Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year XXXX, Volume X, IssueY, 1090399

Predictive Simulation of Seawater Intrusion Control Measures in a Coastal aquifer

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Cite as: Mini, P. K., Singh, D. K., Sarangi, A., Predictive Simulation of Seawater Intrusion Control Measures in a Coastal aquifer, J. sustain. dev. energy water environ. syst., 1090399, DOI: https://doi.org/10.13044/j.sdewes.d9.0399

ABSTRACT

Many coastal aquifers are facing seawater intrusion due to overexploitation of freshwater. In this study, the groundwater flow and solute transport in a coastal aquifer of Minjur, in India was simulated considering the possible cases of aquifer recharge, freshwater draft, relocation of pumping wells etc. using numerical modelling software. The groundwater flow model MODFLOW and solute transport model MT3D were calibrated for a seven-year period and validated against dataset for two years, which gave satisfactory results**.** The sensitivity analysis of model parameters revealed that hydraulic head was greatly influenced by the horizontal hydraulic conductivity.The model was used to predict the response of coastal aquifer to four potential scenarios like aquifer recharge, reduced pumping, relocation of pumping wells and a combination of these scenarios. Effectiveness of various management scenarios was evaluated based on their ability to improve groundwater level and salinity in observation wells/piezometers, to reduce the affected area and restrict the advancement of seawater-freshwater interface. The result of predictive simulation indicated that the combination of scenarios such as reduction in ground water pumping by 25% from semi confined aquifer, increased pumping by 25% from unconfined aquifer, increased recharge fromrivers byconstructing check dams have the potential to restrict the seawater-freshwater interface movement and improve groundwater quality in Minjur aquifer. These control measures would be effective in shifting the interface towards the coast by 1.0 km in unconfined aquifer and 1.5 km in semi confined aquifer by the year 2025.

KEYWORDS

Coastal aquifer, Seawater intrusion, Groundwater, Numerical modelling, Recharge

INTRODUCTION

Groundwater is a major source of freshwater in the coastal regions. However, over exploitation of groundwater from coastal aquifer can cause the natural equilibrium

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between freshwater and seawater to be disturbed which result in seawater intrusion into freshwater aquifer. Seawater intrusion has been identified as a critical issue to be addressed in coastal regions due to its irreversible effect on the groundwater water quality.Research on various management alternatives to control sea water intrusion started way back in 1960s. The transient effect of battery of injection wells on seawater intrusion into coastal confined aquifers was analyzed by Mahesha [1] using a quasi 3-D finite element model. The injection wells were found to be effective in controlling the intrusion and reduction of intrusion up to 60–90 % was achievable under favourable conditions. The study on performance of the injection wells in single and double series along the coast indicated a reduction of seawater intrusion through proper selection of the injection rate and spacing between the wells [2]. The subsurface barrier was found to be effective in controlling seawater intrusion under critical conditions of continual pumping of the aquifer without recharge [3]. The transient motion of the interface owing to uniform natural recharge was explored using a 1-D finite element model and the annual reduction of interface achieved was found to be 5-6 % of the initial length of intrusion [4]. Rejani *et al.*[5] developed a 2-D groundwater flow and transport model of the coastal basin using Visual MODFLOW package for analyzing the aquifer response to various pumping strategies.Reduction in withdrawals and injection of freshwater or treated waste water reduced the interface movement in Chennai coastal aquifer according to the simulation conducted using MODFLOW and MT3D [6]. The simulation with a 3-D density-dependent numerical model developed with FEFLOW revealed a decreased tendency of seawater intrusion if groundwater exploitation does not reach an upper bound of pumping [7].The effect of subsurface barrier in controlling seawater intrusion was reported by Mohan [8]. Mahesha [9] also studied the effect of subsurface barrier on the movement of the seawater-freshwater interface in coastal aquifers for a wide range of freshwater pumping rates using a Galerkin finite-element model. The results indicated that barrier was able to check the advancement of intrusion significantly. The results of groundwater modelling by Senthilkumar and Elango [10] predicted an increase of 0.1-0.3 m in groundwater levels in the upstream side of river due to the effect of subsurface barrier.

