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Understanding Impacts of Groundwater Extraction on Flow Dynamics in Multi-aquifers of Ho Chi Minh City Area, Vietnam

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DOI: https://doi.org/10.14796/JWMM.S533

ABSTRACT

Understanding the dynamic characteristics of the groundwater flow budget is crucial for effective water management. This study investigates the groundwater budget in the Ho Chi Minh City (HCMC) area by the application of groundwater flow modeling. A 3D model was built to simulate groundwater flow in aquifer systems in Ho Chi Minh City, using extensive hydrogeological data from 400 borehole logs, along with climate, hydrological, and groundwater extraction data. The model was calibrated in both steady-state and transient conditions, with monthly data from 1995–2007, and then validated using five years of monthly groundwater level monitoring data from 2008–2012. In general, the calibrated and validated models show a good match between calculated and observed groundwater levels, with R^2 values > 0.8. The model results illustrate that recharge rates in HCMC vary according to local geological conditions and fluctuate seasonally due to changes in climate factors such as rainfall and evaporation. The annual recharge rate did not significantly change during 1995–2012. A groundwater depression cone was observed in the city center, with a maximum groundwater level approximately 50 meters below mean sea level (bmsl). Groundwater extraction increased sixfold from 1995–2012, which is the main cause of groundwater level decline. This study also found that the river system plays an important role in maintaining the groundwater balance in the area. As a result, increased groundwater exploitation has induced a fourfold rise in river leakage, while groundwater discharge to the river decreased by 35% during the same period. These changes potentially contribute to increased risks to groundwater quality, a reduction in base flow within the river system, and greater vulnerability of the natural ecosystem.

1. INTRODUCTION

Groundwater is an essential resource in nature because it can sustain ecosystems, maintains river base flows, and helps prevent land subsidence and seawater intrusion. More importantly, many people (~ 2.5 billion) globally are using groundwater as major drinking water sources

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Ha, Q-K., and S. Koontanakulvong. 2024. "Understanding Impacts of Groundwater Extraction on Flow Dynamics in Multi-aquifers in the Ho Chi Minh City Area, Vietnam." *Journal of Water Management Modeling* 32: S533 https://doi.org/10.14796/JWMM.S533 www.chijournal.org ISSN: 2292-6062 ©Ha and Koontanakulvong 2024.

(Grönwall and Danert 2020). Groundwater resources are also recognized as important factors for resilience of the urban area to climate change (La Vigna 2022). Groundwater resources are under increasing pressure to meet future fresh water demands due to population growth, urbanization, social-economic development, and climate change (Döll 2009; Kundzewicz et al. 2008). Poor management of groundwater exploitation such as inappropriate groundwater plans, excessive extraction can destroy the balance of groundwater flow and induce further environmental problems such as groundwater depletion, contamination, seawater intrusion (Jasechko et al. 2024), and land subsidence (Galloway and Burbey 2011; Molle and Closas 2020).

Groundwater flow modeling is recognized as a promising tool for improving groundwater planning and management, providing a comprehensive understanding of aquifer systems (Zhou and Li 2011; Anderson et al. 2015; Maskooni et al. 2024). Groundwater flow modeling can be used to delineate water flow pathways through aquifer systems and quantify the contribution of various water sources for water balance such as recharge, leakage from river, discharge to river, and impact of groundwater extraction. Modeling can also predict future groundwater levels, as well as the movement of contamination sources. Understanding the groundwater budget and groundwater flow pathways are crucial for development of a groundwater use plan and sustainable groundwater management (Zhou 2009; Sophocleous 2002; Freeze and Cherry 1979). Therefore, groundwater modeling is widely applied in managing this critical resource (Anderson et al. 2015; Maskooni et al. 2024; Taweesin et al. 2018). However, groundwater flow models have various uncertainties, stemming from a lack of background data and incorrect conceptualization of the hydrogeological system. Collection of more data is always suggested as the strategy for improving the accuracy of groundwater model results (Anderson et al. 2015; Maskooni et al. 2024)

Ho Chi Minh City is the most rapidly developing city in Vietnam. Groundwater is a crucial resource for water supply in the area providing ~40% of total water used for drinking and industrial purposes in 2012 (Vuong and Long 2016). However, groundwater resources in the area are also facing significant challenges such as declining groundwater levels, salinization, contamination, and land subsidence (Minh et al. 2015; Ha et al. 2019). Ha et al. (2022) indicated that groundwater quality in recharge areas is susceptible to anthropogenic sources, leading to high NO_3 concentrations and low pH in shallow groundwater. Subsequently, shallow groundwater is contaminated by the high concentration of trace metals. Ngo et al. (2015) suggested that over-extraction of groundwater and urbanization are responsible for groundwater contamination and salinization. The decline in groundwater levels has also contributed to land subsidence in the area. Several studies also applied groundwater modeling in the areas. For example, Tran and Koontanakulvong (2020) and Pham and Koontanakulvong (2018) applied groundwater modeling for the estimation of groundwater and river water interaction. Tran and Koontanakulvong (2020) simulated groundwater flow budgets in the HCMC area; however, the study focused on only 4 aquifers and was calibrated using limited monitoring wells (n=23). Pham and Koontanakulvong (2018) simulated groundwater in the Sai Gon River interactions, concentrating on three main shallow aquifers.

This study aims to provide a thorough understanding of the groundwater level distribution and the flow dynamics under impacts of groundwater extraction in the HCMC area. The study gathered a large dataset of 400 borehole logs, 49 monitoring wells, 18 climate stations, and 8 water level stations in the area. The groundwater flow model was applied to simulate groundwater levels and the flow budget in 5 main aquifers. The models were calibrated and validated with large observation data and thus, the results may provide comprehensive information on groundwater systems in the area. The model can be used for the further application of groundwater plans and development in the HCMC area.

2. STUDY AREA

HCMC is a megacity of Vietnam, covering an area of 2095 km^2 (Figure 1). The city's population grew from 6.2 million in 2005, to 7.7 million in 2012, and 9.3 million in 2022. The topography of HCMC ranges from 0 to 30 meters above sea level. The area experiences a monsoon climate with two distinct seasons: the rainy season from May to November, and the dry season from December to April. Annual precipitation is approximately 1,900 mm, with mean temperatures ranging from 27.5°C in September to 29.5°C in March (GSO 2016). Land use patterns in the area have rapidly changed, and the urban areas expanded 4.8-fold from 1990 to 2012, because of economic development and urbanization (Nguyen et al. 2016; Son et al. 2017; Kontgis et al. 2014).

