Groundwater Recharge Estimation in Kathu, Phuket using Groundwater Modelling

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ABSTRACT: Kathu is a district of Phuket Island in Thailand, and is the district with the largest number of communities in Phuket. Groundwater is the main water supply on Phuket. Urbanization is occurring very rapidly on Phuket and this has stimulated water demand at an accelerating rate. A lack of fresh water and the results of over-use of groundwater could be serious problems in Phuket in the near future. The study described in this paper simulated groundwater recharge flux in Kathu, using groundwater modelling to estimate groundwater recharge. The simulation was carried out across the locations in Kathu for the period, 2006-2016. Historical Groundwater well data were collected and used to create a groundwater model. The trial and error method was applied to the recharge flux to obtain matches between simulated and observed figures of groundwater heads or levels within acceptable ranges of error. Finally, it was concluded that the groundwater recharge in Kathu is currently able to maintain the groundwater level, although groundwater has been withdrawn at a highly accelerating rate, especially between 2012 and 2016. The positive trend in the recharge rate can be attributed to increasing efficiency in the use of water catchment areas, high rainfall, and rising sea levels.

KEYWORDS: Phuket groundwater, Recharge flux, Groundwater level changing, Groundwater modelling, Urbanization.

1. INTRODUCTION

Phuket Island has experienced extensive urbanization and an associated shift away from a largely agricultural economy to one that is shaped by the growth of tourism. Kathu is one of three districts on Phuket Island, (Thalang, Mueang, and Kathu) and has the highest number of communities among the three districts on the island.

Groundwater provides the main water supply on the island. Groundwater recharge is a hydrologic process where water moves downward from surface water to groundwater. Scrosbie et al., (2005) defined recharge as the water percolating into the lower limits of the vadoze zone and reaching the water table. Groundwater is recharged naturally by rain and snow melt and by surface water. However, recharge can be impeded by human activities which can result in loss of topsoil and overuse of the groundwater with a concomitant reduction in recharge which may also lead to the lowering of the water table. Groundwater recharge is a key component in most simulated models of groundwater flow or the recharge process (Healy and Cook, 2002). However, the rate of aquifer recharge is one of the most difficult factors to measure in the evaluation of groundwater resources (Sophocleous, 1991). Moreover, the covering of the surface in urban areas, normally has the effect of reducing groundwater recharge (Lerner, 1990) and over abstraction in urban areas causing falling water tables has traditionally been a concern (Yang et al., 1999). Thus, groundwater recharge is an important factor in sustainable groundwater management.

The purpose of this study is to create a groundwater model of Kathu, using the PMWIN-MODFLOW software application based on historical groundwater data, to estimate the recharge flux during the period, 2006-2016. 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.

1.1 Groundwater situation in Kathu district

Population growth, industrialization, and urbanization in Phuket, have been higher than predicted due to rapid increases in the populations of both residents and tourist every year. The resident population increased from 221,835 to 351,909 people (58.6%) between 1997 and 2011 (ISET et al., 2014) and the number of tourists visiting Phuket increased from 2.5 million in 2009 to 12 million people in 2015. Due to the increasing number of tourists, the number of large buildings, especially hotels has dramatically increased as have other forms of infrastructure. Further, the demands on natural resources have increased, and in particular the demand for groundwater presents a significant challenge. For example, in 2005, forest areas occupied 23.40% of the land, and rural and agriculture land accounted for 21.73%. However, by 2009, these figures had been reduced by 3.19% (10.051 km^2) and 10.95% (15.598 km^2) respectively, due to land being transformed into residential areas (Papagorn and Sangdao, 2012). In addition, the increase in building and built-up areas will cause significant land cover which will increase runoff and thus reduce groundwater recharge. Consequently, the groundwater level is predicted to decline.

On the other hand, ISET et al. (2014) estimate that water demand will increase by 4% per year. In 2003, water demand was 42 million m3/year, while in 2012 it was reported as 52 million m3/year and is predicted to be 61 million m3/year in 2017, 78 million m3/year in 2027 and will reach 101 million m3/year by the year 2037. According to the data recorded by the Thai government, Phuket groundwater extraction has increased dramatically from 4,262 m3/day in 2012 to 53,096 m3/day in 2016. Extraction in Kathu particularly, has increased greatly from 732 m3/day in 2012 to 9,186 m3/day in 2016. This increasing overexploitation of groundwater resources is likely to affect the groundwater system.

