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Hydrogeological and groundwater modeling studies to estimate the groundwater inflows into the coal Mines at different mine development stages using MODFLOW, Andhra Pradesh, India

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ABSTRACT

The Singareni Collieries Company Ltd (SCCL) is exploiting coal in the Godavari valley coal fields spread over 5.33 km^2 in Andhra Pradesh, India. In the area, six workable coal seams have been identified in Barakar formation by the analysis of the geologic logs of 183 bore wells. A finite difference based numerical groundwater flow model is developed with twenty conceptual layers and with a total thickness of 320 m. The flow model was calibrated under steady state conditions and predicted groundwater inflows into the mine pits at different mine development stages. The groundwater budget results revealed that the mining area would receive net groundwater inflows of 5877 m^3 day^{-1}, 12,818 m^3 day^{-1}, 12,910 m^3 day^{-1}, 20,428 m^3 day^{-1}, 22,617 m^3 day^{-1} and 14,504 m^3 day^{-1} at six mine development stages of +124 m (amsl), +93 m (amsl), +64 m (amsl), +41 m (amsl), +0 m (amsl) and −41 m (amsl), respectively. The results of the study can be used to plan optimal groundwater pumping and the possible locations to dewater the groundwater for safe mining at different mine development stages.

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1. Introduction

The construction of an excavation often means penetrating the local or regional groundwater table, which may cause water inrush into the excavation [37]. If the host rock is significantly permeable, it can become a big problem for the excavation operations. Dry working conditions are preferable as they reduce wear and tear of machinery, reduce earth moving costs that improve the slope stability and therefore safety can be assured in mining operations. There are number of methods available for the mine management and they are dewatering, diversion, sealing or a combination of these methods. In order to identify the most economic and low cost method, it is very essential to identify the source of groundwater seepage. The successes of dewatering operation depend on the understanding of the local and regional groundwater regime. This requires estimation of the actual water inflows into mine pits to plan the dewatering operations.

The potential impact of ground water inflows to a mine is often evaluated in three phases. The first phase involves collection of the hydrology and hydrogeologic information in the area including geologic structure, aquifer parameters such as hydraulic conductivity of the formation, groundwater storage and the dimensions of the aquifer to estimate the actual inflows [19]. In the second phase potential impacts and causes of mining operations on groundwater regime are to be carefully evaluated through regular monitoring of the groundwater levels in the bore wells and collection of groundwater seepage information into the pits [33]. The estimation of inflows coupled with structural mapping of the geology gives very valuable information to determine and control the volume and occurrence of groundwater inflows. In the third phase, inflows can be estimated through dewatering, computer modeling or through the application of practical experience [19,15].

A computer model can be used to simulate groundwater flows into the mines as the excavation of the mine enlarges. The regular monitoring of groundwater levels and the amount of groundwater withdrawal are required to update and to calibrate/validate the model for every stage of the mine development. Numerical models can be a powerful tool to solve the number of ground water related problems associated with mining and mine closure. But specific features must be addressed and that requires a deep understanding of the mining environment [22,33]. Effective dewatering strategies should be developed to minimize operational cost and to minimize the impact of groundwater pumping in the mines on groundwater regime in the area.

In recent years, ground water numerical flow modelling has become an important tool for the mine safety legislation to protect the underground mines from heavy groundwater seepage. Many researchers successfully utilized numerical models to estimate the groundwater inflows into highly karst aquifer systems [3,25,33], into coal mines [32,38] and into the granitic aquifers [34]. The correct modelling approach depends on the scale of the modelling application [34].

The present study aims to convert the part of existing Srirampur underground coal mines into open cast mines with depth up to 311 m that are located in Adilabad district of Andhra Pradesh state in India. The study has got major importance due to its huge coal reserves that will have major impact on energy security of India, in particular of Andhra Pradesh. The increase in depth of exploitation of coal mines are subjected to water inrush into the mines. For the protection and safe sustainable mine exploitation needs to understand the groundwater seepage into the mine pits. In the present study area extensive deep borehole (upto 1000 m depth) drilling engineering methods are deployed and distributed throughout the area to understand the typical mining sub-surface hydrogeologic setting for the conversion of under groundwater mining to open cast mining. This has led to deep understanding of structural geology of the area and more reliable conceptualization of the typical aquifer system in the groundwater flow model.

The objective of the present study is to estimate the groundwater inflows into mine pits at different mine development stages for optimal groundwater dewatering plans using numerical groundwater model. This paper describes how the numerical flow model (MODFLOW 2005) can be applied to solve the issues related to ground water inflows into coal mines depending on the different mine development stages.

2. Location of the study area

Srirampur open cast block covers about 5.5 km^2 in Mancherial mandal of the Adilabad district, Andhra Pradesh (A.P) (Fig. 1). The study area lies between North Latitude of 18°49′04″ to 18°51′12″ and East Longitude of 79°29′17″ to 79°32′02″. The area experiences a sub-tropical monsoon climate with a hot dry summer from March to the mid of June followed by the rainy season up to the mid of October. The temperature ranges from 30.6 to 48.6 °C during the summer period and the minimum ranges from 9.1 °C to 29.6 °C during winter season. The average annual rainfall varies from 690 to 1510 mm with a mean of 1100 mm and the humidity ranges from 38% to 100% during the summer and winter seasons, respectively.

3. Geology of the study area

The Srirampur Coal field area is a part of Godavari Valley Coal field that belongs to the Lower Gondwana group of rocks. The stratigraphy in the area as reported by [29] is shown in Table 1. Srirampur Opencast Project area is highly complicated block in whole of the Godavari Valley Coalfield. No structural features were observed on the surface, because the block is mostly covered by soil/alluvium deposits. Therefore, the geological structure/stratigraphy of the block has been deciphered mainly based on the sub-surface data from boreholes drilled upto 1000 m in this block. In some parts of the Godavari Valley coalfield, the nature of depositional pattern causes rolling in the attitude of