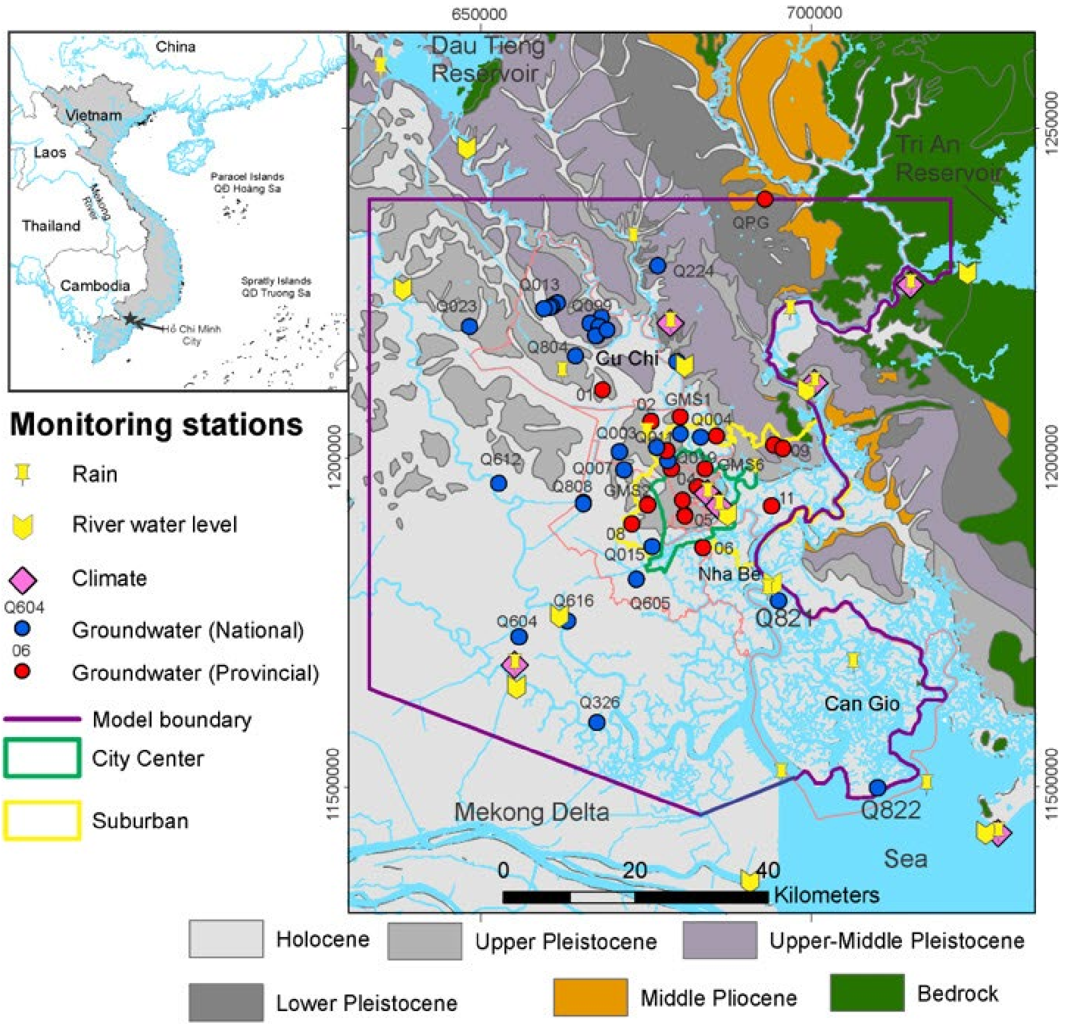

Figure 1 Location of Ho Chi Minh City, model boundary, rain, river water, climate, and groundwater monitoring station plotted on hydrogeological map.

HCMC has two main river systems running through it: the Dong Nai River system and the Saigon River system. The Dong Nai River originates from the Lang Biang Plateau at an altitude of 1,777 m, with a basin area of 45,000 km^2, and annually provides 15 billion m^3 of water. On the Dong Nai River, there is the Tri An Lake, constructed in 1986, with a capacity of 2.542 billion m^3. The Saigon River is 201 km long, originating from Cambodia, with a basin area of 1,700 km^2 up to Dau Tieng Lake. This river is also a source of freshwater for domestic use and irrigation in Ho Chi Minh City. Dau Tieng Lake has a capacity of 1.45 billion m^3. HCMC has nearly 100 km of coastline, with an irregular semi-diurnal tide regime. In one month, there are two high tides and two low tides. Throughout the year, peak tides occur in December and January, and reach their lowest levels in June and July, with a difference of about 0.5 m. The tidal amplitude during the dry season (March and April) is around 2.5 to 3 m. On the Dong Nai River, tidal influence extends nearly 200 km upstream from the river mouth. The impact of tides directly affects the water levels of rivers and canals, causing reverse flow and leading to saltwater intrusion deep inland, salinizing the groundwater layers in coastal areas (SVGMD 2004).

The geology is characterized by thick layers (~ 300 m) of unconsolidated sediments. The sediments were deposited in the areas during Miocene to Holocene periods, overlying Mesozoic to Paleozoic bedrocks (SVGMD 2004). The Holocene sediment, rich clay and organic matter, are distributed along rivers and low elevation areas (<2 m). On the land surface, the Pleistocene sediments are also observed in the area where elevation is generally greater than 2 m and are composed of highly permeable materials, such as fine to coarse sand and some lateritic gravel. These Pleistocene outcrops are identified as recharge zones for the region's aquifer systems (Ha et al. 2019).

Water is used for irrigation, industrial, and domestic purposes. Irrigation water is sourced from groundwater, as well as primarily from the Saigon and Vam Co Dong River systems, and partly from the Dau Tieng Reservoir via artificial canals. Water for domestic and industrial use is drawn from surface water, with 40% of the supply coming from groundwater (Vuong and Long 2016; Ngo et al. 2015). The main aquifers supplying groundwater in the study area are the Middle-Upper Pleistocene aquifers ($qp^{2,3}$) and the underlying Middle Pliocene aquifer (n_2^2) (Vuong and Long 2016).

Climate change, sea level rise, and anthropogenic activities such as urbanization, annuitization, and agriculture are threatening the surface water quality in Ho Chi Minh City. In the city center the river water quality is generally poor in high in nutrients such as NH_4, PO_4, coliform, and trace metals. However, in the lower gradient area of the river system, water becomes salinized and cannot be used for drinking (Nguyen et al. 2021; Nguyen et al. 2019). Groundwater in higher elevation areas is acidic, with high NO_3, *Al* concentrations. But in low land areas, groundwater is contaminated by *Fe, Mn* and salinity (Ha et al. 2019; 2022; Ngo et al. 2015). Over extraction of groundwater induces salinization in the coastal area, while anthropogenic sources are the main cause of groundwater quality deterioration in the high-altitude area (Ha et al. 2022).

3. METHOD

Groundwater flow modeling in this study is conducted in various steps, including data collection, conceptual model development, calibration, and validation (Figure 2).

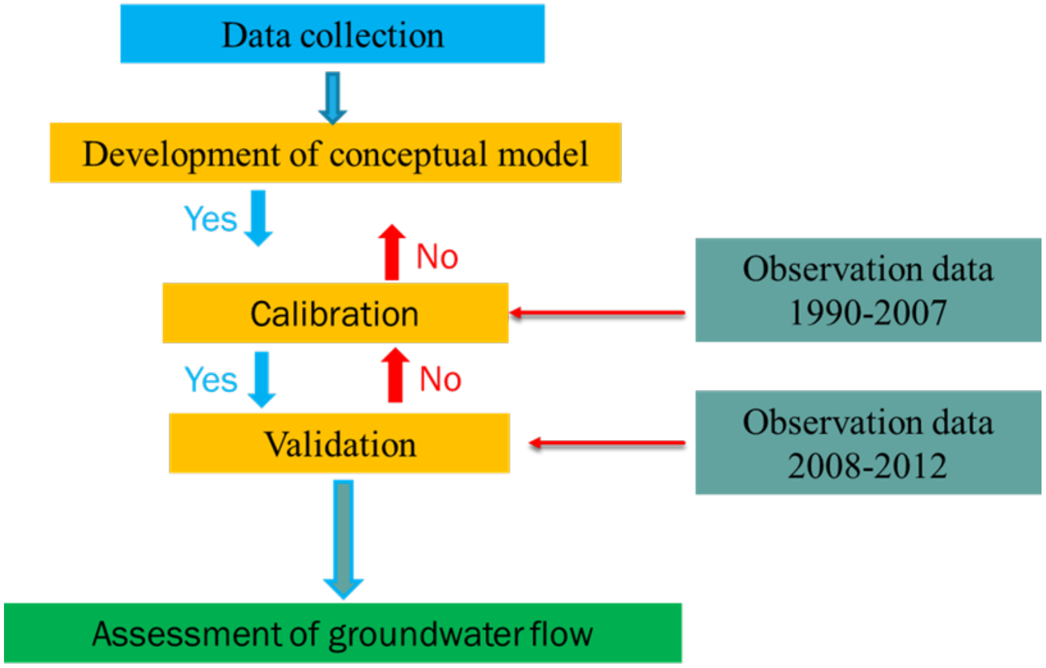

Figure 2 Flow chart of the study methods.