1.2 Site description

Phuket is the biggest island in the southern part of Thailand with an area of 576 km^2 and is a renowned tourist destination. The average rainfall is 2,500 mm/year. Kathu is the smallest district in Phuket (compared to Thalang and Mueang districts) with a land area of 67,034.km^2, but has the largest number of communities (26 communities). The number of households is 4,386 households and the population is 6,487 people. Agricultural land accounts for 24.84 km^2 and there are 32 industrial areas (ISET et al., 2014). Kathu is situated in the southwest part of the island and the land is mostly high hills and mountains. The area lies between longitudes 980° 15'10" and 980° 21'50" East and latitudes 70° 58'30" and 70° 51'50" North (Figure 1). In response to the increase in urbanization, demands on natural resources have also been increasing rapidly with land use for building increasing and urban areas expanding.

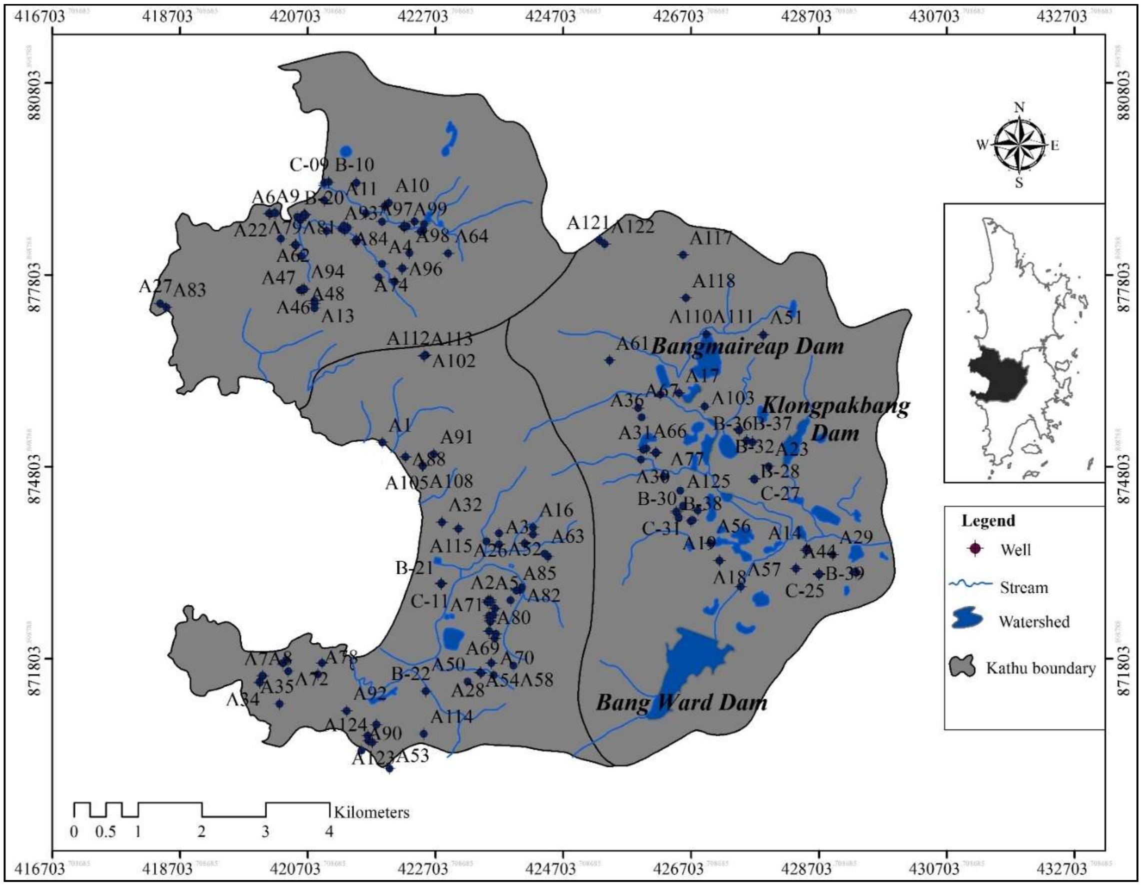

Figure 1 Hydrogeological and well map of Kathu, Phuket

Increasing water demand is a particular problem which is leading to overuse of the available resources. The watershed areas are mainly on the western side (Kathu sub-district) of Kathu district. Kathu has 42 mining ponds and 3 dams, Bangward, Klongpakbang, and Banmaireap. The Bangward dam is located at the biggest watershed area in Phuket with a water capacity of 7.31 million m^3. Its location in Kathu sub-district is shown in Figure 1. The Banmaireab dam can hold 4.2 m^3 of water and the Klongpakbang dam has a water capacity of 2.6 m^3. The Kamala and Patong sub-districts are the coastal areas facing the Andaman Sea which are most famous for tourism.

