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EXPECTED GROUNDWATER DEVELOPMENT AND WATER SECURITY IN DEFICIT SMALL TOURISM ISLAND

Jutamas Srisuk[1], Pinit Tanachaichoksirikun[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: The lack of freshwater resources on small tourism islands causes a critical issue with direct effects for the quality of life within local communities and the long-term sustainability of tourism activities. This problem is particularly worsened in regions lacking centralized community water supply systems, where groundwater serves as a crucial source of water for domestic consumption. This study aims to assess the feasibility of developing groundwater resources for establishing a community water supply system on small tourism islands. The research employed a mathematical groundwater model using the MODFLOW program to simulate groundwater flow and analyze the zone budget, based on head contour data and land use patterns in the study area. The results revealed that the most suitable location for groundwater development is the lowland community area, which functions as a discharge zone with high potential for groundwater accumulation and circulation. The MODFLOW simulation accurately demonstrated the quantity and flow direction of groundwater, providing valuable insights for planning a sustainable water supply system to enhance long-term water security for small tourism islands.

Keywords: Groundwater Development, Community Water Supply, Zone Budget, Modflow, Small Tourism Island

1. INTRODUCTION

The world is currently facing a freshwater scarcity crisis, affecting both the quality and quantity of available water [1]. This issue severely impacts people's quality of life, particularly on small islands. These islands have geographical and natural resource limitations, making access to freshwater for consumption difficult. They primarily rely on rainwater and groundwater, which have become insufficient due to increasing human activities, especially the continuously expanding tourism sector [2-3]. As a result, the demand for water has risen, placing further pressure on already limited water resources.

Si Chang Island is an area clearly facing significant challenges related to freshwater scarcity and contamination [4]. At present, the island lacks a community water supply system, as previous attempts to produce municipal water from seawater have failed, and existing reservoirs are unable to retain water due to leakage issues [5]. Consequently, residents must rely on collecting rainwater in storage tanks and importing freshwater from external sources. This results in high costs not only for the water itself but also for transportation, making freshwater unnecessarily expensive—despite being a necessity that should be affordably accessible.

Given these challenges, this research highlights the importance of establishing a community water supply system on Si Chang Island to promote sustainable self-reliance in freshwater resources. The primary objective of the study is to identify and evaluate suitable groundwater sources for developing a raw water supply system. To achieve this, the study utilizes geological data, Geographic Information Systems (GIS), and MODFLOW software to construct spatial models that systematically and accurately analyze groundwater behavior and flow direction in the area [6].

The integration of MODFLOW modeling with zone budget analysis is internationally recognized as a critical tool for assessing groundwater potential and supporting sustainable water resource management. For example, in India, semi-arid Palar sub-basin, MODFLOW was employed to simulate groundwater flow, enabling an accurate assessment of the groundwater balance and effectively supporting local water management strategies [7]. In Egypt, Visual MODFLOW was combined with Multi-Criteria Decision Analysis (MCDA) to inform future pumping plans, while zone budget was applied to assess the suitability of different zones for groundwater source development [8]. Similarly, in Ethiopia's Tana Basin, MODFLOW-NWT was used to examine the effects of climate change on groundwater levels, with zone budget helping to evaluate changes in groundwater systems under various scenarios [9].

In Thailand, GIS techniques are integrated with MODFLOW to simulate groundwater flow with high accuracy. Zone budget was applied to assess water balance within designated zones, serving as a foundation for long-term sustainable water resource management strategies [10–12]. These examples demonstrate that the combined use of MODFLOW and zone budget not only enables detailed simulations of groundwater dynamics but also supports sustainability assessments for water resource utilization. This approach is adaptable to conditions specific to Thailand, particularly in small island areas like Si Chang Island where freshwater resources are limited. Applying these tools is expected to significantly enhance the scientific planning and implementation of a sustainable community water supply system.

2. RESEARCH SIGNIFICANCE

This research addresses the urgent need for a reliable freshwater supply on small tourist islands by focusing on the identification and evaluation of suitable groundwater sources in areas with limited hydrogeological data. By applying MODFLOW modeling, the study offers critical insights into the development of a sustainable community water supply system. Its findings contribute to closing existing data gaps and supporting informed decision-making for long-term water resource management. Moreover, this approach is transferable to other island regions facing similar challenges, providing a valuable framework for improving water security and accommodating the continued growth of the tourism sector.

