Groundwater flow modeling in the basaltic hard rock area of Maharashtra, India

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Abstract

The ecological sustainable development and planning of groundwater resources is an excessive challenge for many countries currently facing water insufficiency. The main focus of this work was to determine the direction of groundwater flow, head value, and water level using the steady-state finite difference model (MODFLOW software) in basaltic formations in Maharashtra, India. The MODFLOW model was integrated with ground data using Geographic Information System (GIS) for sustainable groundwater resource management in the hard rock terrain. The MODFLOW-2005 model simulated the interaction between heads and time in 2014–18 by steady-state conditions. In this present study, four observation wells were selected. During the field survey, four observation wells have been monitored regularly as per the Central Groundwater Board guidelines. MODFLOW software has been conceptualized as a double-layered rigid and fractured aquifer area feast over 18,312 m × 11,265 m area. This research demonstrates that the integration of GIS, conventional fieldwork, and mathematical model can support to understand groundwater demand and supply in a better way.

Keywords GIS · Groundwater flow modeling · MODFLOW · Maharashtra

Introduction

Many countries are heavily on the availability of groundwater. In semi-arid areas, groundwater supplies are more relative to various areas (Collins Johnny et al. 2016; 2017; Khare and Varade 2018). For better planning groundwater resource development, it is essential to understand the development of comprehensive conceptual models and

systematic solutions or numerical methods of groundwater flow modeling (Mayer et al. 2007; Lasya 2015; Jackson 2007). The modeling of groundwater flow has developed a precious tool to assess the effect on groundwater resources of current and forthcoming operations (Lachaal et al. 2016; Sathish et al. 2015; Siva Prasad et al. 2021). Mendonca et al. (2005) found out the activity and actions of the aquifers in extreme circumstances. The balance between water

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and its removal has disrupted the overall depletion of soil water (Kushwaha et al. 2009). The data trouble of knowing related to groundwater flow and the lithology formations. To overcome this kind of issue by computer-based numerical groundwater modeling programs may be utilized (Raazia and Dar 2021; Rane et al. 2021a; Abraham et al. 2021). The assessment of the natural resources planning to development of sustainable water, decreasing of land and water resource degradation on forecasting of water level heads (Kumar 2013; Rane et al. 2021b). The identification, estimate, and remediation of groundwater pollution have concerned scientists and academicians for improvement and better solutions for groundwater level increases (Datta 2002). Groundwater research based on mathematical modeling has intended to test its capacity and evolving systems (Gupta et al. 1990; Khadri et al. 2016a, b; Sharief et al. 2021). The incidence and drive of soil waters in every basin varies with their geological location, climate, precipitation, drainage, topography, and extent. Because the groundwater reservoir follows the drainage basin, basin level, and groundwater studies are very important for the budgeting in the reservoir (Takounjou et al. 2009; Pande et al. 2017; Omar et al. 2020).

The groundwater model typically contains two elements. One is a hydrological model (Zhou et al. 2011) and other is a quantifiable by numerical equations. The MODFLOW is the most frequently employed model for modeling and studying groundwater flow for three-dimensional finite-difference soil–water flow. This model has developed by Michael G., Mc Donald, and Arlen W. Harbaugh. Many data and a comprehensive explanation of the flow arrangement are mandatory to create the most effective usage of MODFLOW (Mondal et al. 2011; Lachaal et al. 2016; Moharir et al. 2017). The effects on the Goharkoo Plain aquifer of the artificial recharge and the best place to apply the watershed planning by using the MODFLOW software (Rezaei and Sargezi 2009). The results indicated that the response of aquifers to artificial refill was positive and that artificial refill had no destructive effect on water (Rezaei and Sargazi 2009; Nozarpoor et al. 2014). The main aim of the work was to simulate the head of steady-state using a numerical flow model and the water level of the monitoring wells for different years and evaluate the groundwater flow in the basaltic formations.

