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ORIGINAL STUDY

Aquifer Characteristics and Groundwater Flow Modeling for Sustainable Water Resources Development and Planning using MODFLOW Software in India

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ABSTRACT

MODFLOW is one of the most commonly used numerical models for simulating groundwater flow. Its structured data design and compatibility with GIS tools make it suitable for groundwater assessment and planning. Groundwater forms an important part of the hydrological cycle and occurs within the pore spaces of sedimentary rocks or within fractures in hard rock terrains. Although its distribution beneath the surface is not always uniform or predictable, it is still considered one of the cleanest, most accessible, and quickly available freshwater sources. Numerical groundwater models help convert complex subsurface processes into simplified relationships that describe flow behavior. Even though such models do not provide a single unique solution, they are useful in representing water level variations and groundwater movement for different hydrogeological settings. With improvements in computational technologies, groundwater models have become important tools for hydro-geologists for resource evaluation, scenario testing, and future prediction. The outcomes of this research will help in supporting better and more sustainable groundwater management in the region.

Keywords: Groundwater flow, Groundwater modeling, Aquifer, Hydrologic

1. Introduction

Groundwater potential zone mapping and groundwater modeling studies across India have established that GIS, Remote Sensing, AHP and MODFLOW are the most widely applied approaches for groundwater assessment. The delineation of groundwater potential zones in the Southern Western Ghats using GIS and AHP achieved nearly 85% accuracy, classifying the basin into “very high” to “very low” zones [1] Another study strengthened this approach by integrating remote sensing, GIS and multi-criteria decision-making techniques and validating the results with 28 and 98 pumping wells [2] Hydrological simulation using MODFLOW has also been widely applied; for example, the Mahesh River basin study demonstrated how MODFLOW can be calibrated using historical data from 2013–2014 [3].

Groundwater flow and contaminant transport modeling shows that arsenic behaviour is largely governed by hydro stratigraphy and climatic conditions [4], and similar modeling in basaltic hard rock regions of Maharashtra was used to determine direction of flow and hydraulic heads [5], MODFLOW/MT3DMS further indicated pollution concentration in the central part of the Noyyal basin [6] and groundwater flow modeling in Musi basin estimated a groundwater velocity of 0.26 m/day and predicted contamination movement from lakes [7].

Numerical modeling in North Bengal predicted arsenic migration under pumping induced stress [8] Groundwater vulnerability studies using water

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quality index and MODFLOW identified contaminant transport and flow direction in the Poiney sub-basin [9] Recharge estimation studies in semi-arid regions using HYDRUS-1D and MODFLOW quantified recharge as 22.2% of monsoon rainfall MODFLOW-based studies have also quantified inflow/outflow, such as in Cachar with 28.47 mcm inflow and 27.45 mcm outflow [10].

Several studies predict depletion — e.g. Hiranyakeshi watershed predicts major decline within a decade and Bemetara district predicts 2.5–4 m decline by 2024 [11] Other studies confirm sustainable conditions such as the Narmada basin or partial criticality such as Solani watershed [12]. MODFLOW has also been used to analyses management alternatives — suggesting reduction in pumping and runoff injection in sandstone aquifers [13] Higher resolution 3-D models have also [14] been used including large-scale canal command areas (Assessment of Groundwater Pollution from Industries in Agra Region 2017).

Multi-layer MODFLOW/MT3D simulations have also predicted uranium contamination rise in Punjab [15]. Overall, these paper-wise findings establish that Indian researchers are using a wide range of GIS-MCDM and MODFLOW techniques for potential zone mapping, flow simulation, recharge estimation and contaminant prediction under current and future stress scenarios across multiple hydrogeological terrains.

Groundwater has been a crucial driver of socio-economic development in India, serving as a pillar of water security for agriculture, domestic use, and industry. India is the world's largest consumer of groundwater [16]. However, this essential resource has faced challenges over the years, with declining groundwater levels becoming a significant concern. This decline can be attributed to the escalated demand brought about by population growth, urban expansion, and industrialization since the 1980s [17]. To exacerbate the situation, there is a growing trend of extracting groundwater from greater depths, contributing to a decline in groundwater quality in various parts of the country [18].

A concerning aspect is that much of this extracted groundwater is non-renewable, as replenishing it occurs much more slowly than extraction rates, sometimes spanning thousands of years [3]. To tackle this issue and prevent the depletion of groundwater resources, it becomes crucial to comprehend how aquifer systems respond to artificial stresses. This understanding is vital to prevent the depletion of groundwater levels and avoid overdrawing from these sources. Moreover, the future might witness even greater reliance on groundwater due to limitations in surface storage capacities, compounded by the unpredictable nature of monsoons. Predicting the trajectory of declining groundwater levels amid various stresses in a given area becomes a pivotal task. Such foresight is essential for effective and sustainable groundwater management, preventing potentially catastrophic consequences for groundwater availability in the years to come [19].

In recent times, groundwater modeling has emerged as a pivotal tool in exploring, forecasting, and remediating groundwater-related issues. This method plays a key role in the planning, design, execution, and management of groundwater resources. Simulation modeling, in particular, stands out as an invaluable means to achieve these objectives. It delivers a platform to simulate diverse scenarios, help understand complex aquifer behaviors, and enable informed decision-making. Groundwater modeling, India can move toward a more sustainable future, providing that this useful resource supports its growth without compromising the environment [20].

Groundwater modeling is a powerful tool for digitally simulated real-world groundwater systems in a virtual format [3, 21]. It encompasses a range of components, including conceptual and numerical models, working together to represent a groundwater system accurately. Converting complex groundwater flow equations into Finite Difference equations [22] can solve these models using specific initial and boundary conditions to generate real-time groundwater scenarios [13]. This process demystifies intricate groundwater flow equations, enabling a better grasp of groundwater's behavior. One fundamental modeling approach involves utilizing three-dimensional finite-difference groundwater flow models like MODFLOW, which the US Geological Survey initially developed. MODFLOW's popularity stems from its adaptable modular structure, making it suitable for handling a wide array of complex hydrogeological systems [5]. Enhanced computer hardware, software capabilities, and Geographic Information Systems (GIS) have further empowered the modeling process, creating more sophisticated three-dimensional groundwater flow simulations.

Groundwater simulation models offer a valuable platform for studying complex problems from a broader perspective and devising optimal economic, social, and environmental solutions [19]. A model serves as a representation, albeit an approximation, of real-world situations. Specifically, a mathematical model indirectly simulates groundwater flow through governing equations [3, 5]. In the present context, we focus on mathematical models, which provide conceptual descriptions or approximations of physical systems using mathematical equations [18].

However, it is important to note that these equations do not provide exact depictions of real-world processes. The use of a model depends on how closely the mathematical equations align with the actual physical system being modeled. To accurately assess a model's utility, a comprehensive understanding of the physical system and the assumptions underlying the derivation of the mathematical equations is necessary [23]. The equations utilized in modeling are built upon simplifying assumptions, often concerning factors such as flow direction, aquifer geometry, and aquifer heterogeneity or anisotropy [18, 24].

Due to these assumptions and the inherent uncertainties in data values the model requires, it is critical to acknowledge that a model is an approximation, not a precise replication of field conditions. Models serve as valuable tools but do not replicate reality itself. Assumptions and simplifications are essential due to the intricate nature of hydrogeological formations and the limitations in available field data [5]. The accuracy of model predictions hinges on successfully calibrating and verifying model simulations. Even minor errors in predictive simulations can lead to significant discrepancies in forward-projected solutions. To assess the accuracy of predictive simulations, monitoring hydraulic heads and groundwater chemistry (performance monitoring) is necessary [25]. Proper numerical modeling entails a comprehensive protocol, from defining modeling objectives and conceptualizing the model, to designing, calibrating, validating, predicting, conducting sensitivity analyses, and performing post-audits. Prior to conceptualizing a model, it is imperative to secure data related to aquifer geometry, hydraulic parameters, and prevailing boundary conditions. By adhering to a systematic modeling process and acknowledging the limitations and assumptions inherent to modeling [3], we can harness the power of groundwater simulation models to gain valuable insights into complex hydrogeological systems and make informed decisions for sustainable resource management [5].

This study is so important for understanding of aquifer condition and groundwater flow based on the MODFLOW software. Such kind of research is so important for groundwater resources and this model so tough for running and provides the best results for this study area. We have observed very limited studied available on this topics and areas. Hence we have targeted this research for effective management of groundwater resources and planning in the semi-arid region.

In the context of this study, the primary goal is to predict the anticipated decline in groundwater levels within affected aquifers over the next decade (2021–2026), considering the current rate of groundwater abstraction. By employing groundwater simulation models, it becomes feasible to address issues holistically, finding solutions that balance technical, economic, social, and environmental considerations. However, it is important to recognize that mathematical models simulate groundwater flow using equations [19], they are approximations rather than exact representations of real-world physical processes. In the present study, a combined surface water and groundwater modeling approach was adopted to understand the hydrologic behavior of the Mahesh River basin. A conceptual model was developed using the Groundwater Modeling System (GMS), and MODFLOW was used as the main modeling package. Important input parameters such as recharge, pumping, return flows, source/sink components, and land/soil classes were included in the model.

The main important objectives as follow as: First, The model was calibrated using observed groundwater levels from 2018 to 2020 to reduce the difference between simulated and observed water levels. Second, refinement was done by adjusting transmissivity values and boundary conditions based on geological and hydrogeological information. Third objective is to project groundwater flow conditions for the period 2021–2026, with a focus on the response of basaltic aquifers. Last objective, they act as tools that offer conceptual insights into complex systems and guide decision-making processes. These models help us predict potential outcomes and evaluate the implications of different management strategies.

The researches hypothesis, that the MODFLOW numerical model can effectively simulate groundwater flow and predict groundwater level variations under different hydrogeological conditions. By integrating hydrogeological parameters and spatial datasets, the model can represent subsurface flow processes and support groundwater resource assessment. Although groundwater distribution is often complex and uncertain, numerical modeling provides a reliable approach to analyze groundwater movement and recharge–discharge dynamics. The study assumes that MODFLOW-based simulations will improve the understanding of groundwater behavior and assist in sustainable groundwater management and planning. Therefore, the model is expected to provide useful insights for evaluating groundwater availability and predicting future groundwater scenarios in the study area.

