International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 07 Issue 07 July 2024
DOI: 10.47191/ijcsrr/V7-i7-41, Impact Factor: 7.943
IJCSRR @ 2024
www.ijcsrr.org

# Modeling Contaminant Transport from a Red Mud Pond – A Case Study from South India

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**ABSTRACT:** The present study focused on impact assessment of redmud pond on groundwater using numerical groundwater flow and contaminant transport modeling using pertinent data including water quality and 2D electrical resistivity imaging data. The observed groundwater depths range from 1.2 to 25.8 meters below ground level with deeper levels observed in upstream and higher elevated regions in the study area. Elevated pH and electrical conductivity (>3000 µS/cm) characterize the Redmud ponds, while other groundwater samples meet BIS drinking water standards. Major ion concentrations contouring indicates high total dissolved solids (TDS) around Redmud ponds due to leakage and in the downstream due to domestic sewage pollution. Most locations adhere to BIS drinking water limits except for one downstream site. The resistivity data indicated hard formations (>18 m depth) with resistivity >500 Ohm.m, weathered basalt (12-18 m, 60-150 Ohm.m), and saturated water (12 m, 1-5 Ohm.m). Contaminated aquifers (<1 Ohm.m) are detected up to 3 m depth, and noticed accumulating contaminated water (27 m depth) in the NW corner of the Redmud pond from seepage. Predominant groundwater flow from the Redmud pond towards public water bodies and streams is highlighted by simulated contaminant transport model. Collaboration and comprehensive management are recommended to protect the watershed's environmental integrity and public health.

**KEYWORDS:** Contaminant transport, Groundwater, MODFLOW, MT3DMS and Red mud

## I. INTRODUCTION

Groundwater contamination in industrial areas poses significant environmental and public health concerns globally [1], [2]. Understanding the complex interactions between groundwater flow patterns and contaminant transport processes is crucial for effective management and remediation strategies. In recent years, the use of advanced numerical models such as MODFLOW (Modular Three-Dimensional Finite-Difference Groundwater Flow Model) and MT3DMS (Modflow Transport Model for Three-Dimensional Multispecies Solute Transport in Groundwater) has revolutionized the field of hydrogeology, offering unparalleled insights into the dynamics of groundwater systems in industrial settings.

*Groundwater Flow Modeling with MODFLOW:*

MODFLOW, developed by the U.S. Geological Survey, is a widely adopted numerical model for simulating groundwater flow in three dimensions. It discretizes the subsurface domain into a grid of cells and solves the groundwater flow equation using finite-difference methods. In industrial areas, where groundwater extraction, recharge, and contamination are prevalent, MODFLOW provides a robust framework for analyzing the effects of anthropogenic activities on groundwater flow regimes [3], [4],[5],[6].

Recent studies have highlighted the versatility of MODFLOW in industrial hydrogeology. For instance [7], employed MODFLOW to investigate the impact of industrial pumping activities on groundwater levels and flow velocities in a heavily industrialized region. By incorporating field data on pumping rates, aquifer properties, and boundary conditions, the study provided valuable insights into the spatial and temporal variations of groundwater flow, aiding in sustainable groundwater management practices.

*Contaminant Transport Modeling with MT3DMS:*

MT3DMS, an extension of MODFLOW, specializes in simulating multispecies solute transport in groundwater systems. It accounts for advection, dispersion, and various chemical reactions, making it indispensable for assessing the fate and transport of contaminants in industrial environments. MT3DMS enables researchers to model the migration of multiple contaminants, their interaction with the subsurface matrix, and the potential risks to human health and the environment.

Recent advancements in contaminant transport modeling using MT3DMS have been demonstrated by Wang et al. [8], who investigated the migration of industrial pollutants in a contaminated aquifer beneath a manufacturing facility. By coupling MT3DMS with MODFLOW, the study evaluated the effectiveness of different remediation strategies, such as pump-and-treat systems and in-situ bioremediation, in mitigating contaminant plumes. The findings underscored the importance of accurate characterization of hydrogeological parameters and the need for dynamic modeling approaches to address temporal variability in contaminant sources and hydrological conditions.

*Integration and Applications:*

The integration of MODFLOW and MT3DMS facilitates comprehensive modeling of groundwater flow and contaminant transport processes in industrial areas. By coupling these models, researchers and environmental practitioners can assess the impacts of industrial activities on groundwater quality, design efficient remediation strategies, and support regulatory decision-making processes.

In industrial settings where the release of hazardous substances poses a threat to groundwater resources [9], [10], accurate modeling becomes paramount. The combined use of MODFLOW and MT3DMS enables stakeholders to simulate various scenarios, evaluate potential risks, and devise proactive measures to safeguard groundwater quality and public health.

Groundwater flow and contaminant transport modeling using MODFLOW and MT3DMS aided electrical resistivity techniques represent powerful tools for assessing and managing groundwater contamination in industrial areas [11],[12],[13],[14]. Recent advancements in modeling techniques have enhanced our understanding of the complex interactions between hydrogeological processes and anthropogenic activities, thereby supporting informed decision-making for sustainable groundwater management and remediation efforts.

## 2. STUDY AREA

The study focuses on Hindalco's Belagavi unit in Karnataka, comprising an alumina plant, a research center, and a carbon paste plant (Fig. 1). Operational since 1969, it has evolved into a major exporter of specialized alumina and hydrates for non-metallurgical uses such as ceramics, refractory, and fire retardants, with over 120 product grades catering to 600+ customers across 32 countries. The unit has received national awards for energy conservation, R&D, and environmental safety.

