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ALTERNATIVE APPROACH TO GROUNDWATER MODELING IN DATA-DEFICIENT REGIONS

Pinit Tanachaichoksirikun[1], Jutamas Srisuk[1], Uba Sirikaew[1] and *Uma Seeboonruang[1]

[1]School of Engineering, King Mongkut's Institute of Technology Ladkrabang, Thailand

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ABSTRACT: Groundwater modeling served as a valuable tool for understanding groundwater flow patterns and systems. In the lack of observational data region, the complexity of the groundwater aquifer posed challenges, limiting the accuracy of real-time predictions of groundwater levels. To address this problem, alternative approaches must be devised to effectively calculate groundwater flow and budget. This entails leveraging factors such as the environment, geological characteristics, as well as recharge and discharge areas to align with regional groundwater flow theories. In this study, a three-dimensional groundwater simulation model was employed to develop groundwater flow and budget using data available in 2023. The model calibration and validation processes demonstrated a close correspondence between observed and simulated hydraulic head data. Sensitivity analysis revealed that boundaries and recharge significantly influenced model outcomes. The water budget conducted under steady flow conditions highlighted the lateral groundwater inflow in the aquifer layer as a crucial recharge component. Additionally, groundwater flow from recharge to discharge zones emerged as a pivotal aspect, particularly in areas with intensive development activities. These findings held implications for groundwater management models, serving as indispensable tools for informed decision-making and alternative considerations.

Keywords: Groundwater Modeling, Approach to Groundwater Modelling, Data-Deficient Region, Modflow, Lack of Data

1. INTRODUCTION

Groundwater is the largest water source on the Earth. It is contained within the pores and fractures of underground rocks, constituting about 0.61% of the water supply and it is also one of the important water resources for human life and ecosystems [1]. The method for monitoring groundwater, i.e., drilling observation wells, was expensive cost and time-consuming [2,3]. However, in many islands e.g., Si Chang Island, the method for groundwater monitoring was challenged due to the labor, transportation, and tools. Consequently, finding alternative methods to study groundwater variability and storage potential was critical, especially for countries facing water shortages [4-6].

Si Chang Island, Thailand, was selected as a research site due to its status as a small tourist island facing water scarcity and contamination issues [7,8]. Recently, Si Chang Island's water situation was constrained by limited surface water storage capacity, given its mountainous terrain and direct connection to the Gulf of Thailand. Additionally, the existing reservoir was unable to retain water due to leakage [9]. Consequently, reliance on groundwater became crucial for Si Chang Island. However, understanding the patterns and characteristics of groundwater flow was limited. Like many other small islands, Si Chang often lacked data for groundwater analysis and development. This posed a significant challenge to the efficient utilization of groundwater resources.

Groundwater flow modeling was employed in this study to aid in decision-making, utilizing the widely used MODFLOW software to investigate the flow patterns and dynamics of groundwater systems and to enhance groundwater management [10,11]. In conjunction, modern geospatial techniques such as Geographic Information Systems (GIS) were used to prepare meteorological data, providing a more efficient and effective tool for groundwater exploration compared to traditional hydrological methods which are time-consuming and costly [12]. This approach also served as an alternative solution to address the lack of field data.

Groundwater flow modeling using MODFLOW software can estimate the water quantity under specified hydraulic conditions. In this study, the process of constructing a three-dimensional groundwater flow model was carried out in conjunction with groundwater development theory to analyze and address data gaps in the Si Chang Island area, under limited available data such as landscape characteristics, geology, soil properties, and land use. This was done to create a conceptual model and define the scope and conditions of the mathematical model, which included model calibration and validation, as well as sensitivity analysis to assess the impact of key model parameters on model outputs [13,14]. This highlights the capability of the methodology used and the adequacy of the minimal data available for studying groundwater flow in the area. Furthermore, it provides a guideline for preparing missing data for studies in small island areas facing data scarcity, like the Si Chang Island study area, in order to enable more efficient and effective planning for sustainable water resource management.

2. RESEARCH SIGNIFICANCE

A key contribution of this research lies in its development of methodologies to address data scarcity and limitations inherent in small island study areas. By synergizing theoretical frameworks with empirical field investigations to construct groundwater flow models, sufficient data can be generated to analyze groundwater flow dynamics. Moreover, fostering stakeholder engagement and interdisciplinary collaboration is essential to overcome these challenges and deepen our comprehension of hydrogeological principles. Ultimately, this research provides invaluable insights to inform water resource management strategies and sustainable development initiatives.

3. STUDY AREA

Si Chang Island is located in Tha Tew Wung Subdistrict, Si Chang District, Chonburi Province, Thailand. It was an island situated in the Gulf of Thailand, east of Sriracha District, Chonburi Province. The coordinates were in UTM Zone 47P of 1,451,000 - 1,458,000 North and 694,500 - 698,000 East. Si Chang Island covered an area of 6.45 km^2. It far approximately 117 km from Bangkok (The Capital City).

The northern and western parts of the island were characterized by the high Rocky Mountains. The eastern part of Si Chang Island was a flat area, where the communities were located. The southern part of the island was characterized by a high hill. The shape of Si Chang Island was narrow and long, with a width of 800 meters from west to east and a length of 5,800 meters from north to south. The elevation of the land surface ranges from 1 to 193 meters above mean sea level [15], as shown in Fig. 1.

Rainfall data from the Si Chang Rain Gauge Station in Chonburi Province [16], an analysis of monthly rainfall from 2012 to 2021 revealed a clear downward trend in rainfall after 2013. However, during the period 2014 to 2021, the distribution of rainfall in each month showed an increase in rainfall during the rainy season, while there was very little rainfall during the dry season. This resulted in a significant decrease in overall rainfall because of climate change on rainfall intensity and distribution.

