NUMERICAL MODELLING FOR ASSESSING SEAWATER INTRUSION IN COASTAL AQUIFER

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Abstract: *The coastal regions are an important part of the earth's ecosystem. They accommodate 50% of the world population. Many coastal regions in the world are facing the problem of sea water intrusion due to over exploitation of groundwater for meeting the water demand for irrigation, industrial and domestic requirement. Along the vast stretch of Indian coast, increase in groundwater salinity due to seawater intrusion in fresh water aquifer is a serious problem. In this paper, an attempt has been made to apply Processing Modflow for Windows (PMWIN) to assess seawater intrusion in a coastal aquifer in Minjur, Tamil Nadu. The PMWIN was calibrated and validated for hydraulic properties and stresses. The calibration performance was assessed in quantitative terms like Mean Error (ME), Mean Percent Error (MPE), Root Mean Square Error (RMSE), coefficient of determination (R^2) and Nash-Sutcliffe Efficiency Index (E). The ME, MAE, RMSE and MPE for unconfined aquifer in predicting the hydraulic head was -0.02 m,0.60 m,0.71m and -2.77 % respectively and that for predicting the groundwater salinity was -89 mg/lit, 192 mg/lit, 306 mg/lit and -4.63% respectively. Results of calibration and validation revealed that MODFLOW and MT3D could be used for assessment of seawater intrusion and groundwater quality. Water level in unconfined aquifer was dropped to 7.5 m below mean sea level by the year 2008. The position of freshwater- saltwater interface represented by TDS line of 2.0 kg/m^3 was at 10.5 km from sea coast. Results of predictive simulation revealed that under prevailing pumping rate, water level would be lowered to a maximum of 17.5 m below man sea level by the year 2025. Consequently, the freshwater-seawater interface would extend to a distance of 11.5 km from the coast.*

Keywords: *Coastal aquifer, seawater intrusion, numerical modeling, calibration, validation*

1. Introduction:

Seawater intrusion is a serious issue, exacerbated by increasing demands for freshwater in coastal regions of the world. The increasing threat to groundwater availability in coastal region has become a major concern in India also. The high level of fertility of the soil and rich groundwater resources available in coastal delta and alluvial plains promoted intensive agricultural activities and human settlement along the vast stretch of Indian coast. This has resulted in huge demand for water, over exploitation of freshwater of coastal regions and pollution by saltwater intrusion. This endangers the sustainable use of this important resource. In this context, the management of coastal aquifers assumes greater significance.

Seawater intrusion studies would be the subject of attention and research in future considering expected increase in population, urbanization, expansion in industries and tourism in the coastal regions. The problem will be aggravated due to the predicted increase in sea level rise as a result of global warming ([2]; [5]). [16] also reported that sea level variations have a significant influence on the sea water intrusion process.

Numerical modeling has been considered as a primary tool to understand groundwater flow and saltwater movement in coastal aquifer [9].The major benefits of numerical modeling is that it provides methods to represent the important features of complex groundwater system in a form that can be used to analyze the past and present groundwater flow and salt movement under different stresses. The behaviour of the system under expected stresses in future can also be analyzed and predicted accurately by numerical modeling. Such an analysis is often not possible by conducting field studies alone. Numerical modeling considerably save time and cost of experiments which are otherwise required to find out the effectiveness of various measures suggested to control seawater intrusion.

A number of groundwater flow and transport models like MODFLOW, FEFFLOW, GFLOW, ChemFlux, FLOWPATH, Visual MODFLOW, SUTRA, Chemflow, 3DFEMFAT, AQUA3D, AT123D, Groundwater Vistas, HST3D, MicroFEM, MOC, MODFLOW SURFACT, SEAWAT, MT3D, MODPATH, MODFLOWwin32, PEST, PROCESSING MODFLOW, Visual GROUNDWATER are available for simulating seawater intrusion [10]. A review of seawater intrusion simulation models are reported by [3] also. [21] presented the state of knowledge in seawater intrusion research, methods for assessing and managing seawater intrusion and areas for future research.