Environmental concerns center around red mud, a hazardous byproduct of alumina production. Initially stored in ponds spanning 70 hectares until 1984, the process shifted in 1985 to dry stacking. Rainwater from this area is collected in ponds, posing risks of $Na_2CO3$ and NaOH leachate affecting groundwater.

Geospatial and Environmental Solutions (GES) monitored groundwater impacts around red mud ponds in February 2021, conducting comprehensive hydrogeological surveys. Ongoing monitoring of 27 wells from 2022-2023 tracks seasonal groundwater levels and quality. GES have carried out groundwater level monitoring and surface and groundwater quality analysis in and around redmud ponds during February 2021. During the study period, a watershed base investigation has been carried out which cover redmud pond area. Detailed geophysical and hydrogeological investigations have been carried out in and around redmud ponds of Hindalco. Seasonal groundwater levels and water quality is monitored at 27 observation wells during between 2022-2023. Finally, a numerical groundwater flow and contaminant transport modeling is constructed to predict the impact of redmud pond on groundwater.

## 3.0 DATA AND METHODOLOGY

### *3.1. DATA:*

Groundwater samples and red mud pond water has been collected from study area. The subsurface information on aquifer structure and contaminant mapping has been done using advanced geophysical technique. In the present research paper, groundwater flow and contaminant transport modelling discussed is reported.

### *3.2. GROUNDWATER FLOW AND CONTAMINANT TRANSPORT MODELLING:*

Groundwater flow modeling typically involves solving partial differential equations governing fluid flow in porous media. Various numerical techniques such as finite difference, finite element, and boundary element methods are employed to discretize the governing equations. These models often incorporate parameters such as hydraulic conductivity, porosity, and boundary conditions to simulate groundwater flow accurately.

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Contaminant transport modeling extends groundwater flow models by including advection, dispersion, sorption, and reaction processes. Advection represents the movement of contaminants with the flowing groundwater, while dispersion accounts for spreading due to velocity variations. Sorption describes the attachment of contaminants to solid surfaces, and reactions involve transformations such as biodegradation or chemical reactions.


**Fig. 1 Loation of the study area**

For the present study area, a finite difference-based groundwater flow and contaminant transport model is constructed using MODFLOW and MT3DMS, which solves 3D diffusion equation (partial differential equation) of Darcy law. The partial differential equation describing three-dimensional transport of contaminants in groundwater [15], [16],[17] can be written as

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_j}\right] - \frac{\partial}{\partial x_i}(v_i C) + \frac{q_s}{\theta}C_s + \sum_{K=1}^{N} R_k \text{............}(1)$$

where,

C - concentration of contaminants dissolved in groundwater

t - time

$x_i$ - distance along the respective Cartesian co-ordinate axis

$D_{ij}$ - hydrodynamic dispersion coefficient

$v_i$ - seepage or linear pore water velocity

$q_s$ - volumetric flux of water per unit volume of aquifer representing sources (positive) and sinks (negative)

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$C_s$ - concentration of sources or sinks

$\theta$ - porosity of the porous medium

$R_k$ - chemical reaction term

Assuming that only equilibrium controlled linear or non-linear sorption and first order irreversible rate reactions are involved in the chemical reactions, the chemical reaction term can be expressed as [18]

$$\sum_{k=1}^{N} R_k = -\frac{\rho_b}{\theta}\frac{\partial \bar{C}}{\partial t} - \lambda\left[C + \frac{\rho}{\theta}\bar{C}\right] \quad \text{.......................(2)}$$

where

$\rho_b$ - the bulk density of the porous medium

$\bar{C}$ - the concentration of contaminants sorbed on the porous medium

$\lambda$ - the rate constant of the first-order rate reactions, rewriting equation 1 as

$$\frac{\rho_b}{\theta}\frac{\partial \bar{C}}{\partial t} = \frac{\rho_b}{\theta}\frac{\partial C}{\partial t}\frac{\partial \bar{C}}{\partial C} \quad \text{..............(3)}$$

We can rewrite equation (1) by substituting equation (2) and (3) as

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_j}\right] - \frac{\partial}{\partial x_i}(v_i C) + \frac{q_s}{\theta}C_s - \frac{\rho_b}{\theta}\frac{\partial \bar{C}}{\partial C}\frac{\partial C}{\partial t} - \lambda\left(C + \frac{\rho_b}{\theta}\bar{C}\right) \quad \text{......(4)}$$

Rearranging terms we get

$$R\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_j}\right] - \frac{\partial}{\partial x_j}(v_i C) + \frac{q_s}{\theta}C_s - \lambda\left(C + \frac{\rho_b}{\theta}\bar{C}\right) \quad \text{.........(5)}$$

where R is called the retardation factor, defined as

$$R = 1 + \frac{\rho_b}{\theta}\frac{\partial \bar{C}}{\partial C} \quad \text{...................(6)}$$