2. Materials and methods

2.1. Study area

A hydrogeological simulation study has been introduced for the Gokhali area in Indapur Taluka, Pune

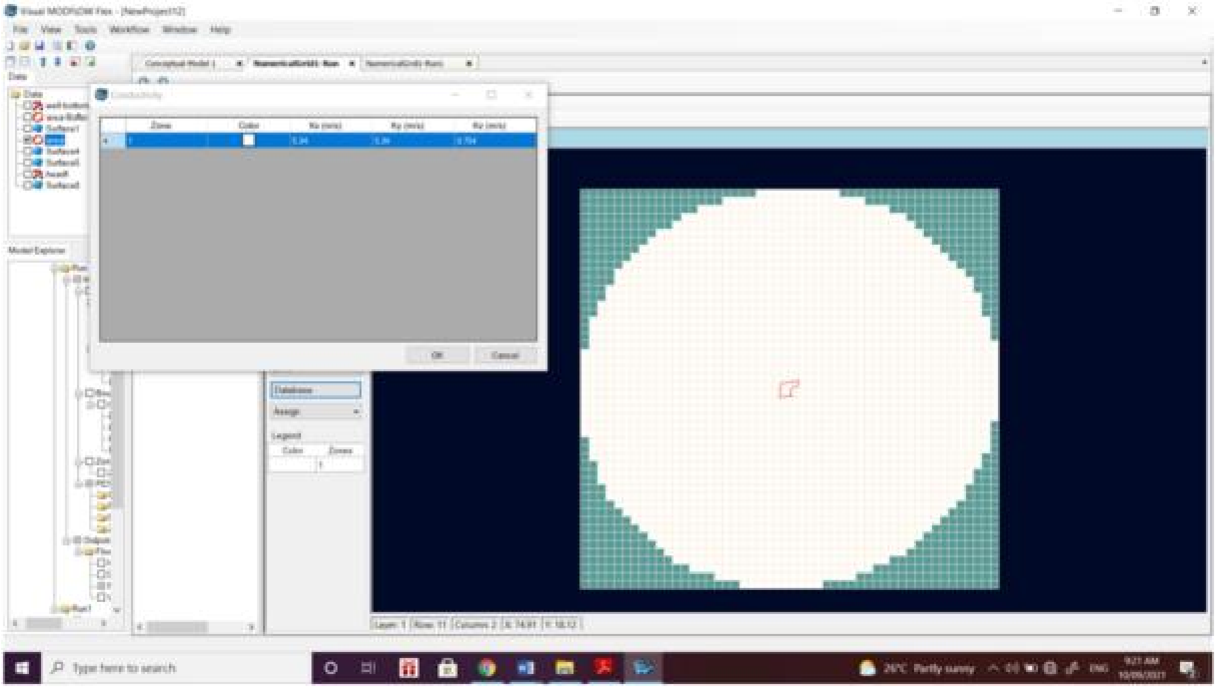


Fig. 1. Hydraulic Conductivity Values layer 1 and 2 (Basaltic) the Model.

District, Maharashtra. This study aims to improve and calibrate a three-dimensional groundwater flow model that signifies present field situations using experimental data. The validated model will be applied to assess a planned pumping situation. The modelled area covers a 40-km radius buffer near Gokhali Village. This method will improve understanding of regional groundwater dynamics and support sustainable groundwater management. Study area maps are shown in Fig. 1.

2.2. Aquifer characteristics

Aquifer I is a shallow, unconfined phreatic aquifer composed of Deccan Trap basalt, with granular layers 3–14 m thick that support groundwater recharge. Aquifer II is a deeper semi-confined to confined basalt aquifer, characterized by 1–3 m thick fractured zones that significantly influence recharge and flow. Variations in thickness and structure affect their hydrological behavior, making accurate representation essential for reliable groundwater modeling (Table 1).

This study uses Visual MODFLOW Flex (Waterloo Hydrogeologic) to simulate, validate, and predict groundwater levels in the study area, and to compare predicted results with observed data. The software is based on the MODFLOW code developed by McDonald and Harbaugh (1988), which simulates three-dimensional groundwater flow using a finite-difference approach. The following section outlines the materials and methods adopted for groundwater modeling.

2.3. Data requirement for modeling

Ideally, groundwater modeling requires extensive spatial and temporal data, but practical and cost limitations often restrict data collection. Therefore, data gathering should align with modeling objectives and required accuracy. A simplified initial model using limited data can be developed and refined through sensitivity analysis to identify key data gaps. The required data are broadly classified into two groups: physical framework data and hydrogeological framework data, as outlined below.

Table 1. *Details of* Aquifer characteristics types.

Number of Aquifer	Type of Aquifer	Aquifer Condition
Aquifer 1	Aquifer- I/Shallow/Phreatic/ Unconfined aquifer- DT Basalt	The Granular rocks Thickness (m) ranges between 3 and 14 m which acts ground water recharge of the model area.
Aquifer 2	Aquifer- II/Deeper/Semi-Confined/ Confined Aquifer - DT Basalt	The Fractured rocks Thickness (m) ranges between 1 and 3 m which acts ground water recharge of the model area.

2.4. Basic data required for model conceptualization

The basic information required for developing a conceptual groundwater model includes Google imagery, northing and easting coordinates for defining the buffer zone boundaries, and geologic maps with cross-sections. Additional essential data inputs include land use/land cover (LULC) maps, observation well details, pumping test results, aquifer geometry, and system boundaries. contour maps representing the elevation of the top and bottom surfaces of the aquifers to be modelled are also necessary for accurate spatial representation and understanding of the subsurface conditions.

2.5. Hydro geologic framework

To determine the initial piezo metric heads, we will first collect water table and piezo metric point data, supported by maps and interpolated values for all aquifer units, which will form the baseline input for model initialization. Historical datasets on groundwater levels, piezo metric head variations, surface water levels, and stream discharge records will be compiled to understand temporal groundwater behavior. Hydraulic properties such as hydraulic conductivity (K) and specific storage (Ss) will be spatially represented through maps and cross-sections, along with the storage characteristics of aquifers and confining beds. Relevant hydraulic parameters of surface water bodies and streams, including conductance, will also be mapped to interpret groundwater–surface water interactions. Additionally, groundwater recharge and withdrawal details will be incorporated to ensure a balanced groundwater budget. Overall, this comprehensive dataset, supported by spatial visualizations and cross-sectional profiles, will facilitate a deeper understanding of aquifer systems and support sustainable groundwater management decisions.

2.6. Input parameters

The model's parameters have been derived directly from comprehensive field studies and a thorough analysis of pumping tests conducted in the region. In the model's stratified layers, hydraulic conductivity values have been assigned to distinct zones, namely Zone-1, Zone-2, and Zone-3. These assignments are based on the geological composition, both overlying and underlying, primarily from the Bhilwara Supergroup. This geological formation represents the primary aquifer responsible for water contribution in the study area. Additionally, storage parameters have been meticulously defined for each layer. A series of trial simulations have been performed by systematically adjusting hydraulic conductivity and storage parameters. These iterations aim to achieve a robust agreement between computed and observed water levels, spatially and temporally. Through this iterative process, the model has been fine-tuned to best replicate the observed hydraulic behavior of the aquifer system. This approach ensures that the model captures the complex hydraulic interactions within the subsurface and effectively predicts the movement of water using geological formations in the study area. One of the crucial input parameters in the modeling process is the initial piezo metric heads, which require precise specification. This study gathered groundwater level data from a network of 31 observation wells, including one specialized Piezo-well. GIS software was employed for cell-based interpolation to achieve spatial representation. The study area encompasses a flat terrain, with an average elevation ranging from 541 meters to 564 meters above mean sea level (amsl). These values were utilized to establish constant head boundaries. These boundaries were strategically positioned along the northwestern and south-eastern perimeters of the model, effectively defining the hydrological conditions. Fig. 2 shows the defined property zones of MODFLOW modeling.

2.7. Input for ground water modeling

The following data are generated for the ground water modeling. The data are required to run the model to get the required output (Table 2).

2.8. Input of observation wells

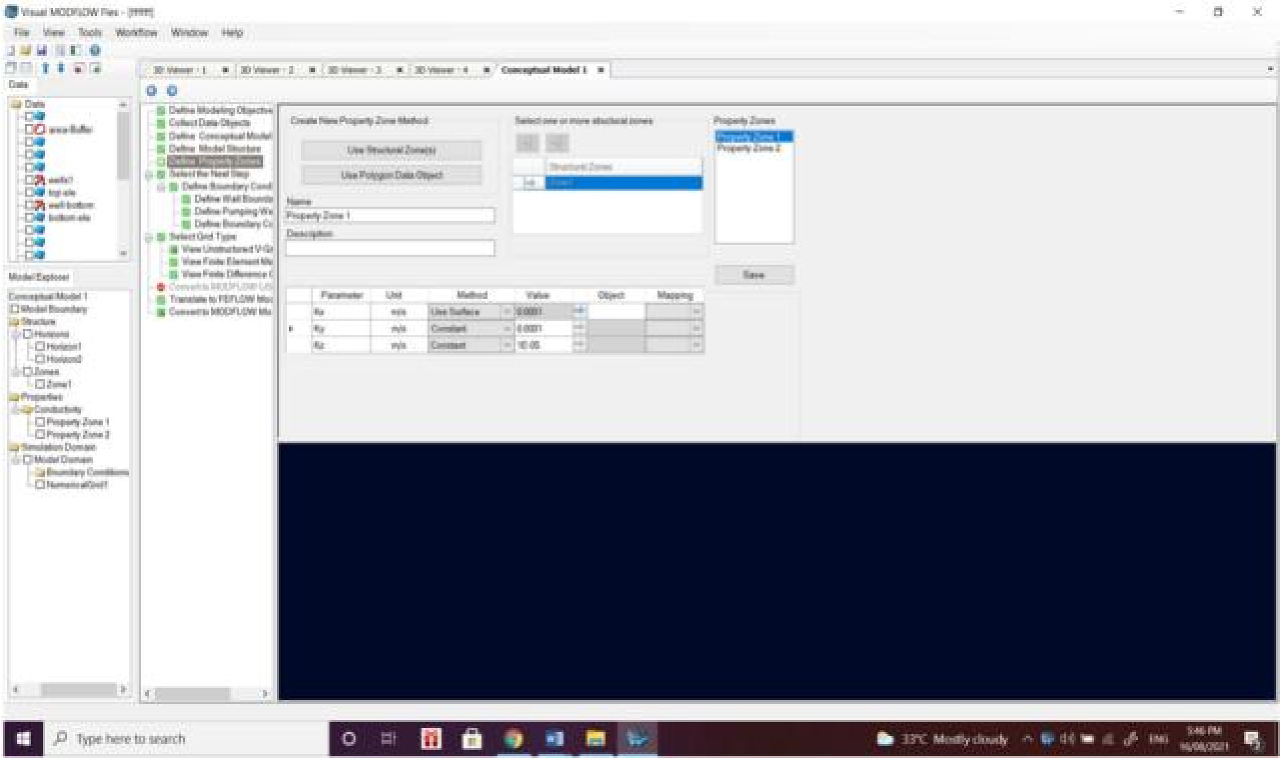
Total 31 observation wells are considered including one Piezo well. Data has been considered from 1st April 2010 to 30th August 2021 has been used for cell wise interpolation through GIS software.

2.9. Input of pumping wells

Total 31 pumping wells are considered including from the 5 km buffer area. Data has been used for cell wise interpolation through GIS software. Pumping Rate m_3_d is -75, -35 and -75 during the simulating period. The model was run to predict the regional groundwater head in area until the year 2021. As per the final, zone budget and scatter plots showing which observation and pumping well in fitted during various stress period (Fig. 3).

