwater abstraction rate in the dry season is smaller than that in the rainy season. Thus, groundwater abstraction is not the cause of this difference.

(3) The increase in impervious surface area

The average rainfall of this area is rather high, from 1 850 mm/a to 2 150 mm/a, in which the rainfall in the rainy season is from 1 700 mm to 1 900 mm, accounting for nearly 90% of the annual rainfall. Therefore, groundwater recharge mainly occurs in this season. When the CN increases due to urbanization, the infiltration may decrease and that leads to the decline of GWL in the rainy season.

To assess the effect of increasing CN, infiltration is calculated based on the difference between accumulated rainfall depth (*P*) and accumulated precipitation excess (*Pe*). According to SCS method, *Pe* is calculated as follows:

$$P_e = \frac{(P-0.2S)^2}{P+0.8S} \tag{5}$$

Where: *S* is the potential maximum retention, which is determined by the following practical formula:

$$S = \frac{25400 - 254\text{CN}}{\text{CN}} \tag{6}$$

In Equation (6), the value of CN is adjusted by the accumulated rainfall of the previous 5 days. Using daily rainfall data from 2011 to 2018 of So Sao station located in the center of the study area, the results of infiltration calculation by CN of 2011 and 2018 are shown in Table 9, which includes four administrative units with the highest urbanization rates and the calculation was done for the rainy season. It shows that infiltration has decreased by 83~110 mm, or 16%~24% compared to the first year of this period.

The Pliocene aquifers are quite deep with positive pressure so the GWL are less affected by changes in surface area on a small scale, whereas the Pleistocene aquifers are more affected due to the shallow depth. The relatively high rainfall during the rainy season and a significant increase in CN over a relatively large area has led to a high reduction in infiltration. These may be the reasons that the decline of the water level in shallow aquifers in the rainy season is more evident than in the dry season.

Table 9 Infiltration change in the rainy season over the period of 2011-2018

ID	Administrative units	Infiltration rate (mm/season)		Change (%)
		CN of 2011	CN of 2018	
1	Tan Uyen Town	570	460	19
2	Di An Town	428	326	24
3	Thuan An Town	455	357	22
4	Thu Dau Mot City	509	426	16

2.4.3 The effect of △ CN on water level trend in rainy season

In this part, the data included in the analysis are trends in water levels during the rainy season with the consideration of confident levels and △ CN in the buffer zone of the wells. Of all 35 wells, 24 wells have a decreasing water level while the rest have an unclear trend. Of all the 24 wells with the decreasing trend, 16 wells have the confidence level of over 80%. For more stable statistical results, the wells are divided into 2 groups, in which Group 1 has 16 wells mentioned above, and the remaining wells belong to Group 2. The results are presented in Table 10, showing that:

In the Pleistocene aquifers, the wells in Group 1 have a higher △ CN than those in Group 2, which is most evident in the buffer zone of 3 km with a difference of 1.2. Thus, the radius of 3 km can reflect the influence of urbanization on the water level of this aquifer more clearly.

In the Pliocene aquifers, the wells in Group 1 have a negligibly higher △ CN than those in Group 2, from 0.4 to 0.6 with the radius of 3~7 km. There is no difference of △ CN with the radius of 1 km.

The above statistical results also show that an increase in impervious surface can significantly reduce the GWL in the Pleistocene aquifers but the effect is not clear in the Pliocene aquifers. It is possible that this effect will be more remarkable in the deeper layers if the CN changes over a large area and for long time.

Table 10 The mean of △ CN by group, buffer radius and aquifers

Group	Series	Number	△ CN by buffer radius			
			1 km	3 km	5 km	7 km
1	Pleistocene	6	5.8	5.7	5.4	5.1
	Pliocene	10	4.6	4.9	4.8	4.8
2	Pleistocene	5	4.8	4.5	4.6	4.5
	Pliocene	14	4.7	4.5	4.4	4.2
Difference	Pleistocene		1	1.2	0.8	0.6
	Pliocene		-0.1	0.4	0.4	0.6

3 Conclusions

In this study, results show that over-exploitation of groundwater for development purposes is causing GWL to drop rapidly in most wells in both Pleistocene and Pliocene aquifers. However, when considering the water level trend between the dry and rainy seasons, it shows that the water level in the rainy season decreases more clearly than in the dry season in the Pleistocene aquifers, which is related to the increase in impermeable surface area due to urbanization and industrialization.