3.1 Data collection

This study collected a large dataset including a hydrogeological map scale 1:500 000 for the Southern Vietnam Plain, 400 well logging records, and pumping test results (hydraulic conductivities, aquifer thickness, specific storage) of 98 wells from previous studies by the Division for Water Resources Planning and Investigation for the south of Vietnam (Table 1). Monthly surface water levels from eight stations along major rivers, including the Saigon, Dong Nai, Vam Co Dong, and Vam Co Tay, were recorded between 1980 and 2012. Climate data, such as daily rainfall, temperature, and evaporation, were collected from 18 climate stations over the same period (Figure 1). The monthly groundwater levels from 1995–2012 were retrieved from 45 and 28 wells of the National Monitoring Network and the groundwater monitoring network of HCMC and Binh Duong province, respectively. Groundwater extraction data including extraction rate, operation time, and well depths were collected from the DONRE database and previous studies by DWRPIS. All data were checked for missing or abnormal values before being used.

Table 1 Data collection and sources for this study.

Data	Extraction information	Sources
Hydrogeological map scale 1: 500 000 for Southern Vietnam Plain	Distribution of aquifers	Division for Water Resources Planning and Investigation for the south of Vietnam
400 Well logging	Top, bottom and lithology of aquitard, and aquifer	
98 pumping test results	Hydraulic conductivity, Specific storage	
38 monitoring wells from National Groundwater Monitoring Network	Water level during 1995–2012	
11 monitoring wells from Groundwater Monitoring Network in HCMC and Binh Duong province	Water level during 2000–2012	Ho Chi Minh City Department of Environment and Natural Resources. Binh Duong Department of Environment and Natural Resources.
08 Surface water monitoring	Water level during 1980–2012	Southern Regional Hydrometeorological Center
18 climate stations	Rainfall, temperature, and evaporation 1980–2012	Southern Regional Hydrometeorological Center

3.2 Model development

After collection, the data is prepared for groundwater flow modeling. Three-dimensional finite difference numerical models of the HCMC area's aquifers were conducted using the MODFLOW 2005 code of USGS. The program is useful and widely used over the world to understand groundwater flow and groundwater balance in various scales (Harbaugh 2005). The input parameters for the flow model include hydrological strata and characteristics, boundary conditions, recharge flux, river water level, and conductance coefficients, etc.

Groundwater system

According to a previous report from a local agency (SVGMD 2004), the aquifer systems in HCMC are divided into 7 main layers, including the formation of Holocene (*qh*), upper Pleistocene (qp^3), upper-middle Pleistocene ($qp^{2,3}$), lower Pleistocene (qp^1), middle Pliocene (n_2^2), lower Pliocene sediment (n_2^1). Each layer comprises an aquifer and aquitard. To build the 3D hydrogeological strata (Figure 3), 400 well logging data provided an in-depth understanding of the hydrogeological architectures of the aquifer system below the study area. Based on the well logging information, the elevation of top and bottom layers is interpolated by inverting the distance weight method. The model domain covers about 4000 km^2, divided into 800 x 800 m grids and 11 layers. Layer 1 represents the clay layer of Holocene sediment and the upper Pleistocene sediment. Layer 2 represents the qp^3, layers 3 and 4 represent the $qp^{2,3}$ confining unit and aquifer, respectively. Layers 5 and 6 represent the qp^1 confining unit and aquifer. Layers 7 and 8 represent the n_2^2 confining unit and aquifer. Layers 9 and10 represent the n_2^1 confining unit and aquifer, and Layer 11 represents the bedrock.

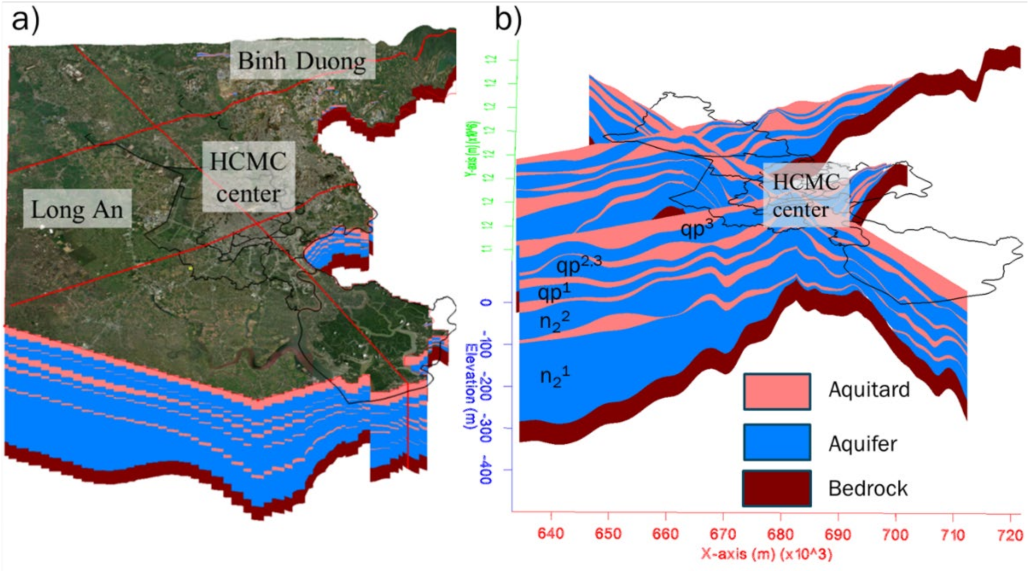

Figure 3 3D view of the (a) constructed model, and (b) the cross-sections of the model.

Boundary condition

HCMC is in the downstream area of the Dong Nai River system and adjacent to the Mekong Delta (Figure 1). The aquifer system in HCMC is connected to the Mekong Delta aquifer system (Figure 3). It is not possible to extend the model boundary to cover the entire Dong Nai River Basin, and for the Mekong Delta to reach the physical boundary of the aquifer system. Therefore, the model uses the Dong Nai River as the boundary from the east, and Vam Co Tay River as the boundary in the southwest. Arbitrary boundaries were selected for the western and northern parts (Figure 4). These boundaries were placed sufficiently far from HCMC to avoid influencing the groundwater modeling results. The specific head and general head are assigned as boundaries conditions of the model (Figure 4). The water levels of the boundaries are interpolated from nearby monitoring wells, which recorded groundwater levels from 1995–2012.

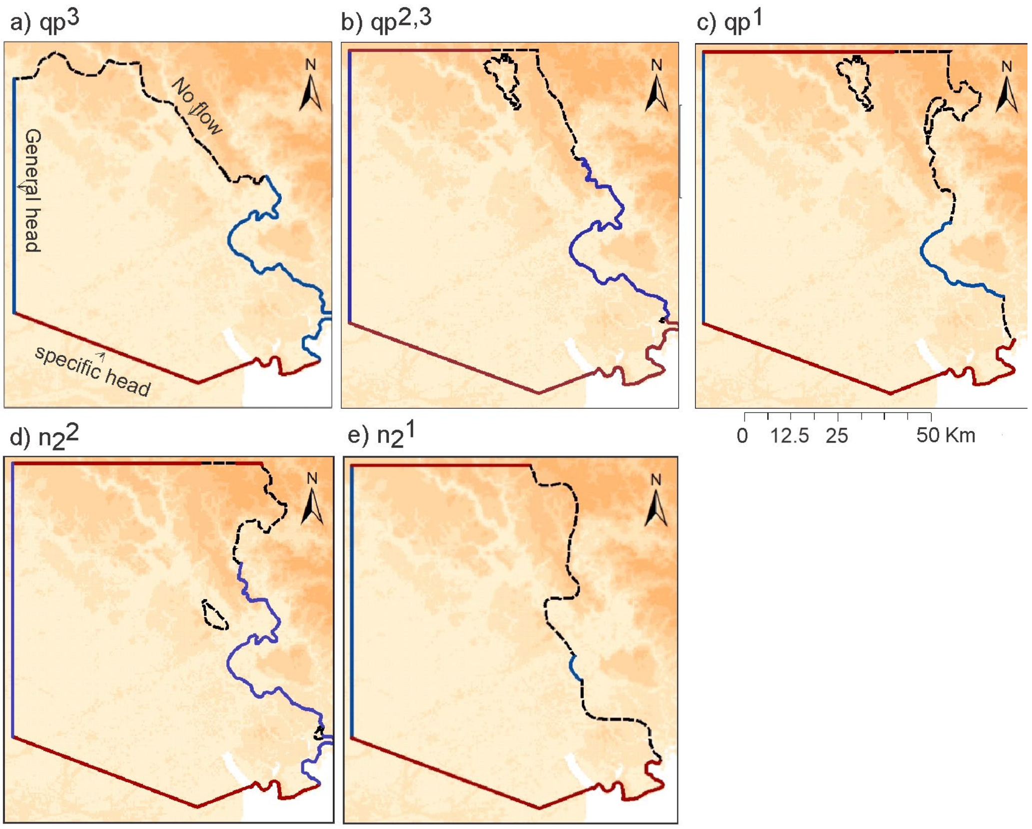

Figure 4 Boundary conditions of aquifers 1,2,3,4, and 5 which stand for qp^3, $qp^{2,3}$, qp^1, n_2^2, and n_2^1 aquifers, respectively.