3. GROUNDWATER BUDGET

A groundwater budget is an evaluation of the continuous flow of water into and out of a groundwater system, which must remain in balance over time. The water balance equation is used to quantify the total volume of water entering and leaving the system or a defined groundwater storage area. The difference between inflows and outflows indicates the change in groundwater storage, either as an increase or a decrease, as expressed in Eq. (1)

$$I - O = \Delta S \qquad (1)$$

Where: I = Inflow, O = Outflow, ΔS = Change in Storage. When considering a groundwater storage area at the sub-basin level, as illustrated in Eq. (1), and focusing specifically on the groundwater budget, the equation can be written as follows:

$$I + G_{in} + Q_g - G_{out} - E_g - T_g = \Delta S_g \qquad (2)$$

Where: I = Recharge from the surface to the aquifer, G_{in} = Groundwater flow into the system, Q_g = Flow into and out of the system via streams, G_{out} = Groundwater flow out of the system, E_g = Evaporation from groundwater, T_g = Transpiration from groundwater by plants, ΔS_g = Change in groundwater storage

In this study, the groundwater balance will be analyzed separately for each zone to illustrate spatial variations in groundwater inflow and outflow. This analysis will support the identification of areas that are both suitable and potentially sustainable for future development.

4. STUDY AREA

Si Chang Island, a small island in the Gulf of Thailand, is located approximately 12 kilometers off the coast of Si Racha District and about 36 kilometers from Chonburi City. The island covers a land area of approximately 7.65 square kilometers and is surrounded by an additional 9.65 square kilometers of marine territory.

The island's terrain is predominantly composed of rocky hills and mountainous areas, with around 80% of the total land area consisting of elevated peaks. The highest point, situated in the northern part of the island, reaches approximately 192 meters above sea level [13]. The topography is characterized by uneven elevation distribution: about 67% of the area lies between 0–50 meters above sea level, 26% between 50–100 meters, 6% between 100–150 meters, and only 1% exceeds 150 meters, as shown in Fig. 1.

These geographical features, particularly the limited flatland and rugged terrain, present significant challenges for freshwater resource management, especially in terms of groundwater recharge and resilience to climate change impacts.

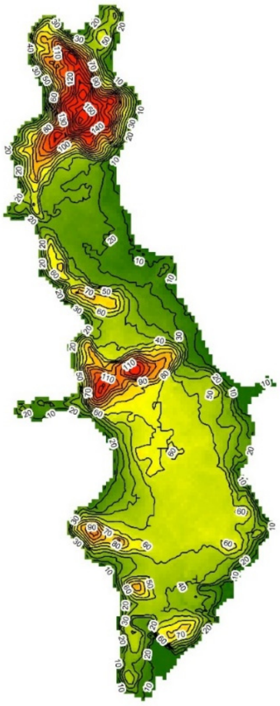


Fig. 1 Location and slope in Si Chang Island [13]

4.1 General and Topography

Based on the geological map of Chonburi Province [14], Si Chang Island is primarily composed of sedimentary rocks from the Chonburi Group, which were deposited during the Carboniferous–Permian (CP) period. These formations include sandstone, argillaceous limestone, shale, and chert. Such rock types can store groundwater within limestone caverns and fracture systems (jointing systems) [15].

The island's terrain is mostly limestone mountains, especially in the north, while the east and southwest consist of granite. The western coast features rocky outcrops, cliffs, and some sandy beaches. Groundwater is found at depths of approximately 50 meters, primarily within limestone layers where it's stored in caverns or fractures within the limestone. The expected groundwater yield is less than 2 cubic meters per hour, with a low total dissolved solids (TDS) content of less than 500 mg/L [16].

4.2 Rainfall and Temperature

Si Chang Island's climate is influenced by both the northeast and southwest monsoons, resulting in three distinct seasons: the hot season (mid-February to May), the rainy season (June to October), and the dry season (November to mid-February).

Average temperatures range between 25°C and 35°C, with April and May typically being the hottest months of the year. According to data from the Si Chang Island rainfall station [17], the island receives an average annual rainfall of approximately 1,000 to 1,200 millimeters, the majority of which occurs during the monsoon season. However, a declining trend in precipitation has been observed, particularly during the dry season, when rainfall is minimal. Even during the rainy season, precipitation tends to be intense yet unevenly distributed, leading to temporal and spatial variability in water availability.

