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Hydrogeological characterization of groundwater resources in Kathu District, Phuket

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សង្ខិត្តន័យ

កាធូ (Kathu) ជាស្រុកមួយស្ថិតក្នុងខេត្តភូកេត កោះភូកេតនៃប្រទេសថៃ ដែលមានភាពរីកចម្រើនខ្លាំង និងមានប្រជាជនរស់នៅយ៉ាងច្រើន។ ការរីកដុះដាលនៃទីក្រុងដែលមានសន្ទុះយ៉ាងលឿនឥតឈប់ឈរនេះ អាចបណ្តាលឲ្យមានការខ្វះខាតទឹកយ៉ាងធ្ងន់ធ្ងរទៅថ្ងៃអនាគត។ ការសិក្សានេះធ្វើការពិនិត្យទៅលើលក្ខណៈពិសេសនៃប្រភពទឹកក្រោមដី ដើម្បីសិក្សាពីស្ថានភាពនៃបញ្ហាទឹកក្រោមដីនៅស្រុកកាធូនេះ។ ទិន្នន័យទឹកក្រោមដីត្រូវបានប្រមូលចេញពីអណ្តូងស្នប់នានានៅតំបន់នោះ ដើម្បីស្វែងយល់កាន់តែច្បាស់អំពីប្រវត្តិនៃបម្រែបម្រួលនីវូទឹកក្រោមដី ដោយពិនិត្យទៅលើលក្ខណៈផ្សេងៗនៃស្រទាប់សិលាដែលអាចស្រូបនិងផ្ទុកទឹកផងដែរ។ វិធីសាស្រ្ត Cooper-Jacob distance-drawdown ត្រូវបានយកមកអនុវត្តដើម្បីវាយតម្លៃកម្រិតលំហូរនៃទឹកឆ្លងកាត់ស្រទាប់ឆ្អែតទឹក (Transmissivity) ដែលហៅកាត់ថា T និងកម្រិតបញ្ចេញនិងផ្ទុកទឹកនៃស្រទាប់ឆ្អែត (Storativity) ដែលហៅកាត់ថា S ដោយផ្អែកលើទិន្នន័យ

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តាមអណ្តូងនីមួយៗ។ ផែនទីនៃការប៉ាន់ស្មានសក្តានុពលទឹកក្រោមដីត្រូវបានបង្កើតឡើងតាមវិធីសាស្ត្រវិភាគត្រួតគ្នា ដោយប្រើបច្ចេកវិទ្យាប្រព័ន្ធព័ត៌មានភូមិសាស្ត្រ ដែលហៅកាត់ថា GIS ដើម្បីសិក្សាសក្តានុពលទឹកក្រោមដី។ ទំនាក់ទំនងជិតស្និទ្ធរវាងតម្លៃ T និងសមត្ថភាពជាក់លាក់ SPC របស់អណ្តូងនីមួយៗត្រូវបានអង្កេត ដោយប្រើមេគុណកំណត់ R^2 = ០.៩៨៣។ លទ្ធផលនៃការសិក្សាបានបង្ហាញថា តម្លៃ T និង S និងសក្តានុពលទឹកក្រោមដីមានកម្រិតខ្ពស់បំផុតនៅឃុំកាធូ (Kathu) ដែលស្ថិតនៅភាគខាងកើតនៃស្រុកកាធូ (Kathu)។ ការសិក្សានេះបង្ហាញលទ្ធផលត្រូវគ្នានឹងលទ្ធផលនៃការសិក្សាអំពីសក្តានុពលទឹកក្រោមដីរបស់ Charoenpong, Suwanprasit, និង Thongchumnum (2012) ផង និងបានបង្ហាញពីភាពកាន់តែលម្អិតនិងកាន់ត្រឹមត្រូវផង ដោយសារការអនុវត្តវិធីសាស្ត្រនីមួយៗសុទ្ធតែត្រូវបានផ្ទៀងផ្ទាត់ ដើម្បីឲ្យការប៉ាន់ស្មានសក្តានុពលទឹកក្រោមដីមានភាពជឿជាក់។

Abstract

Kathu is a densely populated and rapidly urbanizing district in Phuket City, Phuket Island in Thailand. Urban growth is accelerating demand for groundwater, with water scarcity expected to become a serious problem in the future. This study characterizes the subsurface hydrogeological conditions in Kathu to assess this groundwater problem situation. Groundwater data were collected from boreholes to better understand the historical context of variations in groundwater levels, along with the properties of aquifer, such as aquifer thickness, in the region. The Cooper-Jacob distance-drawdown method was used to estimate the transmissivity (T) and storativity (S) of each well, which was then mapped using a GIS overlay method to estimate groundwater potential. A close correlation between T and the specific capacity (SPC) of each well was observed with a coefficient of determination (R^2) of 0.983. The highest T, S and groundwater potential were observed in Kathu sub-district in the eastern part of Kathu. The results for groundwater potential show good agreement with those of Charoenpong et al. (2012), whereas the present study is more detailed and accurate. Thus, the method used in this study has been verified as viable for reliably estimating groundwater potential.

