Songklanakarin J. Sci. Technol.
45 (1), 51–58, Jan. – Feb. 2023

http://www.sjst.psu.ac.th

Original Article

Groundwater recharge in Mekong River Delta: An application of the water-table fluctuation method in the Long Xuyen Quadrangle and the Ca Mau Peninsula

Le Thi Thuy Van[1, 2*], Rungruang Lertsirivorakul[1], Bui Tran Vuong[3], and Chau Hong Thang[4]

[1] *Department of Geotechnology, Faculty of Technology,*
Khon Kaen University, Mueang, Khon Kaen, 40002 Thailand

[2] *Department of Geology, University of Science-Vietnam National University Ho Chi Minh City,*
Ho Chi Minh City, 700000 Vietnam

[3] *Division of Water Resources Planning and Investigation for the South of Vietnam, Ho Chi Minh City, 700000 Vietnam*

[4] *Faculty of Geography, University of Education, Ho Chi Minh City, 700000 Vietnam*

Received: 19 May 2022; Revised: 10 October 2022; Accepted: 29 November 2022

Abstract

Local groundwater recharge was determined using the Water Table Fluctuation method in the Long Xuyen Quadrangle and the Ca Mau Peninsula to refine existing estimates in a range of aquifer lithologies in light of climate change. The approach takes advantage of long term monthly water level records of Vietnam by Division of Water Resources Planning and Investigation for the South of Vietnam. An analysis of water levels in eight observation wells during four climatically distinct years (2005, 2009, 2013, and 2020) was used in combination with the monthly meteorological data. Groundwater recharge was estimated by the Water Table Fluctuation method to vary from 95.7 to 150.4 mm/year and account for 5.3 to 7.5% of the total rainfall. The estimates fall within the range of values used in regional-scale recharge models and demonstrate the potential of the Water Table Fluctuation method for resolving spatial and temporal variations of groundwater recharge.

Keywords: groundwater recharge, water-table fluctuation, climate change, Mekong River Delta

1. Introduction

Groundwater is an essential and valuable resource in the Mekong River Delta region (MRD) of southern Vietnam and supplies water to households, irrigation, aquaculture, and industrial purposes. Although surface water, such as rivers, lakes, and canals, is the main source of water for irrigation, greater irrigation demand during the dry season has resulted in increases in groundwater withdrawals (Boretti, 2022). As a result, groundwater levels and storage have decreased rapidly since 1991 (Minderhoud *et al.*, 2017). The exploitation of the uppermost, unconsolidated Holocene aquifer is limited by poor water quality, and the deeper aquifers provide most of the region's groundwater supply. As a result, the deep aquifers have been significantly impacted by over-pumping and declining water levels (Minderhoud *et al.*, 2017). The lower water levels cause serious problems such as seawater intrusion into the coastal aquifers (Le, Lertsirivorakul, Bui, & Schulmeister, 2020) and induce ground subsidence throughout the region (Erban, Gorelick, & Zebker, 2014). The ability of deep aquifers to repel or battle against seawater intrusion is affected by freshwater recharge to maintain positive hydraulic heads and prevent extension of the seawater mixing zone. Measurements of the shallow aquifer recharge are of value for

---

*Corresponding author
Email address: lttvan@kkumail.com

understanding the constraints in the deep aquifer's water budget models. The study supports not only protecting the shallow aquifer but also reducing salinity seepage into the underlying aquifers. Furthermore, it reveals a better understanding of the hydrogeologic conditions providing better quality and higher yields from the deeper aquifers. Finally, this will support successful development strategies for the protection and sustainable uses of local groundwater resources.

The main sources of recharge to the Holocene aquifer are percolation from rainwater and surface water of the river channels (Nguyen *et al.*, 2021). The region receives most of its abundant annual rainfall during the rainy monsoon season. With its dynamic rainfall amounts, interlacing drainage canals (Jenn, Hoang, Le, Pechstein, & Nguyen, 2017), and long coastlines (Figure 1), MRD is predicted to have a more complex recharge pattern than the inland parts of the country. Given the dry-season stress imposed on the aquifers by local agriculture and urban development, the calculation of groundwater recharge (GR) becomes even more meaningful in the current climate change context. The significant spatial heterogeneity in aquifer materials and dynamic regional climatic conditions make it difficult to estimate the vertical recharge used in groundwater models (Wagner, Bui, & Renaud, 2012).

Studies of GR in the region are quite limited and are typically regional in extent. Lacombe *et al.* (2017) established a regression model and GR map for the entire lower basin of the Mekong River and estimated a groundwater recharge rate (GRR) of 500 mm/year (Lacombe, Douangsavanh, Vongphachanh, & Pavelic, 2017). Bui *et al.* (2014) modeled recharge from 1999 to 2010 using the Water and Energy Transfer between Soil, Plants, and Atmosphere under Quasi Steady State model (WETSPASS), in which GR rate is a function of hydrometeorological data, including precipitation, potential evaporation, wind speed, temperature, groundwater depth, land use, slope, and topography and integrated them in a single study on a regional scale (Bui & Truong, 2014). The WETSPASS model calculated much lower recharge rates of the entire MRD than the Lacombe study, ranging from 140.0 to 157.8 mm/year. While these models are useful at the regional scale, they are less applicable on a local scale, since they do not take local geologic and climatic variabilities into account. In this study, an approach relies on a single groundwater well to evaluate local shallow GR using the Water Table Fluctuation (WTF) method.