The process of urbanization and industrialization of BD province in the period of 2011-2018 has made the impervious surface area increase significantly. In towns and city, the increase in impervious surface is in the range of 21.1% to 32.8%, while in rural areas the increase is between 6.0% and 9.6%. The increase in impervious surface has caused the increase of CN from 3.4 to 4.9, especially in towns and city. At the observation wells, by the buffer zones with radius of 1 km, 3 km, 5 km and 7 km, CN has an increase from 1.7 to 7.8, in which the high increases are associated with wells located in the urban area.

The increase of △CN induces the decrease of recharge capacity of groundwater. The rapid increase of the CN may have been the main cause of the decline of GWL in the Pleistocene aquifers, which is more evident in the rainy season than in the dry season. It is shown that both the number of wells with GWL decline and the rate of decline at the same location in the rainy season is higher than those in the dry season. In this area, the rainfall in the rainy season tends to increase over years, and the groundwater abstraction rate in the rainy season is smaller than in the dry season. Therefore, the increase in impervious surface area is the major reason for the more evident water level decline in the rainy season compared to the dry season.

In addition, the statistical results show that the wells in which GWL tends to decrease have the average △CN higher than the rest, and the difference depends on the radius of buffer zone and the depth of the aquifer. Compared to the Pliocene aquifers, the Pleistocene aquifers show the effects of the CN changes on the GWL more clearly.

Compared to the shallow aquifers, the effects of CN on the GWL are more evident in the deeper aquifers with bigger radius of buffer zones. Therefore, if the CN changes over a large area and for a long time, it will also affect the GWL in the deep aquifers.

Acknowledgements

This research used data and documents from the project “Planning the ground level and urban surface water drainage in Binh Duong Province”. We sincerely thank the organizations related to this project.

References

Abushandi E, Merkel B. 2013. Modelling rain-fall runoff relations using HEC-HMS and IHACRES for a single rain event in an arid region of Jordan. Water Resources Management, 27: 2391-2409.

Aish A, Batelaan O, De Smedt F. 2010. Distributed recharge estimation for groundwater modelling using WETSPASS, case study: Gaza Strip, Palestine. Arabian Journal for science and Engineering, 35(1B): 155-164.

Arnold CL, Gibbons CJ. 1996. Impervious surface coverage: The emergence of a key environmental indicator. Journal of the American Planning Association, 62(2): 243-258.

Aronica GT, Lanza LG. 2005a. Hydrology in the urban environment. Hydrological Processes, 19(5): 1005-1006.

Aronica GT, Lanza LG. 2005b. Drainage efficiency in urban areas: A case study. Hydrological Processes, 19(5): 1105-1119.

Bhatta B. 2009. Analysis of urban growth pattern using remote sensing and GIS: A case study of Kolkata, India. International Journal of Remote Sensing, 30: 4733-4746.

Bui DD, Kawamura A, Tong TN, *et al*. 2012. Spatio-temporal analysis of recent groundwater-level trends in the Red River Delta, Vietnam. Hydrogeology Journal, 20: 1635-1650.

Dams J, Woldeamlak ST, Batelaan O. 2008. Predicting land-use change and its impact on the groundwater system of the Kleine Nete catchment, Belgium. Hydrology and Earth System Sciences, 12(6): 1369-1385.

Dewan AM, Yamaguchi Y. 2009. Land use and land cover change in Greater Dhaka, Bangladesh: Using remote sensing to promote sustainable urbanization. Applied Geography, 29(3): 390-401.

Dwarakish GS, Ganasri BP. 2015. Impact of land use change on hydrological systems: A review of current modeling approaches. Cogent Geoscience, 1(1): 1115691. Doi: 10.1080/23312041.2015.1115691

Eshtawi T, Evers M, Tischbein B. 2016. Quantifying the impact of urban area expansion on groundwater recharge and surface runoff. Hydrological Sciences Journal, 61(5): 826-843.

Fadil A. 2011. Hydrologic modelling of the Bouregreg watershed (Morocco) using GIS and SWAT Model. Journal of Geographic Information System, 3(4): 279-289.

Fohrer N, Haverkamp S, Eckhardt K, *et al*. 2001. Hydrologic response to land use changes on the catchment scale. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and

Atmosphere, 26(7-8): 577-582.

Foster S, MacDonald A. 2014. The 'water security' dialogue: Why it needs to be better informed about groundwater. Hydrogeology Journal, 22: 1489-1492.

Hamad JT, Eshtawi TA, Abushaban AM, *et al*. 2012. Modeling the impact of land-use change on water budget of Gaza Strip. Journal of Water Resource and Protection, 4: 325-333.