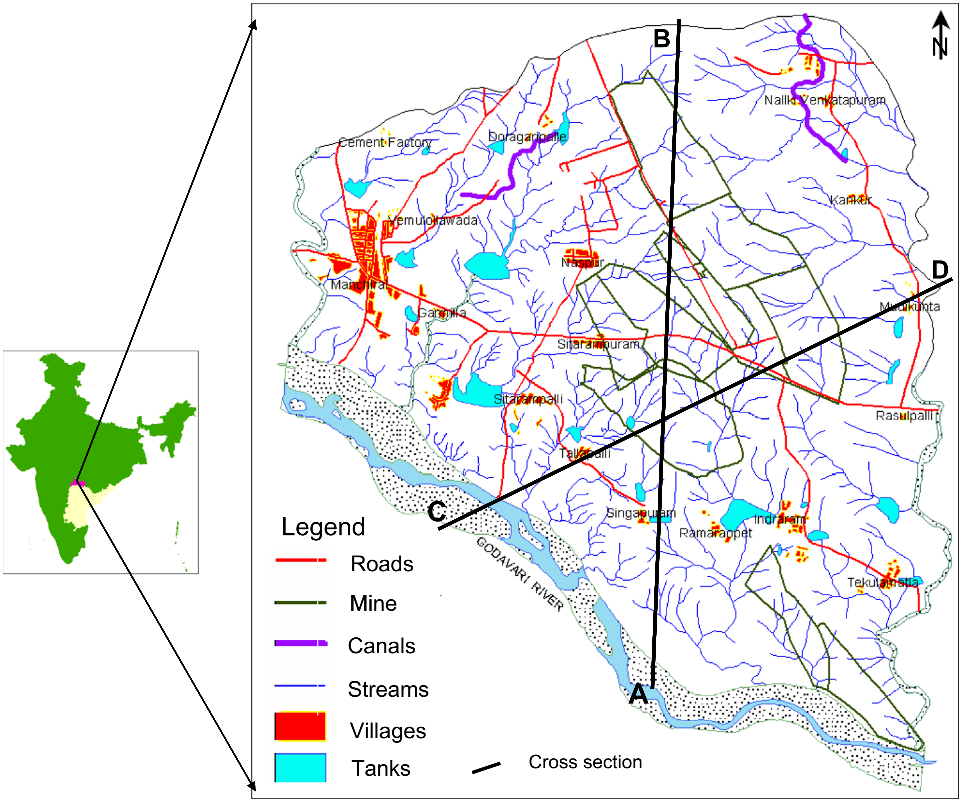


Fig. 1. Location map of the Srirampur OCP-II area in the Adialabad district, SCCL, A.P.

Table1
Stratigraphic succession of Srirampur OCP-II and IIa inclines block.

Age	Group	Formation	General lithology	Maximum thickness (m)
Recent			Soil cover	5.00
Permian	Lower gondwana	Barren measures	Medium to very coarse grained gray/greenish ferruginous sandstone with subordinate clays/sandy shales	140.77
		Barakar	Predominantly grey/white medium to coarse grained sandstone with coal seams/shale and clays	250.00
		Talchir	Fine to medium grained greenish sandstones, silt stones, clays and pebbles beds	35.64+
		Unconformity		
Proterozoic		Sullavai	Red and white banded fine grained sandstone and quartzites.	

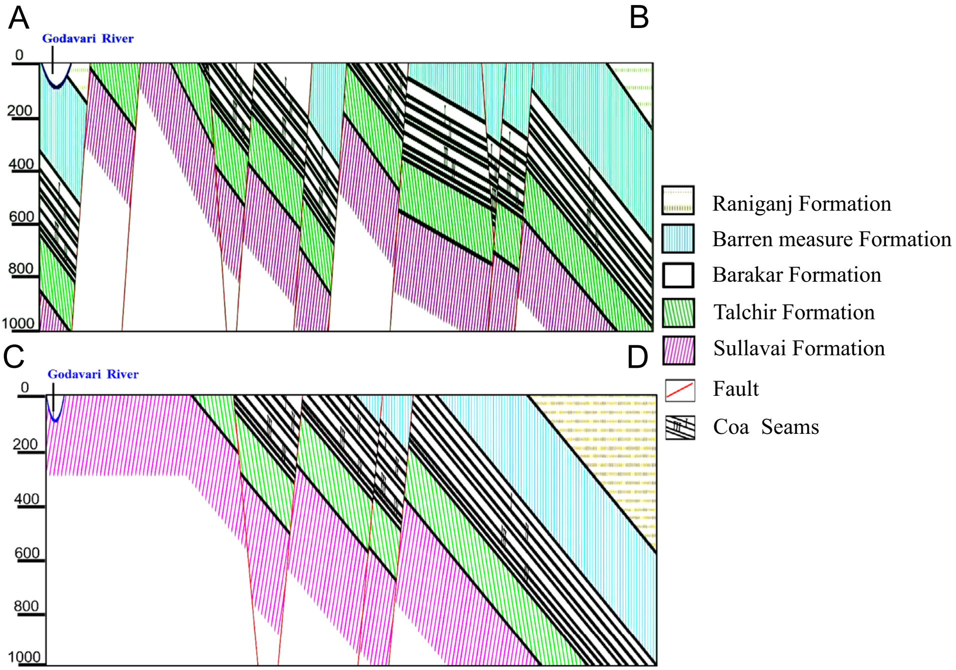


Fig. 2. Geological cross sections of the bore holes along the cross section of AB and CD in the Srirampum OCP-II in the Adilabad district, A.P.

beds that otherwise could be attributed to faulting as the surface exposures were very scanty. Initially 43 boreholes were drilled in the area by Mineral Exploration Corporation Limited (MECL). In view of its intricate structure, 51 additional boreholes were drilled by SCCL in the block. The structure of the block was interpreted using the 94 borehole data by SCCL. After opening of the SRP-2 and SRP-2A inclines, it is observed that the structures of underground workings are at variance with the structure interpreted. Once again, a number of additional boreholes were drilled totalling to 183 boreholes up to March 2000. Normally, around 8 to 12 boreholes per km^2 were to be drilled to delineate the block for the board and pillar method of working, whereas 34 boreholes per km^2 were drilled in the block due to the complexity of its structure [30].

The block is characterized by unusual swings in the strike direction of coal deposit which was further accentuated due to the presence of 41 faults of various dimensions and directions. The analysis of the faults revealed that 11 are Dip faults, 6 are Strike faults and the remaining 25 faults are Oblique, Dip oblique or Strike oblique faults. Nearly 30 of them, trend in the WNW-ESE to NNW-SSE. Remaining 11 faults trend almost N–S direction. A perusal of the fault throw direction shows that 27 faults dip towards east. While the rest of them towards the west. The throw displacement ranges from 1 m to 250 m and each fault shows decreasing/increasing trend along its direction. The gradient of the coal measures varies from 1 in 4 to 1 in 13. The block, which was initially projected as an underground mine under the SRP-2&2A inclines, could not be continued as its exploitation strategies challenged often due to the presence of numerous faults. Due to favourable stripping ratio and for optimum extraction of coal seams, the SRP-2,2A blocks are recommended for conversion into an opencast mining.

The complexity and vertical disposition of different formations in the area are shown in Fig. 2 with two typical cross sections. These figures indicated that the rock types includes medium to very coarse grained grey/greenish ferruginous sandstone with subordinate clays/sandy shales. The top layer contains weathered soils upto a depth of 5 m which is underlined by Barren measure formations encountered at different depths. These formations were underlined by Barakar formation which consists of predominantly grey/white colour medium to coarse grained sandstones with coal seams and clays extend up to 250 m depth. It has been underlined by Talchir formation which consists of fine to medium grained greenish sandstones, silt stones clays and pebble beds followed by unconformity. The basement of formation in the area belongs to the Proterozoic age Sulluvai red white banded fine grained sandstones and quartzites (Fig. 2).

The Barakar formations are found to be embedded with 8–10 coal seams which are divided into upper and lower members. The upper member starts from the base of VI coal seam up to the Barren measures/Barakar formation in the top with a total thickness 180 m. The lower member extends further deep upto 1000 m from the bottom of the VI coal seam.

