A PROJECT REPORT

ON

"Development of Groundwater Flow Modelling Using GMS in Tirap Coal Field"

Submitted in partial fulfilment of the requirements

for the award of the degree of

MASTER OF TECHNOLOGY

In

WATER RESOURCE ENGINEERING

Under

ASSAM SCIENCE AND TECHNOLOGY UNIVERSITY

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CERTIFICATE OF SUPERVISOR

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KRITIKA GAYAN (PG/C/23/31)

A Student of M-Tech 3^{RD} Semester to the Department of Civil Engineering, Assam Engineering College for the successful completion of the course **CEW202322 DISSERTATION PHASE-1** as a partial fulfilment of the degree in **Master of Technology in Water Resource Engineering**, Civil Engineering, has been carried out under my guidance and supervision.

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CERTIFICATE OF HEAD OF THE DEPARTMENT

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DECLARATION BY THE CANDIDATE

I, a student of the Department of Water Resource Engineering, Civil Engineering, Assam Engineering College, hereby declare that I have compiled this report on the topic titled **"Development of Groundwater Flow Modelling Using GMS in Tirap Coal Field"** in 3^{rd} Semester as a part of my M. Tech curriculum.

I also declare that the same report or any substantial portion of this report has not been submitted anywhere else as part of any requirements for any degree/diploma etc.

Date:

NAME	**ROLL NO.**	**SIGNATURE**
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ACKNOWLEDGEMENT

It gives me a great sense of pleasure to present the report on **"Development of Groundwater Flow Modelling Using GMS in Tirap Coal Field"** completed during my **M. Tech 3rd Semester**.

I would like to express my gratitude and would like to acknowledge **Dr Triptimoni Borah**, Professor, Civil Engineering Department of Assam Engineering College, Jalukbari, Guwahati for her able guidance and constant encouragement in every step of the project. Her, sincerity, thoroughness and perseverance have been a constant source of inspiration for us. It is only her cognizant efforts that my endeavors have seen light of the day.

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ABSTRACT

Mining activities significantly impact groundwater systems, leading to challenges such as mine flooding, resource depletion, and contamination risks. This project focuses on developing a comprehensive groundwater flow model using the Groundwater Modelling System (GMS) to address these challenges in the Tirap Zone, Tinsukia district, Assam—a region with active mining operations.

The study aims to predict mine flooding scenarios post-closure, estimate sustainable groundwater yields, design efficient recharge and recovery systems, and assess the migration of contaminants within the aquifer system using a Groundwater Modelling System named MODFLOW. The methodology involves collecting and analysing hydrogeological, geospatial, and mining-related data to simulate groundwater dynamics and evaluate potential impacts under different scenarios. The outcomes will provide insights into groundwater management strategies to mitigate adverse effects, enhance resource sustainability, and minimize environmental risks. This work contributes to the development of a framework for managing groundwater in mining areas, ensuring a balance between resource utilization and ecological conservation.

Keywords: Tirap OCP, Groundwater Modelling System (GMS), MODFLOW, Mine flooding, Recharge, Environmental Risks.

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1 INTRODUCTION

1.1 OVERVIEW

Groundwater plays a critical role in supporting the socio-economic and environmental needs of mining regions. However, mining activities often result in significant alterations to the natural hydrogeological system, leading to challenges such as mine flooding, reduced groundwater availability, and contamination risks. In the Tirap Zone of Tinsukia district, Assam, where mining is a prominent activity, understanding and managing groundwater resources is essential for ensuring the sustainability of post-mining landscapes.

This project aims to develop a groundwater flow model using the Groundwater Modelling System (GMS) to address key concerns related to the hydrogeological impacts of mining in the region. Specifically, the study focuses on predicting post-closure mine flooding scenarios, estimating sustainable groundwater yields for long-term use, designing effective recharge and recovery systems, and assessing the potential migration of contaminants.

The outcomes of this study will provide a scientific basis for decision-making in mine water management and groundwater sustainability planning. By integrating advanced modelling tools like GMS MODFLOW with field data, the project seeks to contribute to the development of strategies that balance economic development with environmental protection in the Tirap Zone.

1.2 STUDY AREA

The study area of the project is located in the Makum Coalfields of Tinsukia district, Assam, India, covering a 10 km radius around the Tirap Opencast Project (OCP). The total aerial extent of this study area is approximately 425.68 km^2. The Tirap OCP is a coal mining project with a mining lease area of 586.91 hectares. The area is situated between latitudes 27°11'45" N to 27°24'05" N and longitudes 95°40'00" E to 95°54'15" E, falling within the 83M/15 topographical sheet. It lies in a geologically significant region underlain by Tertiary formations of Eocene and Oligocene age, characterized by carbonaceous sandy shale, sandstone, and coal seams.

The terrain ranges in elevation from 83 m to 1148 m above mean sea level, with the mining area situated on topographic highlands. This region is characterized by diverse landforms, ranging from alluvial plains to highly dissected hills and valleys. The alluvial plains, formed by the Burhi-Dihing River, the largest south-bank tributary of the Brahmaputra in Upper Assam are a prominent feature. The Burhi Dihing River flows within this radius, along with other rivers such as the Tirap and Telkong Wa Rivers. These rivers provide important hydrological features within the study area.

Fig 1.1: Study Area Map, Tirap OCP, NEC, Makum Coalfields

1.3 OBJECTIVES

The primary objectives of this study are:

i. ***To Predict mine flooding post-closure:*** To forecast the behaviour of groundwater and its eventual recovery in a mining area after mining operations cease and dewatering activities are stopped.

ii. ***To estimate sustainable groundwater yields:*** Determining the amount of groundwater that can be extracted from an aquifer or groundwater system over the long term without causing undesirable consequences.

iii. ***Design recharge and recovery systems:*** Involves creating infrastructure and processes that allow for the controlled replenishment of groundwater (recharge) and the sustainable extraction of water from aquifers (recovery).

2 LITERATURE REVIEW

Surinaidu and et. al (2014) This study aims to estimate groundwater inflows into coal mines at different mine development stages in Andhra Pradesh, India, using hydrogeological studies and numerical groundwater flow modelling (MODFLOW). The goal was to plan optimal dewatering strategies for safe mining operations. Analysis of geological logs done from 183 boreholes to understand subsurface conditions. Pumping tests performed to estimate aquifer parameters such as hydraulic conductivity and transmissivity. The study includes Development of a finite-difference groundwater flow model (MODFLOW) with 20 conceptual layers. The model was calibrated using observed groundwater levels. Scenario-based predictions were done of groundwater inflows at different mine floor depths. The study then identifies aquifer characteristics, structural faults, and recharge-discharge dynamics. Equivalent porous medium (EPM) approach used to represent fractured rock aquifers. The study concludes that:

- Predicted groundwater inflows into the mine pits varied by development stage, ranging from 5,877 m^3/day at +124 m above mean sea level (AMSL) to 22,617 m^3/day at 0 m AMSL.
- Faults and geological structures were identified as major contributors to groundwater seepage.
- Groundwater budget calculations highlighted the role of lateral flows and the influent nature of the nearby Godavari River.

The study provided a comprehensive framework for designing dewatering schemes and enhancing safety in coal mine operations.

Li and Wang (2019) To analyse the catchment and capture zones of a pumping well in unconfined aquifers influenced by mountain-front recharge, using a simplified conceptual model and numerical simulations. A simplified model was developed to simulate groundwater flow influenced by segmental inflow from mountain-front recharge. Assumptions included steady-state flow, isotropic aquifers, and negligible vertical flow. MODFLOW was used to simulate groundwater flow in this study. MODPATH tracked particle flow to delineate catchment and capture zones. Sensitivity analysis explored the impacts of aquifer parameters and well placement on capture zones. Catchment zones were categorized into four types based on hydraulic connectivity. Shape factors and travel times were analysed for various scenarios. The study concludes:

- Four types of catchment zones were identified, influenced by well placement and aquifer parameters.
- Capture zones exhibited varying shapes and travel times depending on the well's location and pumping rates.
- Sensitivity analyses highlighted key parameters like inflow width, pumping rate, and aquifer dimensions.
- Results provided insights for optimizing well placement and delineating protection zones for sustainable groundwater management.

Lyu and et. al (2021) The paper presents "Calculation of groundwater head distribution with a close barrier during excavation dewatering in confined aquifer". The study aims to develop an analytical method to calculate groundwater head distribution inside and outside an excavation pit during dewatering in a confined aquifer, considering the blocking effects of waterproof barriers. In this study, equations were derived based on groundwater flow principles under two conditions: (i) constant water head and (ii) constant pumping flow rate. 3D simulations were conducted to validate the proposed analytical equations. The analytical model was then compared with experimental field data to verify its accuracy and applicability. The study demonstrates that:

1. The waterproof barrier alters groundwater seepage direction, increases seepage path length, and reduces seepage area, leading to significant changes in groundwater head distribution.
2. The proposed analytical equations accurately predict groundwater head distribution, showing good agreement with both numerical and experimental results.
3. The method is practical for engineering applications involving excavation dewatering in confined aquifers.

Dahl and et. al (2023) To develop a probabilistic neural network (PNN) methodology for predicting hydraulic head changes in groundwater models with high accuracy and speed, including uncertainty estimates. This approach aims to improve groundwater resource management and decision support systems. Simulations were done using the MODFLOW model for a test case in the San Pedro River Basin. Training data were generated from 1,000 simulations with variable well locations and pumping rates. Design of Neural Network includes construction of a Multilayer Perceptron Neural Network (MLP-NN) trained to predict hydraulic head changes as a distribution (mean and standard deviation) and Selection of hydrological attributes and spatial features as input variables. Training and validation of the MLP-NN model was trained and validated using the

MODFLOW-simulated data and then compared with traditional methods like the Response Matrix (RM) approach and MODFLOW. The results of this study show that

- The MLP-NN achieved high accuracy in predicting hydraulic head changes, comparable to MODFLOW, but was approximately 130 times faster.
- Unlike the RM method, the MLP-NN effectively captured non-linear responses in the groundwater model.
- The network provided uncertainty estimates, enhancing decision-making reliability.
- The methodology demonstrated flexibility for various well system configurations without additional training.