2.10. Model domain and grid

The initial step in the simulation process involves importing a digital image of the site to be modeled.



Name: Property Zone 1

Description:

Parameter	Unit	Method	Value	Object	Mapping
Kx	m/s	Use Surface	0.0001		
Ky	m/s	Constant	0.0001		
Kz	m/s	Constant	1E-05		

Fig. 2. Showing the how to define the Property Zones.

Table 2. Details of *Data Input.*

Data	Source of Data
River, Water body	Survey of India Topo Sheet /Satellite Imagery (NRSA)
Rainfall	IMD
Geology	Geological Survey of India
Geomorphology	Interpreted from Satellite Imagery
Topography (Physiography) – Surface elevation	Carto-DEM Data, NRSA
Aquifer Parameters	Pumping test
Hydraulic conductivity, Kx, Ky, Kz and Specific capacity, Specific Storage, Porosity	CGWB Reports and Pumping test
Lithology	CGWB Report
Aquifer Thickness	CGWB Report
Ground water level	Field observation from the Key wells
Software	Visual Modflow flex 2016

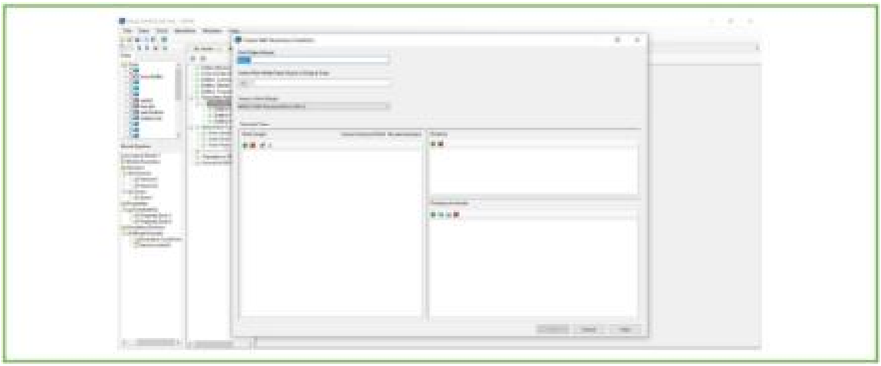


Fig. 3. Showing of Pumping well edit screen.

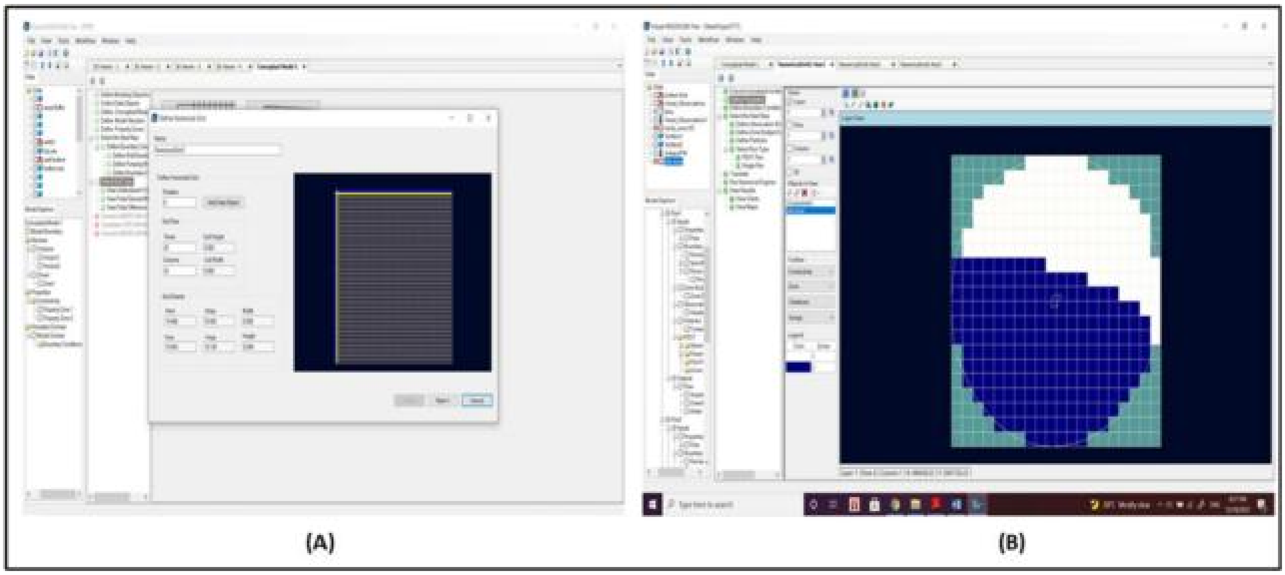


Fig. 4. Showing of how to define the MODFLOW Grid a) Model Grid, b) Numerical Grid.

This image is generated by scanning a map of the target area. In the case of studying the impact of groundwater pumping on both surface and subsurface water dynamics, a groundwater flow model was employed. The study area encompassed a buffer region around the Plant, with a diameter of 5 kilometers, aimed at conceptualizing the groundwater model.

To translate the conceptual model into a numerical one and spatially discretize it, the entire region was divided into a grid of 60 columns and 50 rows, each measuring 500 meters by 500 meters, thus forming a model domain (Fig. 4a and b).

The three-dimensional representation of this model, which comprises two layers, is depicted below the model grid. Boundary conditions were defined along the edges of the simulation domain, encompassing both the top and bottom of the model. Their primary role is to demarcate the model region from the external environment, and they are crucial for solving the groundwater flow equation. These boundaries can be classified as either physical (real) or hydraulic (artificial). In this context, all wells within the model were assigned pumping well boundary conditions, reflecting their influence on the system. Boundary conditions are essential components defined at the edges of a simulation domain, including the top and bottom. They primarily demarcate the model region from the external surroundings and are crucial for solving the groundwater flow equation. These boundaries can be classified into two categories: physical boundaries that correspond to real-world features, and hydraulic boundaries that are introduced artificially to facilitate the modeling process. In the context of the simulation, each boundary is associated with specific conditions that dictate how water interacts with it. In this model, a particular focus has been given to wells, which are designated as pumping wells and assigned a specific boundary condition. The proper specification of boundary conditions is paramount for accurately representing the behavior of the groundwater system within the model. By appropriately defining these conditions, the model can reflect real-world scenarios and provide insights into how water flow interacts with the surrounding environment (Fig. 5a and b).

3. Distribution of conductivity and storage parameter values

Hydraulic conductivity data acquired from pumping tests were instrumental in constructing the model. For the model, the vertical hydraulic conductivity was set at 10% of the horizontal hydraulic conductivity. This hydraulic conductivity, which spans from 3 m/day to 10 m/day, characterizes the variability in this particular layer. Layer-specific hydraulic conductivity values were assigned based on outcomes from the pumping tests. The specific storage values were obtained by dividing the Storativity values obtained in the field by the thickness of the aquifer. The range for specific storage was established as 0.00001 to 0.0001. Similarly, the range for specific yield was defined as 0.04 to 0.2. These adjustments ensured that the model closely aligned with the actual hydrogeological conditions of the site.

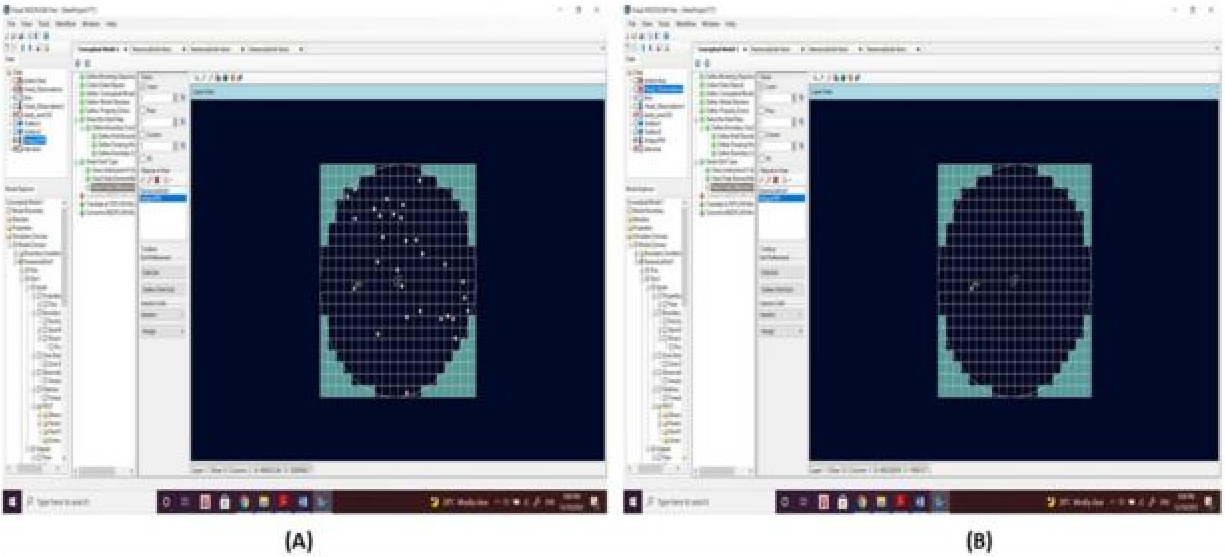

(A) (B)

Fig. 5. Boundary Condition – Constant Head, b) Pumping well input to model.

3.1. Initial head

The initial heads for all the aquifers are derived from the ground water level data collected during field studies. Additionally, the long-term ground water level data obtained from the Central Ground Water Board (CGWB) has been used to validate and refine these initial head values. The layer-wise distribution of initial heads (2018 to 2020) is as follows: These initial head values are crucial inputs for numerical groundwater flow models, as they provide the starting point for simulating the movement of groundwater within aquifer systems. The incorporation of field data and long-term observations from authoritative sources like the CGWB enhances the accuracy and reliability of these initial head estimates, leading to more accurate groundwater flow simulations and predictions.

The initial conditions in a simulation refer to the distribution of groundwater levels throughout the system at the start of the simulation, essentially acting as boundary conditions in the time dimension. It is a common practice to choose a steady-state head solution from a well-calibrated model as the initial condition. In the context of this study, the steady-state head solution from the groundwater levels of the year 2010 was utilized as the initial condition during the calibration period. Similarly, for the validation period, the steady-state head solution derived from the groundwater levels of 2021 was used as the initial condition. To appropriately account for the inflow and outflow within the subsurface, the boundary conditions were defined based on several factors including rivers, recharge, and evapotranspiration. These boundary conditions play a crucial role in accurately representing the interactions between the groundwater system and external factors.

3.2. Aquifer geometry

The ground elevation has been generated using Carto-DEM data for the model area. The layer thickness has been generated from the surface elevation using 30 key well data. The generated elevation for the key wells the elevation for other layers and were interpolated. For all the layers the reduced level (AMSL) surface has been generated and the same is used as input for the model. The aquifer geometrical distribution for each layer is presented below (Fig. 6).