Study area

The area lies in Akola and Buldhana districts, Maharashtra, India (Fig. 1). Two types of geology areas are classified into basaltic rock and alluvium formations (Fig. 2). The 95% hard rock is presented in the Akola and Buldhana districts (Pande et al. 2017). This rock is composed of alluvium and Deccan

basalt disposed of horizontally and crossed by sophisticated joint sets. In hard rock types, the incidence and drive of groundwater are restricted to open fracture systems, including fissures and joints in non-weathered areas and even in the porous region of weathered formations. In rocky regions, both the space and depth of the weathered thickness are discontinuous. Therefore, the strength of weathering affects the recharge of groundwater during hard rock formation. Three types of formations, such as Atali, Lokhanda, and Amdapur, are essential geology and the basaltic rocks. Various alluvium types, viz. sand, silt, clay, and gravel have been deposited in this study area. Which are elated sediments by the river are observed adjacent in the Balapur Taluka. The average precipitation is 800–900 mm. The northwest part of the district is small in size and rises in the southeast part of the district of Washim (Fig. 1).

Hydrogeological and geology

In general, basaltic rock formations have occupied traverse the entire area. In basaltic formation, the presence and drive of groundwater have been confined to open fracturing systems, such as splinters and intersections, in un-weathered areas, and even in the porous area of weathered basaltic rocks. The weathered thickness has broken in space and profundity in basaltic rock (Khadri et al. 2013). The intensity of the weathering influences the recharge of soil water in basaltic formation. The Maharashtra state has separated into five soil water provinces on the origin of geological formations. The basaltic rock area, which occupies 81 percent of the state territory, is a significant soil water province in which the soil water

Fig. 1 Grid map of the of study area

Fig. 2 Location map of the arid area

potentials of the state have been estimated. A basaltic rock has underpinned over 95 percent in Akola and Buldhana districts (Pande et al. 2018). The area observed carious rock and soil classes such as current alluvial deposits like sand, silt, clay, gravel, etc. The drainage types have been necessary for groundwater flow modeling with hydrogeological characteristics and indicators measured through a lithological underpinning. A satellite image shows the drainage types and texture of geomorphological landform and type of rock, recommend soil features, and the site drainage condition (Fig. 3). The dendritic

and sub-dendritic drainage pattern usually shows the incidence of uniform rocks (Varade et al. 2014), i.e., maximum basaltic rock found using drainage characteristics in the study area (Pande et al. 2018).

Fig. 3 Geomorphological landforms in study area

Fig. 4 Flow chart of methodology

Materials and methodology

The hydrological data, hydrogeological information, rainfall, and water level data were collected from different organizations (Fig. 4). The initial stage of the database was recognized, which contains borehole information such as physical parameters like hydraulic conductivity, storage coefficient, pumping, water level, and rainfall, and water levels data

during the period 2014–2018. The model was selected and incorporated all of these complications and assess different options and future conditions. For the simulation of groundwater flow adjustment, the values of the input factors adjust to suit the ground conditions under some appropriate criteria.

The numerical model has been utilized to simulate the water level head during 2014–18 years. The numerical model has two layers, (i) the first layer is hard rock, and (ii) the second layer is the weather aquifer zone. These two layers are used to compute head values using the steady-state method available in the MODFLOW software. After preparing the conceptual model, the study part was discretized into 40 columns and 50 rows with a width and 450 m. According to the directions and hydrogeological views on groundwater, the north's primary input area is a basaltic rock. The model was standardized with the method of steady-state approach according to the hydrographer and based on hydraulic and aquifer data, and the hydraulic conductance of the aquifer with the specific output was obtained (Fig. 5).

Model setup and run

Groundwater model input data is inflow. This model was created for development of water flow model through steady-state method. In the visual mudflow, transient method was run for estimation of groundwater flow model, and after that model was converted to numerical modeling (Fig. 6).

Fig. 5 Active, inactive flow, head wells, and observation wells in the modeling

Fig. 6 Engine to run windows

Rate of inflow–Rate of outflow = Rate of change

Scientifically define, it is,

$$Q = -kiA \quad (1)$$

where Q = discharge, K = hydraulic conductivity, i = hydraulic gradient, and A = area of flow.