3 METHODOLOGY

3.1 DATA COLLECTION

The data required for developing the groundwater flow model and assessing the impact of mine dewatering were collected from various sources, including field investigations and secondary data. The key data include:

- **Topography and Elevation Data**:
  - Digital Elevation Model (DEM) derived from Shuttle Radar Topography Mission (SRTM) data with a resolution of 30 m.
  - Surface elevation ranging between **83 m and 1148 m AMSL**.
- **Hydrogeological Data**:
  - Aquifer parameters including **hydraulic conductivity (Kx, Ky, Kz)**, specific yield, and storage coefficients derived from pumping tests and literature.
  - Subsurface lithology and aquifer geometry determined from exploratory borehole data.
- **Geological Data**:
  - Geological formations, including coal seams and surrounding strata, classified as **carbonaceous sandy shale, sandstone, and ferruginous sandstone** from Eocene and Oligocene age.
- **Rainfall Data**:
  - Annual average rainfall of **2265.7 mm** over 25 years, with recharge rates of 10 – 12% of rainfall used for modelling (based on CGWB norms).
- **Boundary Conditions**:
  - Rivers (e.g., Burhi Dihing) and their hydraulic interaction.
  - Location of Existing wells.
  - Recharge is defined at the Top layer.

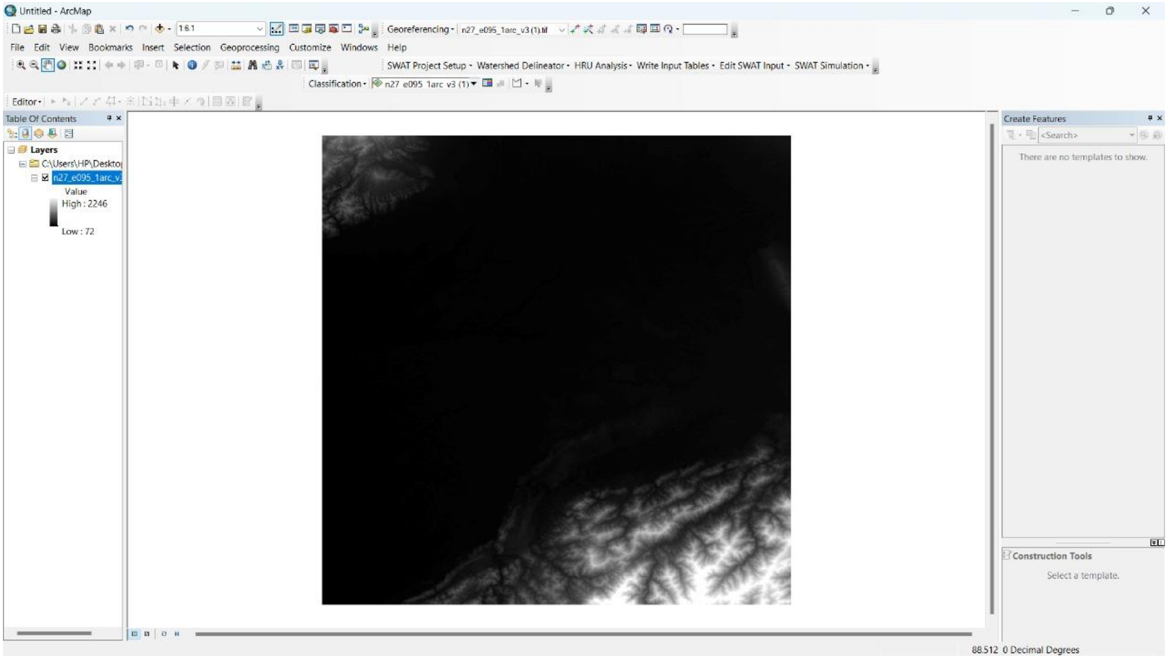


Fig 3.1: Digital Elevation Model (DEM).

Table 3.1: Aquifers parameter Table.

Parameter	Value	
Top of aquifer (m) range of elevation	Surface Elevation: 97.56 – 1109.46m	
Bottom of aquifer (m) range of elevation	Bottom Layer: -50.47 to 1012.93 m	
Initial Piezometric Heads (m AMSL)	Layer1	139.61– 327.78m
	Layer2	-
	Layer3	-
Aquifer Type	Layer1	Phreatic aquifer
	Layer2	Aquiclude - 1
	Layer3	Aquifer with less potentiality (Semi-confined)
	Layer4	Aquiclude - 2
	Layer5	Aquifer with less potentiality (Semi-confined)
	Layer6	Aquiclude - 3
K (m/Day)	Layer1	1
	Layer2	0.1
	Layer3	0.5
	Layer4	0.1
	Layer5	0.5
	Layer6	0.1
Specific yield (%)	Layer1	2%
Storage Parameters	Layer1	0.02
	Layer2	0.013
Recharge applied	200-220 mm/year *(Based on the CGWB Ground Water Estimation Committee-2015 Norms)*	

Table 3.2: Formation and Thickness of all the 6 layers.

Hydrogeological Unit	Formation	Thickness (m)
Phreatic aquifer (Top)	Soil, sub-soil, alluvium consisting of sand, clay and gravel.	15 - 160
Aquiclude	Coal seam (8' seam) **(working)**	2 - 2.5
Poor aquifer (middle)	Fine grained sandstone, shale, clay, silt stone and mud stone	60 -160
Aquiclude	Coal seam (20' seam) **(working)**	6 – 7
Poor aquifer (Lower)	Fine grained sandstone, clay, shale, mudstone and siltstone	20 – 70
Aquiclude	Coal seam (60' seam) **(working)**	16 -18
Poor aquifer (Lower)	Baragolai formation (clay, claystone, shale and siltstone)	5 – 30

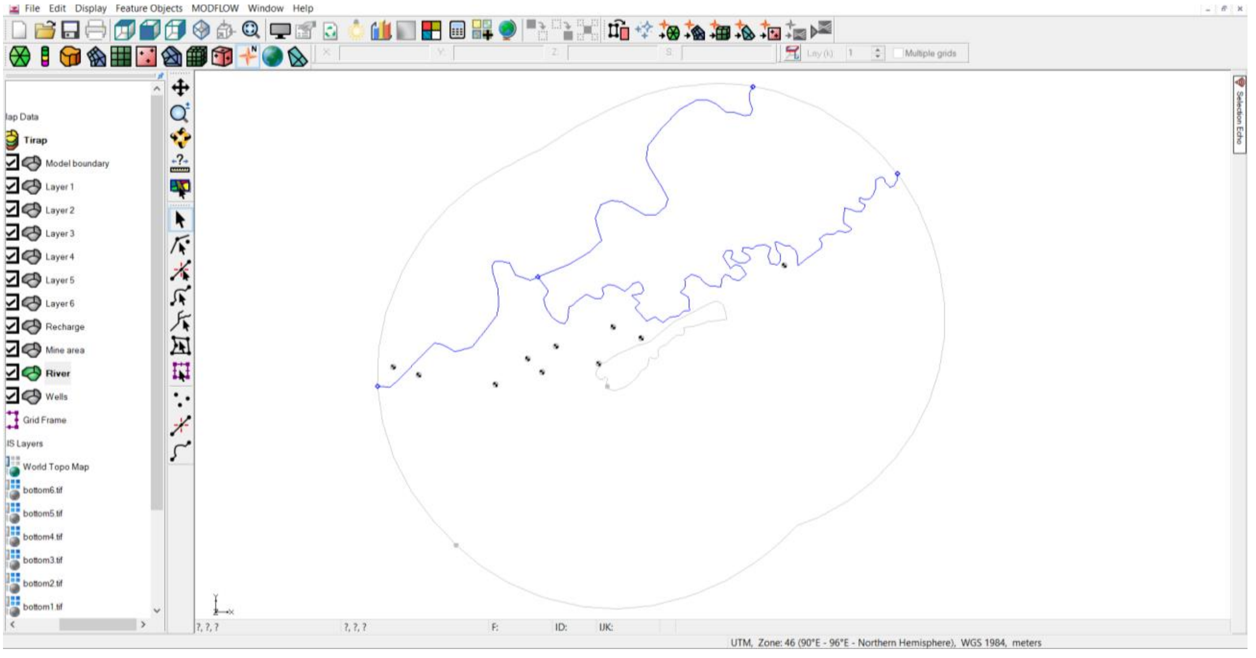


Fig 3.2: Boundary Conditions (Rivers, Wells and Recharge).

The figure shows all the boundary conditions used in the model. The blue coloured arcs represent Rivers, black points represent Wells (10 wells) and Recharge is included in the whole model area with a constant rate in the Steady State.

3.2 CONCEPTUAL MODEL DEVELOPMENT

A conceptual hydrogeological model was developed to represent the aquifer system and groundwater flow in the study area.

1. **Aquifer System Definition**:
    - A 6-layer model was created:
        - 3 aquifers (unconfined phreatic aquifer and semi-confined aquifers in deeper layers).
        - 3 aquicludes separating the aquifers.
2. **Model Domain and Grid Design**:
    - A 10 km radius (425.68 km²) was considered for the study area.
    - The model grid was defined with **200 m x 200 m cells**, resulting in **114114 cells**, of which **70656 are active**.
3. **Boundary Conditions**:
    - **Recharge Boundary**: Rainfall recharge of **200–220 mm/year**.
    - **River Boundary**: Interactions with Burhi Dihing and other local rivers.