3.3. Ground water model area

The model area is created covering 10 km radius from the plant boundary (as per CGWA Guidelines). The below figure shows the model area covering the plant boundary and river and reservoir. As the area is covered by agriculture land. It is considered as storage zone in Fig. 7a.

3.4. Model evaluation criteria

In order to appraise the act of the calibration and validation of the MODFLOW- depend on arithmetical model, coefficient of determination (R2) as statistical criteria was used. The description on equation of coefficient of determination (R2) is given below

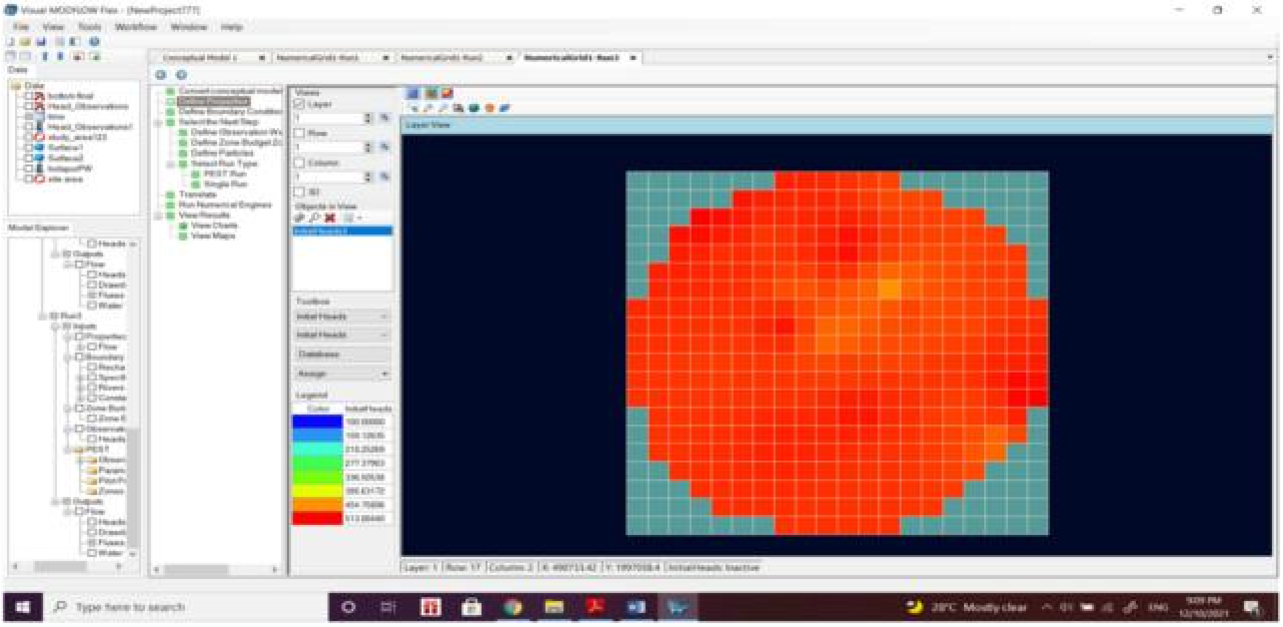


Fig. 6. Showing of Initial Head.

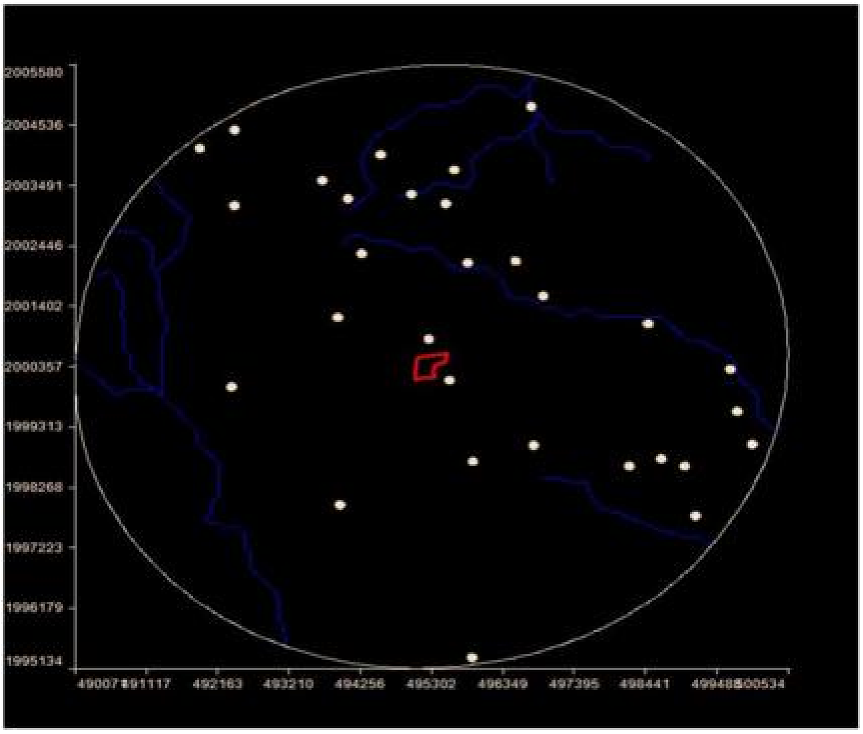


Fig. 7. Model showing the Model Boundary, River and mines site.

(Eq. (1)).

$$r = \left[\frac{\sum_{i=1}^{n} \left\{ \left(Q_A - \underline{Q}_p \right) \left(Q_A - \underline{Q}_p \right) \right\}}{\sqrt{\sum_{i=1}^{n} \left(Q_A - \underline{Q}_p \right)^2} \sqrt{\sum_{i=1}^{n} \left(Q_A - \underline{Q}_p \right)^2}} \right] \quad (1)$$

mean of simulated groundwater levels (m), and N is the number of observations. The best-fit between observed and simulated groundwater levels under ideal conditions would R2 = 1 and acceptable value of R2 is more than 0.85. Coefficient of Determination (R2) can also be calculated from Coefficient of Correlation (R) value. Coefficient of Determination

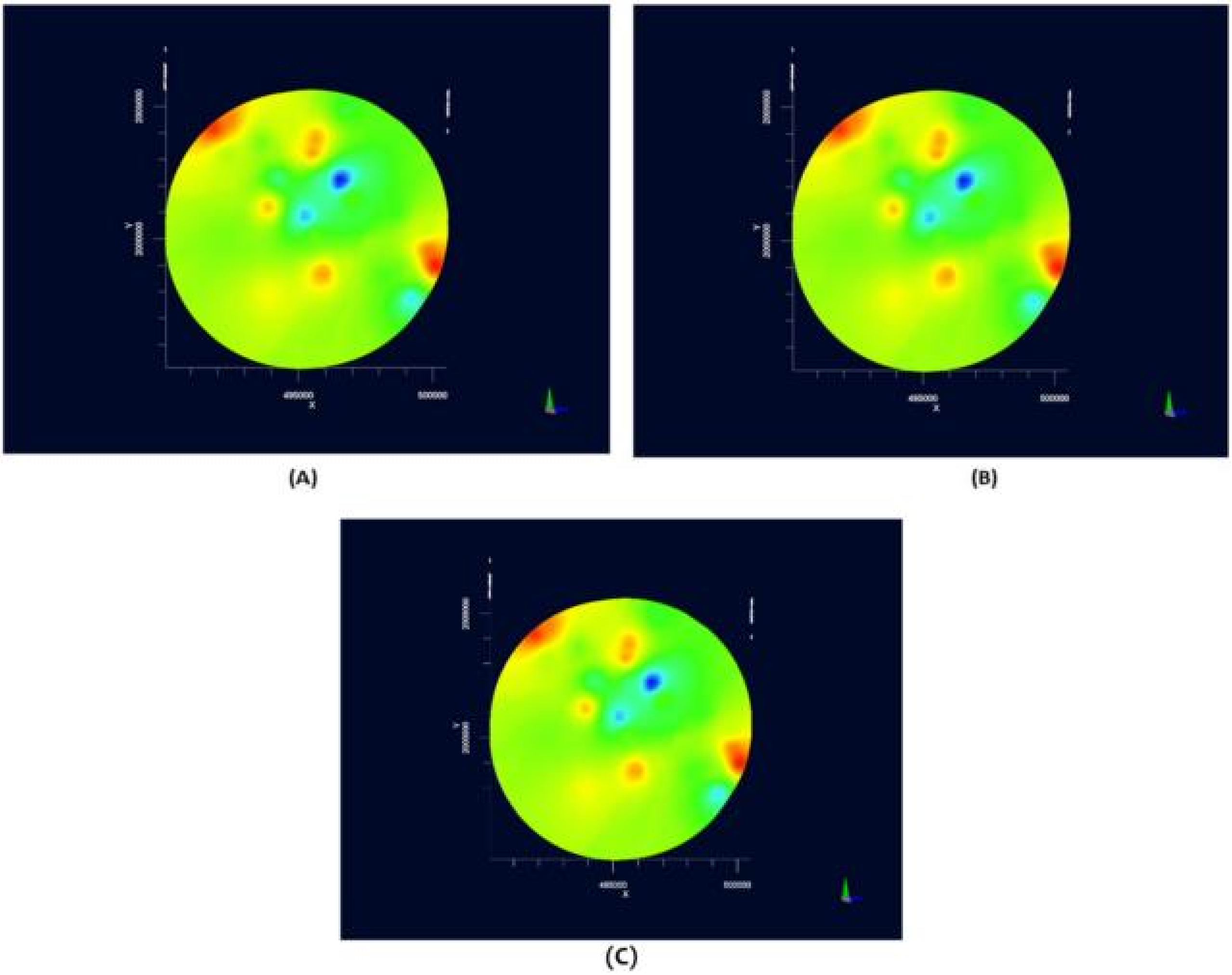


Fig. 7a. A) Surface Elevation (Ground) of the Model Area, B) Bottom Elevation (m, amsl) of the Top Layer Aquifer-I Phreatic Aquifer Basalt Unconfined aquifer, C) Bottom Elevation (m, amsl) of the Aquifer- II Deeper Semi-Confined Confined Aquifer.

(R2) is equal to Coefficient of Correlation (R) X Coefficient of Correlation (R). Visual MODFLOW flex software will give Coefficient of Correlation (R) value in the model result.

3.5. Modeling protocol

The methodology employed in this study to formulate a numerical model comprises a series of structured steps. These steps encompass data collection and acquisition, processing of primary data, temporal and spatial discretization of the model, model conceptualization, incorporation of parameter inputs, and subsequent numerical model development. Following this development, the model undergoes a thorough calibration process, validation against real-world observations, and sensitivity analysis. This iterative approach aids in the identification of crucial data gaps, allowing for their subsequent analysis. The model evolves progressively through the incorporation of additional data into the expanding database, resulting in its refinement over time. The Fig. 8 shows the adopted methodology of modeling groundwater flow in hard rock. Fig. 7a shows the representation of aquifers and surface elevation.