The WTF method provides an estimate of GR by analysis of water level fluctuations in observation wells (United State Geological Survey, 2017). The method assumes that rising water levels in unconfined aquifers are a result of the vertical recharge (Gumuła-Kawęcka *et al.*, 2022; Healy & Cook, 2002). The WTF method is employed for estimating rainy-season recharge in spatial variation of both geologic and climatic conditions. It was conducted during four monitoring periods to determine recharge rates in the long term for the shallow unconfined aquifers in the LXQ and CMP in Vietnam and is based on four periods of water level and rainfall monitoring that reflect changing climatic conditions that have occurred in the region in recent years. The results are expected to contribute to the GR data input to groundwater flow modeling. Then, model simulations were used to predict seawater intrusion in the coastal aquifers in the MRD, which is also facing seawater intrusion problems due to overexploitation (Le *et al.*, 2020).

2. Background

Many methods have been used in previous studies to calculate GR. Examples of such methods are numerical modeling, using a program that simulates the effects of natural and artificial factors on GR, such as the WETSPASS model (Sahinkuye, Silungwe, Tarimo, & Kashaigili, 2022), Soil and Water Assessment Tool (SWAT) (Wolf, 2015), Soil and Water Assessment Tool-Groundwater Flow Model (SWAT-MODFLOW) (Chung, Kim, Lee, & Sophocleous, 2010), Hydrologic Evaluation of Landfill Performance (HELP) (Andaryani *et al.*, 2022), Rainfall Infiltration Breakthrough (Uribe *et al.*, 2015), regression model (Lacombe *et al.*, 2017) and Rainfall-Runoff Model (RRM) (Uribe *et al.*, 2015). In addition, there are other methods such as empirical methods: a direct method of measuring the GR from rainfall (Andualem, Demeke, Ahmed, Dar, & Yibeltal, 2021); Chloride Mass Balance method (CMB), based on the conservation of mass between atmospheric and subsurface Chloride contents (Segobaetso, Tafesse, Mapeo, & Laletsang, 2022); Isotope Method, which uses ^{2}H, ^{3}H, ^{18}O isotopes and some artificial radioactive isotopes suitable for research in evaluating the origin of water as well as the GR from rainwater and surface water (Hamed *et al.*, 2022). In general, all these require an accurate understanding of hydro-meteorology, land-use, and topographic features, and a level of computational complexity that cannot always be supported (Huet, Chesnaux, Boucher, & Poirier, 2016). The more accessible and well-established water table fluctuation can be used to calculate the GR at a much smaller scale and is a lower-cost alternative to the regional-scale methods (Lutz *et al.*, 2015). The method requires two basic input parameters: temporal groundwater head data and the aquifer's specific yield (S_y), to calculate the GR. The WTF method also has been used effectively in many different climatic regimes given the dependence of water level fluctuations on climatic conditions such as rainfall, evapotranspiration, atmospheric pressure, entrapped air, and temperature variations. Even when the precipitation is lower than evaporation, water level fluctuations can occur (Healy & Cook, 2002). With its tropical monsoon conditions, high seasonal rainfall, and evaporation events, MRD provides ideal conditions for evaluating the dynamic water level fluctuations that can occur in unconfined aquifers. Furthermore, a decrease in groundwater withdrawal activities in recent years due to the poor quality of the unconfined Holocene aquifer have eliminated water level fluctuations caused by pumping in monitoring wells. All the above conditions are acceptable for applying the WTF method to calculate GR in the study area. The WTF method also provides a potential alternative to more comprehensive models in a region where groundwater data are limited.

3. Materials and Methods

3.1 The study area

The uppermost unconfined Holocene aquifer exists at the near land surface throughout the Long Xuyen Quadrangle and the Ca Mau Peninsula (LXQ and CMP) (UTM 48N

440,000m E, 948,000m N and 645,000m E, 1,220,000m N), except for small mountainous regions in An Giang and Kien Giang provinces (Figure 1). The area is characterized by a tropical monsoon climate, with distinct annual rainy and dry seasons. The southwest monsoon prevails in the rainy season (from May to November), while in the dry season (from December to April in the following year) in the northeast monsoon is dominant (Japan International Cooperation Agency, 2013).

The complex geology of the Holocene aquifer is the result of migration of fluvial channels and historic coastline and is composed of sediments ranging from clay to medium sand. On average, the aquifer is approximately 89 m deep across the MRD region (Bui *et al.*, 2014).