4. Aquifer characteristics

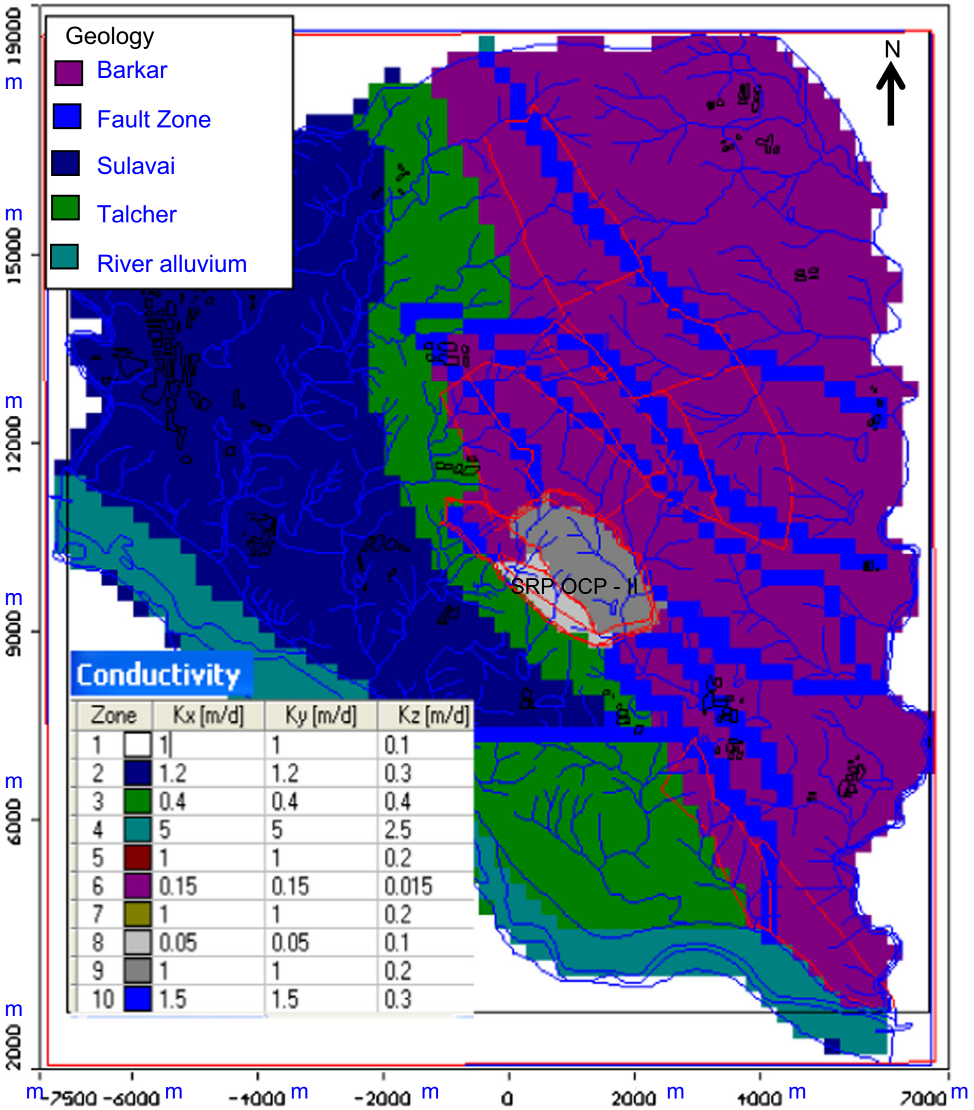
Aquifer performance test was conducted in the block during April 2006 by SCCL. The well is constructed up to a depth of 208 m. The depth to the groundwater level is 5.62 m during April 2006 and the groundwater was found under confined conditions. The test has been conducted with a constant discharge of 197 $m^3\ day^{-1}$. The observed maximum drawdown was 21.46 m in the test well and 6.98 m in the observation well -1 at a distance of 10 m and 5.47 m in observation well -2 at distance of 15 m from the test well. The data has been analyzed using Cooper and Jacob method to obtain the aquifer parameters [4]. The estimated hydraulic conductivity is $9 \times 10^{-2}\ m\ day^{-1}$ and transmissivity 11.16 $m^2\ day^{-1}$ with a storativity of 3.1×10^{-4} [30].

5. Groundwater flow modeling

The variability and complexity of three dimensional heterogeneous subsurface hydrogeologic settings strongly influence the groundwater flow. The reliable conceptualization of the aquifer can be described accurately only through careful hydrogeologic analysis and practice. The numerical model can be better tools to understand the complex groundwater flow process in the typical hydrogeological conditions. Groundwater flow model was constructed in the sub-basin covering the Srirampur Open Cast Project area using Visual MODFLOW [18,1,11] to simulate the groundwater conditions and to evaluate the optimal dewatering scenarios. MODFLOW 2005 is cell-centered, 3D-finite difference model and is the most widely used for calculation of the steady state or transient saturated groundwater flow [13,14,7]. In the present study a steady state groundwater flow model was developed as no major seasonal groundwater level fluctuations were observed in the study area.

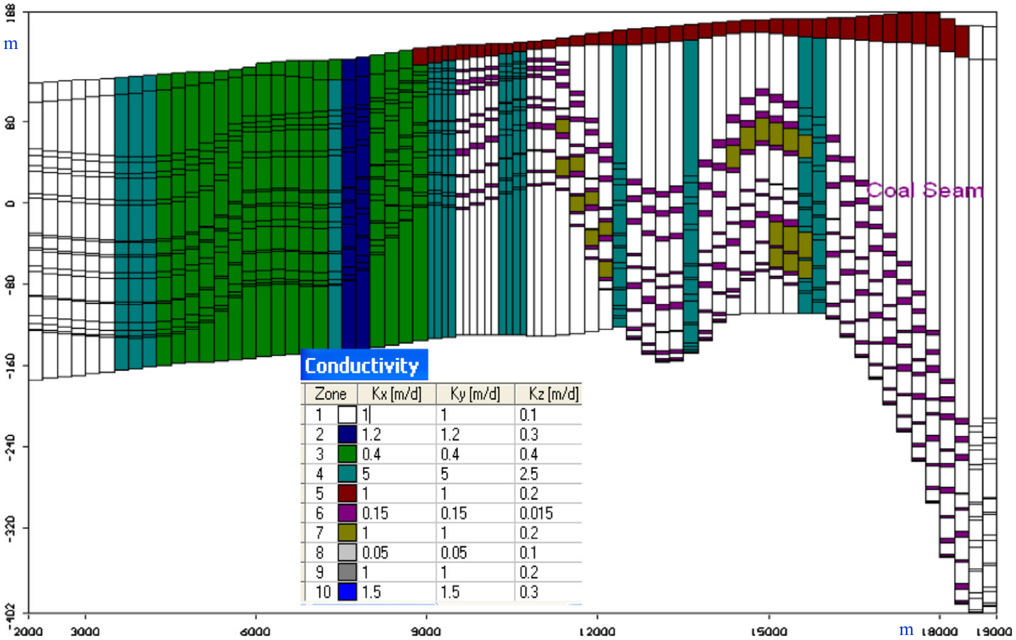
5.1. Aquifer conceptualization and discretization