Successful calibration and validation of numerical models simulating various aspects of hydrological system were reported by researchers. [19] performed transient calibration of a simulation model developed for Balasore coastal basin, India by adjusting model parameters like horizontal and vertical hydraulic conductivities and storage coefficient and hydrologic stresses like recharge and river seepage for MODFLOW. [11] used calibrated and validated models MODFLOW and MT3D for planning management strategies for seawater intruded coastal aquifer. The results of calibration and validation were evaluated by means of mean error (ME), mean absolute error (MAE) and root mean square error (RMSE) ([12]; [19]; [11]). After calibration and validation, sensitivity analysis was performed to find the most influential model parameters ([15]; [19]).

In this study, calibration and validation of groundwater flow and solute transport models were performed so that the models can be used for assessing seawater intrusion in a coastal aquifer.

2 Materials and methods

2.1 Study area

The study area is situated in Thiruvallur District of Tamil Nadu State in South India (Figure 1). It is a coastal aquifer located between 13^{0}15’0” and 13^{0}20’50” North latitude and 80^{0}12’40” and 80^{0}18’05” East Longitude. An area of 150 sq. km. was considered for simulation. It is bounded on east by Bay of Bengal and has a length of about 10 km along the sea coast. The study area is bounded on north by Kattur village, south by Pattamandri village and west by Vannipakkam village. The area experiences subtropical climate with a mean annual rainfall of 1276 mm. 61.8% of this rainfall is obtained during the North East monsoon and the rest during South West monsoon and summer seasons.

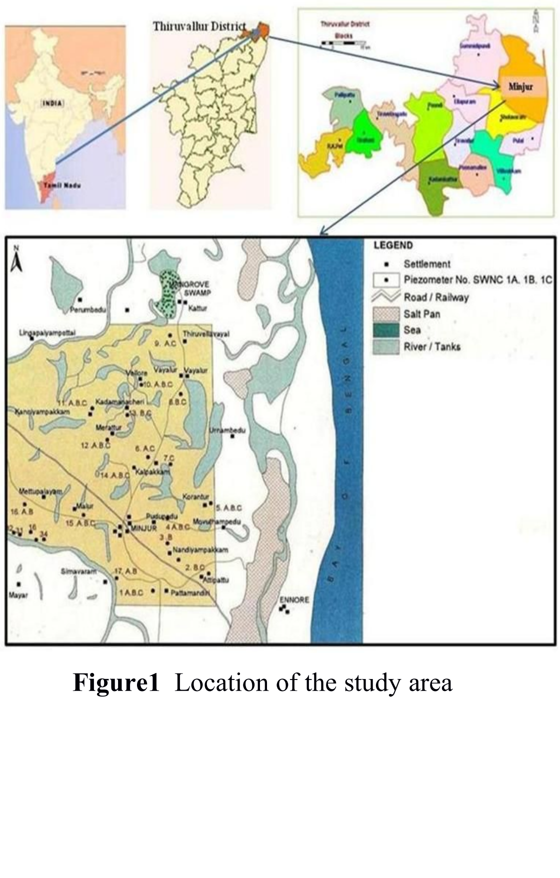


Figure1 Location of the study area

2.2 Overview of Numerical model

The groundwater flow model –MODFLOW and solute transport model- MT3D available in Processing Modflow for Windows (PMWIN) [6] were used for the present study for simulating groundwater flow and solute transport respectively. MODFLOW is the USGS Modular Three-Dimensional Groundwater Flow Model [13]. MODFLOW has become the standard groundwater flow model due to its ability to simulate a wide variety of systems, publicly available documentation and USGS peer review. The modular structure of MODFLOW consists of a main programme and a number of independent subroutines called packages/modules. In MODFLOW, groundwater flow within an aquifer is simulated using a block centered finite difference approach. It can simulates transient and steady state groundwater flow in complex hydraulic conditions with various hydrological processes and can be used for large aerial extent and for multi aquifer modeling. MODFLOW is capable of calculating flux across the flow boundaries. Boundary conditions include specific head, specific flux and head dependent flux.

