การประเมินค่าเติมน้ำใต้ดินทางธรรมชาติด้วยการใช้แบบจำลองสำหรับเกาะภูเก็ต ประเทศไทย

Groundwater Modelling for Natural Recharge Estimation in Phuket Island, Thailand

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Received : 23 March 2021

Revised : 4 May 2021

Accepted : 3 August 2021

บทคัดย่อ

เกาะภูเก็ตเป็นจังหวัดหนึ่งของประเทศไทยที่มีอัตราการเติบโตของความเป็นเมืองสูงนำมาซึ่งปัญหาอุปทานของน้ำโดยเฉพาะน้ำใต้ดิน ค่าการเติมน้ำใต้ดินเป็นตัวแปรที่สำคัญในระบบของน้ำใต้ดินและเป็นตัวแปรที่ไม่สามารถวัดค่าได้โดยตรงและมีความยากลำบากในการประมาณค่า งานวิจัยนี้เป็นการใช้แบบจำลองน้ำใต้ดินในการประมาณค่าการเติมน้ำใต้ดินทางธรรมชาติด้วยโปรแกรม PMWIN-MODFLOW แบบจำลองระบบน้ำใต้ดินตั้งแต่ปี พ.ศ. 2549 ถึง 2559 ถูกใช้สำหรับประมาณค่าการเติมน้ำใต้ดินด้วยวิธีการเรียนรู้แบบลองผิดลองถูก ค่าการเติมน้ำใต้ดินจากแบบจำลองในแต่ละปีได้มาจากการเทียบค่าระหว่างเปลี่ยนแปลงระดับน้ำใต้ดินที่ได้จากแบบจำลงและเปลี่ยนแปลงระดับน้ำใต้ดินที่ได้จากการวัดภาคสนามจนมีผลทางสถิติที่น่าเชื่อถือได้ ค่าการเติมน้ำใต้ดินที่ได้จากแบบจำลองถูกนำมาสร้างแผนที่ค่าการเติมน้ำใต้ดินสำหรับเกาะภูเก็ตด้วยวิธีการทางเทคโนโลยีภูมิสารสนเทศ ผลลัพธ์ของแผนที่แสดงว่าค่าการเติมน้ำใต้ดินของเกาะภูเก็ตสูงสุดที่ทิศตะวันออกเฉียงใต้ของเกาะและพื้นที่ส่วนใหญ่ของเกาะมีค่าการเติมน้ำใต้ดินปานกลาง สุดท้ายการประเมินค่าการเติมน้ำใต้ดินของเกาะภูเก็ตในการศึกษานี้จะช่วยในการบริการจัดการและการพัฒนาน้ำใต้ดินในอนาคต

คำสำคัญ : น้ำใต้ดิน ; การประมาณค่าการเติมน้ำใต้ดิน ; PMWIN-MODFLOW ; แบบจำลองน้ำใต้ดิน ; เกาะภูเก็ต

Abstract

Phuket, one of the most popular places in Thailand, where urbanization and population are highly increasing, is facing issues of water supply as part of which comes from groundwater resources. Recharge is one of the most important and difficult parameters to estimate the volume of infiltrated water crossing the water table and becoming part of the groundwater flow system. In this study, the simulation of the groundwater flow system using Processing MODFLOW for Windows (PMWIN-MODFLOW) was carried out for the time of 2006 to 2016. Groundwater data were utilized to present the historical groundwater data and to characterize the aquifer information for setting up model geometry. The trial-and-error method was used to estimate the recharge flux based on historical groundwater data. The model was validated by the good matches between simulated and observed groundwater levels with an acceptable range of errors. The average recharge map of Phuket during 2006 – 2016 was created by GIS techniques for providing the spatial data of the groundwater databases. The high recharge areas locate in the south-eastern part of Phuket and most areas of the Island have moderate recharge rates. There are some small areas where have the low recharge rate on Phuket Island. The recharge estimation from groundwater simulation in Phuket could help to manage the future development of the groundwater system in Phuket Island as being a critical parameter of groundwater resources.

Keywords : groundwater ; recharge estimation ; PMWIN-MODFLOW ; groundwater modeling ; Phuket

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Introduction

Phuket Island is one of the most productive and intense tourism areas in Thailand. Water supplied to Phuket's urbanization has dramatically been a high priority for water consumption in all sectors on the Island. Groundwater is an important water resource for water supply and the primary source of Phuket's water supply. Over the last few decades, the rapid expansion of urbanization, a scarcity of water consumptions, and an increment of groundwater discharge in Phuket Island led to a significant understanding of the groundwater studies. Therefore, groundwater is the most important constraint against future development in Phuket Island. However, both natural processes and anthropogenic activities mainly affect the groundwater systems; therefore, the proper management to maintain the situation of groundwater resource is being required for optimizing both economic and social benefits (Kumar, 2013). Adequate knowledge of groundwater resources is critical for successful groundwater management (Bagher & Rasoul, 2010). Groundwater recharge is a hydrologic process where water percolates into the lower limits of the vadose zone and reaching the water table (Crosbie *et al.,* 2005). Recharge is a key component in most simulated models of the groundwater flow or the recharge process and the rate of aquifer recharge is one of the most difficult factors to measure in the evaluation of groundwater resources (Healy & Cook, 2002; Yang *et al.,* 1999; Sophocleous, 1991). Thus, groundwater recharge is an important factor in sustainable groundwater management, especially in places such as Phuket, where the major source of water is groundwater. The first research of the recharge estimation in Phuket was conducted by Tesfaldet *et al.* (2019). The chloride mass balance (CMB) method was carried out in comparison with the water table fluctuation (WTF) method in the watershed area of Phuket. However, the results of the CMB are not suitable for a coastal area since the chloride concentration can be disturbed by the seawater intrusion problem and the limitation of WTF is unable to account for a steady rate of the water table; therefore, the modeling and numerical techniques are appropriate for a coastal area such as Phuket.

