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ASSESSMENT OF SALINE WATER INTRUSION IN A COASTAL REGION OF KERALA, INDIA

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Abstract

The behavior of groundwater flow in coastal aquifers is influenced by variations in salinity and density levels. Models for groundwater flow and solute transport are employed to analyze the impact of these variations. In this study, a groundwater flow and solute transport model was developed for the coastal aquifer of the Bharathapuzha River. Visual MODFLOW 2.8.1 and MT3D were utilized for modeling groundwater flow and solute transport, respectively. Water level and quality data were collected from 18 observation wells in the field on a monthly basis from 2012 to 2021. Additionally, monthly water level data from four wells managed by the Central Water Commission (CWC) were incorporated as input for the models. Hydrogeological properties of the aquifer, such as specific yield, porosity, and specific storage, were obtained from the Groundwater Department and available literature. The model was calibrated and validated using field data and subsequently employed to predict groundwater flow and solute transport in the area. The results indicate that the river stretch is highly susceptible to saltwater intrusion. Salinity levels in certain wells (wells 7, 8, 13, and 14) exceeded the acceptable limits for drinking water as per the BIS standards. Based on model predictions, saltwater intrusion is projected to extend approximately 4.8 to 5 km from the Ponnani estuary, laterally upstream along the river course, within the next 10 to 15 years if pumping rates increase by 5 to 10% from the current rate. If the pumping rate rises by 15 percent, the intrusion may extend up to 6 km from the coast. Therefore, it is crucial to implement optimal freshwater withdrawal strategies and mitigation measures in these areas to safeguard the coastal aquifers. Restricting groundwater usage along the river banks within a lateral distance of at least 5 km from the seashore is recommended.

Keywords: Bharathapuzha, groundwater model, MT3D, Visual MODFLOW

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1. Introduction

The coastal regions of Malappuram district in Kerala where large fishermen community is seen have a high population density of 1158 persons/km^2 (Asir Ramesh et al., 2021). In order to cater to the demand for domestic, agricultural and industrial uses, people need to depend on surface water as well as ground water (Velis et al., 2017). As the demand for water increases and surface water availability is declining, groundwater turns out to be the major source of freshwater (Mondal and Singh, 2009; Wada et al., 2010). Climate change also causes temperature variations which affect the saltwater intrusion in the coastal aquifers (Ahmed et al., 2020; Minar et al., 2013). To mitigate the problems of water scarcity, water pollution, and ecological problems, a realistic analysis of the groundwater and related information is needed (Bidwell, 2005). Bharathapuzha is one of the major rivers in the Malappuram district (George and Athira, 2020) which flows through the district and drains into the Arabian Sea near Ponnani. The main issue faced in this area is the saltwater intrusion into the coastal aquifers during the summer months (April-

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May) when the rainfall is almost nil. During monsoon season, this issue is less serious (June-November).

Saltwater intrusion as explained by Barlow and Reichard (2010) is the infiltration of seawater into the coastal groundwater systems and getting mixed with the nearby fresh water. Different methods have been developed by researchers for assessing saltwater intrusion into nearby aquifers (Abd-Elhamid and Javadi, 2011; Bhattacharya and Datta, 2005; Hussain et al., 2019). By simulating the groundwater flow and saltwater movement using mathematical models, future saltwater distribution in the coastal aquifer can be predicted and controlled. In the study conducted by Datta et al. (2009), simulations are used for evolving planned pumping strategies for controlling the saltwater intrusion in a coastal aquifer. Dibaj et al. (2020) developed a 3-dimensional finite difference model which was used for studying the influence of sea-level rise on saltwater intrusion into the Pingtung coastal aquifer in Taiwan. In the study done by Akhtar et al. (2022), the results of groundwater models were used for the effective management of groundwater resources in the Wadi Al-Jizi aquifer, and it was found that the higher pumping rates in the upcoming years are expected to cause further groundwater quality degradation.

Recent years have seen major advancements in model analyses and evaluation (Gleeson et al., 2021; Maxwell et al., 2015). According to aquifer conditions, abstraction rates, urbanization and economic development, seawater intrusion problems vary from one area to another. The quality and chemical constitution of groundwater depends on many natural and man-made factors (Khatri and Tyagi, 2014). Studies have been conducted by various researchers to understand the saltwater intrusion in different parts of India (Prusty and Farook, 2020; Sukumaran and Raj, 2020). Scientists from various parts of Kerala state have also reported high salinity levels along the coastal regions (Senthilkumar et al., 2019; Sreedharan and Pawels, 2018).

The increasing population in the coastal stretch of Kerala has resulted in rising demand for water for domestic, industrial, agricultural and allied purposes. Ponnani being a thickly populated town in the coastal stretch of Malappuram district is facing a severe shortage of good quality drinking water. In this study, an area from Ponnani to Tavanur along the course of river Bharathapuzha was selected as the study area to understand the extent of saltwater intrusion. The present study aimed to understand the intrusion regime of saline water into the aquifer near the sea in the Ponnani region. The pace and direction of groundwater movement through aquifer systems are determined using groundwater flow models. Groundwater modeling was carried out using Visual MODFLOW 2.8.1, developed by Waterloo Hydrogeological Inc. The analysis of saltwater intrusion utilizes MT3D numerical engine in Visual MODFLOW.

2. Study area

The area selected is along the southern bank of the estuary of Bharathapuzha and is bordered by several brackish lagoons in the south and the Arabian sea in the west. The area lies between 10.76º to 10.85º North latitude and 75.88º to 76º East longitude. Fig. 1 shows the geographic location of the area under study. The study area involves part of the Tavanur and Ponnani regions of the Bharathapuzha river basin. The total study area is approximately 50 km^2. It has a more or less flat topography with a gentle slope in the west and south direction (Fig. 2).