MT3D [22] uses a modular structure similar to that implemented in MODFLOW. This model structure makes it possible to simulate advection, dispersion and sink/source mixing and chemical reactions. MT3D uses a mixed Eulerian- Lagrangian approach to the solution of three- dimensional advection-dispersion transport equation. MT3D is based on the assumption that changes in concentration field will not affect the flow field independently. This allows the user to construct, calibrate and validate a flow model independently. After the flow simulation, MT3D receives the calculated hydraulic heads and various flow terms saved by MODFLOW for simulating the salt movement in groundwater system. The flow chart of the numerical modeling using MODFLOW and MT3D is shown in Figure 2. Considering all the above aspects, PMWIN was selected in the present study.

2.3 Numeric model setup

The numerical model setup consisted of the following main stages.

2.3.1 Development of conceptual model

The geological profiles of the area revealed that the aquifer system consists of three layers- the upper unconfined aquifer and bottom semi confined aquifer separated by an aquitard. The unconfined aquifer is directly connected to rivers Araniyar and Korattalaiyar. The average thickness of unconfined aquifer is 27 m. Modelling of the unconfined aquifer is presented in this paper.

2.3.2 Discretization of the study area, initial and boundary conditions

The study area was aerially discretized by dividing it into 60 columns and 40 rows. The grid spacing was 250 m x 250 m. Thus, total number of cells over the area was 2400. The west of the study area is hydraulically connected to the sea and it formed the constant head (Dirichlet) boundary. On all other sides, flow boundaries were assigned as there were no physical or hydraulic barriers. The hydraulic head and groundwater salinity in the observation wells recorded in January 1999 was used as the initial condition. The constant head boundary was assigned a hydraulic head of 0 m and TDS of 35000 kg/m^3.

