

RECHARGE ESTIMATION AND SITE IDENTIFICATION FOR MANAGED AQUIFER RECHARGE IN SUPHANBURI, THAILAND USING GIS AND MODFLOW

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ABSTRACT: This study focuses on groundwater recharge estimation and site identification for Managed Aquifer Recharge (MAR) in Suphanburi, Thailand, an agriculturally intensive region increasingly affected by floods and droughts. An integrated approach combining Geographic Information Systems (GIS), water balance analysis, and groundwater simulation using Visual MODFLOW was applied to assess recharge potential. Key factors, including land use, slope, and hydrogeology, were analyzed to delineate 5 suitable recharge zones. Field data from 13 observation wells collected between 2014 and 2024 were used to calibrate and validate the groundwater model. The model has high accuracy with R^2 values of 0.983 (Calibration) and 0.992 (Validation), and normalized $RMSEs$ of 5.97% and 5.20%, respectively. The result showed that the highest recharge rates were 343.42 and 320.39 m^3/day , observed in urban and industrial zones near the Tha Chin River, with capacities sufficient to support over 1,600 people. This research provides a practical and replicable framework for MAR site selection and implementation, supporting data-driven water management strategies in flood and drought-prone regions.

Keywords: Groundwater Recharge Estimation, Water Resource Management, Flood and Drought, Site Identification, Managed Aquifer Recharge (MAR)

1. INTRODUCTION

Floods and droughts are recurrent and persistent challenges throughout Thailand, particularly in lowland areas adjacent to the mountainous regions of the central plains. These regions are characterized by steep topography, which exacerbates flash floods and recurring water-related disasters. Conventional solutions have proven insufficient in providing long-term resilience. In response, both governmental and private sectors have increasingly adopted water management approaches inspired by the late King Bhumibol Adulyadej's Sufficiency Economy Philosophy. This research directly addresses this critical gap by developing a scientifically robust and practically applicable Managed Aquifer Recharge (MAR) to support adaptive water resource management in vulnerable regions. These systems aim to capture and store excess rainwater during the wet season for use in the dry season, thereby simultaneously mitigating flood and drought risks with minimal financial investment and environmental disruption.

Managed Aquifer Recharge (MAR) is the intentional process of directing excess surface water—such as stormwater, river flow, treated wastewater, or seasonal runoff—into underground aquifers to enhance groundwater storage. It can be implemented through engineered and nature-based systems, including infiltration basins, recharge ponds,

injection wells, percolation tanks, riverbank filtration, and soil-aquifer treatment units. Unlike natural recharge, which is slow and unpredictable, MAR provides a controlled method for increasing groundwater availability and improving the reliability of water supplies. This is especially valuable in regions with strong wet-dry seasonality, rising water demand, and increasing climate-related extremes.

The key purposes of MAR are to strengthen groundwater security, reduce drought vulnerability, mitigate flood risks, and support long-term water management. By storing surplus wet-season water underground, MAR protects water from evaporation, salinity intrusion, and surface contamination while helping stabilize groundwater levels, reduce aquifer depletion, limit land subsidence, and enhance water quality through natural filtration processes.

The concept of MAR has gained international recognition as a strategic response to water resource variability [1-2]. In the United States, particularly in California, Arizona, and Texas, large-scale MAR such as the Kern Water Bank have been successfully implemented to stabilize water supplies for agriculture and urban use during multi-year droughts [3]. Israel and Australia have incorporated MAR into national water strategies, especially in arid and semi-arid zones, using techniques such as infiltration basins, injection wells, and riverbank filtration to enhance groundwater reserves [4-5]. In India, particularly in the drought-prone state of Rajasthan,

community-based MAR projects have demonstrated significant benefits in improving aquifer recharge, water quality, and agricultural productivity [6]. China also invested in artificial recharge programs as part of their national water sustainability frameworks [7-8]. These global experiences underscore the scalability and adaptability of groundwater recharge to diverse climatic, geological, and socio-economic contexts.

