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RESEARCH ARTICLE - HYDROLOGY

Management of dewatering schemes in an open cast mine operation using groundwater flow modeling: a case study of karst aquifer, Tamil Nadu, India

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Abstract

An efficient dewatering scheme helps the management authority of mines in decision-making on the minimum quantity of withdrawal of groundwater from open-cast mines to avoid excessive groundwater withdrawal from the mines. Karst aquifers are characterized by a dual flow system consisting of Darcy flow and non-Darcy flow in the Matrix and conduits respectively. Due to lack of site-specific data, it is difficult to model the flow behavior in the dual flow system. This study evaluated equivalent porous medium (EPM) approach and the hybrid approach/combined discrete-continuum approach (CDC) for modeling groundwater flow in a karst aquifer and found that hybrid approach is suitable for modeling the flow in the karst aquifer system. Hybrid approach is applied to derive the optimum dewatering scheme for safe mining of limestone in the Adanakurichi limestone mines of Tamil Nadu, India and was found that an additional 20% increase in pumping is required in the year 2020 compared to 2016 to bring the water level to the limestone bottom. Wavelet coherence diagram was used to identify the interrelation between rainfall and groundwater levels, and also between the groundwater levels at different locations. The results from the study will be helpful for the better management of groundwater control operations in karst aquifers, under various safe level of operations. MODFLOW 2005 was used to model the aquifer based on EPM approach and for modeling based on hybrid approach conduit flow process (CFP) Mode 1in MODFLOW was used.

Keywords Karst aquifer · Groundwater modeling · Equivalent porous media model · Hybrid approach · Conduit flow · MODFLOW

Introduction

The success of a dewatering scheme for open cast mining operation depends on understanding the groundwater flow in the region. Unplanned dewatering may lead to excessive pumping from the mines which result in devastating effect on the water levels in the nearby area. That too, if the nearby area is highly dependent on agriculture, the over-pumping would lead to a disaster. When the dewatering operations are to be from karst aquifers, management of dewatering operations will be difficult. Karst aquifers are formed due to the dissolution of carbonate rocks such as limestone and sandstone. Groundwater flow in a karst aquifer is very complex due to these conduits. The homogeneity and isotropy assumptions of the groundwater flow problems are not valid in case of Karst aquifers. Also, Darcy's law is applicable only if the flow is laminar. The flow in porous media fulfills these conditions, but in Karst aquifers, the flow will not be laminar. This leads to difficulty in the groundwater modeling of karst aquifers. In the past, many modeling approaches had been used for the karst aquifer flow modeling. The simplest model is the equivalent porous media approach. Here fractures/conduits are replaced with high permeable cells and laminar flow is assumed in both the conduits and matrix

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continuum (Long et al. 1982; Scanlon et al. 2003; Linde Quinn et al. 2006; Putnam and Long 2009; Varalakshmi et al. 2014; Surinaidu et al. 2014). Most commonly used code for EPM approach is US Geological Survey MODFLOW code (McDonald and Harbaugh, 1988). Scanlon et al. (2003) conducted a study to evaluate lumped and distributed parameter-based equivalent porous media approaches for simulating regional groundwater flow in a karst aquifer. MODFLOW-96 code was used for the distributed parameter model. The lumped parameter model developed by Barrett (1996) was used to simulate water levels and spring discharge for 1989–1998. The models were applied to the Barton Springs Edwards aquifer, Texas. The results showed that, if the modeling study is to simulate spring discharge either distributed or lumped parameter models can be used. Lindgren et al. (2004) also simulated the Edwards aquifer with a laminar EPM in which the anisotropic effects of faults were incorporated in the model using the MODFLOW horizontal-flow barrier. Varalakshm et al. (2014) used EPM approach using MODFLOW to develop a three-dimensional groundwater flow model for weathered and fractured formations in the Osmansagar and Himayathsagar catchments in India. Surinaidu et al. (2014) used MODFLOW to estimate the groundwater inflow into the Godavari valley coalfields in Andhra Pradesh, India.

In actual cases, due to the presence of conduits, groundwater flow may or may not be laminar. Another approach is the hybrid approach/combined discrete-continuum approach (CDC), in which discrete karst conduits are coupled with matrix continuum. (Kiraly 1998; Liedl et al. 2003; Reimann et al. 2011; Saller et al. 2013; Xu and Hu 2017). Turbulent conduit flow simulation known as conduit flow process (CFP) was added by Shoemaker et al. into MODFLOW (Shoemaker et al. 2008). In the CFP for MODFLOW, there are three options to represent conduit. In CFP-Mode 1, conduits are assumed to be consisting of discrete pipe network. In CFP-Mode 2, a high-conductivity zone for representing turbulence, instead of a conduit. CFP-Mode 3 is a combination of Mod 1 and Mod 2. Conduit network and various parameters namely position, elevation, diameter, roughness, etc. to describe the conduits are required in CFP -Mode 1. In many cases, the exact position and the specific characteristics of the highly permeable conduit system like shape, elevation, diameter, etc. are unknown (Bakalowicz 2005). Reimann and Hill (2009) examined a single conduit surrounded by a matrix using the CFP code. They compared the performance of CFP mode 1 and EPM. MODFLOW 2005 was used for simulation based on EPM approach and concluded that incorporating turbulent flow in a discrete conduit network improves the performance of the model, especially during extreme hydrological condition such as low recharge conditions. Hill et al. (2010) conducted a local-scale study comparing the performance and accuracy of MODFLOW-2005 to CFP by modeling a site near Weeki Wachee, Florida. Using CFP mode 1, simulated the discharge and water levels of the karst aquifer. Overall, it was found that the CFP model produced more accurate results than the MODFLOW 2005 model. Hill et al. (2010) mentioned in their study that, this increase in accuracy is due to the exchange parameter between conduit and matrix, and not to the modeling of turbulent flow by CFP. Saller et al. (2013) have modified an existing Equivalent porous media model (EPM) developed by Putnam and Long (2009) for the Madison aquifer in western South Dakota (USA) to include the conduit network. Putnam and Long used MODFLOW to develop the EPM model. Saller et al. used MODFLOW-CFP Mode 1 for the coupled continuum pipe-flow approach. In their study, they identified the location of conduits based on tracer studies. The model was calibrated with the head observation well data and spring flow.

Precipitation is one of the major sources of groundwater recharge. Understanding the response of groundwater level with respect to precipitation is very important for groundwater management. A few studies have been carried out in the application of Wavelet Coherence analysis in water resources applications. Torrence and Webster (Torrence and Webster 1999) applied the method of wavelet coherency to the El Nino–Southern Oscillation (ENSO) and monsoon indices for Indian Monsoon. Nourani and Mousavi (2016) used cross-wavelet coherence analysis to evaluate the groundwater level pattern at different time scales. Roshni et al. (2019) used Wavelet Coherent Analysis (WCA) to study the interdependence between different model inputs and output variables of Feedforward Artificial Neural Network (FFANN) and the hybrid WANN model to study the groundwater fluctuation. Sithara et al. (2020) used wavelet coherence diagram to determine the influencing variable in sea level projection studies. Qi et al. (2018) used a method that combines singular value decomposition and cross-wavelet approaches to identify the spatiotemporal relationship between groundwater level dynamics and precipitation for Napoli River Basin, Northeast China. The results showed that the major mode of relationship between groundwater and precipitation was divided into four patterns in the study area and the response of groundwater level dynamics is very sensitive to heavy precipitation in all patterns.

The India Cement Limited (ICL) is the largest cement producer in south India. ICL is carrying out lime stone opencast mining from the Adanakurichi limestone mines in Tamil Nadu India for cement manufacturing. Mining of Limestone from the Adanakurichi limestone mines is facing a complex hydrological problem due to the seepage of water from the limestone aquifer and it causes flooding in that areas, which disrupts the mining operations. To control the groundwater seepage from the lime stone aquifer, it is necessary to dewater the same for facilitating the mining operations. The mine

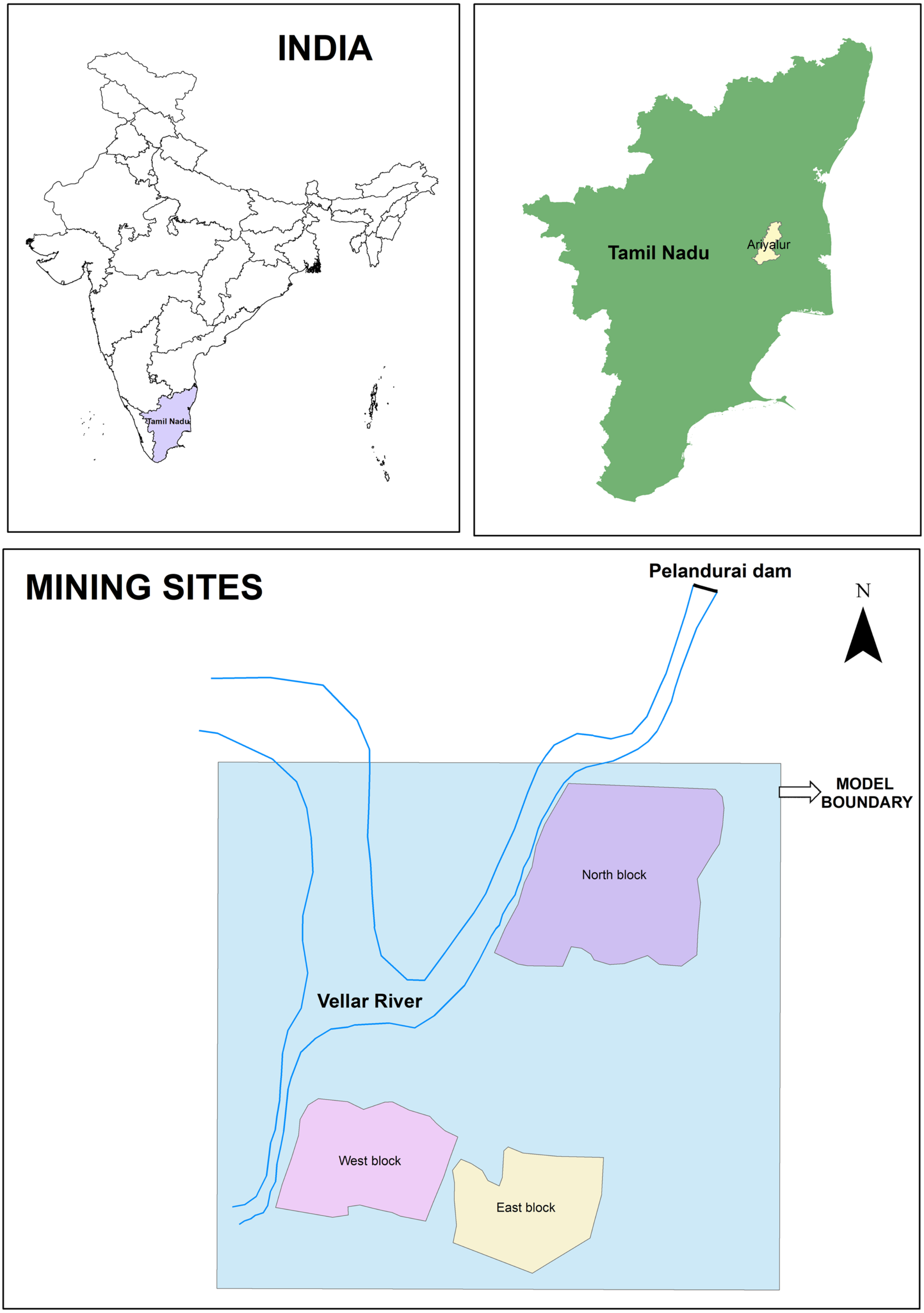


Fig. 1 Study area

Table 1 The lithology and stratigraphy

Sl no	Age	Formation	Hydro-geologic unit
1	Cenozoic	Alluvium, sandstone/lime stone/marl	Water Table aquifer/
		Lime stone fractured/weathered	Confined aquifer 1/
		Lime stone/sand stone	Confined aquifer 2
2	Mesozoic (Cretaceous)	Calcareous clay	Low permeability