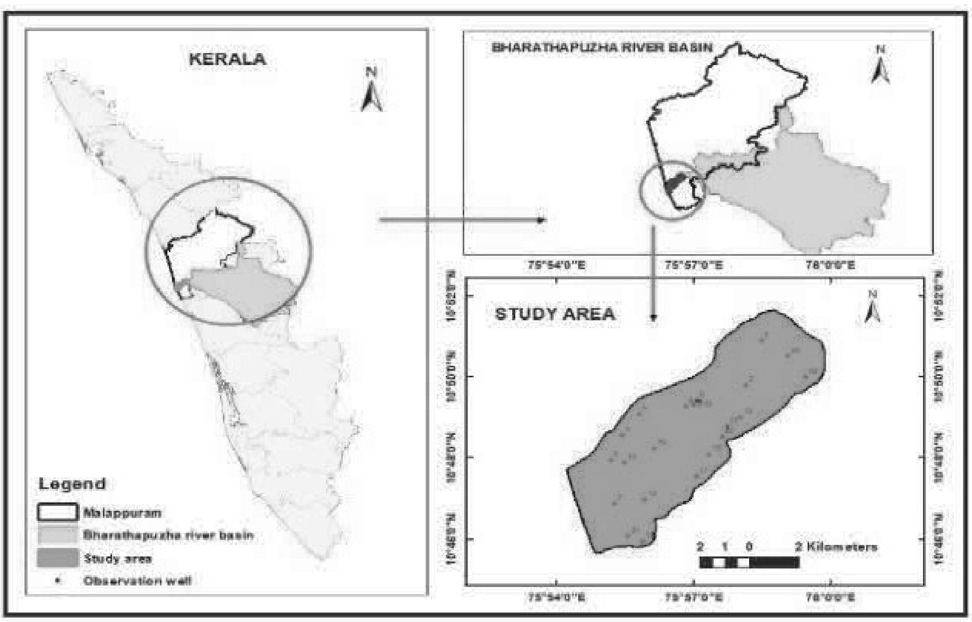


Fig. 1. Location of the study area with observation wells

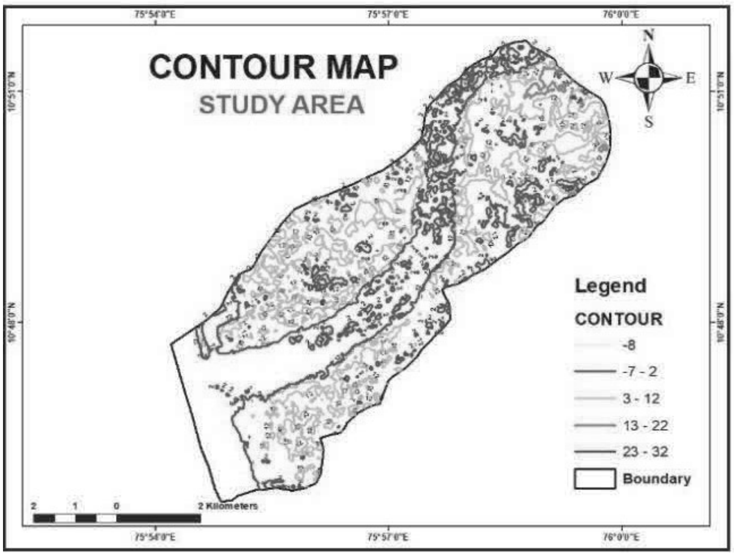


Fig. 2. Topographic map of the study area

The Ponnani-Tavanur area receives an annual rainfall of around 2940 mm. The region, has a topography of undulating type, the western part having the lowest elevation of around -7 m to -2 m below MSL. The highest elevation is in the north-east region which is at an elevation of about 12-20 m, and is gently sloping towards the Arabian sea.

The distinctive alluvial landforms in the area are of recent to sub-recent age which is the most potential aquifer in the district (CGWB, 2013). The recent alluvial formation consists of coastal alluvium, riverine alluvium, and valley fill. The coastal alluvium is mainly composed of sand, silt, and clay.

The groundwater here occurs under water table conditions. Here for modeling purposes, two layers are considered. Location details of groundwater monitoring wells are given in Table 1 and are shown in Fig. 1. The aquifer properties used in the model were derived from the available literature, well logs at two sites, data collected from Public Works Department (PWD) and Central Ground Water Board (CGWB) reports, etc., and presented in Table 2. K_x, K_y, and K_z represent the hydraulic conductivities in the longitudinal, lateral and vertical directions respectively. Kz is taken as 10 percent of Kx and Ky.

2. Materials and methods

A network of eighteen existing observation wells (open wells) was selected for water level monitoring in the study area which was distributed over the area. The monitoring of the water levels was done every month and water samples were collected for analysis from January 2012 to December 2021. Each sample represents the quality of water in that particular area and gives a rough idea about the groundwater quality in that area. Four groundwater monitoring open wells of Central Water Commission located within the study area at Chamravattom, Eswaramangalam, Ponnani, and Tavanur were also used for the study. This data was also imported to the model domain.

The depth of the water level in the observation wells was measured at monthly intervals with the help of a water level recorder. The groundwater table fluctuation was assessed by analyzing the average depth to groundwater level in the observation wells. Saltwater intrusion along the coastal area was assessed by measuring the level of salinity in the water samples collected from the 18 observation wells, selected for this purpose (Table 3). These samples were tested for salinity using the digital water analyzer.

The three-dimensional modular finite-difference groundwater model MODFLOW developed by US Geological Survey (USGS) was used for flow simulation. The groundwater system in MODFLOW is discretized into a grid of cells. The head is determined at a single location known as the node for each cell. Visual MODFLOW, the graphical interface for MODFLOW was used in the study.

2.1. Mathematical model for groundwater flow

The movement of groundwater through a porous medium with a constant density can be well explained using a partial differential equation (McDonald and Harbaugh, 1988). This equation is a combination of Darcy's law and the water balance equation and is solved by the model.

This partial differential equation representing groundwater flow is given by Eq. (1).

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right)=S_S\frac{\partial h}{\partial t} \quad (1)$$

where h is the potentiometric head of the aquifer, W is the flux per unit volume (volume basis), Ss is the specific storage, Kx, Ky, and Kz are the hydraulic conductivity values along the three directions, and t represents the time.