With the advent of high speed computers, numerous computer codes capable of simulating seawater intrusion were developed. The models can be used to evaluate the response of the aquifer under various seawater intrusion control strategies [11].Reilly and Goodman [12] presented a review on historical advancement in the quantitative analysis of seawater intrusion in coastal aquifers. Werner *et al.*[13] summarized the evolution and current status of seawater intrusion research in terms of seawater processes, measurement, prediction and management. Comprehensive review of groundwater flow and solute transport models used for simulation of seawater intrusion was presented by Kumar[14].

Huyakorn *et al.*[15] simulated the density dependent seawater intrusion in coastal aquifer using a 3-D finite element model. Cau *et al.*[16] investigated the causes of saltwater intrusion in the Oristano plain on the west coast of Italy using a 3-D finite element model CODESA 3D to simulate coupled flow and solute transport processes in variably saturated porous media and reported that groundwater pumping caused a significant saltwater encroachment. Misut *et al.*[17] used SUTRA model to investigate seawater intrusion into the groundwater system of western Long Island, New York. Sherif *et al.*[18] used MODFLOW and MT3D to simulate seawater intrusion in the coastal aquifer of Wadi Ham, United Arab Emirates.The effects of pumping and climate change on the extent of seawater intrusion analyzed by Mansour *et al.*[19] revealed that a reduction in the pumping rate would be necessary to protect fresh groundwater. Experimental and numerical studies performed to determine the effect of flow barrier wall, recharge well and a combination of these to control seawater intrusion in unconfined coastal aquifer showed that a combination of flow barrier and freshwater injection forced the saltwater to retreat to a greater extent compared to the measures separately [20]. According to Momejian *et al.*[21] Geospatial Quality Assessment (GQA) models and Groundwater Vulnerability Assessment (GVA) models had limited ability to accurately delineate seawater intrusion.The hydrological and economic feasibility of Aquifer Storage and Recovery (ASR) of excess desalinated water and Managed Aquifer Recharge (MAR) using Tertiary Treated Waste Water (TTWW) to manage stressed coastal aquifers in Oman showed MAR as a smart water governance technology to mitigates stresses on coastal aquifer systems in arid zones [22].

Many researchers linked simulation model with optimization model to decide optimal pumping and recharge for controlling seawater intrusion. In integration with groundwater flow simulation model, Rejani *et al.*[23] developed optimization model to decide optimal pumping schedule and cropping patterns for Balasore coastal basin, India. Groundwater flow simulation- non linear optimization methodology was demonstrated by Ganesan [24] to determine well location, optimal pumping and injection rates for coastal aquifer facing seawater intrusion. A 3-D hydrogeological model combined with optimization model was used to assessthe strategies for controlling sea water intrusion in Gaza strip (Palestine) coastal aquifer [25]. Christelis and Mantoglou [26] studied pumping optimization of coastal aquifers using sea water intrusion models. The optimal pumpages to arrest the deterioration of the coastal aquifer had been derived using a linked simulation-optimization approach and response matrix approach [27]. Singh [28] also analyzed various optimization techniques like Genetic Algorithm (GA) and Artificial Neural Network (ANN) for managing seawater intrusion. A review on the combined application of simulation-optimization modelling approach for the seawater intrusion management of the coastal aquifers was presented by Singh [29].

The freshwater water supply in east coast of India is severely affected by seawater intrusion mainly due to over exploitation. It is predicted that the water demand along this coast would increase by 50% in 2025 [30]. Gopinath *et al.*[31] also reported that severe problem of water supply in eastern coastal India is due to the sea water intrusion into aquifers as a result of growing industrialization, urbanization, groundwater withdrawals and sea-level rise. Experimental studies for deciding appropriate measures for seawater intrusion control are time consuming and costly affair. In this context, simulation studies are important for coastal aquifers severely affected by seawater intrusion in understanding the behaviour of the aquifer system and to evaluate the response of the aquifer under various seawater intrusion control strategies.