River boundary

River boundaries are also assigned for the main rivers in the area. River water level data from 1995–2012 are collected from the Southern Regional Hydrometeorology Center. Eight river stations are located within the study area, as shown in Figure 1.

Recharge rate

The recharge (RCH) package (Harbaugh 2005) is used to simulate recharge to the groundwater system. Recharge applied to the model is defined as:

$$Q_R = R*DELR*DELC \tag{1}$$

Where:

Q_R = recharge flow rate applied to the model at the horizontal cell and expressed as fluid volume per unit time (m^3/day),
R = recharge flux (m/day), and
$DELR*DELC$ = cell area.

In this study, the initial recharge map was created based on the Southern Vietnam Plain hydrogeological map with a scale of 1:500 000, collected from the Division for Water Resources Planning and Investigation for the south of Vietnam (SVGMD 2004) (Table 1). The high permeability sediment areas will be assigned more recharge fluxes. The initial recharge rates in each zone were assumed to be a function of effective rainfall:

$$R = aX+b \tag{2}$$

Where:

R = recharge flux (m/day),
X = effective rainfall (m/day), and
a, b = coefficients of each recharge zone. Will be adjusted during calibration of groundwater model (Figure 5).

Effective rainfall is defined as the difference between total rainfall and actual evapotranspiration:

$$X = P - ET \tag{3}$$

Where:

P = average daily rainfall for each river basin and calculated based on Thiessen polygon method (m/day), and
ET = average daily evapotranspiration (m/day).

The assumptions were also used in a previous study in Thailand (Suthidhummajit and Koontanakulvong 2018), and HCMC (Ha and Koontanakulvong 2015), and provided reasonable results of groundwater flow modeling.

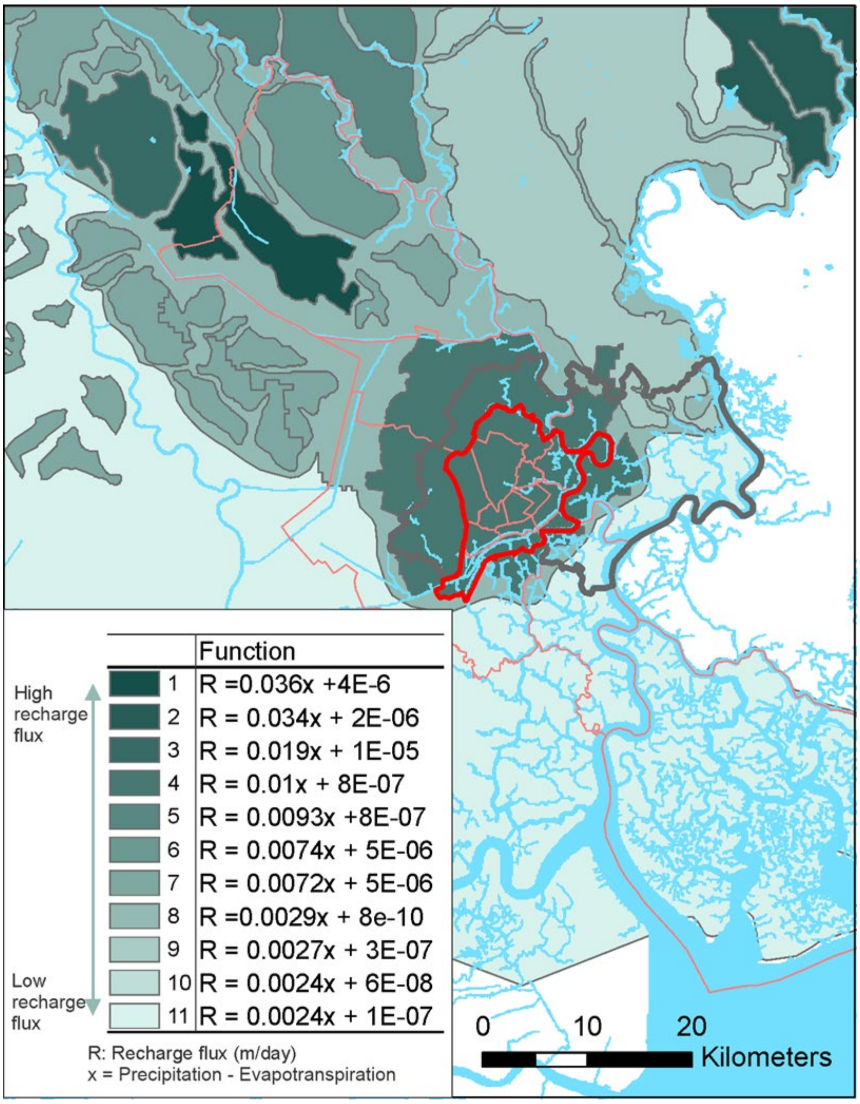

Figure 5 Groundwater recharge flux as function of effective rainfall (precipitation – evapotranspiration).

Aquifer parameters

Initial aquifer parameters such as hydraulic conductivity (*K*), specific storage (*Ss*), and specific yield (*u*) were assigned to the model based on 98 pumping test data collected from Division for Water Resources Planning and Investigation for the South of Vietnam (Table 2). The hydraulic conductivities of qp^3, $qp^{2,3}$, qp^1, n_2^2, n_2^1, and n_1^3 are in the range of 1.6–54.7 m/day (mean 14.8), 1.7–56.2 m/day (mean 14.4), 0.9–44 m/day (mean 12.3), 0.7–29.0 m/day (mean 11.6), 1.4–26.7 m/day (mean 7.4), and 3.0–8.1 m/day (mean 5.6), respectively. The specific storage of qp^3, $qp^{2,3}$, qp^1, and n_2^2 aquifers range respectively from 0.00019 to 0.0028 with mean values of 0.00597, from 0.00012 to 0.0111 with mean values of 0.00276, from 0.00049 to 0.00361 with mean values of 0.00117, and from 0.00001 to 0.00072 with mean values of 0.00037. Only one pumping test was conducted in the n_2^1 and provided the specific value of 0.00315. Values of vertical hydraulic conductivities are assumed as one-tenth of the horizontal hydraulic conductivity values. The hydrogeological parameters were adjusted during calibration.

Table 2 Thickness, hydraulic conductivity, and specific storage in multi-aquifers of Ho Chi Minh City.

