NUMERICAL MODELLING OF GROUNDWATER FLOW IN MEDIPALLI OPEN CAST MINE AREA, TELANGANA, INDIA

Major Project Thesis

Submitted by

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CERTIFICATE

This is to certify that PARSA SANTHOSH MADHAV CHANDRA has carried out his major project in partial fulfillment of the requirement for the degree of Master of Science in Environmental Studies and Resource Management on the topic "NUMERICAL MODELLING OF GROUNDWATER FLOW IN MEDIPALLI OPEN CAST MINE AREA, TELANGANA, INDIA" during January 2017 to May 2017. The project was carried out at the National Institute of Hydrology, Roorkee.

The thesis embodies the original work of the candidate to the best of our knowledge.

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This is to certify that the work that forms the basis of this project "NUMERICAL MODELLING OF GROUNDWATER FLOW IN MEDIPALLI OPEN CAST MINE AREA, TELANGANA, INDIA" is an original work carried out by me and has not been submitted anywhere else for the award of any degree.

I certify that all sources of information and data are fully acknowledged in the project thesis.

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LIST OF ABBREVIATIONS

Amsl	Above mean sea level
ANN	Artificial Neural Network
CHD	Constant Head package in Visual MODFLOW
CWC	Central Water Commission
EPM	Equivalent Porous Medium
GEC-97	Groundwater Estimation Committee-1997
GMS	Groundwater Modelling Systems
GRAM	A semi-distributed mass-balanced model for systems
GUI	Graphical User Interface
IMD	Indian Meteorological Department
MAE	Mean Absolute Error
ME	Mean Error
MOCP	Medapalli Open Cast Project
MODFLOW-88	Modular three-dimensional finite difference Groundwater Flow model
MODFLOW-NWT	Modular three-dimensional finite difference Groundwater flow model with Newton-Raphson Solver
MODFLOW-USG	Modular 3D finite difference groundwater model for Unstructured grids
MT3DMS	Modular transport, 3D Multi species model
RCH	Recharge Package
RMSE	Root Mean Square error
SE	Standard Error
SCCL	Singareni Collieries Corporation Limited.
TDS	Total Dissolved Solids
TVD	Total Variation Diminishing method
VSS-NET	3-D model pipe networks routed through variably Saturated porous media.

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ABSTRACT

Sustainable groundwater management is a worldwide challenge. Numerical modelling is one such tool which addresses this challenge. Regional scale modelling of groundwater flow is necessary for planning and management of groundwater resources. The aim of the study is to numerically model the groundwater flow in Medapalli Open cast block area. Medapalli Open Cast Block is a coal mine operating under Singareni Collieries Company Limited SCCL in Telangana, India. It is spread across and lies near river Godavari. The observation well locations and depth to water level data are collected from SCCL. A finite-difference based groundwater flow model is developed in Visual MODFLOW using MODFLOW-2005 code with forty conceptual layers and with a total thickness of 240 m. The model is constructed based on the geological and spatial data of the study area. The model calibration is performed at steady state conditions through trial and error method. In addition to this, a solute transport model is developed using MT3DMS code at steady state conditions. The results indicate that the computed water table values fairly match the observed water table values and the simulated flow direction is towards the river Godavari, in accordance with the field conditions and following the general topography of the region. The solute, i.e. (TDS) migration extends up to a maximum distance of 168 m along the periphery of Medapalli open cast block towards the river. The study shows that the impact of fly ash deposition in Medapalli Open cast mine on the groundwater quality in the vicinity of the open pit will be very less and no harmful effects will be observed as the contaminant levels decrease steeply along the periphery of the mine and concentration of the plume is reduced sharply.

Keywords: Groundwater flow Model, Visual MODFLOW, Medapalli Open Cast block, solute transport, Numerical modelling

Chapter 1: Introduction

Groundwater is a valuable resource available for mankind catering their industrial, agricultural and domestic needs. Groundwater in a system is dynamic in nature and never at rest. The volume of groundwater varies due to various recharge and discharge options, resulting in fluctuation of water table. Hydrological equilibrium is attained over a long period when average recharge equals average discharge and change in hydrological equilibrium due to various anthropogenic activities results in undesirable side effects (lowering of water table, contamination of groundwater & aquifer depletion) leading to unrest in distribution, movement and occurrence of groundwater. Intensive developments in industrial and agricultural areas in past decades has had large impacts on groundwater settings, especially on a regional scale, in which use of the resource varies. Evaluating hydrologic response to human induced problems is very complex involving various factors like geological properties, input and output stresses and climatic variability. Advancements in tools and techniques used for groundwater extraction facilitated wider use of groundwater leading to higher abstraction rates and depletion. To reduce groundwater overdraft, a conceptual understanding of aquifer behavior to induced hydraulic stresses is required. Groundwater models provide deep insights into the complex system behavior and (when appropriately designed) can assist in developing conceptual understanding (Kumar, 2015). Although, constant observation of these factors gives us a conceptual understanding about the rapidly changing functionality of the system, a ground water model reduces the uncertainties, spatial heterogeneities and increases the approximation towards real world conditions. A model may be defined as a simplified version of a real-world system (here, a groundwater system) that approximately simulates the relevant excitation-response relations of the real-world system (Bear Jacob, 1992). It is simply a replicate of field conditions. Groundwater modelling involves simulation of groundwater flow through mathematical representation of physical processes that occur in a system through a governing equation and equations that describe initial (time-dependent) and boundary conditions. Boundary conditions are mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at boundaries of problem domain. (Anderson). The fewer the simplifying assumptions, the higher the complexity. The assumptions here are related to the geometry of investigated domain, nature of porous medium, fluid properties and flow regime. A groundwater flow model calculates groundwater heads and flow rates across the system domain and even on the boundaries. A solute transport model calculates the amount of dissolved substances in groundwater. Groundwater models can be used to calculate water and solute fluxes between the groundwater system under consideration and connected source and sink features such as surface water bodies, pumping bores and adjacent groundwater reservoirs

One of the complex applications of groundwater modelling is open pit mines, where groundwater flow in an aquifer subjected to numerous stresses created by deep mining process is being modelled. Aquifer system under mine area is generally heterogeneous in nature with varying hydraulic properties emerged due to fissures, pit lakes and mine voids. A natural understanding about the geology of the study area is required to effectively characterize complexities associated with open pit mines. This is achieved through numerical modelling. Numerical models can be a powerful tool to solve the number of groundwater related problems associated with mining and mine closure (Surinaidu et al. 2014) . To generate accurate results through numerical models developed to simulate groundwater properties in mining environments, it is important to prepare high standard datasets regarding aquifer properties and flow dynamics of the system. Choosing the right approach for modelling depends upon the scale and heterogeneity of the region. In porous media settings, an understanding of geologic heterogeneity along with knowledge of how system works is critical for appropriate conceptual or numerical modelling. The key factor in analyzing flow field is the degree of interconnectedness and this factor has to be addressed to enhance predictive simulations. Updated models like SEEP/W helps in addressing this factor. The realistic description of heterogeneity and anisotropy of hydraulic parameters is a general problem of groundwater modelling applications, solved through model calibration and validation (Rapantova et al., 2007). Groundwater Models are useful in simulating groundwater flow scenario under different management options and thereby taking corrective measures for sustainable use of water resources through conjunctive use approach. (Mohanty et al ., 2013).

Surface mining, however exerts an undesirable effect on the environment in general and groundwater. The impact of mining on groundwater should be studied both qualitatively and quantitatively. The qualitative impact is indirect and is mostly due to waste generated through coal conversion processes and disposal of such waste in old open pits. Hydro geochemical analysis of groundwater is an important qualitative approach to study the dynamic movement of pollutants in groundwater system. Fly ash is a key waste generated through many industries and this is filled in open cast mines. A major difficulty of disposing such major qualities of ash is the possible leaching of pollutants into surface and groundwater. (Prasad and Mondal, 2008). Solute transport models are appropriate tools to simulate the concentration heads and develop management strategies by predicting future transport scenarios.

1.1 Purpose of the study

The purpose of the study is to numerically model the groundwater flow in Medapalli Open cast mine area and assess the impact of fly ash deposition in the open mine pit on the groundwater quality in the vicinity of the open mine pit

1.2 Objectives of the study

To carry out groundwater flow modelling in Medapalli Open Cast block area, the objectives of the study area are as follows:

- ✓ To analyze the groundwater levels in the study area
- ✓ To model the groundwater flow through numerical simulation in the study area.
- ✓ To assess the impact of fly ash deposition on groundwater quality in the study region.

Chapter 2: Literature review

2.1 General

A groundwater model is the simplified version of a field situation, here a groundwater system. There are two types of groundwater models, physical model and mathematical model. Physical models represent physical processes in a smaller scale (ex: laboratory sand tanks) and simulate ground water flow directly. A mathematical model describes the processes boundaries of a system through a governing equation subjected to boundary conditions to simulate the groundwater flow. Initial conditions are required for time dependent models. Mathematical models are solved wither analytically or numerically. An analytical model makes simplistic assumptions (Ex: a homogeneous porous medium) to solve the given problem. Here the space and time are considered as continuous entities and can be solved without computer too. A numerical model involves discretization of time and space facilitating varying model input parameters. This helps in representing a complex system in a realistic way. Numerical Models require more computation time than analytical models and are solved using computers only. Significant advances in groundwater flow analysis were driven with the introduction of MODFLOW, a model code used to simulate groundwater heads and flow directions. MODFLOW was first released in 1988 as MODFLOW-88 (McDonald and Harbaugh, 1988) and was later upgraded to MODFLOW-2000(Harbaugh et al., 2000) and MODFLOW-2005 (Harbaugh, Arlen, 2005). To simulate solute transport, codes like MT3DMS (Zheng, 1990) were introduced which helped hydrologists to model groundwater contamination. Several Graphical User Interfaces (GUI's) were developed to integrate MODFLOW codes. The most widely used GUI's are Visual MODFLOW (Hydrogeological, 2001), Processing Modflow (Chiang and Kinzelbach, 2001), Groundwater vista (Rumbaugh and Rumbaugh, 2005) and Groundwater Modelling systems (GMS). These user interfaces helped in ease of modelling process and enabled use friendliness with model codes. The application of GIS for model building and visualization, facilitated wide use of these interfaces to model large and complex groundwater systems. Open pit mines constitute exhibit complex geological characteristics and careful analysis is required to replicate such conditions.

2.2 Groundwater Modelling using Visual MODFLOW

Varalakshmi et al. (2014) investigated the long-term effects of pumping on groundwater in hard rock aquifer using Visual MODFLOW. Groundwater recharge is estimated using GEC-1997 methodology and the estimated values were used to simulate the model.

Field et al. (2017) proposed an integrated approach coupling ArcGIS and 3D finite difference model using Visual MODFLOW to simulate groundwater flow in context of developing sustainable groundwater management plan. The effect of recharge, hydraulic conductivity and steam bed conductance were tested during sensitivity analysis and results indicated that recharge is more sensitive compared to others in this well field with limestone formations. Lack of data reflected in poor characterization of physical system with many assumptions and simplifications. A proper data set is necessary for effective representation of groundwater flow in physical systems.

Mohanty et al. (2013) simulated groundwater levels in Kathajodi-Surua inter basin, Orissa using a finite difference based Visual MODFLOW coupled with Artificial Neural Network (ANN) model. The simulated groundwater heads by Visual MODFLOW and ANN models were compared and ANN provided better predictions. Explicit characterization is required for numerical models, unlike ANN which works on limited parameters obtained as a function of discrete boundaries. Numerical models reflect complete water balance of the system, whereas ANN models do not provide the entire dynamics of the system. Associated changes in input values of parameters in ANN models leads to complete model rebuilding. This study found out that ANN models should be used in predicting short term effects whereas numerical models should be considered for long term effects.

Woodward et al. (2016) highlights the challenge of collecting field data and power of modern calibration tools coupled with uncertainty techniques to assess groundwater flows in small scale systems. A groundwater flow model was developed using MODFLOW-NWT code and is simulated at transient state conditions. Uncertainty analysis revealed that high resolution water head data and slug test results were not sufficient to determine the spatial patterns of hydraulic conductivity at complex sites. This informative data turned out to be insufficient to accurate solutions. This study proved that Null space Monte Carlo analysis, an uncertainty assessment technique is a robust tool to calibrate and predict hydrological models.

Weiss & Razem (1984) states that the numerical models have helped to estimate values of hydraulic properties, identify the sensitive parameters and provide quantitative descriptions of the groundwater budget. A quasi three-dimensional finite difference model is developed to simulate groundwater flow in a mine block undergoing strip mining for coal.

2.3 Mass transport Modelling using Visual MODFLOW

Gurunadha Rao et al. (2001) states that the extension of pollution in groundwater is due to heavy pumping of water for irrigation which attributed to seepage from a stream due to stream aquifer interaction thus carrying surface water effluents to groundwater. Groundwater contamination in and around Medak Industrial area is studied using mass transport model developed in Visual MODFLOW using MT3DMS code. Due to absence of major surface water sourced in the industrial area, the dependency on groundwater is high leading to greater exploitation of contaminated groundwater in the area. TDS Concentration is computed for a fixed period of two years. The results outlined that the plume is expanding in the sub surface region along the hydraulic gradient, indicating that advection is the dominant mechanism of spreading. Divergent flow patterns were produced in the model due to inaccuracies in simulation caused by undermining the complex nature of the study area.