Currently, the numerical groundwater modeling using MODFLOW which has been developed by USGS is being widely employed in the world to study both surface and groundwater resource systems, landscape management and impact of further development scenarios, and so on (Kumar, 2013; Lalehzari *et al.,* 2010). PMWIN 5.3 is a computer application upgraded from MODFLOW for windows and uses the finite difference method to solve the differential equation in the porous media flow for recharge (Lalehzari *et al.,* 2010; Chiang, 2005). PMWIN 5.3 model with the trial-and-error method calibrated with historical groundwater data (e.g. groundwater level) was used by Puttiwongrak *et al.* (2018) to estimate the groundwater recharge flux from 2006 to 2016 in Kathu district, Phuket, Thailand. A good agreement between observed and simulated groundwater levels was created. According to their result, the average groundwater level in their study area gradually rose due to the increment of groundwater recharge predictably caused by many ways including high precipitation rate, aquifer types as well as seawater intrusion caused by Andaman sea level rise, even though there was high extraction rate of groundwater. The simulation of groundwater resource behaviors in Ramhormooz Aquifer, Iran, was done by Saatsaz *et al.* (2011) by applying MODFLOW and PMWIN 5.3. In their study, the trial-and-error method was used to be a model calibration by comparing the simulated and observed groundwater levels. Their result showed a good correlation between simulated and observed groundwater level with the regression coefficient and mean error, 0.99 and 0.78 respectively. Based on their simulation result, some bad issues including water-logging, soil salinity, and contamination should be concerned because of the shallow depth of the groundwater table (less than 1 m from the ground surface).

The objective of this study is to create a groundwater model of the Phuket aquifer system using the PMWIN-MODFLOW software application based on historical groundwater data to estimate the recharge flux during the period 2006 to 2016. This can help to explain the relationship between the historical groundwater data, i.e., changing levels of groundwater and groundwater extraction between 2006 and 2016.

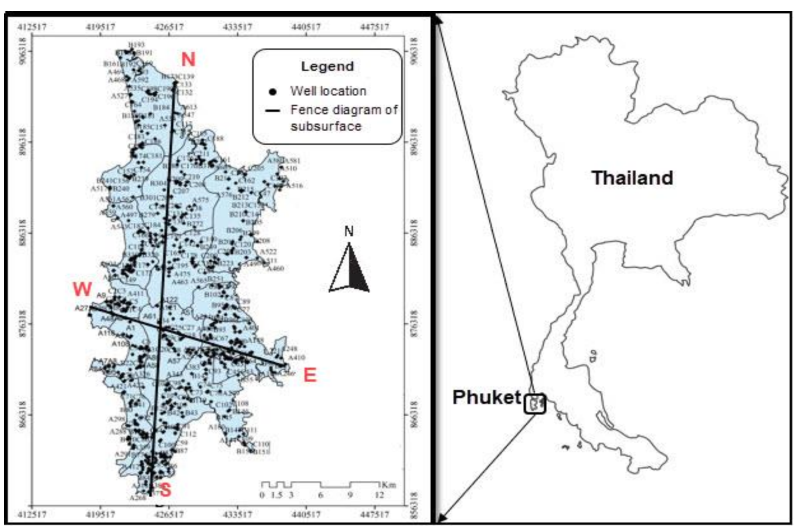

Figure 1 Site area description including groundwater wells distributions and fence diagram lines (E-W and S-N)

Methods

Site description and general hydrogeology

Phuket is the biggest island and attractive tourist destination located in the southern part of Thailand with an area of 576 km^2. The area lies between longitude 98°15’ and 98°40’ east, and latitudes 7°45’ and 8°15’ north (Fig.1). Phuket is divided into three districts including Thalang, Meung, and Kathu. The number of tourists has increased incredibly from approximately 2.5 million tourists in 2009 to almost 9 million tourists in 2013 and over 12 million tourists in 2015. Phuket geological structure is based on the tectonic history of the Southern part of Thailand structured by a major fold in North-South alignment and relates to intrusive granite. Phuket Island is, moreover, included in fold and fault structures. The fold was caused by the intrusion of granite in the Cretaceous age, while the fault was related to plate tectonic of fault zone or subduction zone in the Andaman region. The hydrogeological aquifers of Phuket located in the Southern Peninsula have also been classified into two groups (unconsolidated and consolidated aquifers). The unconsolidated aquifers are called Rayong-Satoon aquifers including 1) recent and old beach sand aquifer, 2) floodplain deposit aquifers, and 3) colluvium aquifers. In the case of the consolidated aquifer, Phuket aquifers are Meta-sedimentary aquifers and Granitic aquifers. Water supply sources in this area obtain from two main significant sources: surface water and groundwater. Catchment areas are the main sources of surface water on the island which is assumed 34.12 million m^3 and catchment raining areas are divided into 24 small catchments and 188 short streams in the Eastern part, 63 streams in the Southern part of the island, and 9 significant canals in the western part.