dewatering is done by drilling wells in the karst aquifer. The main aim of the study is to comparatively evaluate the EPM model and the hybrid approach for predicting groundwater flow in the karst aquifer in the Adanakurichi limestone mines to determine the amount of pumping required for safe mining. For Equivalent Porous media approach MODFLOW 2005 and for hybrid approach, MODFLOW CFP-Mode 1 were used. After calibration, the model was demonstrated for predicting future scenarios.

Most of the modeling studies in India related to groundwater withdrawal for open cast mine operations from karst aquifers are done using equivalent porous media approach. In previous studies related to Karst aquifer modeling, most of the work describes the applications where the fracture network is known. The present study focuses on finding the fracture network through inverse modeling and carryout modeling studies to determine the dewatering schemes. The modeling of dewatering scheme in Karst aquifer to derive optimal pumping strategies is a unique modeling concept is the main thrust of this paper. Also, use of Wavelet Coherence for clustering the well along with numerical modeling is a new approach.

Materials and methods

Study area

The study area is in Adanakurichi limestone mines, Ariyallur district of Tamilnadu, India (Fig. 1). The terrain is more or less flat with a gentle slope from East to West. The highest elevation is 65 m above Mean Sea Level in the east and lowest of 42 m above Mean Sea Level towards western side. The drainage is controlled by the Vellar river, which runs on the northwestern side of the West block and almost parallel to the Western boundary of North block. The total extent of Adanakurichi limestone mine is 5.59 km^2.

Geology

Geologically the area is underlain by sedimentary formations ranging in age from Cretaceous to Cenozoic of Indian Stratigraphy consisting of sandstones, limestones, clay, marl, and unconsolidated alluvium. The lithology and stratigraphy are shown in Table 1. The groundwater generally under phreatic to confined conditions. Base on this, the aquifer system is conceptualized into three hydrogeological units: the upper water-table aquifer, the middle confined aquifer (Karst aquifer), and the lower confined aquifer. The conceptual model is given in Fig. 2. The thickness of the Karst aquifer varies from 12 to 66 m. A few bore logs in East and West block shows fractured limestone. The exact locations and fractures in the study area are unknown and no tracer test had been conducted in the area. Karst features such as sinkholes and springs don't exist in the area.

Climate and rainfall

The area is characterized by tropical climate with long and severe summer, moderate monsoon, and mild winter. March to May are summer months which are followed by the Southwest monsoon (June to August). However, the real monsoon months are September, October, November, and December when the area is influenced by Northeast monsoon, which is followed by winter months. About 15% of the rainfall is brought by the southwest monsoon 70% is brought by the northeast monsoon and the balance is spread over the rest of the months of the year. Highest rainfall is in November and the minimum rainfall occurs in the month of February. The maximum number of rainy days is also recorded in November and minimum in March. The winter starts in December and continues till the end of February. The average annual rainfall of this area is 1200 mm based on 70 years' average. The mean wind speed at maximum temperature (40 °C) is 8.5 km per

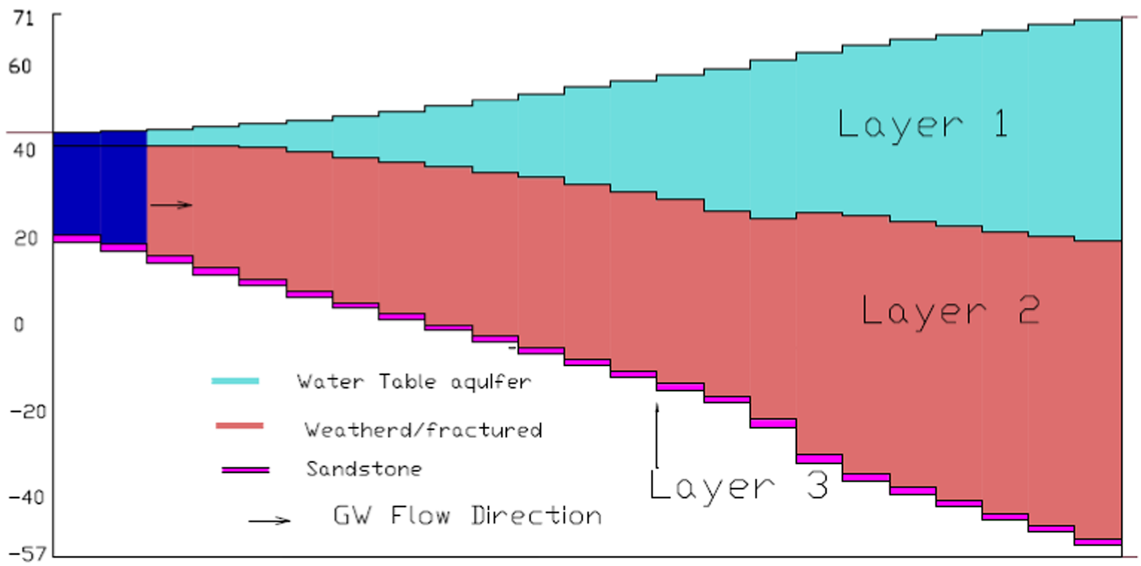


Fig. 2 Model conceptualization

hour. The maximum and minimum temperatures are 41 °C and 21 °C respectively.

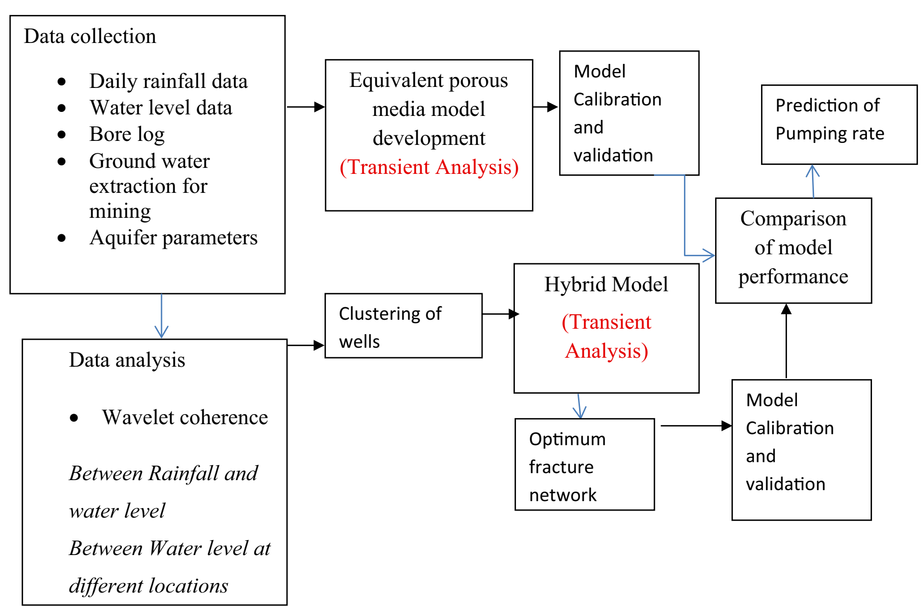
Data used

The following data had been collected from The India Cement Limited (ICL), Tamil Nadu, India.

- Water level data during 2012 to 2016 for 7 wells
- Aquifer parameters based on the pumping test conducted by India Cement Limited
- Pumping rate from the existing wells during 2012 to 2016
- Lithological data from 76 bore wells details
- Monthly rainfall data during 2012–2016

The overall methodology is shown in Fig. 3. The main aim of the work is to compare the EPM model and hybrid approach in modeling the karst aquifer in limestone mining area to get the required future pumping. The main problem in the study area is due to the seepage of water from the karst aquifer which causes flooding and thus disrupts the mining operations. To control the ground water seepage from the karst aquifer, it is necessary to dewater the same for facilitating the mining operations. This is achieved through

Fig. 3 Methodology



a number of groundwater pumping wells in the aquifer and a transient analysis was performed. Since the exact location of fracture or conduits is not known, Wavelet Coherent Analysis (WCA) is performed to cluster the wells based on influence of rainfall on groundwater level and also based on the water level coherence between different locations. This was required for the hybrid approach. In the hybrid approach, the lithological details and information obtained from Wavelet Coherence analysis were used to obtain an initial pattern of the network, and during the calibration, it was slightly varied and determined the optimum network. Using the best model pumping was predicted for the year 2020.