Aquifer	Thickness (m)				Hydraulic conductivity (*K*, m/day)				Specific storage (m^{-1})			
	N	Mean	Max	Min	N	Mean	Max	Min	N	Mean	Max	Min
qp^3	18	21.3	46.5	7.6	18	14.8	54.7	1.6	13	0.00597	0.02810	0.00019
$qp^{2,3}$	23	33.5	65.0	10.0	23	14.4	56.2	1.7	8	0.00276	0.01110	0.00012
qp^1	23	32.7	63.9	8.0	23	12.3	44.0	0.9	5	0.00117	0.00361	0.00049
n_2^2	21	44.1	70.8	20.5	20	11.6	29.0	0.7	2	0.00037	0.00072	0.00001
n_2^1	12	44.5	80.1	4.2	12	7.4	26.7	1.4	1	0.00315	0.00315	0.00315
n_1^3	2	44.3	53.4	35.1	2	5.6	8.1	3.0				

Groundwater abstraction

To simulate groundwater extraction in this study (Figure 6), data on the location and extraction rates of wells in HCMC, Binh Duong, and the Long An provinces were collected from the Division for Water Resources Planning and Investigation for the South of Vietnam (DWRPIS) and the Ho Chi Minh City Department of Natural Resources and Environment (DONRE). In the area, groundwater is extracted using 3 main techniques, including dug wells, private wells, and industrial wells. The dug well was installed by digging several meters to collected water in the shallowest part. The private wells are household wells that are installed by uncontrolled techniques. Normally, the private wells and dug wells can extract a small amount (<10 m^3/day) of groundwater daily that supplies one or two family's demands and can sometimes be used for irrigation of several thousand m^2. The industrial wells are used for water supply plants or industry and can provide more than 200 m^3/day to thousand m^3/day. In 1999, HCMC had about 95 000 private wells, and increased to 260 000 private wells in 2008. According to the survey in 2012, the total private wells are about 342 657 m^3/day. Cu Chi district had the highest number of private wells (>100 000 wells), following Hoc Mon, District 12, and Binh Chanh. Generally, the suburban areas have more private wells due to a lack of water supply systems. The private wells mainly extracted (96.4% of the total wells) water from the qp^3 and $qp^{2,3}$ aquifers. Total industrial wells are about 2800 wells. The industrial wells are normally installed in deep aquifers like $qp^{2,3}$, qp^1, n_2^2, and even n_2^1. According to the DWRPIS data, the total groundwater extraction rate in HCMC was 360,000 in 1995 and increased about 54,000 m^3/day/year, until 1999. According to recorded data from 2004 to 2009, the Department of Natural Resources and Environment (DONRE) of HCMC issued new and renewed groundwater extraction licenses for about 300 000 and 410 000 m^3/day during the 2004–2007 and 2007–2012 periods, respectively. The extraction rate of groundwater in HCMC increased to 720 000 m^3/day in 2010 and remained stable until 2012. In Long An Province, the groundwater extraction rate was about 200 000 m^3/day in 2010 and increased at a rate of about 50 000 m^3/day/year. According to the data from the Binh Duong DONRE, from 1997 to 2012, the province approved 1227 licenses for groundwater extraction with total rate of 190 000 m^3/day.

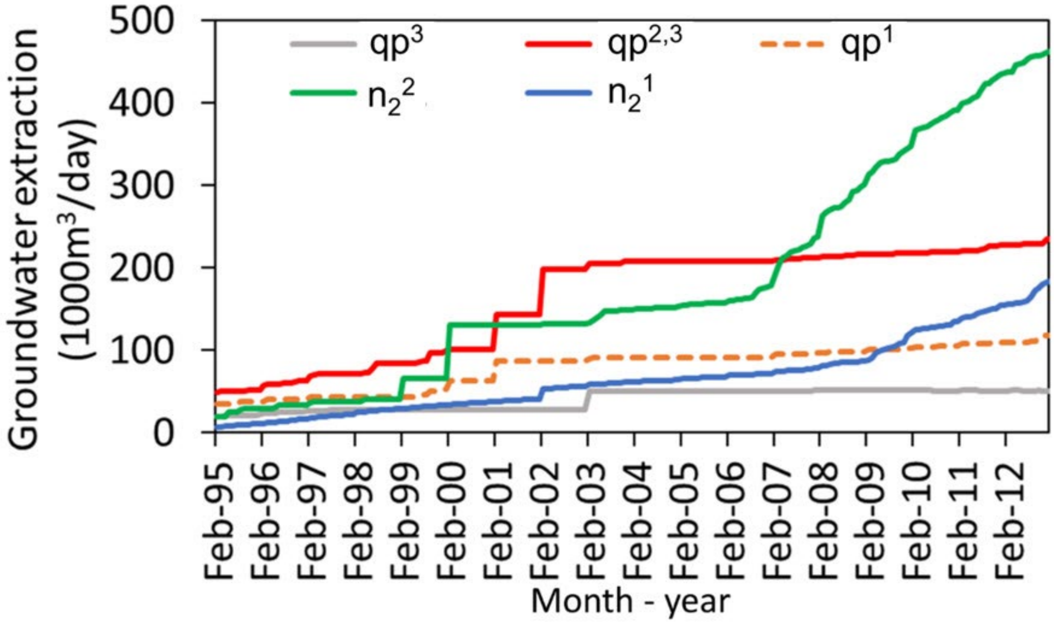

Figure 6 Groundwater extraction rate in qp^3, $qp^{2,3}$, qp^1, n_2^2, and n_2^1 aquifers

3.3 Model calibration and validation

Model calibration involves adjusting unknown hydrogeological parameters to minimize the discrepancy between observed and modeled groundwater levels (Anderson et al. 2015). Calibration can be done in steady state and transient conditions. In the steady state condition, calibration only adjusts the boundary conditions, hydraulic conductivities, and recharge rate. Calibration in the steady state condition can provide a basic understanding on groundwater flow in the area (Anderson et al. 2015). In this study, researchers conducted steady-state models for the years 1995 and 2007.

Transient simulations were conducted over a twelve-year period (1995–2007) with monthly time steps (total 144 steps). The model was calibrated iteratively by modifying independent hydraulic properties, recharge rate, and taking note of the model error between observed and simulated hydraulic heads from observation wells, and their locations within the modeling domain. The model error is quantified by calculating mean error (*ME*; Equation 4) and root mean square error (*RMSE*; Equation 5) and R^2 value of linear regression analysis.

$$ME = 1/N \sum_{i=1}^{N}(O_i - M_i) \qquad (4)$$

$$RMSE = \sqrt{1/N \sum_{i=1}^{N}(O_i - M_i)^2} \qquad (5)$$

Where:

O = Observation groundwater levels, and
M = Modeled groundwater levels.

Verification was conducted to validate the model results, with simulations run in monthly steps from January 2008 to December 2012 to assess the realism of the calibrated model. For the verification process, the groundwater flow model parameters were kept the same as in the calibrated model to evaluate the realism of the groundwater model. The R^2, *ME,* and *RMSE* were also calculated to evaluate the validated model.

4. RESULTS AND DISCUSSION

4.1 Calibration and validation

The calibrated steady-state model demonstrated a good matching ($R^2 = 0.84$) between observed and calculated data. The average residual errors (*ME*) were approximately 0.21 m for the 1995 simulation and 0.53 m for the 2007 simulation. The root mean squared error (*RMSE*) was 1.58 m and 2.13 m for the simulation in 1995 and 2007, respectively.

The mean groundwater level in the transient model also showed a good match between observed and modeled data (Figure 7; Table S1). The mean *RMSE* values were 1.2, 1.6, 1.8, 2.4, and 1.3 m for qp^3, $qp^{2,3}$, qp^1, n_2^2, and n_2^1 aquifers, respectively. The relationship between observed and modeled groundwater level also shows R^2 values of 0.93, 0.9, 0.95, 0.95, and 0.8 for qp^3, $qp^{2,3}$, qp^1, n_2^2, and n_2^1 aquifers, respectively.