4. Results and discussion

4.1. Model conceptualization

Groundwater models have become broadly used tools for hydrogeologists to bring out a diversity of tasks [3]. The process begins with an examination of compositions, transport mechanisms, and the fundamental factors that guide them, all of which are pertinent to the specific medium properties [18]. These conceptual frameworks are subsequently translated into mathematical models that represent the flow using governing equations, incorporating both primary conditions and boundary conditions [20]. To

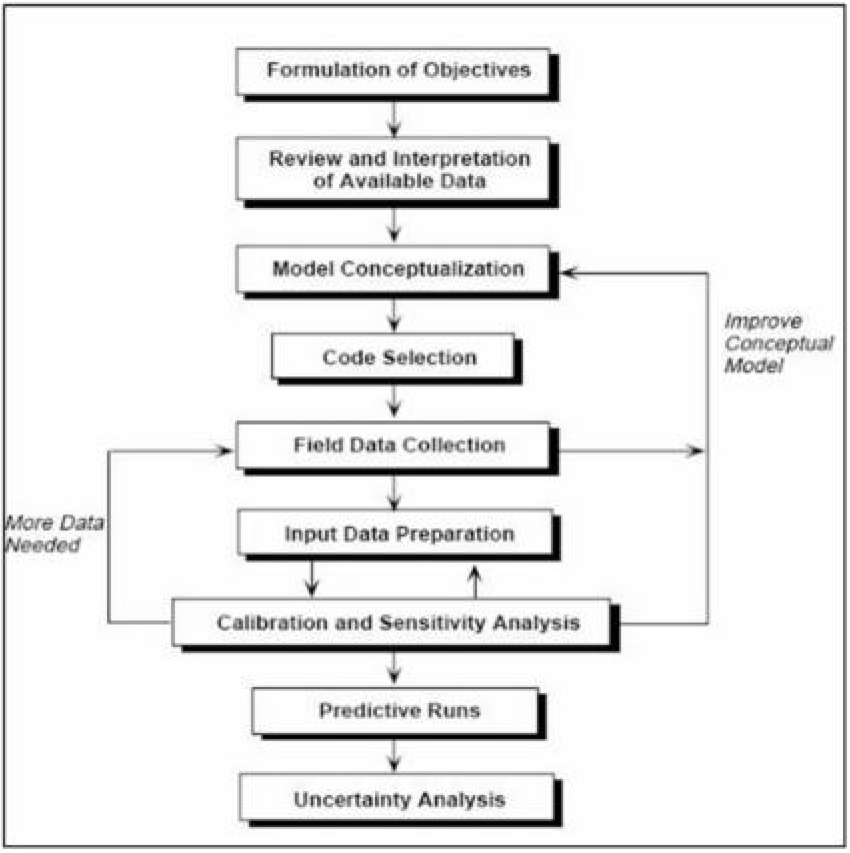


Fig. 8. Modeling Protocol.

arrive at a solution, this mathematical representation can be further translated into numerical models [7], and corresponding computer programs (codes) can be developed to solve the equations using computational resources. Within the MODFLOW platform, the governing flow equation, which underpins the entire process, is central to these operations (Eq. (2)).

Groundwater Flow Equation used in MODFLOW:

$$\frac{d}{dx}\left(Kxx\frac{dh}{dx}\right)+\frac{d}{dy}\left(Kyy\frac{dh}{dy}\right)+\frac{d}{dz}\left(Kzz\frac{dh}{dz}\right)+W = Ss\frac{dh}{dt} \qquad (2)$$

Where: Kxx, Kyy, Kzz are hydraulic conductivities along x–y–z-axes which are parallel to major axes of hydraulic conductivity; h is Piezometric head; W is the volumetric-type flux in unit volume representing sink or source terms; Ss is specific storage coefficient termed as the groundwater volume

The MODFLOW platform was specifically designed for simulating aquifer systems under certain conditions: (1) when the flow is in a saturated state, (2) Darcy's law can be applied, (3) the groundwater concentration remains constant, and (4) the primary direction of hydraulic conductivity or transmissivity remains consistent within the aquifer system. To create a comprehensive understanding of the study area, a conceptual model was developed based on hydro-geologic information and on-site investigations [10]. The lithology analysis confirmed the presence of an unconfined aquifer in the study area. Various data, including the study area's boundaries, ground and top layers, aquifer thickness, and parameters like hydraulic conductivity, porosity, storativity, transmissivity, specific storage, specific yield, and aquifer top and bottom elevations, were integrated to formulate the conceptual model. This conceptual model served as the foundation for designing and implementing a numerical model of the study area using Visual MODFLOW Flex software [11]. The general ground level was found to be at 552.5 meters above mean sea level (AMSL). Within the plant area, the surface elevation exhibited variations, ranging from 564 meters AMSL in the southern portion to 541 meters AMSL in the northern part.

The top layer, which remains unconfined and spans the entire area, is established as the initial layer with a thickness of approximately 115–120 meters.

Table 3. Salient Features for Groundwater Modeling.

S.No	Particulars	Details
1	Total Model Area	10 Sq. km
2	Model Start Date	1st April 2015
3	Model End Date	30th Sept. 2021
4	Run Type	Transient State
5	Minimum Easting	495000
6	Maximum Easting	500000
7	Minimum Northing	2000000
8	Maximum Northing	200500
9	No. of Rows	60
10	No. of Columns	50
11	No. of Layers	2
12	No. of Observation Wells	30
13	No. of Pumping Wells	1
14	Boundary Conditions Used	Study area 40 km buffer, Recharge & River

The overall depth considered for the model encompasses 1100 meters. The upper boundary of Layer 1 is determined through interpolation using Geographic Information System (GIS) software based on reduced level (ground level) data. The model's geographical extent is determined by assessing hydrogeological conditions, geological contacts, and distinct groundwater boundaries. Consideration of groundwater flow patterns and hydrogeological variations in the region plays a pivotal role in determining the model's domain and boundary conditions. These factors are assessed by contouring water table elevation data using GIS-based tools [13]. The lower boundary of the layer is defined on a grid basis using interpolated data derived from the base levels of existing open wells in the study area. The simulation of this layer assumes an unconfined state [26]. Based on comprehensive water level monitoring across the project site, it is evident that the depth to the water table remains relatively shallow within the surrounding study region. Specifically, the depth to water level or the primary aquifer generally ranges from 2.5 meters below ground level (bgl) to 13 meters bgl (Table 3 and Fig. 9).

4.2. Model calibration – Steady method

At this phase of the research, a foundational model was established and physically fine-tuned in the stable, steady-state circumstances. The steady-state methodology adopts that the groundwater levels observed are representative of the overall scheme behavior [4]. The initial model, referred to as the base-case model, incorporates initial approximations of aquifer material goods and hydrological variables. To initiate the calibration procedure, the groundwater scenario of 2018 was adopted as the initial condition for the aquifers. Given the availability of piezo metric head data spanning three years, multiple trial runs were conducted by adjusting the hydraulic conductivity and storage factors. The goal was to accomplish a favorable arrangement among the computed and observed groundwater levels both spatially and temporally. This iterative calibration process involved modifying two key parameters:

(a) **Recharge Rates**: Adjustments were made to the rates at which water infiltrates the aquifer system.

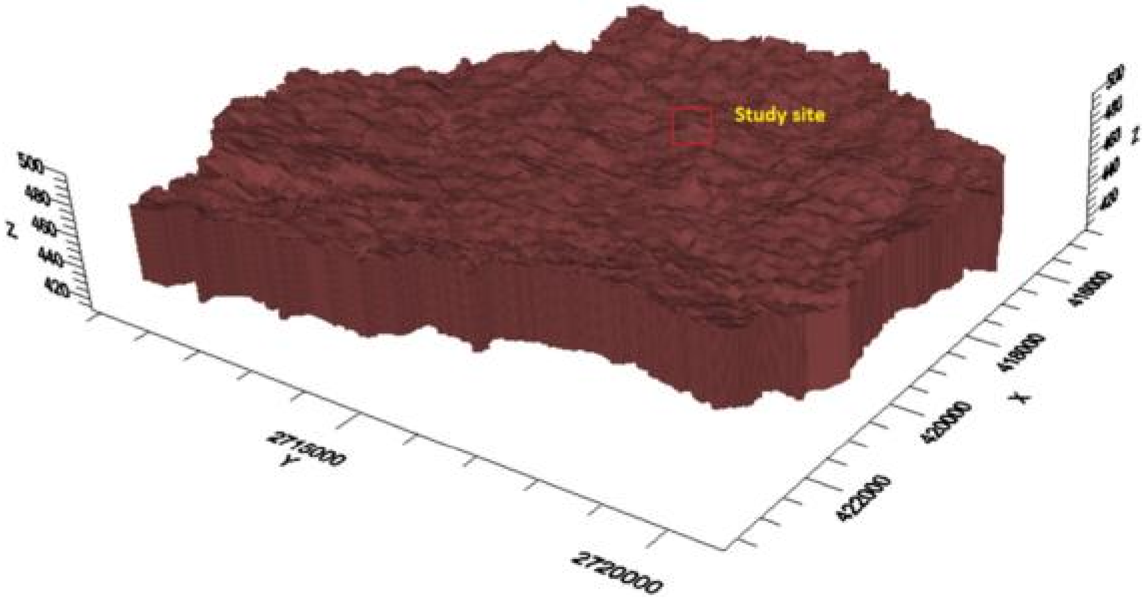


Fig. 9. Showing of Aquifer 3D-Layers.