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Keywords: hydrogeological characterization, groundwater potential, transmissivity, storativity, aquifer, overlay

Background

Phuket is the largest island in Southern Thailand, with an area of 543 km^2, and an annual average rainfall of 2,500 mm (TMD, 2014). Phuket Island is a renowned tourist destination and in recent years has experienced rapid growth in both population and tourism, coupled with rapid urbanization. Kathu District) is a major site of this growth due to the popular tourist beaches of *Pa Tong* and *Kamala*. Between 1997 and 2011, the population of the district increased by 58.6%, from 221,835 to 351,909 people. More recently, tourists visits to Phuket increased from 2.5 million in 2009 to 12 million in 2015 (ISET, 2013, 2014). This growth has seen an increase in the construction of new buildings, especially large hotels and other infrastructure (Charoenpong et al., 2012). These factors combined have caused a dramatic increase in water demand, placing increased pressure on groundwater resources on the island. Thus, securing a sustainable water supply in Kathu has become a priority agenda across multiple sectors (A Puttiwongrak, Kong, & Vann, 2018).

Groundwater is the primary water supply for Kathu District. Over the last few decades, groundwater extractions have declined across the entire island, leading to increased interest in groundwater research in Phuket (Charoenpong et al., 2012). Despite this, water supply has not been able to keep pace with the maximum daily water demand, which is expected to rise to over 180,000 m^3/day by 2025 (ISET, 2014).

Groundwater availability is a key constraint to future development on Phuket Island, especially in Kathu District. Surface water resources are limited

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and mainly located mainly to the west of Kathu, in Kathu sub-district. They comprise forty-two mining ponds and three dams: *Bangward*, *Klongpakbang*, and *Banmaireap*. *Bangward* dam in Kathu sub-district has the largest catchment, with a capacity of 7.31 million m^3. Improved knowledge of the groundwater potential in Kathu is urgently required.

Previously, Charoenpong et al. (2012) has monitored groundwater potential in Phuket Province. They used an inverse distance weighting method to predict trends in the specific capacity (SPC) of groundwater resources using kriging and spline interpolation models. These results were mapped to define zones of groundwater potential in Kathu in an attempt to identify hidden groundwater resources. Additional work was then completed to extend the model to map groundwater potential zones across the whole of Phuket Island, which were compared with a map compiled from data generated by alternative methods (Charoenpong et al., 2012).

A Puttiwongrak et al. (2018) modelled groundwater recharge rates in Kathu and concluded that they were currently sufficient for maintaining groundwater levels, despite an acceleration of withdrawals particularly between 2012 and 2016. This was attributed to increased efficiency of water consumption in the catchment, higher rainfall, and rising sea levels. A second study was also conducted to determine the groundwater potential on Phuket Island using geo-electrical data. This was found to be higher in the central and northern parts of the island, along with some specific areas in the south. Meanwhile, groundwater potential was found to be poor in the far north of the island and along the eastern and western flanks (Avirut Puttiwongrak, Men, Suteerasak, & Vann, 2020).

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The present study aims to characterize the groundwater situation in Kathu and map groundwater potential and extraction rates between 2006 and 2016. Measurements for aquifer thickness, transmissivity (T), and storativity (S) will be used to assess the effectiveness of applying the Cooper-Jacob distance-drawdown method to pumping test data from observation wells. This will be followed by the use of a GIS overlay method to determined groundwater potential and compare it with historical data.

Research Methodology

Phuket City is rapidly urbanizing, shifting from a largely agricultural to a tourist economy. Kathu district has one of the highest population densities in the Phuket and is reliant on groundwater. Characterizing the subsurface hydrogeological conditions including (i) aquifer thickness (ii) flow properties; and (iii) groundwater level in the district is important for water conservation objectives.

Kathu is a relatively small district in Phuket, when compared with *Talang* or *Mueang.* The district has a land area of just 67 km^2 and is situated in the southwest of Phuket Island between longitudes 980 15’10” and 980 21’50” east and latitudes 70 58’30” and 70 51’50” north. It is surrounded by highlands (Figure 1). The district comprises just the three sub-districts of *Kathu*, *Patong*, and *Kamala*; which contain 26 settlements, more than any other district. This includes 4,386 households and a population of 6,487. Agricultural land covers 24.84 km^2 and the are 32 industrial sites across the district (ISET, 2013, 2014).

Historical groundwater data were collected for Kathu over a period between 2006 and 2016 from observations, reports, and other published data.