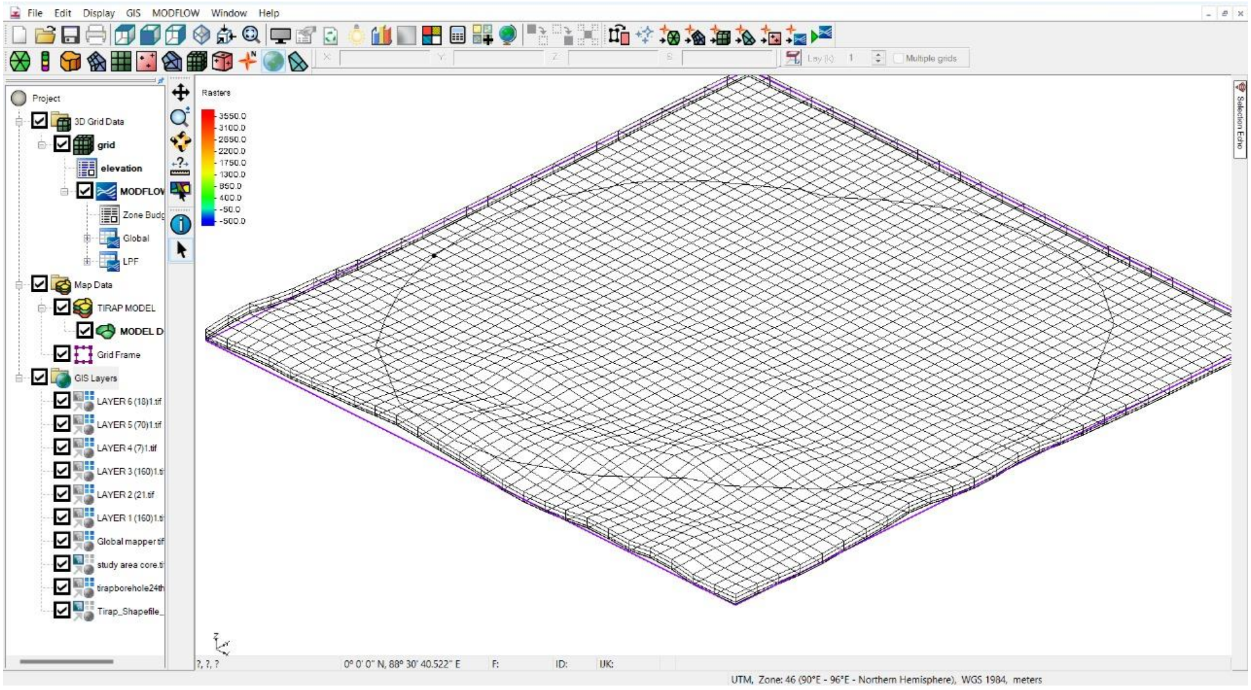


Fig 3.3: 3D grid with 6 layers and Model Boundary.

The figure shows 3D grid with 6 layers and cell size of 200 m x 200 m. The elevations of all the layers are interpolated using DEM.

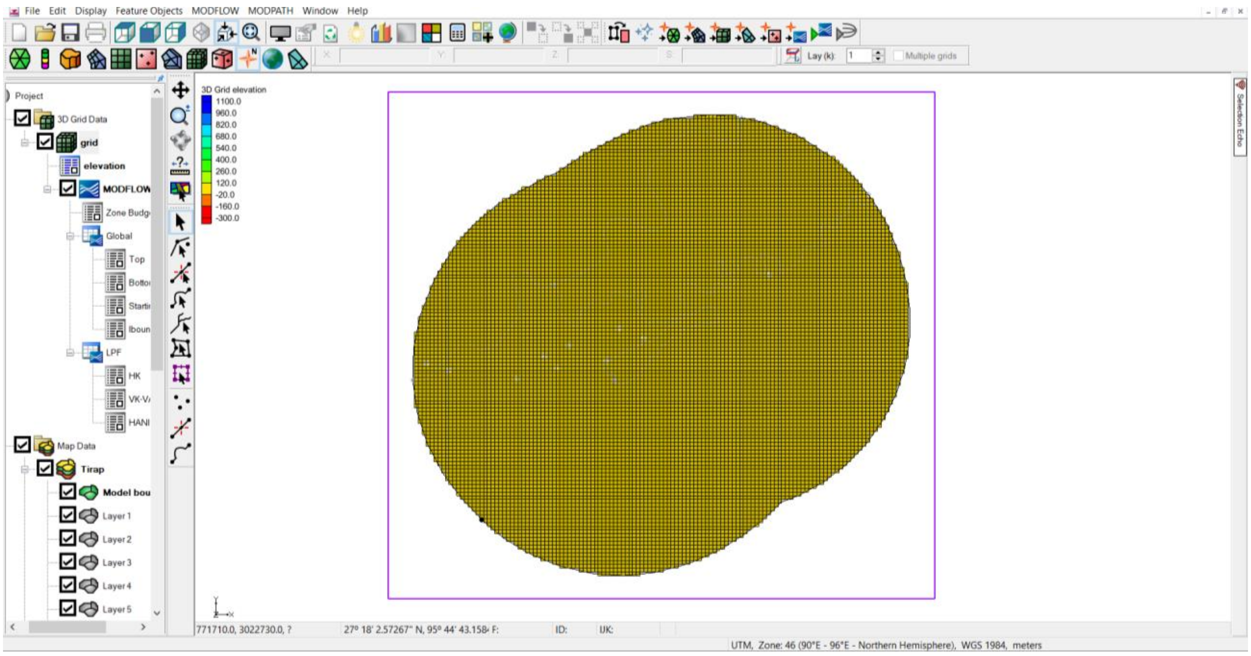


Fig 3.4: Active cells in the Model Boundary.

The Figure shows 70656 active cells within the Model boundary out of 114114 total cells of the Grid frame.