4.3 Land Use

Fig. 2 shows the land use classification of Si Chang Island. Based on land use data from the Department of Land Development, approximately 70% of Si Chang Island remains as green space, primarily composed of deciduous forests—either mature or under active restoration [18]. Urbanized areas, including residential zones and built structures, occupy around 16% of the island, reflecting a moderate level of human development.

The remaining land uses are distributed as follows: industrial areas (3.37%), government facilities (2.58%), harbors (0.42%), laterite pits (1.40%), and beaches (3.67%). Surface water bodies are minimal, collectively accounting for less than 2% of the island's total area. A more detailed land use classification includes deciduous forest under restoration—36.46% (2.36 km^2), mature deciduous forest—35.09% (2.27 km^2), urban areas and structures—16.01% (1.00 km^2), and other functional zones such as government offices, industrial zones, gravel pits, and ports—collectively covering less than 1 km^2**.** Water sources, including reservoirs and natural water bodies, comprise only 0.52% and 0.48% of the area, respectively [18].

These land use characteristics have a direct influence on the island's groundwater recharge potential. While forested and natural soil areas promote effective infiltration and aquifer recharge, the expansion of impervious surfaces—such as buildings and roads—can significantly reduce permeability. Consequently, integrated water resource management must carefully balance the retention of permeable land cover with the demands of built infrastructure.

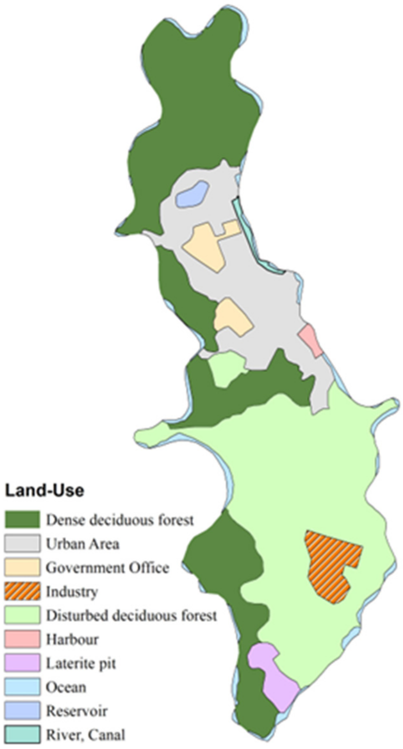


Fig. 2 Land use in Si Chang Island [18]

4.4 Water Quality

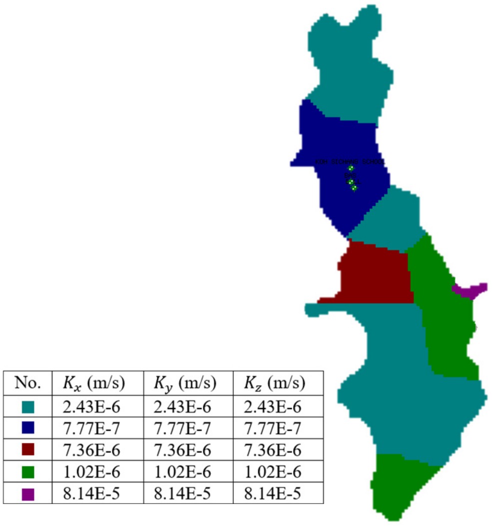
According to the drinking water quality standards established by the Department of Health in 2020 [4], the overall water quality on Si Chang Island is classified as "acceptable." This classification indicates that the water may be used for consumption in the absence of alternative sources. However, water treatment is required prior to use due to the presence of coliform bacteria and Escherichia coli (E. coli), which are commonly associated with gastrointestinal illnesses such as diarrhea.

In contrast, the southern part of the island—an uninhabited area designated for waste disposal—shows contamination from several hazardous substances, including arsenic and fluoride, at concentrations exceeding permissible limits. As a result, the water quality in this area is deemed unsafe for any purpose, including human consumption.