In 2020, Thailand Land Development Department found that approximately 70% of Si Chang Island was classified as green space, consisting primarily of natural forests. Developed areas, including urban communities, account for approximately 16% of the total land area. Natural water bodies, such as reservoirs, make up approximately 1% of the island's area [17].

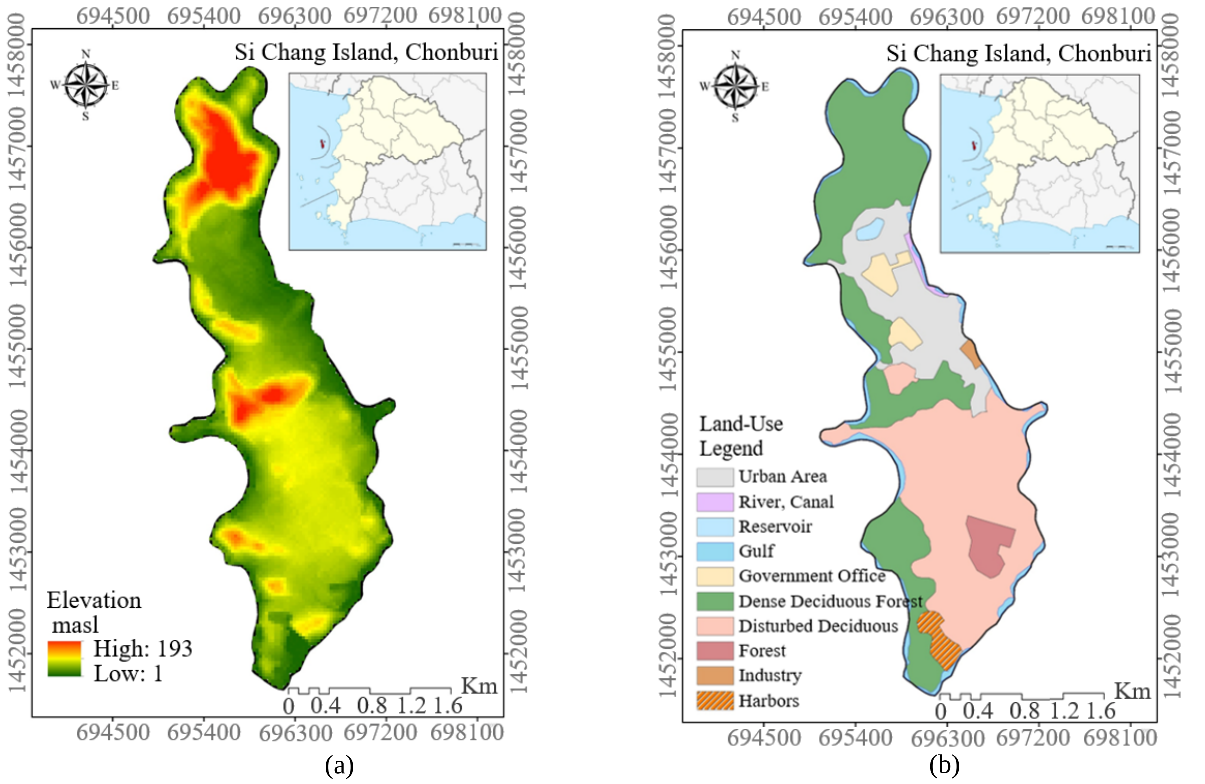


Fig. 1 Si Chang Island: (a) elevation, 2020 (b) land use, 2020

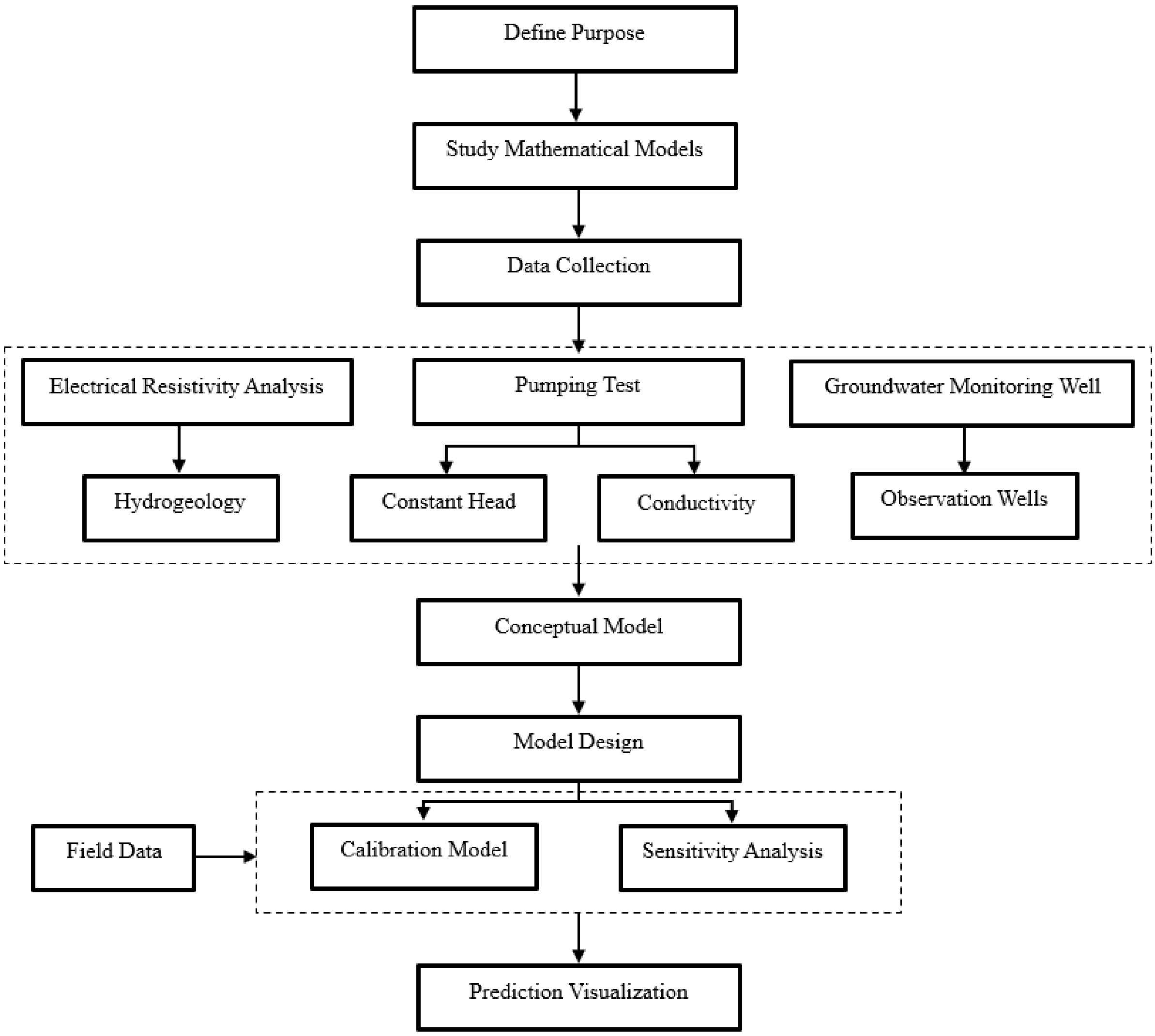


Fig. 2 Flowchart of the research

3.1 Geology

Geological Map of Chonburi Province [18], Si Chang Island was composed of sedimentary rocks belonging to the Chonburi Group, deposited during the Carboniferous-Permian (CP) period. These rocks include sandstone, argillaceous limestone, shale, and chert. These rock types possess groundwater storage properties in the form of underground limestone cavities and jointing systems [19].

Si Chang Island exhibits a distinct geological structure, with limestone mountains dominating the northern region. Most of the island is composed of limestone, except for the eastern side between Laem Wang and Laem Hin Khao, and a small portion in the southwest near the southern tip of the island, where granite is found. The western coastline of Si Chang Island is characterized by a combination of sandy beaches, rocky outcrops, and cliffs. These geological features suggest that groundwater is primarily stored within the limestone aquifers. However, the estimated groundwater potential is relatively low, with a yield of less than 2 m^3/hr. and a total dissolved solids (TDS) concentration of less than 500 mg/l.

4. METHOD

Fig.2 illustrates the research process. The data used in the study was collected from field surveys, the Royal Thai Survey Department, the Thailand Land Development Department, the Thai Meteorological Department, and the Si Chang Local Government. Due to limited data on Si Chang, lack of field surveys, and budget support, the analysis of water resources and groundwater storage on Si Chang was conducted by integrating geographic information system (GIS) technology [12], and the groundwater model (MODFLOW) to simulate the characteristics of the area and groundwater flow, as well as calibrating and validating the model with data from field surveys to ensure accuracy and precision.

This research gathered preliminary data on Si Chang Island from government agencies. However, the data was found to be insufficient for analysis to create a conceptual model and define the model's scope. The lack of data on hydrogeological characteristics, observation wells, hydraulic conductivity coefficients, and groundwater levels was identified as a major limitation in constructing a groundwater flow model. Therefore, field surveys are necessary to collect additional data and analyze parameters using groundwater development theories. This will enable the analysis and management of missing data on Si Chang Island, see Table 1.