Table 1. Details of groundwater monitoring wells

Well Name	*X- coordinate (m)*	*Y-Coordinate (m)*	*Ground elevation from msl (m)*	*Alluvium depth (m)*	*Hard rock depth from ground surface (m)*
OW 1	606510.41	1199384.42	20	19.7	-5
OW 2	605900.22	1197352.9	14	13.7	-11
OW 3	603847.87	1196459.66	13	12.8	-12
OW 4	603520.14	1196381.23	10	9.8	-15
OW 5	601687.89	1196017.31	9	8.6	-16
OW 6	601017.37	1195054.41	10	9.6	-15
OW 7	600709.07	1191929.72	6	5.6	-19
OW 8	600548.10	1193926	5	4.6	-20
OW 9	603964.03	1196651.78	8	7.6	-17
OW 10	604100.15	1196576.67	10	9.6	-15
OW 11	605174.63	1195488.68	11	10.6	-14
OW 12	605703.20	1195887	11	10.6	-14
OW 13	601901.10	1192136.47	6	5.7	-19
OW 14	601091.90	1193814	16	15.7	-9
OW 15	601818.56	1190225.11	11	10.7	-14
OW 16	602284.3	1194461	10	9.8	-15
OW 17	603952.09	1193183.26	9	8.8	-16
OW 18	606506.17	1199343.26	9	8.7	-16
OW 19	603847.87	1196459.66	13	12.7	-12
OW 20	604077.09	1196576.49	12	11.7	-13
OW 21	601913.22	1188074.77	5	4.7	-20
OW 22	607585.07	1198679.9	18	17.5	-6

Table 2. Hydrogeology of the study area

Model properties	*First layer (alluvium)*	*Second layer (hard rock)*
K_x (md^{-1})	45	9
K_y (md^{-1})	45	9
K_z (md^{-1})	4.5	0.9
S_s Specific storage (m^{-1})	0.0005	0.0001
S_y, Specific Yield	0.069	0.022
Effective Porosity	0.2	0.16
Total Porosity	0.3	0.16

Table 3. Monthly average values of salinity (mg/l) for the period 2012-2021

Well no	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*July*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1	341	280	250	240	340	299	290	220	230	310	159	300
2	387	497	587	697	747	477	437	427	436	459	537	517
3	188	140	190	355	523	340	310	280	260	240	217	270
4	538	608	668	828	780	528	508	558	632	602	588	598
5	532	602	662	822	774	522	502	552	626	596	582	592
6	447	500	470	500	610	350	420	540	530	499	513	360
7	554	610	750	1080	1340	760	440	500	610	470	544	610
8	800	860	950	1210	1620	980	850	760	710	770	860	900
9	523	593	653	813	765	513	493	543	617	587	573	583
10	532	602	662	822	774	522	502	552	626	596	582	592
11	178	130	280	345	513	330	300	292	250	222	207	260
12	430	500	560	720	672	420	400	450	524	494	550	490
13	735	700	940	1410	1860	890	840	790	780	740	702	800
14	737	807	867	1027	979	727	707	757	931	901	857	797
15	587	657	717	877	829	577	557	607	781	751	707	647
16	571	641	701	861	813	561	541	591	765	735	691	631
17	381	451	511	671	623	371	351	401	575	545	501	441
18	261	331	391	551	503	251	231	281	455	425	381	321

The three-dimensional Modular 3D Solute Transport Model (MT3D) is efficient in simulating solute transport in complex hydrogeologic situations. It is specifically designed to handle adjectively-dominated transport issues and works in connection with MODFLOW.

The boundaries of the area were marked in Google Earth Pro and converted into BMP format. The study area was discretized into 2500 cells (50 rows and 50 columns divided into grids with a spacing of 250 m x 250 m). The imported base map was georeferenced and the data files were added in ASCII format and as text files. The grid formation is shown in Fig. 3.

There were mainly four major pumping wells identified in the study area. Two major pumping wells of Kerala Water Authority and two near the Ponnani harbor. The pumping wells are mainly used for irrigation, household purpose and for harbor needs. Data from the four pumping wells were also collected. Pumping data is imported as a text file. The negative sign indicates the pumping rate and the positive sign indicates injection.

Field observations of elevation and head observations from observation wells are given as input to the Visual MODFLOW to get model output values. Coordinates for the position of observation wells were also imported. The wells were marked to grids with the head observation well menu. Depth to water table from year 2012 to 2018 were added to the model. Water levels from year 2012 to 2021 were entered through the edit screen of observation wells.

The hydrogeological properties like initial head, conductivity, storage, bulk density, species properties, concentration at the beginning and dispersion values were also given as inputs to simulate real conditions.

2.2. Boundary conditions

Any model's boundary conditions must reflect how the system interacts with its surroundings. For the groundwater flow models the boundary conditions will explain the flow exchange between the external system and the model. The accuracy of these data affects the output of the models. The MODFLOW-supported boundary types river, constant head, recharge, and constant concentration were selected for the study region. The Arabian Sea at the western border is regarded as a constant head boundary. The internal boundary condition known as the river head is used to simulate how a surface water body may affect the flow of groundwater. River was taken as the specified head boundary condition, and here the river Bharathapuzha was taken as the river head boundary (Fig. 4).

The elevation at river points, river bottom elevation, and conductivity details were given as input. The effect of flow between the rivers and aquifer was simulated by dividing the rivers into reaches containing single cells. Conductance of these rivers was calculated using the following equation (Eq. 2):

$$C = \frac{K \times L \times W}{M} \tag{2}$$

where,
C = Conductance, $m^2d^{-1,}$
L = Length of river reach through a cell, m
K = Vertical hydraulic conductivity of riverbed, md^{-1},
W = Width of river in a cell, m
M = Thickness of riverbed, m.

Aerial recharge mainly occurs due to percolation from rainfall which moves into the groundwater system. In the model, recharge was assigned using the 'assign' option while recharge (mm/year) was calculated using Eq. (3).

$$R = 3.984(Rav - 40.64)^{0.5} \tag{3}$$

where, R represents the recharge in centimeters, and Rav is the average annual rainfall in centimeters (Chandra and Saxena, 1975).