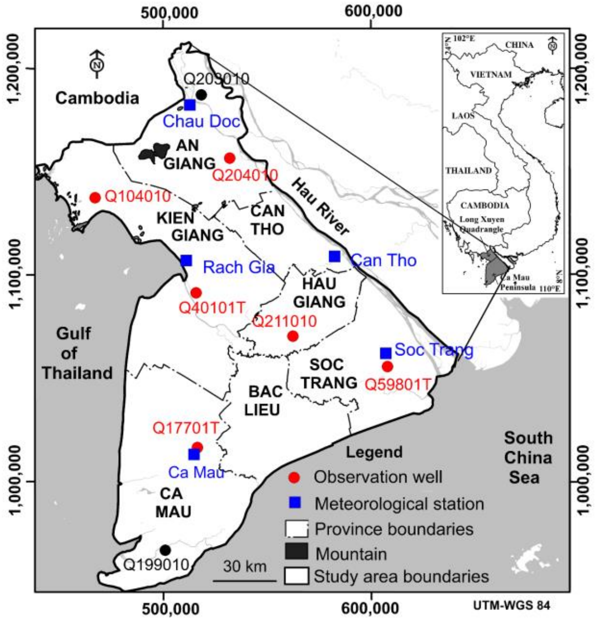

Figure 1. The locations of observation wells and meteorological stations

3.2 Wells and water level measurements

Eight study locations that belong to the national groundwater monitoring network of Vietnam were selected that represent both various sediment textures and different climatic conditions. Monitoring wells (identified with the labels Q104010, Q59801T, Q203010, Q40101T, Q17701T, Q199010, Q211010, Q204010) and water level data for each well were evaluated (Table 1). Drillhole logs for each well site were used to identify aquifer materials at each site (Table 2).

The WTF method requires a specific yield (S_y) for each site. The S_y is the volumetric ratio of the water that a saturated rock or soil will yield by gravity to the bulk volume of the rock or soil (Healy & Cook, 2002; Johnson, 1967). Given its limited use, few estimates of S_y have been made for the Holocene aquifer. S_y values, however, can be assigned for each site based on an empirical relationship between sediment texture and S_y established by Johnson (1967). The assigned S_y values range from 0.05 to 0.21 (Table 2) for the eight locations (Figure 3) examined.

3.3. Estimating Δh and recharge rate (R)

The WTF method calculates recharge rates, R, based on head observations in wells and estimates for specific yield as,

$$R(t_j) = S_y \times \Delta h \qquad (1)$$

where $R(t_j)$ [L] is recharge occurring between times t_0 and t_j [T], S_y is specific yield (dimensionless), and $\Delta h(t_j)$ is the peak water level rise attributed to the recharge period [L] (Figure 2). The value for Δh is determined by extending a declining water level trend line and measuring the head difference between the extrapolated line and the peak water level rise (Healy & Cook, 2002).

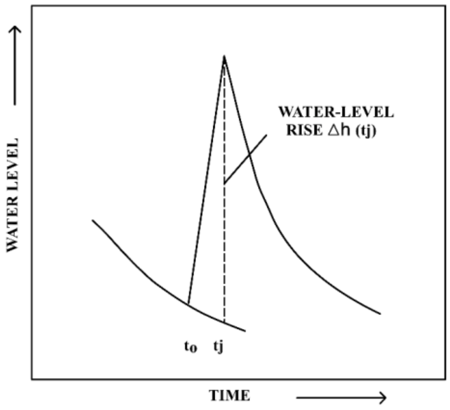

Figure 2. The estimation of water-level rise $\Delta h(t_j)$ (Healy & Cook, 2002; United State Geological Survey, 2017)

Table 1 Statistics of monthly groundwater head (m) in observation wells during the periods of 2005 (22 months), 2009 (22 months), 2013 (19 months), and 2020 (17 months) (DWRPIS, 2021)

n=80	Monthly groundwater elevation (m)								
	Q104010	Q40101T	Q59801T	Q211010	Q203010	Q20302T	Q204010	Q17701T	Q199010
Min	-2.45	-1.71	-3.02	-0.81	-4.09	-4.89	-4.28	-0.88	-1.02
Max	0.13	0.81	0.77	0.67	1.95	1.22	-0.34	1.18	1.12
Average	-1.26	-0.75	-1.19	-0.41	-2.83	-3.57	-2.62	-0.30	-0.45
SD	0.46	0.46	0.80	0.29	1.31	1.38	1.04	0.40	0.48

Table 2. Geologic logs for observation wells (DWRPIS, 2021)

Depth (m, bmsl)	Q104010	Q40101T	Q59801T	Q211010	Q203010	Q204010	Q17701T	Q199010
0 to 2	Sandy clay	Clay/Organic clay	Sandy clay	Silt	Silty clay	Silty clay	Silty clay	Clay/Organic clay
2 to 4	Sandy clay	Clay/Organic clay	Sandy clay[a]	Silt	Silty clay	Silty clay	Clay/Organic clay [a]	Clay/Organic clay
4 to 6	Sandy clay[a]	Clay/Organic clay[a]	Sandy clay	Silt[a]	Silty clay	Silty clay	Clay/Organic clay[a]	Clay/Organic clay [a]
6 to 8	Sandy clay[a]	Clay/Organic clay [a]	-	Silt[a]	Sandy clay[a]	Silty clay	Clay/Organic clay [a]	Clay/Organic clay [a]
8 to 10	-	Clay/Organic clay	-	Silt	Sandy clay[a]	Silty clay	Clay/Organic clay	Clay/Organic clay
10 to 15	-	-	-	-	Sandy clay	Silty clay	Clay/Organic clay	-
15 to 20	-	-	-	-	-	Silty clay	-	-
20 to 25	-	-	-	-	-	Fine sand[a]	-	-
25 to 33	-	-	-	-	-	Fine sand[a]	-	-
S_y^b	0.07	0.05	0.07	0.08	0.07	0.14	0.05	0.05