Analysis of data

Wavelet Coherent Analysis (WCA) has been applied to study the time-varying correlation between various factors influencing the karst hydrology as a function of frequency. The wavelet coherence diagram can be used to compare tw-time series in time–frequency domain and is an indicator of relationship between variables in a time–frequency frame, with values ranging from 0 (low coherence) to 1 (high coherence). The groundwater level is mainly influenced by rainfall and the groundwater draft for opencast mining. The exact location of fracture or conduits is not known. To cluster the wells based on influence of rainfall on groundwater level and also based on the water level at different locations, WCA was performed. The Wavelet Coherence of two-time series is given by Eq. (1) (Torrence and Webster 1999; Grinsted et al. 2004):

$$R_n^2(s) = \frac{\left|S\left(s^{-1}W_n^{XY}(s)\right)\right|^2}{S(s^{-1}\left|W_n^X(s)\right|^2.S(s^{-1}\left|W_n^Y(s)\right|^2}, \tag{1}$$

where S is a smoothing operator, s is the scale, $W_n^X(s)$ and $W_n^Y(s)$ are wavelet transforms of $X(n)$ and $Y(n)$ time series. Smoothing is necessary, otherwise, coherency would be identical at all scales and times. $W_n^{XY}(s)$ represents the cross wavelet spectrum between $X(n)$ and $Y(n)$:

$$W_n^{XY}(s) = W_n^X(s)W_n^{Y*}(s) \tag{2}$$

$$S(W) = S_{\text{scale}}\left\{S_{\text{space}}(W(s,\tau))\right\}, \tag{3}$$

where $W_n^{Y*}(s)$ is complex conjugate of $W_n^y(s)$, τ is the position, S_{scale} represents the smoothing along the wavelet scale axis, S_{space} represents smoothing in time axis.

Torrence and Webster (1999) defined the Morlet smoothing operator as:

$$S_{\text{space}}\left(W(s,\tau) = \sum_{k=1}^{N}(W(s,\tau))\frac{1}{s\sqrt{2\pi}}\exp\left(-\frac{\left(\tau - x_k\right)^2}{2s^2}\right)\right) \tag{4}$$

$$S_{\text{space}}\left(W(s_k,X) = \frac{1}{2m+1}\sum_{j=k-m}^{k+m}\left(\left(S_{\text{space}}W(_{S_j}X)\right)(0.6s_j)\right), \tag{5}$$

where Π is a rectangular function, j is a scaling function, N is sequence length. 0.6 is decided on experience for Morele wavelet. More details about wavelet coherence are available in the studies carried out by Torrence and Webster (Torrence and Webster 1999) and Grinsted et al. (2004). In this study, the wavelet analysis was performed by using the Matlab toolbox.

The modeling approach

The equivalent porous medium (EPM) model

The EPM approach assumes that the entire region including conduits and rock matrix has equivalent porosity. In this approach, karst aquifer can be taken similar to a porous medium. Large channels and faults in karst aquifers are represented as high hydraulic conductivity zones. EPMs solve the continuity equations valid laminar flow conditions. MODFLOW is one of the most commonly used porous media model.

MODFLOW is a computer program that can simulate three-dimensional ground-water flow through a porous medium. (McDonald and Harbaugh 1988). MODFLOW was designed as a modular structure in which each option is independent of other options. Thus new capabilities can be added with only minor modifications to the source code (McDonald and Harbaugh 1988). MODFLOW was originally documented by McDonald and Harbaugh in (1984). MODFLOW underwent several overall updates. MODFLOW 2000 (Harbaugh et al. 2000) was used in this study. The partial differential equation of groundwater flow used in MODFLOW is (McDonald and Harbaugh 1988):

$$\frac{\partial}{\partial x}k_{xx}\frac{\partial h}{\partial x} + \frac{\partial}{\partial y}k_{yy}\frac{\partial h}{\partial y} + \frac{\partial}{\partial z}k_{zz}\frac{\partial h}{\partial z} \mp W = S_s\frac{\partial h}{\partial t}. \tag{6}$$

k_{xx}, k_{yy}, and k_{zz} are hydraulic conductivity along x, y, and z axes respectively, h represents the piezometric head, w represents the volumetric flux per unit volume, S_s is the specific storage and t is the time. This partial differential equation with specified initial and boundary conditions represents the mathematical model of a groundwater flow system. In

MODFLOW, Eq. (6) is solved using block centered finite difference approach.

Hybrid approach

In this method, both the matrix aquifer and the conduit system are superposed for simulating the karst aquifer behavior. The matrix and the conduit system exchange groundwater at the contact points. The head difference and an exchange coefficient determine this exchange. Compared to other models, hybrid approach has the advantage that these models can simulate both turbulent and laminar flow. Using pipe flow equations, flow in the conduits is modeled and requires various parameters to describe the conduits namely roughness, tortuosity, diameter, and critical Reynolds number. The MODFLOW-CFP package based on coupled continuum pipe flow model can used to simulate the flow through the conduits and matrix.

The Darcian groundwater flow is coupled with pipe flow in the conduit flow process package in MODFLOW. The conduits where high-velocity groundwater flow occurs and the exchange between conduits and matrix domain is simulated through the MODFLOW-CFP model. The standard 3D partial differential equation given in Eq. (6) is used to describe the matrix.

In CFPM-1, for laminar flow conditions, Hagen-Poiseuille equation is used and for turbulent flow conditions, the Darcy-Weisbach equation is used. Equation (7) represents the volumetric flow rate in laminar flow conditions and Eq. (8) volumetric flow rate turbulent flow conditions:

$$Q = \frac{-A\rho g d^2 \Delta h}{32\mu \Delta l \tau} \tag{7}$$

$$Q = \sqrt{\frac{|\Delta h| g d^2 \pi^2}{2\Delta l \tau}} \log\left(\frac{2.5v}{\frac{2|\Delta h| g d^3}{\Delta l \tau}} + \frac{k_c}{3.71d}\right)\frac{\Delta h}{|\Delta h|}. \tag{8}$$

In Eq. (7), Q is the groundwater flow rate in the pipe in L^3/T, A is the cross sectional area of the pipe normal to the flow direction [L^2], ρ represents the density of water [M/L^3], g represents the acceleration due to gravity [L/T^2], d represents the diameter of the pipe [L], Δh represents the change in head throughout the length of the pipe in the particular cell [L], μ represents the water viscosity [M/LT], Δl represents the pipe length in the cell [L], and τ is the pipe tortuosity. The tortuosity is a unit less value and it act like a multiplier to Δl to account for bends and twists.

Velocity and pipe roughness variables is additionally included to compute the rate of flow for turbulent flow. In Eq. (8) v represents pipe velocity the and k_c [L] represents the mean roughness of the pipe wall. If the roughness value is high it represents a rough pipe. The flow rate is low in a rough pipe. A low roughness value represents a smooth pipe with negligible effect on the flow rate. The exchange equation to connect the pipe network and the matrix continuum is given in Eq. (9):

$$Q_{\mathrm{ex}} = \alpha_{j,i,k}\left(h_{in} - h_{j,i,k}\right), \tag{9}$$

where Q_{ex} is the volumetric exchange, h_{in} represents the head at conduit node in, $h_{j,i,k}$ represents the head in matrix cell that contains the pipe. ($\alpha_{j,i,k}$) [L^2/T] represents the conduit wall conductance. This equation assumes that ground-water exchange is not turbulent. Negative Q_{ex} indicates exchange flow is from the porous media into the conduit pipe(s). Conversely, positive Q_{ex} indicates flow is from the conduit pipe(s) into the porous media. Two options are available for assigning conduit wall conductance ($\alpha_{j,i,k}$). In the first option, users can directly give the conduit wall conductance. In the second option, using pipe geometry data conduit wall permeability terms (Kj,i,k), and $\alpha j,i,k$ is internally computed using Eq. (10):

$$\alpha_{i,i,k} = \frac{\sum_{ip=1}^{np} K_{j,i,k} \pi d_{ip} \frac{1}{2}\left(\Delta l_{ip} \tau_{ip}\right)}{r_{ip}}, \tag{10}$$

where $K_{j,i,k}$ is the conduit wall permeability term [LT^{-1}] in MODFLOW cell j,I,k; d_{ip} is the diameter [L] of pipe ip connected to node in; Δl_{ip} is the straight-line length between nodes [L] of pipe ip connected to node in; τ_{ip} is the tortuosity(Unitless) of pipe ip connected to node in; r_{ip} is the radius of pipe ip.

Results and discussion

Analysis of data

The groundwater level is mainly influenced by rainfall and the groundwater draft for the Karst aquifer in the study area. The groundwater control for mining is through a number of wells and the entire quantity of groundwater pumped out from limestone mines is utilized in the cement factory and also for meeting the drinking water requirement in the area. The wavelet coherence diagram can be used to compare two-time series in time–frequency domain. To compare the influence of rainfall on groundwater level and also to check the interdependence of groundwater levels at different sites Wavelet Coherence Diagram was used. This is necessary to cluster the wells since the fracture network in unknown in the area. In the Wavelet Coherence Diagram, the direction of the arrow indicates the phase relationship between two-time series. The arrow from towards right indicates a positive coherence. The color bar on the right represents the coherence. Yellow suggests that the coherence between the time series is strong. Blue means that the coherence is weak, and the minimum is zero. The location of observation wells used for the analysis is shown in Fig. 4. Figure 5 shows the time series of water level in observation wells and the rainfall. For a developing country like India getting continuous water level data was difficult. The water level data was available 4 times in a year. The data were interpolated for other months based on the available 4 data sets. From Fig. 5 it is clear that a declining trend was observed for the groundwater levels in all the wells, whereas the rainfall shows no significant trend. Thus it is clear that the declining trend in groundwater level is due to groundwater pumping for mining. Also from Fig. 5, it is clear that groundwater levels varies with temporal variations in rainfall. The wavelet coherence between the rainfall and groundwater level is shown in Fig. 6. From Fig. 6 it is clear that significant coherence exists between rainfall and groundwater level in all the wells during period 8 to 12 for the entire period of analysis. In TW24 high coherence exists during period 6 and 7 for a short time span. and shows a positive coherence. Tw 19 and TW13 shows medium