A general groundwater flow calculation may be written in Cartesian form as:

$$\frac{\delta}{\delta x_i} \left(k_{ij} \frac{\delta h}{\delta x_j} \right) = S \frac{\delta h}{\delta t} + W \quad (2)$$

where S is the precise storage, L^{-1} ; W is the volumetric flux per unit volume (– for outflow and + for inflow), T^{-1} ; and K is the hydraulic conductivity.

When compressibility is ignored, efficient porosity is almost equivalent to certain yield. This parameter is utilized to compute the average flow velocity in MODFLOW using the porous media. The aquifer characteristics are given as follows in the MODFLOW model collated from GSDA, CGWB reports (Table 1):

Model conceptualization

A detailed study of geology, borehole lithology, and fluctuations in the water level of the pools produced the conceptual model. In weathered rocks have been found in the study area (Fig. 6). The head of the groundwater in wells that penetrated the weathered rock's creation and penetrated wells into the formation was more in the basaltic rock formation. Hence, one layer supposes unconfined aquifer have observed as the highest and down weathered and fracturing rocks.

Boundary condition

Mathematical boundary conditions must be included in the model for hydrological landscapes together and in the model area (Xu et al. 2009). Boundary selection depends on the

hydrogeological condition and purpose of the aquifer model in the study area.

Numerical model

The visual module is the most detailed and user-friendly handled platform in three-dimensional groundwater flow for practical application and transport of pollutants. As groundwater interactions have been simulated and changes in groundwater chemistry have been calculated, water resources professionals have a comprehensive established of tools needed to address groundwater quality, water source, and supply safety efforts (Wenyue et al. 2003). The hydraulic connections between the confined aquifer and the aquifer could be helpful to generally designate the water system in the field of research as non-homogeneous, isotropic, and non-stant flux as Eq. (3).

$$\begin{aligned} \frac{\delta}{\delta x} \left[K \frac{\partial H}{\partial x} \right] + \frac{d}{dy} K \frac{\partial H}{\partial y} + \frac{\partial}{\partial z} K \frac{\partial H}{\partial z} + W = \mu_s \frac{\partial H}{\partial t} \quad (x, y, z) \in \Omega, t \geq 0 \\ H(x, y, z, t) \Big|_{t=0} = H_0(x, y, z) \quad (x, y, z) \in \Omega \cup S_1 \cup S_0 \\ H(x, y, z, t) \Big|_{s_1} = H_1(x, y, z, t) \quad (x, y, z) \in S_1, t \geq 0 \end{aligned} \quad (3)$$

$$\begin{aligned} \mu \frac{\partial H}{\partial t} = K \left(\frac{\delta H}{\delta x} \right)^2 + K \left(\frac{\delta H}{\delta y} \right)^2 + K \left(\frac{\delta H}{\delta z} \right)^2 \\ - \frac{\partial H}{\partial z} (K + P) + P \quad (x, y, z) \in S_0, t \geq 0 \end{aligned}$$

where Ω is demonstrated domain (m^2); (x, y, z) is spatial coordinates (m); S_0 is the phreatic surface; S_1 is the Dirichlet area; $H_1(x, y, z, t)$ is the water head at S_1 ; H is the potentiometric head (m); $H_0(x, y, z)$ is the first water head; K is hydraulic conductivity; μ_s is the elastic storativity; W is a volumetric flux per unit volume representative springs (m^3d^{-1}); S_s exact storage coefficient demarcated as the volume of water released from storage per unit change in head per unit volume of porous material (d^{-1}); P is the flux per unit area and time (md^{-1}) and t is time (d).