Phuket historical groundwater data

Industrialization and urbanization in Phuket have been higher than predicted due to rapid annual increment of the populations of both residents and tourists. The number of large buildings, especially hotels, has dramatically increased as having other forms of infrastructure. Furthermore, the demand on natural resources has increased, e.g. in 2005, forest areas occupied 23.40% of the land, and rural and agricultural land accounted for 21.73%, then these areas had been reduced by 3.19% (10.051 km^2) and 10.95% (15.598 km^2), respectively, by 2009 (Boupun & Wongsai, 2012). Consequently, the demand for groundwater presents a significant challenge due to the transformation of land into residential areas. The water supply has remained inadequate due to the distribution networks and ineffective management. Additionally, groundwater development through well drilling becomes an alternative source of potable water. The Department of Groundwater Resources (DGR) of Thailand has reported that the water resources of Phuket Island are relied mainly on groundwater (70%), while the surface water resources are 30% of the total water resources. Likewise, the DGR has also recorded that Phuket can store the water 20% of precipitation for being potable water, whereas the runoff toward the sea is approximately 80% of precipitation.

Groundwater well data were gathered from 2006 to 2016. The data were taken from well observations (616 data), well reports (334 data), and published data (216 data) as shown in Fig.1. The total data collected within 10 years accounts for a total of 1,761 data throughout Phuket Island. All data were classified based on 5 parameters including well location, groundwater level, layer type, layer depth, and groundwater extraction rate. They were analyzed to determine 3 main classes of information that could then be used for groundwater simulation such as 1) subsurface information, 2) groundwater level changes, and 3) historical groundwater extraction. The data for groundwater level changes in Phuket were obtained from a network of observation wells and piezometers covering the Kathu, Meung, and Thalang district from 2006 to 2016. The groundwater level measurements were recorded monthly intervals during each year. The raw data on groundwater levels were processed to indicate the groundwater level against the corresponding time in each district with the monthly data then accumulated into yearly data.

Graphs of the groundwater level over time in Kathu, Meung, and Thalang districts are presented in Fig. 2 a, 2 b, 2 c, respectively. Finally, the groundwater level over the study period in the entire Phuket area was established as shown in Fig. 2d. The groundwater extraction data were obtained from 373 wells from 2006 to 2007, 461 wells between 2008 and 2012, and up to 1,115 wells from 2013 to 2014. The purposes for which the groundwater uses were classified into five sectors, 1) domestic, 2) industry, 3) commerce, 4) tourism, and 5) agriculture. The data were recorded monthly starting from October 2006 until April 2014. Thereafter, the groundwater extraction figures from those five sectors were combined for each year as shown in Table 1. In terms of the groundwater extraction data in 2015 and 2016, they were taken from the summary report of the annual groundwater situation in Thailand (DGR, 2012). Unfortunately, water extraction data were only recorded for the entire Phuket area and were not categorized into districts or sub-districts. Table 1 shows the average rate of groundwater extraction and respective groundwater level in Phuket and each district from 2006 to 2016

Table 1 Phuket groundwater data during 2006 – 2016

Year		2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Avg. Extraction Rate (m^3/day)		3039	3549	4262	4262	4262	4262	4262	19066	40329	51150	53096
Avg.	Kathu	-5.70	-6.97	-5.47	-6.75	-5.64	-8.81	-6.08	-3.99	-3.83	-3.96	-4.03
Ground	Meung	-6.55	-5.95	-7.63	-8.92	-7.89	-6.89	-6.50	-5.42	-5.15	-5.46	-5.77
water level	Thalang	-7.46	-6.29	-7.02	-6.52	-7.53	-5.99	-6.10	-4.22	-4.72	-4.82	-4.91
(m)	Phuket	-6.57	-6.41	-6.71	-7.40	-7.02	-7.23	-6.23	-4.54	-4.57	-4.75	-4.91