5. METHODOLOGY

This study employed a systematic approach that integrated field investigations, spatial analysis, and numerical modeling to simulate groundwater flow and assess the feasibility of groundwater resource development on Si Chang Island. The methodology involved collecting and analyzing geological and hydrogeological data from the area, developing a conceptual model of the groundwater system, simulating groundwater flow using Visual MODFLOW software, calibrating the model against observed field data, and analyzing multiple scenarios to evaluate the potential and formulate strategies for sustainable groundwater management on the island.

5.1 Conceptual Model And Boundary Condition



No.	K_x (m/s)	K_y (m/s)	K_z (m/s)
🟦	2.43E-6	2.43E-6	2.43E-6
■	7.77E-7	7.77E-7	7.77E-7
🟥	7.36E-6	7.36E-6	7.36E-6
🟩	1.02E-6	1.02E-6	1.02E-6
🟪	8.14E-5	8.14E-5	8.14E-5

Fig. 3 Hydraulic conductivity of the topsoil layer

The conceptual model of Si Chang Island was developed using topographic, geological, hydrogeological, soil, and land use data. The model's upper boundary was defined as a recharge boundary representing rainfall infiltration, while its outer boundaries were assigned as constant head boundaries due to the island being surrounded by seawater. The model comprises six layers: the top layer is an unconfined aquifer; the second layer consists of colluvial deposits; the third through fifth layers represent confined limestone aquifers; and the bottom layer is modeled as a no-flow boundary, corresponding to impermeable bedrock. The thickness of each layer was defined based on local hydrogeological characteristics. Groundwater abstraction from existing wells was incorporated as pumping boundaries. Reservoir boundaries were excluded from the model due to the limited water storage capacity of local reservoirs.

5.2 Hydraulic Conductivity

In this study, hydraulic conductivity (K) values were assigned based on the assumption that the subsurface is heterogeneous and isotropic. The top layer, representing an unconfined aquifer, was assigned spatially variable hydraulic conductivity values, as illustrated in Fig. 3 For layers 2-5, which correspond to confined limestone aquifers, hydraulic conductivity values are summarized in Table 1.

Table 1 Parameters for groundwater model layers

No.	K_x (m/s)	K_y (m/s)	K_z (m/s)
Layer 2	3.50E-5	3.50E-5	3.50E-5
Layer 3	4.75E-6	4.75E-6	4.75E-6
Layer 4	1.50E-6	1.50E-6	1.50E-6
Layer 5	6.50E-7	6.50E-7	6.50E-7
Layer 6	7.75E-7	7.75E-7	7.75E-7

5.3 Recharge

Groundwater recharge in the study area was estimated by delineating recharge zones based on land use and soil characteristics, in combination with local rainfall data. Varying recharge percentages were assigned to each land use category to reflect differences in infiltration potential.

Table 2 Initial groundwater recharge rate

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

5.4 Zone Budget

The study area was divided into six budgeting zones, as illustrated in Fig. 4, based on predominant land use types, including agricultural, urban, forested, and industrial areas. Each land use type exhibits distinct patterns of water consumption and groundwater flow, which are essential for evaluating groundwater inflow and outflow within each zone. The assessment integrates multiple factors, such as rainfall, infiltration capacity, local water demand, and geological conditions.

This integrated approach facilitates the effective identification of zones with high potential for groundwater resource development.

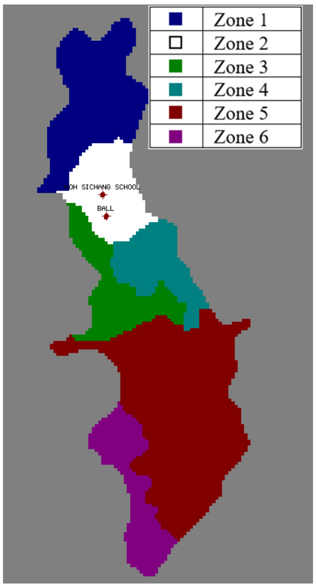


Fig. 4 Zone budget

5.5 Scenarios

A numerical groundwater flow model was employed to simulate the impacts of recharge variations across six designated zones under three climate change scenarios: RCP2.6, RCP4.5, and RCP8.5. The simulation was conducted over a 10-year period, from 2025 to 2035.