Table 1 Aquifer properties

Sr. No.	Model properties	Hydraulic conductivity (K_x in m/d)
1	Hydraulic conductivity in longitudinal direction, K_x m/sec	0.000018
2	Hydraulic conductivity in lateral direction, K_y m/sec	0.000018
3	Hydraulic conductivity in vertical direction, K_z m/sec	1.2e-3
4	Specific yield, S_y	0.0026
5	Effective porosity	0.17
6	Total porosity	0.32
7	Transmissivity, m2/sec	7.2e-3
8	Specific storage S_s (1/m)	1e-6

Results and discussion

The constructed model was utilized to estimate the effect of the groundwater flow system in hard rock regions on water levels. Detailed field information of the geology, lithology, and fluctuations of water levels in wells (Table 2) have been developed in the conceptual model of the process. The area was observed, and so many areas were affected due to the weathered rocks, groundwater issues, and climate change impact on the aquifer zones and rocks formation. The groundwater head was approximately the same in the wells that penetrated only to the weathered layer and in wells that penetrated the hard rock layer (Pande et al. 2019; Gebere et al. 2021). Therefore, the top and bottom of weathered and broken rocks may be treated as a single unconfined aquifer. In this analysis, the aquifer area for creating groundwater resources in the basaltic hard rock region developed four observation wells.

MODFLOW output

The model has given a better presentation of water level contours for groundwater flow modeling understanding in layers 1 and 2. It is provided to well water flow modeling related graphs of calculated vs observed heads using the steady-state method, calibration of the residual histogram, and residual and max head changes vs iteration number. These output graphs can be used for water balance and groundwater estimation (Fig. 7).

Model calibration

It contains varying values input parameters to fit the ground situations entire an adequate criterion (Guzman et al. 2015). Manual calibration is estimated by the trial and error method. Model calibration is required that ground situations at a place be correctly definite. After many times, runs and estimated groundwater heads were coordinated fairly reasonably with observed and calculated values (Fig. 8).

Table 2 Static groundwater level fluctuation for the year 2014–18

Sr. No.	Monsoon static water level 2014 (meter)	Monsoon static water level 2018 (meter)	Fluctuation of static water level (meter)	Aquifer type
1	10.20	6.70	3.50	Large grain basalt
2	12.00	9.00	3.00	Fine hard basalt
3	11.50	10.00	1.50	Weathered basalt rock
4	12.10	8.20	3.90	Alluvium

Fig. 7 Groundwater level head of layers 1 and 2

Fig. 8 Groundwater level head calibration of layers 1 and 2

Steady-state calibration

The study of groundwater flow modeling is essential for the calibration and observation of water heads using steady-state conditions (2016b). In this study selected the

steady-state method has been proved representation water levels as compared to other methods. The PEST program of the model looks for the alteration between the models' calculated values (determined with the initial values) and the observed field values. PEST runs the MODFLOW as many

Fig. 9 Head vs. times for wells

Fig. 10 Residual and max head vs iteration number

times as may be necessary and searches for a hydrologic factor usual total of squared deviations (objective function) between model—computed and the observation was reduced to a minimum (Malekinezhad et al. 2018). The model was developed for the computation of water level head spreading and groundwater statuses. Groundwater fluctuation has been measured using MODFLOW (Khadri et al. 2016a; Hani et al. 2007). The study of groundwater modeling has been considered the steady-state condition method (Brandyk et al.

2021). This method has been reflected the groundwater situation during 2014 and 2018 years. This study selected four observation and pumping wells were involved for calculated vs observed water level heads graph (Figs. 9, 10, and 11). A groundwater flow model helps forecast the groundwater fluctuations in upcoming periods, the hard basaltic area, and may be adopted for groundwater recharge structures. In order to optimize the number of iterations, the default values of coefficients were used (Fig. 12). The steady-state

Fig. 11 Calculated vs observed head using steady-state method

calibration is the best method in MODFLOW software and shows accurate values in the output graph (Malekzadeh et al. 2019). In this model calibrated specific yield values for the 1st layer (upper layer) vary from 0.03 to 0.05 and the specific storage for the 1st layer is 0.00015.

MODFLOW simulation

The 2014 and 2018 periods display a simulated groundwater level for the study area. Layer-1 groundwater heads simulated range between 325 and 347 m in the numerical modeling (Figs. 13 and 14). The groundwater heads have been simulated (Fig. 15). The groundwater heads have been simulated (Fig. 15).