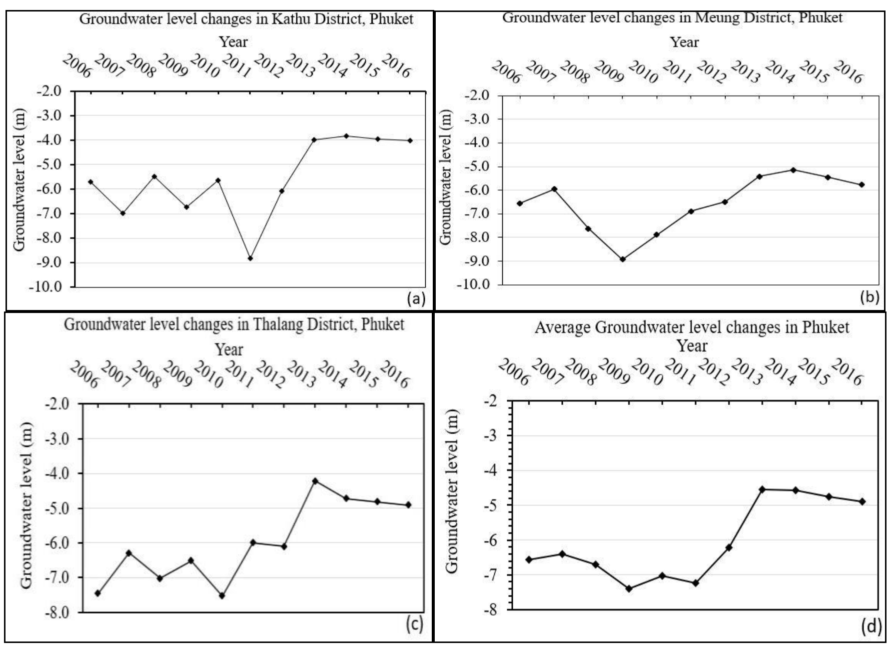

Figure 2 The fluctuation of groundwater level from 2006 to 2016: (a) Kathu district, (b) Meung district, (c) Thalang district, (d) average groundwater level in Phuket

Groundwater simulation

The groundwater simulation was performed based on historical groundwater data which were collected and analyzed from the groundwater well data. The PMWIN-MODFLOW software application was used to simulate the groundwater level in Phuket Island. The subsurface aquifers of Phuket were chosen for groundwater modeling based on their geological location and the information recorded by the local government. The simulations were conducted for the entire three districts as described below.

Subsurface geometry

Subsurface layers of all sub-districts of three districts in Phuket Island are depicted by groundwater well data as shown in Fig. 3. The first layer (top layer) is composed of sand, clayey sand, and loose soils as classified to be fine-grain layers, while the second layer is composed of weathered and fractured rocks which are called

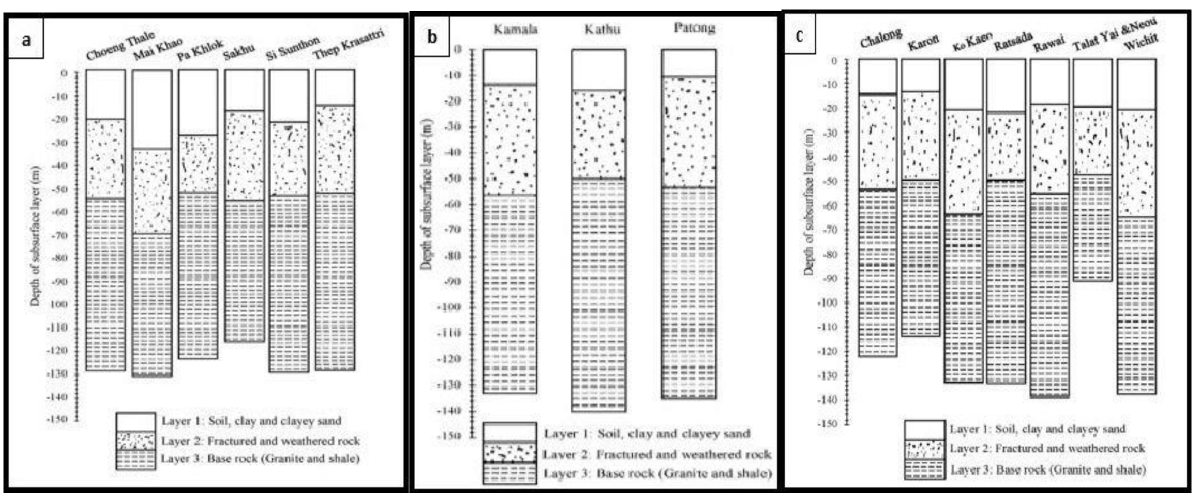

Figure 3 Sub-surface layers in each district: (a) Mueng district, (b) Kathu district, (c) Thalang district

coarse-grain layers in this research. The third layer (bottom layer) is regarded as the basement that was mainly granite and some shale. In addition, the average thickness of subsurface layers in Phuket is 18.27, 36.55, and 73.71 m for the first, second, and third layers respectively. Fence diagrams of cross-section line E-W and S-N (Fig.1) were done along with groundwater from North-South and East-West across Phuket Island as shown in Fig. 4. Therefore, the aquifer of Phuket is formed by the first and second layers as an unconfined aquifer. The Phuket aquifer is part of an unconsolidated aquifer called the Rayong-Satoon aquifer. The subsurface geometry shows