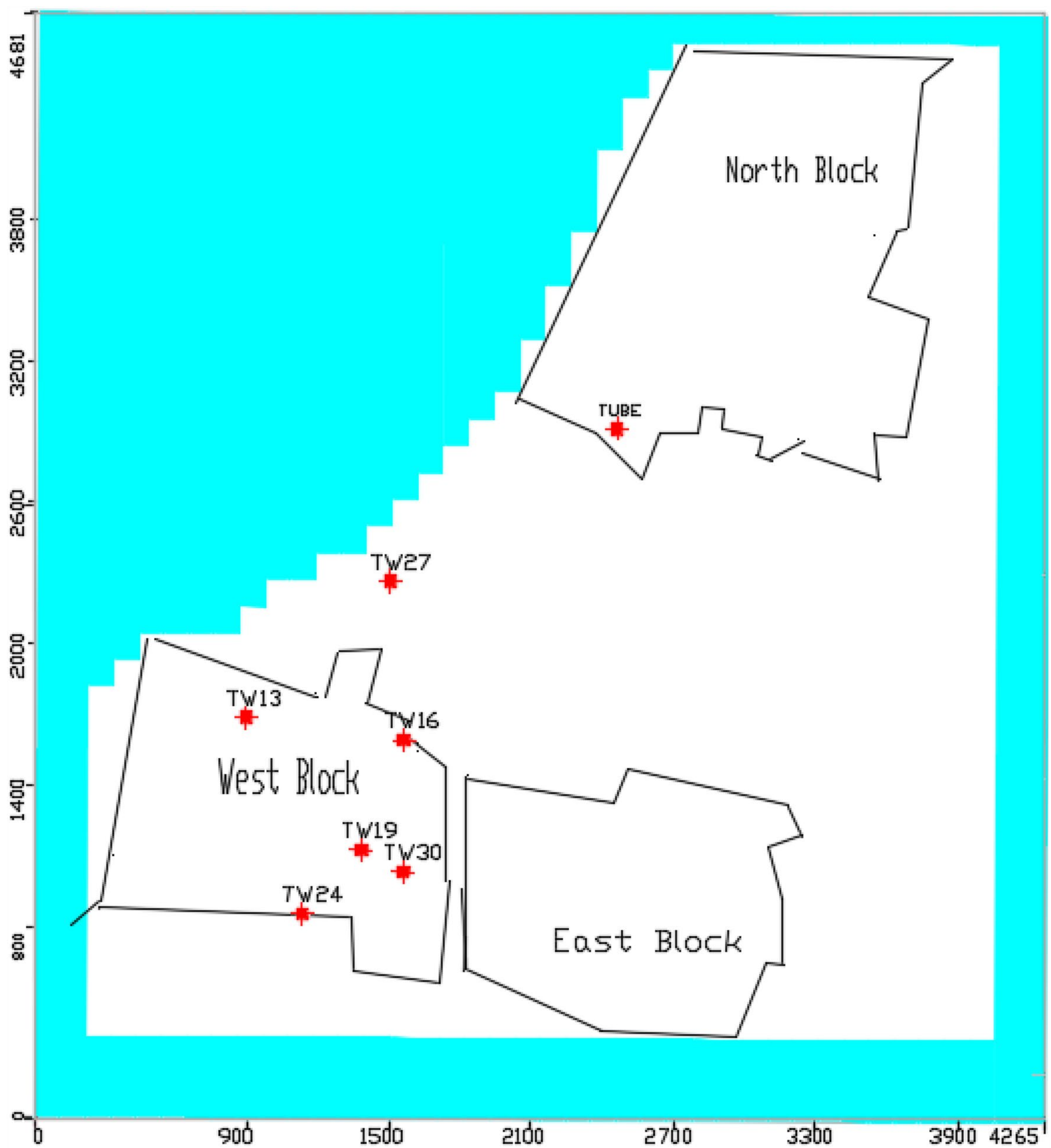


Fig. 4 Location of observation wells

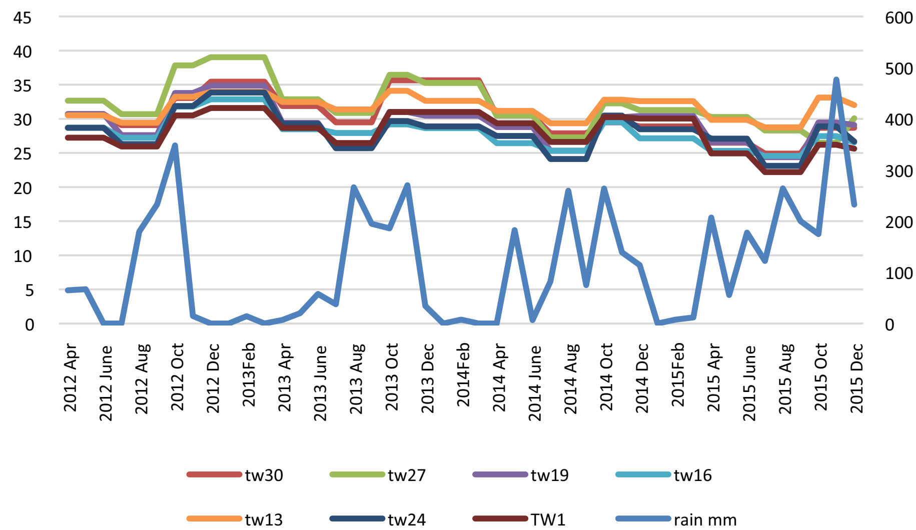


Fig. 5 Variation of groundwater level (wrt msl) and rainfall (mm)

coherence during the period 6 and 7 for a short time span. Figure 7 represents the Wavelet Coherence between groundwater levels at different observation wells. 21 combinations were tried and the results show that significant coherence exists between the wells TW1–TW13, TW1–TW19, and TW13–TW19. But based on the observation wells shown in Fig. 3 the coherence between TW1–TW13 and TW1–TW19 is a mere coincidence. From the wavelet coherence between rainfall and groundwater levels and between different wells, it is clear that TW13 and TW19 may be screened in the same fracture zone. Further studies are needed to confirm it.

EPM model

MODFLOW 2005 was used to model the aquifer based on EPM approach. Visual Modflow was used as a pre and post-processor for MODFLOW. Discretization of study region into grids is required for finite difference-based simulation. The model contains 41 rows and 40 Columns with a grid spacing of 100 m × 100 m (Fig. 8). Based on borehole details obtained, the geological cross-section of the study area is conceptualized as three layer system. Based on the 76 bore log data, the elevation of three-layers is interpolated. The location of bore holes is given in Fig. 9. The maximum elevation obtained is 60 m and minimum elevation is -50 m. The bottom elevation of limestone layer is given in Fig. 10. The groundwater extraction details were collected for 5 years from the study area and is given in Table 2. The Hydro-geologic parameters for flow modeling are the hydraulic conductivity and storage properties. Based on pumping out test the aquifer parameters were estimated by ICL and is given in Table 3. The boundary conditions adopted in the hydrodynamic model were the river boundary condition, general head boundary, and recharge boundary conditions (Fig. 11). The river on the western side is represented as a river boundary condition. The water body on the northern side away from the model boundary is represented as general head boundary. Clay with low permeability is present at the bottom and assumed as no-flow boundary. The recharge is considered as 10 percent of rainfall (GEC 2015) and is applied at the top layer. The horizontal hydraulic conductivity and storage values were slightly adjusted until a close correlation between the simulated head and observed heads at the observation wells is obtained and the normalized root mean square (RMS) in the range of 10% or less. The model is calibrated using the water level data in 6 observation wells during the years 2012–2016. The calibrated value of hydraulic conductivity for limestone layer was 40 m/day. The calibrated value of specific storage for limestone layer was 0.002 m.

Hybrid approach

For the hybrid approach, the CFP-Mode 1 in conduit flow process in MODFLOW 2005 was used. Modelmuse was used as pre and post-processor. The model was created with 41 rows, 40 columns, and 3 layers. In lime stone layer, matrix hydraulic conductivity is set at 40 m/day, which is based on the calibrated value of EPM approach and conduits were also inserted into the model. Pipe nodes and pipes were created for the conduits. The pipe nodes are at the centers of their respective model cells. CFP-Mode 1 requires many parameters namely conduit location, diameter, roughness, tortuosity, an exchange coefficient. In this study, for computing the volumetric exchange between conduit and matrix, Pipe geometry data and conduit wall permeability terms

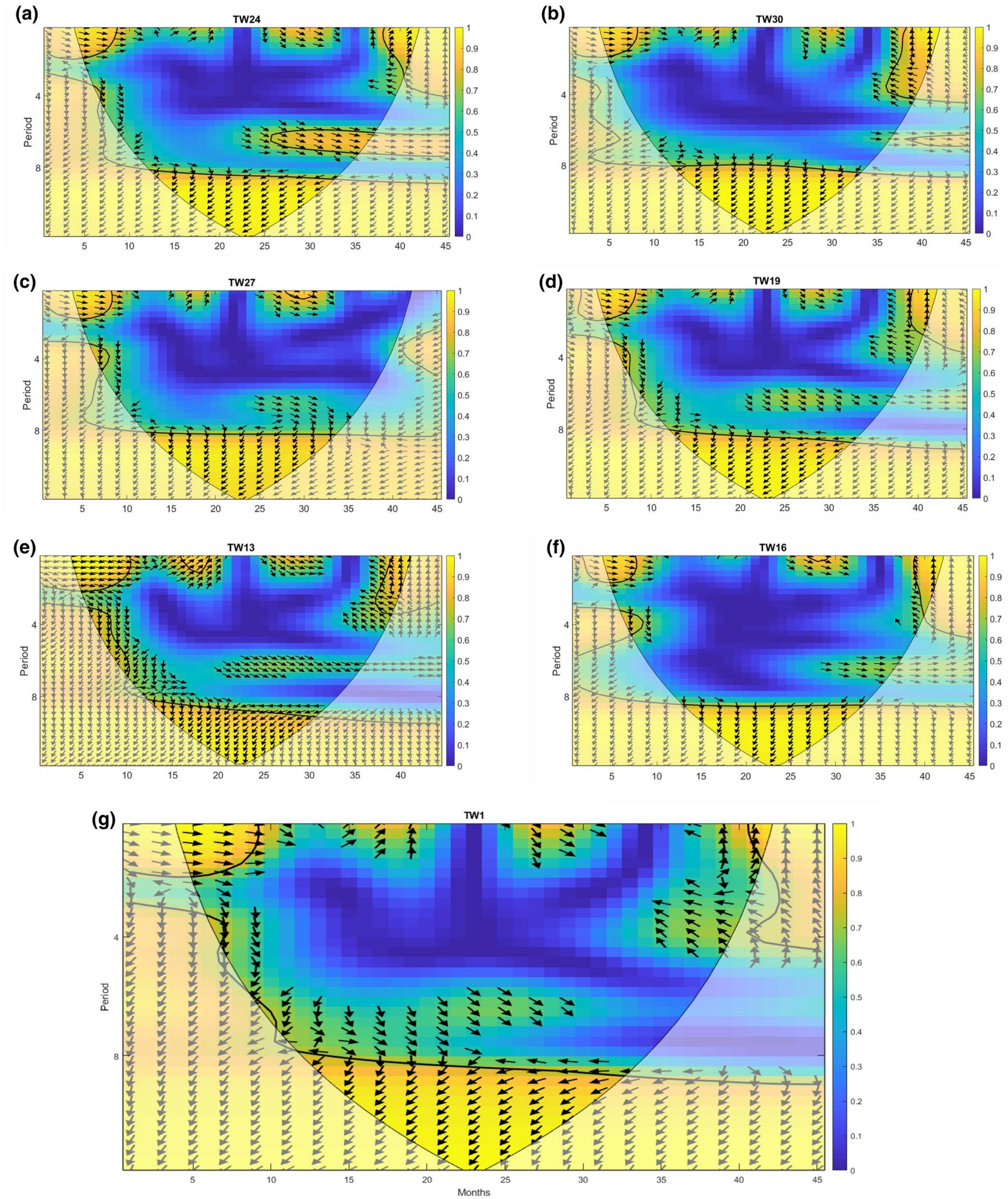


Fig. 6 Wavelet coherence diagram between rainfall and groundwater levels in observation wells **a** TW24 **b** TW30 **c** TW27 **d** TW19 **e** TW13 **f** TW16 **g** TW1

