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Article

Numerical Simulation and Prediction of Groundwater in Bac Ninh Urban Area, Red River Delta: Balancing Urban Expansion with Sustainable Resource Management

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Abstract. This study utilizes the FEFLOW model to simulate groundwater dynamics in the Bac Ninh urban area, located in the Red River Delta, to assess the impact of increased water extraction due to urbanization and industrialization. Two scenarios were analyzed: Scenario 1, which maintains current extraction rates, and Scenario 2, which includes four new groundwater supply stations. The results of Scenario 1 show a gradual decline in groundwater levels, particularly in areas distant from rivers, but levels remain within allowable limits. Wells near rivers exhibit more stable groundwater levels due to natural recharge. Scenario 2 results in a larger decline, especially in distant areas, but the strategic placement of new wells near rivers helps mitigate the impact by enhancing natural recharge. The study concludes that future water demands, projected to increase by 12,500 m^3/day by 2025 and 23,000 m^3/day by 2030, can be met without exceeding the allowable depletion levels, provided that groundwater resources are managed effectively. The use of the FEFLOW model highlights the importance of optimizing well placement and extraction rates to ensure groundwater sustainability in Bac Ninh.

Keywords: Bac Ninh urban area, Red River delta, groundwater modeling, FEFLOW DHI.

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1. Introduction

Bac Ninh urban area, with an area of approximately 354 km², includes Bac Ninh City, Tu Son Town, and the districts of Yen Phong, Tien Du, and a part of Que Vo District. Bac Ninh is one of the provinces with the highest population density in Vietnam, with around 1.5 million people as of 2023. Most of the population is concentrated in rapidly developing urban areas and industrial zones, creating pressure on water resources due to rapid industrialization and urbanization. Groundwater aquifers are one of the main water sources serving the needs of daily life and production.

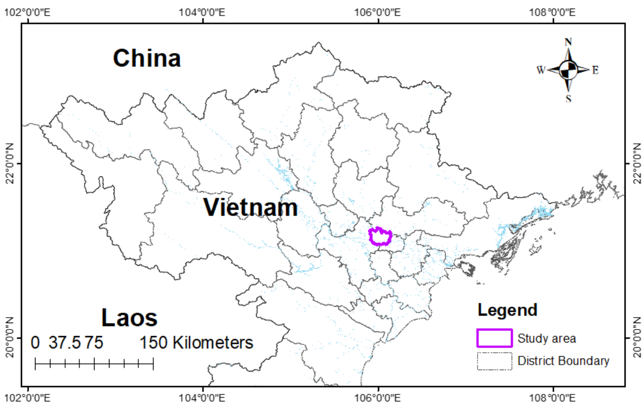

Fig. 1. Location of study area.

Previous studies on hydrogeology in Bac Ninh have focused on assessing groundwater resources and the impact of urbanization and industrialization on these resources. Detailed surveys on the geological structure and groundwater potential in Bac Ninh and surrounding areas have been conducted as part of previous studies (Giang, 2021) [1], which conducted detailed surveys on the geological structure and groundwater potential in the region. Additionally, groundwater monitoring projects by the National Center for Water Resources Planning and Investigation (NAWAPI, 1996) helped track groundwater extraction and assess the development impacts on these resources. Studies on saline intrusion and climate change in Bac Ninh (Truc & Duc, 2017) [2] highlighted the effects of climate change on the quality and quantity of groundwater. Furthermore, research by Giang et al. (2021) on the variability of the Pleistocene and Holocene aquifers provided important information on the area's geological and hydrogeological structure, proposing sustainable groundwater management measures. As demonstrated by previous research on similar urban areas, such as the 3D geological modeling and geotechnical studies of Phnom Penh's subsoils (Engineering Geology, 2014), understanding subsurface characteristics is crucial for effective resource management [3]. These studies have significantly contributed to a better understanding of Bac Ninh's hydrogeology and provided recommendations for protecting groundwater resources in the context of economic development and climate change.

Currently, the groundwater extraction capacity is approximately 86,000 m³/day, with about 48,646 m³/day extracted from concentrated well fields, 22,383 m³/day from individual wells, and 17,001 m³/day for agricultural production using Unicef wells, primarily from the main Pleistocene aquifer.

According to the Water Supply Plan for 2025 and 2030, the demand for groundwater extraction is expected to increase by 12,500 m³/day by 2025 and by 23,000 m³/day by 2030. Recent studies have demonstrated the importance of groundwater management in urbanizing regions, particularly in Southeast Asia and areas with similar geotechnical conditions [4]. To understand the impact of groundwater extraction on groundwater resources, several studies have been conducted, including stratigraphic studies [1] to determine the thickness of the aquifer, pumping tests to determine effective porosity, groundwater level monitoring [5, 6], and finally, the development of a detailed groundwater model for Bắc Ninh based on the Red River Delta built on FEFLOW. FEFLOW software is widely used for simulating groundwater flow and contaminant transport in subsurface environments. This software applies the Finite Element Method (FEM), allowing for the modeling of complex phenomena such as groundwater flow, temperature distribution, and the spread of contaminants within aquifers. Diersch (2013) [7] provides a detailed guide on the application of FEFLOW in groundwater flow studies, highlighting the software's ability to simulate complex hydraulic conditions.

Although FEFLOW was chosen for this study due to its advanced capabilities in simulating groundwater flow using finite element methods, other models, such as MODFLOW and HEC-RAS, were also considered. MODFLOW, a popular tool for groundwater flow modeling, is highly efficient for more straightforward, less heterogeneous systems but lacks the capacity to handle more complex hydrogeological scenarios like FEFLOW. HEC-RAS, on the other hand, is predominantly used for surface water flow simulations and does not offer the same level of functionality for subsurface modeling. By opting for FEFLOW, we can account for the detailed stratigraphy and variable boundary conditions present in the Bac Ninh urban area, allowing for more accurate predictions of groundwater dynamics. However, it should be noted that FEFLOW requires more computational resources and expertise in model setup compared to MODFLOW, which is widely used and supported due to its simplicity and ease of use.

In this study, FEFLOW was applied to simulate the groundwater system in the Bac Ninh urban area, which is under significant pressure due to rapid urbanization and industrialization. Additionally, Schneider et al. (2009) [8] used FEFLOW to study the interaction between surface water and groundwater at a large dam site in Germany, demonstrating the software's effectiveness in solving complex hydrological problems. Therrien et al. (2010) [9] emphasized the accuracy of FEM in simulating subsurface and surface water flow, especially in heterogeneous environments. This effect has been further demonstrated in recent high-impact publications, such as those addressing groundwater flow and stability in areas affected by rainfall-induced landslides and land subsidence [10], which makes it an ideal approach for the Bac Ninh case study.