Gurunadha Rao & Gupta (2000) studied the contamination of water supply well in Sabarmati river bed aquifer using mass transport modelling. Groundwater heads are simulated in Visual MODFLOW and these heads are used to calculate groundwater velocities using porosity values in MODPATH code. The velocity filed generated is coupled to mass transport model using MT3D code. It was noticed that velocity field is highly sensitive to porosity values and any variation in porosity value results in change in velocity field. While conducting transport modelling in a river bed aquifer, it is important to create a database with precise porosity values.

2.4 Groundwater Models in Mining Areas

Liu et al. (2007) presented a two-dimensional model to simulate and predict mine discharges in Sanshando Gold Mine. Finite Element Method was used to simulate the model and all finite element equations were solved by large non-symmetrical sparse equation. This mine area comprises of a water bearing zone where recharged water pathway and groundwater discharge coexist and taking this zone into account, model was established. An inverse model approach was used to calibrate the model and estimate hydraulic parameters. Numerical Modelling of this area explains the inverse proportion between mine depth and recharged water. As mine depth increases, recharged water increases linearly due to increased drawdown of seawater in the area. This model was used to understand the effects of different factors such as unsteady flow (caused by brine), impervious base depth of water bearing zones and grouting effort. The established model could not forecast an unsteady discharge.

Fernández-Álvarez et al. (2015) developed a groundwater model to numerically simulate the complex hydro-geological conditions in an open pit limestone block. MODFLOW was used to simulate the model in both steady state and transient state conditions. An equivalent continuum approach was applied to integrate spatial scale to entire formation, replacing fractured aquifer. Three practical scenarios were simulated such as multiple iterations with varied input values for recharge and evapotranspiration and partial channeling. Model calibration in this study suggested construction of a new zonation of permeability with respect to degree of fracturing in aquifers. This model renders a quantitative framework to evaluate new operations economically.

Yeh (1981) states that continuous velocity field is required to simulate contaminant transport in sub surface aquifer. Continuous velocity fields are generated to eliminated the problem of discontinuity in simulation and to reduce overall mass balance error in a region. Finite element modelling was used to generate this velocity field subject to initial and final boundary conditions. Two sample problems (Seepage pond problem and Freeze transient problem) were considered and result estimates shows us that central difference Galerkin scheme yielded best results.

Sperling et al. (1992) states that optimal slope angle and groundwater control strategies are two important phenomena's to be considered in an open pit mine at developmental stage. This paper documents a series of case studies where economic analysis, numerical modelling and Monte-Carlo simulation are performed one by one to meet the risk-cost-benefit objective function in designing best groundwater control system in an open pit mine block. Finite Element Modelling was used, coupled with equilibrium slope stability model. This coupled model was computed through Monte-Carlo simulation to calculate risk associated and yield optimal groundwater strategies, enhancing safety and reducing cost.

Soni & Manwatkar (2015) performed seepage modelling for Medapalli Open cast project (MOCP). The purpose of the study was to document seepage occurrences at working faces of MOCP high-wall mining areas. Seepage predictions were carried out using a groundwater model characterizing the complex hydro-geologic conditions in mine area. SEEP/W module of Geo-studio software is used to simulate results in both steady and transient state conditions. Later these results are compared and verified with MODFLOW. Seepage analysis is reported with the help of VWC-pore pressure graphs which outline the water content in coal seams subjected to pore pressure.

Choubey & Shankaranarayana (1990) conducted hydraulic investigations in Jayant block of Singrauli coal field to evaluate aquifer behavior and characteristics. Pumping tests were conducted to calculate hydraulic parameters and identify recharge boundaries. Results indicated that Groundwater levels with 5-7km cut are affected due to surface mining and water levels will be decreasing with increase in cut depths. This paper concluded that water wells must be constructed only in confined aquifer, not in unconfined.

Fitts (2010) presented a new approach for analytic element (AE) modelling of groundwater flow. This type of modelling is important for regions with anisotropic media that are also heterogeneous in ratio and direction. Such anisotropic variations are important factors in seepage analysis in open pit mines. In this approach, modeled region is divided into polygonal subdomains, each having their own flow and aquifer parameters. Fitts compared this model to MODFLOW and extracted similar results with respect to spatial and temporal variation.

Brown & Trott (2014) summarized common shortfalls in approach to models in open pit mines as insufficient a) insufficient hydro-geological investigation b) lack of conceptualization c) the one mathematical model approach d) Unnecessary complexity in models. Every hydro-geology practitioner needs adaptive tools that allow instant decision making and less time consuming. Strategies should be developed in order to choose "the right tool for the job". This paper proposed a new alternative model, named analytical superposition model which works on solution superposition for analytical functions. An open pit mine is selected to test the suitability of this approach. Model is conceptualized with the help of AQTESOLV interface (Duffield, 2007). A new model is constructed with same conceptualization and is simulated numerically through MODFLOW. Results from both the software's are compared and are found to be identical resembling actual field conditions in a much better way. Analytical superposition modelling is neither time consuming nor costly, but "Is it ergonomic?"

Prasad & Mondal (2008) investigated the impact of filling an open cast mine with fly ash on groundwater quality. Coal ash is produced in large quantities in India and is generally deposited in abandoned open pit coal mines or underground coal mines. The major problem with this deposition is leaching of potential harmful contaminants into groundwater, creating a significant problem for environment. An abandoned open pit is selected where fly ash is filled and groundwater samples are collected at different sampling points through bore holes. All the physio-chemical parameters are calibrated using standard procedure. This study concludes that quality of groundwater, about a half kilometer away from mine contained metal concentrations which were quite different from the samples obtained from the mine point. Groundwater quality at the boundary of ash filled zone is slightly affected whereas at 500m away from ash-filled zone, groundwater quality is within standards.

Bair & Parizek (1981) used a modified finite difference model to simulate water table changes in an open pit coal block. Modifications to finite difference model were made to impart all complexities associated with the open pit mine. The established model was calibrated for both steady state and transient state conditions. Results of the model indicate that water levels will be lowered. i.e. a cone of depression will be developed in eight years. The advantage of numerical models is that they can model complex flow systems with varying stresses imposed on it and this advantage is appealing to all, looking for solutions in groundwater problems.

Bair & O'Donnell (1983) developed a numerical model to aid designing and licensing of dewatering systems in mine area. This process is carried out by approximating the total quantity of water inflow rate and invoke into a constant-node network located around the boundary of the mine area and assigning different hydraulic head to each node. This helps in identifying the decrease in inflow rate of the flow system under transient state conditions. This study concluded that site specific data such as geologic settings, hydraulic parameters and boundary conditions are essential inputs to numerical models in simulating and predicting scenarios which facilitates optimal dewatering strategies. Sites with simple geologic setting do not require the services of numerical models as they are costly and time consuming, but numerical models are highly useful tools for complex geological settings like open pit mines.

Aryafar et al. (2009) used SEEP/w software to simulate groundwater recovery processes in artesian wells located at Sangam iron ore in Iran. SEEP/W was used to model the study area in saturated and unsaturated conditions. Model is calibrated with both steady state and transient state conditions. Results extracted from this numerical model are compared to those derived from analytical theis equations to check the accuracy with respect to the observed/field data. This study found out that post-mining lake formations occur at a rapid pace immediately after mine closure. This rapid formation occurs due to difference in hydraulic heads occurred through dewatering strategies.

Martinez & Ugorets (2010) states that groundwater inflows into open pits create significant impacts on environment. An open pit coal block is selected with underlying aquifer divided into two different units, gravel and deep sandstone separated by a shale unit. A Groundwater Model is constructed using MODFLOW-SURFACT code to simulate hydraulic heads in the specified open pit mine. This study emphasizes on the importance of vertical hydraulic gradients in constructing a model. The established 3-D groundwater model can be used to predict indirect inflows to mine (spatial and temporal) and pore pressure, which is an essential input for slope stability analysis.

Bahrami et al. (2014) predicted groundwater inflows into an open pit mine using a finite element model called SEEP/W. This software was preferred over many important codes because of its ability to feature "conductivity function", which defines the relationship between pore pressure and hydraulic conductivity. SEEP/W can be used to simulate hydraulic properties in a heterogenous isotropic media. The inflow results simulated through this model were verified by comparing the output of analytical models (Jacob solution). Inflow response to pit elongation was studied using both numerical and analytical model, with not so accurate results generated from the latter one.

Surinaidu et al. (2013) proposed equivalent porous medium approach (EPM) to represent hydraulic heads and recharge-discharge relationships on a regional scale. A 3D finite difference model is developed through Visual MODFLOW, to assess groundwater inflows into Kuteshwar mines of limestone formation. The region is modelled using EPM to reduce irregularities in flow medium. The model is simulated by MODFLOW-2000 code and groundwater budget is estimated through Zone budget command. Recharge and hydraulic conductivity are two important parameters in calibrating the model, as change in inputs of these parameters could de-calibrate the model. This study indicated that quarry floor level and water table are controlling factors in estimating groundwater inflows. Numerical Modelling helps in developing a deep understanding about river-aquifer interaction in an open pit mine.

Libicki (1982) explains that factors such as depth of depression, geological structures of the region and their spatial disposition, filtration coefficients, specific yield and time play an important role in horizontal and vertical development of groundwater drawdown due to surface mining operations. In the study outlining the changes in groundwater due to surface mining, the author states that open pit mining, when performed under groundwater table results in serious hydrological imbalances in that area. The impact on groundwater due to mining should be studied both quantitatively and qualitatively. Modelling serves as an important tool in determining impact of coal refuse and coal disposal on groundwater quality, to determine movement of pollutant spatially and temporally and to evaluate and predict hydrologic response to different stresses induced on groundwater flow system by mine operations. This study concludes that changes in groundwater should be predicted at planning stage and remedial measures should be introduced to reduce the impact.

Krčmář & Sracek (2014) studied the importance of unstructured grids in developing a model to characterize geological uncertainties such as fault zones, fissures and open mine voids. MODFLOW-USG code was applied to model groundwater at Gbely lignite deposit to design a optimal dewatering plan. Unstructured grid approach was used to calculate flow in fault zones (disconnected cells), by connecting each cell in the grid by allowing the movement of water in all layers in the grid. This was not possible in classical MODFLOW approach. Pinching out of layer problem is also addressed by unstructured grids by including special options at the time of grid design. Replicating steep slopes in a model is a challenging task and this problem is reduced by using MODFLOW-USG thus eliminating the problem of numerical instability caused by difference in water levels in cells. This study gives us deep insights on "how to represent information correctly in a model comprising high complexities?".

Adams & Younger (2001) used different program codes based on the size of the region to model mine discharge in an abandoned mine. For smaller area, they have used VSS-NET program and for larger area, a semi distributed model GRAM is used to conceptualize interconnected volumes of waterbodies at discrete points. Traditional approaches like MODFLOW cannot be used to model mine areas with turbulent flow as they are specifically used to model laminar groundwater flow regions.

COOK (1982) emphasized on groundwater problems in open pit mines as consequence of limited data. Major water bearing zones are difficult to detect and it won't be possible to understand severe effects on permeability of major deformations. In this study, author states that pore-water pressure is an important factor in slope stability analysis and measures to depressurize groundwater in mine area can be predicted only through numerical models.

Qiao et al. (2011) studied the influence of coal mining on Karst aquifer systems in northern china. Hydro chemical analysis was performed to evaluate the groundwater quality of that region to check the presence of pollutants and the dynamic nature of pollutants in groundwater caused due to rock-water interaction, is simulated in a 3D groundwater model created in Visual MODFLOW. Inverse relation between mine discharge and hydraulic head was reflected in model results at an area with high concentration and a recharge zone. Multi aspects were not covered in this study. It is important to take different aspects of complex systems into consideration to generate a solid strategy for groundwater management and protection.

2.5 Summary

Various programs were used to numerically simulate groundwater flow in open cast mines. Numerical modelling of groundwater in mining is generally exercised to design dewatering systems, slope stability analysis, seepage analysis and to predict inflows in mines. Numerical models are perfect management tools which facilitate managerial decisions by solving complex problems associated with open pit mines. Although MODFLOW programs are widely used to simulate flow and transport in open pit mines, SEEP/W module gained wide acceptance in modelling groundwater in mining conditions. Research articles related to modelling of groundwater in open pit mines with various geological conditions are presented in this section and these papers exhibit the way of application of models to mine pits and stress on the analysis required for accurate characterization of the groundwater systems in open pit mines. In the view of suitability of MODFLOW and its usage worldwide as an industry standard technique, MODFLOW codes are used for this study.