The discontinuity and anisotropy induced by the fracture networks in the fractured or weathered aquifer systems can be minimized at large scale in an equivalent porous medium (EPM) approach [31,36,33,34]. Therefore, the present study area is simulated as EPM approach using MODFLOW. The entire Srirampur opencast area has been divided into 58 columns and 68 Rows with grid spacing of 250 m × 250 m and 125 m × 125 m in the flow mode. The resistivity investigation and bore well geologic logging are good tools to conceptualize the aquifer system and to understand the subsurface dynamics [23,35,9,17,24]. In the present study the vertical dispositions of aquifer layers are simulated in the model based on the analysis of 183 borehole geologic logs spreads over the area. Then the groundwater model was developed with twenty conceptual layers consisting of Sullavai, Talchir,



Zone	Kx [m/d]	Ky [m/d]	Kz [m/d]
1 ⬜	1	1	0.1
2 🟦	1.2	1.2	0.3
3 🟩	0.4	0.4	0.4
4 🟦	5	5	2.5
5 🟥	1	1	0.2
6 🟪	0.15	0.15	0.015
7 🟫	1	1	0.2
8 ⬜	0.05	0.05	0.1
9 ⬛	1	1	0.2
10 🟦	1.5	1.5	0.3

Fig. 3. Spatial disposition of hydraulic conductivity for each geologic formation in Srirampur OCP2, SCCL, Adilabad District, A.P.



Conductivity

Zone		Kx [m/d]	Ky [m/d]	Kz [m/d]
1	⬜	1	1	0.1
2	🟦	1.2	1.2	0.3
3	🟩	0.4	0.4	0.4
4	🟦	5	5	2.5
5	🟥	1	1	0.2
6	🟪	0.15	0.15	0.015
7	🟫	1	1	0.2
8	⬜	0.05	0.05	0.1
9	⬛	1	1	0.2
10	🟦	1.5	1.5	0.3

Fig. 4. Vertical disposition of different geologic layers and distribution of hydrualic conductivity for each geologic formation in the study area covering Srirampur OCP-II project.

Barakar sandstones and are inter bedded with coal seams, Barren measure and Kamthi formations with a total thickness of about 311 m (Figs. 3 and 4).

5.2. *Model parameters and boundary conditions*

The boundary conditions are a key component of the conceptualization of a groundwater flow system [6,5,20,28,26]. Hydrological boundaries are assigned to the model based on topographic maps and field investigations. The hydraulic conductivity of the different geologic formations are estimated by pumping tests carried out in the area. The estimated hydraulic conductivity of Barakar formation is 0.1 m day^{-1} and for Talcher and Sulavai formations it is 0.5 m day^{-1} and 1.4 m day^{-1}, respectively. In contrast, the hydraulic conductivity of Godavari River alluvium is of 4 m day^{-1} and the hydraulic conductivity of fault zones were found as 1.5 m day^{-1}. The same hydraulic properties were given to the model to simulate the groundwater fluxes across the study area (Figs. 3 and 4). The spatial distribution of hydraulic conductivity is shown in Fig. 3 and vertical distribution is shown Fig. 4. The River boundary condition is assigned to the Godavari River and two perennial streams Pedda vagu in the east and Rallavagu on the west, using the stream bed elevations and River stage collected in 2008. The constant head boundary condition was used in the north eastern part of the area and south east adjacent to the Godavari River which matches with the observed hydraulic heads in the area (Fig. 5). The mine extensions in different scenarios are also shown in Fig. 5. The groundwater seepage from the working mines are being collected in the sumps of various seams at different elevations and then pumped out. The same pumping has been distributed appropriately using appropriate screen location according to the depth of working mines in the mining areas in the flow model (Fig. 6 and Table 2).

In the study area, field level recharge estimations are not available. However, groundwater resource estimation committee (GEC) recommended recharge estimates in different geologic terrains in India based on local climate and geology through the evaluation of a number of field level investigation data throughout India [10]. It is suggested that 10–12% recharge could be considered in

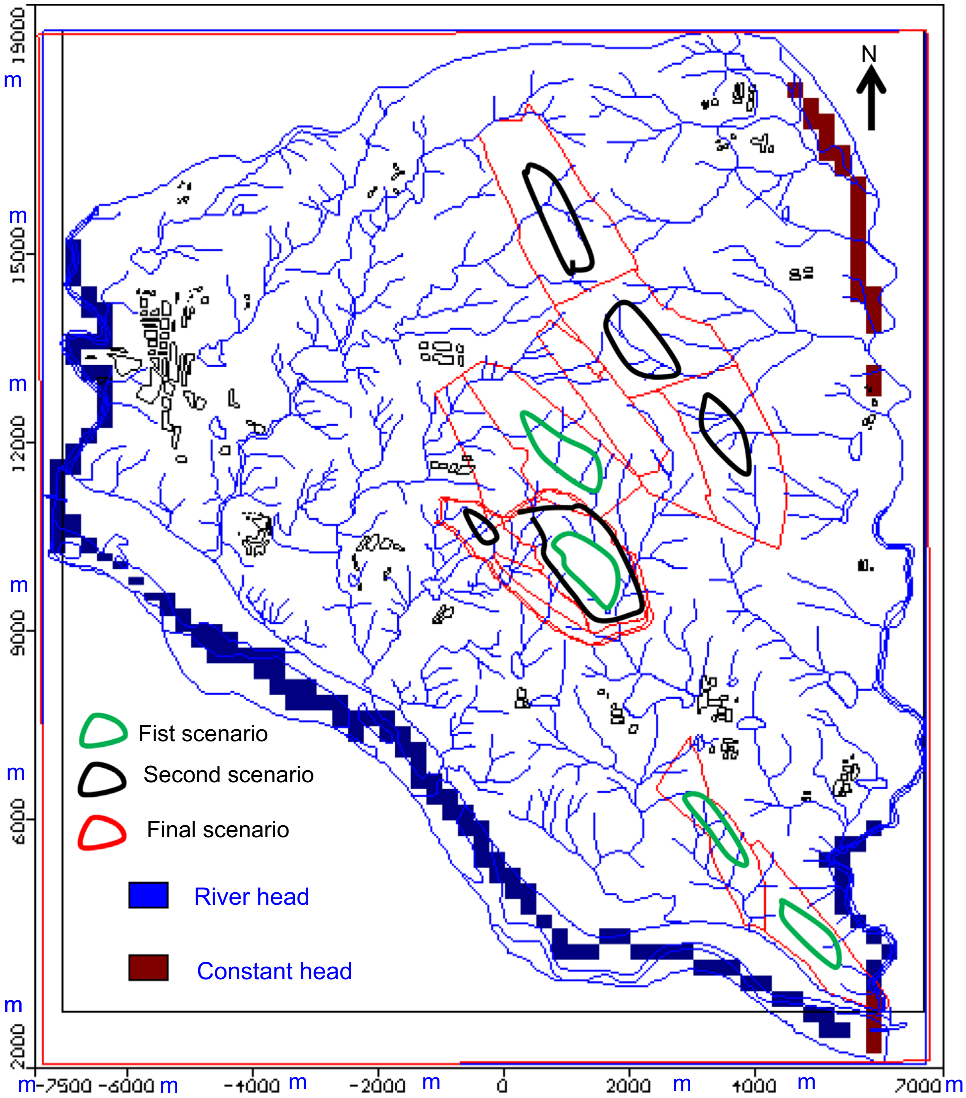


Fig. 5. Boundary conditions and mine extensions in different scenarios in the flow model.

the annual rainfall in hard rock aquifers and 15–30% in alluvial aquifers. So that for the present study, the back groundwater recharge has considered as 12% (110 mm yr^{-1}) in the annual rainfall in the area that was distributed uniformly throughout the area. However, the groundwater recharge in the alluvial formations of the Godavari River course was assigned as 350 mm yr^{-1}.