The present study was undertaken with the objective of developing groundwater flow and solute transport models using the codes MODFLOW and MT3D to simulate seawater intrusion and to evaluate the impact of various possible management strategies for controlling seawater intrusion in the multilayer coastal aquifer of Minjur in Tamil Nadu, India.

METHODS- GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELS SETUP

Spatial and temporal simulation of seawater intrusion require the use of numerical methods to solve the nonlinear governing equations of flow and solute transport through porous media. The partial differential equation of the flow consists of flux equation (Darcy's law) combined with the mass balance equation of water. By combining the flux equation of the solute with its mass balance equation the generic mass balance equation of the dissolved salt transport (advection–dispersion equation) is obtained. The numerical solution of seawater intrusion is completed by coupling and solving these two governing equations of fluid flow and solute transport simultaneously using appropriate boundary and initial conditions. The groundwater flow model– MODFLOW and solute transport model-MT3D of Processing Modflow for Windows (PMWIN) can be used for simulating seawater intrusion in space and time [32]. Effects of well, river, drains, head dependent boundaries, recharge and evapotranspiration on groundwater behaviour under steady and unsteady flow conditions can be simulated efficiently using PMWIN which is a pre and post processor for MODFLOW and MT3D. Three-dimensional partial differential equation used to describe the groundwater flow in unconfined aquifer under specified initial and boundary conditions is given by,

$$\frac{\partial}{\partial x}\left(Kxh\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kyh\frac{\partial h}{\partial y}\right)=-Sy\frac{\partial h}{\partial t}-R \quad (1)$$

Where, Kx, Ky = are directional components of hydraulic conductivity (LT^{-1}), h = Total head (L), Sy= Specific yield, R= General sink/source term, t = Time (T).

MT3D is a solute transport model which can simulate advection, dispersion, sink/source mixing and chemical reactions in aquifer system[33]. It uses the hydraulic heads and other parameters obtained from MODFLOW for simulating the salt movement in groundwater system. The partial differential equation used by MT3D is given by,

$$\frac{\partial}{\partial t}(\theta C)=\frac{\partial}{\partial x_i}\left[\theta D_{ij}\frac{\partial C}{\partial x_i}\right]-\frac{\partial}{\partial x_{ij}}(\theta v_i C)+q_s C_s \quad (2)$$

Where, C is the dissolved concentration of salt (ML^{-3}), θ is the porosity of the subsurface medium (dimensionless), t is the time (T), x_i is the distance along the respective cartesian coordinate axis (L),D_{ij} is the hydrodynamic dispersion tensor (L^2T^{-1}), v_i is the seepage or linear pore water velocity (LT^{-1}), q_s is the volumetric flow rate per unit volume of aquifer representing fluid sources (positive) and sinks (negative) (T^{-1}) and C_s is the concentration of the source or sink flux (ML^{-3}).

CASE STUDY: MINJUR COASTAL AQUIFER SYSTEM

The Minjur coastal aquifer is located in the southern state of Tamil Nadu in India. Geographically, it is 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. The study area covers 150 km^2 and has a length of 10 km along the coast and width of 15 km and is bounded by Bay of Bengal on east (Figure.1). The area experiences subtropical climate with a mean annual rainfall of 1276 mm. Of this, nearly 62 % is received during the North East monsoon and the rest during South West monsoon and summer seasons. The study area is covered by alluvium of two rivers, which consists of sand, clay and sandy clay. The alluvium is underlain by tertiary formations followed by Gondwana clay which rests on the basement of Archaean rocks. For the simulation, the aquifer system was conceptualized as three layer system: unconfined aquifer, aquitard and semi confined aquifer. The thickness of unconfined and semi confined aquifers ranges from 18-27 m and 30-45 m respectively. The thickness of aquitard ranges from 3 to 8 m. Eastern part of the study area is severely affected by seawater intrusion, forcing the farmers to abandon groundwater pumping. The production wells of the Chennai Metropolitan Water Supply and Sewerage Board (CMWSSB) for supplying industrial and drinking water to Chennai city are located along the banks of the two rivers flowing through the area. The large scale pumping done by farmers and CMWSSB since 1960s had resulted in lowering of ground water levels and seawater intrusion into freshwater aquifers [34].