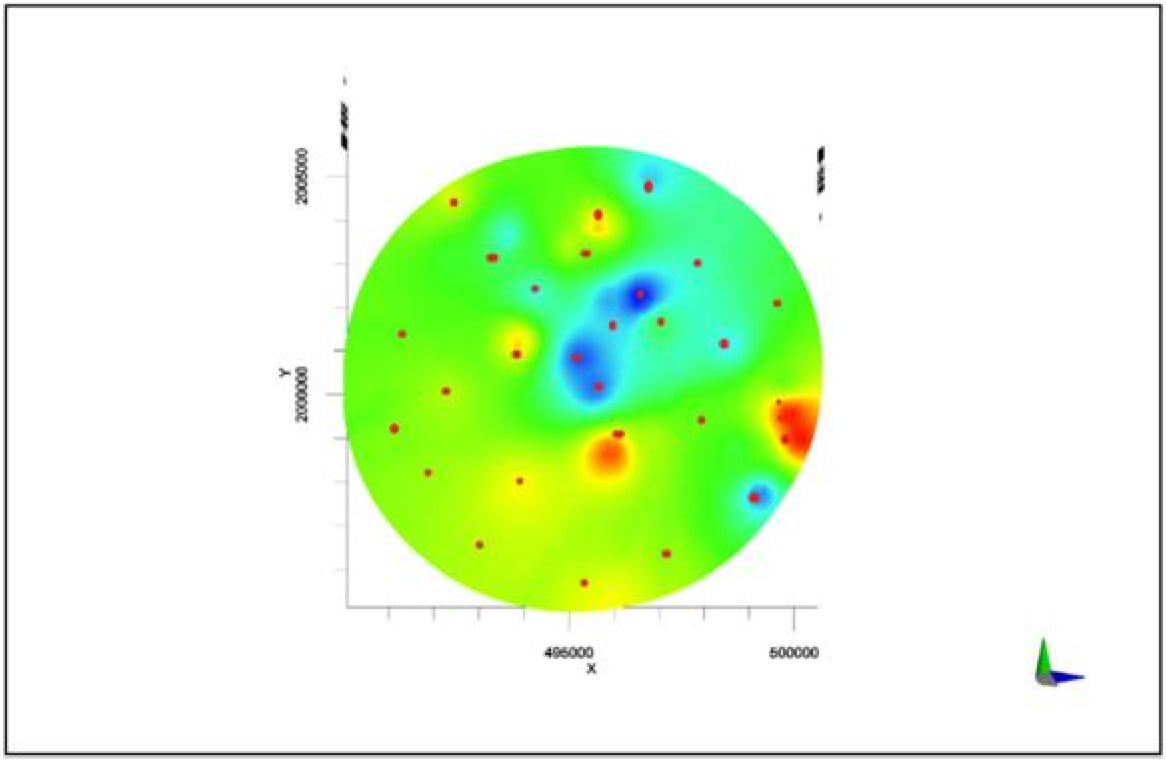


Fig. 10. Showing of Horizontal output of Study Area.

(b) **Horizontal Hydraulic Conductivity:** Changes were made to the capacity of the formation to transmit water horizontally.

The objective of this calibration was to align the modeled water table with the interpreted water table. To assess the model's performance, it was run under steady-state conditions for a single day, and the computed groundwater levels were compared with the observed levels. The results are visualized through contour maps, where the observed groundwater levels are depicted in red contours, while the modeled levels are shown in blue contours. This calibration process aimed to refine the model's representation of the aquifer system and its behavior, ensuring that the simulated groundwater levels closely match the observed data. The adjustments made during this process contribute to enhancing the accuracy and reliability of the model's predictions (Figs. 10 and 11).

4.3. Model calibration - Transient

In this simulation study, groundwater levels were computed across the entire model area before any project activities. The simulation spanned from April 1st, 2010 to August 30th, 2021, covering a timeframe of 365 days per year. The model was run in a transient state for a total of 1920 days, separated into four stress periods corresponding to pre-monsoon, monsoon, and post-monsoon seasons. These stress periods were done by 365, 720, 1440, and 1920 days, respectively. This approach aimed to visualize how pumping and storage changes impacted groundwater levels. The contour maps generated for each of these stress periods are presented in the figures below. These contours demonstrate a consistent match among observed and calculated groundwater head values. To ensure the reliability of the model's outputs, a calibration process was undertaken. Specifically, the model was run to simulate the current pumping scenario from the unconfined aquifer. Throughout the simulation, values for evapotranspiration, recharge, and pumping were assumed to be uniformly distributed across the entire area of the zones. For both stress periods, pumping and recharge values were assigned as net recharge values measured in meters per day. This comprehensive approach to modeling, calibration, and verification helps to provide accurate insights into the impact of various factors on groundwater levels in the studied area.

4.4. Model validation

To assess the accuracy of the revised flow model, a comparison was made between the groundwater

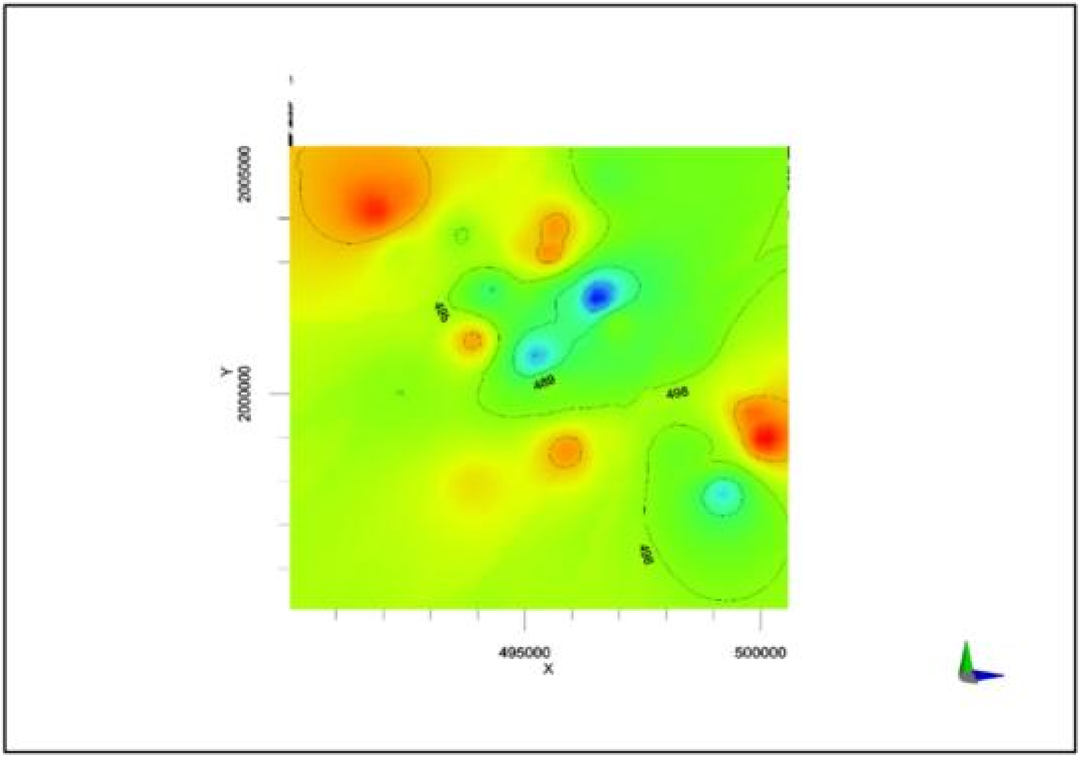


Fig. 11. Showing of Initial head of study area.

heads simulated by the modernised model and the experimental hydraulic heads. The authentication of the model was carried out based on groundwater head observations collected during the timeframe of 2020-2021. The evaluation involved a scatter plot illustrating the results for a span of 1920 days within the aquifers. The scatter plot displayed statistical information, particularly the root mean squared (RMS) value of the residuals for the aquifers. The RMS value calculated was 1.14 meters, indicating a reasonably strong alignment between the levels observed in reality and those simulated by the model. This suggests that the majority of the dataset is situated close to the ideal 1:1 correlation line (Figs. 12 and 13).

4.5. Model run

Boundary conditions and aquifer properties are established for the numerical model, incorporating pumping and observation well objects. Subsequently, the conceptual model's data is translated into the numerical model. Input parameters are entered into the model, and then the VISUAL MODFLOW FLEX module is utilized to estimate the flow budget. Model convergence is achieved through multiple trial runs, involving adjustments to initial head values and aquifer parameters. One key challenge is the uncertainty in hydraulic conductivity due to limited pumping test data, especially in areas with scientifically designed well fields. The model is not suited for steady-state simulations due to the nature of the hard formation area, where inflows and outflows are inherently unequal. Therefore, the focus shifts to transient simulation. The model is executed in a transient state, requiring initial heads and stress periods as essential input data. Stress periods are divided into twelve segments, corresponding to each month of the year. Within each stress period, temporal resolution is further increased by employing time steps to capture monthly variations in heads and flows. This approach facilitates a more detailed understanding of the dynamic behavior of the system. To measure the long-term behavior and predictions of the aquifer system, a predictive model is executed over a span of five years. This extended time frame enables the observation of trends, seasonal variations, and potential long-term impacts. The utilization of a transient simulation over an extended period enhances the correctness of the model's predictions and its applicability to real-world scenarios.

4.6. Predictive model results

A calibrated model was utilized to assess the effect of industrial groundwater withdrawal ended a five-year period. Changes in groundwater levels were

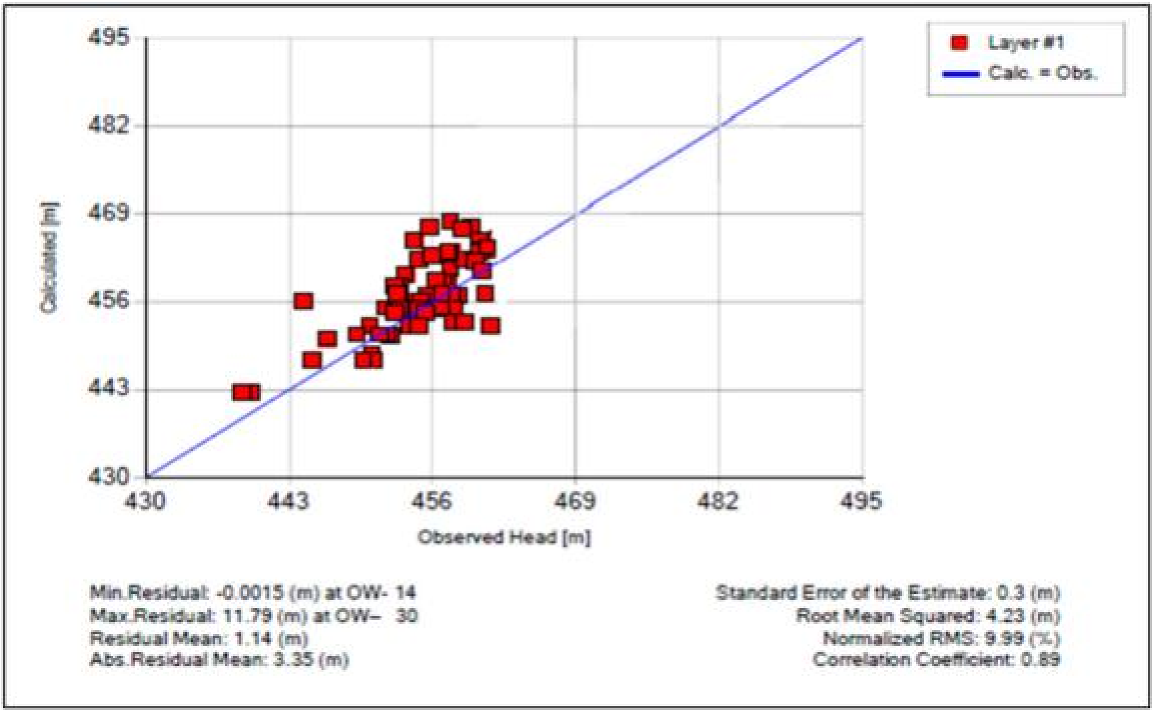


Fig. 12. Showing of Observed Vs Predicated scatter plots for First year.