6. Results and discussions

6.1. Model calibration and sensitivity analysis

Groundwater flow model calibration is achieved through a trial and error method by adjusting the two key parameters i.e., hydraulic conductivity and recharge rates. During the model calibration 22

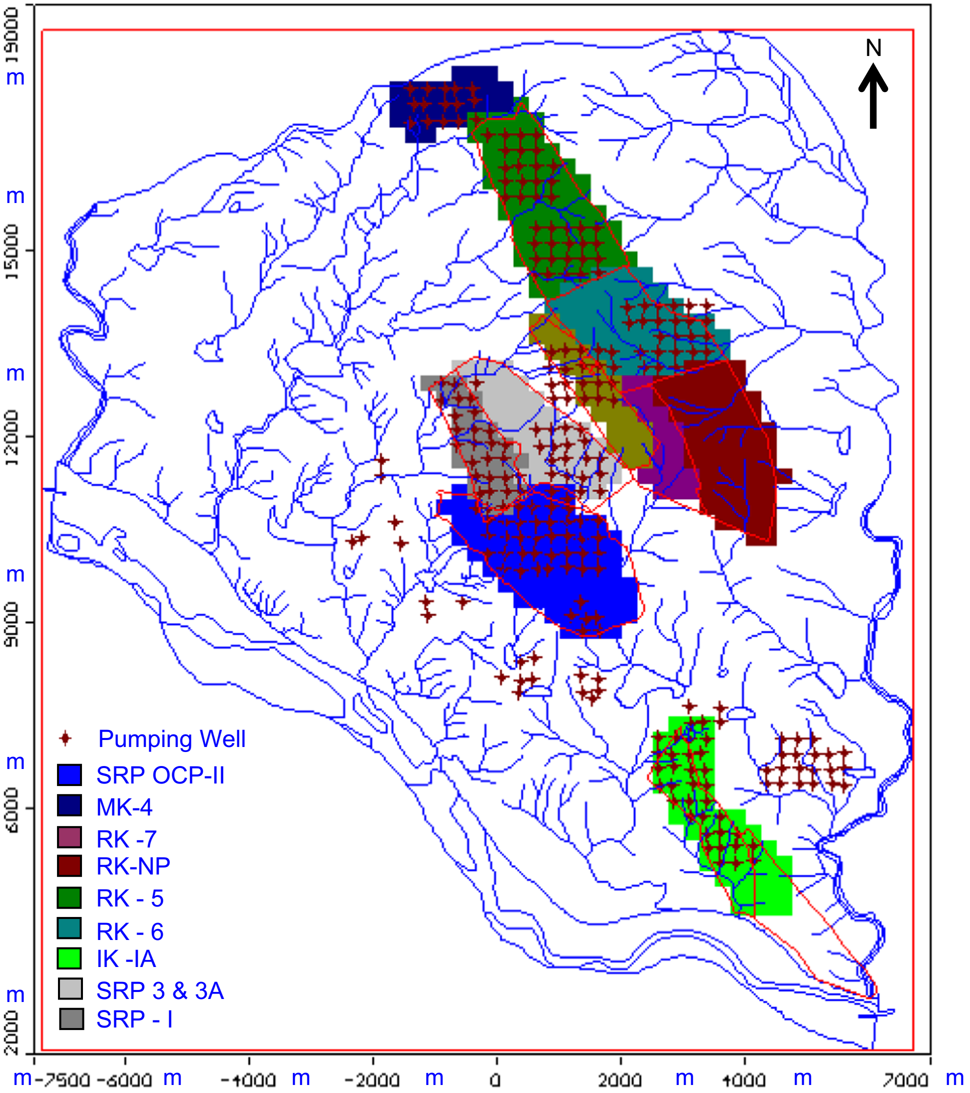


Fig. 6. Pumping from mine floor and in the villages—Srirampur OCP-II project.

Table 2
Groundwater pumping from the existing mines in the study area.

Mine name (shown in Fig. 6)	Pumping from mine floor $m^3\ day^{-1}$
MK-4	4032
RK-5	1940
RK-6	3055
RK-7	4860
RK-8	2022
RK-NP	774
IK-1A	3150
SRP-I	2962
SRP-3 &3A	2916

observed hydraulic heads measured in April 2006 are used (Fig. 7). During the sensitivity analysis [16,12,27,2], it is observed that model is highly sensitive to both hydraulic conductivity and recharge. Then the average hydraulic conductivity simulated in the groundwater flow model has been moderately modified to 0.15 m day^{-1}, 0.4 m day^{-1}, 1.2 m day^{-1} and 5 m day^{-1} for Barakar, Talchar, Sulavai formations and River alluvium, respectively (Figs. 3 and 4). The recharge has been redistributed based on the observed hydrogeology and estimated aquifer hydraulic conductivity by matching observed and computed groundwater heads. The distinction of recharge area, intermediate area and discharge area with the groundwater recharge rates of 100, 90 and 80 mm yr^{-1} respectively have been simulated during the model calibration (Fig. 8). The recharge in alluvial plains of the Godavari River was reduced to 332 mm yr^{-1} (5% was reduced in the initial value). Then the reasonable match between observed and calculated heads is achieved (Fig. 9). At the end of the model