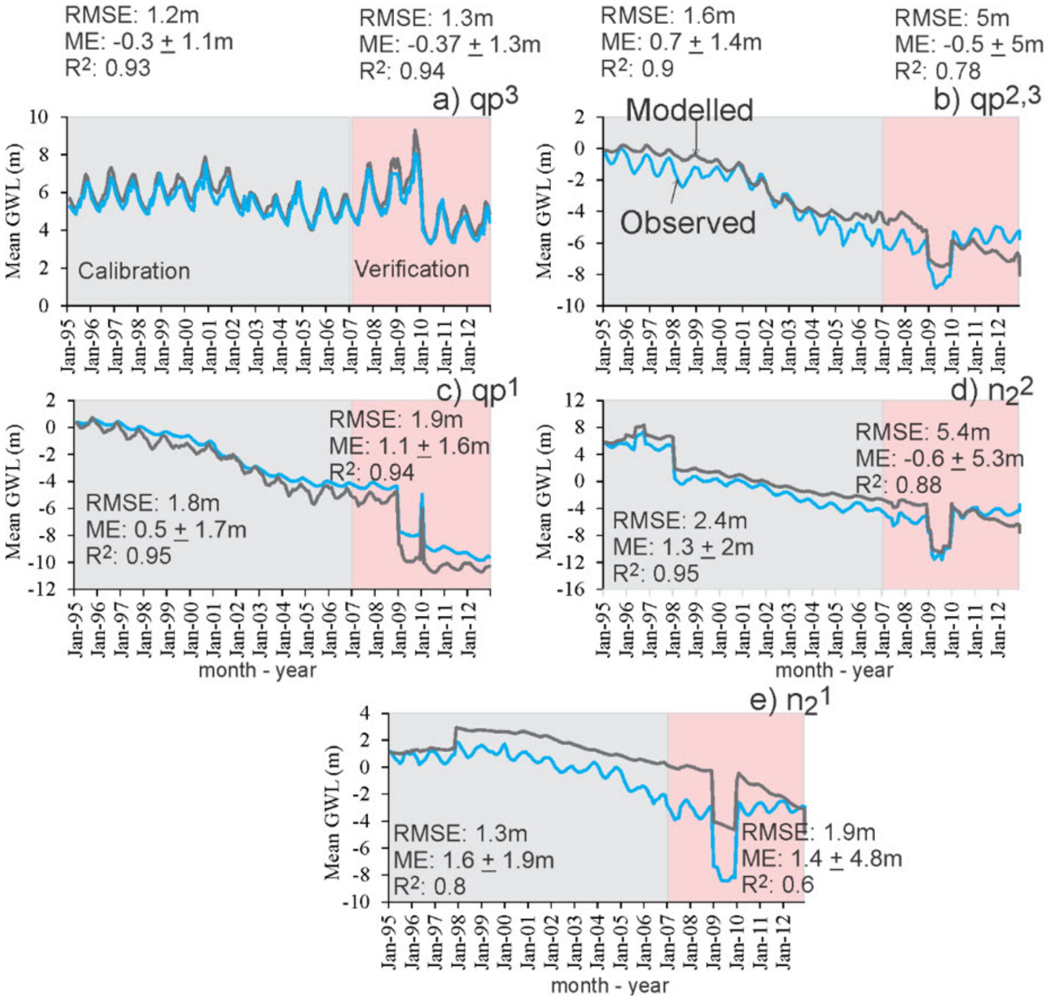

Figure 7 Transient calibration and verification results for qp^3, qp^{2,3}, qp^1, n$_2^2$, and n$_2^1$ aquifers.

Model verification results showed *RMSE* values ranging from 1.3 to 5.4 m, mean error values ranging from -0.4 ±1.3 to 1.4 ± 4.8 m, and the correlation values (R^2) from 0.6 to 0.94 (Figure 7; Table S2). The aquifer qp^3 exhibited the best match between observation and simulation results. The deepest aquifer, n$_2^1$, generally showed modeled groundwater levels that were higher than the observed data. The qp^{2,3} and n$_2^2$ aquifers also displayed similar trends. The modeled groundwater level in qp^1 is generally lower than those observed in the monitoring wells.

Achieving a perfect fit between simulated and observed groundwater levels is challenging due to the complexity of natural systems. Errors can come from various sources, such as the model being too simplified, the complexity of aquifer systems, inaccuracies in the groundwater extraction rate, and insufficient hydrogeological data, including hydraulic conductivities, specific storage, recharge rates, and river conductance. Although the calibrated models have some errors in comparison to monitoring data, they are acceptable for simulating the groundwater flowing systems in the area.

4.2 Groundwater levels

Groundwater levels in the area were generally shallow in depth during 1995 and have declined over time (Figure 7). The groundwater model results also provided the spatial distribution of groundwater levels across different aquifers in the area. For example, groundwater levels in April 2012 varied from 11 to -19 mamsl (meters above mean sea level), 34–50 mamsl, from 38–

49 mamsl, from 46–42 mamsl, and 6.4–-29 mamsl in aquifers qp^3, $qp^{2,3}$, qp^1, n_2^2, and n_2^1, respectively. The cone of depression occurred mainly in the HCMC center (Figure 8). In the rural areas, such as Cu Chi and Can Gio district, groundwater levels are still high with an elevation of >-6 mamsl. The Can Gio district has no groundwater extraction wells, due to saline groundwater. However, in Cu Chi district, many private groundwater wells (100 000 wells) were installed for irrigation and drinking, the lower decline of groundwater levels may relate to the wide distribution of the wells and the high recharge rate in the area (Figure 5).

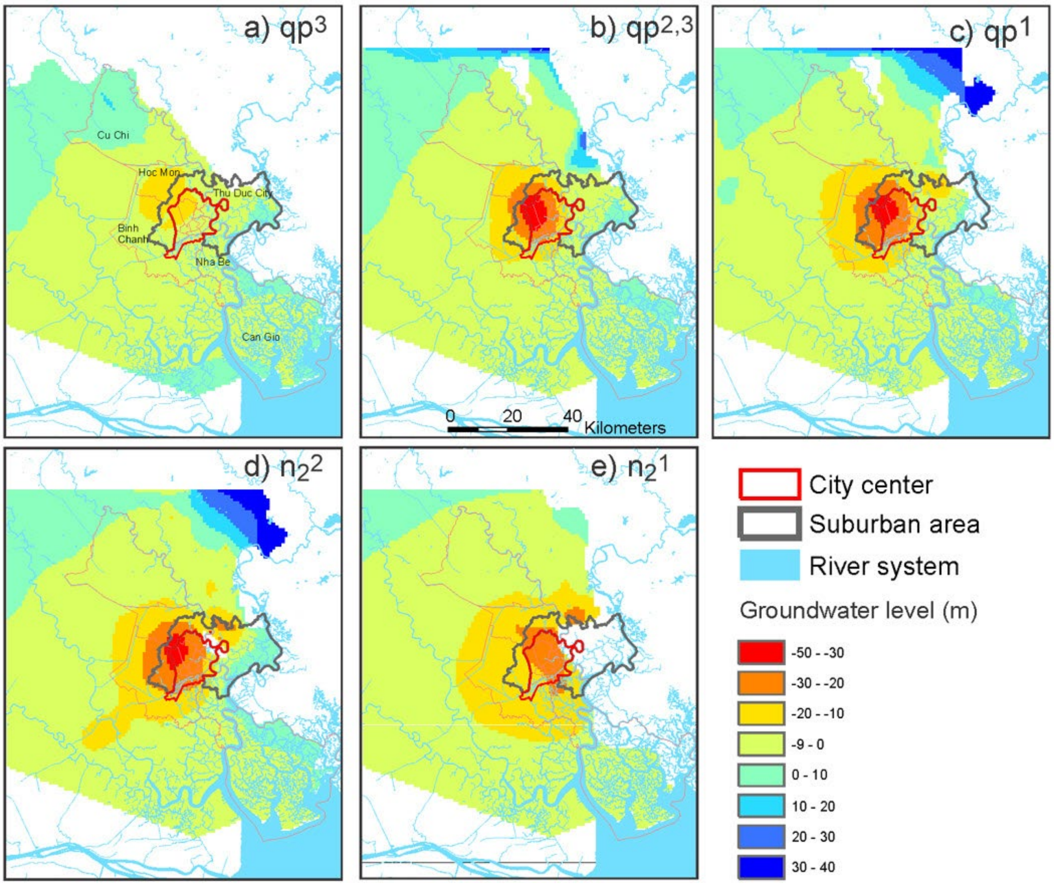

Figure 8 Groundwater levels in qp^3, $qp^{2,3}$, qp^1, n_2^2, and n_2^1 aquifers in 4/2012.

4.3 Groundwater budget

The simulation indicated that the groundwater budget has been changing over time from 1995 to 2012 due to variations in inflow and outflow components (Figures 9, 10). The groundwater balance consists of 2 components as flow in and out. Inflow components include regional flow (boundaries in), flow from riverbed (river leakage in), rainfall recharge, and contribution from the aquifer system (flow from aquifer storage). Outflow components include of regional flow out, discharge to river, and contribution to groundwater storage (flow out to storage) and exploitation.