Therefore, the use of FEFLOW in this study not only helps simulate groundwater flow in detail but also ensures that the simulation results will support sustainable groundwater resource management in the Bac Ninh area.

2. Study Area

2.1. Natural Conditions

The study area, delineated in Fig. 1, comprises an area of approximately 354 km. The northern boundary of the Bac Ninh urban area borders the Cau River, while the southern boundary is adjacent to the Duong River. This region is situated within the tropical, humid monsoon climate of northern Vietnam, characterized by a distinct dry season from November to April of the following year, which contributes approximately 15% of the annual precipitation. The rainy season ranges from May to October, accounting for about 85% of yearly rainfall. The area consistently experiences high relative humidity levels throughout the year, with an annual mean value of around 82% [11].

Climatic data for Bac Ninh reveals an annual precipitation range of 1500 mm to 1800 mm, with evaporation rates varying between 700 mm and 900 mm. The temperature regime exhibits seasonal contrasts, with peak air temperatures reaching 36°C to 38°C during the summer months, while the annual average temperature remains between 23°C and 24°C. The diurnal temperature variation is noteworthy, ranging from 7°C to 14°C in the summer and 4°C to 10°C during the winter season [12].

Bac Ninh features a diverse hydrological network, predominantly influenced by the Duong River and its tributaries, with drainage densities ranging from 1.0 to 1.2 km/km² [11]. The province's terrain is relatively flat, with elevations typically ranging from 3 m to 7 m above sea level, although some areas in the northern part of the province feature low hills reaching up to 300 m. The topography of Bắc Ninh is shaped by several fault systems, including the Northwest-Southeast and Northeast-Southwest faults, which contribute to minor tectonic activity in the region.

The province is part of the Red River Delta's extensive network, and it experiences moderate saline intrusion during the dry season, particularly in areas close to the Duong River [2]. This saline intrusion affects agricultural practices, irrigation systems, and the shallow aquifers that supply water to local communities. The strategic location of Bac Ninh, coupled with its complex hydrological and climatic characteristics, plays a crucial role in the socio-economic development of the region.

2.2. Hydro-Geology Settings

The Bac Ninh urban area, located in the Red River Delta within the Northern Delta region, is experiencing significant water stress due to rapid industrialization and urbanization, characterized by Quaternary deposits. The sediments were deposited in five fining-upward sedimentation cycles, as detailed by Tran, et al (2004) [13]. These cycles span lower to middle Pleistocene, upper Pleistocene, lower to middle Holocene, and upper Holocene ages, exhibiting diverse compositions ranging from coarse-grained alluvial/fluvial deposits to deltaic-lacustrine swamp environment sediments [14]. Geological formations and their implications for groundwater flow have been well studied in Southeast Asia, as demonstrated in recent works focusing on soil slope stability and water resource management in tropical climates [15].

The typical aquifers in Bac Ninh consist of two main layers: the Holocene aquifer and the Pleistocene aquifer (Table 1). The Holocene aquifer is distributed at an average depth of 6.9 meters to 16.8 meters, while the Pleistocene aquifer is found at an average depth of 15.9 meters to 31.8 meters (Fig. 2). The water in these aquifers is primarily fresh. Currently, the wells extracting groundwater use the Pleistocene aquifer, which is the main source of groundwater extraction for the Bac Ninh urban area [1].

Table 1. Overview of the layers incorporated within the groundwater models.

No	Layer	Lithology	Layer's type and symbols
1	Layer 1	Clay silt.	Aquitard 1
2	Layer 2	Holocene sediment porous aquifer with fine sand composition.	Aquifer qh
3	Layer 3	Silty clay.	Aquitard 2
4	Layer 4	Pleistocene sediment porous aquifer comprising gravel, mixed sand, and fine sand.	Aquifer qp

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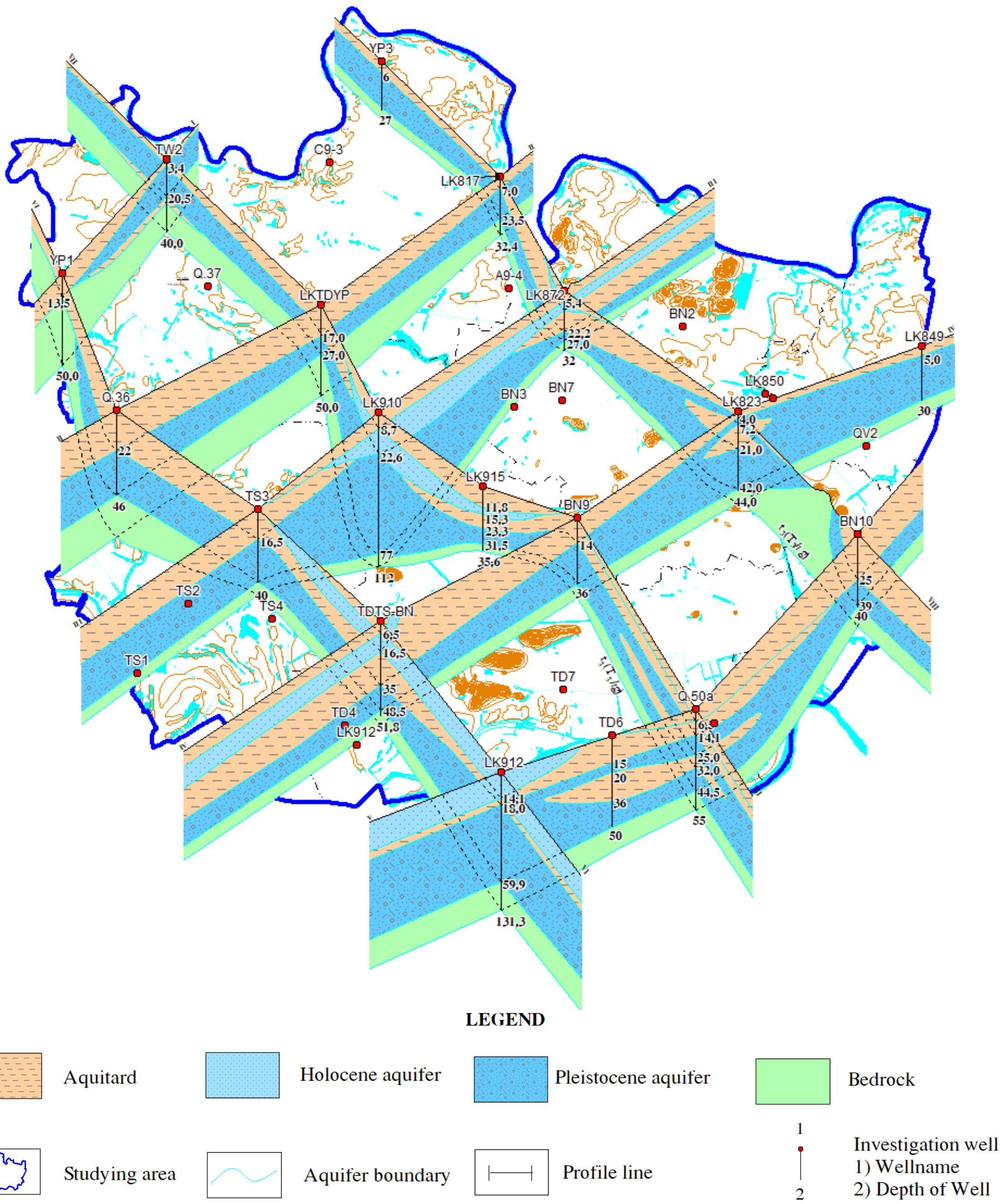