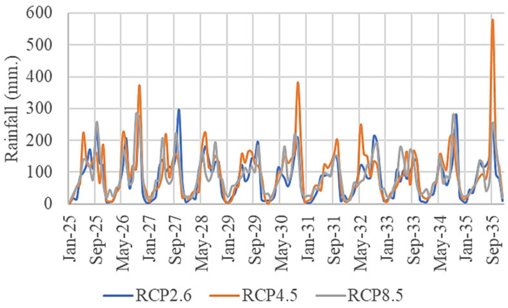


Fig. 5 Rainfall based on climate models, 2025-2035

Future rainfall projections for the period 2025 to 2035, based on the HADGEM2-AO climate model, indicate that the RCP4.5 scenario produces the highest rainfall, reaching nearly 600 mm in October 2035. In contrast, the RCP2.6 and RCP8.5 scenarios exhibit similar trends, with comparatively lower rainfall levels, as illustrated in Fig. 5. The inclusion of all three Representative Concentration Pathways (RCPs) provides a comprehensive perspective on future climate variability, enabling a more robust assessment of potential risks and uncertainties.

6. RESULTS AND DISCUSSION

6.1 Calibration and Verification Results

This model was further developed based on the work of Srisuk et al. [19]. Model calibration and validation were performed by comparing the simulated groundwater levels with observed data from three monitoring wells on Si Chang Island, namely the Football Field Well, the Basketball Court Well, and the Koh Si Chang School Well, all of which are located within the community area. However, due to data limitations [19], this study divided the datasets used for calibration and validation into two periods: groundwater level data from May 2023 for model calibration, and groundwater level data from August 2023 for model validation.

Calibration results (Fig. 6a) yielded a Root Mean Square Error (*RMSE*) of 0.128 meters, a Standard Error (*SE*) of 0.031 meters, a Normalized *RMSE* of 9.158%, and a coefficient of determination (R^2) of 0.997.

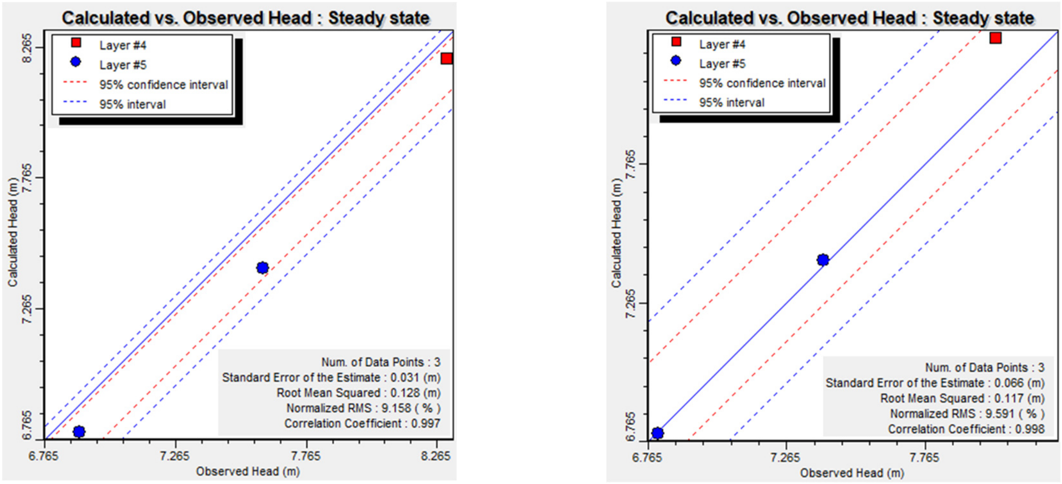
Model validation (Fig. 6b) produced an *RMSE* of 0.117 meters, an *SE* of 0.066 meters, a Normalized *RMSE* of 9.591%, and an R^2 of 0.998.

Both calibration and validation results fall within acceptable thresholds, with Normalized *RMSE* values below 10%, which is considered satisfactory for groundwater modeling applications [20]. Therefore, the model is deemed reliable for use in this study and suitable for further analysis of groundwater potential in the area.

6.2 Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the influence of key parameters on the model's performance [21]. This study focused on assessing the sensitivity of three primary parameters: hydraulic conductivity (*K*), recharge rate, and constant head (*CH*) within the Si Chang Island area.