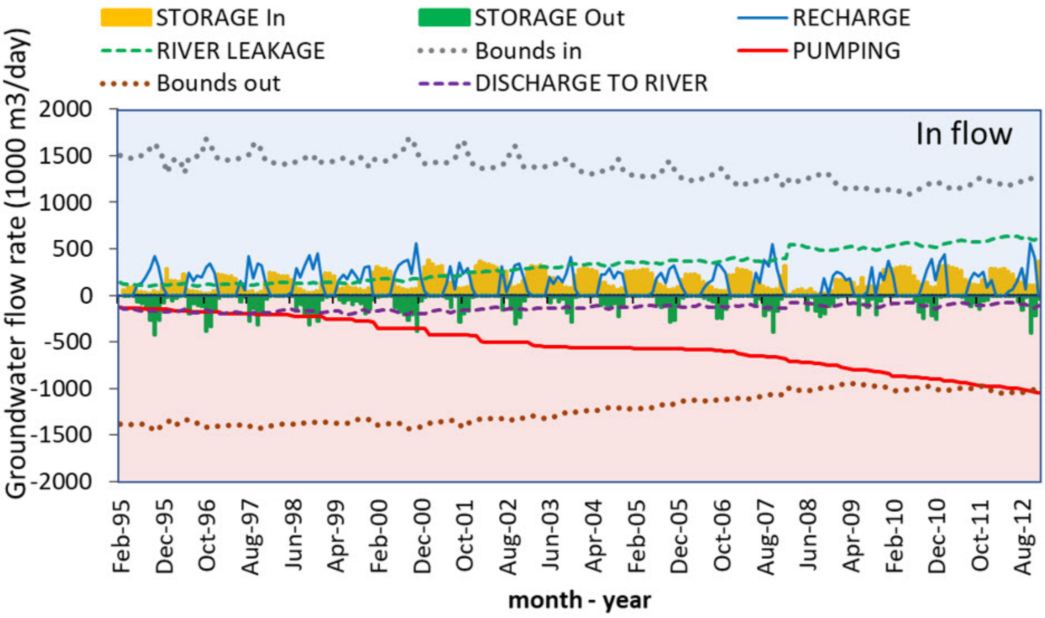

Figure 9 Groundwater flow budget components in HCMC Area during 1995–2012.

The recharge from the river is similar to the recharge from the land surface during 1995 but increased to 588,000 m^3/day in 2012. The increase of the river leakage rate is due to the groundwater level decline by groundwater abstraction. Total groundwater extraction also increases 6-fold from 1995–2012. The groundwater extraction rate was about 140 000 m^3/day in 1995 and increased over time to 1 million m^3/day in 2012. Because of the decline in groundwater levels, discharge to the river also decreased by 35% from 1995–2012.

Tran and Koontanakulvong (2020) also suggested that the groundwater discharge to upstream of the Sai Gon River tended to decrease and the river leak increased according to groundwater pumping. These findings highlight the critical connection between groundwater and river water, which is essential for groundwater management. The HCMC is characterized by the density of the river and canal system, thus river water plays an important role for groundwater recharge. This interaction may bring vulnerabilities to groundwater quality. This is because the river water in the city center of HCMC is highly contaminated by anthropogenic activities (Nguyen et al. 2021). Acceleration of the infiltration rate from the river system can quickly bring contamination to the aquifer. The lowering of the groundwater discharge and the increase in leakage can lower based on the flow in the river system (Mukherjee et al. 2018; Zipper et al. 2024) that may influence the natural ecosystem (Boulton and Hancock 2006).

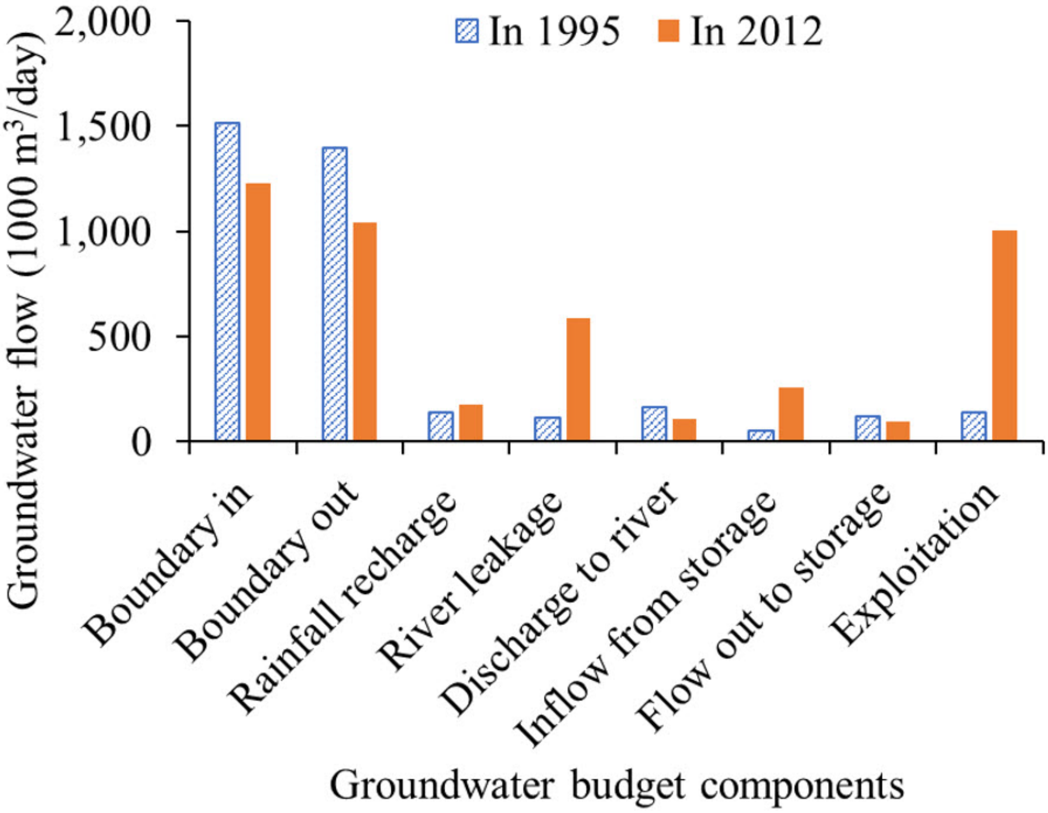

Figure 10 Groundwater balance in the study area in 1995 and 2012.

Over the years, the monthly recharge rate fluctuated with seasons, being higher during the rainy season and negligible during the dry season (Figure 9). This is because rainfall occurs mostly (90%) in the rainy season, while evaporation rates exceed rainfall during the dry season. The average recharge rate was approximately 140 000 m^3/day and 180 000 m^3/day in 1995 and 2012, respectively.

According to the modeling results, the highly recharged area is in a permeable zone, in a high land area (Figure 5). The results also show that the recharge rate is dependent on the hydrogeological condition of the land surface (Figure 1). The estimated recharge rate is much lower than the estimated recharge values of 526 000 m^3/day in HCMC (Vuong and Long 2016). However, this modeled recharge rate is consistent with previous studies (Ha et al. 2019; 2022; Tu et al. 2022). Nguyen et al. (2013) observed a high tritium concentration in shallow groundwater from the high land area, but the tritium concentration was not detected in shallow groundwater in the Holocene sediment area. Tritium is known as an environmental tracer for the identification of groundwater residence time. The occurrence of tritium in groundwaters reveals that the groundwater age is less than 50 years (Chau et al. 2017) or the groundwater is recently recharged. Ha et al. (2022) also suggested that the infiltration rate in the high land area should be high, therefore the area is susceptible to anthropogenic sources. However, the recharge rate in the Holocene sediment area is very low; therefore, the groundwater under the sediment has low tritium concentration (Nguyen et al. 2013; Chau et al. 2017), and in older groundwater and a strong reducing environment (Ha et al. 2022).