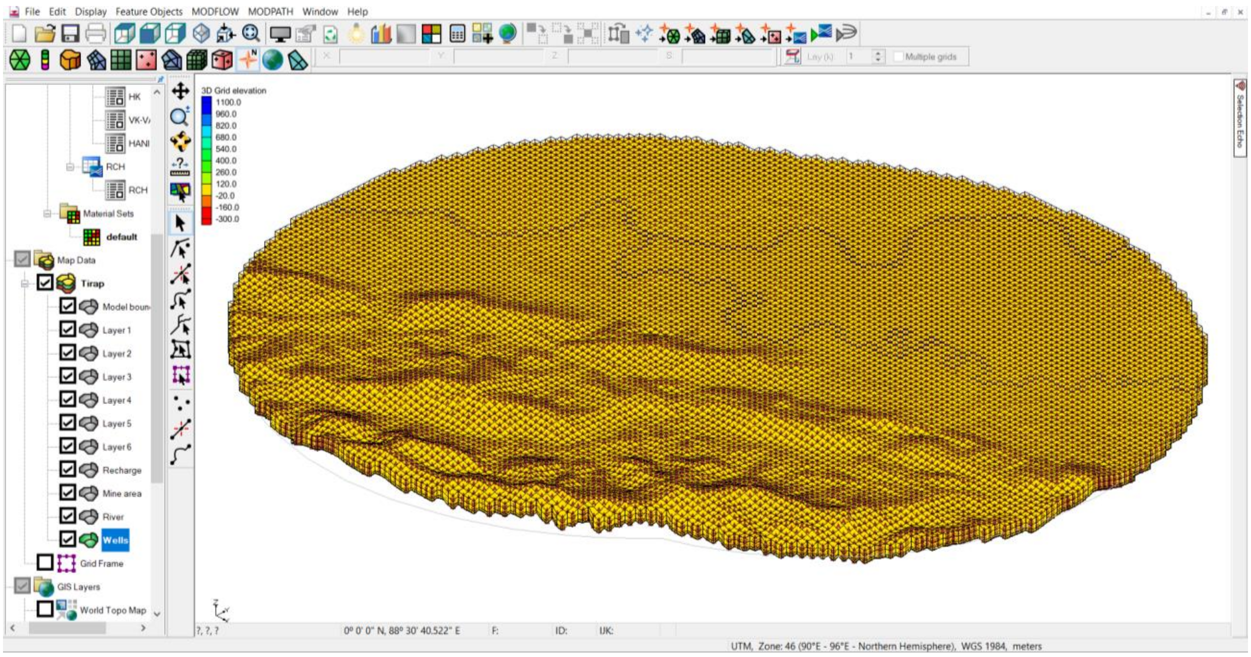


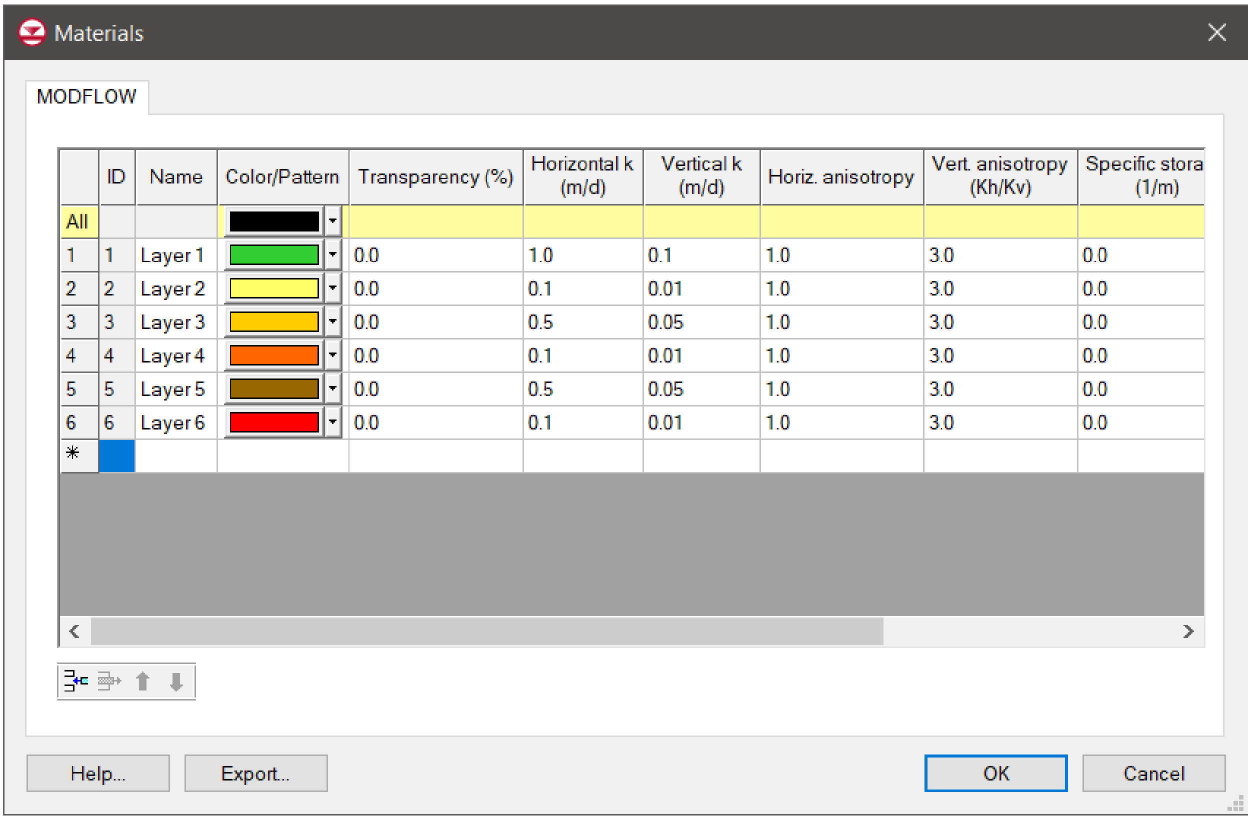
Fig 3.5: Conceptual model and Boundary Conditions.

The figure shows Conceptual Model with variations in elevation and including all the boundary conditions used (River, Wells and Recharge).

3.3 NUMERICAL MODEL SETUP (MODFLOW)

A numerical groundwater flow model was developed using MODFLOW software. The following steps were undertaken:

1. **Grid and Layers**:
   - A 6-layer grid was designed based on lithological and aquifer characteristics.
2. **Input Parameters**:
   - Hydraulic conductivity values ranging from **0.1 m/day to 1.0 m/day** for different layers.
   - Specific yield of **2%** for the unconfined aquifer.



	ID	Name	Color/Pattern	Transparency (%)	Horizontal k (m/d)	Vertical k (m/d)	Horiz. anisotropy	Vert. anisotropy (Kh/Kv)	Specific stora (1/m)
All									
1	1	Layer 1		0.0	1.0	0.1	1.0	3.0	0.0
2	2	Layer 2		0.0	0.1	0.01	1.0	3.0	0.0
3	3	Layer 3		0.0	0.5	0.05	1.0	3.0	0.0
4	4	Layer 4		0.0	0.1	0.01	1.0	3.0	0.0
5	5	Layer 5		0.0	0.5	0.05	1.0	3.0	0.0
6	6	Layer 6		0.0	0.1	0.01	1.0	3.0	0.0
*									

Fig 3.6: Material Sets for all the 6 layers.

The figure shows all the 6 layers and their hydraulic Properties (Horizontal Conductivity, Vertical Conductivity, Anisotropy).

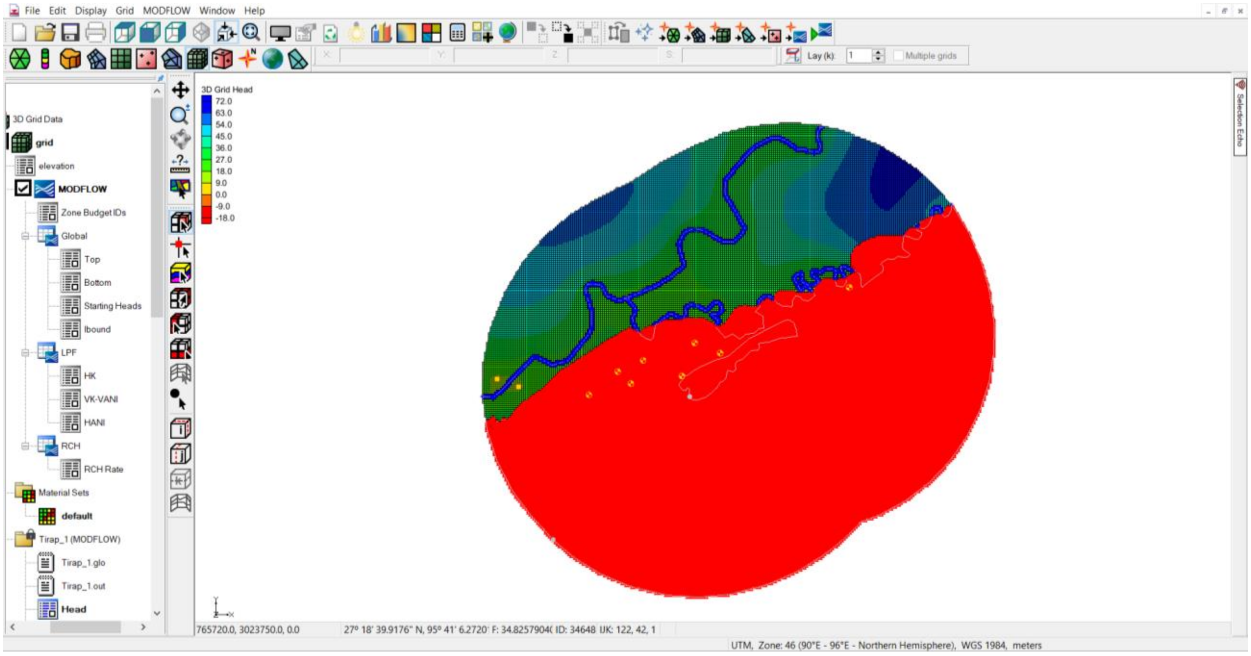


Fig 3.7: Steady State Model Run.

The figure shows Model run in Steady State with Head 72 m to -18 m. The Area in red colour shows Dry zone.

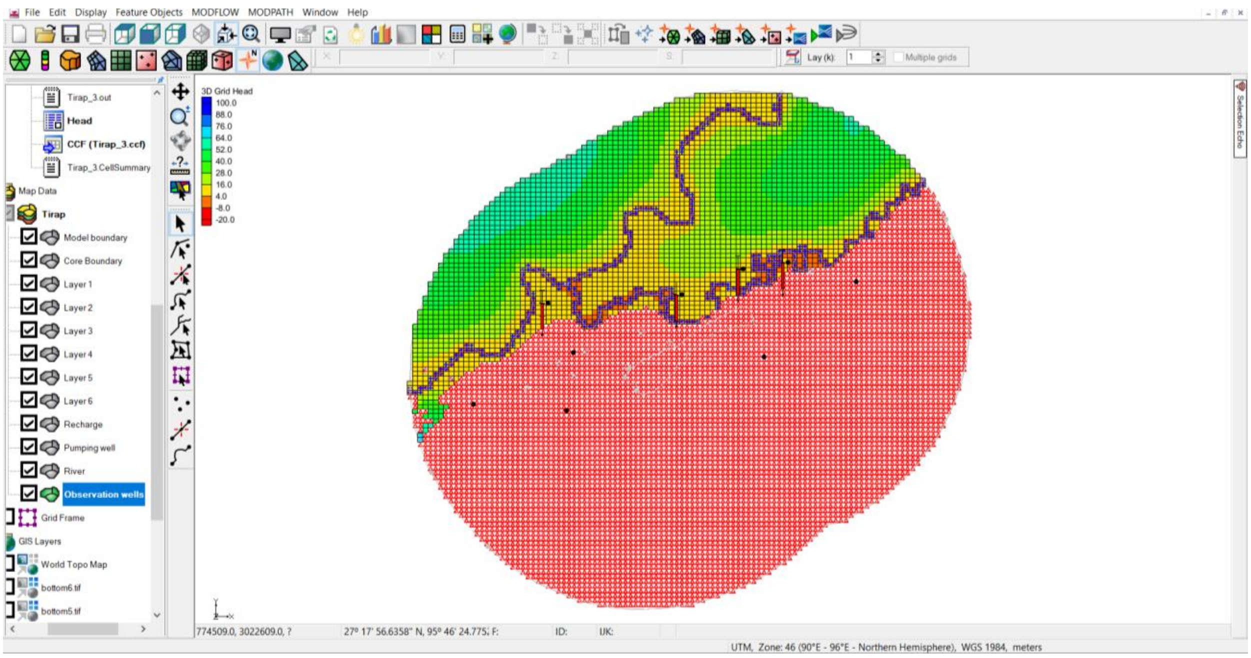


Fig 3.8: Calibration of Steady State Model using observation wells.