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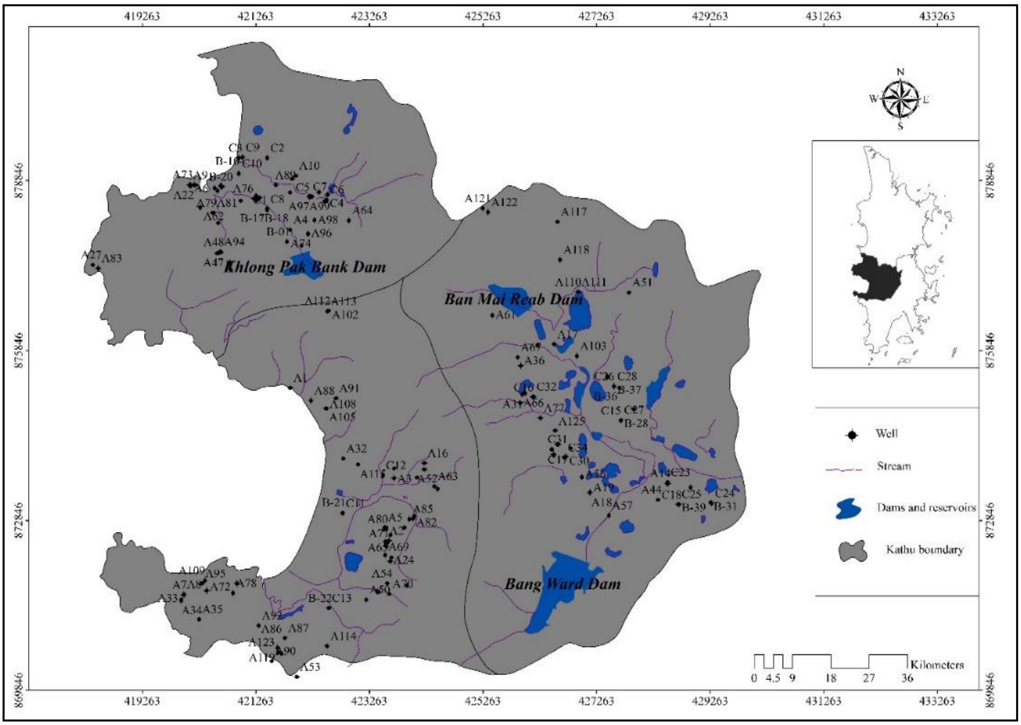
The data was disaggregated by each sub-district: Kathu, Kamala, and Patong, where 87, 105, and 92 bore wells are found respectively. Data were collected for five parameters, including location, groundwater level, layer type, layer depth, and groundwater extraction rates (Bagher & Rasoul, 2010). This data was then analysed to determine (i) subsurface properties (ii) changes to groundwater levels; and (iii) historical groundwater extraction rates across Kathu.

Figure 1. Well map for Kathu, Phuket (ISET, 2013)



Groundwater extraction data were available for 373 wells between 2006 and 2007, 461 wells between 2008 and 2012, and up to 1,115 wells between 2013 and 2016. In Kathu, groundwater consumption is classified by use in (i) households, (ii) industry, (iii) commerce, (iv) tourism and (v) agriculture. This data was recorded monthly between October 2006 and April 2014.

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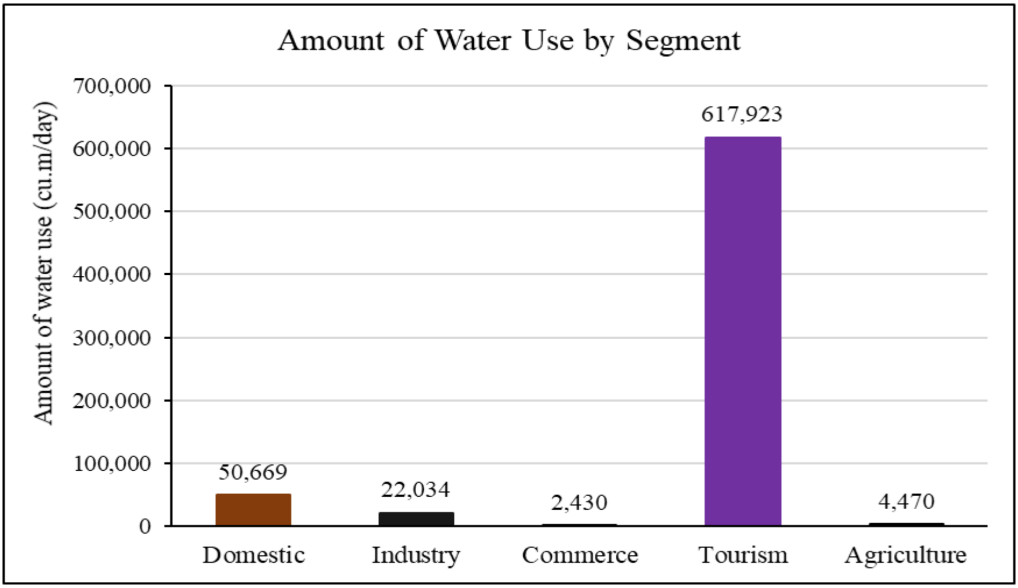
Groundwater extraction rates were disaggregated across these sectors and an annual average extraction rate was determined for the whole city (see Figure 2).