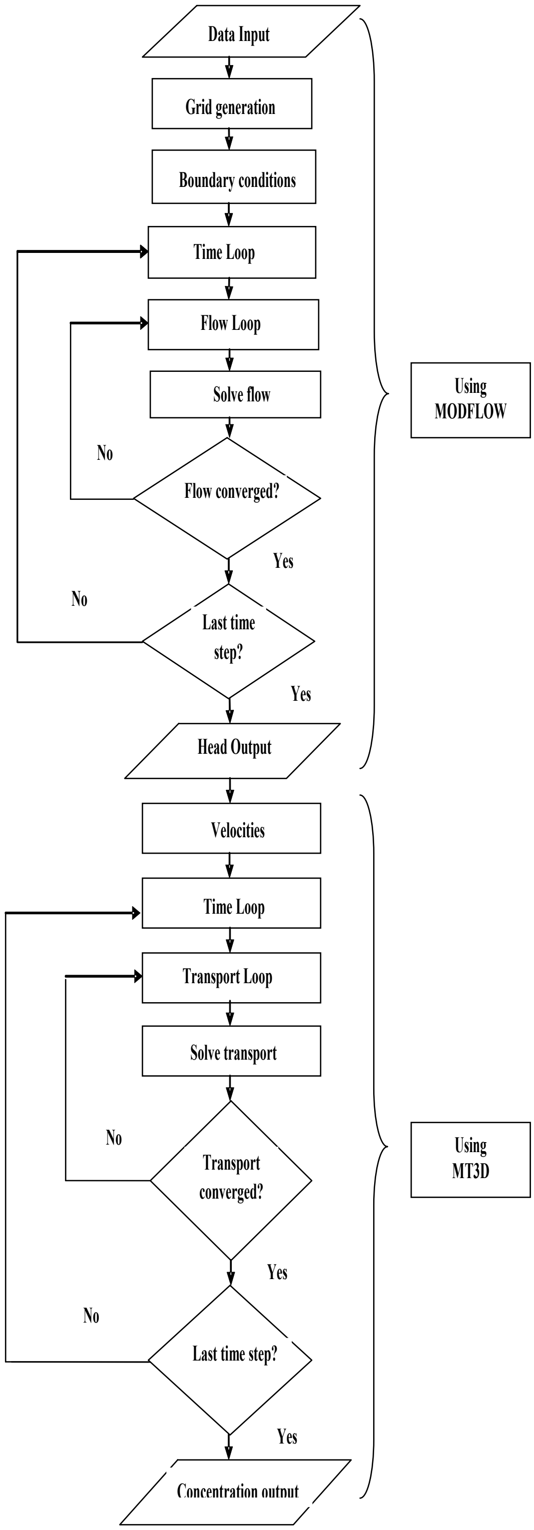


Figure 2 Flow chart of groundwater flow and transport modelling using PMWIN

2.3.3 Estimation of model parameters

The model input includes hydro geological parameters like hydraulic conductivity, specific yield, effective porosity and hydrological stresses such as recharge, abstraction, interflow, river influence and evapotranspiration and top and bottom elevation of layer etc. The geological formation in the study area consists of unconsolidated and semi-consolidated formations with sand, silt and alluvial gravel. The aquifer is nearly homogeneous and isotropic in nature with granular sandy strata. The hydraulic conductivity, specific yield, effective porosity and other properties reported by Groundwater Division [17], [18] and [11], based on studies conducted in the area were used for calibration in the present study. The anisotropy factor was considered as 1.

2.3.4 Time parameters

The time parameters include time unit, the length and number of time (stress) periods and number of time steps within each time period. In the present study, the time unit was taken as day, length of stress period as 183 days, as in many years measurement of water level and salinity in observation wells was taken once in six months. Each stress period was divided into six time steps so that the length of one time step is 30 days. Each time step was further divided into 30 transport steps, thereby reducing the length of transport step as one day.

2.3.5 Hydrological stresses

For the study area, the main component of groundwater recharge consists of recharge from rainfall, return flow from irrigation and percolation from tanks. For alluvial areas of east coast of India, the rainfall recharge is recommended as 16% [4]. Recharge was calculated for the monsoon seasons for the entire calibration and validation period. Since rainfall during non monsoon season is negligible, recharge was assumed to be zero.

The recharge from irrigation return flow was calculated separately for 1st stress period (non monsoon season) and second stress period (monsoon season) based on the recommended norms. It was calculated as percentage of irrigation application as per CGWB norms [4]. Contribution of the tanks/ponds to groundwater recharge was taken as 1.4 mm/day [4] for the period in which the tank had water, based on the average water spread area. The total recharge obtained from different sources mentioned above was entered through the recharge package of MODFLOW.

The number of groundwater abstraction structures like dug wells, bore wells, dug cum bore wells and tube wells etc. existing in the area were collected from Department of Economics and Statistics [7]. Ground water abstraction rates were calculated based on unit draft method [4]. The groundwater abstraction for unconfined aquifer was entered using the well package. The interaction between aquifer and river was simulated using the river package of MODFLOW.

2.3.6 Parameters for solute transport

The solute transport model MT3D requires the parameters like effective porosity, longitudinal dispersivity, ratio of horizontal transverse dispersivity to longitudinal dispersivity (TRPT), ratio of vertical transverse dispersivity to longitudinal dispersivity (TRPV), effective molecular diffusion coefficient, advection parameters etc. In the absence of measured values of these parameters, values available in published literature [11] were used for the initial model run and same were adjusted during the calibration process.

2.3.7 Calibration and validation of groundwater flow and solute transport models

The transient calibration of the developed model was done following the standard procedure given in different literatures ([1]; [20]; [14]). The groundwater levels observed at 13 observation wells for the period 1999 to 2004 during pre and post monsoon periods were used for calibration and that available at 5 observation wells for the period 2007 to 2009 were used for validation.