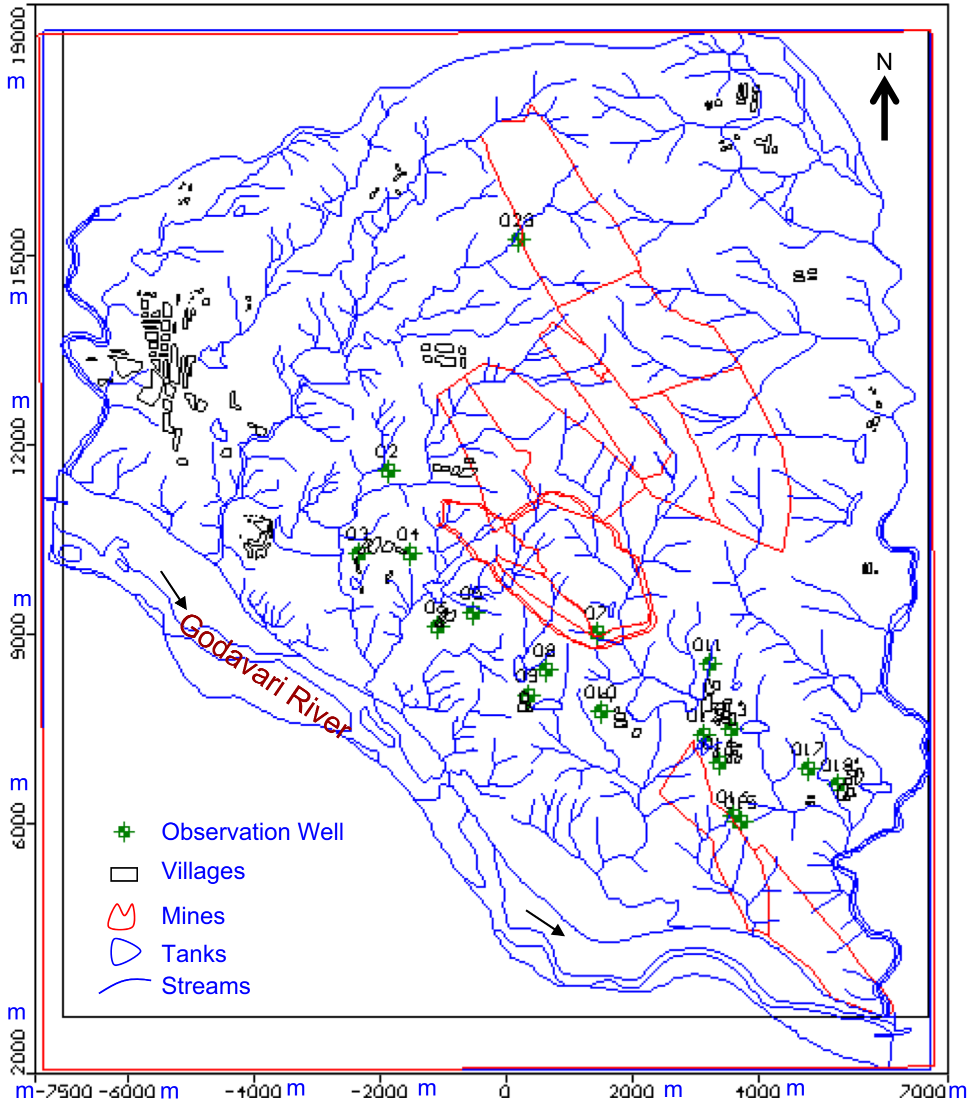


Fig. 7. Location map of observation wells in the Srirampur OCP-II area in the flow model.

calibration the RMS and NRMS errors are 3.2 and 2.1, respectively. The model has been validated with the observed groundwater heads measured in June 2006 and there is no significant change in RMS and NRMS. Therefore, the model was considered as well calibrated for observed field hydrogeological conditions. The computed groundwater contours indicated that the groundwater flow direction towards mine pits from the aquifer and general groundwater flow direction towards the Godavari River from groundwater aquifer (Fig. 10).

6.2. Groundwater budget and model predictions

The regional groundwater budget is estimated using zone budget package in Visual Modflow. The area has been divided into 12 major zones for making groundwater budget computations for the

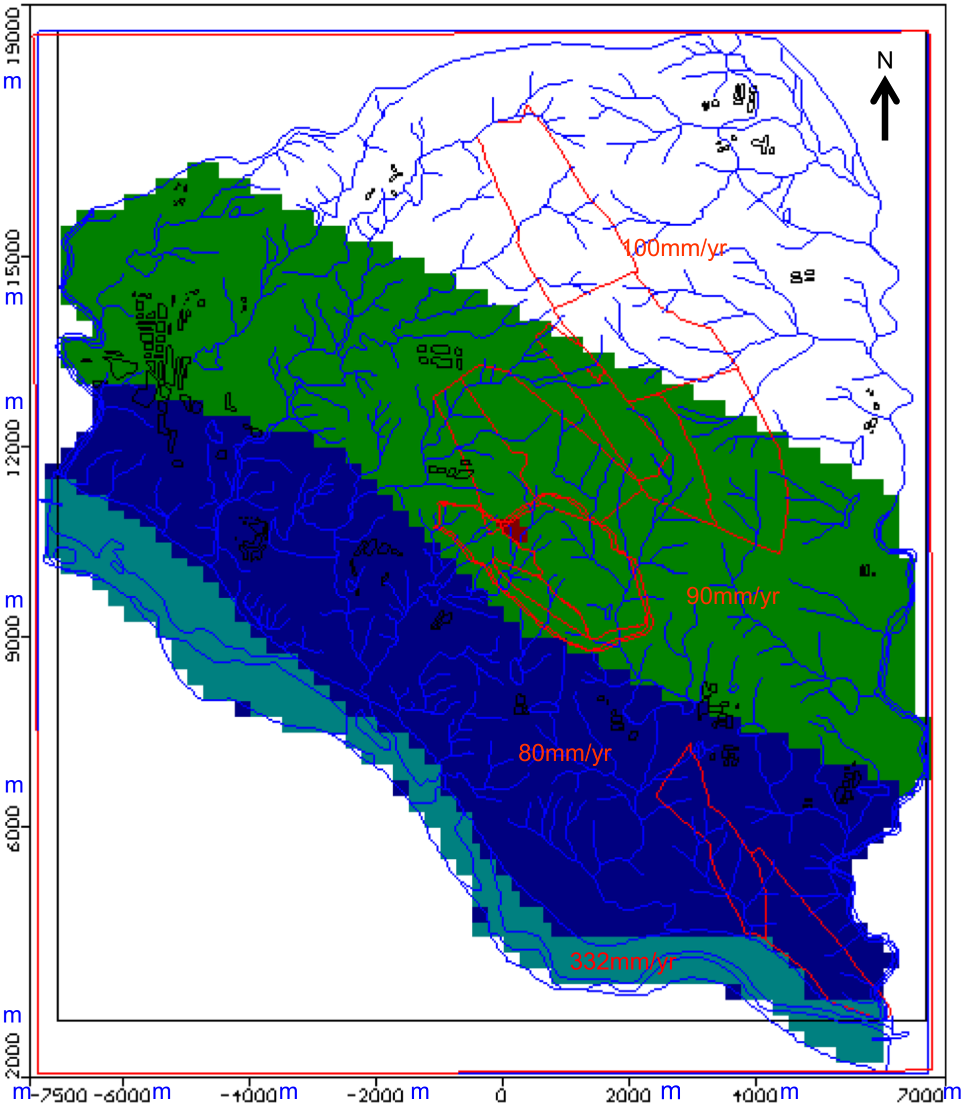


Fig. 8. Simulated distributed groundwater recharge in mm yr^{-1} in the study area.