Figure 2. Water consumption by sector (2006–2016) (Source: Department of Groundwater Resources, 2012)



Extraction data for the period after April 2014 was collected from annual groundwater reports (DGR, 2012). Between 2012 and 2013 a significant gap between recharge and extraction rates was observed due to an increase in groundwater use across all sectors (ISET, 2014). Comparatively higher tourist numbers in *Kathu* (45%), were observed in the neighboring districts of *Meung* District (42%) and *Thalang* (12,.8%) (ISET, 2013). Tourist visits correlated strongly with increased groundwater withdrawals.

As these data were available for the whole island and not at the sub-district or district scale, extraction rates were estimated for each administrative area based on the distribution of wells in *Kamala*, *Patong*, and

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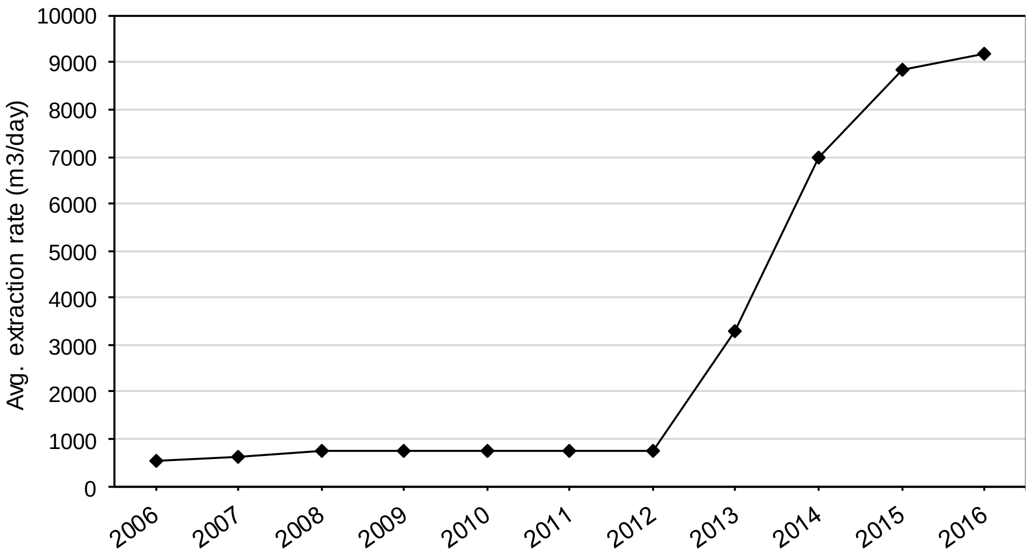
Kathu, respectively (Charoenpong et al., 2012). Phuket City has a total of 1,211 wells, of which 210 (17.3%) were located in *Kathu City*. Of the three sub-districts in Kathu, 75 (35.7%) were located in *Kamala*; 50 (23.8%) were located in *Kathu*, and 85 (40.5%) were located in *Patong*. Groundwater extraction rates at the sub-district level (Appendix 1) across each of the five sectors were combined to determine an average rate for the period between 2006 and 2016 (see Figure 3). This plot shows a significant increase in extraction rates for the period between 2012 and 2016.

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



Aquifer typology, transmissivity, and Storativity

Historical groundwater data including extraction rates and groundwater levels were collected to assist with the characterization of the properties of each aquifer such as layer type and depth. The flow properties (T and S) and each aquifer were estimated using the Cooper-Jacob distance-drawdown method (Alexander & Saar, 2012; Mutch Jr, 2005). These properties were

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mapped, before a GIS overlay method was applied to estimate the groundwater potential.

GIS overlay method

The calculated parameters were transformed into point data with geo-references (WGS 1984) using ArcGIS software to conduct a spatial analysis of the data. Thematic maps of aquifer thickness, S and T were developed as base maps, before they were combined using a weighted overlay method (Kura et al., 2014; Nagarajan & Singh, 2009) to generate a map of groundwater potential for Kathu. Areas with low S values associated with high T values indicate a zone of good groundwater potential (Ndatuwong & Yadav, 2015).

Results and Discussion

Historical groundwater level trends

Monthly data on groundwater level changes were obtained from a network of observation wells and piezometers in the three sub-districts of *Kathu*, *Kamala*, and *Patong* between 2006 and 2016. Raw groundwater data were converted into annual figures for each sub-district. An average value for the groundwater level for the whole of Kathu district was calculates using data from each sub-district (see Figure 4). The groundwater level is shown to fluctuate at each location between 2006 and 2012, before recovering in 2013. The groundwater level of *Kamala* was relatively stable between 2013 and 2016, while it increased gradually at *Patong*. The groundwater level at Kathu increased and then decreased sharply between 2006 and 2010, before gradually increasing between 2010 and 2014; and then again declining between 2014 and 2016. Overall, the average groundwater level increased for