In recent years, many deep wells have been drilled and large amounts of groundwater have been withdrawn in Phuket province and in particular in Kathu district due to increasing water demand resulting from its rapid development.

2. HISTORICAL GROUNDWATER DATA IN KATHU

Groundwater well data were gathered for the period 2006 to 2016. The data were taken from well observations (A1 – A125), well reports (B1 – B39), and published data (C1 – C34) as shown in Figure 1. The total data collected related to 1,761 data throughout Phuket for 10 years. The number of wells in Kathu, Kamala, and Patong sub-districts, was 87, 105, and 92 wells, respectively. All data were classified based on 5 parameters consisting of well location, groundwater level, layer type, layer depth, and groundwater extraction rate. All data were analysed to determine 3 main classes of information that could then be used for groundwater simulation, 1) subsurface information, 2) groundwater level changes, and 3) historical groundwater extraction.

2.1 Historical groundwater level changes

The data for groundwater level changes in Kathu were obtained from a network of observation wells and piezometers covering the Kathu, Kamala, and Patong sub-districts between 2006 and 2016. The groundwater level measurements were recorded at monthly intervals during each year. The raw data on groundwater levels were processed to show the groundwater level against the corresponding time in each sub-district with the monthly data then being accumulated into yearly data. Graphs of the groundwater level over time in Kamala, Kathu, and Patong sub-districts are presented in Figures 2a, 2b, and 2c, respectively. Finally, the groundwater level over time in the entire Kath area was established as shown in Figure 2d.

2.2 Historical groundwater extraction

The groundwater extraction data were taken from 373 data between 2006 and 2007, 461 data between 2008 and 2012, and up to 1,115 data between 2013 and 2014. The purposes for which the groundwater was used were classified into 5 sectors, 1) consumption, 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 were from the 5 sectors were combined for each year as shown in Table 1. For the groundwater extraction data in 2015 and 2016, the data were taken from the summary report of the annual groundwater situation in Thailand (DGR, 2012).

Unfortunately, water extraction data are only recorded for the entire Phuket area and are not broken down by districts or sub-