Equation (5) is the governing equation underlying the solute transport model.
The transport equation is linked to the flow equation

$$v_i = -\frac{K_{ii}}{\theta}\frac{\partial h}{\partial x_i} \quad \text{................(7)}$$

where $K_{ii}$ is a principal component of the hydraulic conductivity tensor and h is hydraulic head.
The hydraulic head is obtained from solution of three-dimensional groundwater flow equation through MODFLOW software [19]

$$\frac{\partial}{\partial x_i}\left[K_{ii}\frac{\partial h}{\partial x_j}\right] + q_s = S_s\frac{\partial h}{\partial t} \quad \text{..................(8)}$$

where $S_s$ is the specific storage of the porous material.
The numerical approaches for solving the mass transport equations are based on computer-based particle tracking methods. They are approximate forms of the advection - dispersion equation (5) as a system of algebraic equations or alternatively simulating transport through spread of a large number of moving reference particles. These numerical approaches deal with variability of flow and transport parameters (hydraulic conductivity, porosity, dispersivity etc.). Velocity values are computed by applying Darcy's equation using calculated hydraulic heads and porosity values [20].

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The present study is simulated in transient model from 2005 to 2022, however model is calibrated for observed groundwater heads measured in February 2005 and validated with October groundwater heads of the year 2020 and the year 2023. Then calibrated model is used to predict contaminant transport until the year 2045.

## 4.0. RESULTS AND DISCUSSION

### *4.1. GROUNDWATER QUALITY AND SUBSURFACE INFORMATION:*

Groundwater depths vary from 1.2 m below ground level (bgl) to 25.8 m bgl in the study area. The deeper ground water level in the upstream and higher elevated areas were noticed. The elevations were range from 716 m amsl to 768 m amsl. pH of red mud pond is alkaline in nature with high electrical conductivity > 3000 micro-semens. However, EC of all other groundwater samples are within the prescribed limits of BIS drinking water standards. The contours of major ion concentrations in groundwater is shown from figure 8 to figure 19. The higher TDS is around Redmud ponds are observed. The high TDS observed in the downstream at one location that is due to domestic pollution leaching from sewage. Other than one location in the downstream, all other locations concentrations are within the limits of drinking water limits of BIS. The location of 2D electrical resistivity tomography (ERT) imaging is shown Figure 2. The ERTS indicated most of the cases hard formation is encountered at the depth of >18 m bgl with a resistivity of > 500 Ohm.m. Weathered basalt existed upto 12 to 18 m depth indicated by 60-150 Ohm.m, saturation of water is identified with 1-5 Ohm.m mostly at 12 m depth. The contaminated aquifer/subsurface is detected with a resistivity of < 1 Ohm.m that encountered at the depth upt to 3 m in the North-West and West side of redmud pond. In the NW corner of redmud, it is observed that contaminated water is accumulated upto the depth of 27 m depth, due to seepage from redmud pond.

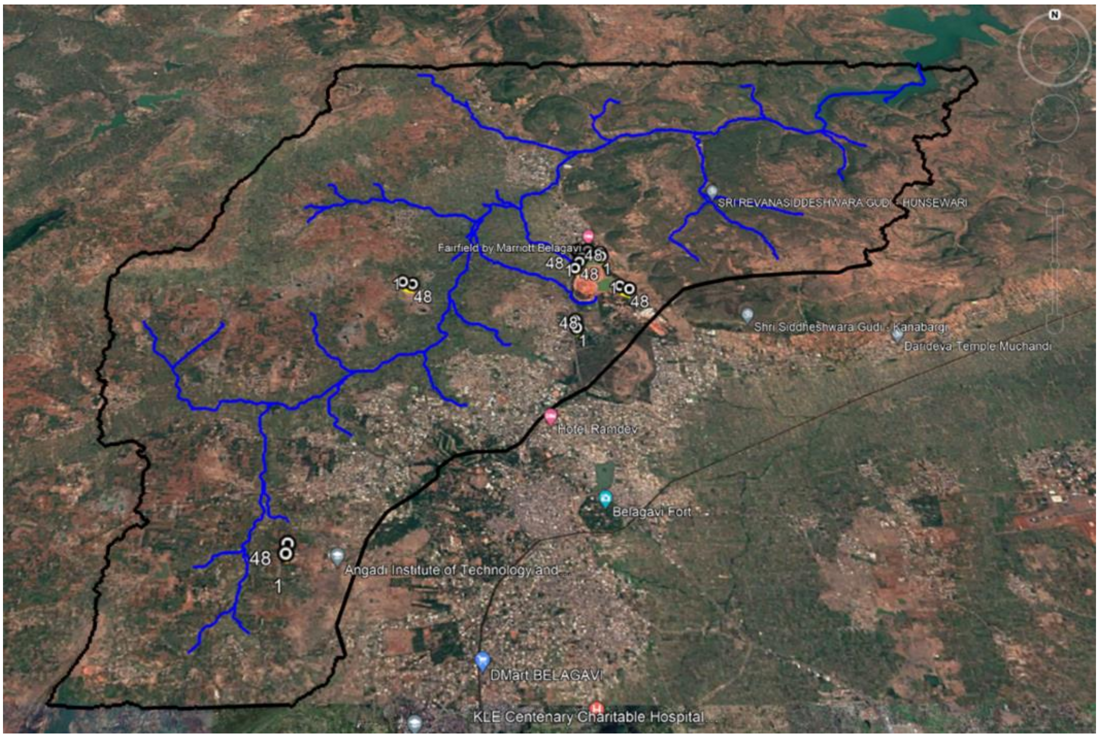


**Fig.2 Location of the ERTs and watershed map**

4.2. Flow and Mass Transport model construction:

The groundwater flow mode has constructed covering entire study area 222 km$^2$ area. The model has been divided into 156 rows and 136 Columns (Fig. 3) with a grid size of 100 m$^2$. In and around Redmud pond, the grid size is around 10 m$^2$.