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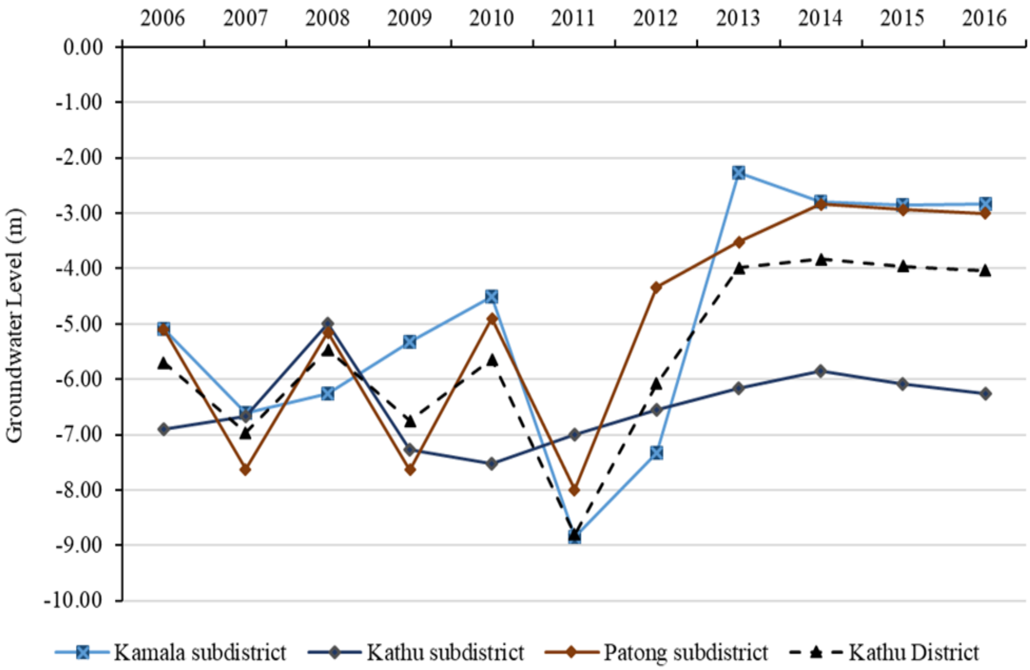
Kathu due to changes in rainfall and local aquifer properties (A Puttiwongrak et al., 2018).

Figure 4. Groundwater level changes in Kathu District (2006 – 2016)



Aquifer thickness and type

The aquifer in Kathu has three subsurface layers as shown in Figure 5a. The first layer comprises fine-grain sediments (soil, clay, and clayey sand) and has an average thickness of 13.52 m. The second layer comprises weathered and fractured rock and has an average thickness of 40.04 m. The final layer is base rock made (granite and some shale), with an average thickness of 81.76 m. Groundwater resources in each sub-district in Kathu are provided via an unconfined aquifer that extends across the first and second layers of an unconsolidated aquifer known as the Rayong-Satoon aquifer (A Puttiwongrak et al., 2018).

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Figure 5. Aquifer characterization in Kathu, Phuket. **(a)** Subsurface layers in each sub-district; and **(b)** Aquifer thickness

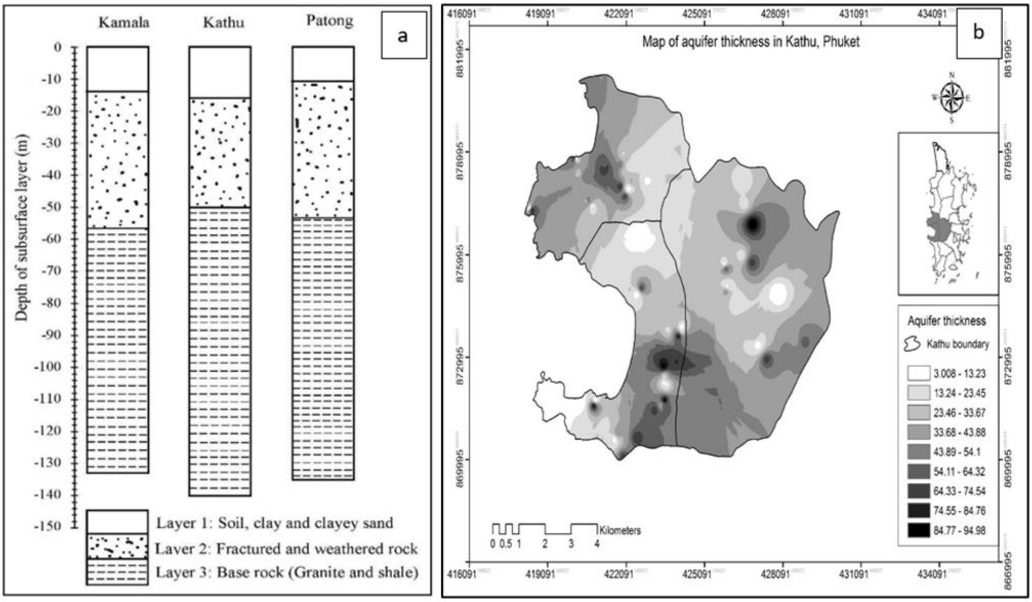

Figure 5a identifies that the second layer is thicker than the first layers in all three sub-districts. While the thickness of the aquifer in *Kathu* (51.23m) sub-district is thinner than for *Kamala* (56.45m) and *Patong* (52.99m) sub-districts, it does not vary significantly (A Puttiwongrak et al., 2018). These results have been mapped in Figure 5b, which shows that aquifer thickness varies by location. The highest groundwater potential is indicated by the thickness of the aquifer in Kathu sub-district. This has a significant impact on groundwater levels.