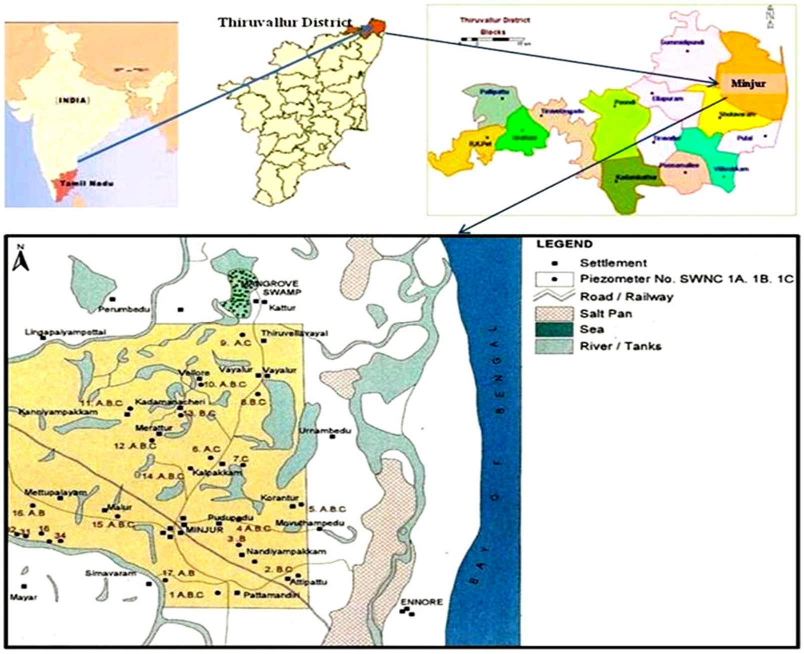

Figure 1. Location of the study area

The model was calibrated for transient conditions of flow in aquifer following the procedure given by Ting *et al.*[35].Pre and post monsoon groundwater levels observed in 13 observation wells and 18 piezometers for the period from January 1999 to January 2005 was used for calibration. After calibration,it is inevitable to perform the quantitative assessments of the degree to which the model simulations match the observations. American Society of Civil Engineers (ASCE) [36] recommended the use of basic statistical measures to describe the performance of the models. In addition to correlation and correlation based measures to assess the goodness of fit of hydrologic model, evaluation measures like summary statistics and absolute error should supplement the evaluation [37]. Moriasi *et al.* [38] suggested Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS) and ratio of the root mean square error to the standard deviation of measured data (RSR), in addition to the graphical techniques, to be used in model evaluation. Even though Nash–Sutcliffe efficiency index is widely used to assess the performance of a hydrologic model, it is advisable to employ other statistical measures before arriving at a definite conclusion [39]. In this study, predictability of models was evaluated using statistical measures like Mean Error (ME), Mean Absolute Error (MAE), Mean Percent Error (MPE), Root Mean Square Error (RMSE), Coefficient of determination (R^2) and Nash-Sutcliffe Efficiency Index (E) as suggested in the literature. After the calibration, the models were validated using the data available for the period of January 2007- December 2008. Sensitivity analysis was performed to understand the influence of various aquifer parameters on hydraulic head. Models were simulated by assigning a 50 % increase and decrease in the calibrated values of the aquifer parameters to assess the sensitivity [35].