"-": no data; "a": observation well's screen depth; "b": assigned S_y values (Johnson 1967)

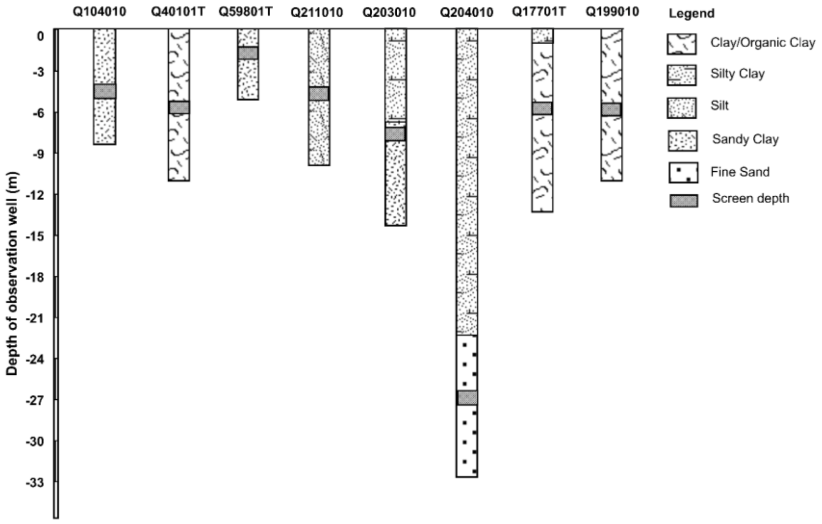

Figure 3. Holocene aquifer observation wells in the LXQ and CMP

S_y values used in WTF analysis may be obtained by several methods. Pumping tests are often used to determine S_y, but none was conducted for the Divison of Water Resources Planning and Investigation for the South of Vietnam (DWRPIS) wells. S_y may also be calculated by using an empirical equation based on the aquifer materials. Where aquifer materials vary with depth, a single S_y value should not be used to represent an entire aquifer (Healy & Cook, 2002). Therefore, empirical S_y values are best applied when the aquifer materials are relatively uniform with depth in the profile. When non-uniform textures occur with depth, if the thickness of the upper material is significant (as is for Q204010, Table 2), S_y value was assigned for the average material texture. In contrast, S_y is only assigned to the material type at the screen depth in wells Q203010 and Q17701T (Table 2). Aquifer materials at most of the well sites selected for this study are uniform with depth (Table 2) allowing us to assign a single empirical S_y value for each site.

3.4 Spatial and temporal GRR distribution maps

To represent the spatial and temporal distributions of GRR, its estimates at the eight-monitoring wells were transformed into maps using a Geographic Information System (GIS). Kriging interpolation method. This is an interpolation technique that weighs values of neighbor position and anticipates values for positions where no measurement was recorded (Bouhout, Haboubi, Zian, Elyoubi, & Elabdouni, 2022), interpolating the recharge distribution. With a sparse group of monitoring wells over a large area, the uncertainty in these interpolation maps is one of the limitations of this study. To verify their reliability, they are compared with the recharge rate calculation using the WETSPASS method (Bui & Truong, 2014). The results are presented in the discussion section.

4. Results

4.1 Determination of Δh

Groundwater levels were used to calculate Δh at eight locations for the years 2005, 2009, 2013, and 2020 (Table 3). The water depths ranged from -4.89 m to 1.95 m during the four years evaluated in all eight observation wells (Table 1) and varied across the study area. Water level trends were used to identify the amplitude of the groundwater level following the model in Figure 2 and the determination of Δh (Table 3).

4.2 Groundwater recharge rate (GRR)

The GRR ranged from 15.5 (at well Q199010 in Ca Mau province) to 283.5 mm/year (at well Q59801T in Soc Trang province) across the site in 2005 using the WTF method (Table 3). In 2009, R ranged from 19.5 (at well Q199010 in Ca Mau province) to 228.2 mm/year (at well Q59801T in Soc Trang province) (Table 3). In 2013, R ranged from 17.0 (at well Q199010 in Ca Mau province) to 189.0 mm/year (at well Q204010 in An Giang province) (Table 3). In 2020, R ranged from 33.5 (at well Q199010 in Ca Mau province) to 449.4 mm/year (at well Q204010 in An Giang province) (Table 3).