Chapter 3: Materials and Methods

3.1 Study area

Medapalli Open Cast Project (MOCP) is a flagship coal mine of Singareni Collieries Company Limited (SCCL) aimed at producing 3million tons of coal per annum using Conventional shovel dumping method and High wall mining. This block covers 3.8 sq. km in Ramagundam Mandal of the Peddapalli district, Telangana. The study area lies between N Latitudes N $18^0$47'00" and $18^0$49'30" and longitudes E $79^0$28'00" and $78^0$30'00". The area experiences a typical sub-tropical climate with hot dry summer from February to June months followed by a good rainy season between July and October and a pleasant winter between November and January. This area receives 85% of annual rainfall during SW monsoon. The average rainfall varies from 620 mm to 1700 mm with a mean of 1097 mm. This area is well drained by Godavari river supported by small tributaries like Ralli vagu and Pedda vagu. Dendritic type of drainage is formed in this area with flow almost perpendicular to Godavari. The buffer zone of 10km radius from the boundary of MOCP has been demarcated and this zone covers an area of about 433.35 sq. km. The buffer zone comprises of undulating terrain, dotted with hillocks and intervening sand patches. The general topography of this buffer zone indicates that the surface elevation in the buffer zone varies from 220m amsl to 120 amsl. River Godavari passes through this area and northern side of the slope toward s the river and southern side slopes towards north east (i.e. towards the river). The areas adjoining river and mine are periodically flooded making it a flood plain of thick un-consolidated alluvium. Major Industries located in buffer zone are NTPC, Kesoram cement, ACC cement and Fertilizer Corporation of India, the depth to water level in this region varies from 0.50 m to 14.98m during pre-monsoon period and 0.50 m to 11.70 m during post-monsoon period. The attitude of phreatic surface in this area is monitored by SCCL in about 50 observation wells located inside the buffer zone. The core area (open cast mine area) has surface elevations ranging from 103 m to 145m and the distance between the core area and Godavari river is approximately 145m. This buffer area comprises of two urban settlements, Ramagundam and Mancherial where domestic consumption of groundwater is very high. In general land use classification indicates that agricultural land dominates the buffer zone followed by waste land and dense vegetation.

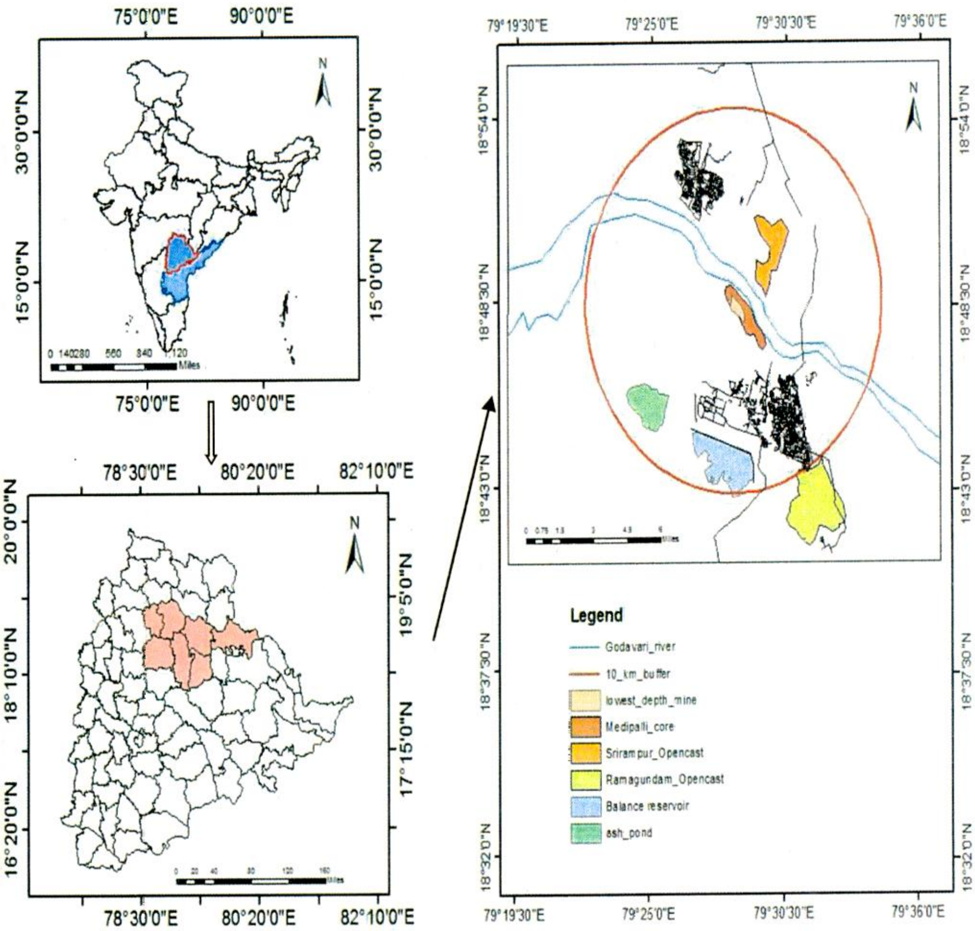

Figure 1: Location map of Medapalli OCP in Peddapalli district, SCCL, A. P

3.1.1 Geology of the Study Area

The Medapalli Open Cast block area is a part of Ramagundam Coal belt, located on the northern part of Pranhita-Godavari valley coal field, situated on the Precambrian platform. The Godavari valley extends over 470 km in strike length from Eluru on the east coast of Andhra Pradesh in the south east through the state of Telangana in the central parts up to Boregaon of Maharashtra in the NW (Bhaskar et al., 2015)and belongs to Lower Gondwanan group of rocks. The Medapalli Open Cast Project (MOCP) is located in the north-western extremity of Ramagundam Coal belt and the general striking of the block is NW-SE direction. The MOCP block lies between latitudes N $18^0 46' 52''$ to $18^0 49' 16''$ and longitudes E $79^0 26' 53''$ to $79^0 29' 57''$ and falls under Survey of India topo sheet No 56N/5 and 56N/9. The block is mostly covered by soil cover and alluvium up to a maximum thickness of 28.96 m and hence no structural features were observed. This soil cover is followed by Recent Permian Barren measures made up of coarse grained greyish feldspathic sandstones intercalated with multi colored clays and micaceous siltstone. A clay bed acts as a formational contact between upper barakar and barren measures. The upper barakar formation extends up to 184m which is made up of coarse grained white sandstone embedded with 8-10 coal seams further divided into upper and lower membranes. These formations are underlined by Talchir formations which are made up of fine to medium pale greenish sandstone with subordinate green shales extending up to maximum thickness of about 85m. The Sullavai group of rocks form the base of the formations, comprising of medium to coarse grained, white to red sandstones and quartzites. This group of rocks belong to Proterozoic age.

Table 1: Generalized Stratigraphy of Medapalli Opencast block (Soni and Manwatkar, 2015)

Age	Group	Formation	General Lithology	Maximum thickness (m)
Recent Permian	Lower Gondwana		Soil Cover and alluvium	28.96
		Barren Measures	Medium to coarse grained greyish white feldspathic sandstones with subordinate clays/siltstones.	25.91+
		Barakar	Upper Membrane: Coarse grained white/grey sandstones with coal seams	183.50+
			Lower Membrane: Coarse grained sandstones with subordinate clays/shales and few thin beds of coal	85.29 +
		Talchir	Fine to medium grained greenish sandstones, silt stones and shales.	83.40+
		----------------------Unconformity-------------------		
Proterozoic		Sullavai	Red and White banded, medium to coarse grained sandstone and quartzites	545

3.2 Methodology

The groundwater modelling process in exercised in many number of stages. Basic knowledge of the hydrogeology, excitation and responses in aquifer systems, flow dynamics and equations that describe flow and solute transport movement, numerical techniques to solve these equation and methods to check the reliability of models is required to start any groundwater modelling exercise. Appropriate site characterization is required for successful model application. The first step in ground water modelling process is preparing a data set, by collecting all the hydro-geological data. The quantitative data set should include data that defines the physical system of groundwater basin and the data that describe the various stresses the aquifer is subjected to. These data sets should be organized before using them to conceptualize the model. The conceptualization stage involves the development of grids that represent the hydro-geological system observed within the study area. These grids illustrate the direction of horizontal flow and vertical flow in the aquifers

The methodology used for the study is as follows

- Compiling groundwater data acquired from all sources (primary, secondary and literary sources)
- Studying topographical features of the region using topography map and Land use changes using LU/LC map.
- Compiling meteorological data and generation of hydrographs to study the trend of phreatic surface.
- Identifying sources of recharge and preparing ground water draft and ground water recharge.
- Groundwater model conceptualization.
- Model Calibration and sensitivity analysis.
- Interpretation of results

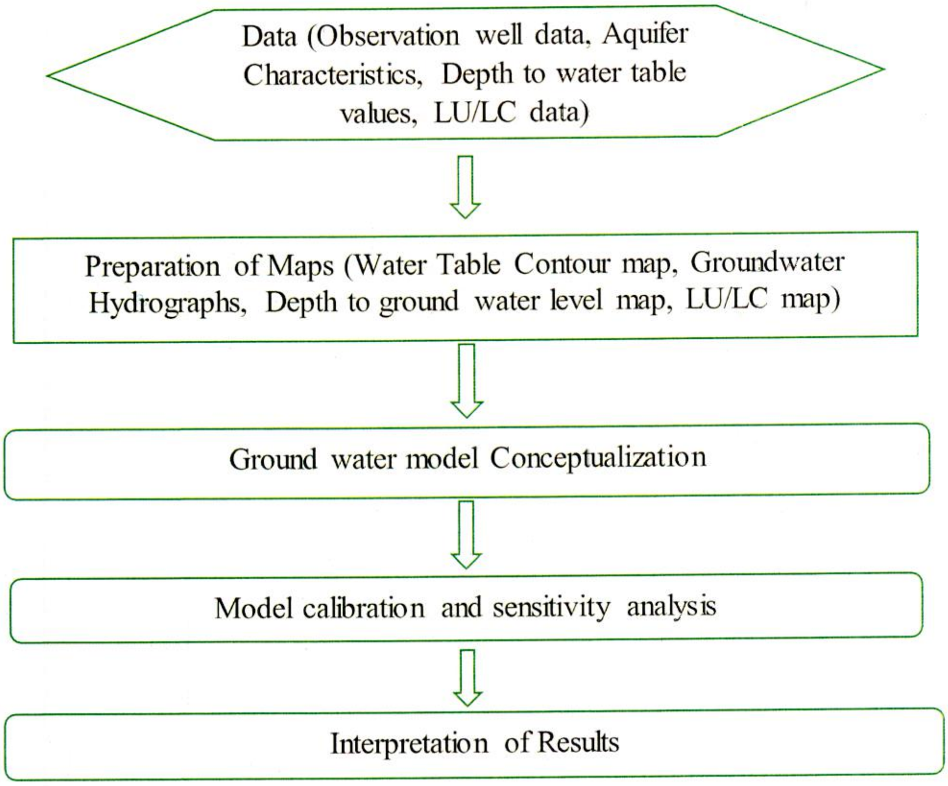

Figure 2: Flow chart representing methodology used for performing groundwater modelling.

3.3 Data Collection and analysis

Monthly rainfall data of 18 years (1997-2015) is collected from a meteorological observatory at SCCL. Monthly evaporation data for period of one year (2010-2011) is collected from IMD station located in Ramagundam. The river stage data is collected from the office of Central water commission (CWC), Mancherial, Telangana, at upstream site located on the periphery of Godavari river basin. Aquifer test was conducted by Exploratory division, MOCP and parameter values for hydraulic conductivity and transmissivity was collected from their report. The geological analysis coupled with other filed data attributed to developing a numerical groundwater-flow model for the region.

3.3.3 Groundwater recharge estimation

Rainfall is the major source of recharge in this area despite the presence of many streams, tanks and lakes. Groundwater budget in the 10 km radius i.e. buffer zone is executed using Groundwater Estimation Commitee-1997(GEC-97) methodology. An equation is developed for estimation of total recharge in this area based on the identified sources of recharge. Net recharge is calculated in both Monsoon and Non-Monsoon seasons. Different equations are developed for different seasons and are as follows

a) Net Recharge in Monsoon is calculated using equation

$$R_n\ (Monsoon) = [R_t + R_G] - [C]$$

where,

$$R_T = R_{sw} + R_{gw} + R_m + R_r$$

and

$$[C] = D + L + A + I$$

R_G = Recharge from Godavari river flood prone area, tanks and ponds (m/day)

R_{sw} = Recharge from return flow of Surface water in kharif season (m/day)

R_{gw} = Recharge from return flow of groundwater in kharif season (m/day)

R_m = Recharge from return flow of mine water let out into streams (m/day)

R_r = Recharge from rainfall (Sedimentary terrain + Hard rock terrain) in m/day

R_T= Total Recharge (in this case for Monsoon period in m/day)

[C] = Total Ground Water Draft

D = Domestic Consumption (m/day)

L = Cattle Consumption (m/day)

A = Agricultural requirement in kharif season (m/day)

I = Inflow of water into coal mines (m/day)

b) Net Recharge in non-monsoon season is calculated using equation

$$R_{nm} = \{(R_T + R_G) - [C]\}$$

Where, $R_T = R_{sr} + R_{gr} + R_m$ and $[C] = D + L + A_r + I$

R_{sr} = Recharge from return flow of surface water in Rabi season (m/day)

R_{gr} = Recharge from return flow of groundwater in Rabi season (m/day)

A_r = Agricultural requirement in Rabi season (m/day)

In non-monsoon period, R_G is taken as zero as river and tanks are dried up and recharge is infinitesimally small.