Therefore, two layers have been selected for groundwater flow modeling based on the numerical modeling in the basaltic rock area (Fig. 15). The numerical modeling has calculated and observed heads to study the groundwater conditions in the hard rock area. In numerical modeling root mean squared observed is 0.72 (m) as per visual modflow software. This groundwater flow modeling can be helpful for the understanding of the groundwater conditions in the basaltic hard rock area under various climate situations.

Discussion and recommendations

The basic groundwater modeling supports the future consideration for sustainable groundwater development (Mondal et al. 2011; Nozarpoor 2014; Pande et al. 2017). The steady-state and numerical models provide valuable material on the groundwater balance, drainage response to different stresses, and the interactions and flow patterns between groundwater. The hydraulic conductivity of the geologic materials that discrete the new and salty groundwater is an improbability of the model and requirements to be examined. The first step is to describe the nature of the model design and its application question and assess the model's intent (Moharir et al. 2017). While it may appear obvious, this is an essential first step that is overlooked in imperativeness to performance.

The model provided valuable data on the area and the basaltic walls. However, because of limited data of hydraulic conductivity, wellheads, and aquifer thickness information on some regions of basaltic rocks in Maharashtra, the steady-state model is not easily employed for detailed groundwater management. The full correctness of the results is based on the quantification of these input factors and the treatment

Fig. 12 Calculated vs. observed head using steady-state method

Fig. 13 Groundwater level head simulation of Layer-1 using numerical modeling

Fig. 14 Groundwater level head simulation of Layer-2 using numerical modeling

Fig. 15 Calculated vs observed head using numerical modelling

of temporal variations under transient and numerical conditions. The results obtained here should not be observed as a perfect simulation but rather as a projection response within fairly realistic input parameters (Khadri et al. 2016a, b). Consequently, the findings should be identified and implemented pleasant both drawbacks and disadvantages associated with the data gaps (Table 3).

Conclusions

The numerical and steady-state flow modeling has given to considered geological and hydrological factors for the groundwater development in the basaltic rock formation. The various aquifer water flow models are software like MODFLOW and are frequently utilized to analyze groundwater flow management. The numerical modeling is very

easily identified and demonstrate the groundwater flow conditions. The groundwater flow modeling is very critical in studying groundwater in basaltic formations. MODFLOW software has to be helpful for groundwater issues and the decision-making system. In the current study, numerical and steady-state flow models were employed to measure water level head calibration and observation of basaltic rock area with boundary conditions and observation and pumping wells. A good technique of dropping groundwater flow modeling errors has been used on the hydrological and geology system. The mudflow model values have been calculated and show a good fit of the measured information, which sign the model is suitable. These results can be significantly applied to flexible soil and water resources planning for effective groundwater planning.

Table 3 Recommendation based on the groundwater flow modeling

Well No	Recommendations
1	Not potential as the rate of improvement is very slow because irrigation demand is more as compared to another region
2	Deeping of the well by 2 mts. can increase the good yield by 25% and 30%
3	Rainwater harvesting and groundwater recharge structures will require groundwater level
4	Potential well for further development of groundwater and surface water