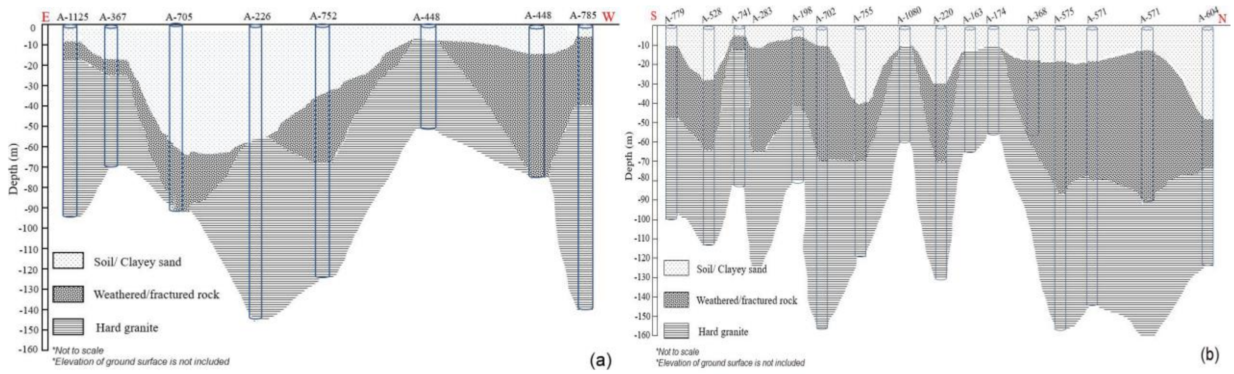

Figure 4 Subsurface layers in Phuket Island: (a) Cross-Section Line E-W, (b) Cross-Section Line S-N

that the second layer is thicker than the first layer. Consequently, in groundwater modeling, the aquifer geometry was averaged across the aquifers to a thickness of the first layer consisting of fine grain aquifers (soil, and clayey sand) and the second layer of weathered and fractured rocks.

<u>*Groundwater modeling*</u>

Groundwater modeling was used to build a numerical model for the study area based on the average thickness of the Phuket aquifer as model geometry above using PMWIN-MODFLOW (Bagher & Rasoul, 2010; Lalehzari *et al.,* 2010). The groundwater flow model produced by PMWIN-MODFLOW is based on a finite-difference of a three-dimensional model simulating underground flow under steady and transient conditions in anisotropic and non-homogeneous porous media, which is described by the partial differential equation:

$$\frac{\partial}{\partial x}\left[K_x\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_y\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_z\frac{\partial h}{\partial z}\right]=W \quad (1)$$

Where K_x, K_y, and K_z are values of the hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (m/s); h is the potentiometric head (m); W is the volumetric flux unit volume representing sources and/or sinks of water, with W < 0 for flow out of the groundwater system, and W > 0 for flow into the system (m^{-1}).

A conceptual model of recharge estimation, as shown in Fig. 5a, was set as the example of the cross-section of the pumping well ID A-368. The conceptual model was created based on the groundwater and hydrogeological data and the subsurface stratigraphy provided by well information. In Fig. 5a, the cross-section is composed of three geological units (the elevation of the top layer is 28m and the total depth is around 60 m). The unconfined aquifer is represented by the multiple layers of the first and second layer and distributes in the study area. The right edge of this cross-section was specific as the constant head (CHD) boundary due to the sea. The

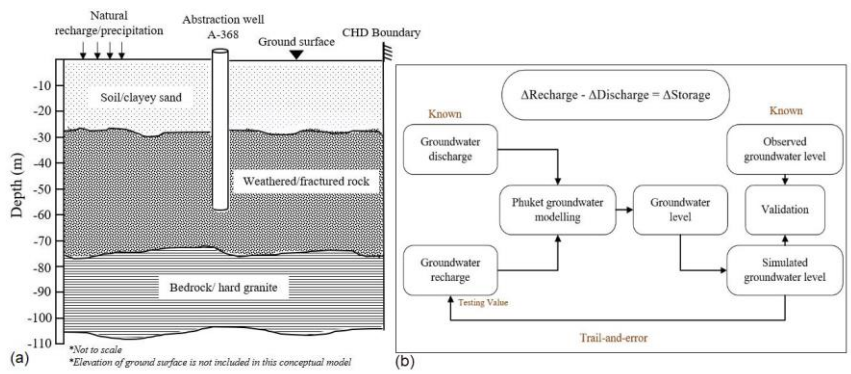

Figure 5 The illustration of (a) the conceptual model of Phuket groundwater simulation for recharge

pumping well is located in the study area, while the recharge is the rainfall infiltration in the entire area. The simulation was performed using trial-and-error operation based on an assumption of the water balance that the groundwater level reacts to the recharge and discharge components as characterization of the groundwater system (ΔRecharge-ΔDischarge=ΔStorage). The evaporation was not taken into account in this study because the study area is the urbanization and tropical areas (the vaporization happens mainly in the sea and the rainy season is throughout the year), thus the assumption was set that the evaporation does not influence the recharge in the study area. The simulation scheme shows in Fig. 5b.