3.4 Governing Equations for Groundwater flow and transport modelling

A general form of governing equation which describes the groundwater flow movement in three dimensions in a constant density medium (Anderson and Woessner, 1992) is

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=S_s \frac{\partial h}{\partial t}-R^*$$

Where K_x, K_y and K_z represents hydraulic conductivities along the x,y,z axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/t); R^* is a general source/sink term that defines the volume of the inflow to the system per unit time.

h = Piezometric head (L)

S_s = Specific Storage Coefficient (L^{-1})

In Steady State Condition

$$\frac{\partial}{\partial x}\left(K_{xx} \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy} \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz} \frac{\partial h}{\partial z}\right)=0$$

The governing equation for three-dimensional solute transport in groundwater (Anderson and Woessner, 1992) is

$$\frac{\partial}{\partial X_i}\left(D_{ij} \frac{\partial c}{\partial X_j}\right)-\frac{\partial}{\partial X_i}\langle c v_i\rangle=R_d \frac{\partial c}{\partial t}+\lambda c R_d-\frac{C' W^*}{n_e}$$

where,

c = Concentration of the solute.

C' = Source concentration.

D_{ij} = Dispersion Coefficient

v_i = component of velocity vector

W^* = source/sink term

n_e is the effective porosity, λ is the first order rate constant and R_d is the retardation factor.

An in-depth understanding of these governing equations, subjected to boundary conditions is required before exercising modelling problem.

3.5 Groundwater flow model using Visual MODFLOW

The variability and complexity of three dimensional heterogeneous subsurface hydro geologic settings strongly influence the groundwater flow. (Surinaidu et al., 2014). Hence careful analysis is required to hydro geologically characterize the aquifer. A groundwater flow model is developed covering Medapalli Open Cast block using Visual MODFLOW to simulate flow and groundwater heads in the study area. Visual MODFLOW is a graphical user interface embedded with MODFLOW programs developed to solve groundwater flow equations. It acts as a platform that integrates MODFLOW, MODPATH, MT3DMS codes to perform 3D groundwater flow and solute transport modelling. Visual MODFLOW allows us to design grids and assign boundary conditions facilitating visual interpretation of input parameters in both 2D and 3D. Five numerical methods are used in groundwater modelling; finite differences, finite elements, integrated finite differences, the boundary integral equation method, and analytical elements (Anderson and Woessner, 1992). Out of these five methods finite difference method is used in this study for numerical simulation. Finite Difference Method (FDM) is used for solving governing equations. It is a technique to solve partial differential equations (PDE) by discretizing the continuous domain of interest using grid points/mesh and by approximating the values to each of these discretized points using finite differences. FDM simulates a value of hydraulic head at each node such that it is also the average value of groundwater head for the whole cell that is developed around the node. Finite differences are easy to understand and require fewer input data to create the grid. In this report MODFLOW-2005 (Harbaugh, Arlen, 2005) is used to simulate steady state groundwater flow and groundwater heads. MODFLOW-2005 is a block-centered finite difference code in which a three-dimensional groundwater flow system is divided into a sequence of layers organized in a roughly horizontal grid or array (Brooks et al. 2014). MODFLOW-2005 is used because of its ability to represent the complexities of groundwater system and simulate hydrologic stresses like recharge, discharge, evapotranspiration and wells. This code can be used for both steady state and transient state conditions. Here in this study, we use MODFLOW-2005 to simulate flow conditions and MT3DMS to simulate concentration gradient in the study area at both steady state and transient state conditions. A geographic information system is used to bring out accuracy in spatial variations of physical features and the model grid to facilitate development of model input files.

3.5.1 Conceptualization and Layer discretization

The MODFLOW program simulates the conceptual model of the groundwater flow system using data sets that describe the hydrogeological units and recharge estimates to calculate hydraulic heads at discrete points and flow within the model domain (Jones et al. 2013). The conceptual model of Medapalli open cast block is based on the observed geological data and hydrological conditions. River Godavari flows from east to west along the northern side of the mine area. The eastern side of the study area comprises of sandstone formations and the region on the western side of study area comprises of hard rock. The Balancing reservoir, present on the southern part of the study area act as a source of recharge to groundwater system in the buffer zone. Equivalent porous medium (EPM) approach is used to conceptualize the model to reduce the model instability caused by fractured networks in aquifer systems subjected to mining stress. A 40-layer groundwater system consisting of fractured barakar formations with subordinate clays have been assumed with a total depth of 240 m from ground surface in flow model. The entire buffer zone (i.e. 10 km radius) including Medapalli open cast block and the perennial river has been divided into 127 columns and 128 rows using grid module in Visual MODFLOW. Initially the grid is developed with 35 rows and 30 columns and later the grid is refined to characterize the mine area using thin layers to effectively represent the flow of vertical conductivity. After refining the grid the final grid consists of 128 rows and 127 columns with varying cell size all over the grid as shown in fig 4. Vertically the study area was subdivided into 40 conceptual layers, each having uniform thickness of 6 m extending up to a depth of 240 m from the ground surface covering the deep open cast block consisting of soil and alluvium cover, barren measures and barakar formations interbedded with coal seams. The model is conceptualized in such a way that the top most layer represents the ground surface of the study area. The cells lying far away from the study area, at very high elevation from ground surface were demarcated as inactive cells using grid module in the software. Model is oriented in such a way that all the grid rows are aligned from north to south and grid columns are aligned from east to west. The surface elevation data is imported using grid module on to the model. This data is prepared using MS-Excel files. Similarly, the location of observation wells and groundwater head data of the model period were also imported to model from Excel data base.

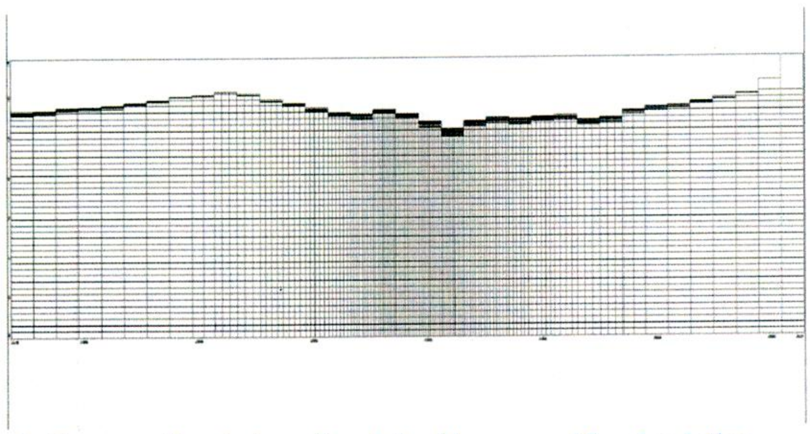

Figure 3: Cross sectional view of model grid prepared for simulating groundwater flow

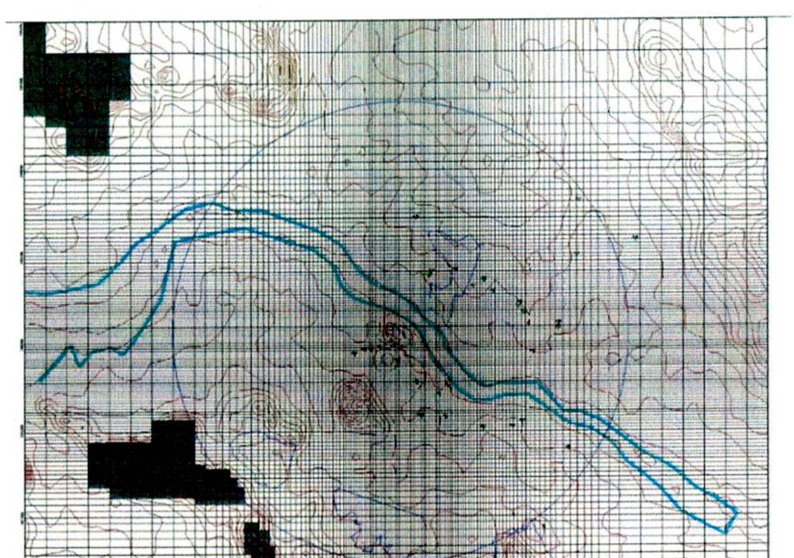

Figure 4: Conceptualized Model grid with inactive zones as colored zones

3.5.2 Boundary Conditions

Boundary conditions in a groundwater flow model are used to specify where water enters and exits the active model domain. Precise selection of boundary conditions is a critical step in conceptualization of groundwater flow model. In steady state simulations, boundaries largely determine the flow pattern. All the hydrological boundaries are assigned based on topographic maps prepared and observed field conditions. River Godavari flows along northern side of quarry area from east to west direction. The boundaries are modelled as Head-dependent flux flow boundaries or mixed boundary conditions where the flux is simulated using the input head value. A constant head boundary condition is assigned to balance reservoir, located south western part of mine pit using Constant head package (CHD) in Visual MODFLOW as shown in fig. A CHD package is time variant specified head package used to simulate specific head boundaries.(Harbaugh et al., 2000) A constant recharge value is given to Godavari river using Recharge package (RCH) and modelled as a part of specified flow boundary. The Recharge package (RCH) is used to simulate a specified flux distributed over the top of the model (Harbaugh et al., 2000) These values were assigned across all layers. The hydro dynamics of groundwater system in the study area is governed majorly by monsoon precipitation. Although most of the rainfall leaves the ground surface in the form of runoff, it is stored in the form of lakes acting as a source of constant recharge into groundwater aquifer. The surface return flow from irrigation doesn't contribute much to groundwater flow dynamics in dry season.

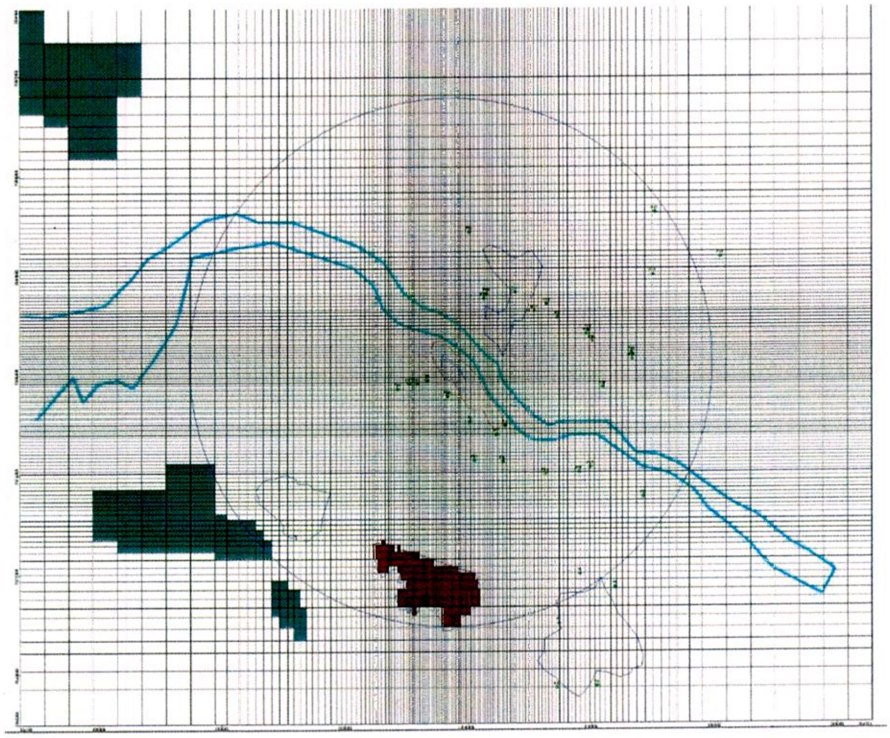

Figure 5: Model grid showing an assigned Constant Head boundary.

The groundwater recharge values vary spatially in the model domain and different values were assigned by creating different zones. River Godavari is considered as a special recharge zone, Zone-2. The eastern part of the quarry area is classified as region of semi consolidated sandstone formation and 12% of annual rainfall is considered as rainfall recharge. The other part in the model domain is classified into Zone 3, as the region of hard rock terrain, considering 11% of annual rainfall as rainfall recharge.

Table 2: Recharge values for different zones created in model domain.