Recent studies emphasize the growing global adoption of MAR as a strategic response to groundwater depletion, climate variability, and rapid land-use change. Rozikulov et al. highlighted significant advancements in MAR technologies and the need for improved monitoring frameworks to support long-term groundwater sustainability [9]. Adnan et al. identified risks associated with contaminant pathways in recharge mining and smelting systems, underscoring the need for site-specific hydrogeological assessment [10]. Nazari et al. demonstrated that numerical groundwater modeling is essential for evaluating recharge performance in complex aquifer systems [11]. Recent contributions such as Mohammed et al. and Romali et al. showed how GIS-based recharge zoning support MAR suitability mapping in data-limited regions, revealing strong potential for applying MAR [12-13].

In Thailand, MAR initiatives have been explored by agencies such as the Thai Department of Groundwater Resources and the National Water Resources Officer. Several pilot studies have been conducted to assess groundwater recharge feasibility in agriculturally intensive areas. Notable examples include MAR studies in Sukhothai, Lamphun, Phichit, and Kamphaeng Phet. However, these projects have often lacked continuity and have not yet been implemented systematically or on a scale. Moreover, previous studies primarily focused on engineering feasibility without fully integrating spatial analysis or mathematical modeling.

Despite progress, many MAR studies in Thailand and abroad rely on short-term data, qualitative suitability mapping, or static GIS analyses that overlook aquifer dynamics and long-term groundwater responses. Few integrate land-use-based recharge estimates with fully calibrated and validated numerical models, and even fewer quantify recharge volumes, storage gains, or potential beneficiaries. This study addresses these gaps through an integrated GIS-MODFLOW framework calibrated with long-term groundwater observations (2014–2024), monthly water-balance estimation, and multi-year recharge simulations (2025–2030). The originality lies in combining field-based calibration, spatial recharge mapping, and scenario modeling to identify optimal MAR sites and generate practical, decision-ready recharge estimates.

The study addresses this gap by developing a comprehensive groundwater recharge model tailored to the Kra Seaw Reservoir area in Suphanburi

Province, a region that frequently experiences extreme variations in water availability. The model utilizes hydrogeological data, GIS, and MODFLOW to simulate recharge potential and optimize aquifer storage strategies. The goal is to enhance water security, agricultural resilience, and long-term resource planning in flood and drought affected zones.

Ultimately, this study aims to provide a scientific basis for MAR implementation by integrating hydrological modeling, water balance assessments, and community-oriented resource planning. It aspires to serve as a decision-support tool for policymakers, water managers, and researchers working toward sustainable water resource management in Thailand and other similar geographic settings.

The paper is organized as follows: Section 2 presents the research significance. Section 3 outlines the water-balance framework. Section 4 describes the study area. Section 5 details the methodology and modeling procedures. Section 6 provides the results and discussion, and Section 7 concludes with key findings and recommendations.

2. RESEARCH SIGNIFICANCE

This study provides a quantitative, model-based framework for identifying suitable Managed Aquifer Recharge (MAR) sites in Suphanburi, Thailand, an area frequently affected by both drought and flood events. Unlike previous studies, the research integrates water-balance estimation, GIS-based land-use recharge zoning, and a fully calibrated MODFLOW groundwater model using long-term observations from 2014–2024. The originality lies in combining spatial analysis with numerical simulation to determine recharge capacity and evaluate aquifer responses under realistic operating conditions. The proposed approach offers a replicable tool for regional water-resource planning, supporting data-driven decisions for sustainable groundwater management in agricultural provinces.

3. WATER BALANCE APPLICATION

A water balance approach is essential to understand how much water enters, leaves, and is stored in a given area over time. This is especially important for designing and evaluating a groundwater recharge system, where the goal is to store excess water underground during wet periods and retrieve it during dry seasons [14-15]. The water balance provides a systematic way to estimate available water resources and determine how much can be recharged into aquifers without causing negative effects.

The water balance in this study is divided into two key components: surface water balance and

groundwater balance.

The surface water balance considers rainfall, runoff, evapotranspiration, and recharge to groundwater. The equation as shown in equation (1)

$$P = ET + S_R + R \pm \Delta V \quad (1)$$

Where P is total precipitation (rainfall) in unit mm., ET is evapotranspiration in unit mm., S_R is surface runoff in unit mm., R is groundwater recharge in unit mm. and ΔV is change in soil moisture or surface water storage in unit mm.