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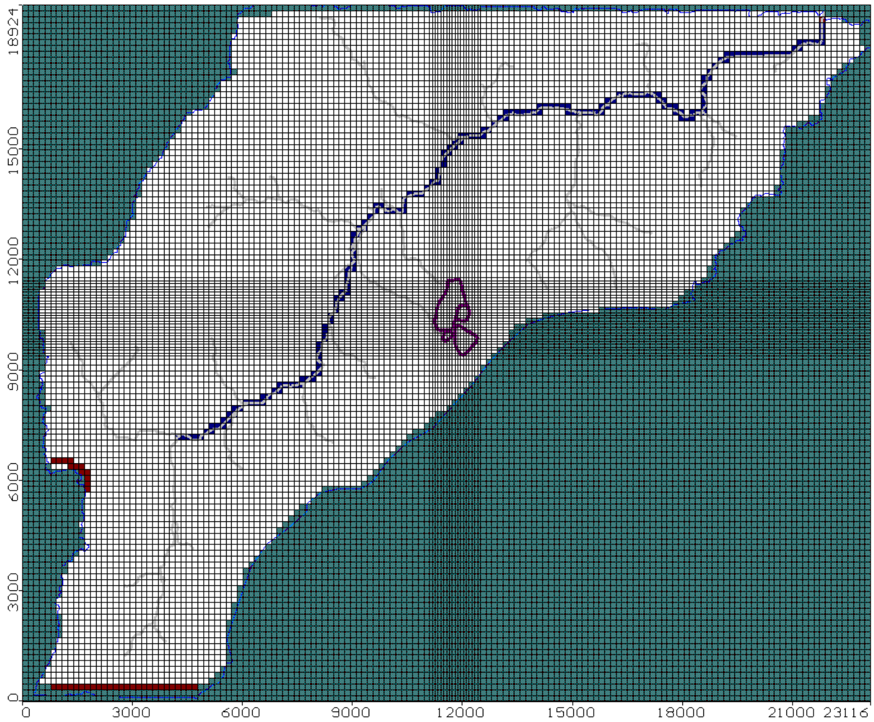


**Fig. 3 Spatial discretisation of study area for groundwater flow and contaminant transport modeling.**

*4.3. Boundary conditions and model calibration:*

The model is calibrated under steady state for the year 2005 using observed groundwater heads at 22 observation wells. The recharge is considered as 12% in annual rainfall, irrigation pumping is considered as 50 $m^3$/day/well throughout the simulation in the place of irrigated areas. During the model simulation and calibration process, model calibration is not improved with changes in recharge. Hence, recharge not changed during the simulation, only hydraulic conductivity is calibrated. The calibrated values are shown in figure 5.

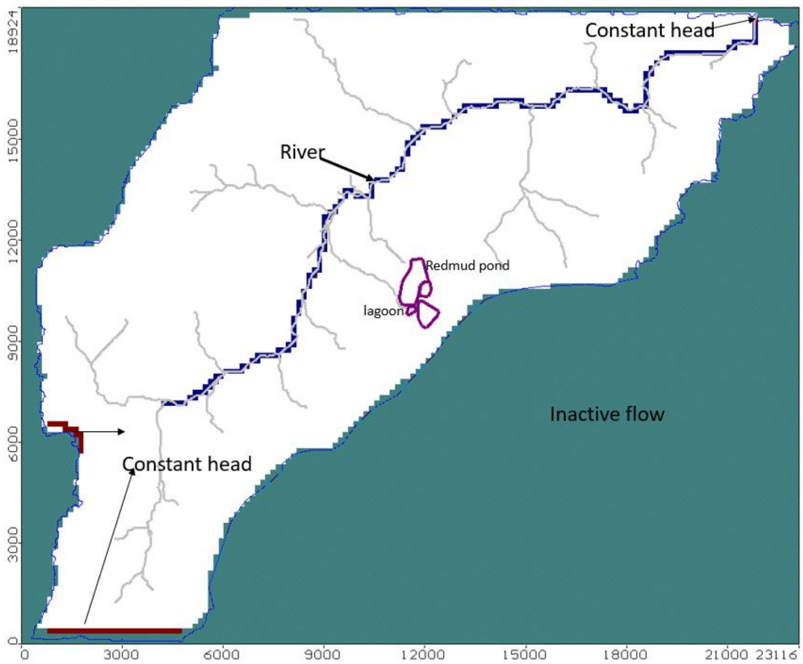


**Fig. 4 Boundary conditions assigned in the numerical model**

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No flow boundary has assigned beyond the watershed boundary. A river boundary condition is assigned in the place of river shown in Figure 4, the width and depth of the river is taken from google earth observation and it is static throughout the simulation. Constant head boundary condition is assigned to allow inflow form the upstream and outflow from the catchment, which matches with groundwater heads in the year 2005. Groundwater pumping is assigned with pumping well package (Fig.5). Groundwater recharge is considered 12% in the annual rainfall. For the steady state, year 2005 rainfall is considered, for transient the rainfall from the year 2005 to 2022 is considered. The groundwater for nonmonsoon season is considered zero. A total of 18 years, two stress periods for year is considered in the model as an observed/calibration period.