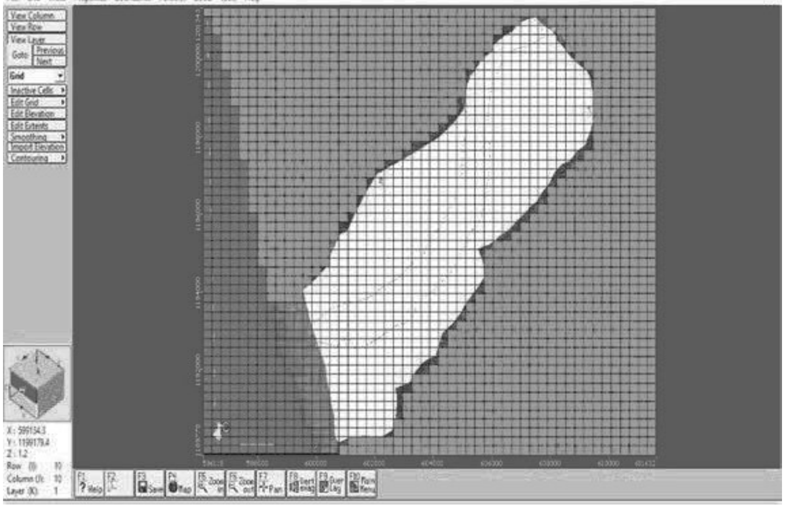


Fig. 3. Grid formation of the study area

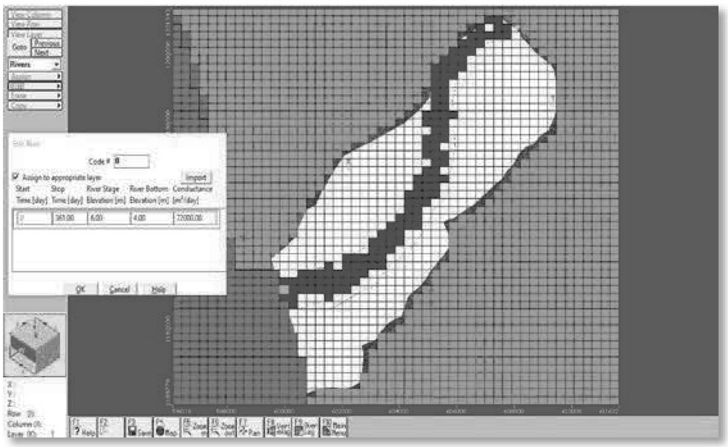


Fig. 4. Edit screen of river

For the study, evapotranspiration is assumed as 10 percent of the total rainfall and considered to be uniform for the entire area (Rejani et al., 2008; Sajeena and Kurien, 2019).

2.3. Model run

The model simulation was done for steady state and transient state conditions of the study region after entering all the input parameters. The initial head, anisotropic factor, layer type, recharge selections, Water Hydrogeological Software (WHS) solver parameters and rewetting options were chosen in an acceptable manner. MT3D simulation involves taking a pre-defined MODFLOW simulation such as porosity, assigning concentrations to the source and sinks, choosing some general simulations and assigning the values for the parameters.

The initial concentration of contaminant for the study area was assigned using the observed water quality data from the study area for the period 2012 to 2021. Salinity from all observation wells at successive intervals are given as input to Visual MODFLOW to get model output values. Coordinates for the position of observation wells were also imported (Fig. 5). Value of constant concentration was given as 35000 mg/L, which is the concentration of salt in sea water (Huang and Chiu, 2018). MT3D was run in MODFLOW with the support of validated parameters. Only transient state simulation was done by selecting proper advection, out/time steps, solver options etc.

3. Results and discussion

The results obtained includes the results of calibration and validation under unsteady-state conditions. The output of the Visual MODFLOW includes head difference, equipotential contours, water table elevation and velocity vectors showing the direction of flow. The extent of saltwater intrusion into the study area is also presented here.

3.1. Model calibration

The model was developed and calibrated for a steady state and transient state of 7 years 2012 to 2018). After processing, Root Mean Square (RMS) error in the equipotential graphs was minimized by varying the values of hydraulic conductivity. Fig. 6 depicts a comparison of simulated head versus measured head for the all the observation wells. According to the results obtained, the simulated and measured water levels in the majority of the wells are in good agreement. The calibration minimized the inaccuracy that was seen during the model run.

Fig. 7 depicts the groundwater contour map following calibration. The water table elevation in the coastal region was relatively low, ranging from -3 to 3 m. The depth to the water table in the study area was between -3 and 16 m (deep blue to red shade). The highest depth to the water table was in the Tavanur-Nariparambu area (red shade).

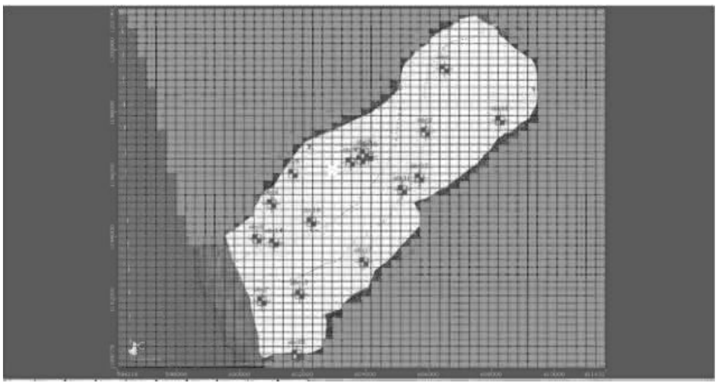


Fig. 5. Adding concentration observation well

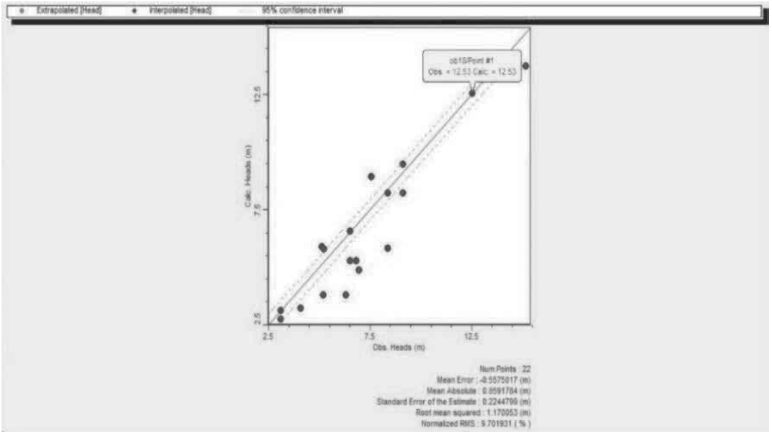


Fig. 6. Model computed vs observed water level (Transient state)