The recharge was tried out multiple times by noting and eliminating errors until matching between the model results (groundwater level) and the historic groundwater table of the field measurement. The aquifer model was set up as a double unconfined aquifer system with a simple model of 60 x 60 m subdivisions and 500 x 500m cell sizes for the Phuket boundary. The boundary condition was set to be CHD boundary along the coastline as a model boundary. The simulation was performed by these models varying from year to year starting from 2006 to 2016. The cells of the model were divided into fixed-heads based on the DEM map and its aquifer condition as

Table 2 Aquifer properties of groundwater simulation

Layer	Aquifer Type	Parameter	Value
1	Fine grain (soil, clay, and clayey sand)	Porosity (φ)	0.36
		Hydraulic Conductivity (**K**, m/s)	6×10^{-9}
2	Coarse grain (weathered and fractured rock)	Porosity (φ)	0.31
		Hydraulic Conductivity (**K**, m/s)	1.09×10^{-6}

shown in Fig. 6. The boundary cells of the model were calculated based on the fixed-heads. Hydraulic heads were calculated in the active cells. The physical parameters used in the model are obtained by unpublished data from the DGR, Thailand as shown in Table 2. The hydraulic conductivity and porosity of the soil and clayey sand were estimated from bore-hole logging data, while standard values of the hydraulic conductivity were selected to represent the second layer of the fractured and weathered rocks.

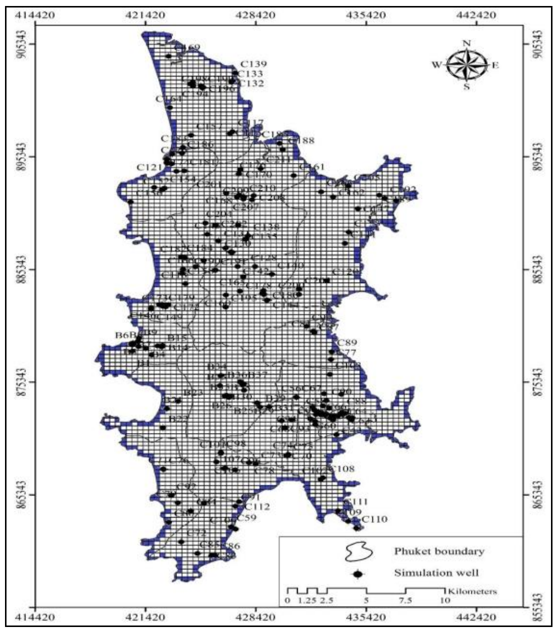

Figure 6 Numerical model of Phuket groundwater simulation for recharge estimation

Results

Model calibration

The availability of observed groundwater data is very important for groundwater modeling. The time between 2006 and 2016 was selected based on the availability of a time series of observed hydrological, meteorological, and groundwater data for the three districts. This model calibration was an iterative process and the model with the resulted (groundwater level) and the historic groundwater table of the field measurement was matched within plausible ranges (Fig. 7). The first step in the model calibration was the determination of the acceptable range of errors between the simulated and observed groundwater levels. The differences in groundwater level refer to residual groundwater levels. In the second step, trial-and-error and inverse simulations were performed until the simulated results were within the acceptable range of error (i.e., $R^2 \geq 0.9$). The model's results (i.e. groundwater heads or levels) were therefore based on an iterative process matching the historic field-

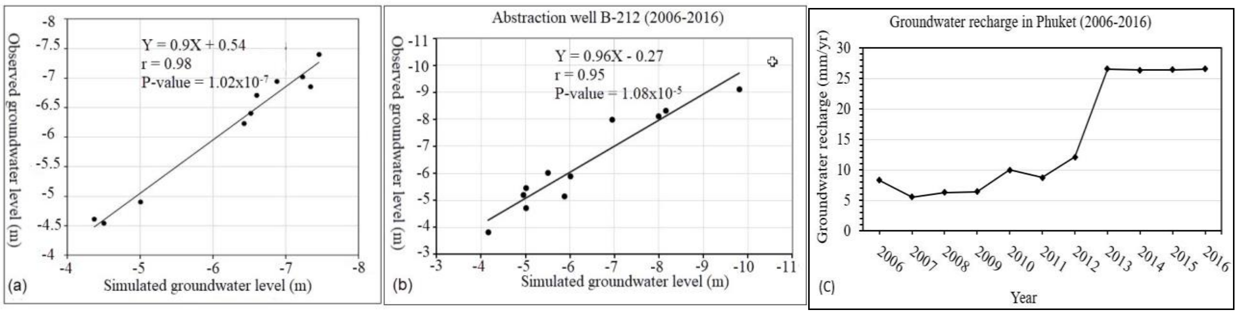

Figure 7 Model validation using observed groundwater level and simulated groundwater level for: (a) all districts in Phuket and (b) example of abstraction well B-212 in Thalang and (c) simulation result of groundwater recharge in Phuket Island