The subsurface of the aquifer/model is conceptualised based on ERT investigations, observed dug well cross-sections during the field work indicated that top weathered zone has a thickness of 15-20 m and it is underlain by a fractured layer of 20-30 m thickness (Fig.6). the model is conceptualised as two layers, first layer is about 15 m thick and second layer is 30 m thick. The hydraulic conductivity of the first layer is considered based pump tests carried out in the previous study at three locations, the conductivity ranges from 0.1 to 2.0 m/day. The upstream of the study area calibrated as 0.5 m/day for the study area, in the middle of study area where more saturation prevails, the hydraulic conductivity is calibrated as 2.5 m/day. For the second layer the computed conductivity as 1.2 m/day. For the contaminant transport modelling, a constant concentration is assigned in the place of redmud ponds based on the analysis of water quality during the year 2005, the concentration is 11820 mg/l and 8600 mg/l on the groundwater surface.

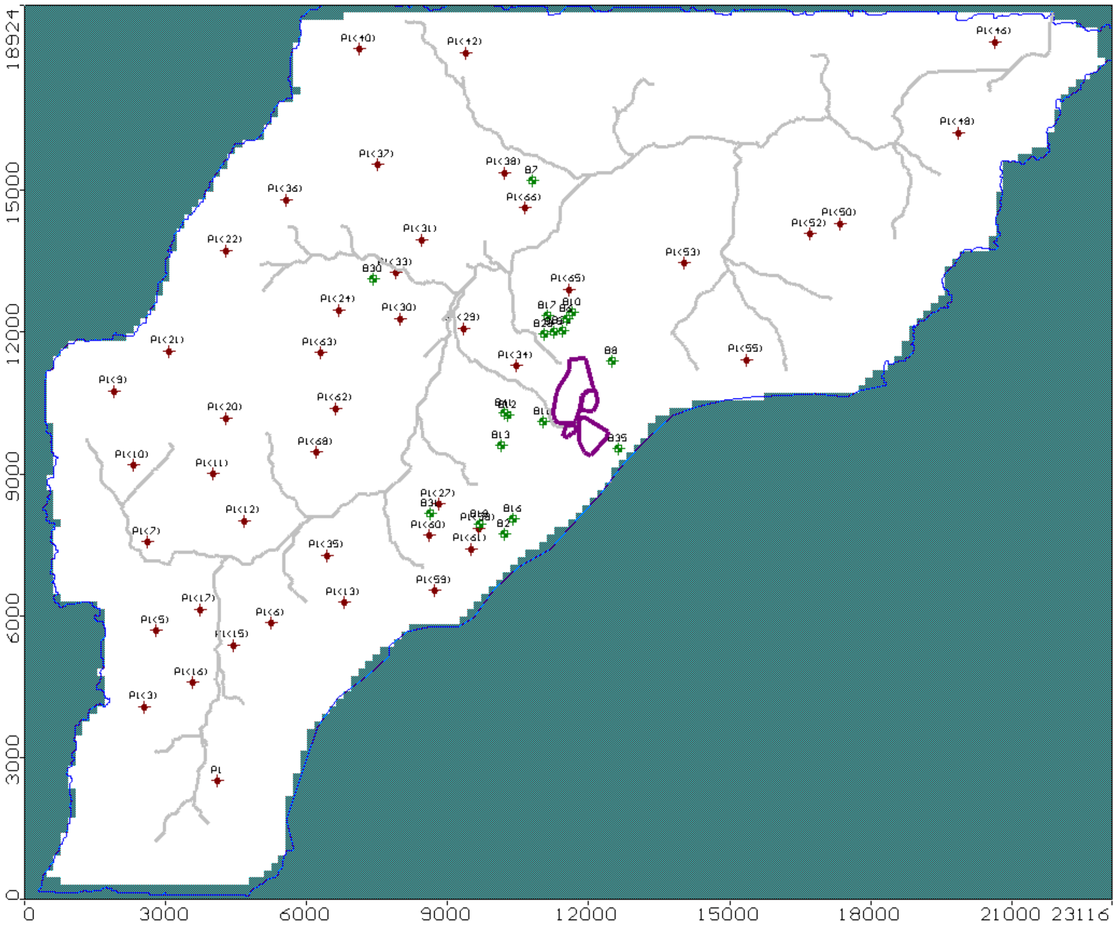


**Fig.5 Lcoation of pumping wells and observation wells in the numerical model.**

Figure 7 is shows observed and computed groundwater heads, it shows that fifteen wells fall in 95% confidential interval. The model calibration is also show that correlation coefficient is 0.96, RMS error is 4.8 m and N RMS is 11.98. The well calibrated model is validated with recent observed groundwater levels of the year 2022. Then it is observed the model RMS is 3.5 and correlation coefficient is 0.97, hence model is considered as reasonability calibrated.