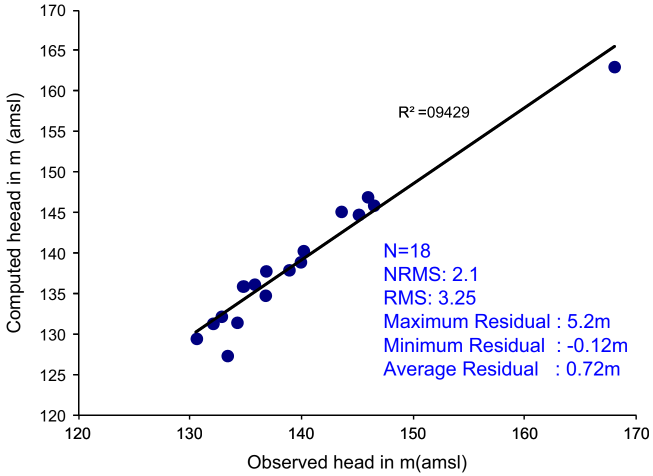


Fig. 9. Computed versus observed ground water level in m (amsl) in the study area.

benefit of mine management authority of SCCL. This could help to SCCL to handled further to update or predict inflows at different mine development stages (Fig. 11). The extent of quarry area and depth of mine floor varies from initial stage to final stage during the open cast mining. Depending on the availability of mine void space, internal dumping of overburden material will take place adjacent to the active mine floor. Hence, groundwater conditions vary dynamically during mine development. The stage wise groundwater mine floors are simulated using stage wise mine plans by incorporating the quarry area, depth and extent of internal dump. Accordingly the hydraulic parameters were modified in the quarry areas under different mine stages in the groundwater flow model.

The groundwater balance for the entire study area for six different mine development stages are presented in Table 3 and Fig. 5. Fig. 5 show that areal extension of mine development in three scenarios. The areal extension has been increased from first to third scenario and depths vary at different development stages. Table 3 explains the groundwater withdrawal scenarios and interactive flows between different layers/zones. The computed groundwater budget for the entire sub-basin indicates that most of the flow is taking place along the fault zones. The predicted groundwater inflows into a different mine pits at different mine development stages is attempted by importing corresponding elevations and the results are shown in Table 4. The net predicted groundwater inflows into the SRP OCP-II mine is 5877 m^3 day^{-1} in the 1st scenario at +124 m (amsl). The next scenario was simulated at +93 m (amsl) mine floor, at this stage the predicted groundwater inflow into the SRP OCP-II is 12,818 m^3 day^{-1}. The third scenario is simulated at +62 m (amsl) mine floor level and the predicted groundwater inflow into the SRP OCP-II mine is 12,910 m^3 day^{-1}. The groundwater inflows at +41, +0 and −41 m amsl are 20,428 m^3 day^{-1}, 22,617 m^3 day^{-1} and 14,508 m^3 day^{-1}. The moderate reduction in groundwater inflows at −41 m amsl than other scenarios is due to reduction in areal distribution of mining.

The controlled groundwater operations in the coal mines covering Zones 3 and 5 indicate uniform lateral flow towards the Mines. The computed inflow is 8000 m^3 day^{-1} from the area towards the working mines RK5 incline and RK6A incline (Table 4). The model computations indicate that Zone 10 (MK4 inc) and Zone 11 (IK1A inc) would be receiving a very meager flows 201 m^3 day^{-1} and 2891 m^3 day^{-1} respectively under current mine development scenario. The backfilling of void spaces with overburden will help to stabilize the groundwater inflow during mine development. A small amount of inflow is expected into the Zone 6 (RK7) and Zone 7 (RK8) due to ongoing mining activities in the Zones 4 and 5. The relative increase in computed inflow into the Zone 8 (SRP3 and 3A) and Zone 9 (SRP1) indicate the influence of lateral flows. The groundwater budget computations at different mine development stages of SRPOCP indicate that the Godavari River is mainly acting as influent

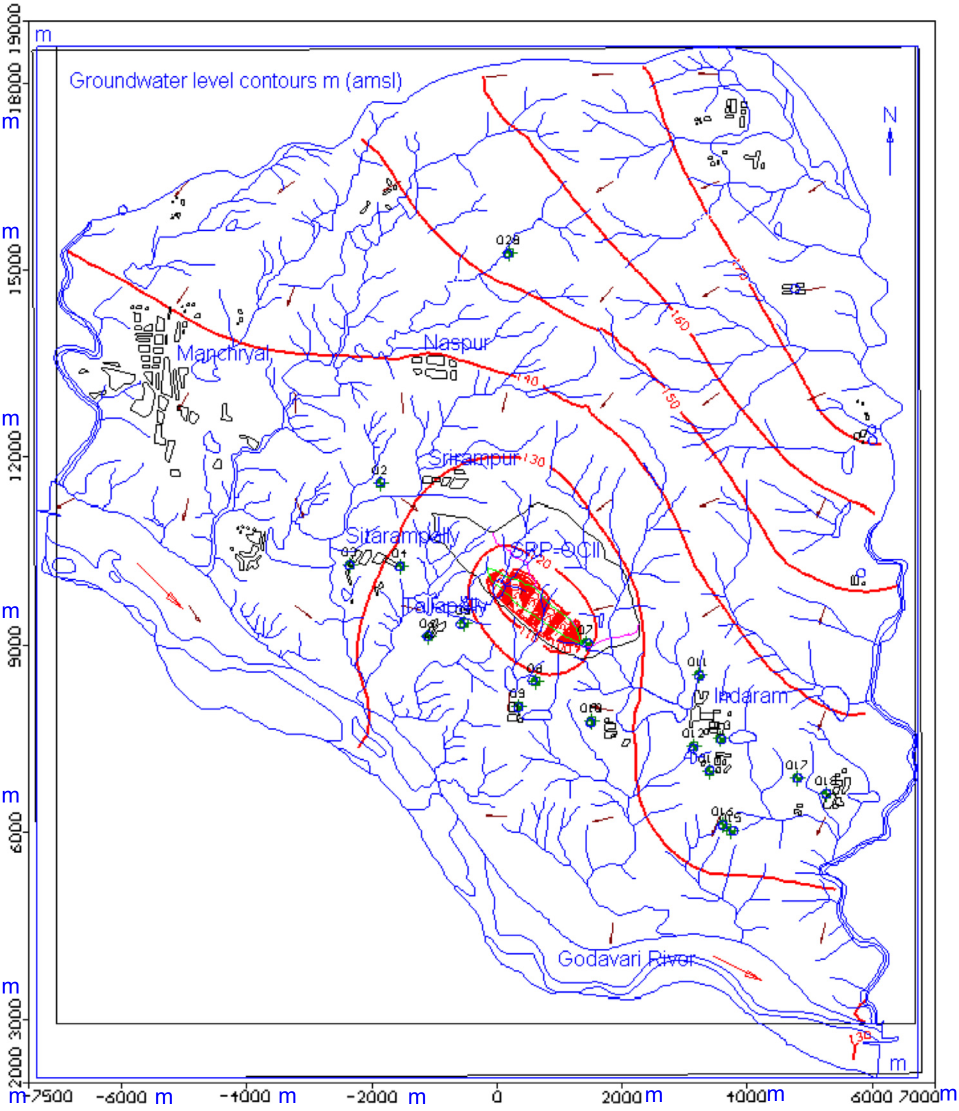


Fig. 10. Computed groundwater level contours in m (amsl) in the study area.

stream during most of the time in the area. The influent nature of the Godavari River provides replenishment of groundwater inflow around the SRP OCP. The groundwater flow model is not considered direct surface runoff into mine pits, therefore in making withdrawals/pumping plans the direct runoff must be considered.