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Declarations

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

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References

- Abraham M, Priyadarshini MK (2021) Numerical modeling for groundwater recharge. In: Pande CB, Moharir KN (eds) Groundwater resources development and planning in the Semi-Arid Region. Springer, Cham. https://doi.org/10.1007/978-3-030-68124-1_9
- Brandyk A, Kaca E, Oleszczuk R, Urbański J, Jadczyński J (2021) Conceptual model of drainage-sub irrigation system functioning—first results from a case study of a lowland valley area in Central Poland. Sustainability 13(1):107. <https://doi.org/10.3390/su13010107>
- Colins Johnny J, Sashikkumar MC, Anas PA, Kirubakaran M (2016) GIS-based assessment of aquifer vulnerability using DRAS-TIC Model: a case study on Kodaganar basin. Earth Sci Res J 20(1):1–8
- Colins Johnny J, Chidambaram SM, Muniraj K (2017) Isolation of wells contaminated by tannery industries using principal component analysis. Arab J Geosci 10:304
- Datta PS (2002) Groundwater situation in New Delhi: red alert Nuclear Research Laboratory, IARI, New Delhi region. World Geol 2:161–165
- Gebere A, Kawo NS, Karuppannan S et al (2021) Numerical modeling of groundwater flow system in the Modjo River catchment Central Ethiopia Model. Earth Syst Environ 7:2501–2515. <https://doi.org/10.1007/s40808-020-01040-0>
- Gupta CP, Thangarajan M (1990) Management of groundwater resources in India using simulation models. Water Resour J 1:34–42
- Guzman JA, Moriasi DN, Gowda PH, Steiner JL, Starks PJ, Arnold JG, Srinivasan R (2015) A model integration framework for linking SWAT and MODFLOW. Environ Model Softw 73:103–116. <https://doi.org/10.1016/j.envsoft.2015.08.011>
- Hani A, Djorfi S, Lamouroux C, Lallahem S (2007) Impact of the industrial rejections on water of Annaba aquifer (Algeria). Eur Water 19(20):3–14
- Jackson JM (2007) Hydrogeology and groundwater flow model, Central catchment of Bribie Island, southeast Queensland. Dissertation, Queensland University of Technology
- Khadri SFR, Pande C, Moharir K (2013) Geomorphological investigation of WRV-1 Watershed management in Wardha district of Maharashtra India; using Remote sensing and Geographic Information System techniques. Int J Pure Appl Res Eng Technol 1(10):832–854
- Khadri SFR, Moharir K (2016a) Characterization of aquifer parameter in basaltic hard rock region through pumping test methods: a case study of Man River basin in Akola and Buldhana Districts Maharashtra India. Model Earth Syst Environ 2:33
- Khadri SFR, Pande C (2016b) Ground water flow modeling for calibrating steady state using MODFLOW software: a case study of Mahesh River basin, India Model. Earth Syst Environ 2:39
- Khare YD, Varade AM (2018) Approach to Groundwater management towards sustainable development in India-Italian. J Groundwater AS 24(308):29–36
- Kumar CP (2013) Numerical modelling of groundwater flow using MODFLOW. Indian J Sci 2:86–92
- Kushwaha RK, Pandit MK, Goyal T (2009) MODFLOW based groundwater resource evaluation and prediction in mendha sub-basin, NE Rajasthan. J Geol Soc India 74:449–458
- Lachal F, Gana S (2016) Groundwater flow modeling for impact assessment of port dredging works on coastal hydrogeology in the area of Al Wakrah (Qatar), model. Earth Syst Environ 2:201
- Lasya CR, Inayathulla M (2015) Groundwater flow analysis using visual modflow. IOSR J Mech Civil Eng 12(2):05–09
- Malekzadeh M, Kardar S, Shabanlou S (2019) Simulation of groundwater level using MODFLOW, extreme learning machine and wavelet-extreme learning machine models. Groundw Sustain Dev 9:100279. <https://doi.org/10.1016/j.gsd.2019.100279>
- Mayer A, May W, Lukkarila C, Diehl J (2007) Estimation of fault zone conductance by calibration of a regional groundwater flow model: Desert hot springs California. Hydrol J 15(6):1093–1106
- Mendonça LAR, Frischkorn H, Santiago MF, Mendes FJ (2005) Isotope measurements and ground water flow modelling using MODFLOW for understanding environmental changes caused by a well field in semiarid Brazil. Environ Geol 47:1045–1053. <https://doi.org/10.1007/s00254-005-1237-y>
- Moharir K, Pande C, Patil S (2017) Inverse modelling of aquifer parameters in basaltic rock with the help of pumping test method using MODFLOW software 8(6):1385–1395
- Mondal NC, Singh VP, Sankaran S (2011) Groundwater flow model for a tannery belt in southern India. J Water Resour Prot 3:85–97
- Nozarpour L (2014) Water resources modeling and management in lower plain, Andimeshk with an emphasis on the evaluation of Jarmeh Artificial recharge. Master's Thesis, ShahidChamran University, Ahvaz
- Omar PJ, Gaur S, Dwivedi SB et al (2020) A modular three-dimensional scenario-based numerical modelling of groundwater flow. Water Resour Manag 34:1913–1932. <https://doi.org/10.1007/s11269-020-02538-z>
- Pande CB, Moharir K (2017) GIS-based quantitative morphometric analysis and its consequences: a case study from Shanur River Basin. Maharashtra India. Appl Water Sci 7(2):861–871
- Pande CB, Khadri SFR, Moharir KN, Patode RS (2017) Assessment of groundwater potential zonation of Mahesh River basin Akola and Buldhana districts, Maharashtra, India using remote sensing and GIS techniques. Sustain Water Resour Manag. <https://doi.org/10.1007/s40899-017-0193-5>
- Pande CB, Moharir KN, Pande R (2018) Assessment of Morphometric and Hypsometric study for watershed development using spatial technology—A case study of Wardha river basin in the Maharashtra India. Int J River Basin Manag Taylors & Francis J. <https://doi.org/10.1080/15715124.2018.1505737>
- Pande CB, Moharir KN, Singh SK, Varade AM (2019) An integrated approach to delineate the groundwater potential zones in Devdari watershed area of Akola district Maharashtra, Central India. Environ Dev Sustain. <https://doi.org/10.1007/s10668-019-00409-1>