Fig. 2. 3D Hydrogeological map of the Bac Ninh urban area [1]. The numerical values accompanying the borehole diagram denote the layers' depths and the borehole's depth. The color and symbols represent aquifers, aquitards and bedrock. Non-aqueous bedrock is modeled as a no-flow boundary condition and is not simulated in the model.

3. Methods and Materials

3.1. Theories Used

Groundwater flow is typically governed by the Darcy equation, as described by Anderson et al. (2015) [16], which is foundational for many groundwater modeling frameworks. The differential equation of motion of groundwater under heterogeneous and anisotropic environments is as follows:

$$\frac{\partial}{\partial_x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial_y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial_z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad (1)$$

where K_{xx}, K_{yy} and K_{zz} aquifer hydraulic conductivities in the x, y and z directions, respectively; Ss specific storage of the aquifer; h hydraulic head in the aquifer; and t: time; W: the source and/or sink of the aquifers

Equation (1), in conjunction with the specified boundary and initial conditions for the aquifers, constitutes a mathematical model for groundwater flow. As mentioned earlier, it is imperative to identify the function h(x, y, z, t) that complies with Eq. (1) and the prescribed boundary conditions to address the equation. The temporal evolution of the variable h will ascertain the characteristics of the groundwater flow, enabling the computation of both the flow rates and the flow direction.

The Localized Model utilized in the study area was derived from the comprehensive model developed for the entirety of the Red River Delta Plain (Regional model). This model was meticulously crafted by the National Center for Water Resources Planning and Investigation (NAWAPI) to facilitate accurate forecasting of groundwater resources across the delta region [17]. The Localized Model domain spans approximately 354 km². Grid cell dimensions are systematically reduced across multiple tiers, from 2000 meters to 100 meters, ensuring that the finer grid step remains at least half the size of the coarser step. The choice of grid cell dimensions, ranging from 100 m to 2000 m, was strategically made to balance computational efficiency and model accuracy. Finer grids (100 m) were utilized in regions requiring higher resolution, such as near river boundaries and high-extraction areas where significant fluctuations in groundwater levels occur. This level of detail was necessary to accurately capture local variations in hydraulic gradients and the influence of extraction activities. In contrast, coarser grids (up to 2000 m) were applied in broader areas with less pronounced water level changes, optimizing computational performance without sacrificing result reliability. This progressive grid refinement ensured smooth transitions between grid sizes, minimizing potential errors associated with abrupt changes in resolution and enhancing the model's stability and accuracy.

This meticulous meshing strategy mitigates potential calculation errors inherent in solving groundwater flow problems using the FEFLOW model. By adhering to such rigorous meshing, the model faithfully captures the study area's boundary conditions and natural hydrogeological characteristics, thus circumventing reliance on assumed boundary conditions. The delineation of the detailed model area (referred to as the Localized Model) from the Regional Model, along with the grid step progression, is visually depicted in Fig. 3.

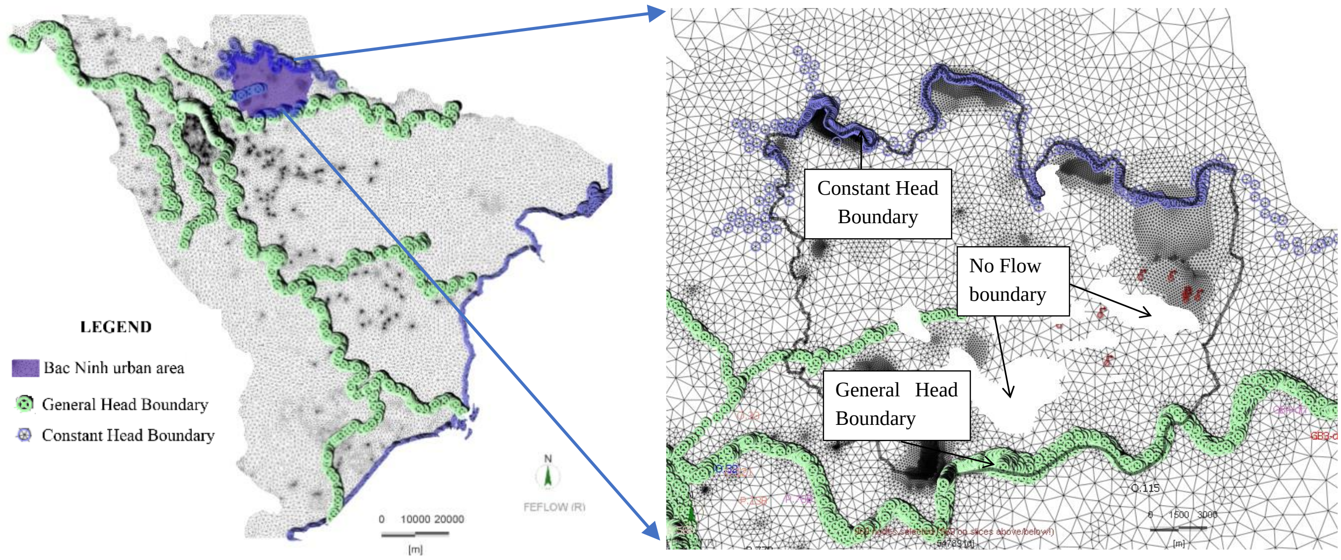

Fig. 3. An integrated modeling approach is implemented, incorporating specific domain delineations, grid resolutions and boundary conditions. This comprises a) a model outlining the Red River Delta in South Vietnam (the Regional Model) and b) a finely gridded model tailored to the unique characteristics of the study area (the Localized Model).