Table 1. Data Analysis of Si Chang Island

Model List	Data Analysis	Source
General	Elevation	Royal Thai Survey Department
	Hydrogeology	Electrical Resistivity Analysis
Hydraulic Head	Observation Wells	Groundwater Monitoring Well
Aquifer Properties	Conductivity	Pumping Test
Boundaries	Constant Head	Pumping Test
Recharge	Land use	Land Development Department
	Rainfall	Meteorological Department

5. CONCEPTUAL MODEL AND BOUNDARY CONDITION

A conceptual model was developed based on an analysis of the topography, geology, hydrogeology, soil layer, and land use. This analysis revealed suitable boundary conditions for the island. The top of the model was defined as a recharge boundary, as the upper zone receives rainfall that infiltrates into the groundwater system. This is one of the most critical boundary conditions. The recharge rate was determined by analyzing land use data, soil layers, and climatic data. The external boundary of the model was defined as a constant head boundary, as the island is surrounded by the sea. Data for this boundary was analyzed using pumping test results due to limitations in the availability of observation wells in the area. Groundwater pumping from wells was defined as a pumping boundary using the well package. The hydraulic conductivity and aquifer thickness were used to determine the pumping rate from each layer in the model. The bottom of the model was defined as a no-flow boundary, as the underlying bedrock is impermeable. Additionally, although there is one reservoir on the island, it does not store water and therefore was not defined as a lake boundary. Groundwater pumping from wells was defined as a pumping boundary, as shown in Fig. 3.

This modeling, Visual MODFLOW, the most widely used software for creating three-dimensional groundwater flow models, was selected. Utilizing the Finite-Difference Method, MODFLOW was developed by hydrogeologists Michael McDonald and Arlene Harbaugh in 1988 to study, understand, and advance the field of hydrogeology [20]. Visual MODFLOW divides the study area into equal-sized rectangular cells using the Finite-Difference Method and employs numerical methods to solve the governing equations for groundwater flow. These equations are transformed into a system of linear algebraic equations and then solved iteratively. In this case, the model domain is discretized into a grid with a cell size of 35×35 meters, resulting in 20,000 cells. The grid was divided into 100 columns (east-west direction) and 200 rows (north-south direction). Additionally, the model is divided into 6 layers. The topmost layer is defined as the topsoil, which is an unconfined aquifer. The second layer is defined as the sediment layer. Layers 3 to 5 are defined as confined aquifers composed of limestone. The bottom layer is defined as the bedrock, which is an impermeable boundary. The thickness of each layer is determined by the hydrogeological characteristics of the area.