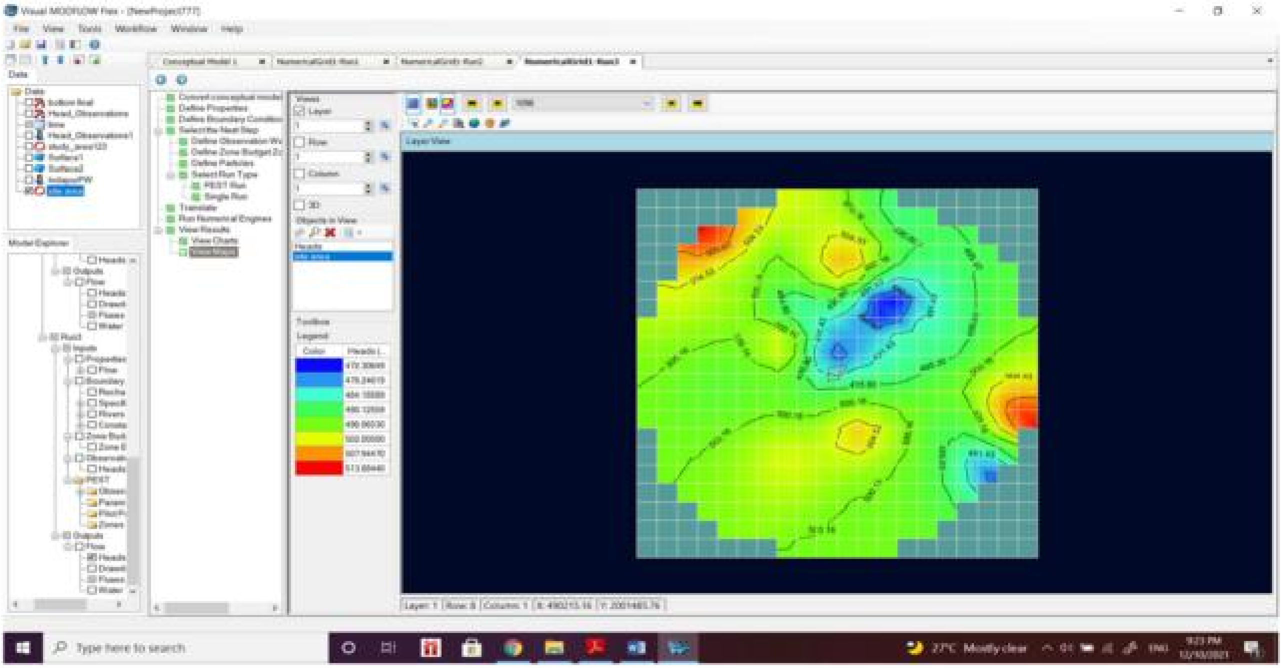


Fig. 13. Showing of Predication and Observed Head END for 1 year.

simulated for the first and fifth years. Notable shifts in groundwater levels were observed around the industrial site, with a decline of 22.4 meters above reference level (mRL) by the end of the first year and -11.9 mRL by the end of the fifth year. By the end of the fifth year, the groundwater depth in the study area reached approximately -9 mRL. Furthermore, drawdown in pumping wells was simulated for the entire five-year span. The collective drawdown across the model area over the five-year timeframe ranged from 4 to 20 meters (Table 4). The simulation indicated that the recharge from the river and rainfall

Table 4. Year wise predicted head and radius of influence.

Year	Initial Head at the site in m	Predicted Head in m	Change in Head in m	Radius Influence
1st Year	470	471.5	1.5	380
2nd Year	470	470.5	0.5	150
3rd Year	470	469.4	0.6	175
4th Year	470	469	01	250
5th Year	470	468.2	1.8	450

effectively contributed to maintaining the groundwater scenario. This suggests that the predicted changes in both groundwater levels and drawdown were relatively modest due to the positive influence of river recharge and rainfall. Fig. 13 shows the Predication and Observed Head END for 1 year. Figs. 14 and 15 shows the scatter plot and maps represent he predication and observed head end for 5-years.

4.7. Quantification of inflows/outflows of various boundary conditions imposed

The key benefit of the VISUAL MODFLOW FLEX is that its mass balance measures deliver a very valuable method to study the source of water providing to a scheme of pumping wells. From mass balance chart for one year and the increasing mass balance chart for 5th year, the variations in the ratio input from many sources have been calculated. From the table below, it can be seen how the fraction influence from many sources variations in the estimated situation for 2024 and 2020 year. A comparison of water inflow and outflow volumes at various boundaries for the initial year of 2020 and the fifth year of 2024. In the first year, the total inflow volume was 861,979 cubic meters, primarily sourced from storage (49.10%), constant head (0.83%), and wells (49.96%). Storage constituted a substantial portion of the inflow, while constant head and well contributions were relatively smaller. Recharge contributed significantly in both years, with 49.96% in the first year and 52.81% in the fifth year. Moving to the

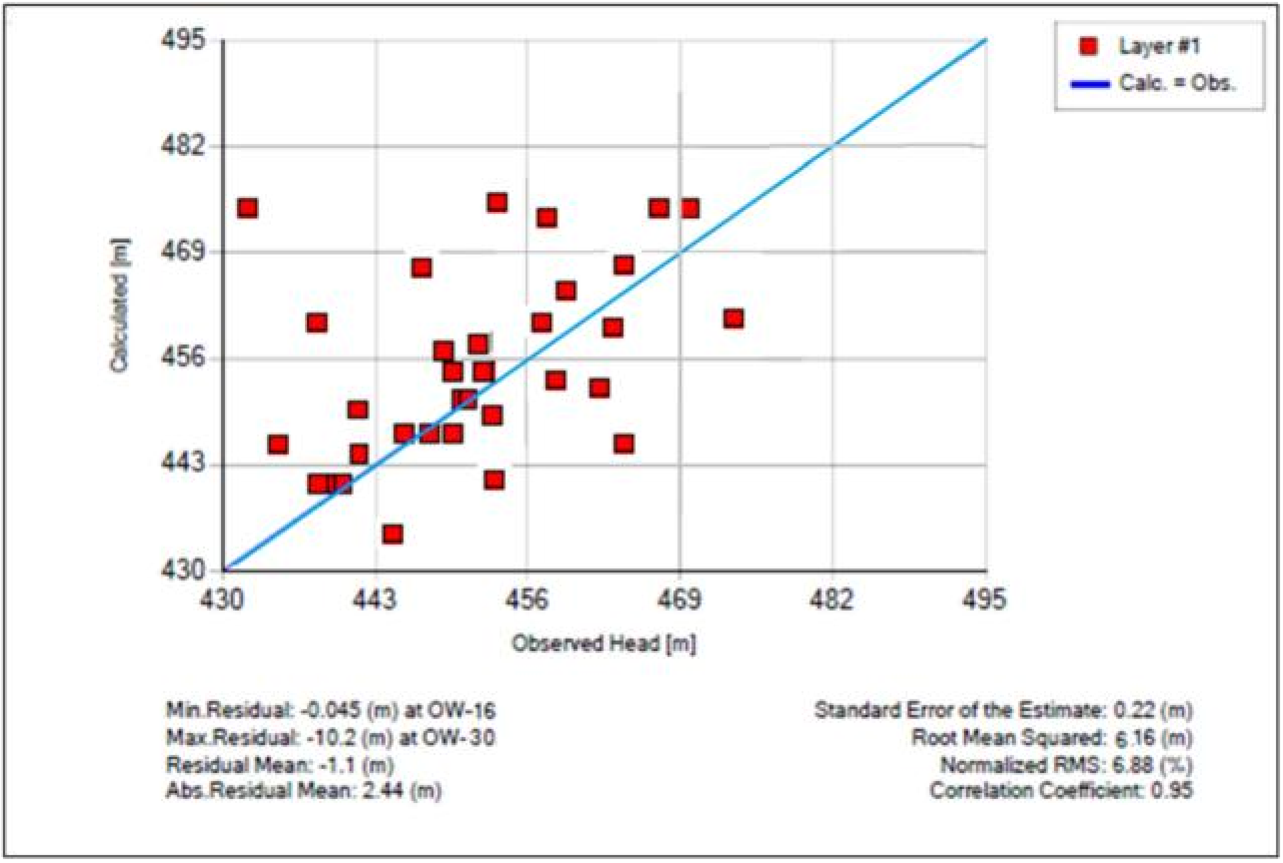


Fig. 14. *Showing of Predication and Observed Head END for 5 year.*

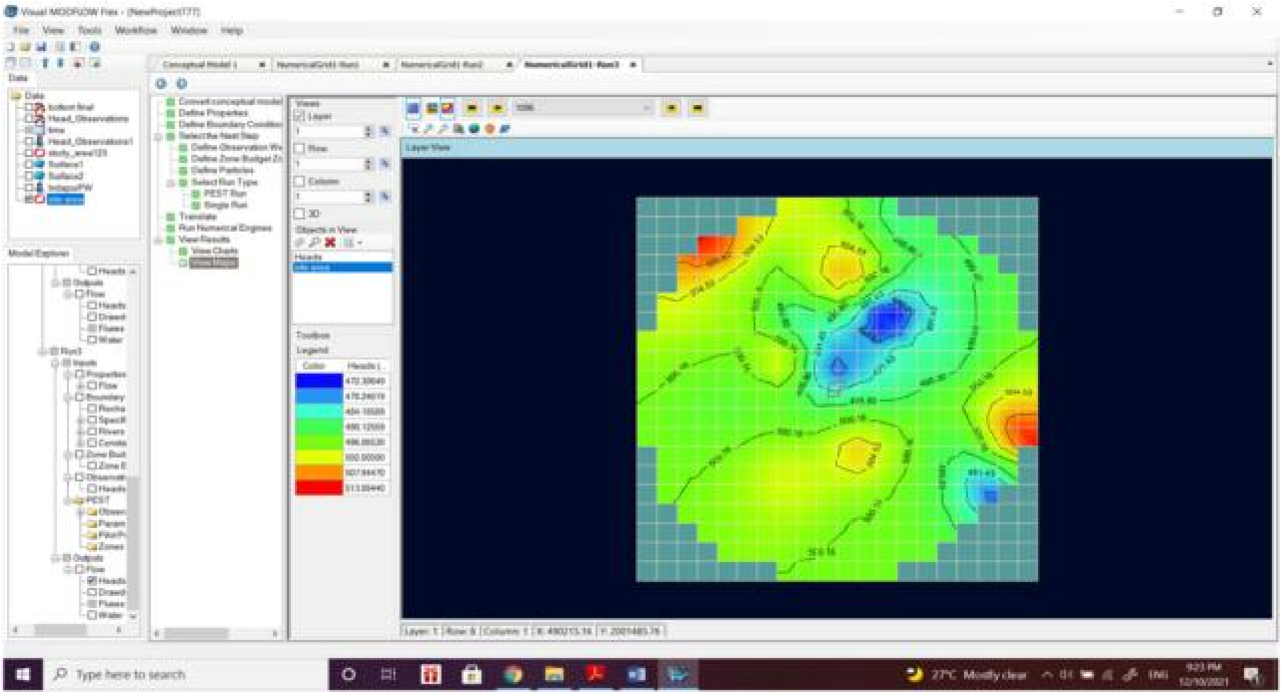


Fig. 15. Showing of Predicted and Observed Head – End for five year.

fifth year, the total inflow increased significantly to 3,910,511 cubic meters. Storage's share decreased to 46.16%, while constant head's contribution slightly increased to 1.02%. The most substantial increase was seen in recharge, accounting for 52.81% of the inflow. Concerning outflow, the first year witnessed a total outflow of 1,545,654 cubic meters, majorly attributed to storage (48.53%), wells (39.12%), and leakage (12.34%). Over time, the outflow in the fifth year amounted to 3,633,211 cubic meters. Storage's share grew to 52.96%, while well contribution decreased to 33.17%, and leakage saw a minor increase to 13.85% (Table 5). This comparison underscores the evolving dynamics of water inflow and outflow over the years, with recharge consistently being a significant contributor to inflow. Storage remains a substantial source but experiences variations due to changing conditions. The shift in well contributions

Table 5. Groundwater budget mass balance.