Transmissivity (T) and Storativity (S)

The Cooper-Jacob distance-drawdown method was applied to pumping test data (pumping rate, drawdown, time of drawdown) from the observation wells in each district. This method can directly calculate the transmissivity (T) and storativity (S) of an aquifer. The method was designed particularly for

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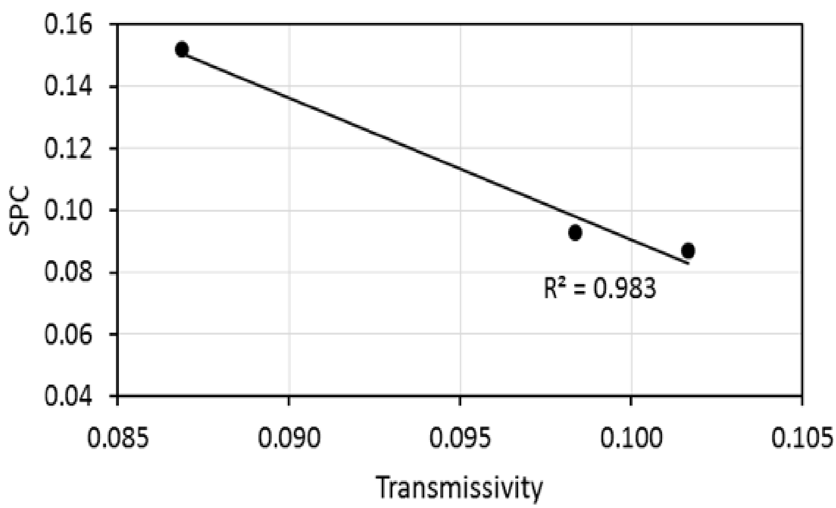
underground confinement, but may also be applied to unconfined aquifers (Alexander & Saar, 2012; Mutch Jr, 2005). The values of T and S were calculated using the following equations:

$$T = \frac{2.3Q}{2\pi(\Delta S)} \quad (1)$$

$$S = \frac{2.25Tt}{r_0^2} \quad (2)$$

where Q is the pumping rate (m^3/d); t is the drawdown time; r_0 is the distance at which the straight line intercepts the zero-drawdown axis; T is transmissivity, which is the rate of flow through a vertical strip of aquifer of unit width under a unit hydraulic gradient (m^2/d); and S is storativity, which is the volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head (dimensionless); and ΔS is drawdown per log cycle of distance.

Figure 6. A comparison of results for T and SPC



A straight line was drawn through the data points and extended to the zero-drawdown axis. The intercept (r_0) is the distance at which the pumping

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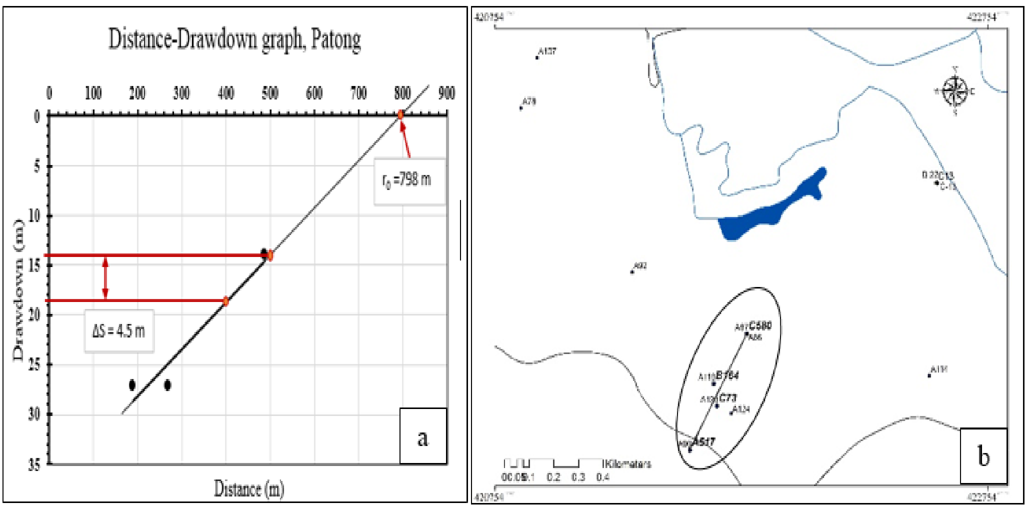
well did not affect the water level. The drawdown per log cycle of distance (ΔS) was determined using a semi-log plot of the field drawdown data (linear scale) versus distance (normal log scale). A straight line was drawn through the field data points and extended backwards to the zero-drawdown axis. The distance at the intercept of the straight line and the zero-drawdown axis was used to determine the distance of the drawdown per log cycle; then ΔS = (h_0 - h), was determined from the slope of the graph (Figure 7).