S. No	Zone	Recharge (mm/day)
1	**Zone 1**: Region of Hard rock terrain	8.78E-05
2	**Zone 2**: River Godavari	0.001728
3	**Zone 3**: Region of semi consolidated sandstone formation	7.93E-05

3.5.3 Initial Conditions

Initial Conditions refer to the head distribution everywhere in the system at the beginning of the simulation and thus are boundary conditions at time. It is a standard practice to select as the initial condition a steady state head solution generated by a calibrated model (Anderson and Woessner, 1992) . A steady-state head solution of 1st October 2010 groundwater level is used as initial condition for calibration period in this study.

3.5.4 Assigning parameter values

The data needed for model input includes the values of aquifer parameters like hydraulic conductivity, transmissivity and specific storage and hydrological stresses such as recharge, evapotranspiration and groundwater withdrawal. The values of aquifer parameters are collected through pumping test conducted by SCCL. The range of hydraulic conductivity applied for calibration is between 0.1 m/d to 1.5 m/d. Similarly, storativity values were lying in the range of 0.00019 to 0.00046. Hydraulic conductivity varies spatially in the model domain and hence it is divided into different zones. Godavari river is assigned a hydraulic conductivity value of 5 m/day. The hilly areas with high surface elevation were classified into three different zones Zone 3, Zone 5 and Zone 6. The spatial variation of hydraulic conductivity is shown in fig 6. The ratio between horizontal conductivity and vertical conductivity is taken as 10 for all the zones to consider aquifer anisotropy. The observation heads coupled with groundwater levels at various depths were imported in the model domain using Well Package in the software. The total recharge is estimated by formula mentioned in section. The recharge from rainfall is estimated through standard procedures mention groundwater estimation methodologies report. As recharge values were estimated through empirical relations they account for uncertainty, thus these values are used for calibration to achieve the best degree of fit.

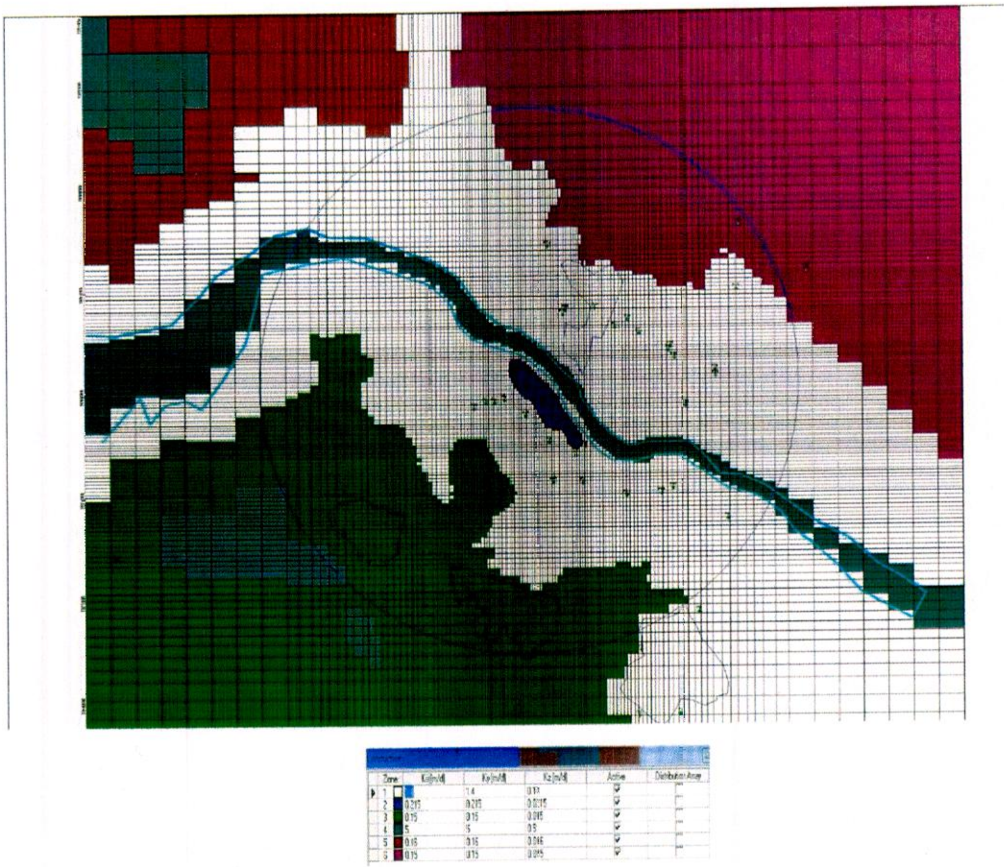

Figure 6: Spatial disposition of hydraulic conductivity in the study area

The purpose of the model is to assess the impact of fly ash deposition in Medapalli open cast block on groundwater flow. Hence, assuming fly ash is already deposited in quarry area, a hydraulic conductivity value of 0.215 m/day is assigned to Medapalli open pit mine extending up to a depth of 220 m covering 35 layers. This is classified as Zone 2. The vertical cross section of Zone 2 is shown in fig. 7.

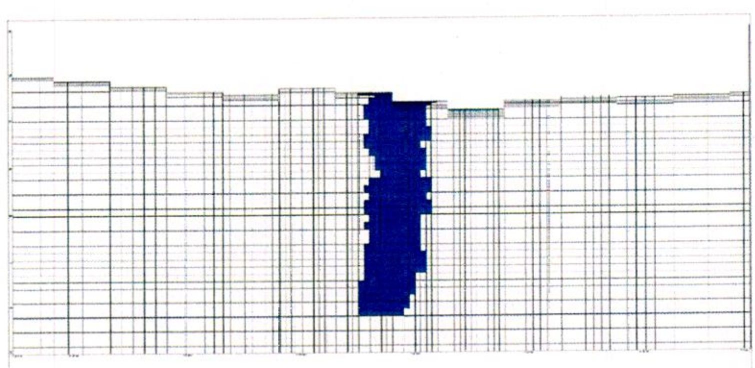

Figure 7: Vertical disposition of fly ash conductivity in Medapalli open pit mine

3.5.5 Transport Model

Mass transport in three dimensions (MT3D) is a computer module supporting simulation of advection, dispersion and chemical reactions of contaminants in three-dimensional groundwater flow systems. (Zheng, 1990). The modular three-dimensional software (MT3D) was originally developed by Zheng and then later documented by (cite). MT3DMS is a new modular transport model which integrates transport solving techniques like finite difference code, particle tracking Eulerian methods and TVD method. It is a comprehensive package to simulate solute transport in complex geological conditions. MT3DMS is capable of advection modelling of miscible contaminants in groundwater systems along with some basic chemical reactions which includes first order kinetic reactions and linear and non-linear sorption. This model is used with flow model created in MODFLOW and is assumed that the concentration field will not change from flow field when measured. Mass transport of Total Dissolved Solids (TDS) is studied in Medapalli open cast block using MT3DMS v 5.2. The initial conditions are used as a setting for TDS concentrations all over the model domain. Assuming the scenario of fly ash being deposited in Medapalli open pit, the source loading at this pit is simulated using initial concentration of 800mg/l at steady state conditions. This concentration value is assigned to Medapalli mine area using Constant Concentration package in software for 35 layers in the model as shown in fig 8.

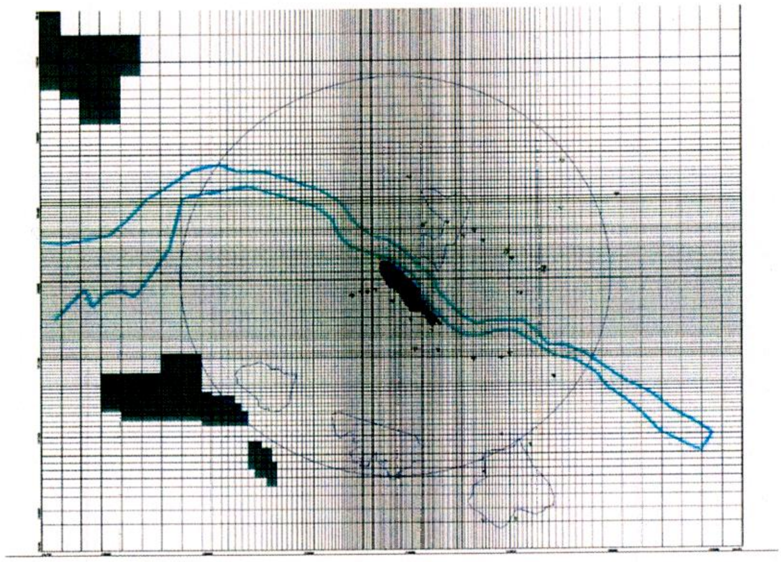

Figure 8: Spatial disposition of fly ash conductivity zone comprising Medapalli OCP.

3.5.6 Criteria for Model Evaluation

The basic objective of model calibration process is to minimize the error. To evaluate the performance of model calibration process different statistical indicators are used such as Mean error (ME), Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), Standard error (SE) and R^2 (Coefficient of determination). All these indicators are explained in Annexure-2.

Chapter 4: Results and Discussions

4.1 Groundwater Flow Modelling for Medapalli Open Cast Block

A three-dimensional groundwater flow model is developed using Visual MODFLOW to simulate groundwater flow in Medapalli open cast mine. This model is run in steady state conditions for the month of June 2010. Recharge values are assigned using RCH package to three different zones, out of which river Godavari is considered as a special zone. A constant head boundary is assigned to balance reservoir using CHD package. Medapalli open cast mine is assigned a hydraulic conductivity value of 0.215 m/day by creating a special zone. Godavari river is assigned a conductivity value of 5 m/day. MT3DMS code is used to simulate TDS transport at steady state conditions, in the open pit mine filled with fly ash. The initial concentration of 800 mg/l is assigned to Medapalli ash pond and longitudinal dispersivity value of 10 is assigned, while designing the transport model. The model was run using WHS solver package accommodating both MODFLOW-2005 and MT3DMS code.

4.1.1 Topography map

The topography map is developed in *"Surfer® 9 (Golden Software, LLC)"* as shown in fig 9. Surfer package uses kriging as an interpolation method to generate contours. The lowest elevation is observed at 90 m amsl and the highest at 370 m. The topographic contours in the map indicate that groundwater flow will be along the gradient. Flow of groundwater in the aquifer is towards the river, which is at lowest elevation in the region. The 10 km buffer zone covering Medapalli open cast project is mostly plain area. This area is drained by perennial river Godavari flowing from east to west. The hilly terrain is in south west, north-east and north-west parts of the buffer zone. The mine area has elevation contour values in the range of 120-140 m amsl and lowest contour is found in the Godavari flood prone area. This region is drained by other small streams like Ralla Vagu, Tolla Vagu and Rali vagu. The Ash pond is located at higher elevation in south western part of mine and the Balance reservoir is present in the southern part at high elevation, thus acting as an important source of recharge in the buffer zone. These topographic contours are used to effectively characterize the model domain in

Visual MODFLOW. The 3-D view of the topography in the region is shown in fig 10.

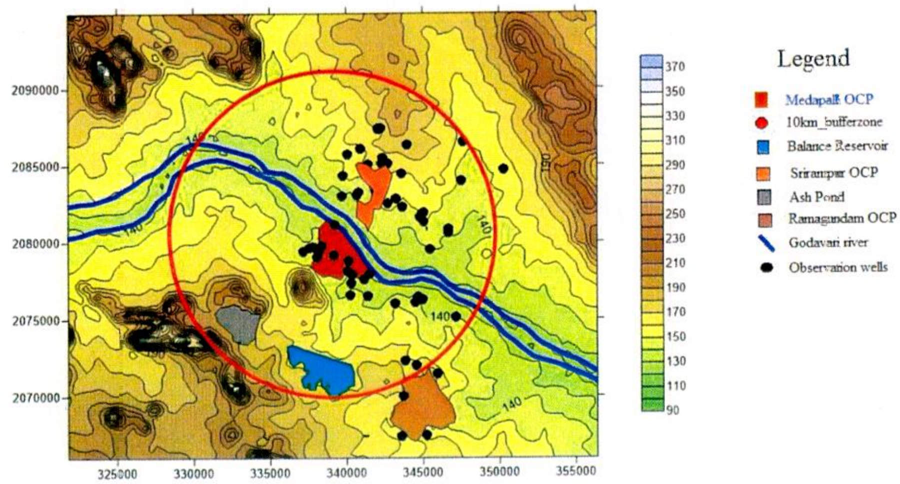

Figure 9: Topographic map of Medapalli OCP

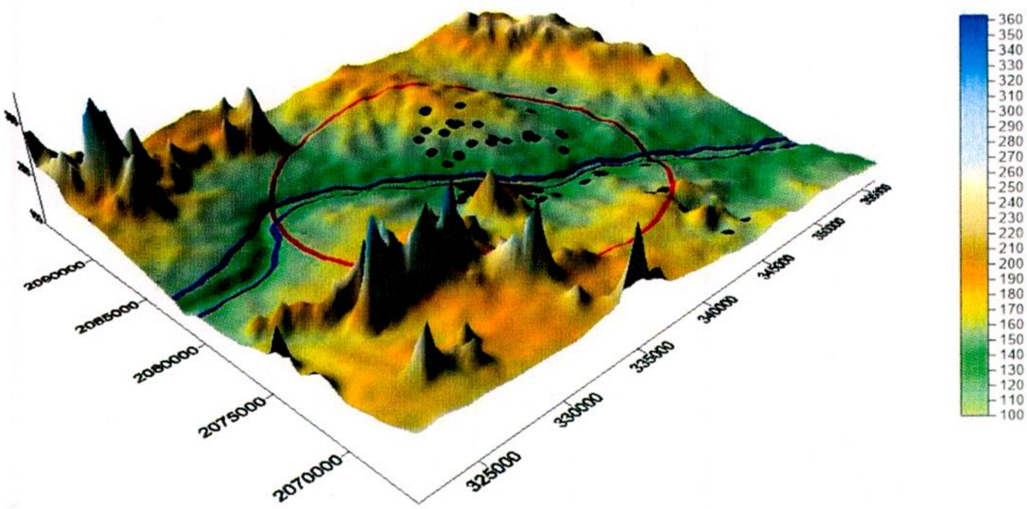

Figure 10: 3D view of topographic surface covering Medapalli Open cast block

4.1.2 Land use/Land cover map

Land use/Land cover in this study area is depicted in fig 11. using Landsat 8 imagery for January 2013, when the study region is predominantly dry. The Landsat image is processed using ArcGIS v 10.2.2 and ERDAS IMAGINE® v14 software's with all necessary corrections and classified using supervised classification. Reserve forest under various density categories account for 12 % of the area in buffer zone and 44.83% of area is under cultivation. 15% of area account for waste land in the buffer zone and 18% is under mines and industrial establishments.