Simulation of groundwater level and salinity under various seawater intrusion control measures

After calibration and validation, models were used to simulate seawater intrusion in the study area. Excessive groundwater pumping is the major cause of seawater intrusion in Minjur aquifer. Effect of this can be compensated to a certain extent by enhancing groundwater recharge from rainfall, regulating groundwater pumping, relocating pumping wells and regulation of flow in rivers and various combinations of these measures. During simulation, the effect of above measures on groundwater levels, piezometric surface, groundwater salinity and movement of freshwater–saltwater interface in both the aquifers were observed. Contour maps of groundwater level and salinity were generated at the end of simulation. Predicted hydraulic heads and groundwater salinities in selected wells in both the aquifers were plotted to study temporal changes in these parameters and compare the effectiveness of various scenarios.

Areas under different Total Dissolved Solids (TDS) classes were determined from TDS contour maps using the irrigation water quality classification of Food and Agricultural Organization (FAO) [40]. For all practical purposes, water is considered as unsafe if Electrical Conductivity (EC) is > 3.0 dS m^{-1}(TDS = 2.0 kg/m^3) and safe if it is < 0.70 dS m^{-1}. In this study, the contour line having EC = 3.0 dS m^{-1} (TDS = 2.0 kg/m^3) was considered to describe the freshwater-seawater interface movement. Predicted values of water levels in three observation wells (2C, 4C, 15C) and three piezometers (2B, 5B, 16B) located in severely affected southern part of the study area were used to study the temporal variations in water level under different management scenarios. Of these, 2C and 2B are located near the coast, 4C and 5B are located at the central part of the area and 15C and 16B are near the Kosasthalai River.

RESULTS AND DISCUSSION

Results of calibration and validation of groundwater flow and solute transport models, predictive simulation of seawater intrusion management scenarios and evaluation of scenario analysis are presented in the following sections.

Calibration and validation results

The summary statistics of simulation of hydraulic head and groundwater salinity of semi confined aquifer is shown in Table 1. The values of statistical measures like ME, MAE, MPE, RMSE, R^2 and Nash-Sutcliffe Efficiency Index are within acceptable limits. Little higher value of MAE (1.04 m) and RMSE (0.83 m) for hydraulic heads can be accepted considering the wide range of observed hydraulic heads. Moriasi *et al.*[38] reported that RMSE is problem dependent, and is affected by the range in the measured values. RMSE of 7.45 m was accepted by Massuel *et al.*[41] as there was a wide range in the observed piezometric heads (145 m to 632 m).The R^2 value of 0.872 can be considered as a reasonable fit. These results indicated that MODFLOW can be used for

Table 1.Summary statistics of hydraulic head and salinity during calibration and validation in semi confined aquifer

Process	Parameter	ME	MAE	RMSE	MPE	R^2	E
Calibration	Hydraulic head	[m]	[m]	[m]	[%]		
		-0.56	1.04	0.83	5.80	0.87	0.81
	Total dissolved solids	[mg/L]	[mg/L]	[mg/L]	[%]		
		63	210	323	1.80	0.89	0.89

Validation	Hydraulic head	[m]	[m]	[m]	[%]		
		0.21	0.86	0.99	-4.0	0.90	0.91
	Total dissolved solids	[mg/L]	[mg/L]	[mg/L]	[%]		
		102	192	220	3.0	0.85	0.83

simulating seawater intrusion in the study area. Model performance parameters for prediction of salinity (Table1) during calibration shows that the MAE is 210 mg/L and RMSE, 323 mg/L. Higher values of RMSE can be attributed to the higher ranges of observed groundwater salinities and can be considered within acceptable limits. The MPE which removes the effect of range in calculated error was very low (1.80 %). Ganesan and Thayumanavan [6] reported that MPE of 4.0 % and 12.0 % for prediction of hydraulic heads were within the acceptable limit. Predictive ability of model was further reflected by higher R^2 value of 0.89 and Nash-Sutcliffe Efficiency Index (0.81). Value of Nash–Sutcliffe Efficiency Index > 0.5 is considered to be satisfactory. These results indicated that the model for simulation of groundwater salinity was also adequately calibrated.