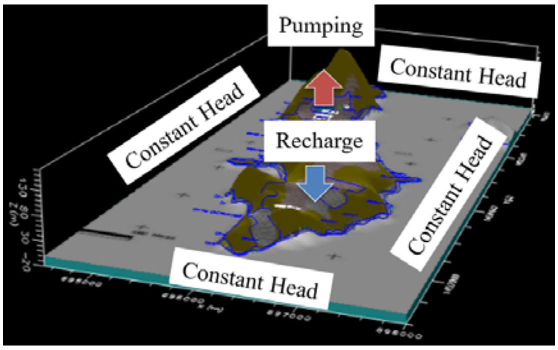


Fig. 3 Conceptual model of Si Chang Island

5.1 Electrical Resistivity Measurements

Si Chang Island lacks hydrogeological data because it is a small island that has not yet been surveyed for soil strata characteristics, groundwater layer arrangements, and groundwater types in the area by government agencies. Access to information is therefore limited. Thus, fieldwork was conducted to perform additional geophysical surveys on Si Chang Island to study the hydrogeological structure of the area. The method used for the survey was specific electrical resistivity measurements. The data from the survey were analyzed and interpreted to determine the depth, thickness, and types of soil and rock layers, as well as the appropriate depth for drilling groundwater wells. This is a preliminary and crucial step in groundwater exploration, as the data obtained from the survey are efficient in terms of cost, time, and data coverage [21]. For this survey, the Schlumberger electrode configuration was chosen.

The raw data from the field resistivity

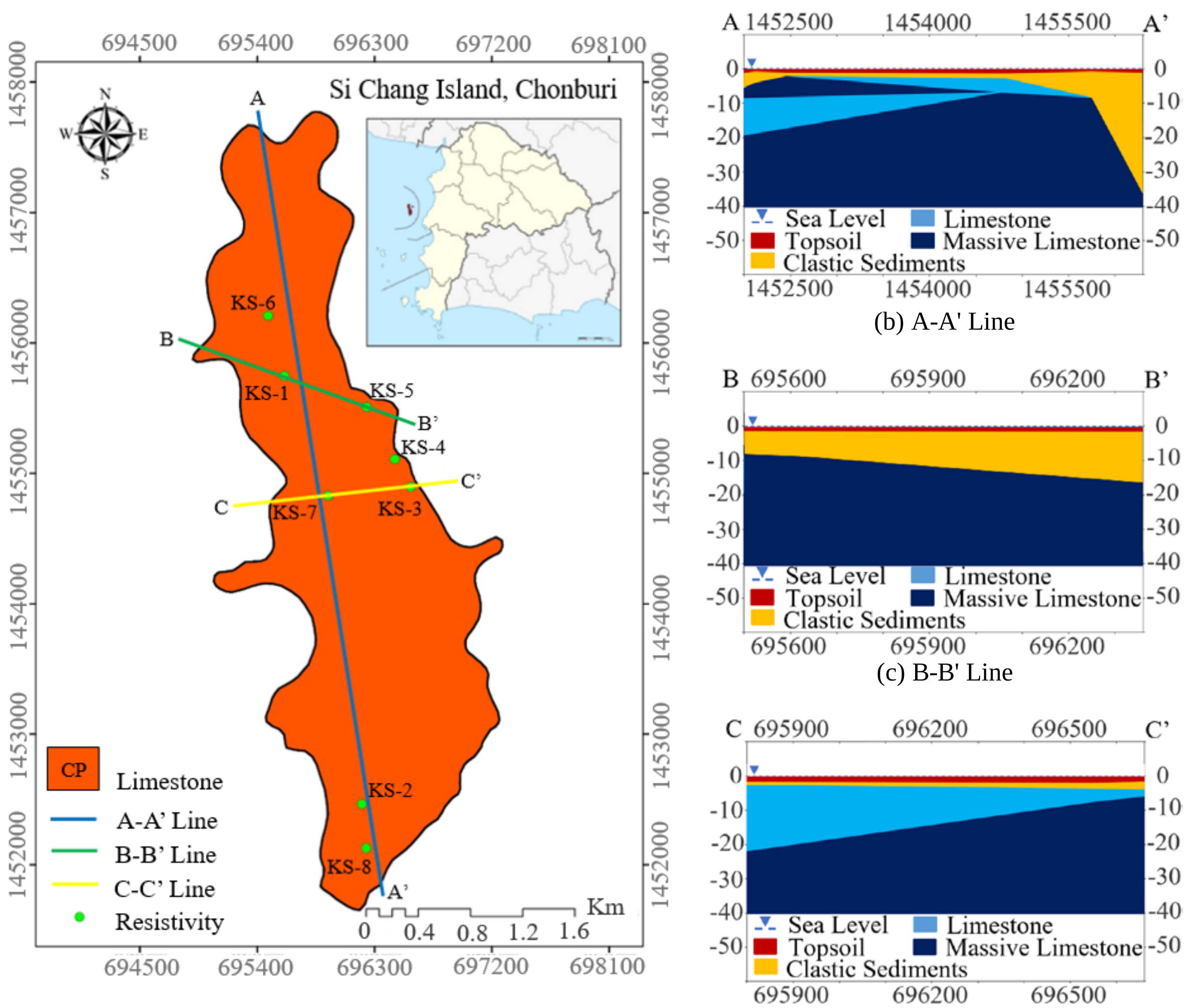
measurements at eight locations, as shown in Fig. 4(a) covering the survey area in Tha Tew Wung Subdistrict, Si Chang District, Chonburi Province, Thailand, was used to generate three geoelectrical cross-sections.

Fig. 4(b) shows cross-section A-A', which runs in a north-south direction, starting from the Si Chang Reservoir and passing through Si Chang District. The length of the cross-section is approximately 5.7 km. The geoelectrical structure revealed that the top layer is topsoil with a thickness of about 1 meter. This is followed by a layer of clastic sediments with limestone interbeds alternating with massive limestone.