At wells Q40101T, Q17701T, and Q199010, aquifer materials are composed of clay materials or clay with high organic material content (Table 2). The S_y range is not given for this material in the classification of Johnson (1967). While the clay has a large porosity, its pore size is small and has a thin film water layer on the solid phase. In contrast, organic clay has a smaller porosity than clay, a larger pore size, and more organic materials. Hence, organic clay has a higher water release than clay. This would suggest a higher drainage capacity for organic clay than those for clay, but it has a smaller value when compared with silt. Therefore, the S_y value of 0.05, the mean value between clay and silt, was assigned to organic-rich clay (Johnson, 1967) (Table 2). The recharge rates at wells Q17701T (42.5, 37.0, 38.0, and 49.0 mm/year) and Q199010 (15.5, 19.5, 17.0, and 33.5 mm/year) are lower than those of Q40101T (91.0, 124.0, 146.0, and 94.0 mm/year in 2005, 2009, 2013, and 2020, respectively) (Table 2). Although the sediments at wells Q40101T, Q17701T, and Q199010 are mostly composed of organic clay, the water level fluctuation at well Q40101T is much higher than at Q17701T and Q199010 (Table 1). This leads to the difference in the recharge estimates above.

Table 3. Estimates of groundwater recharge rate (GRR), in mm/year, and % of recharge compared with total rainfall in 2005, 2009, 2013, and 2020

Periods	Stations	Rach Gia		Soc Trang	Hau Giang	Chau Doc		Ca Mau	
	Obs. wells	Q104010	Q40101T	Q59801T	Q211010	Q203010	Q204010	Q17701T	Q199010
	Materials	Sandy clay	Clay/ Organic Clay	Sandy clay	Silt	Sandy clay	Fine sand	Clay/ Organic Clay	Clay/ Organic Clay
	S_y	0.07	0.05	0.07	0.08	0.07	0.14	0.05	0.05
2005	Δh	2.71	1.82	4.05	0.6	2.83	1.69	0.85	0.31
2009		2.32	2.48	3.26	0.28	1.01	1.58	0.74	0.39
2013		2.05	2.92	1.22	0.37	1.67	1.35	0.76	0.34
2020		1.50	1.88	2.78	0.60	3.28	3.21	0.98	0.67
2005	GRR (mm)	189.7	91.0	283.5	48.0	198.1	236.6	42.5	15.5
2009		162.4	124.0	228.2	22.4	70.7	221.2	37.0	19.5
2013		143.5	146.0	85.4	29.6	116.9	189.0	38.0	17.0
2020		105.0	94.0	194.6	48.0	229.6	449.4	49.0	33.5
2005	% R from rainfall in rainy season	8.9	4.3	14.3	2.7	13.3	15.9	2.0	0.7
2009		9.0	6.9	14.9	1.7	8.8	27.5	2.0	1.0
2013		6.5	6.6	5.0	1.9	15.6	25.2	2.0	0.9
2020		3.9	3.5	11.2	3.1	16.7	32.7	2.2	1.5

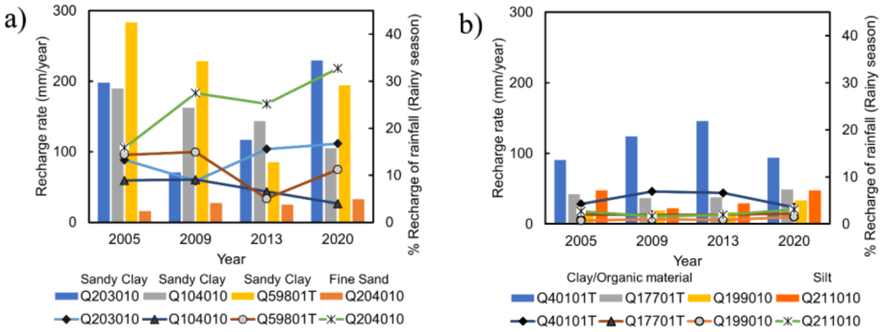

Figure 4. Recharge rates (columns) and % of rainfall in rainy season (lines) in different lithologies: (a) coarse grains, and (b) fine grains

4.3 GRRs and % recharge from rainwater

The % recharges due to rainfall ranged from 0.7% (well Q199010 in Ca Mau province) to 32.7% (well Q204010 in An Giang province) (Table 3) and the total GR in 2005 was 138.1 mm/year, accounting for 7.2% of average rainfall (Table 4). In 2009, it accounted from 1.0% (well Q199010) to 14.9% (well Q59801T) of rainfall in the rainy season (Table 3). The total recharge rate in 2009 was 110.7 mm/year, accounting for 6.0% of average rainfall (Table 4). In 2013, it accounted from 0.9% (Q199010) to 25.2% (Q204010 in An Giang province) of rainfall in the rainy season (Table 3). The total recharge rate in 2013 was 95.7 mm/year, accounting for 5.3% of average rainfall (Table 4). In 2020, it accounted from 1.5% (Q199010) to 32.7% (Q204010 in An Giang province) of rainfall in the rainy season (Table 3). The total recharge rate in 2013 was 150.4 mm/year, accounting for 7.5% of average rainfall (Table 4).