The validation results also revealed that various errors are within acceptable range.The regression analysis of hydraulic head and groundwater salinity showed R^2 value as 0.90 and 0.85 respectively, which are within acceptable limits. Similar results were obtained during calibration and validation of unconfined aquifer of the same area [42]. The calibrated values of input parameters for MODFLOW and MT3D are shown in Table 2.

Table 2. Calibrated values of inputs for MODFLOW and MT3D

Model	Aquifer	Value
MODFLOW		
Horizontal hydraulic conductivity	Unconfined aquifer	20 m/day
	Aquitard	0.00085 m/day
	Semiconfined aquifer	110-150 m/day
Storage coefficient	Aquitard	0.00005
	Semiconfined aquifer	0.00713
Specific yield	Unconfined aquifer	0.15
MT3D		
Longitudinal dispersivity	Unconfined aquifer	250 m
	Aquitard	250 m
	Semiconfined aquifer	250 m
Molecular diffusion coefficient		0.0000864 m^2/day
Effective porosity	Unconfined aquifer	0.25
	Aquitard	0.13
	Semiconfined aquifer	0.4

The sensitivity analysis revealed that the hydraulic head was greatly influenced by the horizontal hydraulic conductivity followed by specific yield in unconfined aquifer. In semi confined aquifer, hydraulic head was greatly affected by horizontal hydraulic conductivity and storage coefficient. This showed that the sea water intrusion was mainly influenced by horizontal hydraulic conductivity in the study area.

Prediction of seawater intrusion under various management scenarios

In this research, a scenario describes a possible management measure that can be implemented in future to control seawater intrusion. Various measures like artificial groundwater recharge, reduction in pumping and relocation of pumping wells in higher recharge zone were considered as scenarios to be simulated to find their effectiveness. The position of seawater-freshwater interface and area falling under the different TDS classes after the simulation of various seawater intrusion control measures were compared for suggesting appropriate management measure for controlling seawater intrusion in the study area. Results of numerical simulation are presented in the following sections.

Scenario I: Recharging the aquifer using 50% of surface runoff. Based on normal rainfall received in the study area, it was estimated that surface runoff of about 245 mm is generated during the monsoon season. In this scenario, it was proposed to use 50 % of the surface runoff for groundwater recharge. Under this scenario, maximum increase in water table would be obtained at a distance of about 5.5 km from coast. A seaward hydraulic gradient would exist from this part of the area. Towards the western side of the area, the water table would remain below Mean Sea Level(MSL) and reverse hydraulic gradient would exist (Figure 2).

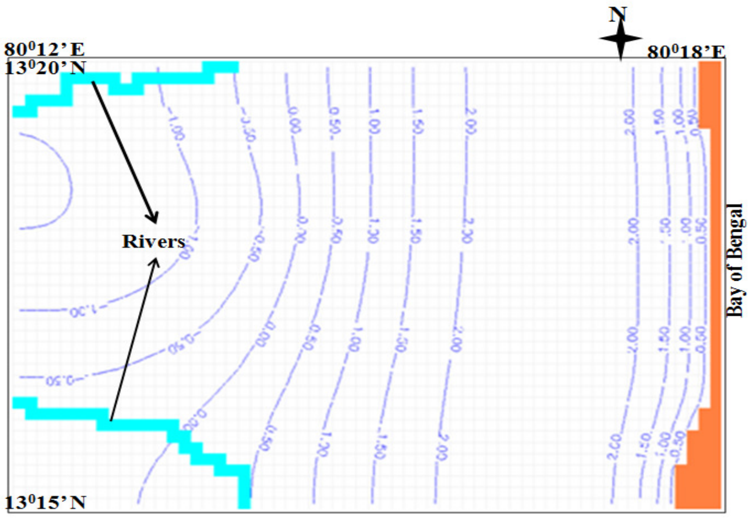

Figure 2. Water table contour map under the scenario I

The freshwater-saltwater interface in the year 2025 under different scenarios in unconfined aquifer is shown in Table 3. Under scenario I, the interface would be positioned at a distance of 9.25 km away from coast compared to 10.5 km in 2008. In case of semi confined aquifer, the interface would be positioned at 11.13 km away from coast, thus moving the same towards sea by 0.125 km compared to the year 2008 (Table 4).