Fig. 4(c) presents cross-section B-B', which runs in a northwest-southeast direction with a length of approximately 1.5 km. The geoelectrical structure revealed that the top layer is topsoil with a thickness of about 0.5 to 1 m. This is followed by a layer of clastic sediments with a depth of 8 to 15 m. No limestone layer was observed within this depth range. Below the clastic sediment layer, a layer of massive limestone is present.

Fig. 4(d) shows cross-section C-C', which runs in a southwest-northeast direction with a length of approximately 1.1 km. The geoelectrical structure revealed that the top layer is topsoil with a thickness of about 0.5 to 1 m. This is followed by a layer of clastic sediments with a thickness of 1 to 4 m. A limestone layer is observed below the clastic sediment layer, and a massive limestone layer is found at the deepest level.

Based on the analysis of the geophysical survey data, the following locations are identified as promising sites for groundwater exploration through boreholes: KS-1: Recommended drilling depth: 60-70 m. The potential aquifer is a limestone water-bearing layer. KS-5 and KS-6: Recommended drilling depth: 50 m. The potential aquifer is a limestone water-bearing layer.



(a) Map of Resistivity Analysis (d) C-C' Line

Fig. 4 Hydrogeological Cross Section Demonstrated by the Resistivity Analysis

5.2 Constant Head

Defining the outer boundary of the model, due to the lack of observation well data around Si Chang Island, the area has a total of 3 groundwater wells, as shown in Fig. 5 Additionally, there is no groundwater level data available. Therefore, fieldwork was conducted to collect groundwater levels from the 3 wells to serve as a database for groundwater level analysis – see Table 2. The Equilibrium Test theory was used, which involves pumping water from a pumping well and requires drilling at least 2 observation wells. The water is pumped at a continuous and constant flow rate (Q) until the water levels in the pumping well and the observation wells decrease and stabilize. Then, the water levels are measured to determine the drawdown or the water levels (h_1 and h_2) in the observation wells at distances r_1 and r_2 from the pumping well. The data from the 3 groundwater wells are used to calculate the groundwater level using Equation 1.

$$K = \frac{Q}{2\pi b(h_2 - h_1)} \ln\left(\frac{r_2}{r_1}\right) \tag{1}$$

Using the average hydraulic conductivity (K) of the aquifer to establish the groundwater level around the outer boundary of the model. The groundwater levels were divided into 3 groups according to the radius of influence from the groundwater well data obtained from the survey, as shown in Fig. 5 It was not possible to do this grid by grid due to the excessive number, which would have resulted in a time-consuming parameter adjustment process in the model. The hydraulic heads obtained from the analysis were set as constant head boundaries in the model.

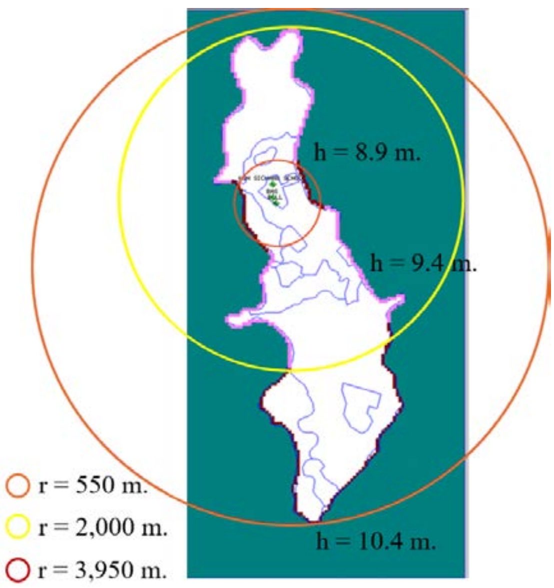


Fig. 5 Constant Head Boundary Analysis

Table 2. Observation Data

Observation Well	Football Field Well	Basketball court Well	Koh Si Chang School Well
UTM E	695680	695638	695642
UTM N	1455620	1455685	1455855
Development Length (m)	100	50	80
Groundwater Level May 2023 (m)	6.9	8.3	7.5
Groundwater Level August 2023 (m)	6.8	8.0	7.4

5.3 Hydraulics Conductivity

In this study, the hydraulic conductivity was assumed that the soil layers are heterogeneous and isotropic due to insufficient data to identify the variation of soil properties in the area. The hydraulic conductivity was the only hydraulic property parameter that was input into the model. The initial hydraulic conductivity values for the topsoil were obtained from a soil survey and sampling on Si Chang Island [22].

The hydraulic conductivity values for Aquifer Layers 1-4 were obtained from pumping tests and by estimating hydraulic conductivity in various rock types [23], as shown in Table 3

Table 3. Parameters for Groundwater Model Layers

Aquifer Layers	K_x (m/s)	K_y (m/s)	K_z (m/s)
Topsoil	3.50E-5	3.50E-5	3.50E-5
Layer 1 Aquifer	4.75E-6	4.75E-6	4.75E-6
Layer 2 Aquifer	2.50E-6	2.50E-6	2.50E-6
Layer 3 Aquifer	1.25E-6	1.25E-6	1.25E-6
Layer 4 Aquifer	8.00E-7	8.00E-7	8.00E-7

5.4 Recharge

The rate of groundwater recharge was estimated by dividing the recharge area into land use types, considering the slope of Si Chang Island, soil properties, and rainfall data from rain gauges on the island. This analysis resulted in the identification of groundwater recharge zones [24]. Then, the recharge was input the data into the model and calibrated the groundwater recharge rate parameters, including the hydraulic conductivity for each layer, along with the observed and calculated groundwater levels under steady-state flow conditions. The simulation was carried out by assuming a constant daily recharge through all three different regions of the model area (mountain, intermediate, and central agricultural regions).