In general, the water level fluctuations follow those of rainfall amounts. The average GRRs are 138.1, 110.7, and 95.7 mm/year, which is consistent with the trend of changes in rainfall namely 1913.08, 1831.00, and 1800.91 mm/year in 2005, 2009, and 2013, respectively. This result is in agreement with the study by Dang *et al.*, 2020, which concluded that rainfall tended to decrease from 1999 to 2017. In this study, the rainfall data for 2020 had increased again (2013.70 mm/year). Along with that, the GR also increased (150.4 mm/year). It can be seen that GR is closely related to climate change conditions. Human efforts to control climate change will have a positive impact on the protection of groundwater resources.

4.4 Relationship between GRR and aquifer lithologies

The wells with coarse-grained sediments are expected to have higher porosity, and higher recharge rates than those at wells with fine-grained sediments. Specifically, for fine sand, the recharge rate varies from 189.0 to 449.4 mm/year (Q204010), while, for sandy clay (Q203010, Q104010, and Q59801T), values ranged from 70.7 to 283.5 mm/year in 2005, 2009, 2013, and 2020, respectively (Table 3, Figures 3, 4a). Conversely, the recharge rates of fine-grained materials such as silt and organic clay are below those of coarse-grained materials (Figure 3, 4b).

5. Discussion

To illustrate spatial and temporal variations, the estimated recharge rates were plotted as contour maps for the four years of study (Figure 5).

A high recharge rate (>250 mm/year) was observed in the northeastern and southeastern parts of the study area in 2005 (Figure. 5a) and then those areas disappeared in 2009, 2013, and expanded in 2020 especially in the northeast due to increased rainfall. In contrast, the coastal areas with the lowest recharge (<50 mm/year) in 2005 increased in size in 2009, 2013, and 2020. Low recharge conditions were primarily focused in the southwest part of the study area in 2005. It was likely to expand across most of the study area in the year 2013 that had the lowest rainfall. When the rainfall increased in 2020, these low recharge zones still reduced insignificantly. This result is consistent with the conclusion of Dang *et al.* (2020) who noted that rainfall was abundant on the western coast (Western Sea or Gulf of Thailand) and diminished gradually towards the eastern coast (Eastern Sea or South China Sea) and inland. Dang *et al.* (2020) also indicated a tendency for the rainy season to start earlier and end later in the western coastal zone of the study area, with season length gradually decreasing towards the Eastern Sea and inland. This relevant result implies that rainfall changes in the context of climate change are closely correlated with GR in the study area.

The northeastern part of the study area is a flood-prone area that undergoes extensive flooding between July and December every year (Nguyen *et al.*, 2021). Nguyen *et al.* (2021) mentioned that the potential of GR to shallow aquifers from surface water in flood-prone areas, where long-lasting and widespread inundations occur regularly, has been higher than in coastal zones. In 2020, when the rainfall developed, these flood zones showed the development of a high recharge rate that is around 250 to 400 mm/year (Figure 5d). This finding supports their observations of the higher GR estimates in the northeastern part than in the rest of the study area.

In addition, hydrochemical characteristics of the Holocene aquifer were observed to vary significantly between seasons of the year, and a close relationship between recharge rate and groundwater quality was concluded. Le *et al.* (2020) concluded that the unconfined Holocene aquifer was saline in most of the study area, except for the northeastern region, and that vertical GR is insufficient to prevent the seawater intrusion. Thus, it can be seen that if GR decreases due to decreased rainfall under the impact of climate change, the seawater intrusion into the coastal Holocene aquifer will become a more serious threat to groundwater quality in the future. The coastal area would likely be more greatly affected than the flood-prone inland areas, as GR from the rainfall declines more in coastal zones than in flood-prone areas (Figure 5).

Table 4. Comparison of the GR determined by WTF method and the DWRPIS model (Bui and Truong, 2014) in 2005 and 2009

Year	Average R (mm/year)		Difference of R (mm/year)	Average rainfall in the LXQ and CMP (mm)	% R of average rainfall in the LXQ and CMP
	The LXQ and CMP (WTF)	The MRD (WETSPASS)			
2005	138.1	157.8	19.7	1913.08	7.2
2009	110.7	140.0	29.3	1831.00	6.0
2013	95.7	-	-	1800.91	5.3
2020	150.4	-	-	2013.70	7.5