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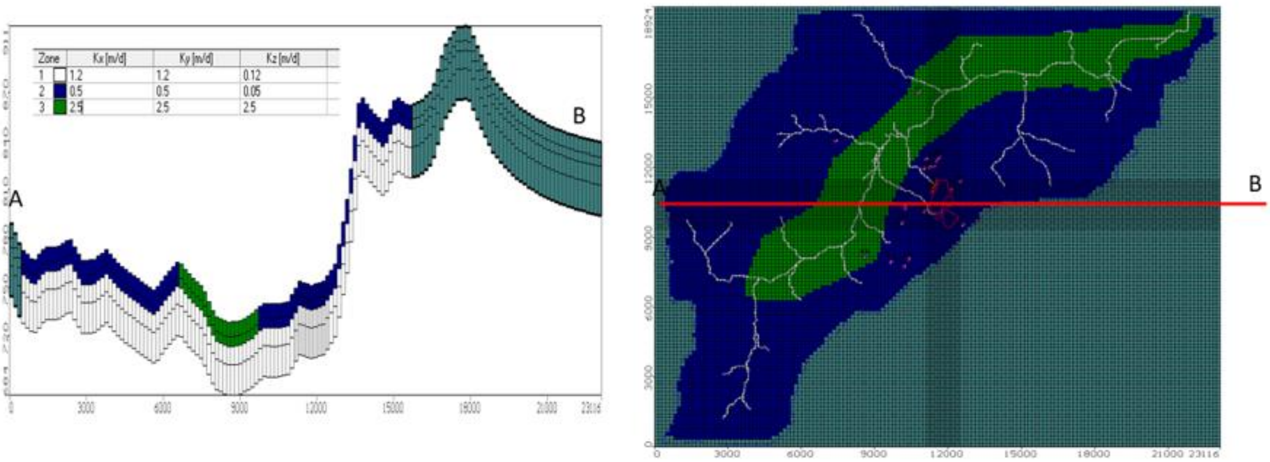