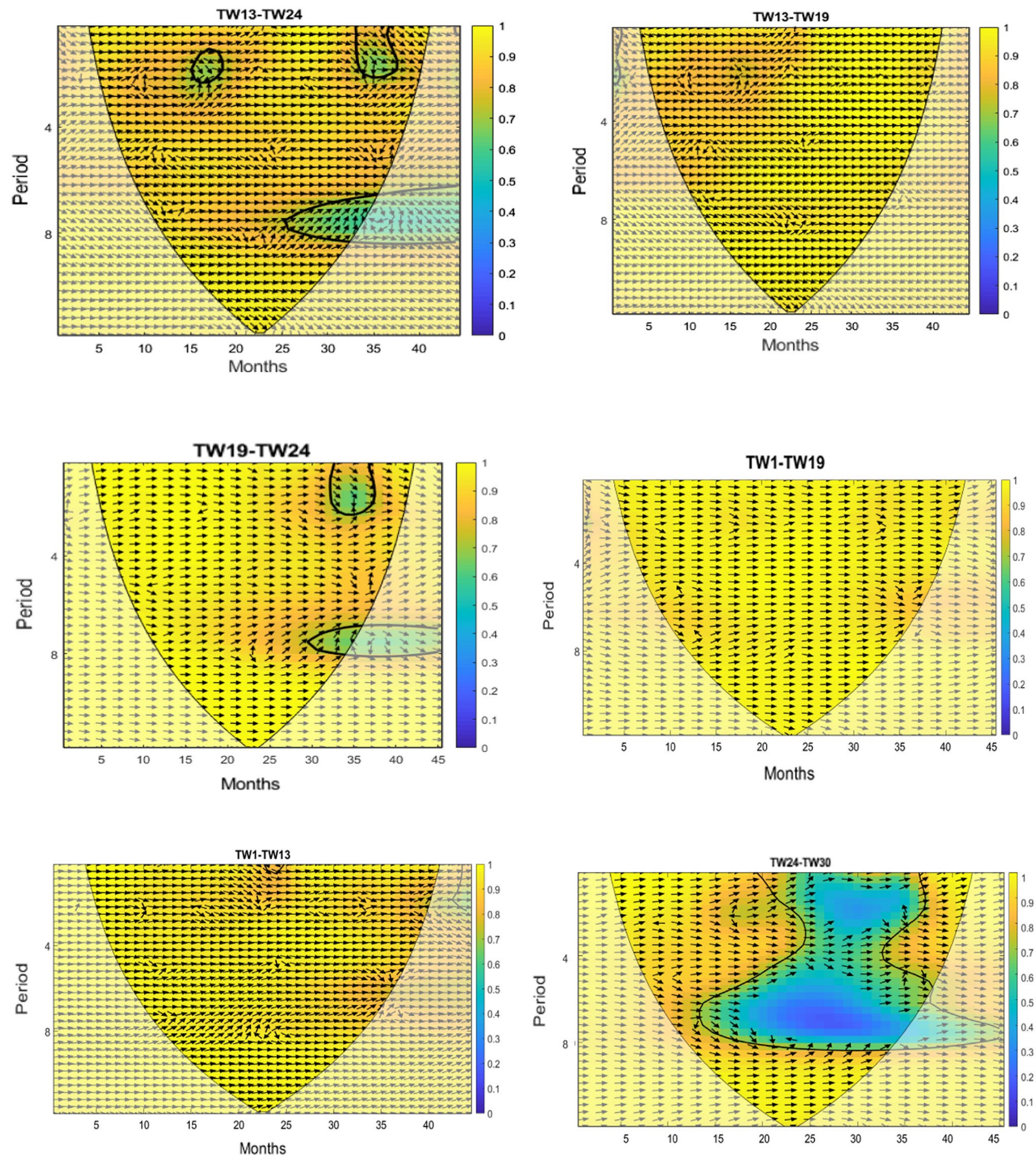


Fig. 7 Wavelet coherence diagram between groundwater levels in different observation wells

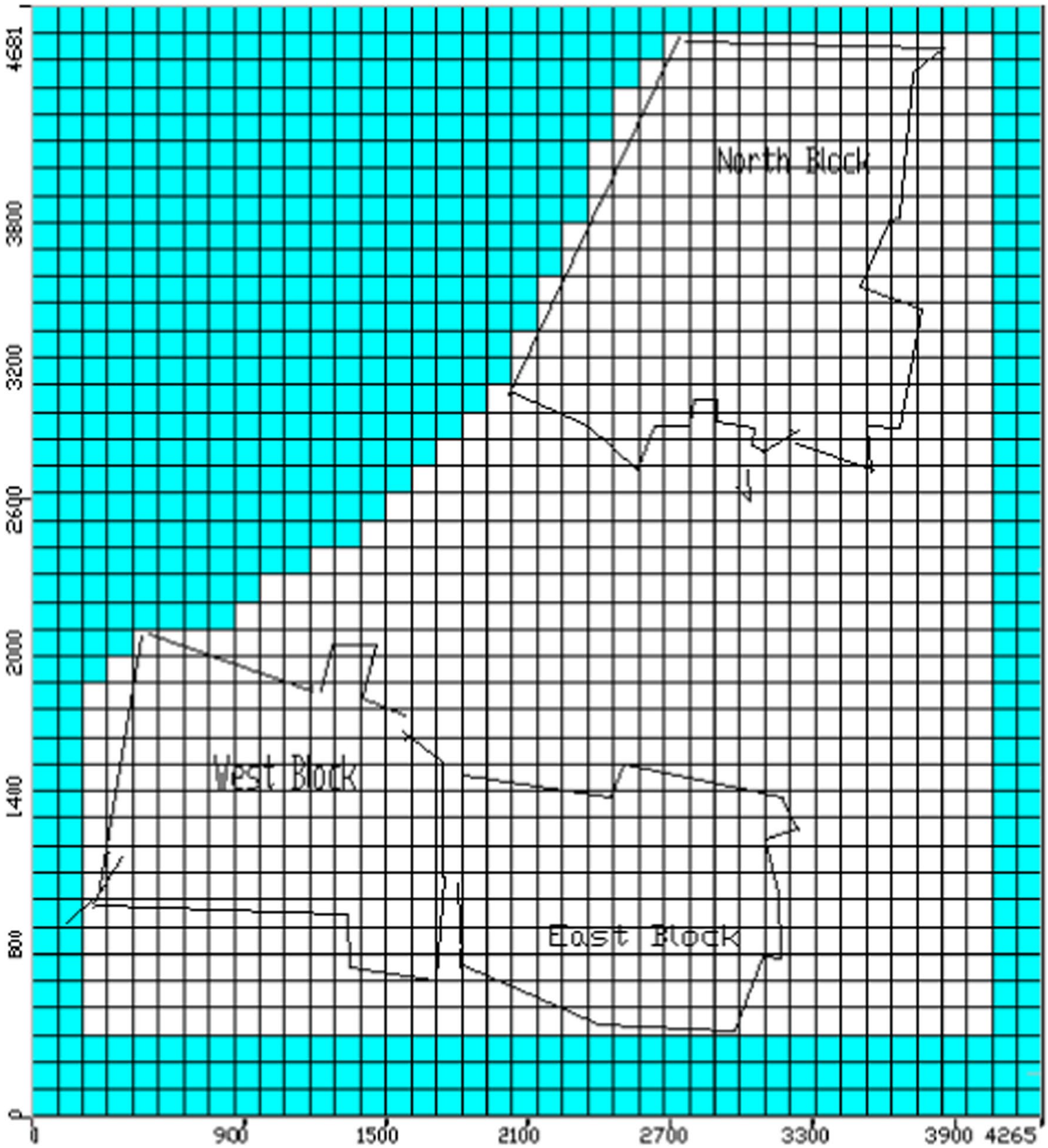


Fig. 8 Areal discretization

($K_{j,i,k}$) are assigned in the model for each node. Initially the conduit network was given based on the borehole details of 76 locations and WCA analysis. The borehole details of a typical bore log are shown in Fig. 12. From Fig. 12 it is clear that the fracture zone exists in between 21.8 to 24.8 m below ground level at the west block. The details were available at 76 locations. Due to lack of data, during calibration, the conduit network and parameters d and $K_{j,i,k}$ verified to get an optimum conduit network and better match between hydraulic head of observed and simulated values. Calibration was done using water level data for the 5-year period between 2012 and 2016. The finally adopted conduit parameters are given in Table 4. The roughness coefficient and the conduit tortuosity were taken as 0.001 and 1 respectively, and these