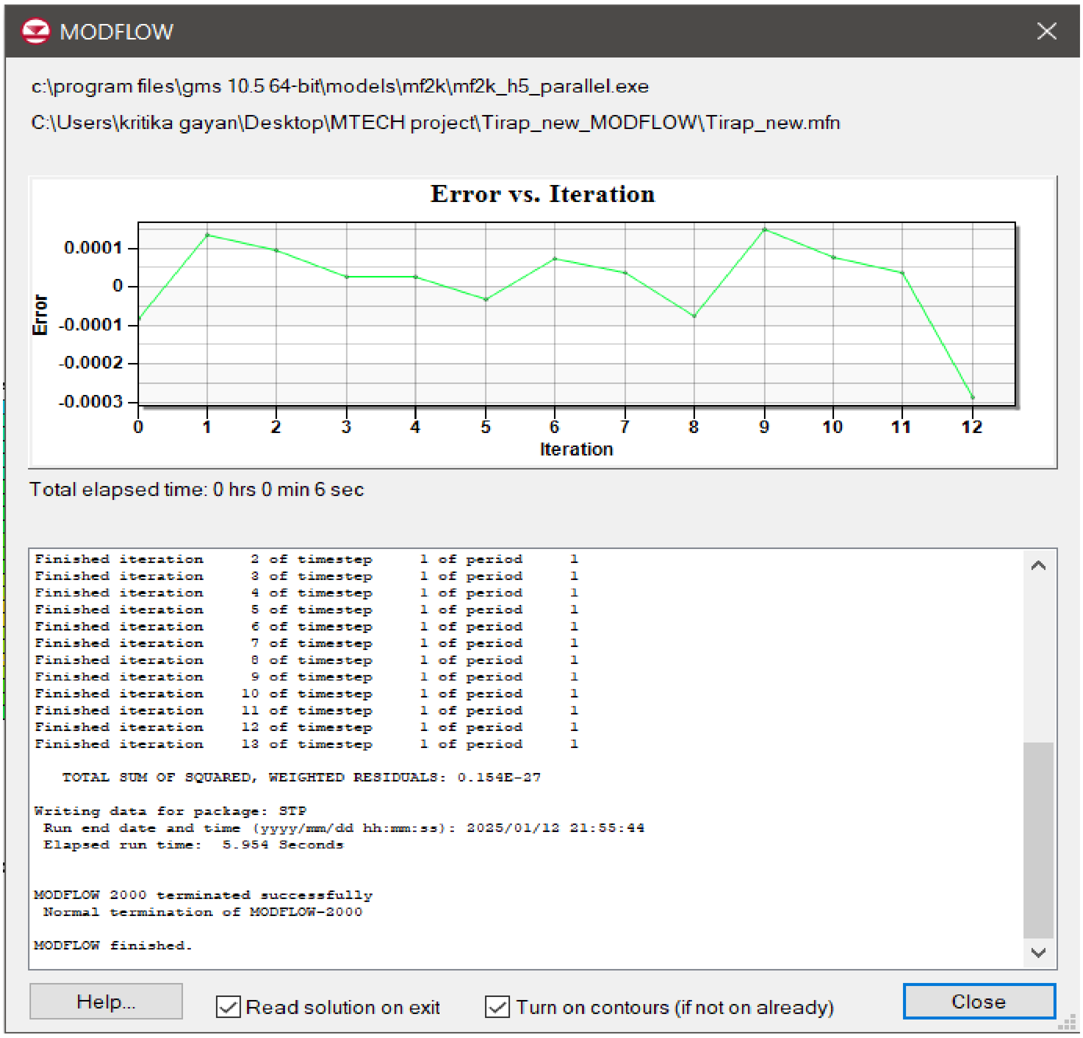


Fig 3.9: Successful termination of Model.

The figure represents successful termination of the model using MODFLOW 2000 package. The graph shows variation between Iteration and Error. The Residual error in this model is 0.154×10^{-27} which is almost negligible.

3. **Stress Periods**:
   - A steady-state simulation was performed to establish baseline conditions.
   - Transient simulations were conducted for **2nd year, 5th year, and 10th year** to model the impact of dewatering:
     - Time steps were subdivided within each stress period for finer resolution.

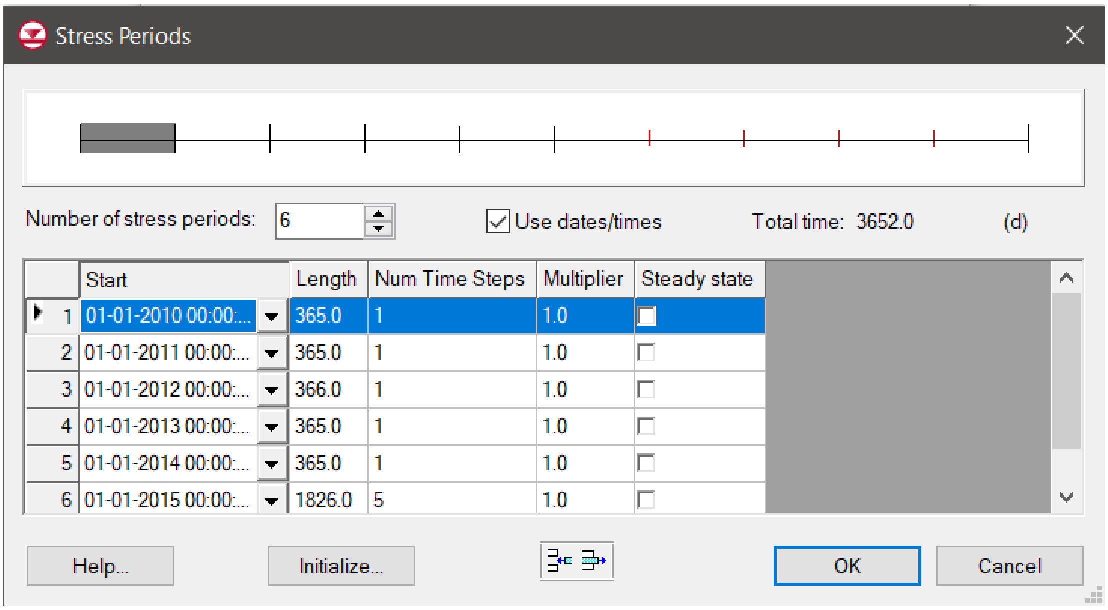


Fig 3.10: Stress periods for transient state model.

4. Well Boundary:

- The Well boundary was assigned to the Transient state model, the flow rates for each well were assigned for 1st, 2nd, 5th and 10th year.

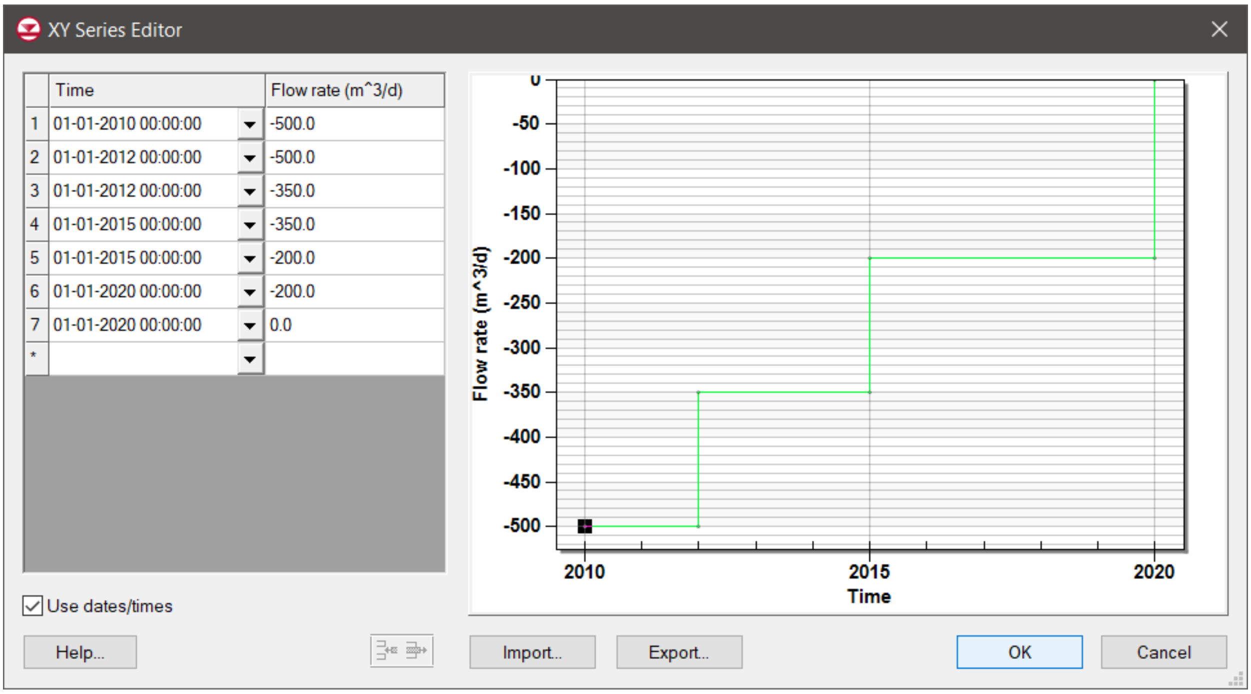


Fig 3.11: Well data for Transient State Model.

5. **Recharge Boundary**:

- The Recharge Boundary was assigned to the top layer, considering 12% of the yearly rainfall data of 25 years (1997-2021) in the transient state.