Inflow from various boundaries in First Year (2020) and Fifth Year (2024)				
	First Year - 2020		*Fifth Year - 2024*	
Sources	*Volume in Cum*	*Percentage*	*Volume in Cum*	*Percentage*
Storage	*424088*	*49.10*	*1805344*	*46.156*
Constant Head	*7200*	*0.83*	*39786*	*1.02*
Wells				
Recharge	*430691*	*49.96*	*2065381*	*52.81*
Total	*861,979*	*100*	*3,910,511*	*100*

Outflow from various boundaries in First Year (2020) and Fifth Year (2024)				
	First Year - 2020		*Fifth Year - 2024*	
Sinks	*Volume in Cum*	*Percentage*	*Volume in Cum*	*Percentage*
Storage	*750152*	*48.53*	*1924324*	*52.96*
Constant Head				
Wells	*604630*	*39.12*	*1205431*	*33.17*
River Leakage	*190872*	*12.34*	*503456*	*13.85*
Total	*1,545,654*	*100*	*3,633211*	*100*

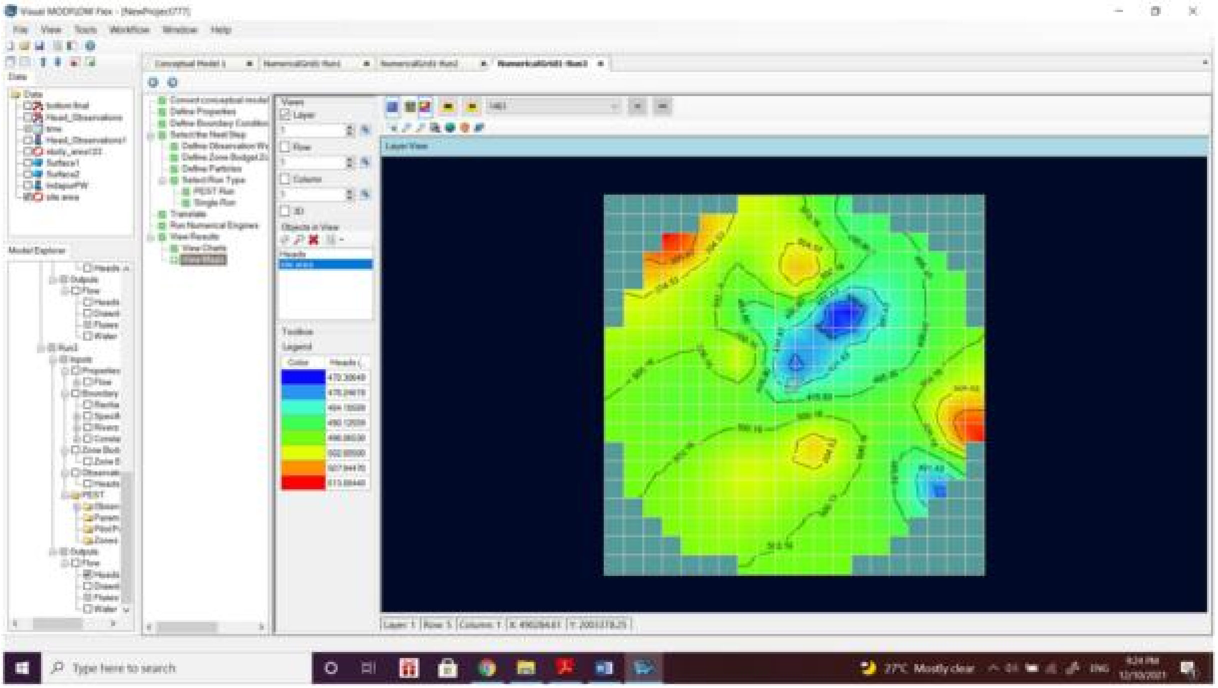


Fig. 16. Showing of Predicted Head – End of 5th year.

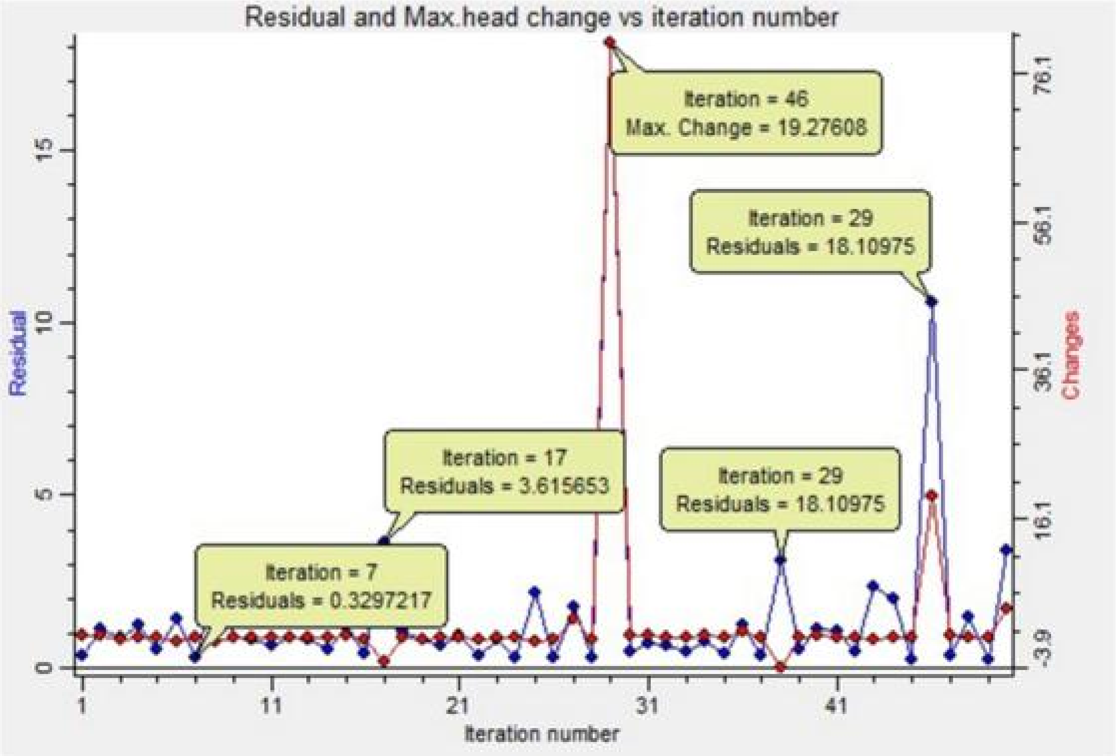


Fig. 17. Showing of Residual and max head change vs iteration number.

highlights potential changes in water extraction patterns. These insights emphasize the reputation of operative water managing plans to ensure sustainable usage and balance between water sources and sinks. The mass balance clearly indicates that the groundwater drawl is only from the recharge quantity. The inflow and outflow from numerous causes and sink for model area is presented below. The predicted and

Observed Head – End for five years is presented in Fig. 15 and the predicted Head – End of 5th year maps shown in the Fig. 16.

Radius of Influence and Draw down (Head changes) for the end of 1st year to end of 5^{th} year in Fig. 16. The year wise Predicted draw down (Head changes) and Radius of Influence is as follows.

4.8. Model outputs

The received model outputs consist of spatial variation maps depicting water table elevation, velocity, and water budget. These maps are illustrated in the provided figure. The model also generated a chart comparing calculated and observed water levels (head) for different years. Utilizing hydrogeological and well data, the visual MODFLOW Pro software was calibrated and validated. For the year 2021, simulated groundwater level (GWL) data were compared to actual observed field data to validate the software's results. The comparison involved the water table elevations of eleven wells over the calibration period. The results indicated a strong agreement between the observed and predicted water table elevations, as evidenced by positive R-squared (R2) values shown in the figure. Moreover, the model's predicted water table elevations exhibited a favorable correspondence with observed data during the validation period. Fig. 17 shows the Residual and max head change vs iteration number for this study area.

5. Conclusion and recommendations

The study results show that pumping will not significantly affect adjoining drinking water or irrigation sources. The maximum impact radius is estimated to be approximately 450 m in the fifth year, and the highest water level will drop by about 1.8 m at the end of that period. Model results also show that pumping for agriculture and other purposes is unlikely to adversely impact nearby pumping wells. Arithmetical analysis and steady-state groundwater flow modeling using MODFLOW are in decent agreement with the measured geological and hydrological circumstances of the basaltic aquifer system.

For enhanced model consistency and correctness, regular monitoring of observation wells and groundwater table levels is important. Moreover, an adequate number of aquifer performance tests (APTs) are essential to get more accurate aquifer parameters. The comparison between observed and simulated values in the MODFLOW model is in good agreement, indicating that the model accurately represents groundwater conditions in the study area. These results can aid in resilient soil and water resource planning and improve groundwater management strategies. However, groundwater development must be carefully achieved due to the high irrigation wants in the nearby areas.

Moreover, deepening observation wells by approximately 2 m can increase groundwater yield by approximately 25–30%. The study also suggests implementing rainwater harvesting and groundwater recharge structures to improve groundwater levels. Furthermore, there is potential for developing new wells to increase water supply in the future, which could further support sustainable groundwater use.

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Conflict of interest

The authors have no competing interests to declare that are relevant to the content of this article.

Data availability

Data will provide as reasonable request by corresponding author.

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N/A

Author contribution

Ravi Sharma: Conceptualization, writing original draft, Investigation, formal analysis, Methodology, Modeling, Validation, Data collection and analysis for modeling purpose, writing review and editing, Supervision, Investigation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used Grammarly in order to check grammar and sentence structure. After using this service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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