The results revealed that the constant head had the most significant impact on simulated groundwater levels, followed by hydraulic conductivity and recharge rate, respectively, as shown in Fig. 7. Variations in the constant head by ±25%, ±50%, and ±75% resulted in substantial changes in groundwater levels, emphasizing the importance of accurately defining boundary conditions that reflect real-world hydrogeological settings. These findings also underscore the necessity for precise field measurements to ensure the reliability of input parameters used in groundwater modeling.



(a) Model Calibration (b) Model Validation

Fig. 6 Calibration and verification results

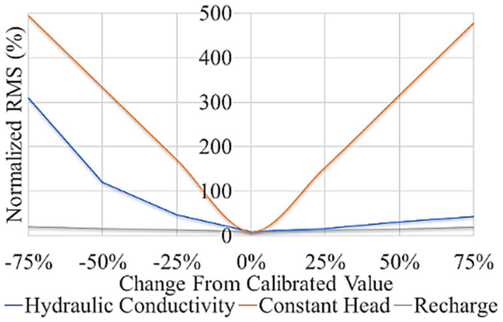


Fig. 7 Model sensitivity analysis

6.3 Groundwater Exploring Scenarios

In this study, groundwater behavior on Si Chang Island was simulated using a Zone Budget approach, which divided the area into six zones. The model evaluated the impacts of climate change over a 10-year period (2025–2035) under three scenarios: RCP2.6, RCP4.5, and RCP8.5.

As shown in Fig. 8, among the six zones, Zone 5—characterized by forested land with favorable infiltration conditions—exhibited the highest average groundwater recharge rate, approximately 1,040 m³/day. However, it also experienced the highest loss to the sea, averaging 860 m³/day, with an additional outflow of 185 m³/day to Zones 3, 4, and 6.

Zone 1, a steep mountainous recharge area, had the second-highest recharge rate at around 670 m³/day but also contributed significantly to seawater loss and lateral flow, transferring about 125 m³/day to Zone 2. Zone 2, a community area and lowland discharge zone, had a low recharge rate (40 m³/day) but received substantial inflow from Zones 1, 3, and 4, totaling about 200 m³/day, with minimal loss to the sea (50 m³/day).

Zone 3 showed an average recharge rate of 345 m³/day, but due to its steep terrain, nearly all recharge was lost to the sea. It received water from Zone 5 and transferred water to Zone 4. Zone 4, also a lowland community zone, had limited recharge and seawater loss but functioned primarily as a transit zone, receiving water from Zones 3 and 5 and discharging to Zone 2.

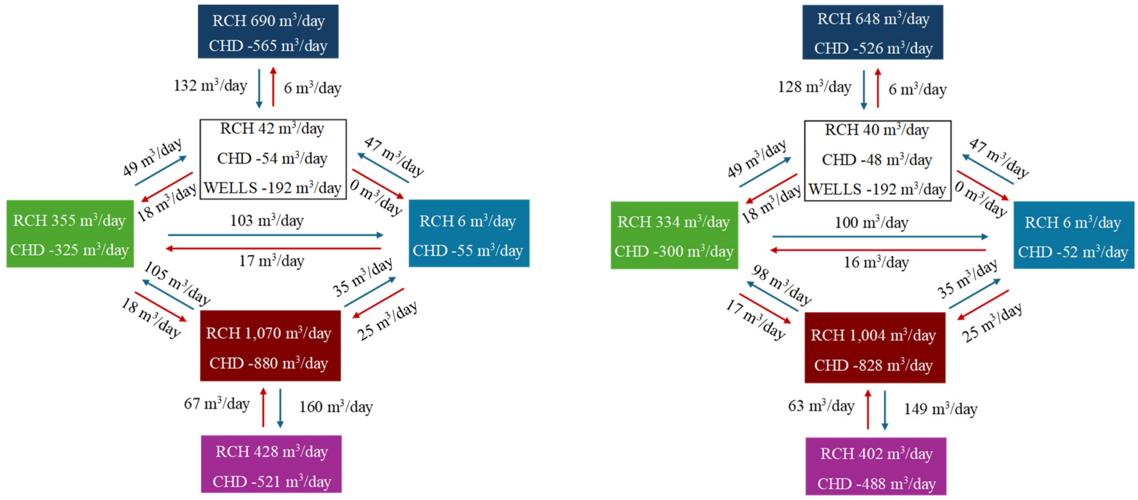
Zone 6 demonstrated relatively high recharge but experienced even greater losses to the sea. It received some water from Zone 5, averaging around 90 m³/day.