The groundwater system is analyzed separately to track how much water is added, used, and stored below ground. The groundwater balance equation as shown in equation (2)

$$R = G + D + W \pm \Delta S \quad (2)$$

Where R is groundwater recharges in unit mm., G is groundwater flow out of the system in unit mm., D is deep drainage to lower aquifer layers in unit mm., W is pumping or groundwater use in unit mm. and ΔS is change in groundwater storage in unit mm.

In the context of this study, the water balance is calculated on a monthly basis to reflect seasonal rainfall and groundwater fluctuations. However, the long-term trends are analyzed on an annual scale to evaluate sustainability. This approach ensures that the groundwater recharge will operate effectively, prevent land subsidence, and avoid environmental damage.

4. STUDY AREA

Suphanburi located in the central region of Thailand. The area was selected due to its high agricultural importance and frequent exposure to both drought and flood events. Suphanburi is also home to key water resources infrastructure, including the Kra Seaw Reservoir and the Tha Chin River, which play central roles in local water management. It far approx. 107 km. northwest of Bangkok. The province covers an area of about 5,358 km². It borders Chai Nat and Uthai Thani to the north, Nakhon Pathom to the south, Ang Thong and Ayutthaya to the east, and Kanchanaburi to the west.

The terrain is mostly flat and consists of low-lying alluvial plains, which are well suited for rice farming and other agricultural activities. The western part of the province, especially Dan Chang, is characterized by rolling hills and forested areas. Elevation ranges from 10 to 400 meters above sea level, with higher

terrain in the west and flatter plains to the east, Fig. 1.

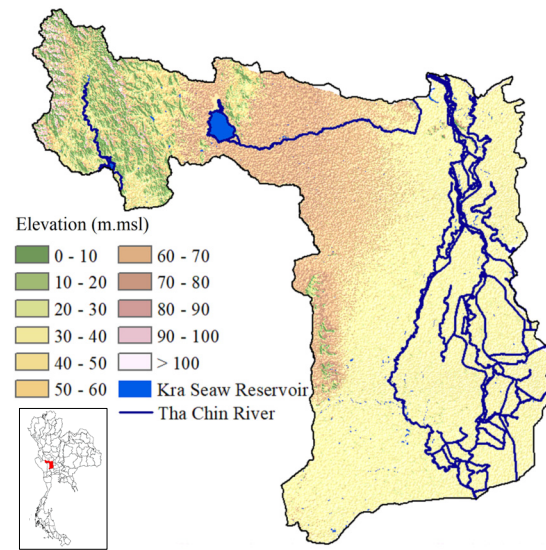


Fig.1 Location and slope in Suphanburi [16]

4.1 Geology and Hydrogeology

The geology is predominantly composed of sedimentary rocks, including sandstone, limestone, shale, and chert, dating back to the Paleozoic–Mesozoic era. In the western regions, such as Dan Chang, igneous rocks like granite and basalt are also found. These geological conditions influence groundwater movement and aquifer characteristics [17].

The Hydrogeology is both unconfined and confined aquifers, particularly in the Tha Chin River basin, where groundwater yield exceeds 2 m³/hr. in many locations. The aquifers are suitable for artificial recharge due to their permeability and storage capacity [18].

4.2 Climate

According to Thai Meteorological Department, Suphanburi is in a tropical zone, with three seasons, summer season in February to May, rainy season in June to October and winter season in November to January [19]. Rainfall data from 2019 to 2023 shows high variability. Peak rainfall occurs from August to October, while the driest months are January to March. In recent years, irregular rainfall patterns, including prolonged dry spells and sudden heavy downpours, have been observed, indicating the growing influence of climate change on local hydrology.