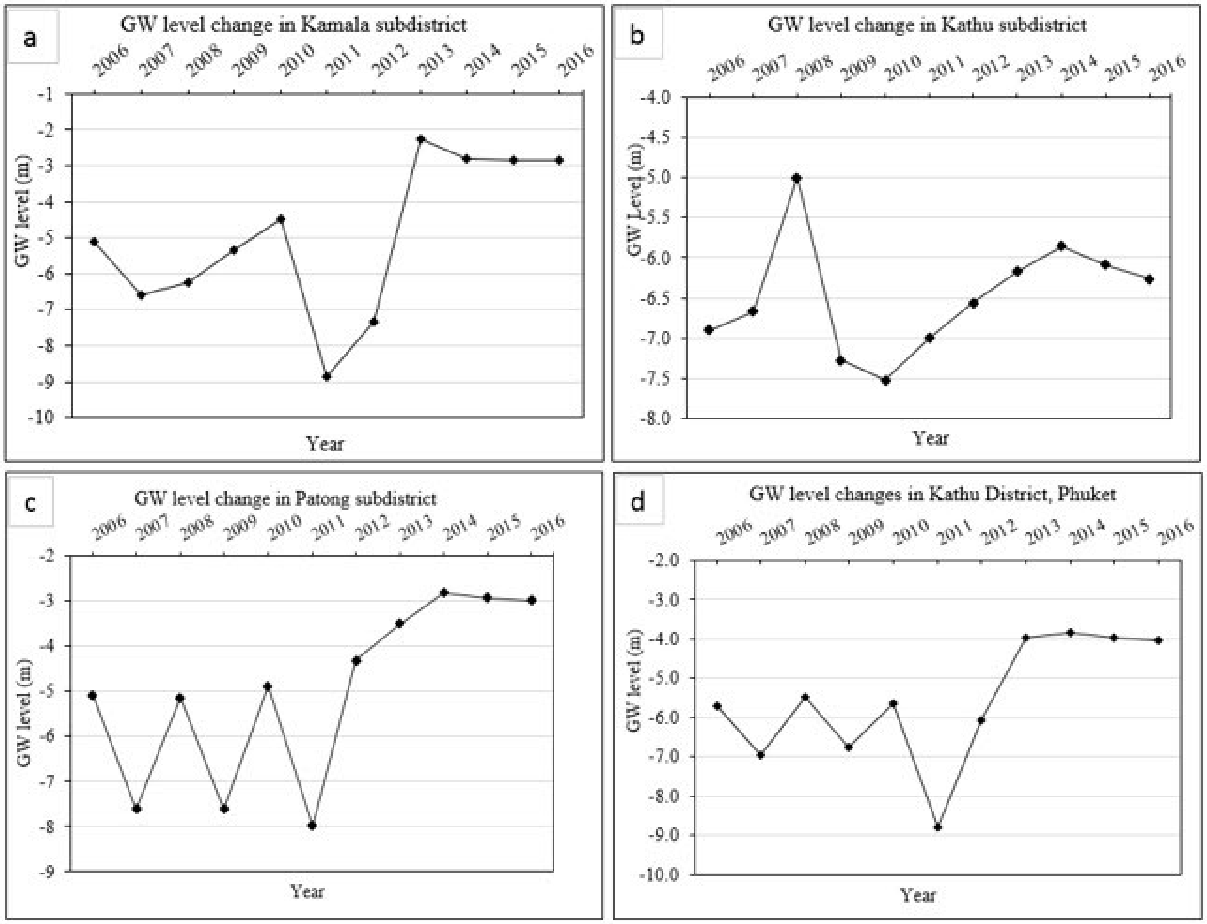

Figure 2 Groundwater level changing during 2006 to 2016: a) Kamala sub-district, b) Kathu sub-district, c) Patong sub-district, d) average Kathu district

Table 1 Groundwater extraction rate in Phuket and Kathu sub-districts during the period 2006-2016 (Source: Department of Groundwater Resources of Thailand, DGR)

Year	Average extraction rate (m^3/day)						
	Phuket	Kathu	Meung	Talang	Kathu subdistricts		
					Kamala	Kathu	Patong
2006	3,039	518	1,279	1,218	185	123	210
2007	3,549	613	1,502	1,428	219	146	248
2008	4,262	732	1,795	1,706	262	174	296
2009	4,262	732	1,795	1,706	262	174	296
2010	4,262	732	1,795	1,706	262	174	296
2011	4,262	732	1,795	1,706	262	174	296
2012	4,262	732	1,795	1,706	262	174	296
2013	19,067	3,303	8,096	7,695	1,180	787	1,337
2014	40,330	6,980	17,108	16,261	2,493	1,662	2,826
2015	51,151	8,849	21,688	20,614	3,160	2,107	3,582
2016	53,096	9,186	22,513	21,398	3,280	2,187	3,718

districts. Therefore, the extraction data for each sub-district (i.e., Kamala, Patong, and Kathu) in the Kathu district were estimated based on the distribution of wells in the three areas, on the assumption that the amount of groundwater extracted was proportionate to the number of wells in the areas. Well distribution data from Saowanee et al. (2012) were used to calculate the ratios of the wells in the Kamala, Patong, and Kathu areas. In 2012, the total number of wells in Phuket was 1,211 and Kathu district had 210 wells equivalent to 17.3% of the total. Similarly, Kathu's, three subdistricts, Kamala, Kathu and Patong had 75, 210, and 50 wells, respectively, equivalent to 35.7%, 23.8%, and 40.5% of the total wells in Kathu district, respectively. Table 1 shows the average rate of groundwater extraction in Phuket and in each sub-district of Kathu from 2006 to 2016. The trend of the average groundwater extraction in Kathu district is shown in Figure 3.

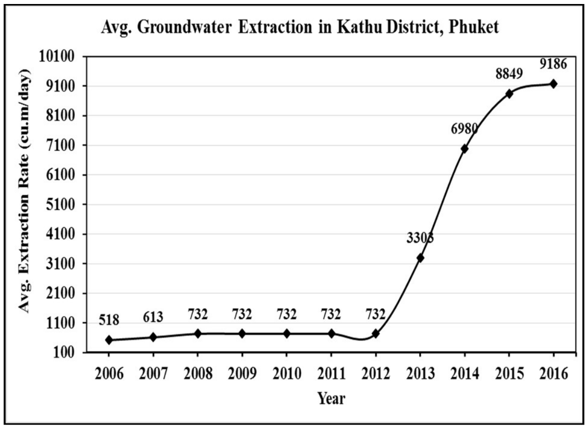

Figure 3 Groundwater extraction average rate in Kathu, Phuket from 2006 – 2016

3. GROUNDWATER SIMULATION

The groundwater simulation was performed based on historical groundwater data which were collected and analysed from the well data. The PMWIN-MODFLOW software application was used to simulate the groundwater level in the study areas. The Kathu district was chosen for simulation because of its geological location and because, based on the information recorded by the local government, its growth and development, are more rapid than the other two districts, Thalang and Meung. The simulations were conducted for the entire Kathu district as described below in sections 3.1, 3.2, and 3.3.