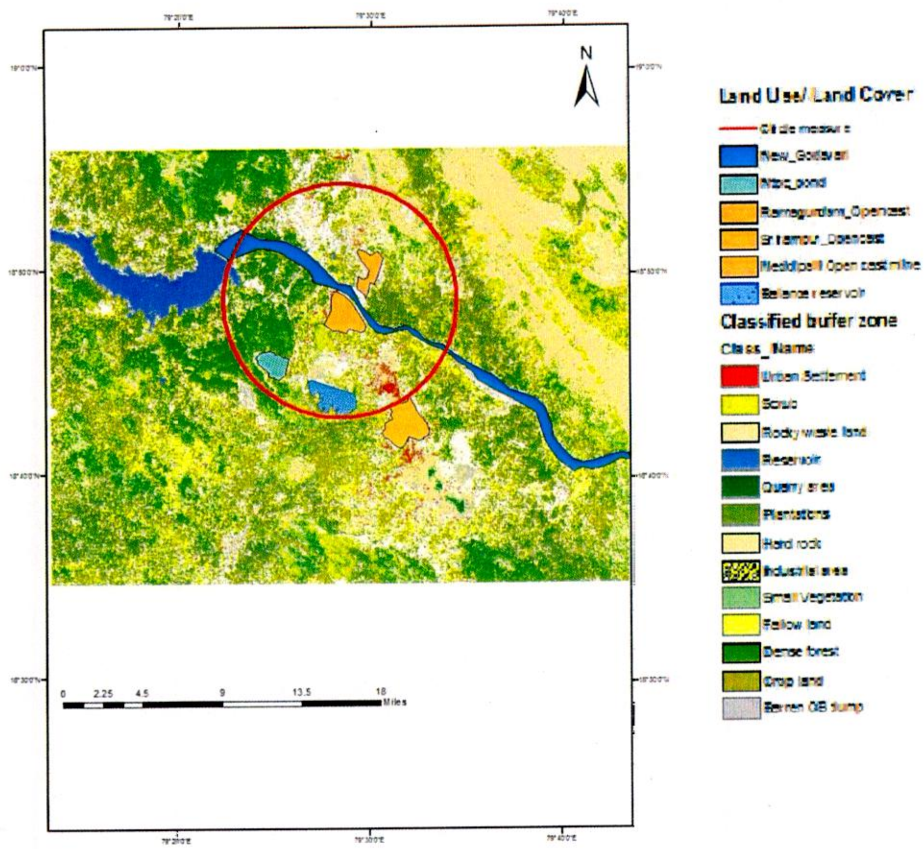

Figure 11: LU/LC map including the buffer zone and mine pit area

4.1.3 Phreatic Surface trend

Trend of phreatic Surface is observed through Ground Water Hydrographs prepared using "Grapher™ 12 (Golden Software, LLC)". The pre-monsoon and post-monsoon trend of phreatic surface in 7 observation wells is graphically represented. Groundwater Hydrographs are used to assess the trend of phreatic surface over a period of 18 years (1997-2015) using rainfall data and depth to water level values collected through observation wells. As, continuous observation of piezometric head is required to evaluate the undulating water table in the region, 7 observation wells with continuous monitoring of data from 1997-2015 are selected. These wells are located at Arunakkagar, Rasulapalli, Tallapalli, S.R Puram on northern side of the river and Ramagundam, Lingapur, Vittalnagar (GDK) on the southern part of the river as shown in fig 12. As clearly revealed from Figures 13-19, The trend of phreatic surface indicates that there is a minimal change in groundwater levels in the region and is very less over the period of 18 years..

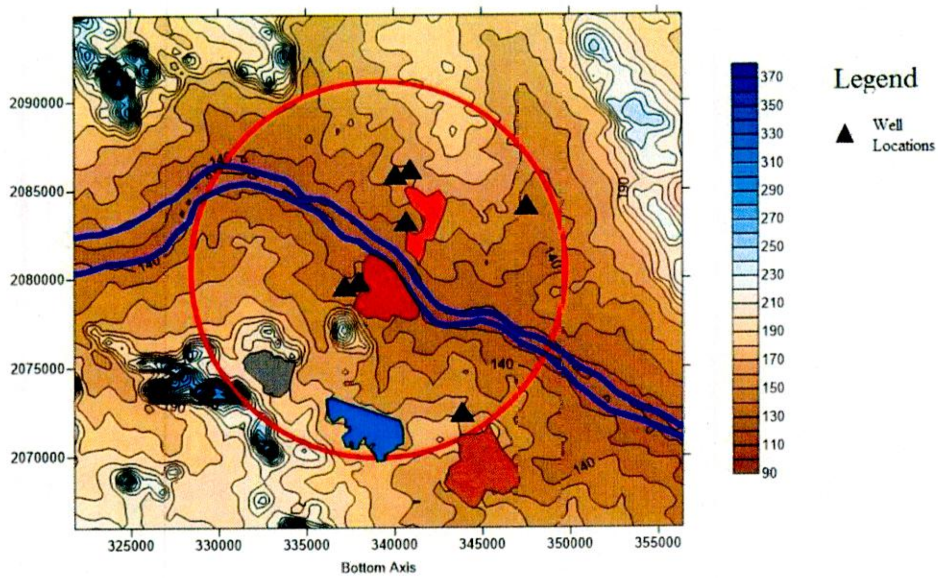

Figure 12: Well locations used generating Hydrographs

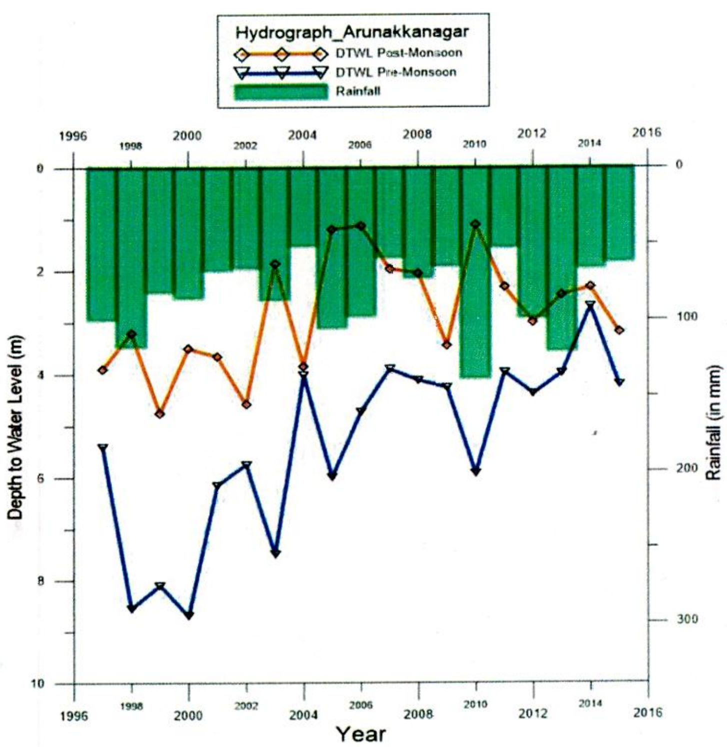

Figure 13: Groundwater Hydrograph for Arunakkanagar observation well, located on northern side of the river

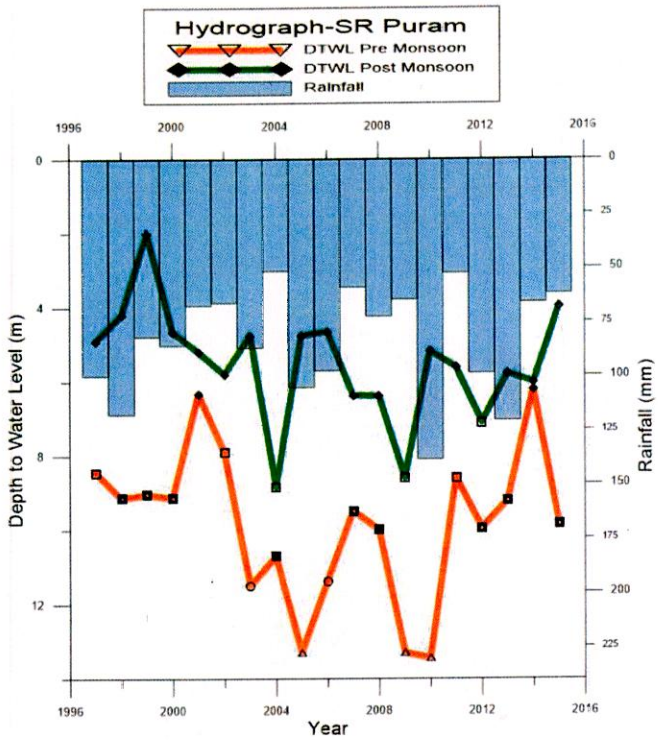

Figure 14: Groundwater Hydrograph for S R Puram observation well located on the northern side of the river

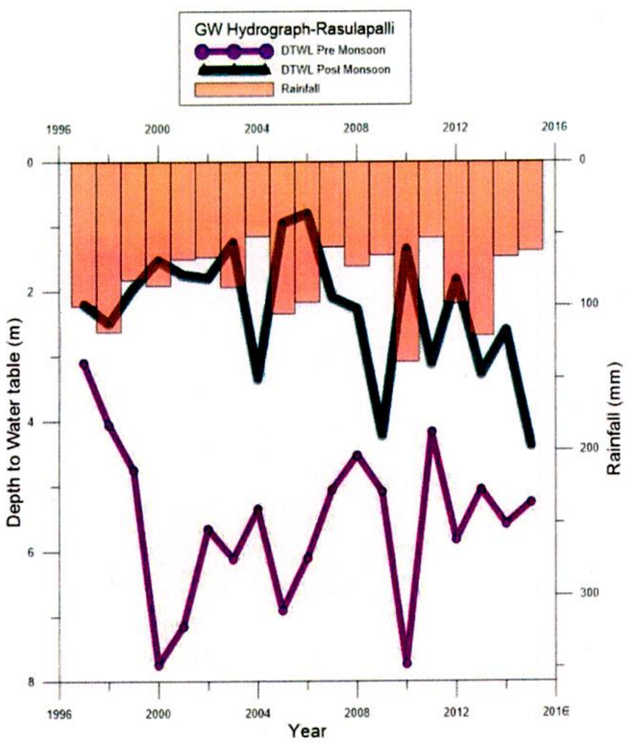

Figure 15: Groundwater Hydrograph for Rasulapalli observation well, located on the northern side of the river

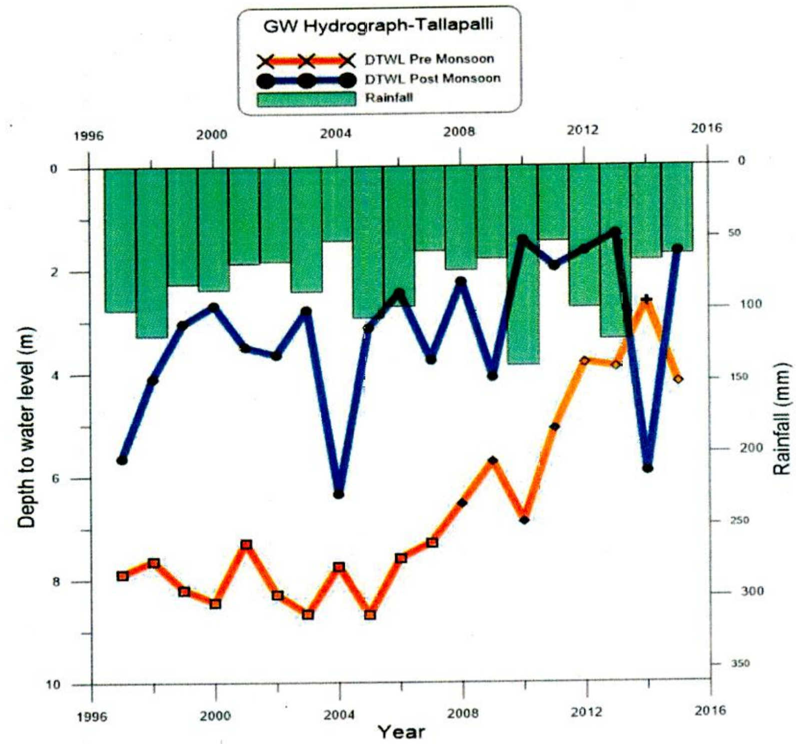

Figure 16: Groundwater Hydrograph for Tallapalli observation well located on the northern side of the river