Across all three climate scenarios, the RCP4.5 scenario resulted in the highest recharge values, particularly in October 2035, which aligns with the projected rainfall trends. However, differences among the scenarios were relatively minor in magnitude.

These findings highlight the effectiveness of spatial groundwater budgeting in identifying recharge and discharge dynamics, even in data-scarce environments. This approach supports informed decision-making for the development of sustainable community water supply systems in vulnerable island settings.

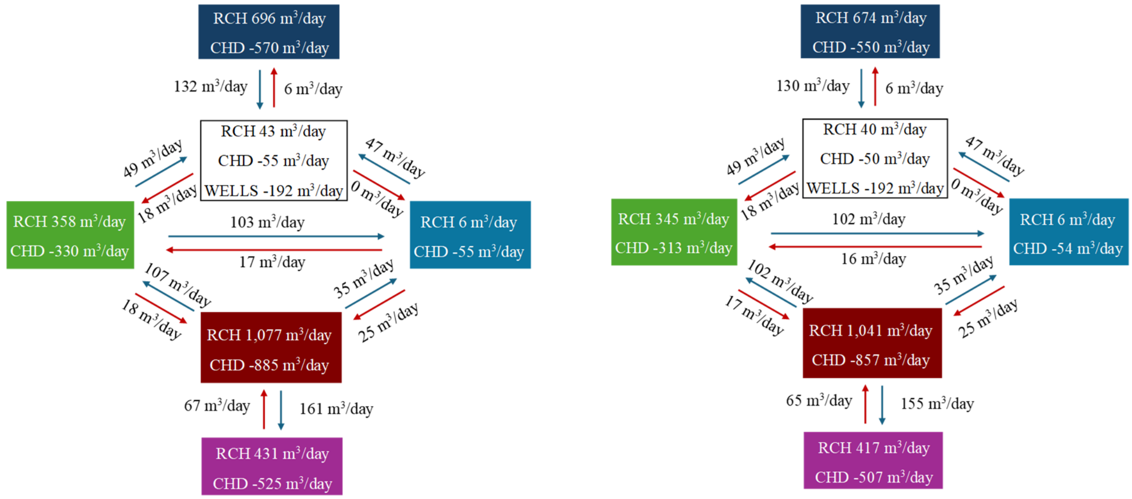
7. CONCLUSION

Currently, Si Chang Island lacks a community water supply system, forcing residents to rely on rainwater harvesting and the importation of freshwater—both of which involve high costs for water and transportation. Consequently, water becomes an unnecessarily expensive resource despite being a necessity. This research aimed to identify and evaluate suitable groundwater sources to support the development of a cost-effective and sustainable community water supply system.



(a) Base Case

(b) HADGEM2-AO RCP2.6



(c) HADGEM2-AO RCP4.5

(d) HADGEM2-AO RCP8.5

Fig. 8 Zone budget analysis under climate change scenarios

A spatial groundwater model was developed using Geographic Information System (GIS) tools in conjunction with the MODFLOW program, under conditions of limited available data. The study analyzed six hydrological zones across three climate change scenarios—RCP2.6, RCP4.5, and RCP8.5—projected for the period 2025–2035 using the HADGEM2-AO climate model.

The findings indicate that Zone 2 is the most suitable area for developing groundwater resources for community water supply under all three climate scenarios. This suitability is supported by both water quality and quantity. Located in a low-lying, populated area that functions as a discharge zone, Zone 2 receives substantial inflows from Zones 1, 3, and 4 while experiencing minimal losses to the sea. In terms of water quality, Zone 2 is also favorable, as it is not directly connected to Zones 5 and 6 in the island's southern region, where groundwater contamination from hazardous substances such as arsenic has been identified. As a result, water from Zones 5 and 6 should be excluded from future water supply planning.

However, concerning water quantity in Zone 5, while there's a high rate of groundwater recharge, there's also a significant amount of water lost to the sea and outflowing from the zone. The findings highlight the importance of accurate data and a thorough understanding of the study area for planning the selection of suitable zones for establishing a community water supply. Both water quality and quantity must be considered to ensure an effective and sustainable solution for the future.

8. ACKNOWLEDGMENTS

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