3.1 Subsurface geometry

Three subsurface layers of Kathu were identified as shown in Figure 4. The first layer consists of fine grain sediments (soil, clay, and clayey sand) with an average depth of 13.52 m and the second layer is weathered and fractured rock with an average depth of 40.04 m. The last layer is the base rock composed of granite and some shales with an average depth of 81.76 m. Therefore, the aquifer of Kathu district in each of the sub-districts (Kamala, Kathu, and Patong) is formed by the first and second layers as an unconfined aquifer. The Kathu aquifer is part of an unconsolidated aquifer known as the Rayong-Satoon aquifer.

The subsurface geometry shows that in all 3 sub-districts, the second layer is thicker than the first layer. The aquifer in the Kathu sub-district is thinner than in the Kamala and Patong sub-districts, but there is actually little difference, i.e. the Kathu aquifer is 51.23 m thick, compared to the Kamala and Patong aquifers which are 56.45 and 52.99 m thick, respectively. Consequently, in the groundwater modelling the aquifer geometry was averaged across the three aquifers to a thickness of 53.56 m including the first layer consisting of fine grain layer (soil, and clayey sand) with an average depth of 13.52 m and the second layer of weathered and fractured rock with an average depth of 40.04 m.

3.2 Groundwater modelling

Groundwater modelling was used to build a numerical model for the study area based on the average thickness of the Kathu aquifer as set out above using PMWIN-MODFLOW. The groundwater flow model produced by PMWIN-MODFLOW is based on a finite difference of three dimensional models simulating underground flow under steady and unsteady conditions in anisotropic and non-homogeneous porous media, which is described by the partial differential as follows

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

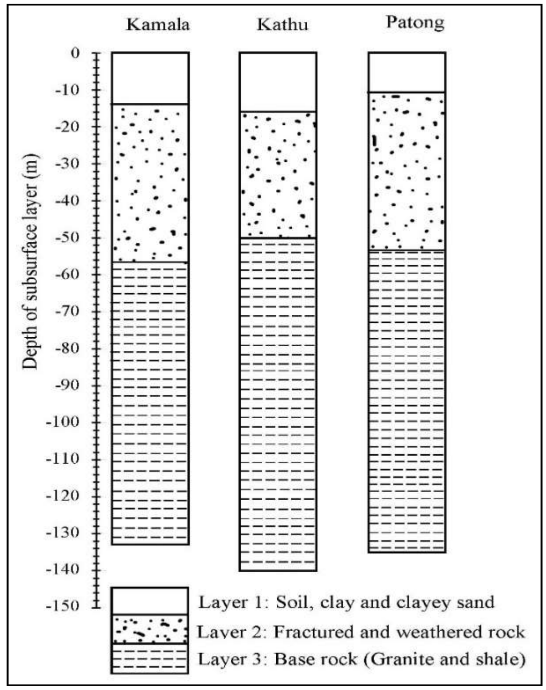

Figure 4 Sub-surface layers in each sub-district in Kathu, Phuket

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 (L/T); h is the potentiometric head (L); 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 (T^{-1}); S_s is the specific storage of the porous material (L^{-1}); and t is time (T).

The aquifer model was set up as a double unconfined aquifer system with the simple model of 30 x 30 subdivisions and 500 x 500 m cell sizes. The boundary condition was set to be no flow boundary along the district boundary of Kathu varying from year to year and flow boundaries. Figure 5 illustrates the no flow boundary of the simulation in the Kathu district. The cells of the model were divided into fixed-heads based on the DEM map and its aquifer condition. The boundary cells of the model were calculated based on the fixed-heads. Hydraulic heads were calculated in active cells. The physical parameters used in the model are shown in Table 2. The hydraulic conductivity and porosity of the soil and clayey sand were estimated by boring log data, while standard values of the hydraulic conductivity and porosity were selected to represent the second layer of the fractured and weathered rocks.

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)	6E-09
2	Coarse grain (weathered and fractured rock)	Porosity (ϕ)	0.31
		Hydraulic Conductivity (k, m/s)	1.09E-06