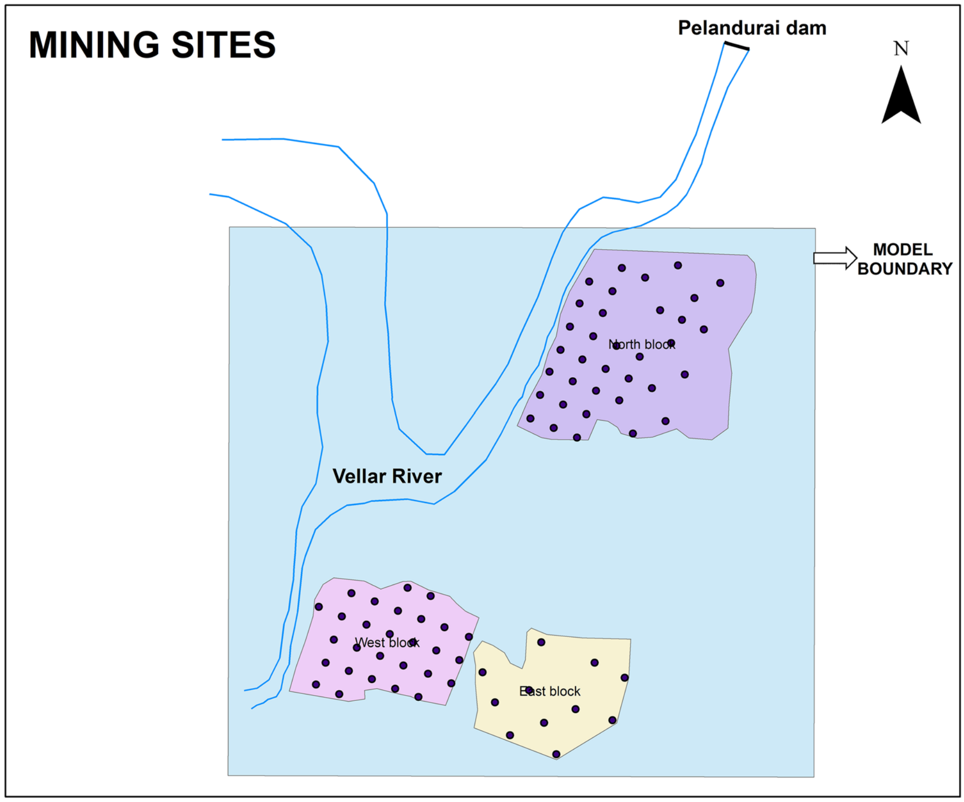


Fig. 9 Location of boreholes

were not changed during model calibration and these values are taken the same for all conduits. The conduit network also changed during calibration and Fig. 13 shows the optimum network. The calibrated model includes eight conduit networks. Determining the distribution and characteristics of conduits was difficult. Further studies are needed to check the locations and properties of conduits obtained in hybrid model. Also during calibration, it was found that the limestone aquifer received lateral influx due to river along the western margin in the study area and this has to be verified by installing seepage meters. With the optimum network, the simulated hydraulic head in limestone aquifer at the end of the year 2016 is given in Fig. 14.

Taylor diagram and calibration charts were used to compare the performance of the EPM and hybrid approach (Figs. 15 and 16). From these figures, it is clear that the hybrid approach performed well compared to the EPM approach. For the wells TW1 and TW27, the EPM model results were not matching with the observed water levels in EPM approach. During calibration of hybrid model, conduits were added near these wells and the performance of hybrid model was found to be good. So the CFP was used for finding the amount of pumping required in future for safe mining operations.

The calibrated hybrid model was applied to predict the pumping rate required for safe mining during 2020 using the optimum network. A trial and error procedure is performed to get the optimum pumping required to attain the water level up to limestone bottom. The recharge was kept constant throughout the prediction period. It was found that 20% increase in pumping rate is required to maintain the water level below the limestone bottom. Based on this, the pumping required per well in North block is 1900 m^3/day whereas in west block it is 1152 m^3/day. The predicted water level at the end of the year 2020 for these two pumping rates is shown in Fig 17. From the figure, it is clear that the groundwater levels will fall by more than 6 m by the end of year 2020 in the East block. Also on the western side of the west block and north block the water level is reached up to the limestone bottom whereas on the eastern side of both the block 5–12 m positive pressure is obtained.

In EPM models, the Karst aquifers are assumed to be an equivalent continuous medium. In Karst aquifers, within the matrix, due to the presence of soluble carbonate rocks,

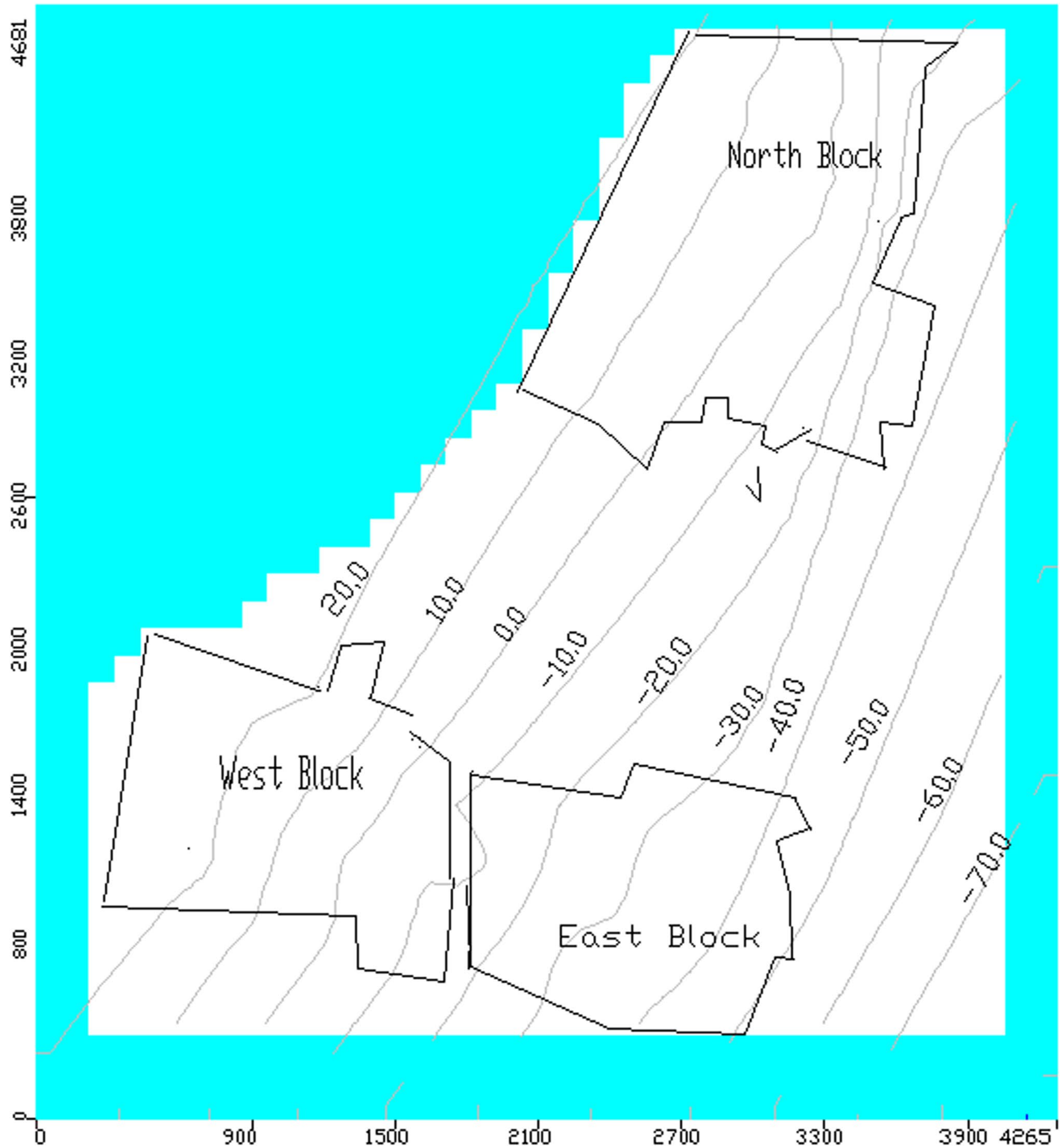


Fig. 10 Bottom elevation of limestone layer

Table 2 Pumping rate

North block		West block	
Year	Average pump discharge (m^3/day)	Year	Average pump discharge (m^3/day)
2012	1056	2012	960
2013	1056	2013	960
2014	1056	2014	960
2015	1440	2015	960
2016	1584	2016	960

Source India Cement Limited

Table 3 Hydrologic parameters

Layer	Hydraulic conductivity (m/s)	Specific storage (s_s) (m^{-1})	Specific yield (S_y)	Effective porosity
Watertable	1.1157×10^{-4}		0.2	0.15
Limestone	5.876×10^{-6}	1×10^{-4}	0.2	0.15
Sandsone	9.256×10^{-5}	0.002	0.2	0.15