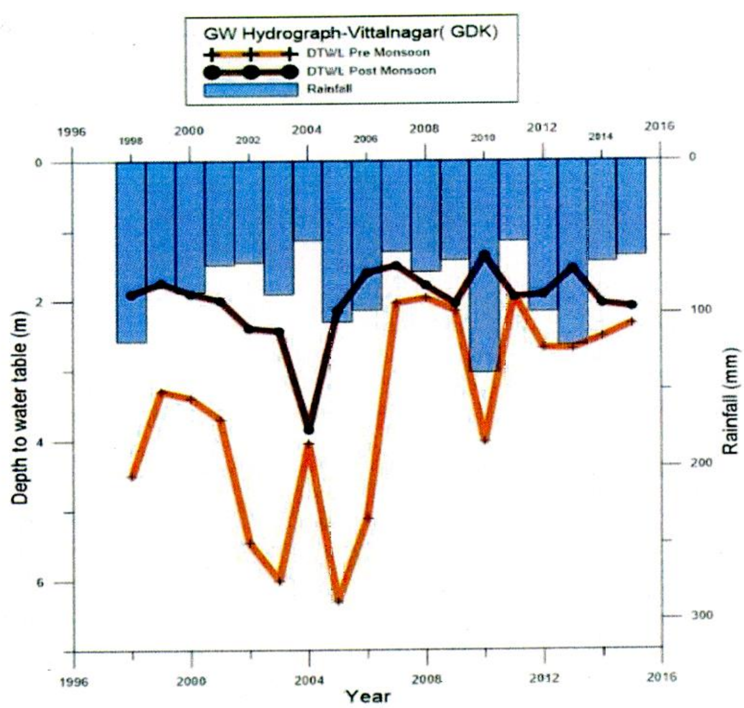

Figure 17: Groundwater Hydrograph for Vittalnagar(GDK) observation well located on the southern side of the river

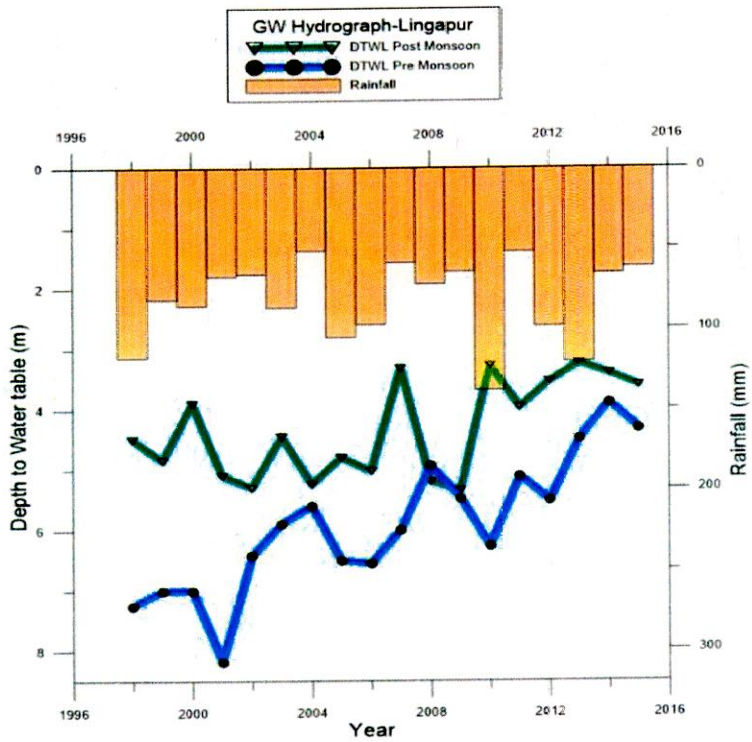

Figure 18: Groundwater Hydrograph for Lingapur observation well located nearby the river

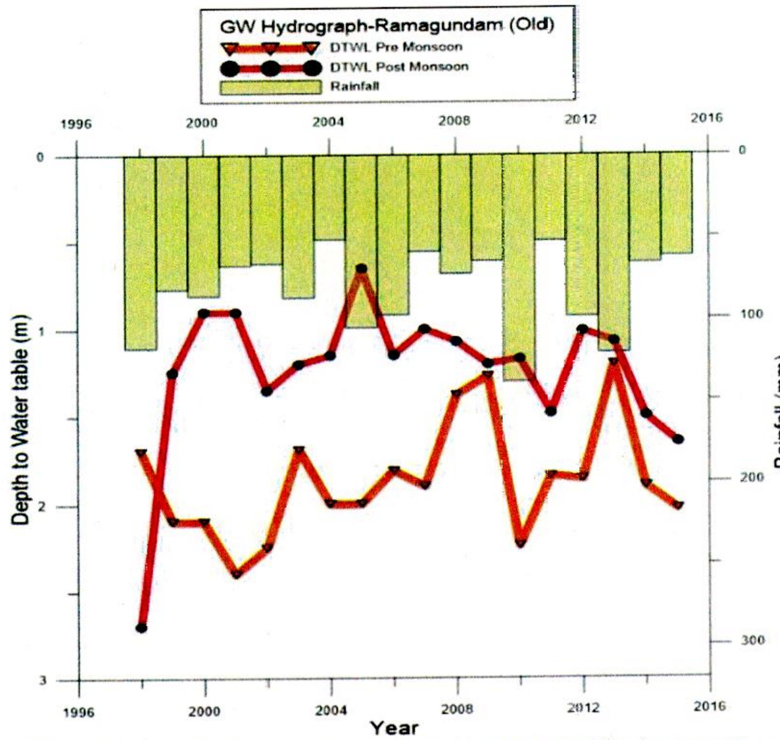

Figure 19: Groundwater Hydrograph for Ramagundam(old) observation well located on the south-western side of the Medapalli mine pit

4.1.1 Model Calibration

Groundwater flow model calibration at steady state is performed by trial and error approach. This is done by adjusting recharge and hydraulic conductivity, two key parameters influencing ground water system. During initial simulation, hydraulic heads from observation wells during post-monsoon were used coupled with hydraulic conductivity values (as assigned in conceptual stage) and recharge values (as calculated using GEC-97 methodology). It was found that the groundwater flow model is more sensitive to both hydraulic conductivity and recharge. These initial values were adjusted during the calibration process to achieve the best fit degree between calculated heads and observed heads. The degree of fit is calculated using statistical means. The statistical indicators along with conductivity values at the study area is presented in table.

Table 3: Performance statistics of numerical model during calibration period

Site	MOCP
Number of Data Points	35
Standard error of the estimate	0.895 (m)
Root Mean Square	5.627 (m)
Normalized Root Mean Square	17.885 (%)
Correlation Coefficient	0.704
Max. Residual	-13.868 (m)
Min. Residual	-0.165 (m)
Residual Mean	-2.108 (m)
Abs. Residual Mean	4.488 (m)

The MODFLOW-generated calibration plot along with 95% interval lines and 95% confidence interval lines for steady state calibration is shown in figure. The 1:1 line lies in between the confidence interval indicating a good calibration for flow model.

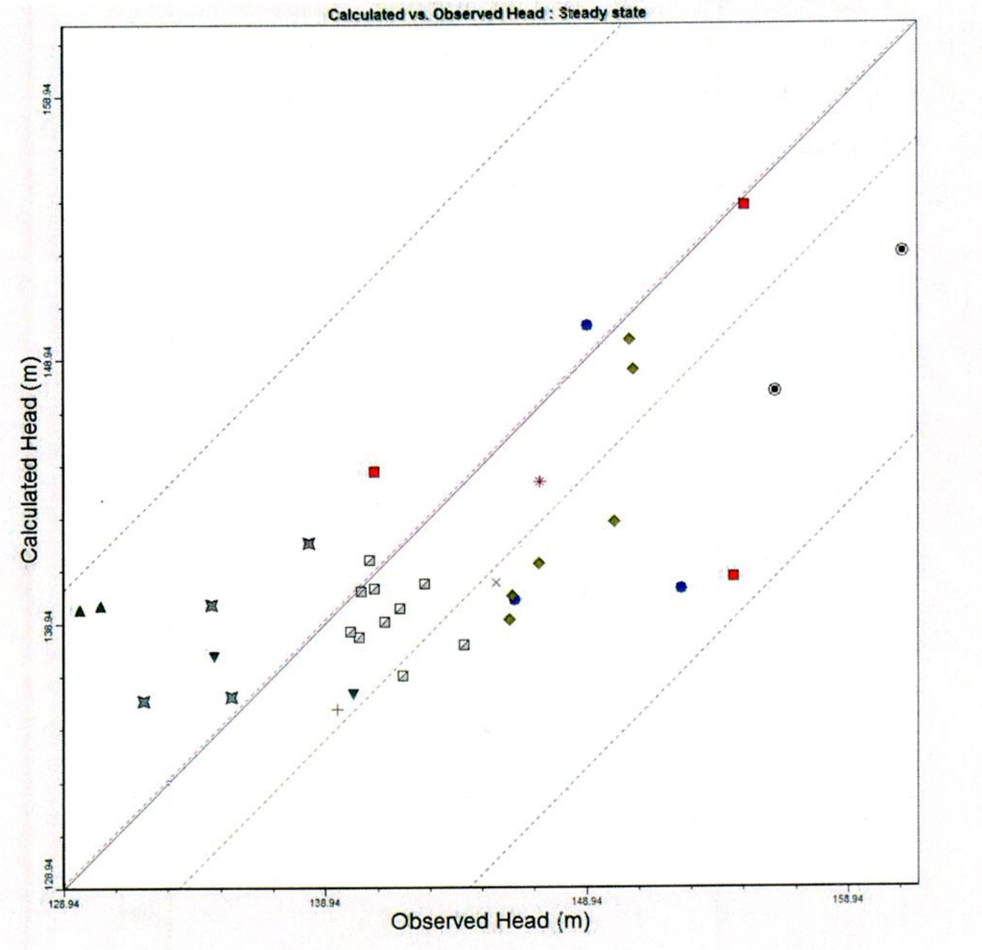

Figure 20: Calibration plot between simulated heads and calculated heads

The computed water level accuracy was judged by comparing the mean error, mean absolute and root mean square calculated. The RMS and NRMS errors are 5.627 m and 17.885%. The calibration result indicated that there is a good agreement between observed head and calculated head. With Correlation coefficient of 0.704, the model is found acceptable. The calibrated parameters set while performing this exercise are constant head boundary, recharge, evapotranspiration, hydraulic conductivity. The velocity field is simulated from flow field with an effective porosity value of 0.15 all over model domain. The model has been validated with observed hydraulic heads collected in October 2010 and it is found out that there is no change in the values of Root Mean Square error and Normalized root means square. Therefore, the model is considered as well calibrated model with respect to observed field conditions. The model generated head contours and velocity field as output. The simulated heads are shown in fig.21 with maximum value of 169.2 m towards southern side of the river and max value of 157 m on the northern side of the river. The head value at the fly ash filled pit mine is 134 m. The head contours follow the topography of the region in general. The simulated contours indicated that the flow of water is towards open mine pits from aquifer following the gradient and general flow direction of groundwater is towards Godavari river from aquifer. The river has significant effect on groundwater system under open pit mine. Unfortunately lack of more number of observation wells in eastern, northern and southern part of the mine, made it difficult to compare the simulated contour heads in these areas.