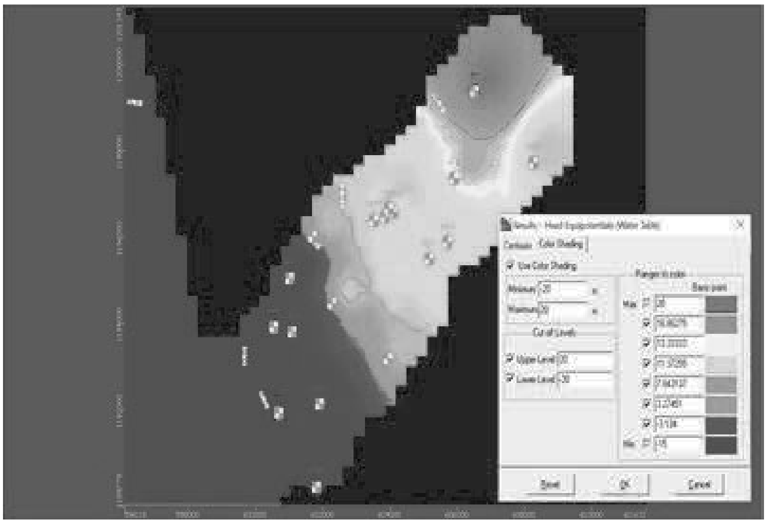


Fig. 7. Computed water table contour map after calibration

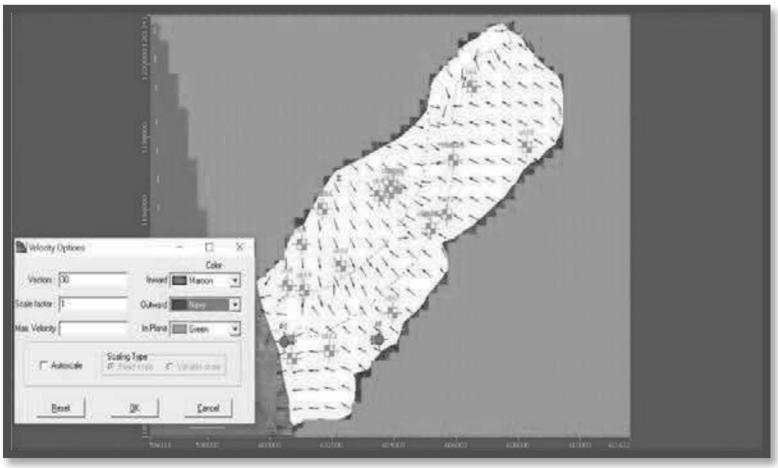


Fig. 8. Velocity vector direction of the study area

From the velocity vectors in Fig. 8, it could be seen that ground water flow actually takes place from the North-East part of the study area and reaches the sea through the river and the land.

3.2. Model validation

In order to find the solution for water scarcity during summer months, the ground water scenario of the study area for the next three years was validated for the period 2019 to 2021 (Fig. 9).

Figure 10 illustrates the groundwater contour map after validation which shows the change in the groundwater table. This groundwater contour map was compared with the water table contour map obtained after calibration (Fig. 7). It could be seen that the green color is changed to light blue color in the coastal areas, also red color changed to orange and green color in north eastern regions (Tavanur and Nariparambu) of the study area, which indicates a drop in water table of about 3 to 5 m in the whole area.

3.3. Model prediction

After proper calibration and validation, the visual MODFLOW model is suitable for prediction of groundwater flow (Gilsha Bai et al., 2022). The rate of pumping was enhanced by 5, 10, and 15% during the validation period 2021, and the validated model was used to estimate saltwater intrusion for the following ten years.

When pumping rate is increased to 5 and 10 percent, and subsequently to 15 percent, there is an abrupt reduction in the water level in the area (Figs. 11a-c). Later, the elevation of the water table remains nearly steady. The reason may be that the water table in some areas may have reached the bed rock (Table 1).

3.4. Contaminant transport modelling

The salt water intrusion was studied using MT3D in VISUAL MODFLOW.

3.4.1. Calibration

The graphs of observed concentration against estimated concentration, observed concentration versus time, and concentration contour map were obtained for salt water intrusion. The model simulated and observed concentrations were comparable at a 95% level of confidence.

Figure 12 shows the calibrated model performance. Fig. 13 shows the concentration contour map after calibration. It is seen that saltwater intrusion is present along the coastal stretch in the Ponnani area. Saltwater intrusion has been extended from 0.5 to 1.6 km from the coast along the length of the river, and varies in its intensity. Saltwater intrusion is observed mainly in Padinjarekkara, Purathur and Ponnani regions after calibration and the highly sensitive area was found to be near Ponnani harbor.

3.4.2. Model Validation

The model was verified for its accuracy and predictive capability within acceptable limits of errors, independent of the calibration data. Validation was done using water quality data of 2019 to 2021, and the concentration contour map is shown in Fig. 14. It was found that the possibility of saltwater intrusion extended laterally for around 0.5 and 0.7 km from the location where saltwater presence was seen after calibration by the end of 2018. This intrusion of 0.5 to 0.7 km is during a short span of three years. It is also seen from the figures that salt concentration increases at different locations, and also increases with time. The extent of lateral movement of salinity is slower when compared to the increase in the intensity of concentration as time increases. The model is prepared for prediction since the model values have good correlation with the observed values.