**Fig. 6 Distribution of hydraulic conductivity in the study area**

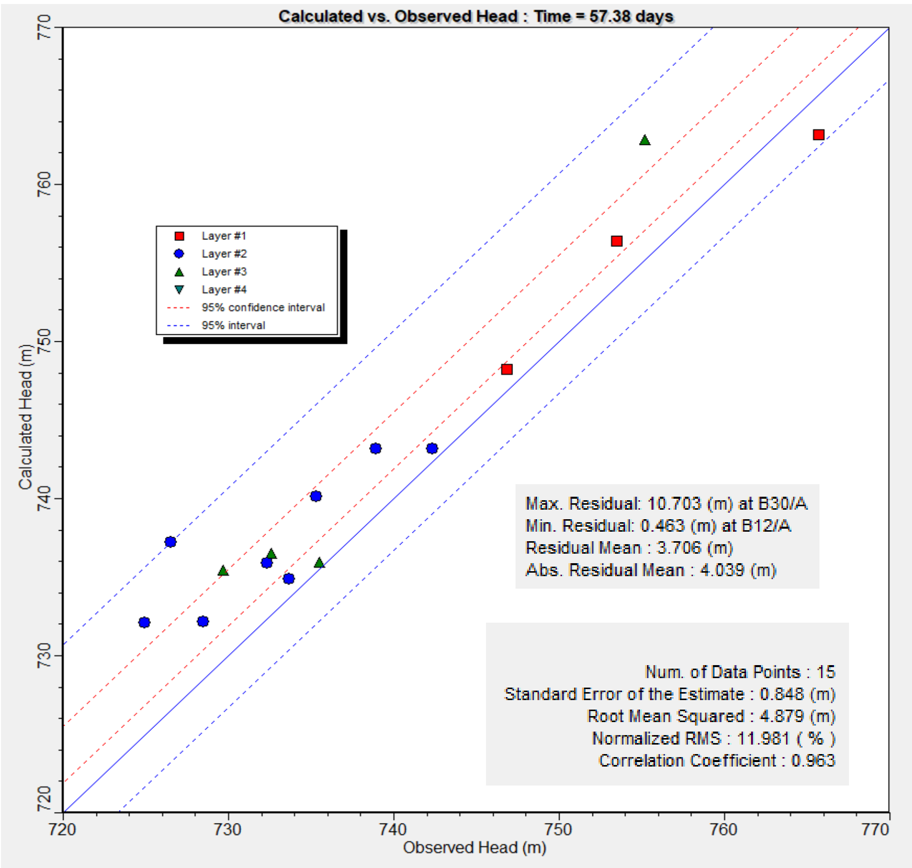


**Fig. 7 Observed and computed groundwater heads for the study area**

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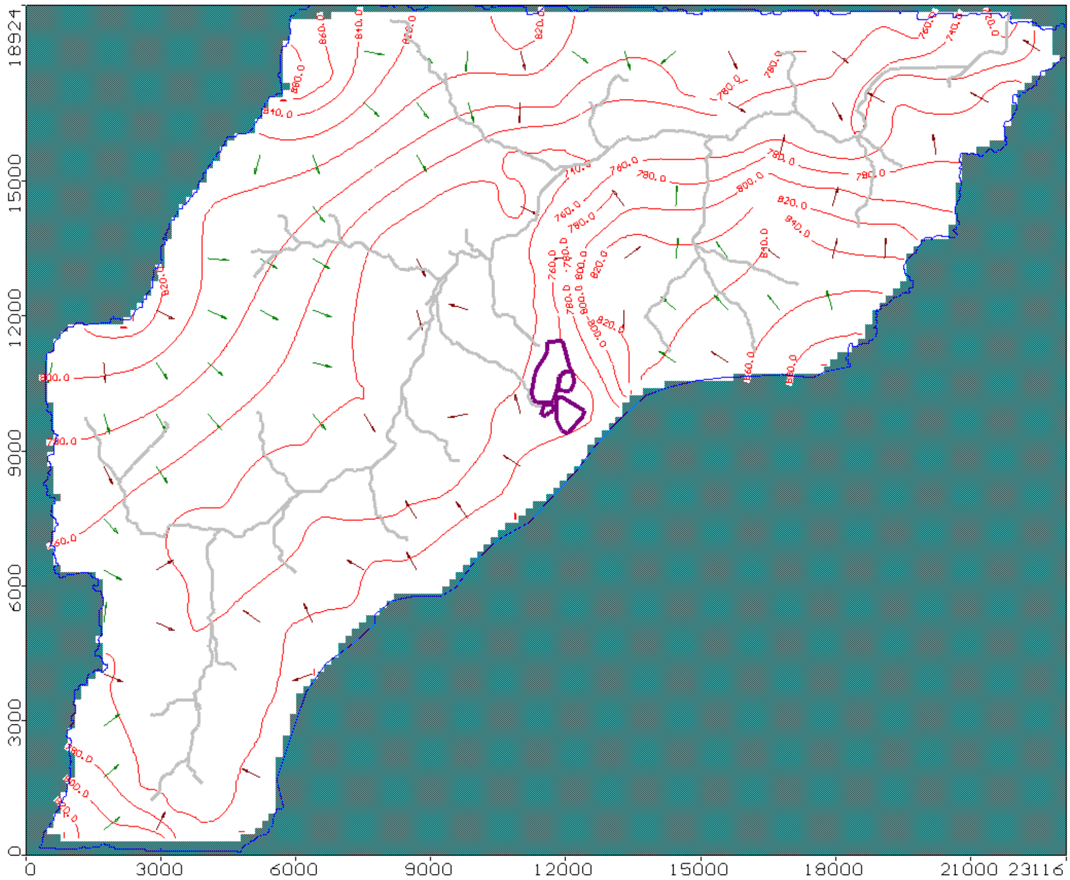


**Fig. 8 Computed groundwater contours and flow direction in the study area**

Figure 8 shows that computed groundwater elevations and velocity vectors (groundwater flow direction) for the first layer extended upto 6 m depth. The maximum groundwater elevation ranges from 770 m amsl to 720 m amsl. The preferential groundwater flow direction toward stream, the groundwater flow direction from the HINDALCO redmud pond show that toward North-West where public water body is existed. The model also indicated upstream part is dried due to high topographic elevations. The model computed that maximum groundwater velocity in the first layer is 0.85 m/day.

Figure 8 indicated groundwater flow direction toward streams and it is ranges from 800 m amsl to 720 m amsl at the depth of about below 15 m. The figure also show that the entire layer is saturated. The maximum groundwater flow direction in the layer 3 is 0.54 m/day (Fig.7).

*4.4. Groundwater Flow and Mass Transport Models:*

The computed contaminant transport spatial distribution is show in Figure 9 from the year 2005 to 2050. These maps shows that concentrations with groundwater flow direction shown in arrows, this clearly indicated that contaminant migration is towards public water body. The maps also shown that in the year 2005 seepage might have started from redmud ponds, by the year 2015, the contamination has moved beyond the highway with TDS around 5000-6000 mg/l, by the end of 2020, more concentrated plume has reached downstream.

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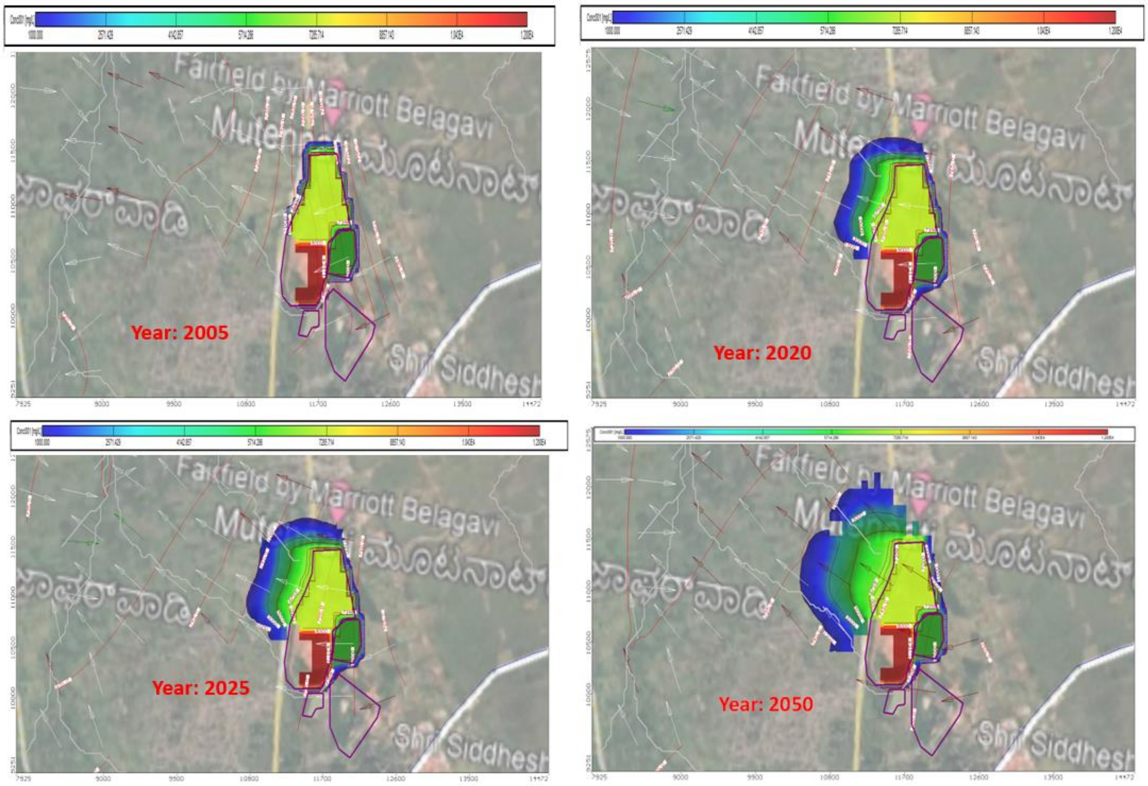