The model of the Bac Ninh was developed based on the Red River Delta Plain (RRDP) - the most recent updated data as follows:

- Updated regional data derived from the Bac Ninh 3D hydrogeological map with a scale of 1/50,000 (see Fig. 1), compiled by Giang et al. (2021) [1]

- A comprehensive survey of the current state of groundwater exploitation, conducted in support of the Hong-Thai Binh rivers basin planning, as presented by D.W.R.M (2020) [18] and Giang et al. (2021) [1]

- Delineation and quantification of direct groundwater recharge across the delta, analyzed by Pham, et al. (2022) [19].

- Assessment of groundwater recharge from the bedrock and the hydraulic interaction between Cau River, Duong River and groundwater in the Bac Ninh and its vicinity, as researched by Giang et al. (2021) via a Pumping test of a well cluster with observation wells drilled perpendicular to the river [1].

The above data set serves as the cornerstone for the Bac Ninh urban area groundwater flow model within the RRDP.

The groundwater flow model was built utilizing the FEFLOW software by DHI version 7.4, with calibration being executed by incorporating data obtained from the national monitoring network and local monitoring network as well as our most recent investigated data. Following the calibration process, the model will be used to predict changes in groundwater levels over time with adjustments to water extraction at major well fields.

3.2. Input Data

Collecting and preparing input data is crucial to developing and calibrating the groundwater flow model

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for the Bac Ninh urban area. These data not only determine the accuracy of the model but also ensure that the model accurately reflects the real conditions of the study area. The input includes data on topography, geological characteristics, groundwater recharge, and existing and future planned pumping wells. All of these factors serve as the foundation for accurately simulating groundwater level changes under the influence of water extraction activities and natural conditions. In the following section, we will delve into the details of the key input data for the FEFLOW model.

- Digital Elevation Model (DEM): This model is created from contour lines and elevation data on a 1:50,000 scale topographic map, covering map sections with 50x50m dimensions. The process within ArcGIS involves two steps:

1) The triangulated irregular network (TIN) method is widely applied in generating digital elevation models (Huang, 1989) [20], ensuring the accuracy of surface representation. Generate a TIN using contour lines, elevation points, and local key elevations. TIN modeling preserves elevation point shapes and sharp peaks.

2) Interpolate the DEM map from the TIN using the Natural Neighbor method, ensuring accurate representation by referencing surrounding points and avoiding elevation anomalies.

- Finite Element Mesh: Based on the characteristics of the aquifer distribution and the project area, it was determined that using a triangular mesh to divide the computational region in the model would provide higher reliability. For the model area of 372.5 km², the grid was divided using triangular prism cells. The mesh was set so that the angle of each triangle is greater than or equal to 30°, avoiding sharp angles that could cause model errors [21]. In the urban area of Bac Ninh, the mesh was refined around the rivers and extraction wells to improve accuracy in water levels and hydraulic gradient changes in each cell. The result of the grid division for Bac Ninh's urban area consists of 367,630 nodes and 583,992 elements across 4 layers. The length of the triangular mesh sides varies from 200 to under 1,000 meters, ensuring that each high-capacity extraction well is located at a grid node.

- Stratigraphic layer classification: The stratigraphic interpolation process encompasses a comprehensive dataset consisting of 728 well logs and 94 well logs in the Bac Ninh urban area, as reported by Giang, et al. (2021) [1]. This dataset is categorized into four distinct layers for the hydrogeological stratification analysis, including the surface aquitard layer (referred to as Aquitard 1), the Holocene aquifer (referred to as qh), the Holocene-Pleistocene aquitard (referred to as Aquitard 2), and the Pleistocene aquifer (referred to as qp) (see Fig. 4).

- Groundwater recharge: The data for groundwater recharge incorporated into the model is derived from the latest research findings as presented by Pham et al. (2022) for RRDP [19]. In Bac Ninh urban area, the amount of recharge for groundwater is taken to be equivalent to 4÷7% of the rainfall according to the average meteorological rainfall measurement data of Bac Ninh meteorological station from 1.400 mm/year to 1.600 mm/year.

- Boundary conditions: The model's boundary conditions, outlined in Section 3.1, incorporate contemporary research. To simulate the conditions of the Cau River in the north and the Duong River in the south, flowing through Bac Ninh city, using Constant Head and General Head Boundary conditions. The water levels of the Cau and Duong rivers are based on data from the SC1 hydrological station and Ben Ho hydrological station under the National Centre for Hydro-Meteorological Forecasting. Results from previous pumping tests by Giang, et al. (2021) [1, 22, 23] show that the Cau and Duong Rivers have a close hydraulic relationship with groundwater, especially the Cau River, where the riverbed intersects the aquifer, creating a direct connection with groundwater.

The groundwater extraction wells are simulated using Type II - Flux boundary conditions. The current state of groundwater extraction in the Bac Ninh urban area is depicted in Fig. 8. The total volume of groundwater extracted across the region is approximately 86,000 m³ per day.

- Large-scale groundwater extraction from well fields includes a Water Treatment Plant (WTP) and a Water Supply Station (WSS) amounting to around 48,646 m³/day, and is represented as active wells in (Fig. 5).

- The current state of individual groundwater extraction from single wells in the study area is primarily concentrated in factories and enterprises located in major industrial zones. The wells predominantly extract water from Pleistocene aquifers, with a few wells tapping into the Triassic aquifer. The total extraction volume is 25,323 m³/day (Fig. 8).

- Rural groundwater extraction consists of small-diameter drilled wells and dug wells used for domestic needs, livestock farming, irrigation, or small-scale businesses with low extraction rates (<10 m³/day). A total of 20,990 wells have been drilled, with a combined extraction capacity of 17,000 m³/day (Fig. 8).

- Initial Head condition: Following the model for the Bac Ninh urban area, the initial water level was set as of December 1996, when groundwater extraction was minimal, and the groundwater levels were less impacted by extraction activities.