7. Conclusions and recommendations

The present study area has simulated complex groundwater flow process in the typical hydrogeological conditions with the help of high resolution hydrogeologic information and numerical

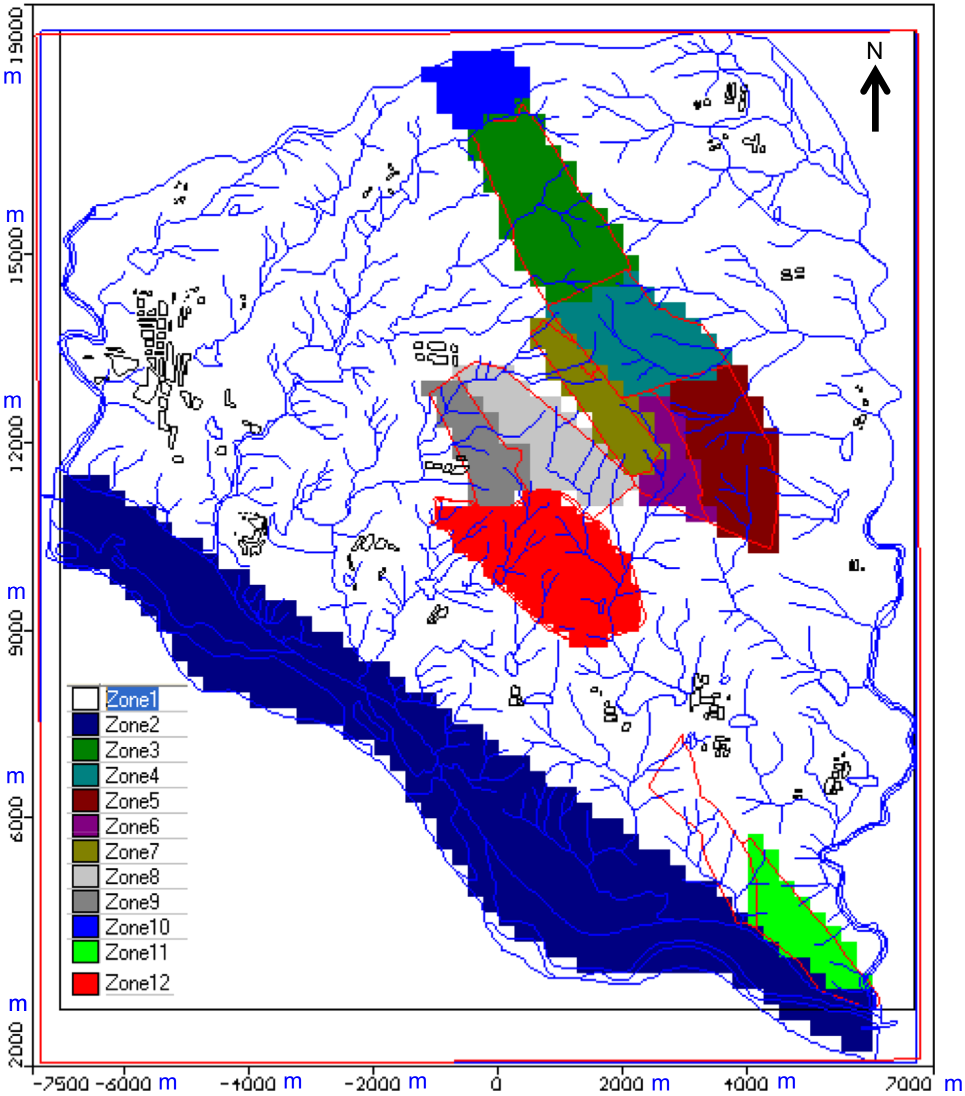


Fig. 11. Different zones for the computation of groundwater balance in the study area.

modeling studies. It provides significant understanding of the groundwater flow in the region using equivalent porous medium approach. The analysis of hydrogeology indicated that faults are controlling factors for groundwater seepage in the area. The groundwater inflow into the quarry is mainly dependent on quarry floor level and surrounding groundwater level. The calibrated numerical model against the measured potentiometric surface under the assumed steady-state conditions predicted that the proposed open cast mine (SRPOCP-II) would require a groundwater pumping of 5877 m day^{-1} in the first stage of development. In the second and third development stages the required groundwater pumping would be 12,818 m day^{-1} and 12,910 m day^{-1}, respectively. In the final stage of mine development 14,504 mday^{-1} of groundwater pumping is required. Groundwater budget in the area indicated that Godavari River mainly receives base flows from the groundwater aquifer system. Further the model could help to mine development authority to know groundwater inflows into mine pits at required depth by updating the models with relevant data to install required pumping infrastructure. The

Table 3
Groundwater balance in the study area.

In put in m^3 day^{-1}		**Out put in m^3 day^{-1}**	
In the first scenario (mine floor at 124 m (amsl))			
Lateral inflow	36,237	Lateral out flow	14,963
Recharge	18,886	Groundwater pumping from the mines	21,763
Godavari River and streams	17,491	Godavari River and streams	35,885
Total = 72,614		Total = 72,611	
In the second scenario (mine floor at 93 m (amsl))			
Lateral inflow	36,583	Lateral out flow	23,176
Recharge	31,751	Groundwater pumping from the mines	22,385
Godavari River and streams	17,052	Godavari River and streams	39,820
Total = 85,386		Total = 85,381	
In the third scenario (mine floor at 62 m (amsl))			
Lateral inflow	36,593	Lateral out flow	23,853
Recharge	31,726	Groundwater pumping from the mines	22,460
Godavari River and streams	17,743	Godavari River and streams	39,739
Total = 86,062		Total = 86,052	

Table 4
Total groundwater inflows into different mine pits in the study area.

Zone name referred in Fig. 11	Net inflows (m^3 day^{-1}) into different zones at different depths in m amsl					
	+124 m	+93 m	+62 m	+41 m	+0 m	−41 m
Zone 2	7617	8,300	8,213	2,792	580	4,746
Zone 3	3412	3,417	3,417	3,636	4,291	3,449
Zone 4	8291	8,716	8,718	12,363	11,095	8,649
Zone 5	6447	6,922	6,920	8,321	−18,334	6,687
Zone 6	−1563	−2,158	−2,160	−2,877	−3,851	−1,834
Zone 7	−3044	−3,517	−3,518	−6,070	−4,477	−3,596
Zone 8	3779	3,993	3,997	9,783	2,929	4,758
Zone 9	421	752	751	2,188	1,332	684
Zone 10	201	82	82	135	288	99
Zone 11	2819	2,785	2,784	2,763	2,791	2,778
Zone 12 (SRP-OCP II)	5877	12,818	12,910	20,428	22,617	14,504

study may be a typical case study for solving similar complicated mining hydrogeological environments. It can help for better understanding of hydrogeologic system to design of optimal groundwater withdrawal schemes for dewatering mine pits for safe mining. The major limitation of the model is uncertainties associated with aquifer parameters simulated in the model can play major role in model results.

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