In the region where Bharathapuzha reaches the Arabian Sea, there is a possibility of saltwater intrusion because there is a fluctuation in flow that matches with the concentration contour map (Fig. 14) of the study area. In the Ponnani and Purathur areas, where the flow direction fluctuated and the concentration was high, there was a clear indication of saltwater intrusion, according to the flow direction and concentration contour maps. The concentration contours match with the possibility of saltwater intrusion in the region where Bharathapuzha joins the sea, and a variability of flow is also seen here (Fig. 8, Fig. 14).

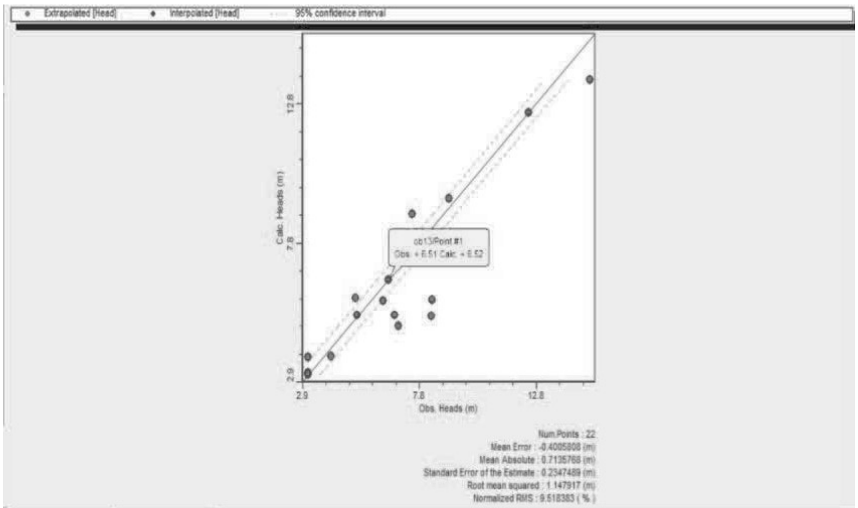


Fig. 9. Model computed vs observed water level after validation

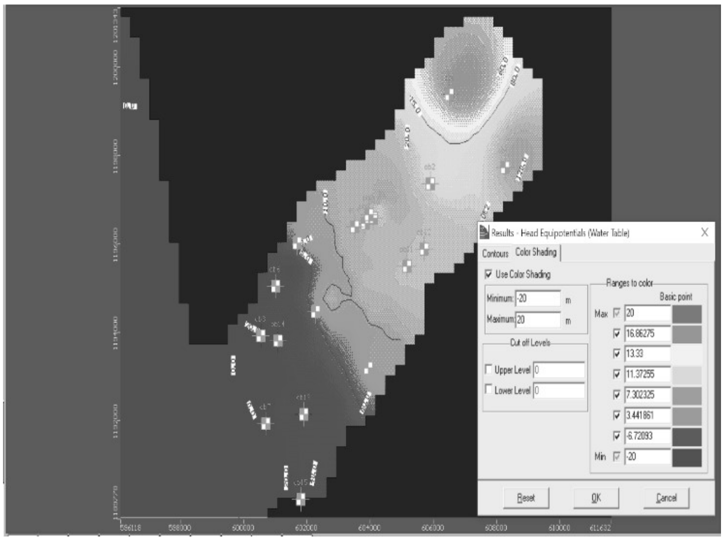
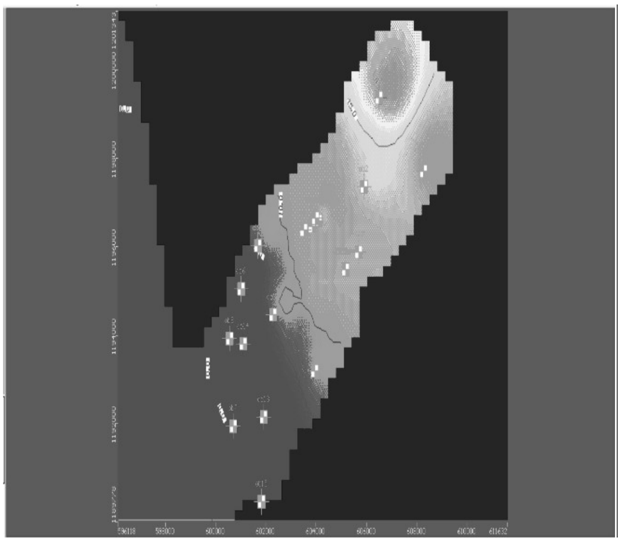
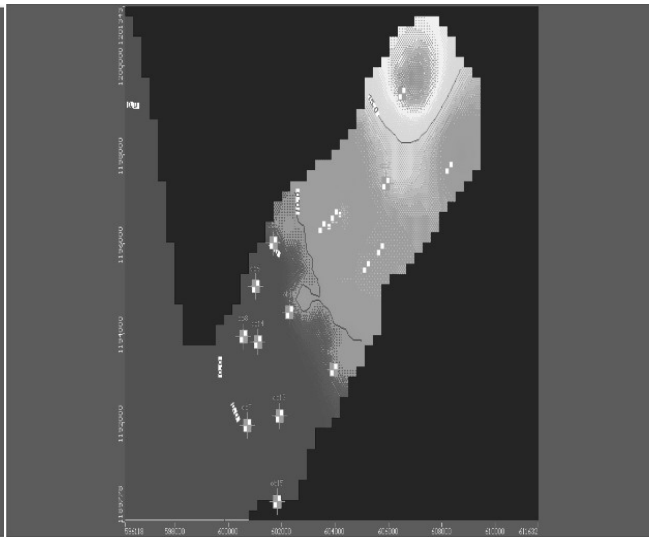