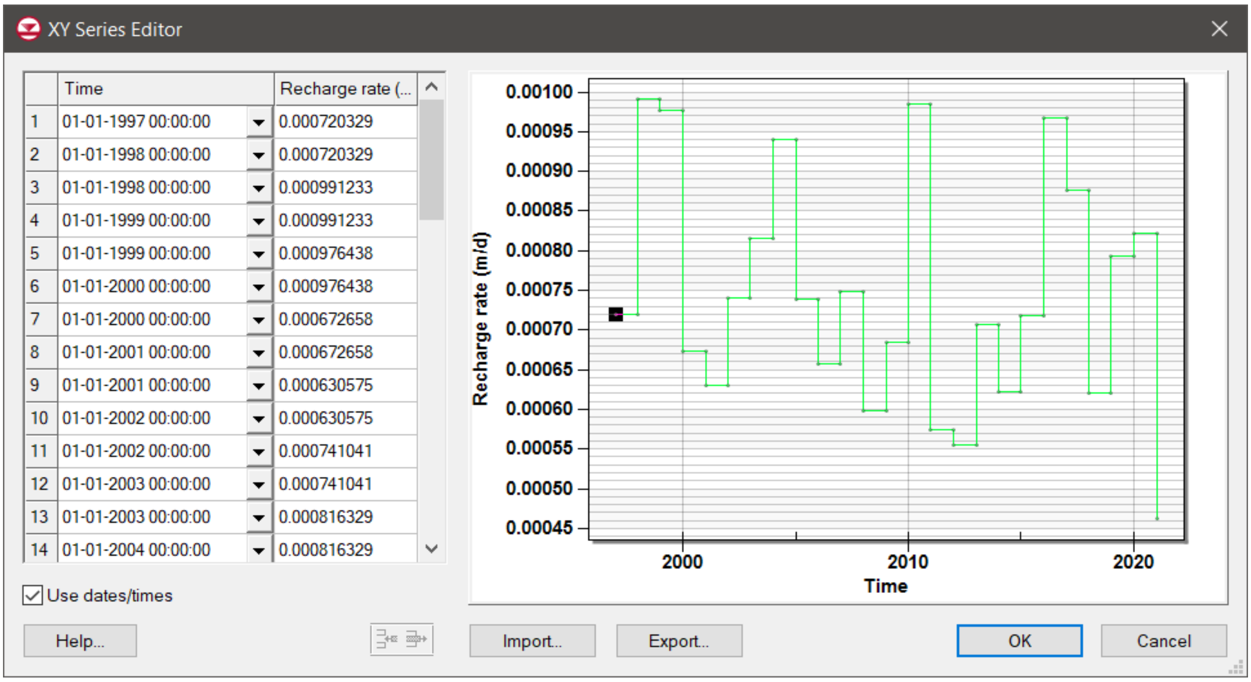


Fig 3.12: Recharge Boundary for Transient state.

The figure shows the recharge boundary assigned to the transient state model along with the Time vs Recharge rate graph.

6. **Drain Boundary**:

- The drain boundary was assigned to the mine area in the transient state, by providing conductance of 10 m^2/d per m^2 from the 2nd year as it was considered that drainage started after 2 years.

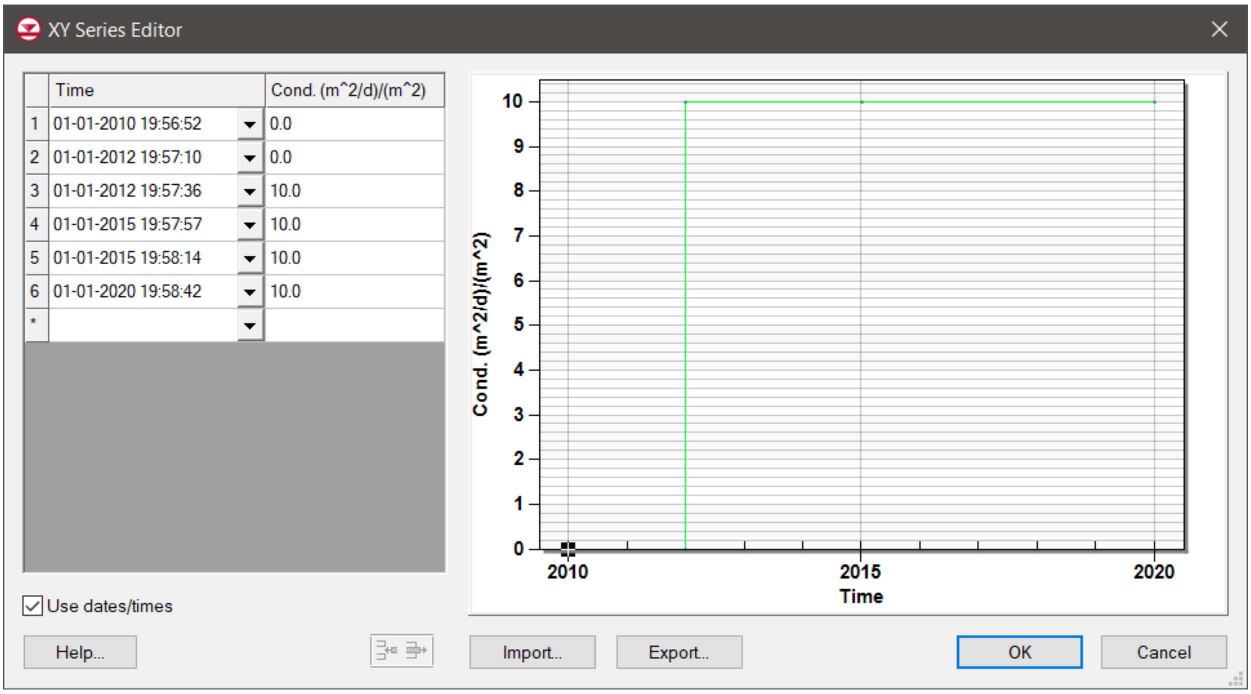


Fig 3.13: Drain boundary condition for the mine site.

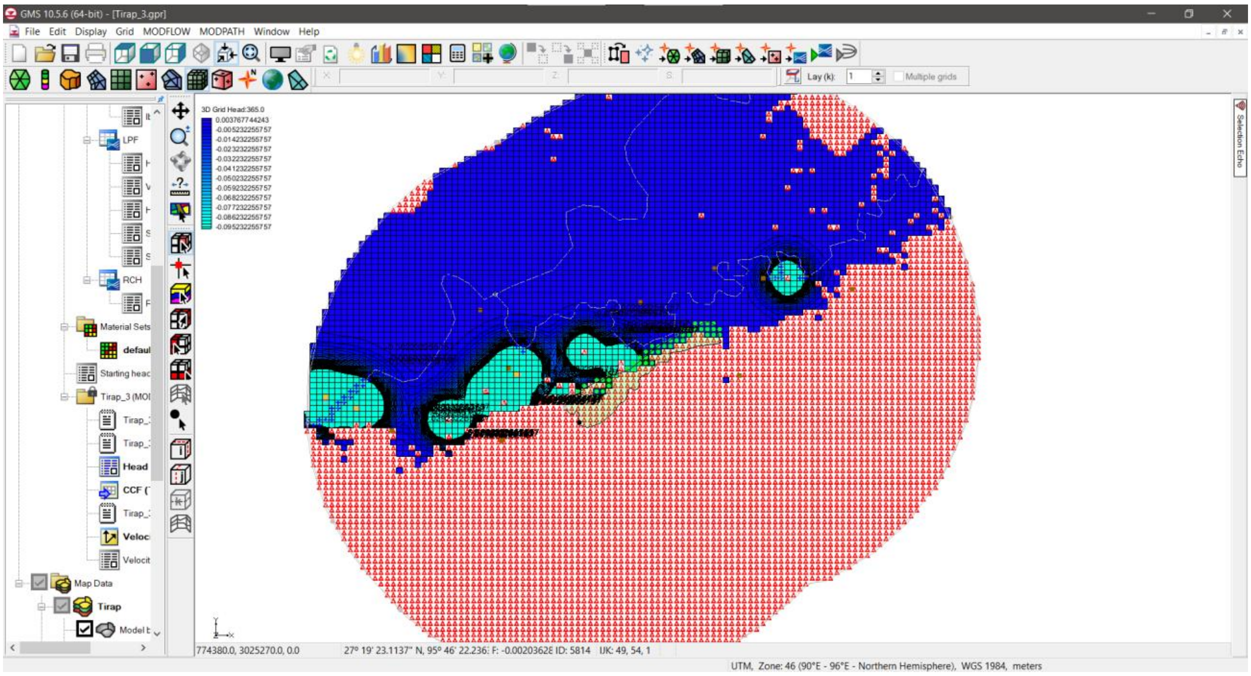


Fig 3.14: Transient State Model.

The Figure shows Transient State Model which includes Pumping wells and contours around it along with drain boundary shown in Green Dots and rivers with white arcs. The cells with red colour represent dry cells.

3.4 PREDICTION SCENARIOS

1. **Impact of Mine Dewatering**:
   - Predicted drawdowns were assessed for 2nd, 5th, and 10th years:
     - 2nd year: Maximum drawdown of **9 m**.
     - 5th year: Maximum drawdown of **11.86 m**.
     - 10th year: Maximum drawdown of **11.69 m**.

3.5 MODEL LIMITATIONS

1. **Assumptions**:
   - Uniform recharge over time.
   - Simplified representation of aquifer properties.
2. **Data Gaps**:
   - Lack of detailed spatial variations in lithology and hydraulic conductivity.

4 RESULTS AND DISCUSSIONS

4.1 PREDICTION SCENARIOS

4.1.1 Impact of Mine Dewatering:

Predicted drawdowns were assessed for 2nd, 5th, and 10th years:

- 2nd year: Maximum drawdown of 9 m.
- 5th year: Maximum drawdown of 11.86 m.
- 10th year: Maximum drawdown of 11.69 m (Due to the effects of recharge, WL due to drawdown in the 10th year increased by 0.17 m).