- Raazia S, Dar AQ (2021) A numerical model of groundwater flow in Karewa-Alluvium aquifers of NW Indian Himalayan Region. *Model Earth Syst Environ*. <https://doi.org/10.1007/s40808-021-01126-3>
- Rane N, Jayaraj GK (2021a) Stratigraphic modeling and hydraulic characterization of a typical basaltic aquifer system in the Kadva river basin, Nashik, India. *Model Earth Syst Environ* 7:293–306. <https://doi.org/10.1007/s40808-020-01008-0>
- Rane N, Jayaraj GK (2021b) Evaluation of multiwell pumping aquifer tests in unconfined aquifer system by Neuman (1975) method with numerical modeling. In: Pande CB, Moharir KN (eds) *Groundwater resources development and planning in the semi-arid region*. Springer, Cham. https://doi.org/10.1007/978-3-030-68124-1_5
- Rezaei M, Sargazi A (2009) The effects of running artificial recharge on the aquifer of Goharkooh Plain. *J Earth Sci* 19:99–106
- Sathish S, Elango L (2015) Numerical simulation and prediction of groundwater flow in a coastal aquifer of southern India. *J Water Resour Prot* 7:1483–1494
- Sharief SMV, Zakwan M (2021) Groundwater remediation design strategies using finite element model. In: Pande CB, Moharir KN (eds) *Groundwater resources development and planning in the semi-arid region*. Springer, Cham. https://doi.org/10.1007/978-3-030-68124-1_6
- Siva Prasad Y, Venkateswara Rao B, Surinaidu L (2021) Groundwater flow modeling and prognostics of Kandivalasa river sub-basin, Andhra Pradesh, India. *Environ Dev Sustain* 23:1823–1843. <https://doi.org/10.1007/s10668-020-00653-w>
- Takounjou FA, Rao VVSG, Ngoupayou NJ, Nkamdjou SL, Ekodeck GE (2009) Groundwater flow modelling in the upper Anga'a river watershed, Yaounde Cameroon. *Afr J Environ Sci Technol* 3(10):341–352
- Varade AM, Shende R, Lamsage B, Doagre (2014) Efficacy of Kumarswamy method in determining aquifer parameters of large-diameter dugwells in deccan trap region, Nagpur District, Maharashtra. *18*(4):461–468
- Wenyue L et al (2003) The application of Visual MODFLOW in numerical groundwater simulation in Daqing region. *World Geol* 2:161–165
- Xu X, Huang GH, Qu ZY (2009) Integrating MODFLOW and GIS technologies for assessing impacts of irrigation management and groundwater use in the Hetao Irrigation District, Yellow River basin. *Sci China Ser E-Tech Sci* 52(11):3257–3263. <https://doi.org/10.1007/s11431-009-0328-5>
- Zhou Y, Li W (2011) A review of regional groundwater flow modeling. *Geosci Front* 2(2):205–214

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