Figure 7. T and S estimation using the Cooper-Jacob distance-drawdown method. **(a)** A straight-line plot of drawdown distance in Patong sub-district; **(b)** The selection of well used for the Cooper-Jacob distance-drawdown method in Patong sub-district



The transmissivity results were verified by comparing them with previous results for specific capacity (SPC) in Phuket (Charoenpong et al., 2012), which demonstrated a strong coefficient of determination (R^2=0.983) as shown in Figure 6. The results for T and S in Kathu were mapped (Figure 8) and show that peak values for T and S are both located in Kathu sub-district.

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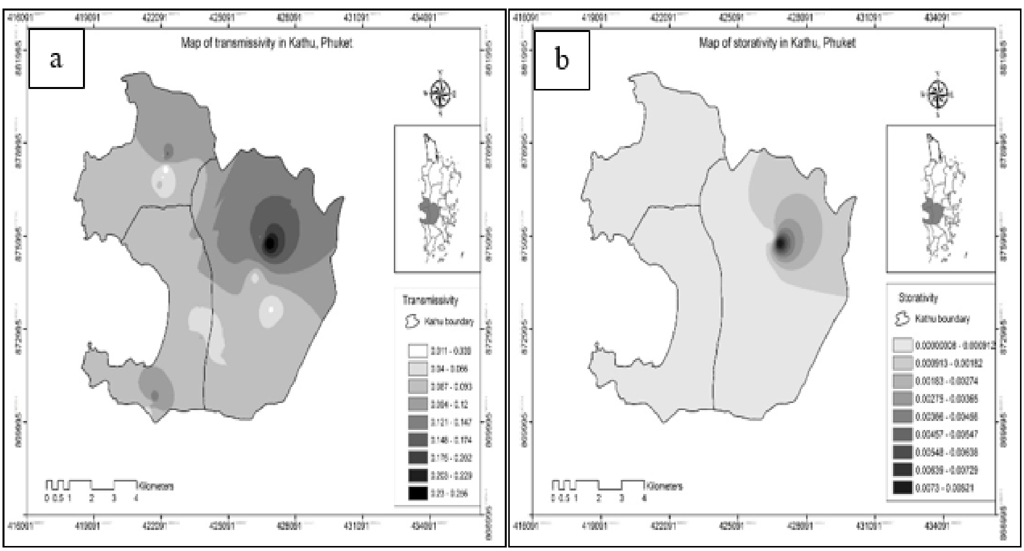
Groundwater potential in Kathu District

A GIS overlay method was used to determine the groundwater potential in Kathu district. Maps for aquifer thickness (Figure 5b), T (Figure 8a), and S (Figure 8b) were overlaid to generate a groundwater potential map depicting areas of high, medium, and low potential (Appendix 2). The map indicates that there is a high groundwater potential zone in the northeast of Phuket, with the highest groundwater potential of groundwater observed at Kathu sub-district. Most areas of the Kathu district have moderate potential, while there are some low potential zones at the junction of the border of Kamala, *Kathu*, and *Patong* sub-districts, as well as at the junction of the middle of *Kathu* sub-district and the headland of *Patong*.

Figure 8. A map of T and S in Kathu district. **(a)** Transmissivity; and **(b)** Storativity



Based on these results: (i) the average groundwater level has been shown to have increased overall due to variations in rainfall and local aquifer characteristics, driven by rapid land changes that impact groundwater

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recharge; (ii) the highest aquifer thickness results correlated with the highest groundwater potential zone at Kathu sub-district; (iii) the results for T and SPC has a coefficient of determination 0.983. When T and S were mapped for Kathu District, their values were both shown to peak in Kathu sub-district. An analysis of groundwater potential in Kathu District demonstrated a positive outcome for future groundwater extractions; and showed good agreement with previous studies (Charoenpong et al., 2012). However, the present study provides a more detailed and accurate map due to several factors.

Discussion

This analysis used bore well data to characterize the subsurface hydrogeology of *Kathu*, *Meung*, and *Thalang* Districts in terms of groundwater level, aquifer types, T and S in agreeance with results from previous studies. Groundwater levels change at different rates in different locations i.e., in Kamala and Patong they fluctuated between 2006 and 2012, before recovering in 2013. In Kamala, the recovery was relatively stable, but in Patong, groundwater levels gradually increased. In Kathu, groundwater levels declined sharply between 2006 and 2010, then increased gradually between 2010 and 2014, before a decline between 2014 and 2016. Overall, across the entire island, the average groundwater level increased. This may be explained by an increase in rainfall during the study period, local aquifer characteristics, and seawater intrusion into the aquifer (A Puttiwongrak et al., 2018).