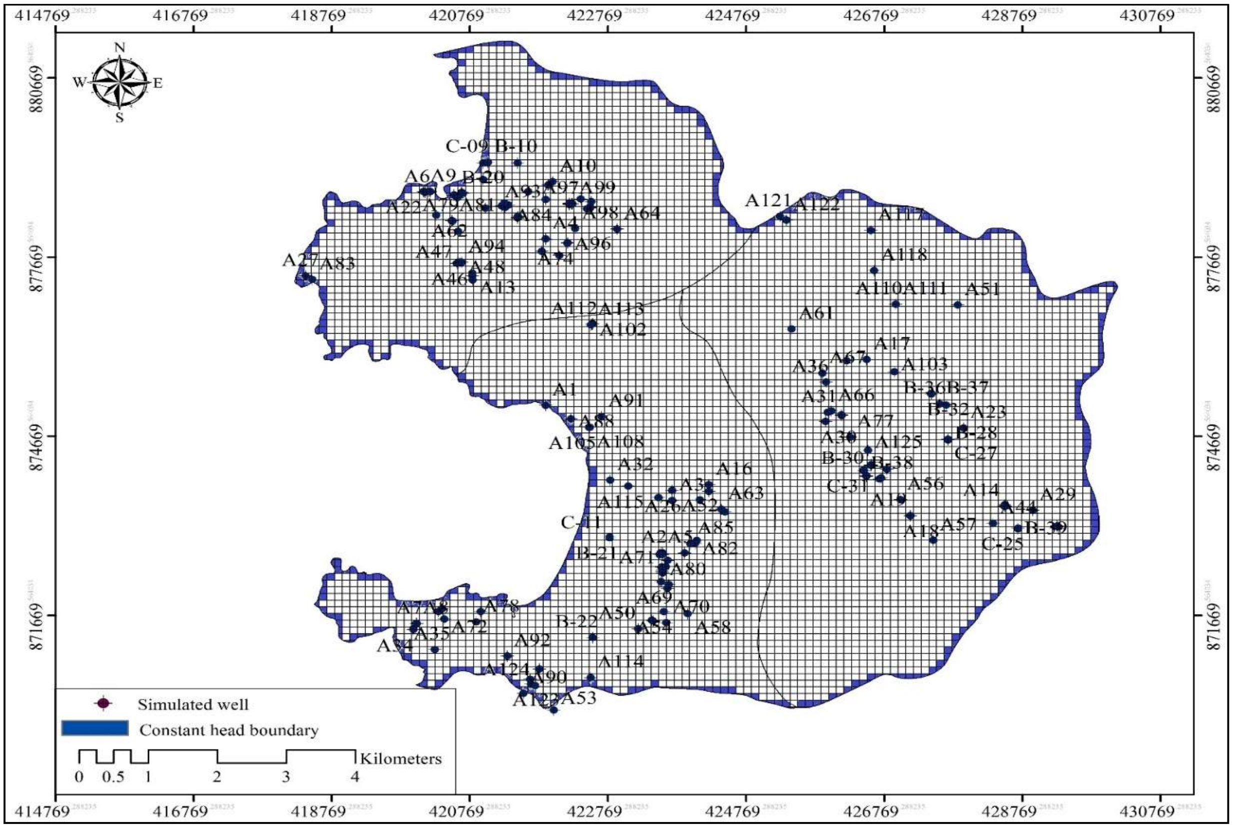

Figure 5 Kathu groundwater model with boundary conditions and the distribution of wells over the Kathu district

3.3 Model calibration

The availability of observed groundwater data is very important for groundwater modelling. The time period between 2006 and 2016 was selected based on the availability of a time series of observed hydrological, meteorological, and groundwater data for the Kathu district. A recharge estimation was performed using a trial and error operation based on the assumption that the groundwater level reacts to the recharge and discharge components as characteristics of the groundwater system (ΔRecharge - ΔDischarge = ΔGroundwater Level). The recharge estimation was conducted several times, each time noting and eliminating errors until a match was achieved between the model results (groundwater level) and the historic groundwater table based on field measurements. This model calibration was an iterative process and the model with resulted (groundwater level) and the historic groundwater table of the field measurement were matched within plausible ranges (Figure 6).

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) are therefore based on an iterative process matching the historic field-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. Verification was performed based on a comparison of the observed and simulated results. There was in good agreement in all areas, with an R^2 are 0.9237 as shown in Figure 6.

Hence, it can be concluded that this model resulted in an accurate simulation. As 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.

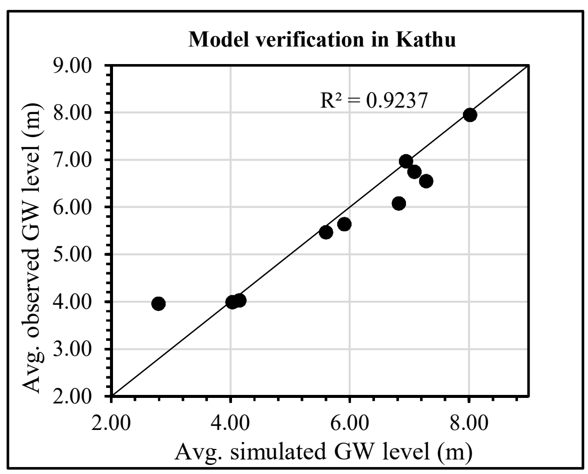

Figure 6 Calibration of simulated and observed groundwater

4. RESULTS AND DISCUSSIONS

The historical groundwater level changes are shown in Figure 2. It can be observed that the groundwater level fluctuated during the period 2006 to 2010, but in 2011 it decreased remarkably recovering in the following year. However, the average groundwater level in Kathu, Phuket increased over the period (Figure 2). While, the groundwater is steeply produced in the last 5 years (Figure 3).