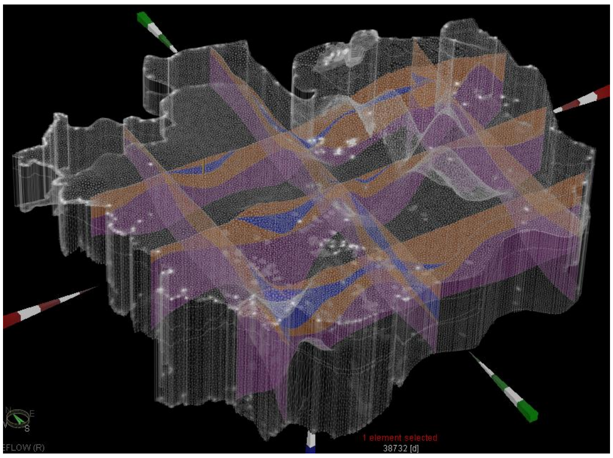

Fig. 4. Mesh and layer in the FEFLOW model. Layer 1, in light brown, represents aquitard 1; Layer 2, in blue, represents the Holocene aquifer; Layer 3, in dark brown, represents aquitard 2; Layer 4, in purple, represents the Pleistocene aquifer. The bedrock is an aquiclude modeled as completely inactive cells or not simulated in the FEFLOW model.

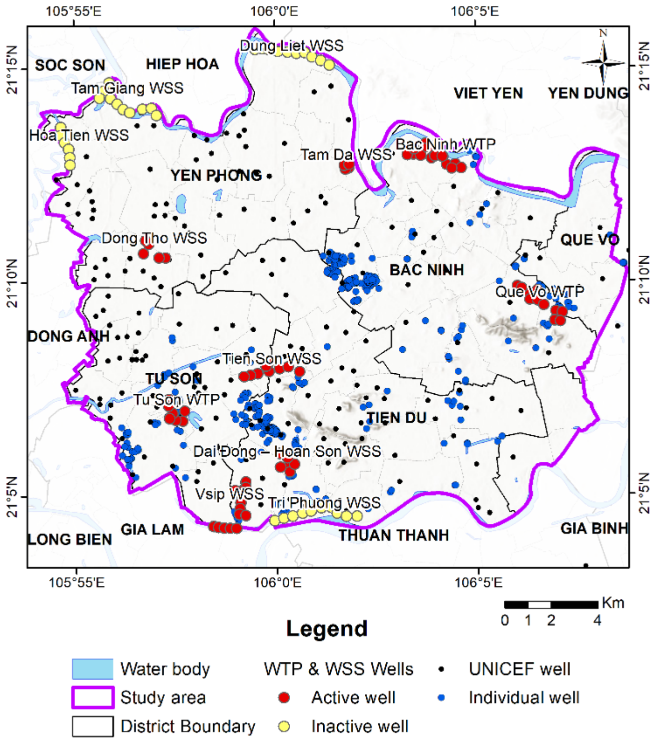

Fig. 5. Groundwater extraction wells in Bac Ninh City. WTP & WSS Wellls refer to wells belonging to the Water Treatment Plant (WTP) and Water Supply Station (WSS). The "active wells" represent the wells currently in operation (SC1), while the "inactive wells" are those not yet in operation but planned to be activated (new wells) in the future (SC 2).

Table 2. Overview of the hydrogeological parameters characterizing and boundary conditions for the FEFLOW model.

No	Parameter	Value/Range	Description
1	Hydraulic conductivity of the aquifer	3 – 90 m/day	Determined based on the results of a pumping test
2	Hydraulic conductivity of the aquiclude	0.001 to 0.003 m/day	The results of the permeability study were determined based on grain size analysis for clay and silty clay sediments.
3	Storativity	0.0013 – 0.003	The storativity is determined based on the results of a pumping test with observation wells in a multi-well experiment [1]
4	Pumping rate	Variable/Fluid boundary	Groundwater extraction rates at well sites
5	No-flow boundary	Bedrock	Impermeable boundaries representing bedrock layers
6	River Boundary	Constant Head	The water level fixed at the river for the model boundary

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Table 3. Groundwater extraction from well fields in Bac Ninh urban area.

No	Wellfield	Year of commencement of GW extraction	Number of wells	Pumping Rate (m^3/ngày)
1	Que Vo Industrial Park Water Supply Station (Que Vo WTP)	2005	12	8,900
2	Bac Ninh Water Plant (Bac Ninh WTP)	1998	21	10,500
3	Tu Son Town water plant (Tu Son WTP)	2007	7	6,056
4	Tien Son Industrial Park Water Supply Station (Tien Son (WSS)	2013	9	1,710
5	Vsip Industrial Park Water Supply Station (VSIP WSS)	2012	15	12,260
6	Dai Dong - Hoan Son Industrial Park Water Supply Station (Dai Dong – Hoan Son WSS)	2019	6	5,040
7	Dong Tho Industrial Park Water Supply Station (Dong Tho WSS)	2000	5	1,680
8	Tam Da Commune People's Committee Water Supply Station (Tam Da WSS)	-	5	2,500
Total			80	48,646

4. Results and Discussion

4.1. Model Calibration

In the study area, a three-dimensional FEFLOW DHI-based model was constructed and subsequently calibrated by comparing the simulated groundwater levels with those observed in the monitoring network. Calibration of the model, addressing instability issues, was carried out utilizing records from local and national monitoring wells covering the period from January 1996 to June 2020. The national and local monitoring network employs a borehole monitoring system within aquifers to serve as reference points for assessing water levels in the model. The dataset used for calibration comprises a total of 18 observational boreholes located in the Pleistocene aquifer. There are no observational boreholes in the Holocene aquifer, as this aquifer is thin, discontinuously distributed, and is not the primary groundwater extraction source. The monitoring data are routinely compiled and stored in the database managed by the National Center for Water Resources Planning and Investigation [5] and the Bac Ninh Department of Natural Resources and Environment [6].

The map shows that the groundwater contour lines (hydraulic head) tend to concentrate in certain areas. Notably, there is a distinct low groundwater region in the central part of the map, where the contour lines are densely packed, indicating a significant drop in groundwater levels in this area (Fig. 6.).