Table 4 shows the initial groundwater recharge rates for the groundwater recharge areas, considering the land use types on Si Chang Island and soil properties. These rates were used as input data for the groundwater flow model. Groundwater recharge rates for urban, port, government, and industrial areas are set to 1% of rainfall because these areas are mostly covered in concrete and have low permeability. Groundwater recharge rates for forest and reservoir areas are set to 15-20% of rainfall because these areas have high permeability. Groundwater recharge rates for natural water bodies are set to 0% of rainfall because Si Chang Island does not have any major rivers. Groundwater recharge rates for marine areas are set to 0% because rainfall in these areas flows directly into the sea. Groundwater recharge rates for gravel pits are set to 30% of rainfall because the soil in these areas has high permeability.

Table 4. Initial Groundwater Recharge Rate [8]

Recharge Zones	Recharge Rate **(%** Rainfall**)**
1. Urban Area	1
2. Dene Deciduous Forest	20
3. Disturbed Deciduous Forest	15
4. Industry	1
5. Harbor	1
6. Government Office	1
7. Laterite Pit	30
8. Reservoir	20
9. River and Ocean	0

5.5 Calibration Technique

The model was calibrated by adjusting the values of parameters, so that the model results are consistent with the data that reflects the actual conditions in nature, such as calibrating the groundwater level obtained from observation wells (Observed Head) with the groundwater level obtained from the model (Calculated Head) to have similar values.

The study area, Si Chang Island, has three observation wells: Koh Si Chang School Well, Basketball Court Well, and Football Field Well. The study divided the calibration and validation data into two periods: May 2023 and August 2023. This showed the limited data of observation wells on the island.

In this model was manual calibration. Although it is a time-consuming method, it is popular for small research areas or areas with limited data. By adjusting model parameters such as hydraulic conductivity (K) and recharge rate, the calculated groundwater level (Calculated Head) is made to be closer to the observed groundwater level (Observed Head). In cases where there is a difference between these two values, the model parameters must be adjusted to make the results closer to the existing real data until an acceptable model is obtained. That is, when the groundwater error is at an acceptable level, namely the standard error (SE) $\leq$ 0.5 meters, the root means square error (RMSE), and the normalized root mean square error (NRMSE) $\leq$ 10%, and $R^2 \geq 0.9$ [25]. However, model calibration is a complex process that requires careful adjustment and evaluation to ensure optimization and reliability.

5.6 Sensitivity Analysis

Sensitivity analysis of the model was conducted to assess the impact of key model parameters on model outputs [26]. This study investigated the sensitivity of changes in hydraulic conductivity (K), recharge rate, and constant head (CH) in the Si Chang Island area by adjusting each constant variable individually and performing repeated calculations to find the relationship between changes in hydraulic conductivity (K) and groundwater level, the relationship between changes in recharge rate and groundwater level, and the relationship between changes in constant head (CH) and groundwater level. The variables were adjusted by ±25%, ±50%, and ±75% of their original values. The objective was to analyze the changes in the normalized root mean square error (NRMSE) of the model in response to changes in these parameters.

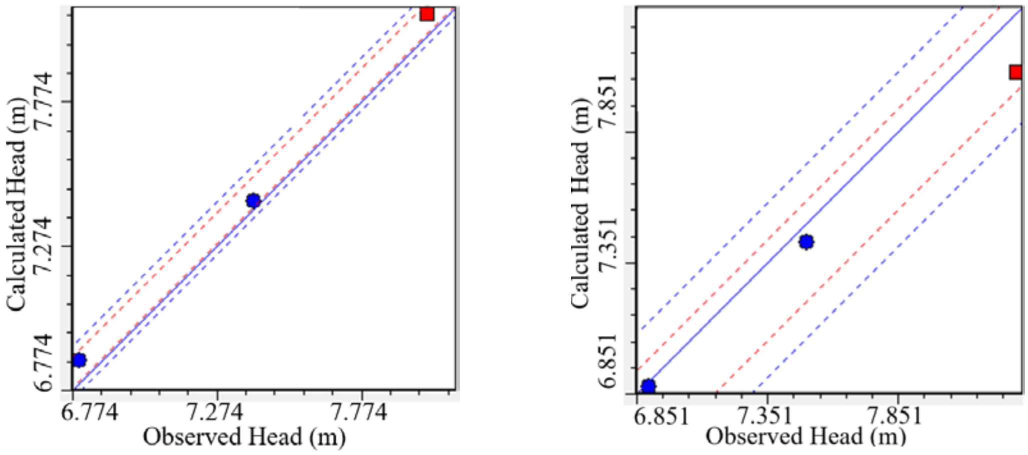
6. RESULTS AND DISCUSSION

6.1 Steady-State Calibration

The groundwater model was calibrated using groundwater level (h) data from three observation wells on Si Chang Island. The calibration was evaluated by comparing the simulated groundwater levels (Calculated Head) to the measured groundwater levels (Observed Head) from the observation wells. The calibration results showed a Standard Error (SE) of 0.016 m, a Root Mean Squared Error (RMSE) of 0.067 m, a Normalized RMS of 5.583%, and a Correlation Coefficient (R^2) of 0.999, as shown in Fig. 6(a). The validation results showed an SE of 0.06 m, an RMSE of 0.134 m, a Normalized RMS of 9.603%, and an R^2 of 0.999, as shown in Fig. 6(b). Both the calibration and validation results are within acceptable limits, with Normalized RMS values below 10%, which is considered acceptable [25]. Therefore, this groundwater flow model can be used to represent the study area and can be used for further groundwater potential analysis.

6.2 Steady-State Groundwater Flow

The groundwater flow simulation results for Si Chang Island under steady-state conditions indicate that groundwater tends to flow toward the discharge areas located in the flatlands. This is because the northern part of the island is mountainous, causing rainwater and recharging from the southern recharge areas to accumulate in the flatlands and eventually discharge into the surrounding sea. The simulated groundwater levels range from 7.5 to 10.5 meters, and the overall groundwater flow pattern is consistent with the conceptual model - see Fig. 7.