During calibration, the simulated values of groundwater levels in observation wells were compared with the observed values. MODFLOW was run several times and the model parameters like horizontal hydraulic conductivity, vertical hydraulic conductivity, specific yield and hydrologic stresses like recharge, river bed hydraulic conductance and groundwater abstraction were adjusted within the reasonable limits in successive model runs, till a close match between observed and simulated hydraulic heads was obtained. After calibrating the groundwater flow model, MODFLOW, the solute transport model MT3D was calibrated by adjusting the model parameters like horizontal and transverse dispersivities, effective porosity and advection parameters. After the successful calibration of the models, the model was validated using the groundwater level and salinity data available for pre and post monsoon seasons of 2007-2009. During validation, model was run by assigning the calibrated hydraulic parameters and adjusting only the hydrologic stresses within the reasonable ranges till the simulated hydraulic head and salinity matched well with the observed hydraulic head and salinity.

2.3.8 Calibration and validation performance measures

The success of model calibration and validation could be evaluated in quantitative and qualitative terms, to find out the degree of agreement between observed and simulated model parameters ([14]; [8]). In the present study, the calibration performance was evaluated by computing quantitative measures like ME, MAE, MPE and RMSE, performing regression analysis and using dimensionless error statistic like Nash-Sutcliffe Efficiency Index (E). The results of validation were also evaluated by computing statistical measures mentioned above.

3 Results and Discussion

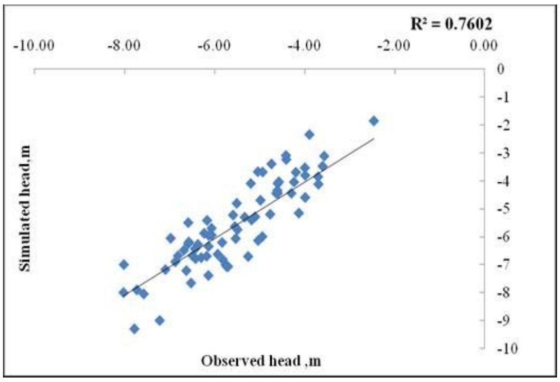
3.1 Calibration results

The summary statistics of simulation of hydraulic head is presented in Table 1. The Table reveals that the mean error (ME) and mean percent error (MPE) of hydraulic heads are reasonably low and are within the acceptable limits. Even though MAE and RMSE show moderately high values, this can be accepted considering the range in the values of observed hydraulic heads.

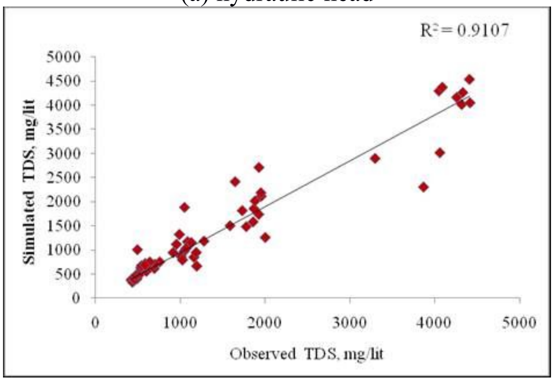
Table 1: Summary statistics of hydraulic head and salinity during calibration

Parameter	ME	MAE	RMSE	MPE	R^2	E
	m	m	m	%		
Hydraulic head	-0.02	0.60	0.71	-2.77	0.76	0.77
	mg/lit	mg/lit	mg/lit	%		
Total Dissolved Solids	-89	192	306	-4.63	0.91	0.93

While reporting the calibration of groundwater flow model, [12] accepted an RMSE of 7.45 m, considering the wide range in the piezometric data values (145 m to 632 m). The Nash –Sutcliffe efficiency Index (E) is 0.77. The value of this index > 0.5 is considered to be satisfactory. The scatter diagram of the observed and simulated hydraulic heads is shown in Figure 3(a). The R^2 value of 0.76 can be considered as a reasonable fit. The results suggest that the model can be used for prediction of hydraulic head in the aquifer. The Table 1 shows the summary statistics of simulation of groundwater salinity. The table shows that the MAE is 192 mg/lit and RMSE is 306 mg/lit. These high values can be attributed to the higher ranges in the observed values of salinity. However, the MPE, which removes the effect of range in the calculated error showed very low values and therefore the