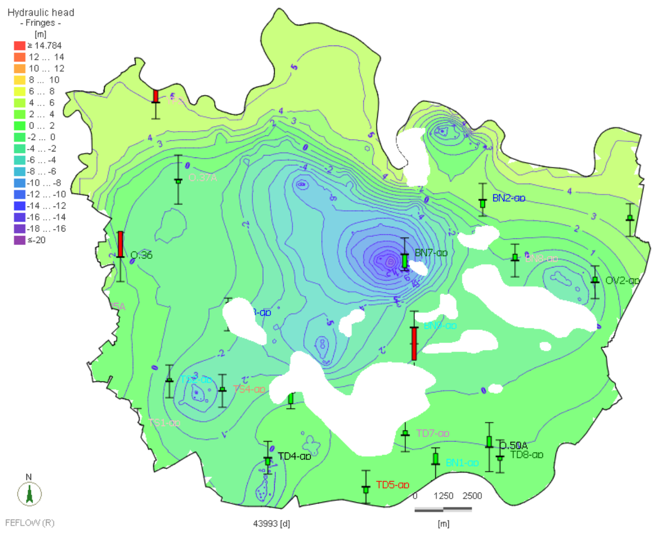

Fig. 6. Hydraulic head of the Pleistocene aquifer as of June 2020 with observation points (green and red). It can be observed that the points with low error (green) are often located in regions with stable or less fluctuating groundwater levels. Conversely, points with higher error (red) tend to appear in areas with significant groundwater level fluctuations, especially near regions with a sharp drop in water levels.

This may suggest heavy groundwater extraction or an area of low-lying terrain where water accumulates and depletes quickly. Some other areas, particularly in the northern and western parts of the map, show higher groundwater levels with more spaced-out contour lines. This could indicate that these regions have more stable hydrological conditions or better groundwater recharge from rivers.

Beyond the visual depictions of calibration outcomes, quantitative summary metrics are computed to gauge the alignment between model simulations and observational data. Three statistical metrics frequently employed to assess model discrepancies include Absolute Residual Mean (ARM), Root Mean Squared Error (RMSE) and Nash–Sutcliffe model efficiency (NSE). Both ARM and RMSE gauge modeling discrepancies, representing the gap between observed and simulated datasets; ideally, these values should be minimal. In the situation of a perfect model with an estimation error variance equal to zero, the resulting Nash–Sutcliffe Efficiency equals 1 (NSE = 1). Conversely, a model that produces an estimation error variance equal to the variance of the observed time series results in a Nash–Sutcliffe Efficiency of 0.0 (NSE = 0).

The comparison between observed and modeled groundwater levels at monitoring boreholes is illustrated in Fig. 6.

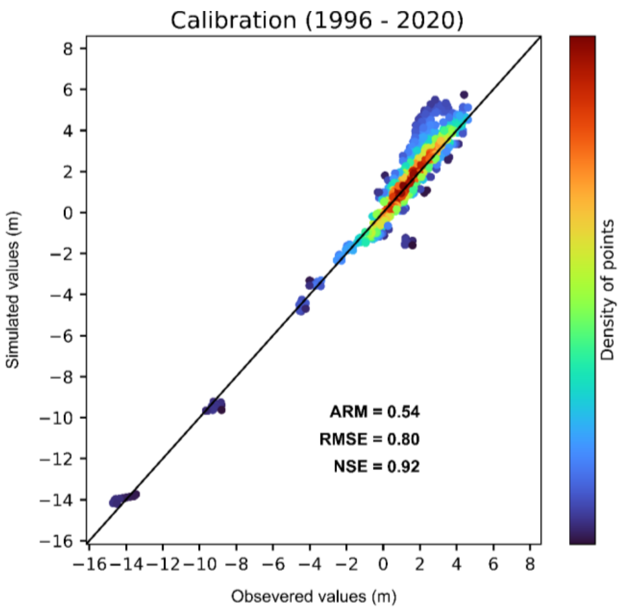

Fig. 7. The comparison between observed and modeled groundwater levels at monitoring boreholes with ARM=0.54 m, RMSE=0.8 and NSE=0.92. An NSE of 0.92 indicates a good model performance, suggesting that the model explains 92% of the variance in the observed data. In practical terms, a model with an NSE of 0.92 is highly efficient and reliable, meaning it closely replicates the observed data.

4.2. Prediction with Present Scenario (SC 1)

After validating the groundwater model, it was run for 360 months (30 years) from January 2020 to January 2050, with monthly intervals. The same pumping rate at present in Section 3.2 was used for predictions. The long-term annual average rainfall from Bac Ninh meteorological station over the past five years was used for the entire modeling period.

Over the years from 2021 to 2050, groundwater levels in the area show a decreasing trend, particularly in the central region of the map. Initially, low areas with declining groundwater levels were already evident in 2021 and continued to expand and deepen over the years. The central area, which had already experienced low groundwater levels, became more severe as the low-level zones expanded and the water levels continued to drop further. The regions with higher groundwater levels in the north and west appeared to remain stable in the early years but gradually began to show signs of a slight decline over time. By 2050, the depletion of groundwater levels had spread beyond the central region and into the surrounding regions (Fig. 7).

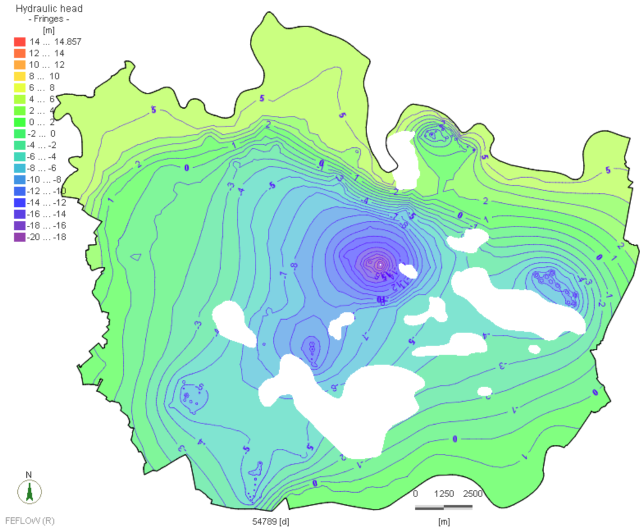

Fig.7. Hydraulic head of the Pleistocene aquifer as of Jan 2050 under SC1

Table 4 presents data on groundwater levels at various water supply stations located in industrial parks and urban areas to 2050. The groundwater level at all extraction wells shows a downward trend over time from 2021 to 2050. This is evident from the groundwater level (GW level) values, which gradually decrease over the years 2021, 2030, and 2050.