Kathu has been found to have three subsurface layers, the first layer comprises fine-grain sediments (soil, clay, and clayey sand) with an average depth of 13.52 m. The second layer comprises weathered and fractured rock with an average depth of 40.04 m. The third layer comprises base rock (granite

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and some shales) with an average depth of 81.76 m. The groundwater resources of each sub-district in Kathu district are connected across the first and second layers by an unconfined aquifer. These unconsolidated aquifers are known locally as the Rayong-Satoon aquifer.

Results for T and S were verified by a previous study via a strong correlation between estimates for T and the SPC of groundwater resources in Phuket (R^2 = 0.983) (Charoenpong et al., 2012). This suggests that the method used in this study is reliable. Mapping the values for T & S for Kathu showed that they peaked in the same area (Kathu sub-district). A GIS overlay method was used to integrate aquifer thickness, groundwater level, transmissivity, and storativity on the same map, showing a strong correlation with groundwater potential results from a previous study at the same location (Charoenpong et al., 2012). Thus, it may be concluded that the Cooper-Jacob distance-drawdown method is reliable for estimating groundwater potential to a high degree of accuracy.

Conclusion

Kathu District, Phuket Island is a strategically located natural port, which is a highly attractive tourism destination. Groundwater is a primary source of fresh water, but a dramatic increase in demand is raising concerns about the sustainability of the resource. This problem is exacerbated by high population, urbanization, and industrialization. Over-extraction linked to land-use changes is a significant factor that impacts the rate of groundwater recharge due to increased run-off rates due to the number of buildings and other infrastructure. This has led to a decline in groundwater levels.

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The subsurface hydrogeological conditions in Kathu were characterized in the study. It was found that the average groundwater level increased overall between 2006 and 2016 due to increased rainfall and local aquifer characteristics. Aquifer thickness was shown to be a strong indicator of groundwater potential, which was higher in Kathu sub-district, which is where values for T and S were also high. A GIS overlay method was used to map groundwater potential in Kathu, which was comparable with a previous study in the same area (Charoenpong et al., 2012). The present study has produced a map that is more detailed and accurate due to a combination of several factors. Thus, it is concluded that applying the Cooper-Jacob distance-drawdown method to pumping test data from observation wells, followed by a GIS overlay method may be used to accurately groundwater potential.

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References

Alexander, S.C., & Saar, M. (2012) Improved characterization of small "u" for Jacob pumping test analysis methods. *50*(2), 256−265.

Bagher, R.M., & Rasoul, M. (2010). Effect of groundwater table decline on groundwater quality in Sirjan Watershed. *35*, 197−210.

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Charoenpong, S., Suwanprasit, C., & Thongchumnum, P. (2012) *Impacts of interpolation techniques on groundwater potential modeling using GIS in Phuket Province, Thailand.* Paper presented at the Proceeding the 33rd Asian Conference of Remote Sensing.

DGR, D. (2012) *Completed Report: Groundwater well observation, study of specific network groundwater well, and groundwater consumption evaluation for groundwater management*.

ISET, T., and NISTPASS (2013) *Urban Vulnerability in Southeast Asia: Summary of Vulnerability Assessments in Mekong-Building Climate Resilience in Asian Cities (M-BRACE)*. Retrieved from Institute for Social and Environmental Transition, Bangkok, Thailand.

ISET, T., and NISTPASS (2014) *Urban Vulnerability in Southeast Asia: Summary of Vulnerability Assessments in Mekong-Building Climate Resilience in Asian Cities (M-BRACE)*. Retrieved from Institute for Social and Environmental Transition, Bangkok, Thailand.

Kura, N., Ramli, M., Ibrahim, S., Sulaiman, W., Zaudi, M., & Aris, A. (2014) A preliminary appraisal of the effect of pumping on seawater intrusion and upconing in a small tropical island using 2D resistivity technique. *2014*.

Mutch Jr, R. (2005) A distance-drawdown aquifer test method for aquifers with areal anisotropy. *43*(6), 935−938.

Nagarajan, M., & Singh, S. (2009) Assessment of groundwater potential zones using GIS technique. *37*(1), 69−77.

Ndatuwong, L., & Yadav, G. (2015) Application of geo-electrical data to evaluate groundwater potential zone and assessment of overburden

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protective capacity in part of Sonebhadra district, Uttar Pradesh. *73*(7), 3655−3664.

Puttiwongrak, A., Kong, S., & Vann, S. (2018) Groundwater recharge estimation in Kathu, Phuket using groundwater modelling. *49*, 4-10.

Puttiwongrak, A., Men, R., Suteerasak, T., & Vann, S. (2020) Groundwater Potential Assessment Using Geoelectrical Data: A Case Study Of Phuket Island, Thailand.

TMD. (2014) *Statistics of Rainfall at Meteorology Station, Phuket Province: 2000-2012*. https://www.tmd.go.th/en/

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Appendix 1. The groundwater extraction rate in the sub-districts of Phuket and Kathu Districts between 2006 and 2016

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

Source: Department of Groundwater Resources of Thailand, DGR (2012)

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Appendix 2. Map of groundwater potential in Kathu, Phuket Island