(a) hydraulic head



(b) groundwater salinity

Figure 3 Scatter diagram of observed and simulated values- calibration

calibration results can be accepted. The scatter diagram of the observed and simulated groundwater salinities (Figure. 3b) shows that the R^2 value of 0.91 can be considered as a reasonable fit. Hence, the calibration results of groundwater salinity are quite satisfactory. The values of various statistical measures indicate that the calibration performance of the model is reasonably high and can be used for predicting the hydraulic head and groundwater salinity in the aquifer under different hydrological processes. The calibrated parameters of aquifer are given in Table 2.

Table 2: Calibrated parameters of MODFLOW and MT3D

Parameters of MODFLOW	**Value**
Horizontal hydraulic conductivity	20 m/day
Vertical hydraulic conductivity	2 m/day
Specific yield	0.15
Parameters of MT3D	
Longitudinal dispersivity	250 m
TRPT	0.1
TRPV	0.1
Molecular diffusion coefficient	0.0000864 m^2/day
Effective porosity	0.25

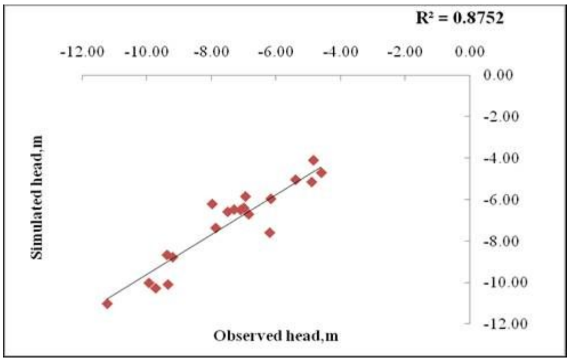
3.2 Validation results

The statistical measures used in assessing the calibration accuracy were employed in assessing the validation accuracy also. The validation results of hydraulic head are depicted in Table 3. The table reveals that various errors are within acceptable range.

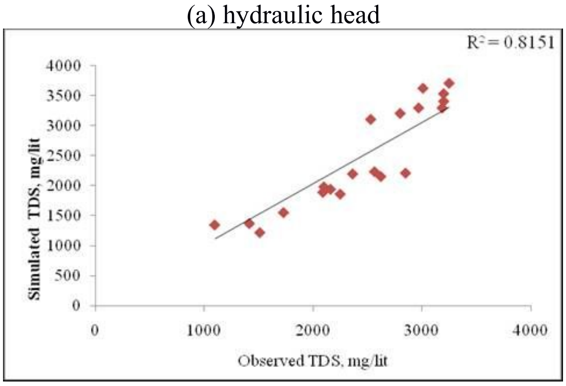
Table 3: Summary statistics of hydraulic head and salinity during validation

Para meter	**ME**	**MAE**	**RMS E**	**MPE**	**R^2**	**E**
	m	m	m	%		
Hydrau lic head	-0.30	0.61	0.75	4.07	0.8 8	0.8 3
	mg/lit	mg/lit	mg/lit	%		
Total Dissolv ed Solids	-8.92	313	355	1.0	0.8 2	0.8 1

The Nash-Sutcliffe efficiency index showed higher values during validation compared to calibration. This may be due to the fact that the validation was done for the period 2007-2009, for which the stresses like groundwater pumping could be estimated accurately due to the availability of data on extraction wells. The scatter plot of the observed hydraulic head and simulated hydraulic head during validation is shown in Figure 4(a).