4.1.2 Flow Mass Balance:

a) Flow Mass Balance for 2nd Year:

Number of selected cells: 0 (data for all cells is displayed below)

	Flow In	Flow Out
Sources/Sinks		
CONSTANT HEAD	0.0	0.0
WELLS	0.0	-8,546.0
DRAINS	0.0	0.0
RIVER LEAKAGE	0.0	-3,524.438163303
HEAD DEP BOUNDS	8,244.991446367	-99,434.87661364
RECHARGE	2,28,598.72879791	0.0
STORAGE	0.0	-1,25,338.406361
Total Source/Sink	**2,36,843.72024428**	**-2,36,843.7211379**
Zone Flow		
FLOW RIGHT FACE	0.0	0.0
FLOW FRONT FACE	0.0	0.0
FLOW LOWER FACE	0.0	0.0
FLOW LEFT FACE	0.0	0.0
FLOW UPPER FACE	0.0	0.0
FLOW BACK FACE	0.0	0.0
Total Zone Flow	**0.0**	**0.0**
TOTAL FLOW	**2,36,843.72024428**	**-2,36,843.7211379**
Summary	**In - Out**	**% difference**
Sources/Sinks	**-0.000893645047**	**-3.7731422e-007**
Cell To Cell	**0.0**	**0.0**
Total	**-0.000893645047**	**-3.7731422e-007**

Fig 4.1: Flow Budget for 2nd year.

1. **Sources/Sinks (Flow in and Flow out)**

- Recharge:
  - Flow In: 2,28,598.73 m³/day.

    This represents the natural recharge to the aquifer system from rainfall or other sources. It is the largest source of water in the system.
- Head-Dependent Boundaries:
  - Flow In: 8,244.99 m³/day.
    - Indicates inflow into the system through head-dependent boundaries (e.g., river-aquifer interaction or constant head boundaries).
  - Flow Out: -99,434.88 m³/day.
    - Represents outflow to head-dependent boundaries, likely through discharge into rivers or other features.
- Wells:
  - Flow Out: -8,546.0 m³/day.
    - Reflects groundwater abstraction for mining dewatering purposes or other well extractions.
- River Leakage:
  - Flow Out: -3,524.44 m³/day.
    - Suggests that water is leaving the aquifer to supply baseflow to rivers or other surface water bodies.
- Storage:
  - Flow Out: -1,25,338.41 m³/day.
    - Indicates water released from aquifer storage due to a decline in groundwater levels caused by stress (e.g., pumping). This value represents a significant source of groundwater outflow.

2. **Total Source/Sink**

- Flow In: 2,36,843.72 m³/day.
- Flow Out: -2,36,843.72 m³/day.

The inflow and outflow balance perfectly, with a very small numerical discrepancy of -**0.000893645047** due to computational precision. This ensures that the model is mass-balanced.

3. Zone Flow

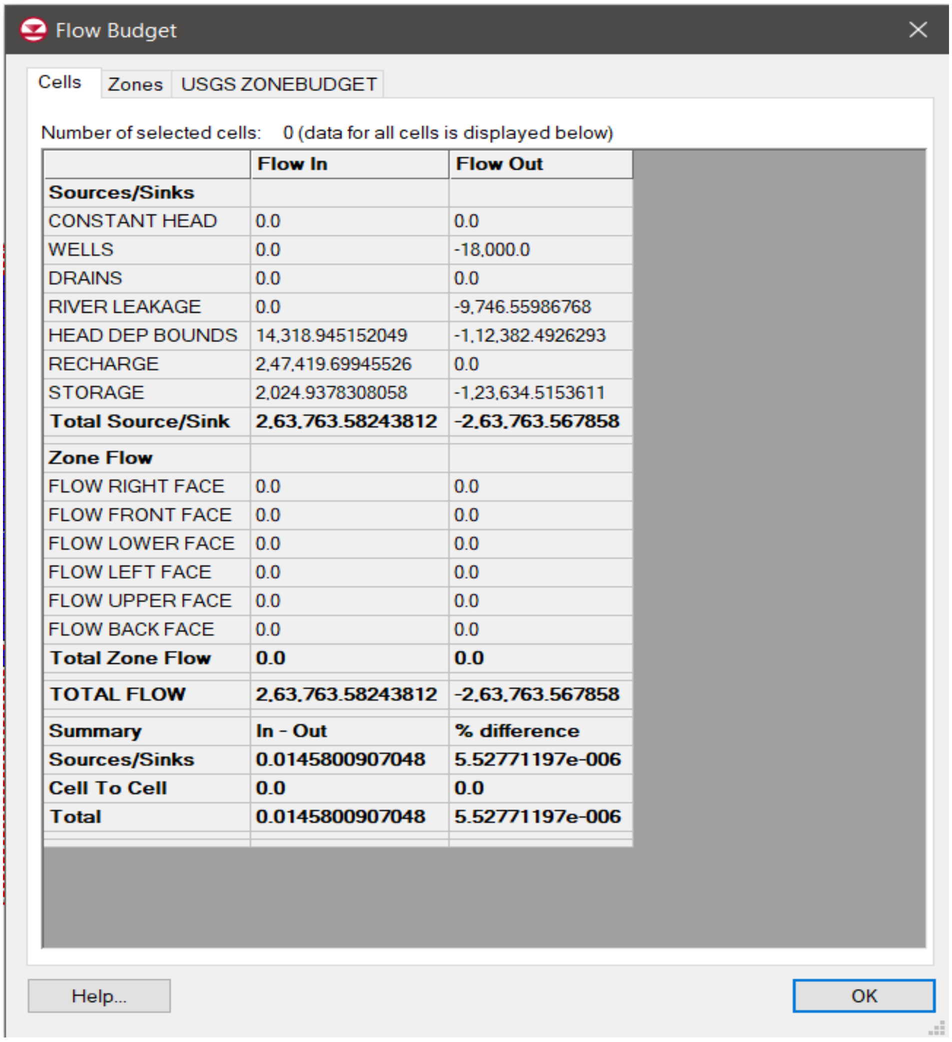
- All directional flows (front, back, right, left, upper, and lower faces) are 0.0 m³/day.
- Indicates no lateral or vertical flows across the model boundaries, suggesting the flow is primarily dominated by internal sources and sinks (e.g., recharge, pumping, and boundary conditions).

4. Summary

- **In-Out Difference:**

  A negligible difference of **-0.000893645047 m³/day**, equivalent to **-3.77e-7%**. This confirms the accuracy of the numerical model and ensures the flow budget calculations are reliable.

b) Flow Mass Balance for 5th Year:



	Flow In	Flow Out
Sources/Sinks		
CONSTANT HEAD	0.0	0.0
WELLS	0.0	-18,000.0
DRAINS	0.0	0.0
RIVER LEAKAGE	0.0	-9,746.55986768
HEAD DEP BOUNDS	14,318.945152049	-1,12,382.4926293
RECHARGE	2,47,419.69945526	0.0
STORAGE	2,024.9378308058	-1,23,634.5153611
Total Source/Sink	**2,63,763.58243812**	**-2,63,763.567858**
Zone Flow		
FLOW RIGHT FACE	0.0	0.0
FLOW FRONT FACE	0.0	0.0
FLOW LOWER FACE	0.0	0.0
FLOW LEFT FACE	0.0	0.0
FLOW UPPER FACE	0.0	0.0
FLOW BACK FACE	0.0	0.0
Total Zone Flow	**0.0**	**0.0**
TOTAL FLOW	**2,63,763.58243812**	**-2,63,763.567858**
Summary	**In - Out**	**% difference**
Sources/Sinks	**0.0145800907048**	**5.52771197e-006**
Cell To Cell	**0.0**	**0.0**
Total	**0.0145800907048**	**5.52771197e-006**

Fig 4.2: Flow Budget for 5th year.

1. **Sources/Sinks:**
   - Wells: There is an outflow of 18,000 m^3/day from wells, suggesting that groundwater is being extracted (likely for pumping).
   - River Leakage: There is a significant outflow of 9,746.55986768 m^3/day to the river, meaning the aquifer is discharging into the river.
   - Head-Dependent Boundaries: There is both inflow (14,318.945152049 m^3/day) and outflow (1,112.3824926293 m^3/day) at the head-dependent boundaries, indicating exchange with external water sources.
   - Recharge: Recharge contributes a significant inflow of 2,47,419.69945526 m^3/day, likely from precipitation or infiltration.
   - Storage: There is an inflow of 2,024.9373808058 m^3/day from storage (indicating water entering storage) and an outflow of 1,23,634.5153611 m^3/day (indicating water being released from aquifer storage).

   The total source/sink flows are balanced:

   - Total Inflow: 2,63,763.58243812 m^3/day
   - Total Outflow: -2,63,763.567858 m^3/day
2. **Zone Flow:**
   - All faces (right, front, lower, left, upper, back) have no flow, indicating no lateral or vertical groundwater flow exchange within zones for this period.
3. **Flow Balance:**
   - The difference between inflows and outflows is **0.0145800907048 m^3/day**, which is negligible and results in a percent difference of **5.52771197e-006%**, confirming a well-balanced flow budget for the simulation.

c) Flow Mass Balance for 5th Year:

Flow Budget

Cells | Zones | USGS ZONEBUDGET

Number of selected cells: 0 (data for all cells is displayed below)

	Flow In	**Flow Out**
Sources/Sinks		
CONSTANT HEAD	0.0	0.0
WELLS	0.0	-9,104.3046875
DRAINS	0.0	0.0
RIVER LEAKAGE	0.0	-16,567.99646181
HEAD DEP BOUNDS	7,818.3286386489	-1,54,947.8890568
RECHARGE	3,16,049.80903625	0.0
STORAGE	10.323974609375	-1,43,258.3004241
Total Source/Sink	**3,23,878.46164951**	**-3,23,878.4906302**
Zone Flow		
FLOW RIGHT FACE	0.0	0.0
FLOW FRONT FACE	0.0	0.0
FLOW LOWER FACE	0.0	0.0
FLOW LEFT FACE	0.0	0.0
FLOW UPPER FACE	0.0	0.0
FLOW BACK FACE	0.0	0.0
Total Zone Flow	**0.0**	**0.0**
TOTAL FLOW	**3,23,878.46164951**	**-3,23,878.4906302**
Summary	**In - Out**	**% difference**
Sources/Sinks	**-0.028980691044**	**-8.9480139e-006**
Cell To Cell	**0.0**	**0.0**
Total	**-0.028980691044**	**-8.9480139e-006**

Help... OK

Fig 4.3: Flow Budget for 10th year.