(a) Model Calibration (b) Model Validation

Fig. 6 Calibration and Verification Results

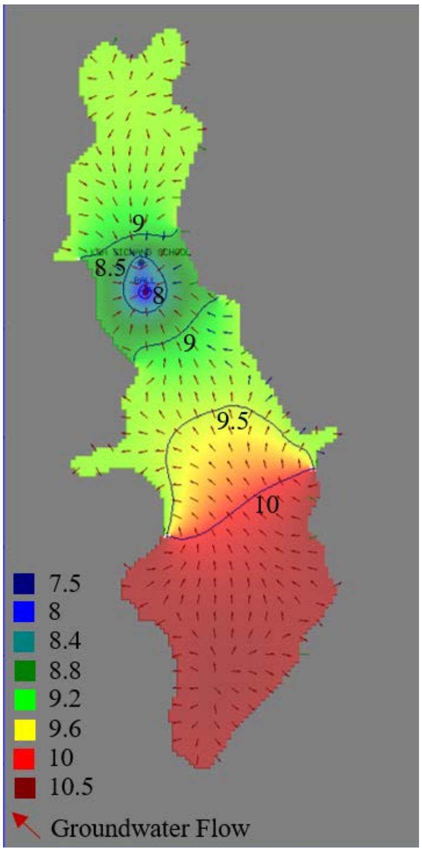


Fig. 7 Simulated Groundwater Flow and Direction

6.3 Result of Sensitivity Analysis

A sensitivity analysis was performed on the model of Si Chang Island by varying hydraulic conductivity (K), recharge rate, and constant head (CH) by ±25%, ±50%, and ±75%. The normalized root mean squared error (NRMSE) was evaluated to assess sensitivity. The model was most sensitive to changes in constant head, followed by hydraulic conductivity, and recharge - see Fig. 8.

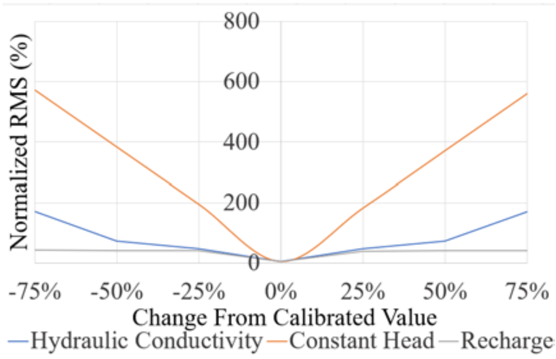


Fig. 8 Model Sensitivity Analysis

6.4 Groundwater Budget

The groundwater budget of the calibrated groundwater flow model with a percent discrepancy of 0.12% indicates that the total inflow to the model is 154,290 m³/yr. from constant head and recharge, while the total outflow from the model is 154,101 m³/yr. from the constant head and wells Table 5.

Table 5. Groundwater Budget

Groundwater Budget	Recharge (m³/yr.)	Discharge (m³/yr.)
Constant Head	84,020	111,485
Wells	0	42,805
Recharge	70,080	0
Total	154,100	154,290

7. CONCLUSION

This study delves into the construction of a three-dimensional groundwater flow model, integrating groundwater development theories to analyze and manage data gaps in the Si Chang Island area. Preliminary data collection from government agencies revealed a lack of information on hydrogeological characteristics, observation wells, hydraulic conductivity values, and groundwater levels, all of which are crucial for groundwater flow modeling. Therefore, geophysical surveys were conducted to investigate hydrogeological characteristics, monitor observation well water levels, determine hydraulic conductivity values, and reveal initial soil layer parameters. Soil layer parameters were derived from field surveys and soil sampling on Si Chang Island [22]. and by estimating hydraulic conductivity (K) values for various rock types [23]. Groundwater levels were determined based on the equilibrium test theory using observation well water level data obtained from field surveys. The model was calibrated and validated using 2023 observation well water level data and analyzed for sensitivity to hydraulic conductivity (K) values, groundwater recharge, and constant head boundary conditions to assess their impact on model results.

The groundwater flow model was calibrated and validated using groundwater level data as a model validation tool. The observed groundwater levels from observation wells (Observed Head) were found to closely match the simulated groundwater levels (Calculated Head), with a correlation coefficient (R^2) of 0.999, a normalized RMS of 5.58%, and a root mean squared error (RMSE) of 0.067 meters. The model validation results also showed a correlation coefficient (R^2) of 0.999, a normalized RMSE of 9.603%, and a root mean squared error (RMSE) of 0.134 meters. Furthermore, the analysis revealed that groundwater level (h) was most sensitive to constant head, hydraulic conductivity, and groundwater recharge (Recharge), respectively. The successful calibration and validation of the groundwater flow model indicates its reliability and applicability for representing the study area and analyzing groundwater potential.

The results of the groundwater balance study of the groundwater flow model in 2023 indicate that the total inflow to the model is 154,290 (m^3/yr.). This inflow comes from two sources: Constant Head: 111,485 m^3/yr., Recharge: 42,805 m^3/yr. The total outflow from the model is 154,100 m^3/yr. This outflow also comes from two sources: Constant Head: 84,020 m^3/yr. Wells: 70,080 m^3/yr. The change in storage is 190 m^3/yr. This indicates that the groundwater system is in a state of slight imbalance, with a small net inflow.

The natural hydrogeological mechanism in the study area plays a significant role in the groundwater flow system. Creating a conceptual model and defining the model boundaries by the actual site conditions is crucial for calibrating the groundwater flow model to achieve an efficient model that can represent the study area for further groundwater potential analysis. However, to enhance the performance of the groundwater flow model, additional soil drilling or groundwater wells should be drilled in the southern part of Si Chang Island. Since the study area is a small island with only three groundwater wells, which are in proximity to the community area, the available data is limited and does not cover the entire area. Therefore, drilling additional observation wells to cover the entire area and all water-bearing layers would increase the model's resolution and accuracy.