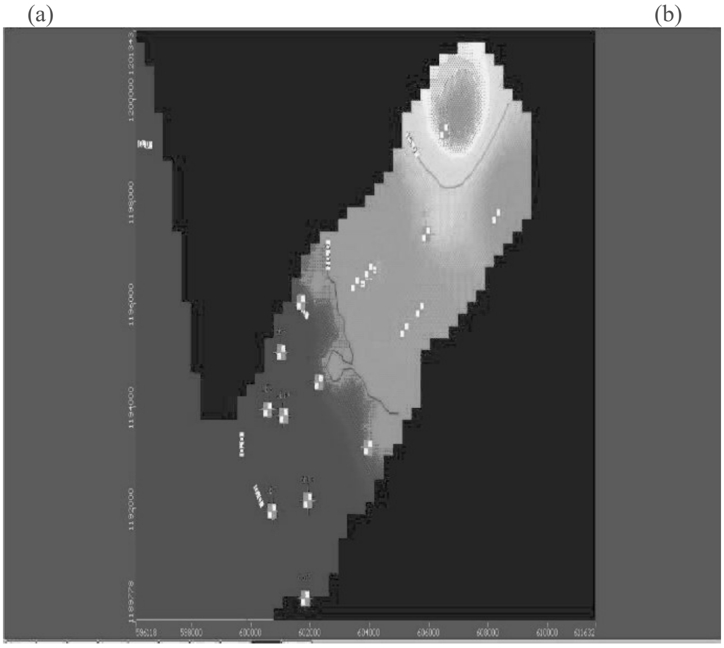
Fig. 10. Water table contour map after validation



(a)



(b)



(c)

Fig. 11. Predicted water table contour maps a. with 5% increase in pumping, b. with 10% increase in pumping and c. with 15% increase in pumping

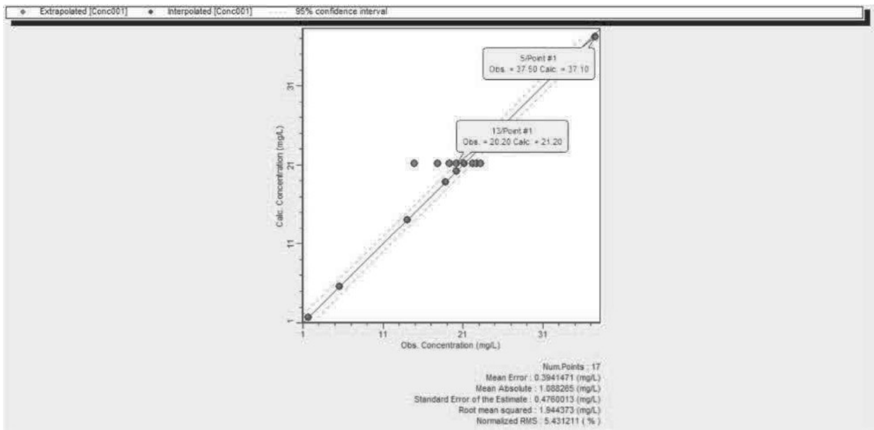


Fig. 12. Simulated vs observed concentration after calibration

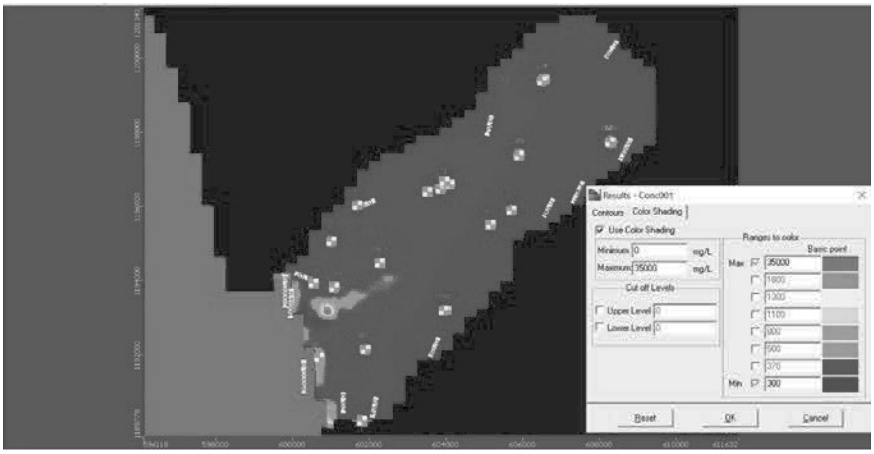


Fig. 13. Concentration contour map after calibration

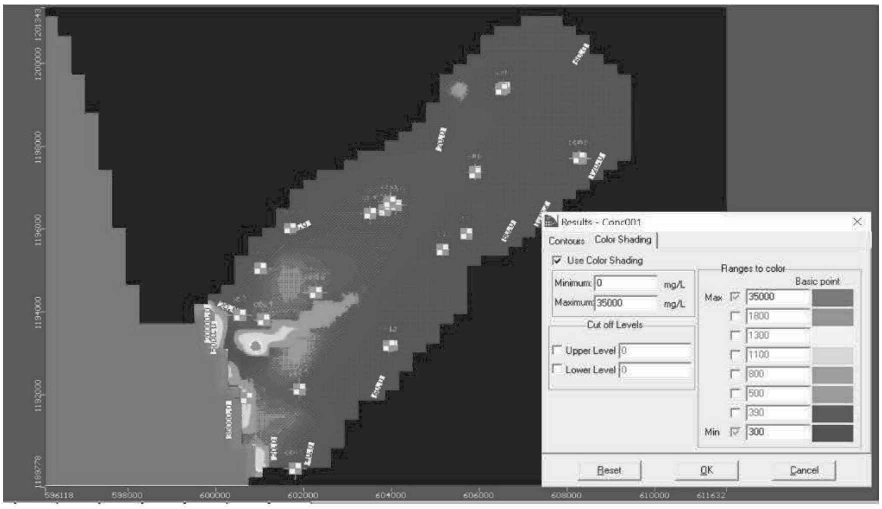


Fig. 14. Concentration contour map after validation (3601 days)

3.4.3. Model prediction

By assuming an increase in pumping rate around 5, 10, and 15%, the validated model was used to predict the trend in future saltwater intrusion for ten years' period (Fig. 15). It is clear from the graphs that concentration in the wells increases with time and pumping. The green color changed to yellow and orange color by the end of the prediction, which indicates the change in concentration over the time as the pumping increases. By the end of 2031, extent of intrusion increases, which extends laterally about 4.8 to 5 km from the estuary along the course of river.