The extraction wells near rivers tend to have more stable water levels, whereas wells located farther from rivers, near bedrock (outcrop) areas, show a relatively more significant decline in water levels. Specifically, The wells at Tien Son WSS show the most significant decline, with groundwater levels dropping from -13.44 m in 2021 to -17.48 m in 2050, representing a decrease of approximately 4.04 m over 30 years (Table 4). The wells at Tam Da WSS experience the smallest decrease, with groundwater levels dropping by only 0.01 m from 2021 to 2050, indicating this area is less affected compared to others (Table 4).

Areas with higher extraction rates, such as the VSIP WSS and Bac Ninh WTP, exhibit more significant decreases in groundwater levels compared to areas with lower extraction rates (Table 4). This highlights the correlation between pumping rates and groundwater depletion.

H_{cp} values represent the allowable groundwater elevation defined by the Vietnam government [24]. The allowable groundwater threshold is determined by half the thickness of the unconfined aquifer or the roof of the confined aquifer. Although there are differences between

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the actual drawdown levels and the allowable levels at each well, all remain within the permissible limits. This could be the result of effective groundwater resource management or favorable natural and hydrological conditions in the area that align with the current groundwater extraction levels.

Maintaining drawdown levels below the allowable limits also helps protect groundwater resources and prevent negative impacts such as groundwater depletion and land subsidence in the Bac Ninh urban area.

4.3. Prediction with varying rates of Pumping (SC 2)

Based on the water levels under Scenario 1 (maintaining the current extraction status), the results indicate that while groundwater levels are declining, they have not yet exceeded the allowable threshold. Some well fields near rivers have shown signs of stabilization. In light of future water demand projections for the Bac Ninh urban area [25], this scenario maintains the current extraction status of wells as outlined in Section 3.2 while adding four additional groundwater supply stations: Dung Liet WSS, Tam Giang WSS, Hoa Tien WSS, and Tri Phuong WSS. These new well fields will increase the total extraction capacity by 12,500 m^3/day by 2025 and 23,000 m^3/day by 2030. Those well fields are represented as inactive wells in Fig. 5.

The new well fields are strategically located near rivers to enhance groundwater recharge from river sources. Detailed extraction capacities for the new well fields are presented in Table 5.

In this scenario, although the new well fields coming into operation result in a more significant decline in water levels compared to Scenario 1, the decrease is not significant. This is because the new well fields are distributed far from the existing ones and are located near rivers, receiving recharge from the rivers during extraction, which limits the drop in water levels. Among the new well fields, Tri Phuong shows the most significant decline, with the water level dropping from 1.25 m in 2021 to -6.45 m by 2050, a total decrease of 7.7 m. However, even by 2050, the groundwater levels would remain above the allowable groundwater elevation. The detailed groundwater elevations at the Water supply station and the allowable water level thresholds are shown in Table 5.

The observed declines in groundwater levels in Scenario 2 are influenced not just by proximity to rivers but also by critical factors such as aquifer hydraulic conductivity, aquifer thickness, and well depths. While natural recharge near river boundaries supports stability, areas farther from rivers, especially those near bedrock outcrops, display more pronounced declines due to limited recharge potential. Additionally, the strategic placement of wells plays a crucial role in this dynamic. Wells positioned closer to rivers benefit from consistent natural recharge, whereas regions with lower hydraulic conductivity or thinner aquifer layers are more prone to depletion. This indicates that aquifer characteristics, combined with well placement strategies, significantly affect groundwater sustainability and resource management.

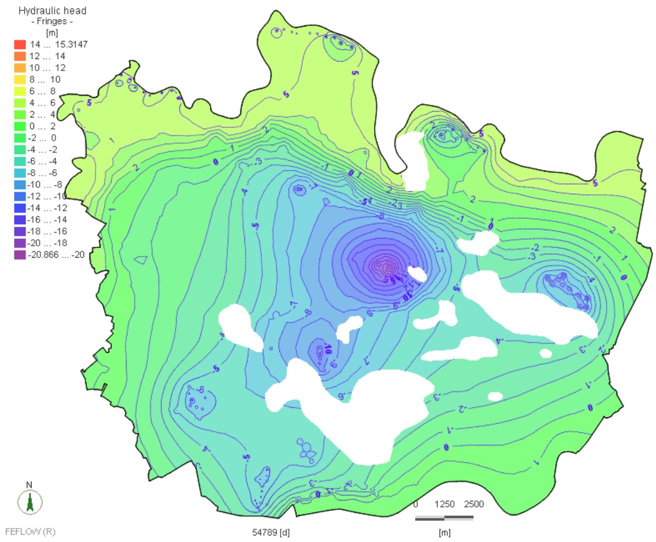

Fig.8. Hydraulic head of the Pleistocene aquifer as of Jan 2050 under SC2

4.4. Discussion

The results of the groundwater simulation highlight the critical role of well placement and proximity to natural recharge sources such as rivers. The importance of well placement and natural recharge sources has been discussed in recent studies, such as those on slope stability and groundwater interaction in geotechnically challenging regions [26]. Natural recharge from rivers plays a critical role in maintaining groundwater levels, as highlighted by Sophocleous (2002) [27] in his study on groundwater-surface water interactions. In Scenario 1, the observed stabilization of groundwater levels near rivers, despite ongoing extraction, underscores the effectiveness of natural recharge in maintaining water balance. In contrast, areas located farther from rivers, particularly those near bedrock outcrops, exhibited a more significant decline in groundwater levels, indicating that these regions are more vulnerable to depletion. The introduction of new well fields in Scenario 2 further illustrates the importance of strategic placement; positioning wells near rivers mitigated the decline in groundwater levels, ensuring that extraction remained sustainable. The primary aim of this study was to establish a baseline simulation using historical rainfall averages to assess the current state of groundwater resources. This approach provides a stable and consistent reference point for understanding current groundwater behavior and trends under existing extraction conditions. While beneficial for evaluating climate impact, incorporating variable recharge scenarios would introduce significant complexities, such as modeling uncertainties due to limited long-term, high-resolution climate data. Additionally, variability scenarios could detract from the primary focus of assessing baseline conditions against current extraction practices. Future studies may explore the impact of recharge rate variability by integrating climate models that can simulate extreme weather conditions and their influence on recharge patterns.

These findings align with previous research conducted in the Red River Delta, which has demonstrated the strong influence of hydrological interactions between surface water bodies and aquifers on groundwater resources. The application of the FEFLOW model in this study, however, offers deeper insights into the spatial variability of groundwater dynamics, particularly in the context of urban expansion. This reinforces the need for adaptive management strategies prioritizing well placement in recharge-prone areas and limiting extraction in regions more vulnerable to depletion.