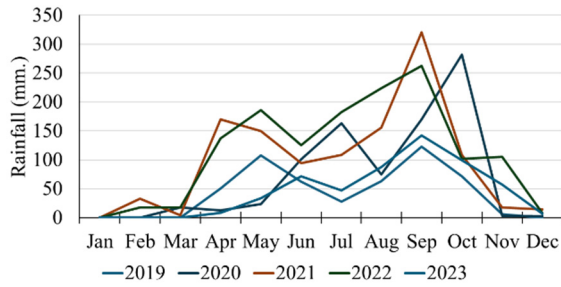


Fig.2 Annual rainfall in Suphanburi

4.3 Land Use and Groundwater Recharge

Land use plays a critical role in determining the feasibility and effectiveness of MAR. Different land types vary significantly in terms of their infiltration capacity, surface runoff generation, and soil permeability, all of which influence how much water can enter and be stored in underground aquifers.

According to Thai Land Development Department, Suphanburi, land use is predominantly agricultural, with other significant uses including forests, built-up urban areas, and water bodies [16]. The major land use categories and their implications for groundwater recharge are described as followed [20].

Agricultural areas (74.3%), especially rice fields and field crops, cover the largest portion of the province. These lands typically have compacted soil due to plowing and machinery, which may limit natural infiltration. However, with appropriate soil management and recharge design (e.g., recharge ponds, infiltration basins), these areas can serve as viable recharge zones. Unused plots or fallow fields may offer better infiltration potential during off seasons. Rice paddies may contribute to shallow recharge but are limited due to frequent waterlogging. Field crops (e.g., sugarcane, maize) have better potential for infiltration if combined with recharge structures.

Forest areas (12%), especially in the western highlands of Dan Chang District, offer high natural infiltration due to deep root systems and less surface sealing. These areas are ideal for natural recharge processes and can be preserved or enhanced as buffer zones for groundwater replenishment. Forested land contributes to low surface runoff and helps stabilize the local hydrological cycle.

Urban and industrial zones (8.3%), including roads, buildings, and paved surfaces, have low infiltration capacity and generate high surface runoff. These areas are unsuitable for natural recharge but can still support artificial recharge through engineered solutions like injection wells, recharge shafts, or stormwater harvesting systems. In densely populated areas, care must be taken to avoid contamination risks.

Aquaculture and Water Bodies (3.5%), such as

ponds, lakes, and irrigation canals can act as recharge reservoirs if they are hydraulically connected to the underlying aquifer. Some areas may allow recharge through percolation, especially if the base is unlined or partially permeable. However, these zones typically have limited recharge capacity without modification.

Miscellaneous zone (1.9%), found at the edges of agricultural zones or near forested hills. Depending on soil type and topography, they may provide good potential for recharge basin development, particularly if located above permeable aquifers.

In this study, land use data was used to classify recharge zones and assign recharge rates for simulation in the Visual MODFLOW model. Forested and agricultural areas were prioritized for MAR development due to their favorable infiltration characteristics. Urban and industrial zones, while limited in natural recharge capacity, were considered for technical interventions like injection wells or treated wastewater reuse.

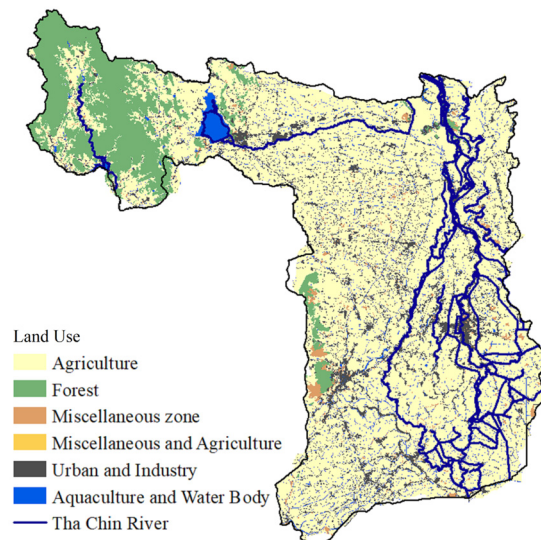


Fig.3 Land use in Suphanburi [16]

5. METHODOLOGY

This study followed a structured approach combining field data, spatial analysis, and numerical modeling to design and evaluate a recharge estimation and site identification for MAR for Suphanburi. The main steps included data collection, conceptual model development, numerical simulation using Visual MODFLOW, model calibration, and scenario analysis.