Source India Cement Limited

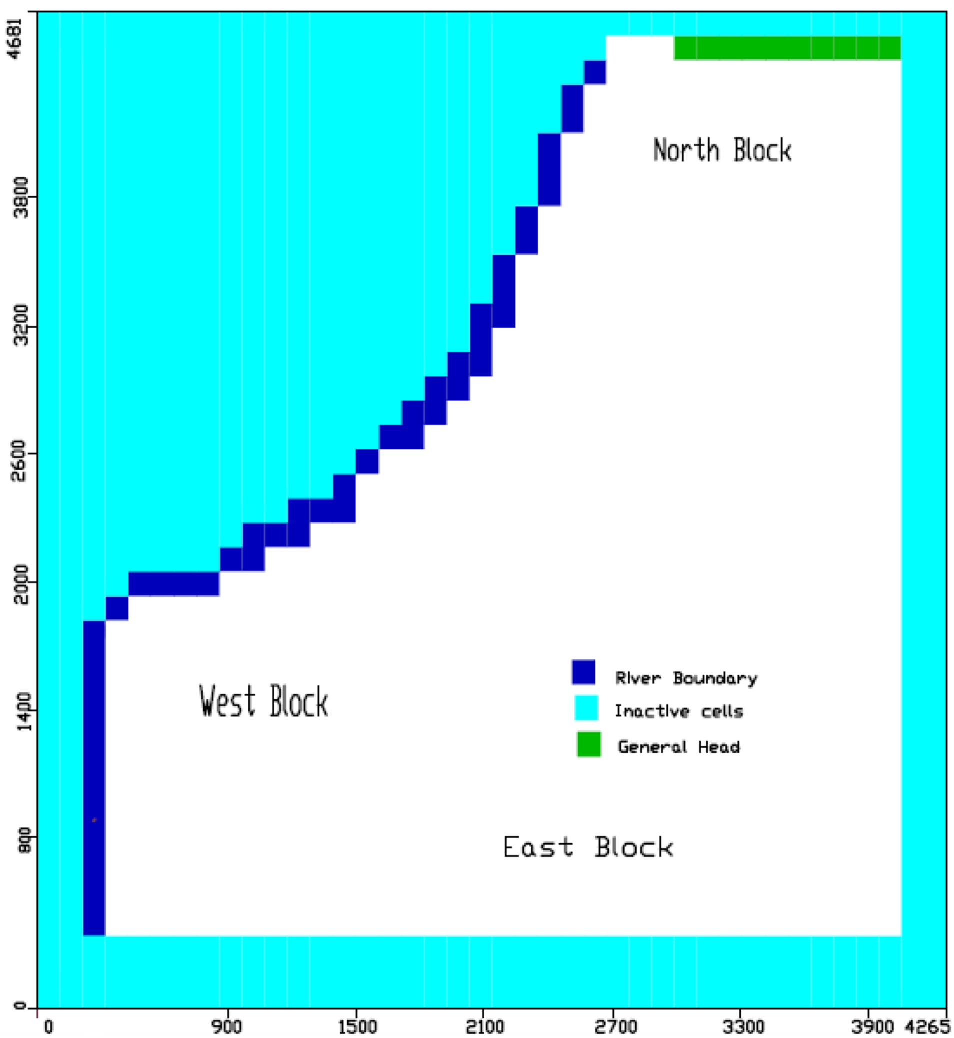


Fig. 11 Boundary conditions adopted

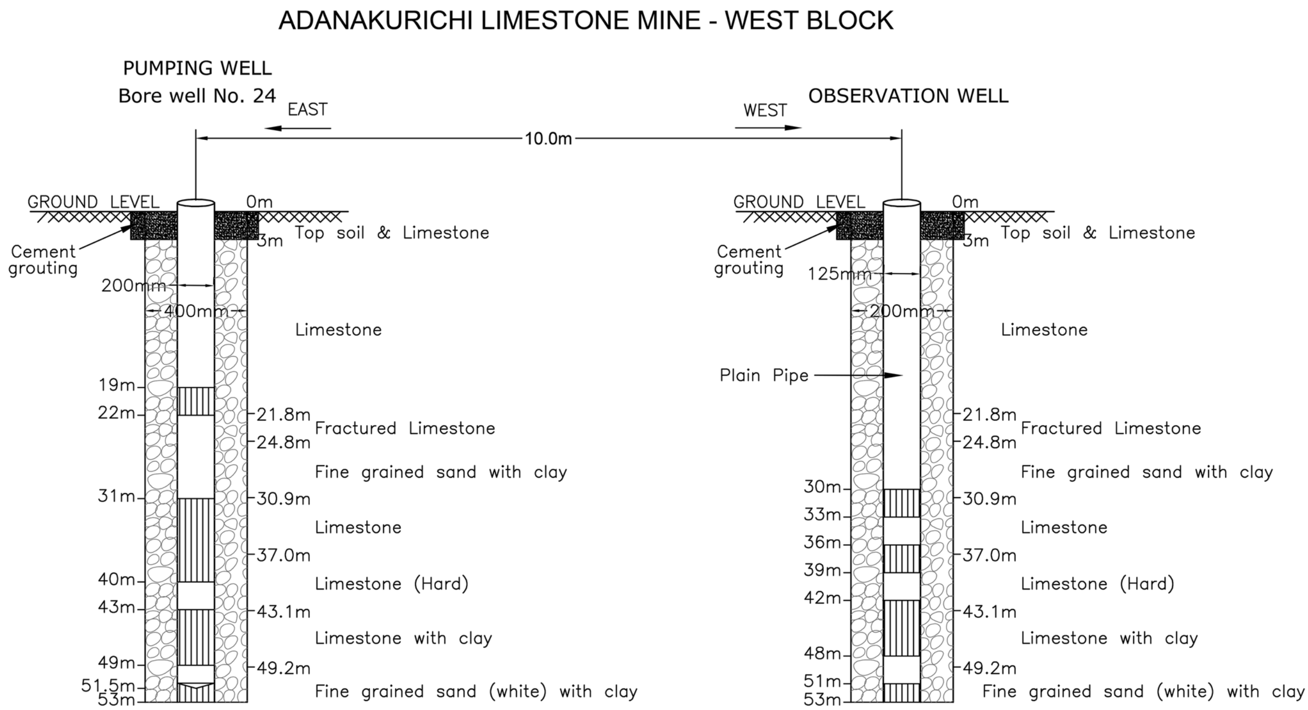


Fig. 12 Litholog details in West Block (*source* India Cements Ltd)

conduit flow network may be created. Thus in case of Karst aquifers, the flow can be laminar and turbulent, whereas in matrix flow is laminar. The hybrid method/the coupled continuum pipe-flow approach requires additional data related to conduits and its distribution. Often these details will be unknown. In the present study, an attempt has been done to determine the conduit distribution and parameters using inverse modeling by utilizing the observed water level data. The EPM model does not consider the turbulent characteristics in highly karstic aquifers and hence will not give an exact picture of the groundwater pumping required for dewatering schemes. Even though in a few studies, it was mentioned that EPM can be successfully applied for karst aquifers (Scanlon et al. 2003), in highly karstic aquifers, if it is required to determine the pumping strategies for dewatering schemes, it is better to opt hybrid approach for modeling.

Table 4 Calibrated values of conduit parameters

Pipe group	Pipe diameter (m)	Pipe wall Permeability (m/d)
A	0.2	100
B	0.15	80
C	0.12	90
D	0.3	50
E	0.1	60
F	0.35	80
G	0.4	120
H	0.5	75

Conclusions

For safe mining of limestone, in this study a three-dimensional equivalent porous media (EPM) approach using MODFLOW and a hybrid approach using CFP -mode 1 was applied to simulate groundwater flow in a karst aquifer. From the comparison of equivalent porous media model and CFP-Mode 1, it was observed that CFP mode-1 performed well. Based on CFP-Mode 1, the optimum conduit network was arrived and eight numbers of pipes were required to attain the optimum conduit networks. The CFP Mode 1 model was applied to predict the pumping rate to attain the water level to the limestone bottom and found that 20 percent of

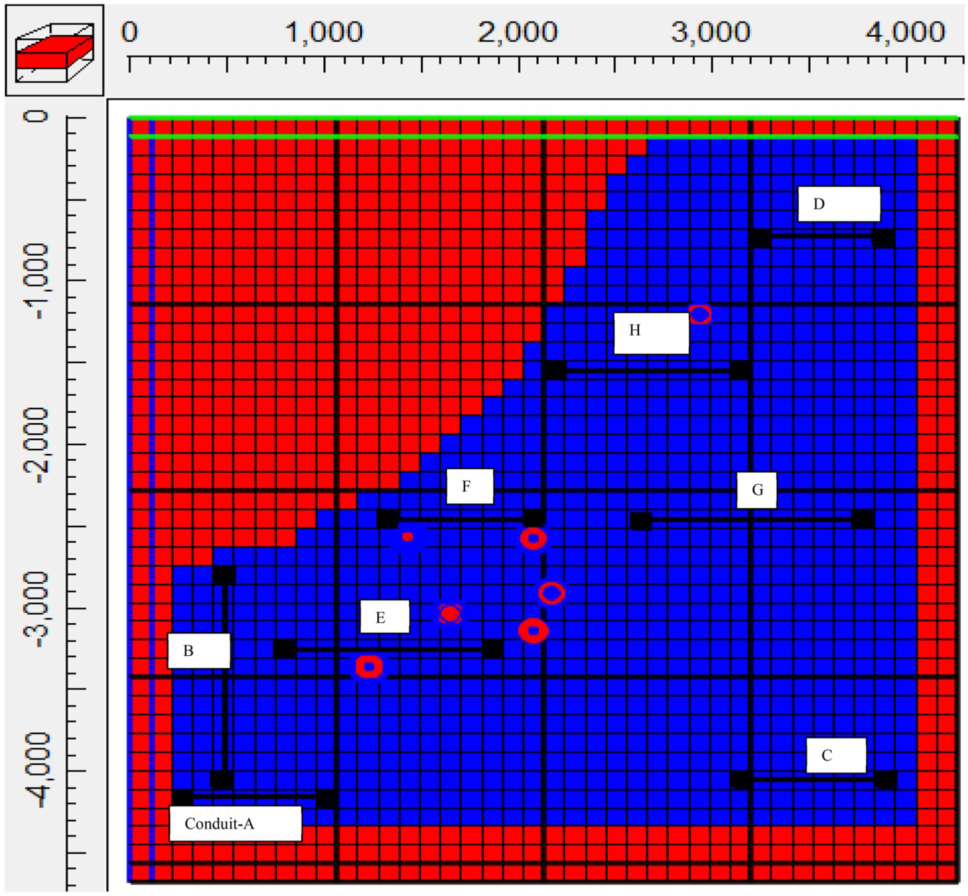


Fig. 13 Optimum conduit network

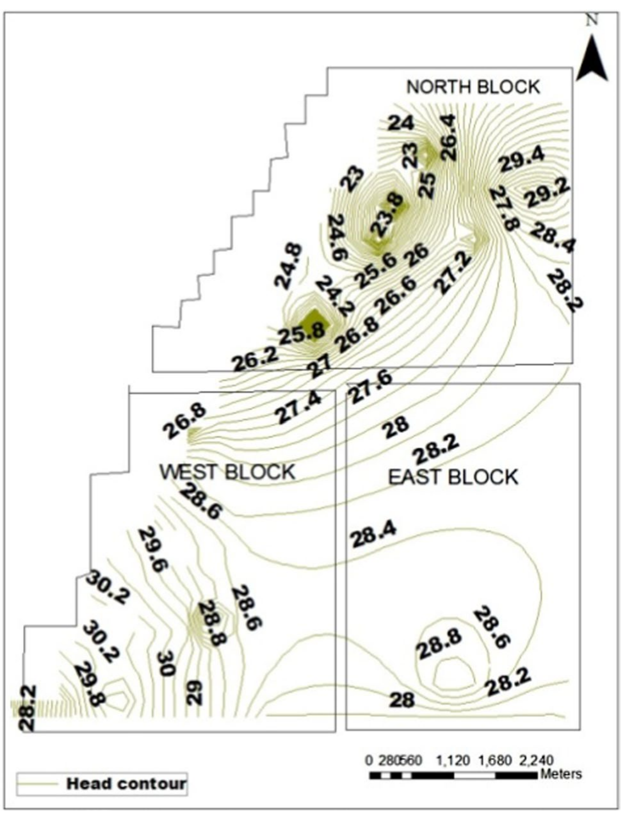


Fig. 14 Simulated hydraulic heads in the limestone aquifer (wrt msl) based on CFP Mode 1 at the end of the year 2016

additional pumping is required in the year 2020 compared to 2016. The specific conclusions arrived at from the study are:

- A declining trend was observed for the groundwater levels in all the wells, whereas the rainfall shows no significant trend. The declining trend in groundwater level is due to groundwater pumping for mining activities.
- From the wavelet coherence between rainfall & groundwater levels and between different wells, it was found that the observation wells TW13 and TW19 coming in the same cluster.
- Taylor diagram and calibration charts were used to compare the performance of the EPM and hybrid approach and was found that hybrid approach performed well compared to the EPM model. The optimum conduit network was obtained from the hybrid approach need to be verified by field observations.
- Using the hybrid approach, the pumping required for dewatering operations for the year 2020 was predicted. The pumping required to maintain water level upto limestone bottom in North block is 1900 m^3/day per well whereas in west block, it is 1152 m^3/day per well.