To meet the projected increase in water demand driven by urbanization and industrial growth, it is imperative to implement comprehensive regulatory measures to prevent excessive groundwater extraction. One key strategy is the introduction of extraction quotas, which would limit the volume of groundwater drawn based on the recharge capacity and health of the aquifers. This would ensure a sustainable balance between extraction and natural recharge, particularly in high-risk areas.

A complementary regulatory approach is tiered pricing for groundwater usage, where extraction beyond set thresholds incurs higher costs. This pricing mechanism would incentivize industries and municipalities to optimize water use and reduce waste. Revenue generated from these fees could be reinvested in enhancing groundwater monitoring infrastructure and supporting projects aimed at increasing artificial recharge, such as the development of infiltration basins or managed aquifer recharge (MAR) systems.

Furthermore, enhanced monitoring and enforcement mechanisms are essential. The implementation of real-time monitoring via observation wells, combined with periodic audits, would ensure adherence to extraction limits and enable more responsive, adaptive management of groundwater resources. The introduction of penalties for non-compliance would further strengthen regulatory enforcement.

Promoting water-efficient technologies in both industrial and agricultural sectors can also significantly reduce groundwater reliance. Incentivizing the adoption of efficient irrigation systems, wastewater recycling, and other water-saving technologies would decrease overall demand for groundwater, particularly during dry periods when natural recharge is limited.

Finally, adopting an integrated land-use planning and water resource management approach is critical. This approach would ensure that new developments, especially in industrial zones, are designed with sustainable water use in mind, incorporating practices such as rainwater harvesting and groundwater recharge strategies.

By implementing these regulatory measures and management strategies, Bac Ninh can effectively safeguard its groundwater resources while accommodating the rising demand from ongoing urban and industrial development.

Despite the robustness of the model, several uncertainties remain that could affect its long-term accuracy. The calibration process was limited by the absence of observational data in the Holocene aquifer due to its thin and discontinuous distribution, which introduces potential errors in areas where this aquifer plays a role. Additionally, the assumptions regarding stable boundary conditions, particularly the interaction between groundwater and surface water from the Cau and Duong rivers, may not fully capture future changes in river flow. Moreover, uncertainties in future groundwater pumping rates, driven by projected industrial and urban growth, further highlight the need for continuous monitoring and adjustments to the model.

5. Conclusion

The groundwater simulation results for the Bac Ninh urban area demonstrate clear trends in groundwater level changes under different scenarios. Scenario 1, which maintains current extraction rates, reveals a gradual decline in groundwater levels across the region, with some stabilization occurring near rivers. Scenario 2, involving the introduction of new well fields, results in a more pronounced decline, but the proximity of these new fields to rivers helps mitigate the overall reduction in water levels.

- Groundwater levels in well fields near rivers remain relatively stable due to natural recharge from the rivers, even with increased extraction rates.
- Well fields located farther from rivers, particularly near bedrock (outcrop) areas, experience a more significant decrease in groundwater levels, emphasizing the importance of strategic well placement near natural recharge sources.
- Higher extraction rates correlate with more substantial groundwater depletion. However, none of the predicted groundwater levels surpass the allowable threshold as defined by national regulations, ensuring that water extraction remains within sustainable limits.
- By 2025 and 2030, the addition of four new water supply stations will increase extraction capacity, especially in areas near rivers, enhancing groundwater recharge. This will support urban and industrial growth without exceeding permissible depletion levels.

In conclusion, careful management of groundwater resources, including strategic placement of wells and monitoring of extraction rates, is essential to meet the growing water demand in Bac Ninh while maintaining sustainable groundwater levels. The results highlight the effectiveness of placing new well fields near rivers to optimize natural recharge and prevent excessive depletion. Continued monitoring and model adjustments will be crucial as urbanization and industrialization continue to expand in the region. Future research should continue exploring groundwater sustainability strategies, as highlighted in recent works such as Modeling of Root-reinforced Soil Slope under Rainfall Condition [28].

Table 4. Lowest groundwater elevation at each wellfield compared to sea level under SC1.

No	Wellfield	Pumping rate (m3/day)	GW level in 2021 (m)	GW level in 2030 (m)	GW level in 2050 (m)	H_{cp} (m)
1	Que Vo WTP	8900	-12.67	-12,85	-13,01	-25.00
2	Bac Ninh WTP	10500	-9.21	-9.22	-9.23	-16.00
3	Tu Son WTP	6056	-6.84	-7.74	-9.09	-15.00
4	Tien Son WSS	1710	-13.44	-14.85	-17,48	-21.00
5	Vsip WSS	12260	-6.30	-7.46	-8.72	-26
6	Dai Dong - Hoan Son WSS	5040	-6.54	-8.38	-10.93	-23
7	Dong Tho WSS	1680	-3.92	-4.16	-4.53	-21
8	Tam Da WSS	2500	-2.54	-2.55	-2.55	-15.00

Table 5. Lowest groundwater elevation at each wellfield compared to sea level under SC2.

No	Wellfield	Pumping rate (m3/day)	Pumping rate (m3/day)	GW level in 2021 (m)	GW level in 2030 (m)	GW level in 2050 (m)	H_{cp} (m)
		2025	2030				
1	Que Vo WTP	8900	8900	-12.67	-12.85	-13.13	-25
2	Bac Ninh WTP	10500	10500	-9.21	-9.22	-9.23	-16
3	Tu Son WTP	6056	6056	-6.84	-7.74	-9.16	-15
4	Tien Son WSS	1710	1710	-13.44	-14.85	-17.63	-21
5	Vsip WSS	12260	12260	-6.30	-7.82	-10.40	-26
6	Dai Dong - Hoan Son WSS	5040	5040	-6.54	-8.54	-11.62	-23
7	Dong Tho WSS	1680	1680	-3.92	-4.17	-4.66	-21
8	Tam Da WSS	2500	2500	-2.54	-2.55	-2.55	-15
9	Dung Liet WSS	3000	5000	5.47	0.6	-1.85	-10
10	Tam Giang WSS	2500	5000	5.47	0.03	-0.59	-16
11	Hoa Tien WSS	2000	3000	5.23	1.63	1.52	-20
12	Tri Phuong WSS	5000	10000	1.25	-4.48	-6.45	-22

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