1. **Sources/Sinks**

- **Constant Head:**
  - There is no inflow or outflow from constant head boundaries, meaning they are inactive in this stress period.
- **Wells:**
  - Outflow due to pumping is 9,104.3046875 m^3/day, reflecting the consistent extraction of groundwater for use.

- **Drains:**
  - No inflow or outflow occurs, indicating that drains are not influencing the system in this period.
- **River Leakage:**
  - A large outflow of 16,567.99646181 m^3/day occurs, signifying that the aquifer is discharging water into the river system. This indicates a strong hydraulic connection between the aquifer and the river.
- **Head-Dependent Boundaries:**
  - There is an inflow of 7,818.3286386489 m^3/day, showing external contributions from connected water sources like nearby aquifers or surface water.
  - Outflow from these boundaries is 1,504.9478890568 m^3/day, suggesting that some water is also leaving the system through these connections.
- **Recharge:**
  - Recharge is the most significant inflow, contributing 316,049.80903625 m^3/day, representing surface water infiltration from precipitation or irrigation.
- **Storage:**
  - However, a substantial outflow of 143,258.3004241 m^3/day indicating water being released from storage to maintain the flow system.
  - The aquifer experiences a small inflow of 10.323974609375 m^3/day, shows that water is being stored in the aquifer, reflecting a net loss of groundwater storage

2. Total Source/Sink Flows

- Inflow: 323,878.46164951 m^3/day
- Outflow: 323,878.4906302 m^3/day
- The negligible difference of 0.028980691044 m^3/day between inflows and outflows indicates that the flow budget is highly balanced, demonstrating a well-calibrated model.

3. Zone Flow

- There is no flow across zone boundaries (right, front, lower, left, upper, or back faces).
  - This suggests that there is no lateral or vertical movement of groundwater between model zones, potentially due to a lack of gradients or boundary interactions within the system.

4. **Flow Balance**

- In-Out Difference: **-0.028980691044 m^3/day**
- % Difference: **-8.9480139e-006%**
- The extremely small percentage difference indicates a negligible error and a balanced flow system.

Surinaidu et al. (2014) has done a similar study to estimate groundwater inflows into coal mines at different development stages and design dewatering strategies for safe mining in Andhra Pradesh, India. They developed a finite-difference model with 20 conceptual layers calibrated using groundwater levels. They incorporated hydrogeological studies, geological logs from 183 boreholes, and pumping tests to estimate aquifer parameters. An Equivalent Porous Medium (EPM) approach was used for fractured aquifers. The study found that groundwater inflows varied with mine depth, faults and geological structures played a key role in seepage, and lateral flows and river interactions were significant in groundwater budgeting. It offered a framework for mine dewatering schemes and enhanced safety for mining operations. It is a site-specific study, focusing on mining operations and geological influences.

5 CONCLUSION

5.1 OVERVIEW

The results of this study provide an in-depth understanding of the groundwater flow dynamics over a prolonged period, as assessed through a flow budget analysis. By examining stress periods like the 5th and 10th years, we identified significant changes in inflow and outflow components, offering insights into system behaviour under varying stress conditions.

5.2 OUTCOMES

5.2.1 For 2nd Year Stress Period:

i. Recharge Dominates Flow In:
   Recharge is the largest inflow component, contributing around **96.5%** of the total inflow.
ii. Storage Loss is Significant:
   A substantial outflow occurs from storage (**53% of the total outflow**), indicating that the aquifer is undergoing depletion to balance the stress imposed by abstraction and boundary conditions.
iii. Groundwater Abstraction Impact:
   - Dewatering through wells accounts for **3.6%** of total outflow.
   - Combined with storage outflow, it highlights the significant impact of mining activities on groundwater levels.
iv. River Leakage and Head-Dependent Boundaries:
   - Outflow via head-dependent boundaries (**42%**) and river leakage (**1.5%**) suggests a loss of water to rivers and surrounding boundaries.

Implications

- The aquifer is heavily reliant on storage and recharge to sustain outflows, which might result in significant groundwater level declines over time.
- Continued abstraction and head-dependent outflows could increase the radius of influence and potentially affect nearby groundwater users and ecosystems.
- Monitoring and adjusting the recharge and abstraction rates are essential to ensure the long-term sustainability of the aquifer system.

5.2.2 For 5th Year Stress Period:

i. Recharge Dominates Inflows:

   Recharge contributes the majority of the inflow, emphasizing the importance of surface water interactions (likely from precipitation or irrigation).

ii. Outflows Are Split Between Pumping and Natural Discharge:
   - Pumping through wells accounts for 9,104.3046875 m^3/day of outflow.
   - Natural discharge to rivers is significant at 16,567.99646181 m^3/day, showing strong connectivity between the river and the aquifer.

iii. Storage Dynamics:
   - The aquifer is losing a significant amount of water to storage (1,43,258.3004241 m^3/day), which could indicate declining water levels over time or adjustments to meet stress demands.

iv. Balanced System:
   - Despite the large flows, the system's inflows and outflows are nearly balanced, with a negligible discrepancy, confirming the reliability of the simulation.

Implications

- The system is stable, with recharge compensating for both pumping and natural discharges.
- The aquifer is experiencing a net loss in storage, which may signal long-term stress or depletion if recharge rates do not increase or pumping is not reduced.
- Strong interaction with rivers highlights the importance of surface water-groundwater connectivity in managing the aquifer.

5.2.3 For 10th Year Stress Period:

i. Recharge Dominates Inflows:
   - Recharge contributes the largest inflow (316,049.80903625 m^3/day) and remains the primary source of water replenishment to the system.

ii. Outflows Are Split Between Natural Discharge and Pumping:
   - Natural discharge to the river is the largest outflow (16,567.99646181 m^3/day), followed by pumping (9,104.3046875 m^3/day). This highlights the dual stresses of human extraction and natural river-aquifer interaction.

iii. Storage Dynamics:

- The aquifer continues to lose a significant volume of water to storage (143,258.3004241 m^3/day). This reflects either a continued stress on the aquifer due to pumping and discharge or adjustments in storage capacity over time.
- A net loss in storage could lead to long-term impacts such as declining water levels if this trend persists.

iv. Stable Model:

- Despite large flow components, the system remains balanced, with inflows and outflows nearly equal, confirming that the model is robust and well-calibrated.

Implications

- The aquifer relies heavily on recharge to offset outflows caused by river discharge and pumping.
- The substantial loss to storage could indicate the aquifer's capacity is being depleted over time, especially if recharge rates do not increase.
- Natural interactions, like river leakage, remain significant, suggesting that surface water-groundwater interactions play a key role in the system dynamics.
- With no inter-zone flow, it appears that the system is relatively isolated, with minimal influence from adjacent zones or lateral movements.

For the 2nd, 5th and 10th year, the system remains in equilibrium, with inflows and outflows balanced. However, the substantial outflow to storage indicates potential long-term stress on the aquifer. The dominance of recharge as an inflow emphasizes the importance of maintaining or enhancing recharge rates to sustain the groundwater system. River leakage and pumping continue to be significant contributors to groundwater loss, highlighting areas of potential concern for sustainable management.

5.3 SCOPE FOR FUTURE RESEARCH

Future research could focus on incorporating climatic variables and anthropogenic influences to develop predictive models that further refine groundwater management practices. The integration of these factors would enhance the robustness of the current methodology and provide a more comprehensive understanding of groundwater sustainability. Ultimately, the outcomes of this study offer critical insights into groundwater flow processes, supporting informed decision-making for sustainable resource utilization in the field of hydrogeology.

6 REFERENCES

1. L. Surinaidu, V.V.S. Gurunadha Rao, N. Srinivasa Rao and S. Srinu (2014). Hydrogeological and groundwater modeling studies to estimate the groundwater inflows into the Coal Mines at different mine development stages using MODFLOW, Andhra Pradesh, India. Water Resources and Industry, http://dx.doi.org/10.1016/j.wri.2014.10.002
2. Haixiang Li and Xu-sheng Wang (2019). A Preliminary Study on a Pumping Well Capturing Groundwater in an Unconfined Aquifer with Mountain-Front Recharge from Segmental Inflow. Ministry of Education Key Laboratory of Groundwater Circulation and Environmental Evolution, China University of Geosciences, Beijing 100083, China; lihaixiangcugb@foxmail.com. doi:10.3390/w11061243
3. Dahl MB, Vilhelmsen TN, Bach T and Hansen TM (2023). Hydraulic head change predictions in groundwater models using a probabilistic neural network. Front. Water 5:1028922. doi: 10.3389/frwa.2023.102892
4. Hai-Min Lyu, Shui-Long Shen, Yong-Xia Wu, An-Nan Zhou (2021). Calculation of groundwater head distribution with a close barrier during excavation dewatering in confined aquifer. Geoscience Frontiers 12 (2021) 791–803.
5. Hydrogeology Department Exploration Division CMPDI, Ranchi "Comprehensive Report on Groundwater condition for Tirap OCP, NEC", March, 2022.