Hardison EC, O'driscoll M, DeLoatch JP, *et al*. 2009. Urban land use, channel incision, and water table decline along coastal plain streams, North Carolina. Journal of American Water Resources, 45: 1032-1046.

Hollis GE. 2010. The effect of urbanization on floods of different recurrence interval. Water Resources Research, 11 (3): 431-435.

Hong Y, Adler R. 2008. Estimation of global SCS curve numbers using satellite remote sensing and geospatial data. International Journal of Remote Sensing, 29: 471-477.

HUANG Tian-ming, PANG Zhong-he. 2010. Estimating groundwater recharge following land-use change using chloride mass balance of soil profiles: A case study at Guyuan and Xifeng in the Loess Plateau of China. Hydrogeology Journal, 19: 177-186.

Jat MK, Garg PK, Khare D. 2008. Monitoring and modelling of urban sprawl using remote sensing and GIS techniques. Int J Appl Earth Obs Geoinf. 10: 26-43.

Jonathan MH. 1994. A practical method for estimating the impact of land-Use change on surface runoff, groundwater recharge and wetland hydrology. Journal of the American Planning Association, 60(1): 95-108.

Kendall MG. 1975. Rank correlation methods. London: Charles Griffin: 272.

Khatri N, Tyagi S. 2015. Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. Frontiers in Life Science, 8(1): 23-39.

Laouacheria F, Mansouri R. 2015. Comparison of WBNM and HEC-HMS for runoff hydrograph prediction in a small urban catch-ment. Water Resources Management, 29: 2485-2501.

Mann HB. 1945. Nonparametric tests against trend. Econometrica, 13: 245-259.

Marsh TD, Davies PA, Pontin JMA. 1983. The decline and partial recovery of ground water levels below London. Proceedings of the Institution of Civil Engineers, 74: 263-276.

McGrane SJ. 2016. Impacts of urbanization on hydrological and water quality dynamics, and urban water management: A review. Hydrological Sciences J, 61: 13, 2295-2311. Doi: 10.1080/02626667.2015.1128084.

Mishra N, Khare D, Gupta KK, *et al*. 2014. Impact of land use change on groundwater-a review. Advances in Water Resource and Protection, 2: 28-41.

O'Driscoll M, Clinton S, Jefferson A, *et al*. 2010. Urbanization effects on watershed hydrology and in-stream processes in the southern United States. Water, 2 (3): 605-648.

Okotto L, Okotto-Okotto J, Price H, *et al*. 2015. Socio-economic aspects of domestic groundwater consumption, vending and use in Kisumu, Kenya. Applied Geography, 58: 189-197.

Pradeep KN, Jivesh AT, Biranchi ND, *et al*. 2018. Impact of urbanization on the groundwater regime in a fast growing city in central India. Environ Monit Assess, 146: 339-373.

Rahman A, Aggarwal SP, Netzband M, *et al*. 2011. Monitoring urban sprawl using remote sensing and GIS techniques of a fast growing urban centre, India. IEEE Journal of Selected Topcis in Applied Earth Observation and Remote Sensing, 4(1): 56-64.

Sahu RK, Mishra SK, Eldho TI. 2012. Performance evaluation of modified versions of SCS curve number method for two watersheds of Maharashtra, India. ISH Journal of Hydraulic Engineering, 18(1): 27-36.

Tang Z, Engel BA, Pijanowski BC, *et al*. 2005. Forecasting land use change and its environmental impact at a watershed scale. Journal of Environmental Management, 76(1): 35-45.

United Nations, Department of Economic and Social Affairs, Population Division. 2018. World urbanization prospects: The 2018 revision. The World's Cities in 2018-Data Booklet (ST/ESA/ SER.A/417).

USACE. 2000. Hydrologic modeling system HEC-HMS technical reference manual. Hydrologic Engineering Center, Davis, CA.

Wada Y, Beek Ludovicus PH, van Kempen CM, *et al*. 2010. Global depletion of groundwater resources. Geophysical Research Letters, 37: L20402.

Wakode HB, Baier K, Jha R, *et al*. 2014. Assessment of impact of urbanization on groundwater resources using GIS techniques-case study of Hyderabad, India. International Journal of Environmental Research, 8(4): 1145-1158.

Walsh CJ, Roy AH, Feminella JW, *et al*. 2005. The urban stream syndrome: Current knowledge and the search for a cure. Journal of the North American Benthological Society, 24(3): 706-723.

WWAP (UNESCO World Water Assessment Programme), 2019. The United NationsWorld Water Development Report 2019: Leaving No One Behind. Paris: UNESCO.