5.1 Grid Design

Based on field conditions and geological structure, the study area was divided into two aquifer layers Upper layer: Unconfined aquifer (shallow

groundwater) and Lower layer: Confined aquifer (deep groundwater).

The grid was divided into a uniform grid of 1×1 km² cells, resulting in 12,204 cells (108 columns \times 113 rows). Each grid cell was assigned physical and hydraulic properties based on field data and soil classification.

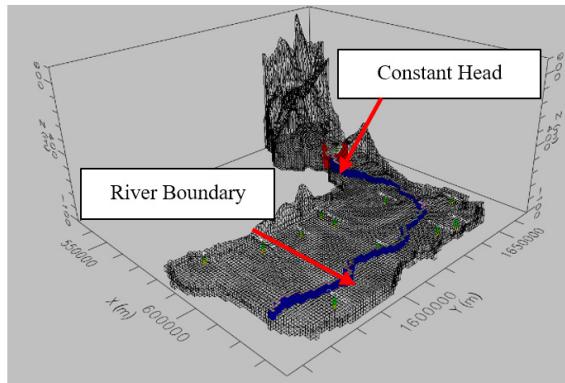


Fig.4 Numerical modeling for Suphanburi.

5.2 Assigning Aquifer Parameters

Key hydrogeological parameters were defined based on soil surveys and groundwater studies i.e. Hydraulic conductivity (K), Specific yield (S_y) for unconfined aquifers, Specific storage (S_s) for confined aquifers as show in Fig. 5 and Table 1.

5.3 Recharge Estimation

Groundwater recharge rates were estimated using a land-use-based recharge coefficient approach. Different recharge percentages were assigned based on land use types as shown in Fig.6 and Table 2.

5.4 Model Calibration and Verification

The model was calibrated by adjusting key parameters (hydraulic conductivity and recharge rate) to minimize the difference between simulated and observed groundwater levels. Groundwater data from 13 observation wells were used to calibrate the model. The calibration aimed to achieve: Normalized Root Mean Square Error ($RMSE$) below 10% of observed values and high correlation ($R^2 > 0.9$) between simulated and observed heads

5.5 Sensitivity Analysis Procedure

The sensitivity analysis was performed by adjusting key parameters ($\pm 25\%$, $\pm 50\%$, $\pm 75\%$) and observing the impact on groundwater levels [21-22]. This helped identify which variables had the greatest influence on model output and supported more

accurate prediction under future scenarios.

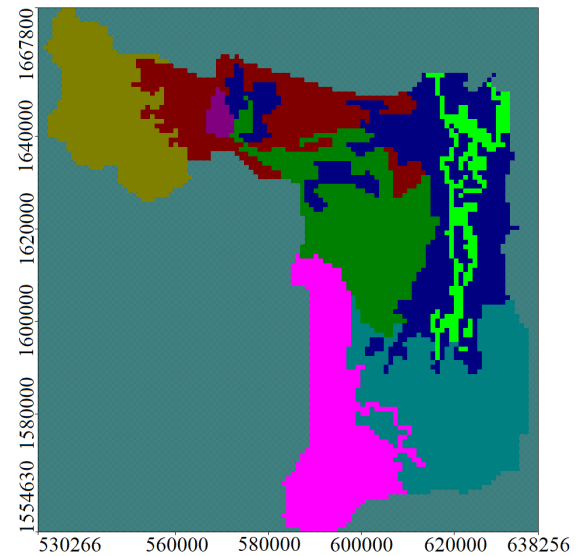


Fig.5 Input parameter zone

Table 1. Hydraulic Conductivity Values

No.	K_x and K_y (m/s)	K_z (m/s)	S_s
1	1.0×10^{-6}	1.0×10^{-9}	1.6×10^{-4}
2	1.0×10^{-7}	1.0×10^{-10}	1.0×10^{-5}
3	5.0×10^{-6}	5.0×10^{-9}	2.0×10^{-4}
4	1.1×10^{-6}	1.1×10^{-9}	5.0×10^{-5}
5	7.5×10^{-6}	7.5×10^{-9}	1.6×10^{-4}
6	1.0×10^{-2}	1.0×10^{-5}	2.0×10^{-4}
7	1.0×10^{-5}	1.0×10^{-8}	2.0×10^{-4}
8	1.0×10^{-3}	1.0×10^{-6}	5.0×10^{-5}