measured values obtained by adjusting aquifer parameters, boundary conditions, and stresses within plausible ranges. Thus, trial-and-error and inverse simulations (recharge estimation) were performed until the simulated parameters were within the acceptable range of errors. Moreover, the statistical analysis was conducted to confirm the relationship between simulation and observation results, the P-value is lower than the conventional 5% ($P < 0.05$). Therefore, the correlation coefficients are statistically significant. Consequently, the validation was performed based on a comparison of the observed and simulated results. There were in good agreement in all areas, with a correlation coefficient (r) of 0.98, as shown in Fig. 7a. Similarly, the good agreement in some collected wells between simulation and observation results were carried out as exemplified by an example of the model validation in the well ID B-212 (Fig. 7b). Hence, it can be concluded that this model resulted in an accurate simulation. Based on a result of the acceptable correspondence between the observed and simulated head, it can be implied that the recharge values in the study areas based on trial and error and inverse simulations are accurate. The simulation result of groundwater recharge in Phuket shows in Fig. 7c.

Groundwater recharge in Phuket Island

According to the historical groundwater level changes as shown in Fig. 2, it can be observed that the average groundwater level in Phuket was fluctuating within different years, e.g., as shown in the contour map of the groundwater flow simulation (Fig. 8a), the groundwater level is not uniform in Kathu district. From 2006 to 2010 the groundwater level was fluctuating with 1.5 m difference. However, between 2010 to 2011 the groundwater level drops sharply to -9.0 m. Then in the following years, groundwater started to recover and the level was increasing dramatically up to 2013, then has remained constant up to the end of the period. Hence, the average groundwater level in the Kathu district was increasing. In the Meung district (Fig. 2b), groundwater level change dropped during 2007-2009 from -6.0 m to -9.0 m. However, the result shows that it recovered in the following years and it went up to about -5.0 m in 2014 and then decreased slowly until 2016. Fig. 2c indicates the groundwater level changes in the Thalang district, which was marked by irregular variation between -7.5 m to -6.2 m within the year 2006 to 2011. Then the groundwater level increased dramatically from about -7.6 m to reach its peak (at -4.1 m) in 2013 and then started falling slightly in the following years to -5.0 m. The groundwater level change in Meung was deeper than that in Thalang. Overall, the historical groundwater level in Thalang was increasing. Consequently, the average groundwater level in the entire Phuket during 2006 - 2011 as depicted in Fig.2d, was decreasing with minor fluctuation. However, the groundwater level increased remarkably in 2011 and reached a peak in 2013, but it dropped insignificantly in the following years to 2016. Overall, the average groundwater level in Phuket was increasing gradually from 2006 to 2016.

Furthermore, Table 1 shows groundwater withdrawals increased during 2006-2016 compared to groundwater level data in Phuket Island. The Table 1 shows that from 2006 to 2012, the amount of groundwater extraction rate per day seems to be stable, then the extraction rate increased remarkably from around 3,039 m^3/day in 2012 to 53,096 m^3/day in 2016. Hence, the average of groundwater extraction in the entire Phuket was increasing from 2012 to 2016. The recharge flux from the groundwater simulation in Phuket, as shown in Fig.7c, shows that groundwater recharge was gradually increasing during the years 2006 to 2012 with an average rate of 8 mm/year. However, a dramatic increment of the recharge flux started in 2013 to 27 mm/year and kept constant at an average rate of 26.5 mm/year up to 2016. Therefore, the groundwater level in Phuket is likely to change based on the groundwater recharge. The recharge is the main factor to control the groundwater system in Phuket and it plays an important role in the balance between groundwater sustainability and groundwater extraction.

Discussions

A suspicion between groundwater level and groundwater extraction, i.e., the groundwater seems to be increasing in overall, even the extraction rate is steeply increased during the last 5 years, can be answered by the groundwater recharge. In addition, the steep increment in both groundwater level and recharge during 2011 - 2013 can be explained by several reasons including rainfall, aquifer characterizations, seawater intrusion, and watershed build-up. The rainfall data for the last 30 years (during 1981 – 2010 in the average rate of 2,271 mm) comparing with unpublished data from the Meteorological Department of Thailand in 2015 (the average rainfall data of 2,485 mm) slightly increased which can help to maintain the groundwater recharge for the entire Island. The aquifer's characteristics of Phuket are also significant factors that can store, transmit, infiltrate, and contact watersheds. The Phuket aquifer is quite shallow which can produce a high recharge and generate high groundwater potential. Similarly, seawater intrusion is another factor to supplement the increments of the recharge because seawater intrudes into the aquifer of the mainland as the natural recharge. Also, Puttiwongrak *et al.* (2019) claimed that the coastal areas (Thalang, Kamala, Chalong, and Rawai) of Phuket are facing the seawater intrusion problem. For the last reason, Phuket has expanded the watershed areas due to dam constructions and expansions during 2008 – 2014 that is a factor to increase the recharge rate in Phuket. To tackle the limitation of the previous study (Tesfaldet *et al.,* 2019) in the coastal area of Phuket and to devise an appropriate technical estimation of the natural recharge, the groundwater modeling using a numerical method as the trial-and-error approach is pertinent to estimate the natural recharge in the study area because of its robust technique and fewer consuming of fieldworks, budgets, and times. Finally, the recharge result was distributed to create the recharge map based on an assumption that the groundwater level is controlled by groundwater recharge, thus the recharge map in Phuket during 2006 – 2016 is mapped using the interpolation technique in GIS as represented in Fig.8b. The geo-spatial analysis with Inverse Distance Weighting (IDW) of the interpolation method was used to interpolate the base maps of recharge rate getting from the simulation. This technique was used to predict possible values of unknown locations through interpolating the values of the measured data. The IDW method was used because it is straightforward, simple, and fast in the calculation and produced reliable results (Kura *et al.,* 2014). The map shows that the high recharge (dark grey color) areas locate in the south-eastern part of Phuket and most areas of Phuket is a moderate recharge rate (grey color). There are some small areas where have a low recharge rate (white color) on Phuket Island.