**Fig.9 Simulated contaminated transport in the study area**

These concentrations transport phenomina in the vertical direction/depth wise also have analysed, these maps were shown below, these maps shown that higher concentrations of contamination are restructured to upto 7 m depth, at the deeper depths the concentration is less than 2000 mg/l. The findings of the simulated groundwater flow and contaminant transport model reveal a concerning trend: the predominant groundwater flow direction is towards a public water body originating from the Redmud Pond, located downstream of Hindalco's industrial complex. This observation underscores the potential risk of groundwater contamination spreading towards vital water resources. The Redmud Pond, a byproduct of industrial activities, serves as a potential source of contaminants, which can leach into the groundwater and migrate downstream. The model indicates that the major flow pathways align with the natural topography, directing groundwater towards streams traversing the entire watershed. This pattern of groundwater flow raises significant environmental and public health concerns. Contaminants from industrial activities, such as heavy metals and other pollutants, may infiltrate the groundwater, posing risks to aquatic ecosystems, drinking water sources, and human health downstream. Furthermore, the proximity of the predominant flow paths to streams heightens the likelihood of contaminant discharge into surface water bodies. The interconnected nature of groundwater and surface water systems underscores the need for comprehensive management strategies to mitigate potential contamination risks.

Effective monitoring and remediation measures are imperative to safeguard the integrity of both groundwater and surface water resources. Regulatory authorities, in collaboration with industries like Hindalco, must prioritize proactive measures to prevent and mitigate groundwater contamination. This may include implementing robust containment measures at the Redmud Pond, enhancing wastewater treatment processes, and establishing buffer zones to protect sensitive water bodies.

Additionally, stakeholders should invest in ongoing monitoring programs to track groundwater quality and identify any emerging contamination trends. Such proactive measures are crucial for maintaining the ecological balance of the watershed and ensuring the continued availability of safe drinking water for surrounding communities.

In conclusion, the simulated groundwater flow and contaminant transport model highlight the urgent need for proactive intervention to address the potential risks posed by industrial activities to groundwater and surface water resources.

## 5.0 SUMMARY AND CONCLUSIONS

Groundwater depths vary from 1.2 m below ground level (bgl) to 25.8 m bgl in the study area. Deeper groundwater levels were observed in upstream and higher elevated areas. Elevations range from 716 m above mean sea level (amsl) to 768 m amsl. The pH of red mud ponds indicates an alkaline nature with high electrical conductivity (> 3000 microsiemens). However, electrical conductivity (EC) in all other groundwater samples falls within the prescribed limits of BIS drinking water standards.

Contours of major ion concentrations in groundwater are shown from Figure 8 to Figure 19. Higher Total Dissolved Solids (TDS) are observed around the red mud ponds. Elevated TDS levels are also noted downstream at one location, attributed to domestic pollution leaching from sewage. Apart from this downstream location, concentrations at all other sites are within BIS drinking water limits.

In most instances, hard formations are encountered at depths greater than 18 m bgl, with resistivity exceeding 500 Ohm.m. Weathered basalt is found at depths ranging from 12 to 18 m, indicated by resistivity values of 60-150 Ohm.m. Saturation of water is identified primarily at 12 m depth, with resistivity values ranging from 1-5 Ohm.m. Contaminated aquifer/subsurface areas are detected with resistivity values below 1 Ohm.m, found at depths up to 3 m in the northwest and west sides of the red mud pond. In the northwest corner of the red mud pond, contaminated water is observed accumulating up to a depth of 27 m due to seepage from the red mud pond.

In summary, the simulated groundwater flow and contaminant transport models indicate that the predominant groundwater flow direction is toward a public water body downstream of the Hindalco red mud pond. The major groundwater flow also moves toward streams throughout the watershed. By implementing comprehensive management strategies and fostering collaborative efforts among stakeholders, it is possible to safeguard the environmental integrity and public health of the affected watershed.

## ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Geospatial and Environmental Solutions (GES) – Dharmavaram – Andhra Pradesh for providing office space to work on the current project.

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*Cite this Article: A. Mounika, L. Surinaidu, C. Kumar (2024). Modeling Contaminant Transport from a Red Mud Pond – A Case Study from South India. International Journal of Current Science Research and Review, 7(7), 5024-5035*