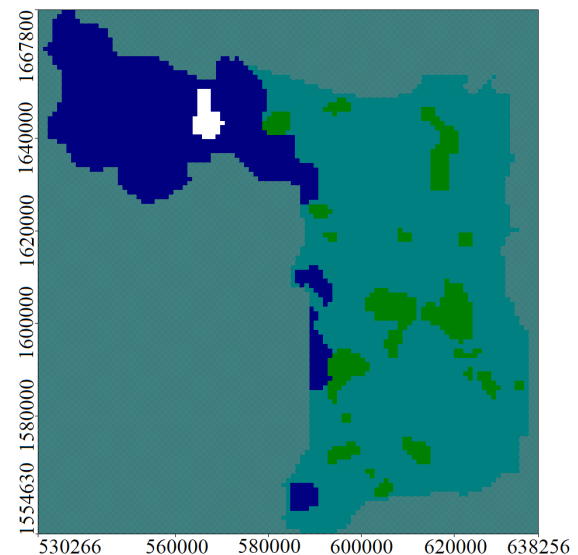


Fig.6 Location of recharge estimation

Table 2. Recharge Estimation Value

No.	Land Use Type	Percent of Rainfall (%)
1	Forest	8
2	Agriculture	4
3	Urban and Industrial	1
4	Water Body	0

5.6 Site Identification

Finally, the model was used to simulate the impact of artificial recharge in five selected zones over a 5-year period (2025–2030). Changes in storage, inflow, and outflow were monitored using the Zone Budget tool in Visual MODFLOW. These simulations helped determine the effectiveness of groundwater recharge in suitable location followed by Tanachaichoksirikun [23].

6. RESULTS AND DISCUSSION

6.1 Calibration and Verification Results

The model was calibrated using data from 13 observation wells across the province in 2014-2019. The comparison between observed and simulated groundwater levels showed strong agreement i.e., Root Mean Square Error (*RMSE*) was 1.28 m, Standard Error (*SE*) was 0.32 m, Normalized *RMSE* was 5.97% and correlation coefficient (*R*²) was 0.983. The verification results using data from 13 observation wells across the province in 2020-2024 was *RMSE* was 1.18 m, *SE* was 0.34 m, Normalized *RMSE* was 5.20% and correlation coefficient (*R*²) was 0.992. These values confirm that the model reliably

represents groundwater behavior and can be used for scenario simulations [24-25].

6.2 Sensitivity Analysis Test

Sensitivity tests showed that hydraulic conductivity had the greatest influence on groundwater levels, followed by recharge rates. Changes of ±25%, ±50%, and ±75% in hydraulic conductivity caused noticeable shifts in water levels, indicating the importance of accurate field measurement of aquifer parameters.

6.3 Scenario Simulations

Locations were selected to test the groundwater budget under artificial recharge conditions over a 5-year simulation period (2025–2030).

The result revealed that Tha Chin River Basin and Urban and Industry experienced positive water storage gains, indicating effective recharge into aquifers. Dan Chang, U Thong, and Pho Phraya zones showed little or no net recharge, due to either low permeability, high extraction rates, or unsuitable geology. This confirms that not all areas are equally suitable for groundwater recharge, and site selection must consider hydrogeological compatibility.