“-”: no data

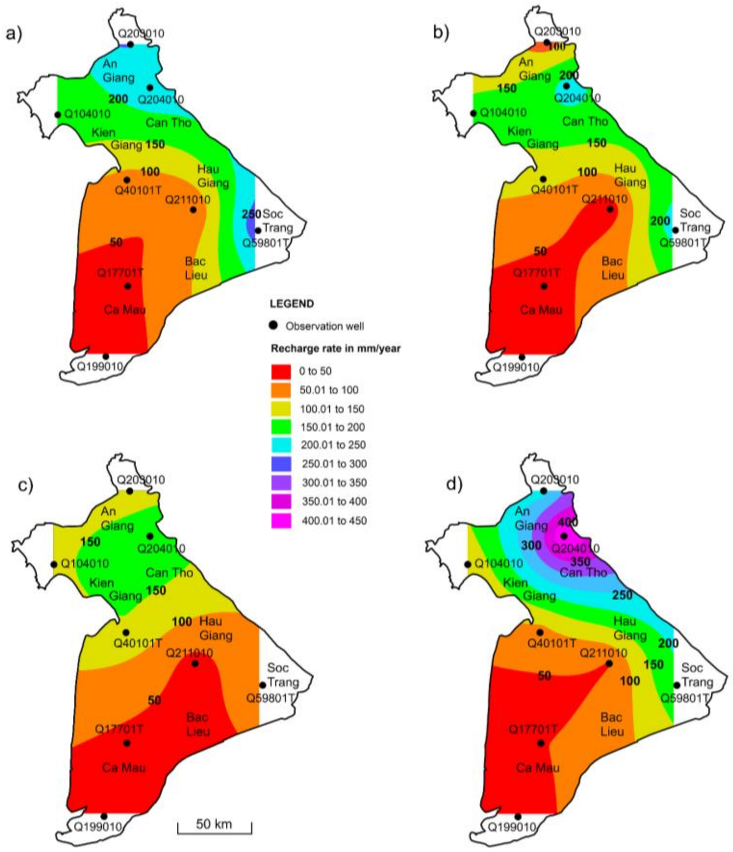

Figure 5. Annual recharge rates at eight locations in 2005 (a), 2009 (b), 2013 (c), and 2020 (d)

The cause of water level fluctuations is sometimes difficult to determine in areas with complex hydrogeological conditions or pumping activities. The assumption was made in this study that the groundwater withdrawals were negligible, but while the water levels at most of the monitoring wells are stable, the Q203010 and Q204010 wells in the An Giang province have had rapid decreases in water levels over four periods (Table 1). These water level data reflect the fact that the aquifer in the An Giang province yields good quality groundwater and is still being exploited. The accuracy of recharge estimates made in the An Giang province will be limited as long as significant pumping occurs. Although there are potential flaws in the application of the WTF method, its simplicity suggests that it is appropriate in certain situations and its use should be encouraged.

6. Conclusions

Annual GRRs were estimated by the WTF method ranging from 95.7 to 150.4 mm/year with 5.3 to 7.5% of the rainfall in recharge. Although the sediment textures of the uppermost Holocene aquifer vary widely across the study sites, temporal trends in GR appear to be primarily related to the rainfall amounts at all locations. Over study periods in which annual rainfall amounts declined, GRRs also declined. The outcome of this work contributes essential information on the need to develop a groundwater flow model for the region, used to predict the seawater intrusion into the coastal aquifer in the local areas, and to prevent long-term aquifer degradation.

Acknowledgements

This research was supported by the Khon Kaen University Scholarship for ASEAN and GMS Countries' Personnel of the Academic year 2016, the Faculty of Technology Scholarship of the Academic year 2016, and the Department of Geotechnology. The authors also extend special thanks to Professor Marcia K. Schulmeister for English revision, editors for their suggestions, and reviewers who greatly improved the paper.

References

Andaryani, S., Nourani, V., Pradhan, B., Jalali Ansarudi, T., Ershadfath, F., & Torabi Haghighi, A. (2022). Spatiotemporal evaluation of future groundwater recharge in arid and semi-arid regions under climate change scenarios. *Hydrological Sciences Journal, 67*(6), 979-995.

Andualem, T. G., Demeke, G. G., Ahmed, I., Dar, M. A., & Yibeltal, M. (2021). Groundwater recharge estimation using empirical methods from rainfall and streamflow records. *Journal of Hydrology: Regional Studies, 37*, 100917.

Boretti, A. (2022). A revised procedure to compute future land losses in the delta of the Mekong River. *Arabian Journal of Geosciences, 15*(17), 1-10.

Bouhout, S., Haboubi, K., Zian, A., Elyoubi, M. S., & Elabdouni, A. (2022). Evaluation of two linear kriging methods for piezometric levels interpolation and a framework for upgrading groundwater level monitoring network in Ghiss-Nekor plain, north-eastern Morocco. *Arabian Journal of Geosciences, 15*(10), 1-17.

Bui, T. V., Ngo, D. C., Le, H. N., Tran, V. B., Pham, N. L., & Pham, V. H. (2014). *Assessment of impacts of groundwater abstraction and climate change on groundwater resources in Mekong delta, Vietnam*. Vietnam: Divison of Water Resources Planning and Investigation for the South of Vietnam.

Bui, T. V., & Truong, C. T. (2014). *Calculating results of groundwater recharge in the Mekong River Delta, Vietnam*. Vietnam: Divison of Water Resources Planning and Investigation for the South of Vietnam.

Chung, I. M., Kim, N. W., Lee, J., & Sophocleous, M. (2010). Assessing distributed groundwater recharge rate using integrated surface water-groundwater modelling: application to Mihocheon watershed, South Korea. *Hydrogeology Journal, 18*(5), 1253-1264.