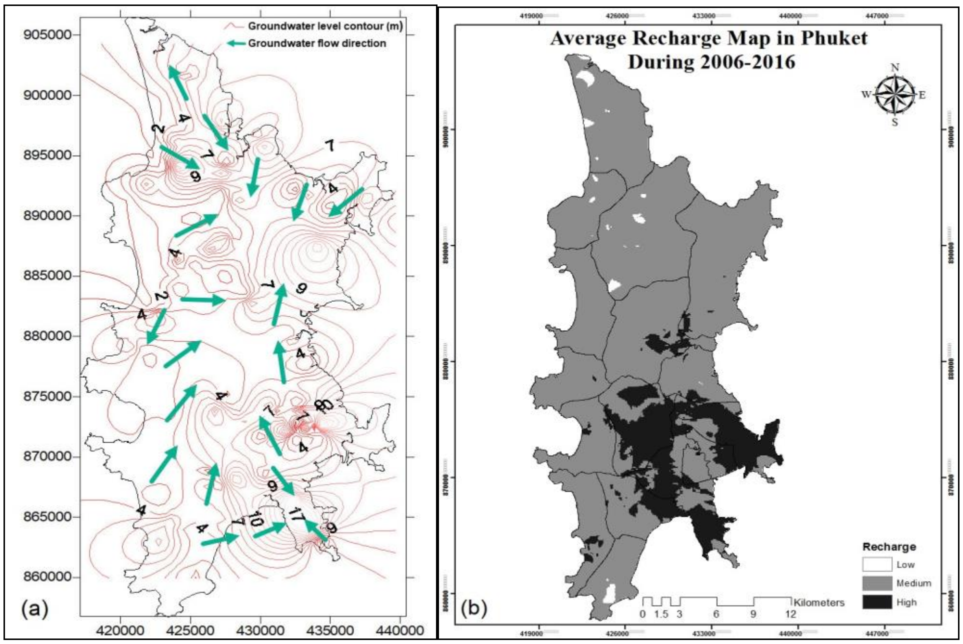

Figure 8 Simulated results: (a) The contour map of the groundwater flow simulation and (b) Groundwater recharge map of Phuket Island during 2006 – 2016

Conclusions

Phuket Island is strategically located as a natural port and has highly attractive for tourism. Groundwater is a significant source of freshwater used for all consumptions, but the Island still has not enough to supply and produce water resources. This problem is exacerbated by its high population, and growth in industrialization and urbanization has led to a dramatic increase in water demand, and groundwater may not be able to meet that demand in the future. In addition, over-extraction of groundwater and land-use changes are the significant factors that impact groundwater recharge because increasing numbers of buildings and other infrastructure can create huge runoff and reduce the groundwater recharge rate in urban areas leading to a decline in the groundwater level. The groundwater modeling described in this paper was carried out in Phuket to simulate the groundwater recharge flux based on historical groundwater data using the PMWIN-MODFLOW software application with a trial-and-error process. The model validation between historical groundwater level and simulated groundwater level data shows good agreement represented by R^2 of 0.9753. Thus, it can be concluded that this simulation method is a method for the estimation of the recharge rate with a high degree of accuracy. The groundwater level and the recharge flux in each district have increased overall for the last 10 years. This situation can be explained by the level of rainfall over the period considered, the local aquifer characteristics, seawater intrusion into the aquifer, and an increase in the island's watersheds. The map indicates that the high recharge zones situated in the south-eastern part of Phuket and the moderate recharge rate areas can be seen in almost entire areas of Phuket, whereas some small areas are having a low recharge rate on Phuket Island. Using the simulation method for recharge estimation can help to constraint future development in Phuket Island for being adequate knowledge of groundwater resources which is critical for successful groundwater management.

Acknowledgments

We are grateful to the Department of Groundwater Resources, Thailand for providing the groundwater data for this study and Assoc. Prof. Dr. Pham Huy Giao from the Asian Institute of Technology (AIT) for his helpful suggestions. We would also like to address our sincere thanks to the Phuket Campus Research Fund, Prince of Songkla University, for providing the budget for this research. Finally, we would like to express special thanks to PSU English Clinic, Faculty of Liberal Arts, Prince of Songkla University, for editing this manuscript for English proofreading.

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