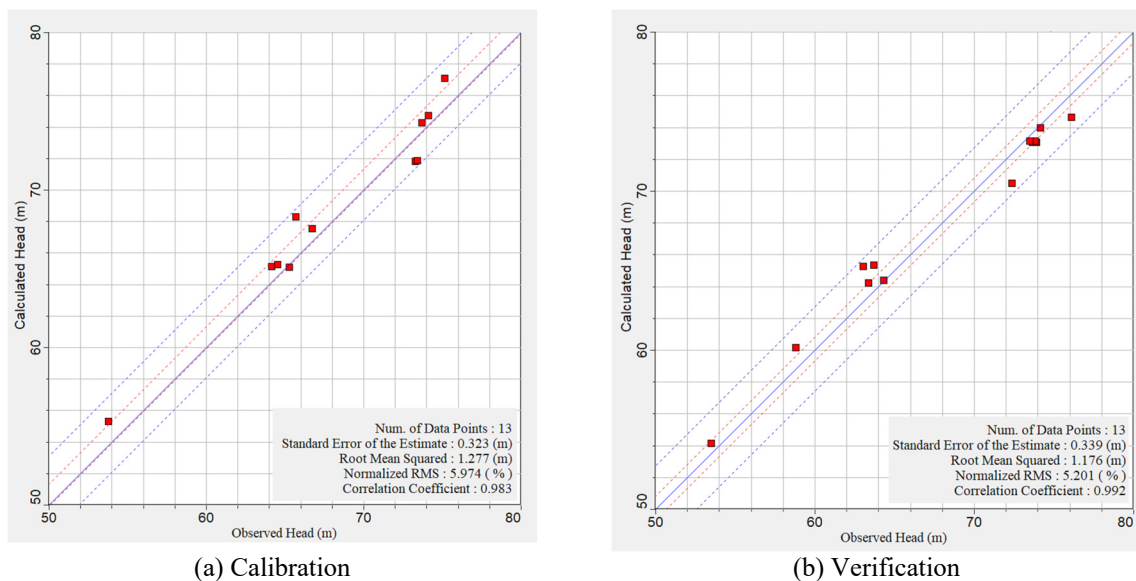


Fig.7 Calibration and verification results

Table 3. Groundwater Recharge Volume and Beneficiaries

Location	Recharge Volume (m ³ /day)	Recharge Volume (liters/day)	Water Use per Person (liters/day)	Estimated Number of Beneficiaries (people/day)
Dan Chang	-1046.94	-1046,940	200	Not Enough
Tha Chin River	320.39	320,390	200	1,601.95
City Center	343.42	343,420	200	1,717.10
Pho Phraya	-1205.03	-1205,030	200	Not Enough
U-Thong	-2039.81	-2039,810	200	Not Enough

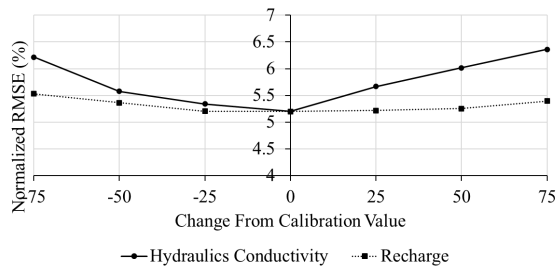


Fig.8 Sensitivity analysis

6.4 Recharge Volumes and Beneficiaries

In 2025-2030, the groundwater recharge simulation estimated the following recharge volumes, including, Tha Chin River area was 320.39 m³/day, and urban and industrial zone was 343.42 m³/day as shown in Table 3. The average per capita water use of 200 liters/day, the number of people who could benefit from the stored water is 1,602 people in Tha Chin River area and 1,717 people in urban and industrial zones. This demonstrates the potential of groundwater recharge to support water needs during dry seasons, especially in urban and semi-urban.

7. CONCLUSION

This study successfully developed and tested a groundwater recharge estimation and site identification approach for Managed Aquifer Recharge (MAR) in Suphanburi, Thailand, using GIS-based spatial analysis and Visual MODFLOW simulations. By integrating hydrological, geological, and land use data, the model identified zones with high recharge potential and evaluated the impacts of artificial recharge under various scenarios.

Simulation results showed that only two out of five selected areas—Urban and Industry and Tha Chin River Basin—had favorable conditions for groundwater budget, based on recharge volume, aquifer response, and safety from contamination. These zones were capable of storing groundwater at rates exceeding 300 m³/day, benefiting more than 1,600 people per site during dry periods.

The findings highlight the importance of site-specific planning, emphasizing that groundwater recharge is not suitable for every area but can be highly effective when applied under the right hydrogeological and land use conditions. Moreover, the study demonstrates how combining local knowledge with scientific tools can support cost-effective and sustainable water management.

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