The recharge flux from the groundwater simulations in Kathu district, as shown in Figure 7, increased slightly during the period, 2006-2012, while the trend of the recharge flux increased remarkably in 2013 remaining constant until 2016. Overall, the average recharge flux in the Kathu district (Figure 7), increased as a result of the increased groundwater level. The historical data for groundwater extraction in Kathu shows a remarkable increase from 2012 to 2016, but the groundwater level has been sustained by the recharge in the study area as discussed above. There are several reasons for the changes in the recharge level over the last 10 years in the Kathu district. Firstly, rainfall has maintained the level of groundwater recharge as shown in Figure 8. The rainfall data shows that rainfall has been higher on Phuket Island compared to other parts of the country. Secondly, the Kathu aquifer can store water and infiltrate and contact other water sources, directly. Moreover the characteristics of the Kathu aquifer which is an unconfined aquifer of significant depth which is close to the surface is able to generate a high groundwater potential. Thirdly, Phuket is located at a coastal area where the groundwater can be recharged by seawater intrusion caused by a rising sea level. Recharge from seawater intrusion is supported by the report of the NOAA (2016) which stated that the Andaman Sea level is rising by an average of about 4.91 mm/year (Figure 9).

Finally, the noticeable increase in recharge levels in 2012 and 2013 is due to new dams coming into use in Kathu which are able to collect water from local watersheds. Kathu now has 42 mining ponds and 3 huge dams. The Bangward dam, as shown in Figure 1, is the biggest dam in Phuket and has a water capacity of 7.31 million m3 and the Bangmaireab and Klongpakbang dams have water capacities of 4.2 million m3 and 2.6 million m3, respectively (ISET et al., 2013). Obviously, therefore, the watershed areas are the most significant mechanism by which groundwater recharge can be maintained in the Kathu, district.

5. CONCLUSION

Phuket Island is strategically located as a natural port and has a high population. Groundwater is a significant source of freshwater used for all purposes but the island lacks land to store water and produce natural resources. This problem is exacerbated by its high population, and growth in industrialization and urbanization has led to a dramatic increase in the demand for water, and groundwater may not be able to meet that demand in the future. Based on ISET et al. (2014), in 2015, the maximum of water demand in Phuket reached the water limitation of around 120,000 m^3/day and this demand has continued to increase. In addition, over extraction of groundwater, and land use and land cover changes are the significant factors which impact the recharge flux rate, 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 modelling described in this paper was carried out in the Kathu district of Phuket to simulate the groundwater recharge flux based on historical groundwater data using the PMWIN-MODFLOW software application in a trial and error process. The result of verification between historical and simulated data shows good agreement represented by an R^2 of 0.9237. Thus, it can be concluded that this simulation method is reliable for the estimation of the recharge rate with a high degree of accuracy. The groundwater level and the recharge flux in Kathu have overall, gradually increased in. 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 water collected and stored from the island's watersheds. Annual rainfall is still high on Phuket Island, and can help to maintain groundwater recharge. The characteristics of the Kathu aquifer are also significant factors in how the aquifer stores water and allows infiltration from and direct contact with other water sources. The Kathu aquifer's characteristics are able to produce high recharge and to generate high groundwater potential. The rising sea level is also a factor, allowing intrusion into the mainland aquifer resulting in higher recharge levels. In addition, Kathu has exploited local watersheds to maintain water supply for the entire island by building dams, and water from streams and canals also help to maintain recharge levels. Hence, groundwater recharge is still maintained in Kathu and helps to sustain the groundwater level.