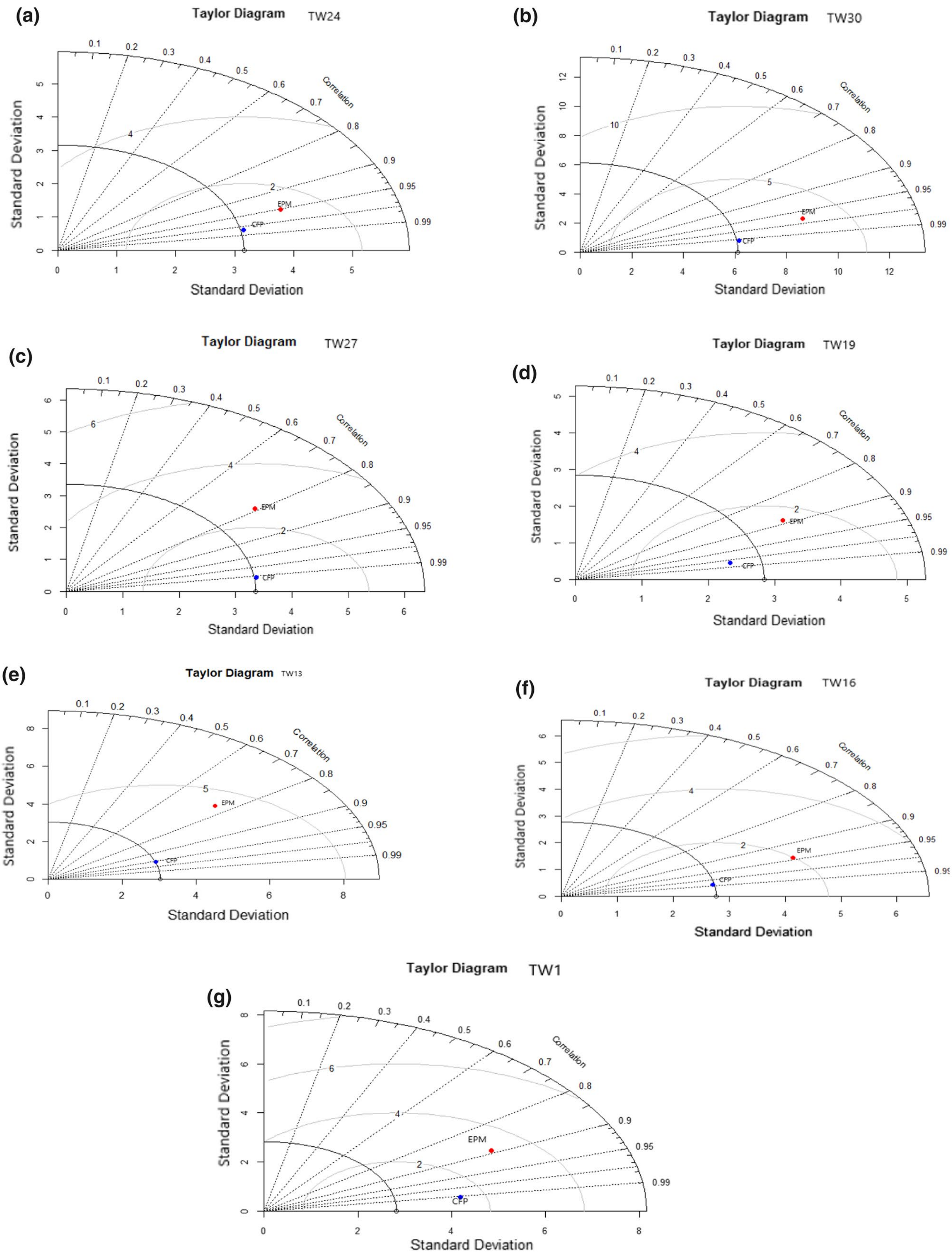


Fig. 15 Taylor diagram **a** TW24 **b** TW30 **c** TW27 **d** TW19 **e** TW13 **f** TW16 **g** TW1

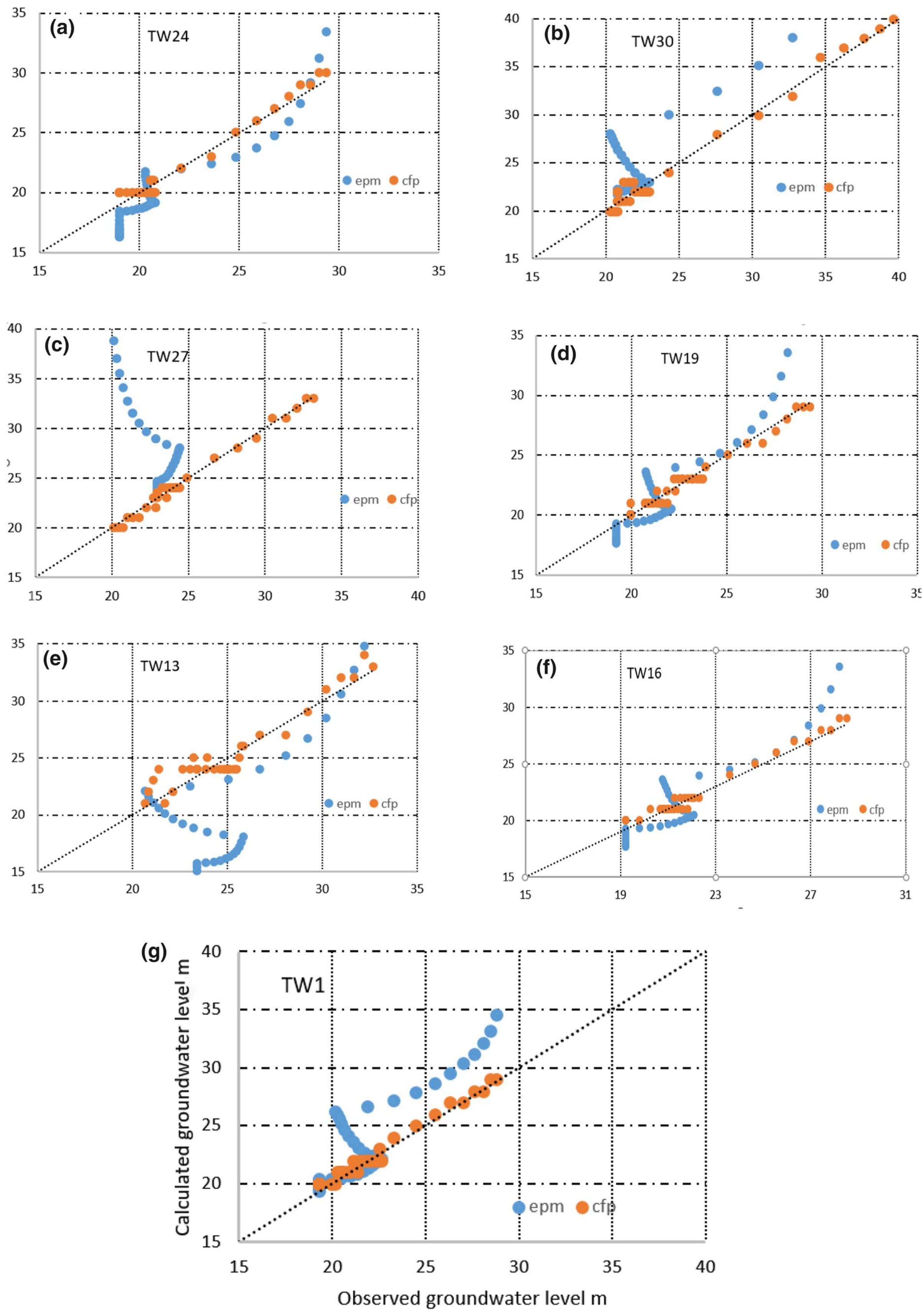


Fig. 16 Comparison of observed and simulated head at different observation wells **a** TW24 **b** TW30 **c** TW27 **d** TW19 **e** TW13 **f** TW16 **g** TW1

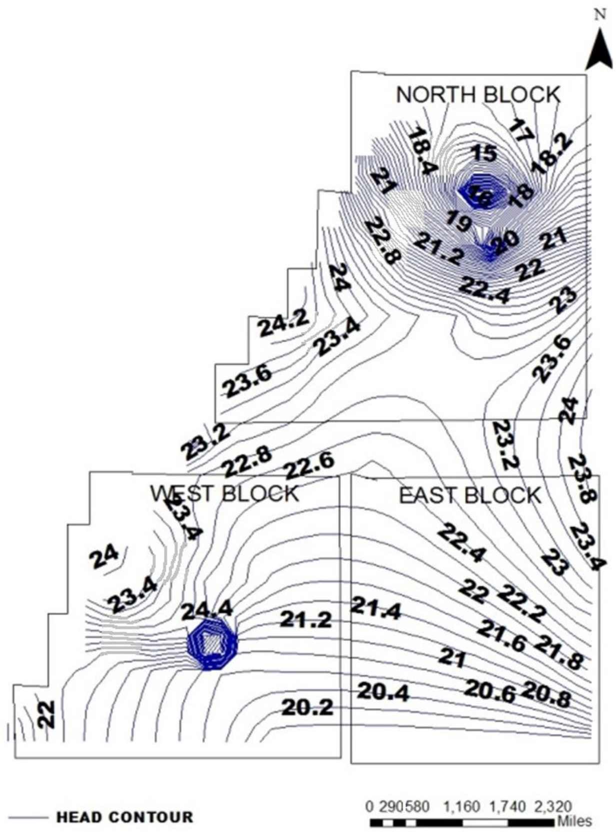


Fig. 17 Simulated contour (wrt msl) at the end of the year 2020

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Authors contributions The idea and problem were conceived by Mohan. Pramada and Anju joined him to formulate the research goals clearly. All authors together framed the methodology. Anju performed the simulations, validation, and visualization of the numerical models. Pramada did analysis part. Mohan and Pramada supervised the work and contributed to the interpretation of the results. The original draft of the paper was prepared by Mohan and Pramada. All the authors provided critical feedback and helped to shape the final version of the manuscript.

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Availability of data and material All data have been procured from India Cement Limited (ICL), Tamil Nadu.

Code availability For Wavelet Coherence Diagram authors have used the code developed by Grinsted which is available on the website https://github.com/grinsted/wavelet-coherence.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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