The boundary flows into the model domain representing water inflow from outside of HCMC, while the outgoing boundary flows account for the water leaving the model domain to surrounding provinces and to the sea. Both boundary inflows and outflows have decreased over time due to groundwater extraction in HCMC and surrounding provinces (Figure 10). The difference (*D*) of boundary inflows and outflows is about 131 000 m^3/day and varies from -50

000 to 320 000 m^3/day. The negative D value was only observed in January 1996. The positive D values increase over time. The increase in D values is attributed to groundwater being extracted from the aquifer system beyond what is replenished by local water sources, including recharge and river leakage. The flow rate from water storage has increased approximately fourfold, while the contribution of water to groundwater storage has decreased by 23%.

5. CONCLUSION

This study utilized a large dataset of hydrogeology, groundwater use, surface water level, and climate to simulate groundwater levels and flow budget in Ho Chi Minh City. The 3D model was calibrated and validated by monthly observation data of 44 monitoring wells from the national monitoring network, and 28 wells from the provincial monitoring network. These models show a good match with observed groundwater levels, with R^2 values > 0.8.

Groundwater modeling results from 1995 to 2012 in Ho Chi Minh City (HCMC) indicated that groundwater recharge from rainfall was approximately 140,000 m^3/day in 1995 and 180,000 m^3/day in 2012. The results also revealed groundwater depletion in the center of HCMC, where levels dropped to as much as 50 meters below mean sea level. Groundwater extraction increased sixfold during this period, and thus is the primary cause of drawdown, posing a significant threat to groundwater reserves in the HCMC area. Due to declining groundwater levels and over-extraction, water infiltration from rivers into the groundwater system increased, while the flow from the aquifer to the rivers decreased. Groundwater levels in boundary areas have also declined due to extraction in neighboring provinces, underscoring the need for interprovincial collaboration for sustainable groundwater management in HCMC.

The groundwater flow model has some uncertainties, primarily due to limitations in data availability. Factors such as recharge rates and groundwater-river interactions are challenging to accurately measure, and the number of monitoring wells is limited. To improve sustainable groundwater management, it is recommended to enhance management infrastructure, such as expanding and optimizing groundwater monitoring networks and systematically collecting precise data on groundwater extraction. Additionally, the impact of expanding urban areas and leakage from water supply systems on groundwater recharge should be considered to improve simulation accuracy.

ACKNOWLEDGEMENTS

This research is funded by Vietnam National University Ho Chi Minh City (VNU-HCM) under grant number: DA2024-20-01.

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SUPPLEMENTARY INFORMATION

Table S1 Compared observed and modeled groundwater levels of calibrated model.

No	Observation well ID	Aquifer	ME	MAE	RMSE
1	Q01302a	qp^3	0.02	0.36	0.45
2	Q09902C	qp^3	-0.9	1.26	1.52
3	Q804020	qp^3	-2.56	2.56	2.65
4	Q808020	qp^3	0.27	0.67	0.85
5	Q00202A	$qp^{2,3}$	1.12	0.37	1.17
6	Q004030	$qp^{2,3}$	0.68	0	1.27
7	Q011340	$qp^{2,3}$	-0.29	0.01	1.6
8	Q808030	$qp^{2,3}$	0.59	0	1.24
9	Q822030	$qp^{2,3}$	-0.29	0.1	0.29
10	Q00204A	qp^1	1.12	1.12	1.18
11	Q015030	qp^1	3.4	3.41	3.97
12	Q02204T	qp^1	-1.77	1.77	1.78
13	Q02304TM1	qp^1	1.4	1.45	1.61
14	Q011040	n_2^2	0.97	1.35	1.62
15	Q22404T	n_2^2	-1.74	1.83	1.93
16	Q80404T	n_2^2	-0.96	0.99	1.12
17	Q808040	n_2^2	2.01	2.03	2.47
18	Q822040	n_2^2	-0.15	0.15	0.15
19	Q022050	n_2^1	-0.3	0.4	0.5
20	Q02304ZM1	n_2^1	0.4	0.5	0.6
21	Q22404Z	n_2^2	-1.7	1.7	1.8
22	Q32604Z	n_2^1	1.3	1.3	1.4
23	Q80404Z	n_2^1	0	0.5	0.6
24	Q808050	n_1^3	2.4	2.6	3.1
25	06D	$qp^{2,3}$	2.46	2.46	2.61
26	08B	$qp^{2,3}$	3.61	3.61	3.85
27	11B	$qp^{2,3}$	0.78	0.79	0.86
28	01B	qp^1	-0.68	0.84	1
29	03C	qp^1	0.27	1.21	1.4
30	04C	qp^1	1.22	1.37	1.59
31	05B	qp^1	3.39	3.4	3.58
32	08C	qp^1	-0.01	2.26	2.84
33	01C	n_2^2	1.32	1.32	1.44
34	02D	n_2^2	0.65	0.94	1.25
35	03D	n_2^2	0.83	1.67	1.89

No	Observation well ID	Aquifer	ME	MAE	RMSE
36	04D	n_2^2	3.92	3.92	4.14
37	05C	n_2^2	7.97	7.97	8.2

Table S2 Compared observed and modeled groundwater levels of validated model.

No	Observation well ID	Aquifer	ME	MAE	RMSE
1	Q01302a	qp^3	0.26	0.44	0.54
2	Q022010	qp^3	0.71	0.71	0.73
3	Q023020M1	qp^3	0.15	0.37	0.45
4	Q09902C	qp^3	-1.72	1.85	2.14
5	Q326010	qp^3	-2.19	2.19	2.2
6	Q804020	qp^3	-2.82	2.82	2.9
7	Q808020	qp^3	-0.51	0.73	0.88
8	Q822010	qp^3	-0.05	0.18	0.21
9	Q00202A	$qp^{2,3}$	-0.38	0.48	0.64
10	Q004030	$qp^{2,3}$	0.51	0.85	1.03
11	Q011340	$qp^{2,3}$	-1.74	1.77	2.07
12	Q02202ZM1	$qp^{2,3}$	0	0.13	0.2
13	Q326020	$qp^{2,3}$	2.77	2.77	2.82
14	Q808030	$qp^{2,3}$	0.65	0.7	0.87
15	Q822030	$qp^{2,3}$	-0.18	0.18	0.21
16	01B	qp^1	-2.16	2.16	2.29
17	03C	qp^1	0.51	0.77	0.92
18	04C	qp^1	-2.54	2.54	2.65
19	05B	qp^1	-3.28	3.28	3.35
20	08C	qp^1	1.84	1.84	1.93
21	11A	qp^1	0.25	0.36	0.43
22	Q00204A	qp^1	-0.71	0.75	0.92
23	Q015030	qp^1	4.17	4.17	4.47
24	Q02204T	qp^1	-1.55	1.55	1.63
25	Q02304TM1	qp^1	-1.13	1.14	1.28
26	Q326030	qp^1	2.29	2.29	2.29
27	Q612040	qp^1	1.8	1.8	1.83
28	Q616040	qp^1	-1.99	1.99	2.06
29	Q821040	qp^1	1.62	1.62	1.71
30	01C	n_2^2	-0.82	0.98	1.16
31	02D	n_2^2	-1.39	1.55	1.76
32	03D	n_2^2	-0.88	1.09	1.4

No	Observation well ID	Aquifer	ME	MAE	RMSE
33	04D	n_2^2	-1.68	1.68	1.99
34	05C	n_2^2	3.1	3.1	3.27
35	Q011040	n_2^2	-1.03	1.24	1.68
36	Q02204Z	n_2^2	0.25	0.34	0.4
37	Q22404T	n_2^2	-2.8	2.91	3.43
38	Q32604T	n_2^2	2.21	2.21	2.22
39	Q604050	n_2^2	2.75	2.75	2.77
40	Q80404T	n_2^2	-2.33	2.33	2.45
41	Q808040	n_2^2	3.55	3.55	3.65
42	Q822040	n_2^2	-0.22	0.22	0.23
43	Q022050	n_2^1	1.21	3.95	4.13
44	Q02304ZM1	n_2^1	-0.96	0.92	1.06
45	Q22404Z	n_2^1	-3.08	1.03	1.19
46	Q32604Z	n_2^1	1.69	4.19	4.27
47	Q604060	n_2^1	8.04	6.1	6.13
48	Q80404Z	n_2^1	-1.27	3.52	3.6
49	Q808050	n_2^1	4.33	11.32	11.36