(a) hydraulic head



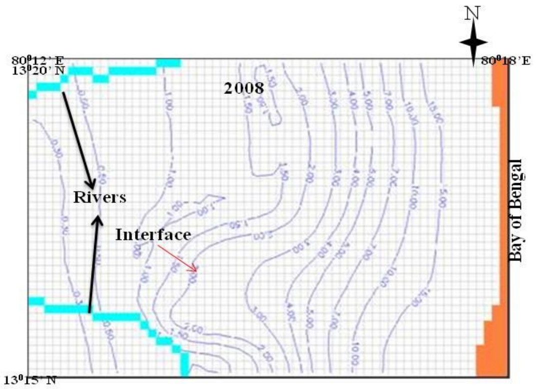
(b) groundwater salinity

Figure 4 Scatter diagram of observed and simulated values- validation

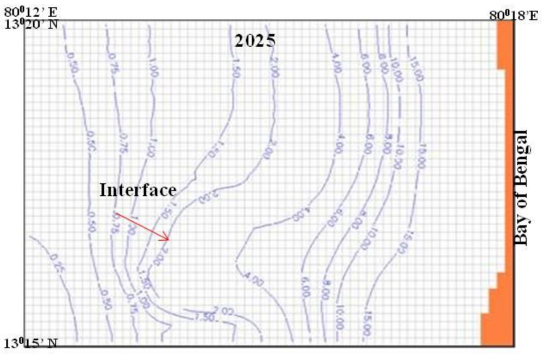
The R^2 value for unconfined aquifer is 0.88, which is quite high and can be considered as a reasonable fit. In the case of validation of model for groundwater salinity, the values of performance measures are presented in Table 3. The Nash-Sutcliffe efficiency index obtained for the aquifer is high. The linear regression analysis of the observed and simulated groundwater salinity is depicted in Figure 4(b) and the corresponding R^2 value is 0.82. However, when compared the figures obtained for calibration, slightly lower values of efficiency index and R^2 are obtained during validation. This difference may due to the fact that the number of observation wells considered for validation was less compared to that used in calibration. Further, the validation was performed with two years data (2007-2009), while calibration was done based on data recorded from 1999 to 2004. However, all the validation performance indicators are high enough to recommend the model for predictive simulation.

3.3 Predictive simulation

Validated models were used to predict groundwater salinity by the year 2025, if the stresses prevailing in the year 2008 were continued for 17 years. The simulation showed that the water table would be lowered to a maximum of 17.5 m below MSL near the western boundary of the study area under this scenario compared to water table depth of 7.0 m in the year 2008. Consequently, the saltwater-freshwater interface (TDS front of 2 kg/m^3) would be located at a distance of 11.5 km from coast compared to its position at 10.5 km in the year 2008(Figure. 5a and Figure 5b).



(a)



(b)

Figure 5 Groundwater salinity in aquifer in 2008 and 2025

Therefore, it is necessary to adopt appropriate measures to control the seawater intrusion. These may include artificial groundwater recharge, reduction in pumping rate and relocation of pumping wells in higher recharge zone Models calibrated and validated models in this study can be used for assessing the impact of various measures to control seawater intrusion and develop appropriate management plan.

4 Conclusion

The coastal aquifer in Minjur in South India has been affected by seawater intrusion problem since 1960's due to excessive groundwater pumping for meeting various water requirements. In order to simulate the movement of interface under different groundwater management alternatives and recommend appropriate seawater intrusion control measures, numerical modelling was carried out using MODLFOW and MT3D. The calibration and validation of the models were done against measured hydraulic heads and groundwater salinities. Calibration performance measures like mean error (ME), mean absolute error (MAE), root mean square error (RMSE), Nash-Sutcliff model efficiency index and coefficient of determination (R^2) indicated a close agreement between measured and predicted hydraulic heads and salinities. Simulation of the models for the year 2025 under the prevailing recharge and pumping rates showed that there would be considerable decline in the water levels and further advancement of interface towards land. The results of calibration and validation revealed that the model has a good capability to simulate the hydrological behaviour of the aquifer system under study.

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