8. ACKNOWLEDGMENTS

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9. REFERENCES

[1] Gleeson T., Befus K. M., Jasechko S., Luijendijk E. and Cardenas M. B., The Global Volume and Distribution of Modern Groundwater. Nature Geoscience, Vol.9, No.2, 2016, pp.161–167.

[2] Wang Y., Chunmiao Z. and Ma R., Review: Safe and Sustainable Groundwater Supply in China. Hydrogeology Journal, Vol.26, No.5, 2018, pp.1301–1324.

[3] Holding S., Allen D. M., Foster S., Hsieh A., Larocque I., Klassen J. and Van Pelt S. C., Groundwater Vulnerability on Small Islands. Nature Climate Change, Vol.6, No.12, 2016, pp. 1100–1103.

[4] MacDonald A. M., Bonsor H. C., Dochartaigh B. E. O. and Taylor R. G., Quantitative Maps of Groundwater Resources in Africa. Environmental Research Letters, Vol.7, No.2, 2012, pp. 024009.

[5] Masih I., Maskey S., Mussa F. E. F. and Trambauer P., A Review of Droughts on the African Continent: A Geospatial and Long-Term Perspective. Hydrology and Earth System Sciences, Vol.18, No. 9, 2014, pp. 3635–3649.

[6] Mekonnen M. M. and Hoekstra A. Y., Sustainability: Four Billion People Facing Severe Water Scarcity. Science Advances, Vol.2, No. 2, 2016, pp. 2–7.

[7] Phonil N., Water Shortage Problems and Solutions: A Case Study of Si Chang Island, Chonburi. Master’s Thesis of Civil Engineering, Burapha University, Thailand, 2003, pp. 76528.

[8] Srisuk J., Seeboonruang U., Sirikaew U. and Tanachaichocksirikun P., A Study of Water Quality for Consumption of Si-Chang Island with Geographic Information System, in Proc. 27th National Convention on Civil Engineering., 2022,

pp. WRE11-(1-7).
[9] Thai Royal Irrigation Department Investigate the Problem of Si Chang Island's Reservoir Being Unable to Store Water. 2021, pp.1-47.
[10] U. S. Geological Survey. MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model — the Ground-Water Flow Process MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model — the Ground-Water Flow Process, 2005, pp. 1-67.
[11] Wilopo W., Putra D. P. E. and Wibowo D. A., Groundwater flow modeling in the Wates coastal aquifer, Kulon Progo District, Yogyakarta Special Province, Indonesia. International Journal of GEOMATE, Vol. 14, No. 41, 2018, pp. 119–125
[12] Mohammed O. A., Sayl K. N., Sulaiman S. O., Mahmood N. S., Allawi M. F. and Al-Ansari N., Geoinformatics-Based Approach for Aquifer Recharge Zone Identification in The Western Desert of Iraq. International Journal of GEOMATE, Vol. 25, No. 110, 2023, pp. 220-234.
[13] Saltelli A. and Annoni P., How to Avoid a Perfunctory Sensitivity Analysis. Environmental Modelling & Software, Vol.25, No. 12, 2010, pp. 1508–1517.
[14] AL-Hashmi S., Gunawardhana L., Sana A. and Baawain M., A Numerical Groundwater Flow Model of Wadi Samail Catchment Using Modflow Software. International Journal of GEOMATE, Vol. 18, No. 70, 2020, pp. 30–36.
[15] Royal Thai Survey Department, 30m x 30m Digital Elevation Model (DEM) Data. Bangkok: Royal Thai Survey Department (personal contact), 2021.
[16] Thai Meteorological Department, Statistical Data of the Meteorological Office, Si Chang Island Station. Bangkok: Thai Meteorological Department (personal contact), 2021.
[17] Thai Land Development Department, Level 3 Land Use Data, 2020, Chonburi Province, in Shapefile format, Bangkok: Department of Land Development Information and Communication Technology Center (personal contact), 2020.
[18] Thai Department of Mineral Resources, Geology and Geological Learning Resources of Chonburi Province. Bangkok: Department of Mineral Resources, 2011, pp. 1-39.
[19] Srisuk K. and Tussanee N., Climate Change and Groundwater Resources in Thailand. Journal of Groundwater Science and Engineering, Vol.5, No.1, 2017, pp. 67–75.
[20] Harbaugh A. and McDonald M., User's Documentation for MODFLOW-96, an update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model. Open-File Report, US Geol. Surv., 1996, pp. 96–485.
[21] Riwayat A. I., Ahmad Nazri M. A. and Zainal Abidin M. H., Application of Electrical Resistivity Method (ERM) in Groundwater Exploration. Journal of Physics: Conference Series, Vol.995, No.1, 2018, pp.012094.
[22] Horpeancharoen W., Seeboonruang U., Sirikaew U., Phusuwan T. and Tanachaichocksirikun P., A Study of Engineering Properties of the Soil on Si – Chang Island for SWAT Modeling. The Proceeding of the 27th National Convention on Civil Engineering, 2012 pp. WRE23-(1-7).
[23] Todd D. K. and Mays L. W. Groundwater Hydrology. 3rd ed. 1980, pp. 1-636.
[24] Pholkern K., Phayom S. and Srisuk K., Potential Impact of Climate Change on Groundwater Resources in the Central Huai Luang Basin, Northeast Thailand. Science of the Total Environment, Vol.633, 2018, pp.1518–1535.
[25] Du X., Lu X., Hou J. and Ye X., Improving the Reliability of Numerical Groundwater Modeling in a Data-Sparse Region. Water, Vol.10, No.3, 2018, pp. 1–15.
[26] Saltelli A. and Annoni P., Sensitivity Analysis. BT - International Encyclopedia of Statistical Science, Lovric M., Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 1298–1301.