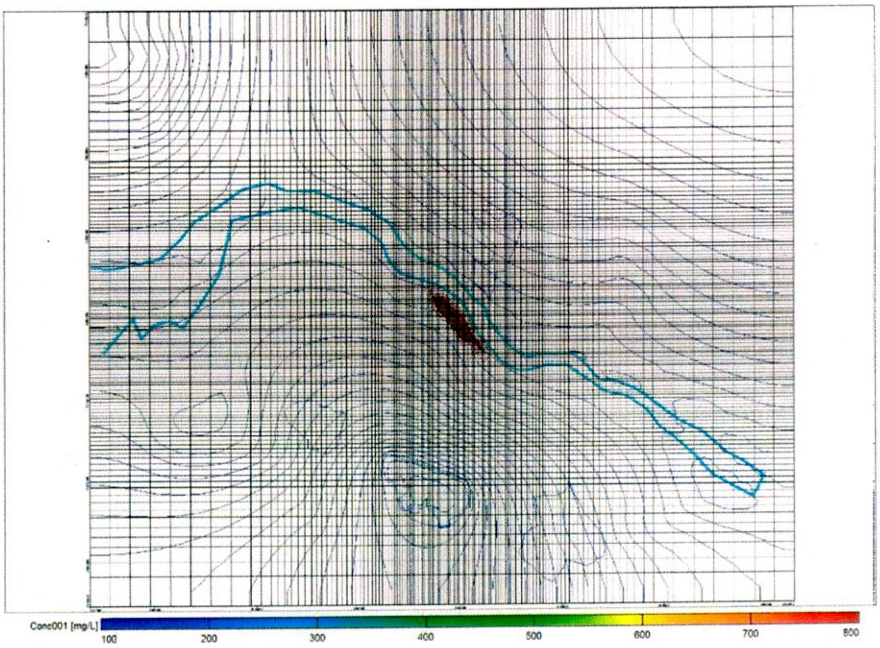

Figure 21: Map showing Head contours generated by numerical simulation

4.3 Solute transport Model

TDS concentrations are simulated using MT3DMS code. The velocity field is generated at regional scale with maximum value of 0.16 m/day. The flow pattern in the model domain is towards the river and follows the topography in general. The solute is migrating along the periphery of open cast mine filled with fly ash. The initial solute concentration is 800 mg/l and as the plume is generated up to a maximum distance of 168 m due to both advection and dispersion mechanisms. The plume concentration along the periphery of mine decreased with minimum concentration of -0.0073 mg/l towards river side and 0.009361 mg/l towards hilly regions.

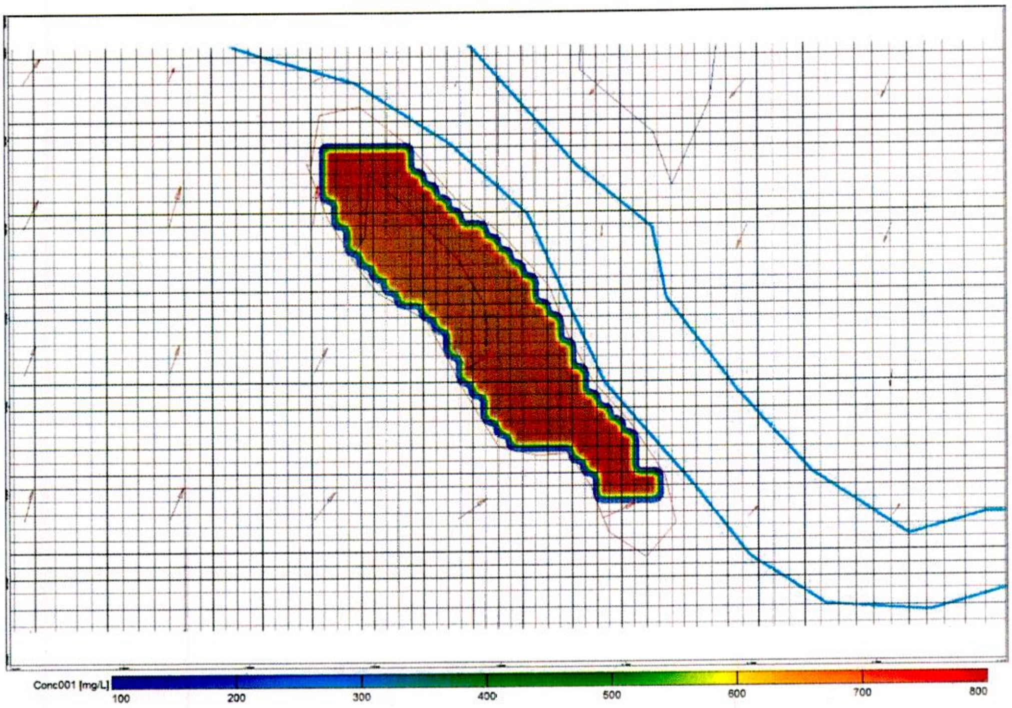

Figure 22:Model domain showing contaminant migration and regional scale velocity field

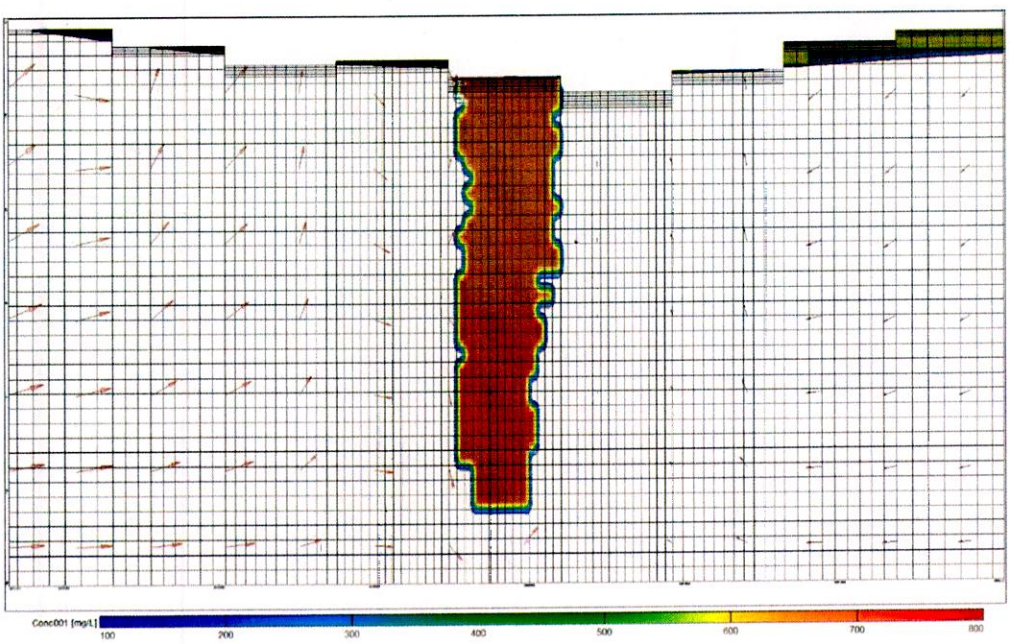

Figure 23: Cross Sectional view of contaminant migration in Medapalli open pit mine

4.4 Concluding remarks

The major findings extracted from model results are as follows

- The topography of the region indicates that the lowest elevation is found in the river flood plain. This area is drained by perennial river Godavari flowing from east to west. The hilly terrain is in south west, north-east and north-west parts of the buffer zone.
- The Land use of the region is observed and major part of the land is used for agricultural activities besides industrial activities. The 10 km buffer zone is drained by Godavari river and multiple streams.
- The undulating water table is evaluated by groundwater hydrographs and these hydrographs indicate that there is minimal water table fluctuation in the region past 18 years.
- A groundwater flow model is developed for Medapalli Open Cast block using steady state numerical simulation through Visual MODFLOW and a good agreement is observed between calculated heads and simulated heads making the groundwater model reliable.
- In solute transport, as the contaminant is not migrating to longer distances no harmful effects will arise due to fly ash deposition in Medapalli open pit mine.

Chapter 5: Conclusions

5.1 Conclusions

Groundwater flow and Solute transport in Medapalli Opencast mine has been simulated using numerical modelling through Visual MODFLOW. The water table fluctuates in response to rainfall recharge near the mine. In pre-monsoon the river, which is adjacent to the mine flowing from east to west receives base flows from aquifer and in post monsoon the aquifer receives influx from the river facilitating the rise in water table in the region. The groundwater flow model is developed using MODFLOW-2005 code by assigning all boundary conditions and parameter values. The solute transport model is prepared using MT3DMS code, by assigning a constant concentration of TDS across the model domain at steady state conditions. The model calibration process revealed that a good fit is observed between measured heads and simulated heads with RMS error of 5.627 m. TDS migration is observed through transport model and the plume extends up to a maximum distance of 168 m from the periphery of Medapalli Opencast mine through advection and dispersion phenomena. The impact due to fly ash deposition in the mine would be very less as the plume concentration decreased rapidly along the periphery of the mine.

5.2 Future Scope of Work

The groundwater flow model developed in this study is simulated in steady state conditions. This model can be used as an input for transient simulations of groundwater flow and solute transport in the study area. More number of observation wells must be located and recorded to perform simulations at transient state. Once the transient model is prepared, this can be further used to predict solute concentrations and groundwater inflows for upcoming years.

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Annexure(s)

Annexure-1: Groundwater Resource Estimation

Medapalli Open Cast Mine is drained by perennial river Godavari and many small streams and lakes. Rainfall is the major source of recharge in this area. Paddy is the major crop grown during both Kharif and Rabi season. Groundwater budget in the buffer zone (10km radius) is calculated as per GEC-97 methodology.

Groundwater Draft

Four major groundwater withdrawal patterns were observed in this area. They are classified as Domestic consumption, Cattle Consumption, Agricultural Requirement and Water pumpage from coal mines.

a) Domestic Consumption

Ramagundam and Mancherial are two major urban settlements in the buffer zone and are provided with water supply from Godavari river. There are 16 operational coal mines of SCCL inside the buffer zone and a total of 27,823 working employees live in townships and colonies. Groundwater is pumped in these townships to provide adequate water supply. Assuming 4 persons per family, the total population dependent on groundwater is estimated as 1,11,292. It is presumed that rural population of 26,665 people depends on open/ bore wells for their domestic needs. As per GEC-97 procedure, per capita consumption rate of 60 litre/day is considered and the domestic consumption is calculated as 0.05058×10^{-4} m/day.

b) Cattle Consumption

Cattle consumption is assumed to be 10 % of projected domestic consumption and is calculated as 0.0052324×10^{-4} m/day.

c) Agricultural Requirement

Paddy is being irrigated in both kharif and Rabi seasons in the buffer zone located at 10km from the periphery of Medapalli Opencast mine. The water requirement is to the extent of 105cm at the rate of 6 to 7 wettings. The groundwater utility is estimated as 0.28767×10^{-4} m/day for both Kharif and Rabi seasons.

d) Pumpage of water from Coal mines

There are 16 coal mines inside the buffer zone. The data regarding the quantity of water pumped out in these 16 mines is collected from SCCL report. The total water pumped from these mines is 1.8025×10^{-4}m/day.

The total groundwater draft in this area is calculated according to the equation described in section 3.2 and it comes out to be 2.14598×10^{-4} m/day.

Groundwater Recharge

The sources of recharge in the study area are rainfall, irrigation return flow of applied surface water, irrigation return flow of applied groundwater, return flow of mine water let out into streams and recharge from surface water bodies. Rainfall is the major source of recharge besides reservoirs, streams and tanks.

Recharge from Rainfall

The mean annual rainfall in this area is 1097.31 mm.

i. Recharge in sedimentary terrain located in eastern side of Medapalli open cast mine is equal to 12% of rainfall. It amounts to 3.6×10^{-4} m/day.
ii. Recharge in hard rock terrain is calculated by assuming 11% of annual rainfall which comes out to be 3.3×10^{-4} m/day.

Recharge from other sources

a) Recharge from return flow of surface water applied for irrigation is equal to 50% of the extent of depth (i.e. 105cm) which is 0.14×10^{-4} m/day.
b) Recharge from return flow of groundwater applied for irrigation around the year in both seasons is equal to 40% of extent of depth, which is 0.115×10^{-4} m/day.
c) Recharge from return flow of mine water let into streams is estimated as 0.668×10^{-4} m/day.

Recharge from surface water bodies including Godavari river is estimated at a recharge rate of 1.44m/day as 17.28×10^{-4} m/day.

The net groundwater recharge is calculated according to the equations described in section 3.3.3 for both monsoon and non-monsoon and these values are used as recharge inputs for different zones across the study area.

Annexure-2: Criteria for Evaluating Model Calibration

To evaluate the performance of model calibration, following statistical indicators are used (Anderson and Woessner, 1992)

Mean Error (ME): The mean error is the mean difference between measured heads and simulated heads.

$$ME = {}^{1}/_{n}\sum_{i=1}^{n}(h_m - h_s)_i$$

Where h_m is the measured head, h_s is the simulated head and n is the number of calibration values.

Mean Absolute error (MAE): The mean absolute error is the mean of absolute value of the differences in measured and simulated heads.

$$MAE = {}^{1}/_{n}\sum_{i=1}^{n}|(h_m - h_s)_i|$$

Root mean squared error (RMSE): The root mean squared error or the standard deviation is the average of the squared differences in measured and simulated heads.

$$RMS = \left[{}^{1}/_{n}\sum_{i=1}^{n}(h_m - h_s)_{i^2}\right]^{0.5}$$

Standard Error (SE):

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(WF)_i(h_m - h_s)_{i^2}}{n - P}}$$

Where $(WF)_i$ are, weighting factors used to indicate the reliability of a head measurement and P is the number of statistical measurements.