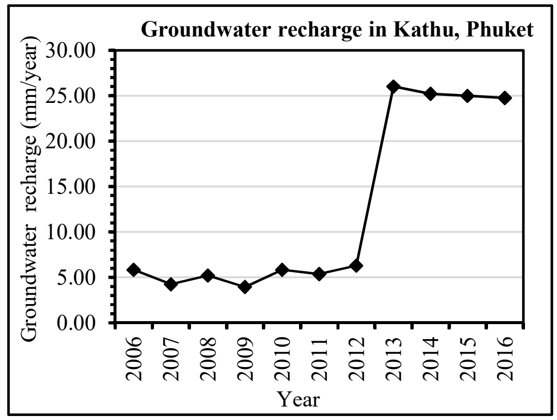

Figure 7 Recharge flux in Kathu district during 2006-2016

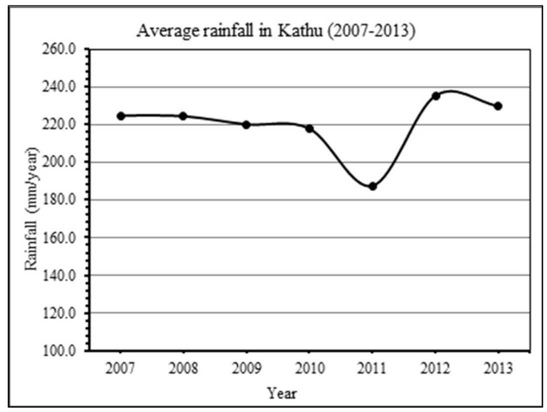

Figure 8 Rainfall data in Kathu Phuket during 2007-2013

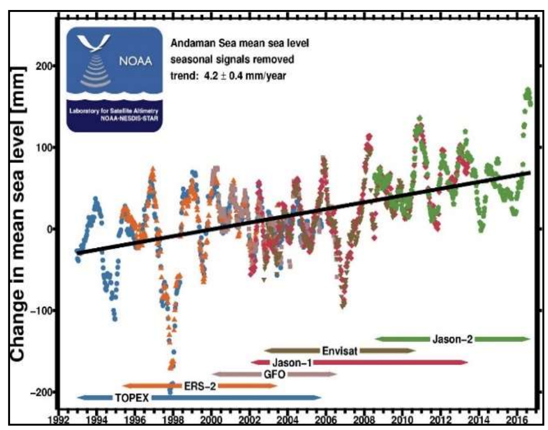

Figure 9 Andaman Sea level rising during 1992 – 2016 (NOAA, 2016)

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7. REFERENCES

Department of Groundwater Recourse (DGR), (2012) "Completed Report: Groundwater well observation, study of specific network groundwater well, and groundwater consumption evaluation for groundwater management". D.M. Printing Co., LTD, Bangkok.

Healy, W. R., and Cook, G. P., (2002) "Using groundwater levels to estimate recharge, "Hydrogeology Journal, 10, pp91-109.

Lerner, N. D., (1990). "Groundwater recharge in urban Areas". IAHS, 198.

Institute for Social and Environmental Transition-International (ISET), Thailand Environment Institute (TEI), and Vietnam National Institute for Science and Technology Policy and Strategy Studies (NISTPASS). (2013) "Mekong-Building Climate Resilient Asian Cities: M-BRACE". Institute of Social and Environment Transition-International Bangkok, Thailand, p98.

Institute for Social and Environmental Transition-International (ISET), Thailand Environment Institute (TEI), and Vietnam National Institute for Science and Technology Policy and Strategy Studies (NISTPASS). (2014) "Urban Vulnerability in Southeast Asia Summary of Vulnerability Assessments in Mekong-Building Climate Resilience in Asian Cities (M-BRACE)". Institute for Social and Environment Transition-International Bangkok, Thailand, p58.

NOAA, (2016) "Andaman Sea level rising during 1992 – 2016", Available online, https://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/LSA_SLR_timeseries_regional.php

Papagorn, B. and Sangdao, W., (2012) "Land use change and the town planning policy of Phuket". groundwater potential modelling using GIS in Phuket province, Thailand", Proceedings of the 33rd Asian Conference on Remote Sensing, Pattaya, Thailand, pp1-4.

Saowanee, C., Chanida, S. and Pun, T., (2012) "Impacts of interpolation techniques on groundwater potential modelling using GIS in Phuket province, Thailand". Proceedings of the 33rd Asian Conference on Remote Sensing, Pattaya, Thailand, pp1-7.

Scosbie, S. R., Binning, P., Kalma, D. J., (2005) "A time series approach to inferring groundwater recharge using the water table fluctuation method". Water Resource research, 41, Issue 1, pp1-9.

Sophocleous, A. M., (1991) "Combining the soil water balance and water-level fluctuation methods to estimate natural groundwater recharge: Practical aspects". Journal of Hydrology, 124, pp229-241.

Yang, Y., Lerner, D. N., Barrett, M. H., Tellam, J. H., (1999) "Quantification of groundwater recharge in the city of Nottingham, UK". Environmental Geology, 38, Issue 3, pp183-198.