Erban, L. E., Gorelick, S. M., & Zebker, H. A. (2014). Groundwater extraction, land subsidence, and sea-level rise in the Mekong Delta, Vietnam. *Environmental Research Letters, 9*(8), 084010. doi:10.1088/1748-9326/9/8/084010

Gumuła-Kawęcka, A., Jaworska-Szulc, B., Szymkiewicz, A., Gorczewska-Langner, W., Pruszkowska-Caceres, M., Angulo-Jaramillo, R., & Šimůnek, J. (2022). Estimation of groundwater recharge in a shallow sandy aquifer using unsaturated zone modeling and water table fluctuation method. *Journal of Hydrology, 605*, 127283.

Hamed, Y., Hadji, R., Ncibi, K., Hamad, A., Ben Saad, A., Melki, A., . . . Mustafa, E. (2022). Modelling of potential groundwater artificial recharge in the transboundary Algero-Tunisian Basin (Tebessa-Gafsa): The application of stable isotopes and hydroinformatics tools. *Irrigation and Drainage, 71*(1), 137-156.

Healy, R. W., & Cook, P. G. (2002). Using groundwater levels to estimate recharge. *Hydrogeology Journal, 10*(1), 91-109.

Huet, M., Chesnaux, R., Boucher, M.-A., & Poirier, C. (2016). Comparing various approaches for assessing groundwater recharge at a regional scale in the Canadian Shield. *Hydrological Sciences Journal, 61*(12), 2267-2283.

Japan International Cooperation Agency, J. (2013). The project for climate change adaptation for sustainable agriculture and rural development in the coastal Mekong Delta in Vietnam (pp. 2-7). Sanyu consultants inc., Newjec inc., Japan: Southern institute of water resources planning, Ministry of agriculture and rural development, the government of socialist republic of Vietnam.

Jenn, F., Hoang, T. H., Le, H. N., Pechstein, A., & Nguyen, T. A. T. (2017). *Baseline Study Ca Mau - Review of studies on groundwater resources in Ca Mau Province* (pp. 1-98). Ha Noi, Vietnam: German Technical Cooperation with Vietnam - Improvement of Groundwater Protection in Vietnam.

Johnson, A. I. (1967). *Specific yield: Compilation of specific yields for various materials*: US Government Printing Office.

Lacombe, G., Douangsavanh, S., Vongphachanh, S., & Pavelic, P. (2017). Regional assessment of ground water recharge in the lower Mekong basin. *Hydrology, 4*(4), 60.

Le, T. T. V., Lertsirivorakul, R., Bui, T. V., & Schulmeister, M. K. (2020). An Application of HFE-D for Evaluating Sea Water Intrusion in Coastal Aquifers of Southern Vietnam. *Groundwater, 58*(6), 1012-1022. Retreived from https://doi.org/10.1111/gwat.13022

Lutz, A., Minyila, S., Saga, B., Diarra, S., Apambire, B., & Thomas, J. (2015). Fluctuation of groundwater levels and recharge patterns in Northern Ghana. *Climate, 3*(1), 1-15.

Minderhoud, P., Erkens, G., Pham, V., Bui, T. V., Erban, L., Kooi, H., & Stouthamer, E. (2017). Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. *Environmental Research Letters, 12*(6), 064006.

Nguyen, L. D., Nguyen, T. V. K., Nguyen, D. V., Tran, A. T., Nguyen, H. T., Heidbüchel, I., . . . Apel, H. (2021). Groundwater dynamics in the Vietnamese Mekong Delta: Trends, memory effects, and response times. *Journal of Hydrology: Regional Studies, 33*, 100746.

Sahinkuye, T., Silungwe, F., Tarimo, K., & Kashaigili, J. (2022). Evaluation of groundwater recharge dynamics using the wetspass model in the Usangu Plains, Tanzania. *Held at the SUA Edward Moringe Campus, Morogoro-Tanzania from 25th to 26th May 2021, 186*, 186.

Segobaetso, T. K., Tafesse, N. T., Mapeo, R., & Laletsang, K. (2022). Groundwater recharge using the chloride mass balance method in the Kanye area, in southeast Botswana. *Journal of African Earth Sciences*, 104534.

United State Geological Survey, U. (2017). Groundwater recharge. Retrieved from https://water.usgs.gov/ogw/gwrp/activities/gw_recharge.html

Uribe, J., Muñoz, J. F., Gironás, J., Oyarzún, R., Aguirre, E., & Aravena, R. (2015). Assessing groundwater recharge in an Andean closed basin using isotopic characterization and a rainfall-runoff model: Salar del Huasco basin, Chile. *Hydrogeology Journal, 23*(7), 1535-1551. doi:10.1007/s10040-015-1300-z

Wagner, F., Bui, T. V., & Renaud, F. G. (2012). Groundwater resources in the Mekong Delta: availability, utilization and risks *The Mekong Delta System* (pp. 201-220). Dordrecht: Springer.

Wolf, M. (2015). *Effects of land use change on groundwater recharge: A case study in the Day River Basin, Vietnam* (Master’s thesis, Utrecht University, Netherlands).