The findings indicate that Bharathapuzha river basin's coastline stretch is affected by saltwater intrusion as a result of a drastic increase in pumping rates.

The intensive zone of intrusion has reached around 2 km from river estuary, i.e., mainly in Ponnani region.

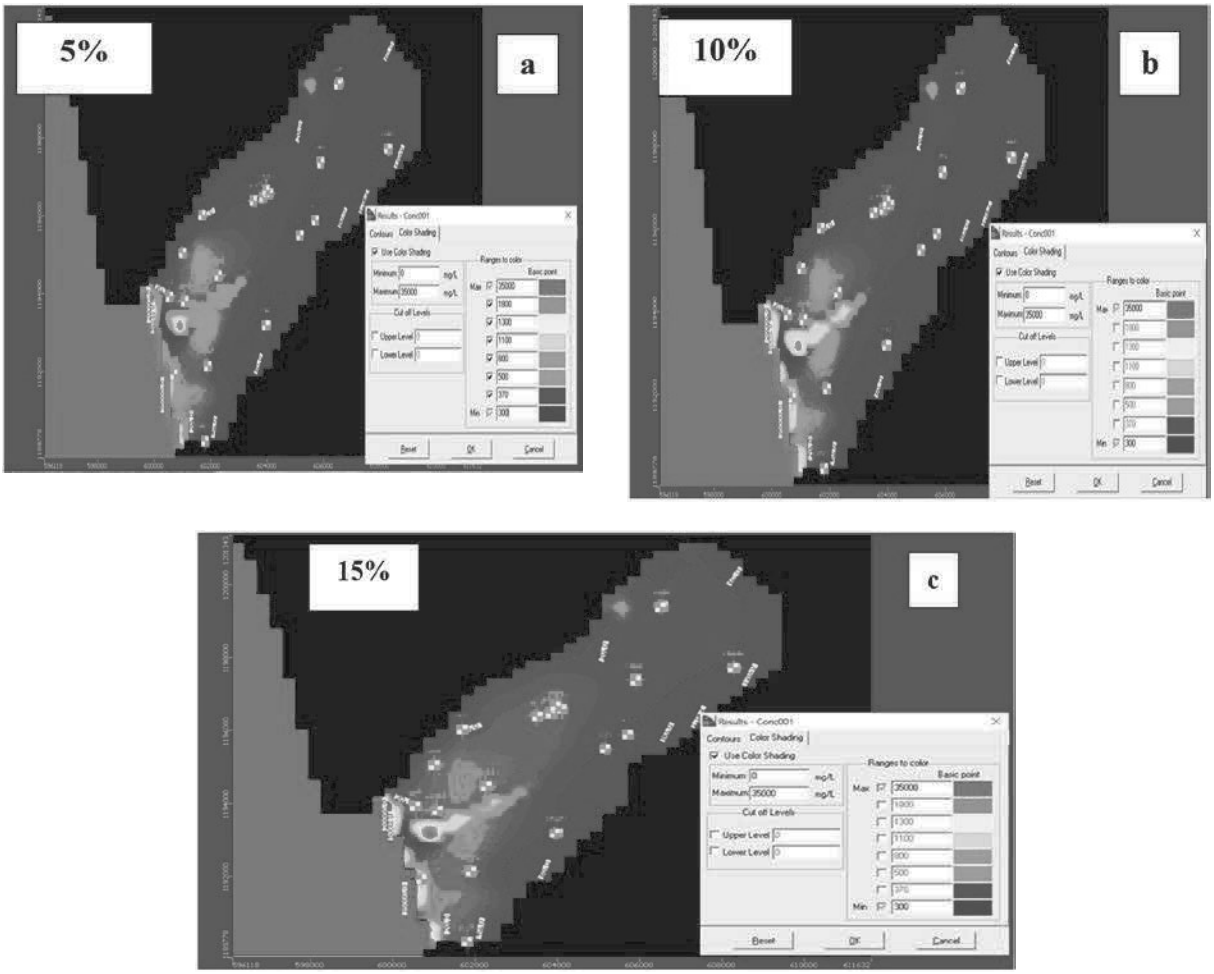


Fig. 15. Concentration contour map after increasing pumping (a) 5%, (b) 10%, (c) 15%

The progress of intrusion towards the coast is predicted using concentration contour maps after pumping rates are increased by 5, 10, and 15%. According to analysis of predicted contour maps, saltwater will encroach onto the land up to around 4.8 and 5 km from the coastline line by 2031, that is as pumping rate increases from 5 percent to 10 percent, intrusion reaches up to Eswaramangalam (approximately 5 km from coast) and reaches up to Chamravattom region (approximately 6 km from the coast) when pumping rate increases to 15%.

4. Conclusions

The groundwater movement and variation in salt concentration in the area was studied using Visual MODFLOW 2.8.1 and MT3D solute transport model. Water table elevation along the coastal stretch lowered by 3 m to 5 m during the study period. Salt water intrusion was observed mainly in Padinjarekkara, Purathur and Ponnani regions (1 to 1.5 km from coast). Intrusion reaches to a distance of 4.8 to 5 km laterally from river estuary along the course of river after ten years of prediction. As pumping rate increases from 5 percent to 10 percent, intrusion reaches approximately up to 5 km from the coast (Eswaramangalam region) and reaches up to 6 km (Chamravattom region) when pumping rate increases to 15 percent.

In the current climate change scenario, global warming and the related sea level rise also pose a serious concern to saltwater intrusion into coastal freshwater aquifers. The activities carried out in the catchment area of the river basin that facilitate the movement of contaminants including sand mining and various types of developmental activities like construction, small-scale industry, and agriculture along the coast accelerates the salt water intrusion in this area. Hence, it is necessary to plan proper mitigation measures in order to prevent the saltwater intrusion in the region. Pumping of groundwater in the coastal regions (up to 5 km from the coast) need to be restricted to reduce the ill effects of saltwater intrusion in the area. Adopting water conservation measures in the catchment area of the river will also help to maintain summer flow in the river, which in turn will prevent lowering of water table in the area during summer months.

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