Table 3.Interface location and area under different TDS classes in unconfined aquifer

Year	Scenario	Interface position from coast[km]	Area under different TDS classes [%]		
			<0.45 [Kg/m^3]	0.45-2.0 [Kg/m^3]	>2.0 [Kg/m^3]
2008		10.50	13.0	37.0	50.0
2025	I	09.25	14.1	41.2	44.7
	II	10.00	15.2	30.3	54.5

	III	09.75	21.4	34.0	44.6
	IV	09.50	25.0	35.2	39.8

Scenario II: Recharging the aquifer by increasing stage of flow in rivers. It was estimated that average surplus flow in Arani River was 120.91 Million Cubic Meters (MCM) and that of Kosasthalai River was about 148.33 MCM. Scenario of recharging the aquifer utilizing the surplus flow in rivers by maintaining a stage of flow of 0.5 m during monsoon and 0.25 m during non monsoon seasons by providing a series of check dams in two rivers was considered for controlling seawater intrusion. The simulation showed that this scenario would improve the ground water table on both sides of the rivers, whereas in areas near the coast, water table would be still below MSL. The groundwater quality will improve slightly near the river. The interface would move 0.5 km towards the coast compared to its position in 2008 (Table 1). Since this measure is effective in improving the groundwater level and quality near the rivers only, this alone would not be sufficient to bring significant improvement in groundwater quality in unconfined aquifer. In semi confined aquifer, the freshwater-seawater interface would move towards the sea by 0.75 km by the end of simulation period in 2025, compared to the year 2008. However, due to the lack of insufficient freshwater for flushing the salts, the above practice would result in slight increase in salt concentration in semi confined aquifer, especially to the eastern side of the rivers. This is evident from the Table 4, as 58.9% of the area would be having salt concentration greater than 2.0 kg/m^3 by the year 2025 under this scenario compared to 55% of the area in 2008. In view of this, the scenarios II in combination with other measures were also considered and the results of simulation are presented in the following sections.

Table 4. Interface location and area under different TDS classes in semi confined aquifer

Year	Scenario	Interface position from coast[km]	Area under different TDS classes [%]		
			<0.45 [Kg/m^3]	0.45-2.0 [Kg/m^3]	>2.0 [Kg/m^3]
2008		11.25	20.0	25.0	55.0
2025	I	11.13	13.8	31.6	54.6
	II	10.50	15.5	25.6	58.9
	III	10.75	20.7	24.7	54.6
	IV	10.00	24.0	26.4	49.5

Scenario III: Relocation of wells in unconfined aquifer combined with Scenario I and Scenario II. The scenario III consisted of combination of measures like increasing the recharge utilizing 50% of surface runoff, increasing stage in river by 0.5 m during monsoon and 0.25 m during non-monsoon seasons and relocating the wells from the severely affected area to the western boundary and near the rivers, in unconfined aquifer. Simulation results indicated that there is good scope for reducing the sea water intrusion by adopting this measure. In the unconfined aquifer the water table would reach above MSL by the year 2025**.** The hydraulic gradient would be reversed and this in turn would result in seaward movement of ground water. This is indicated by the water level in observation wells also (Figure 3). The freshwater-seawater interface would be located at 9.75 km from coast, compared to 10.5 km from the coast in 2008 (Table 3).

In semi confined aquifer, this scenario would raise the piezometric surface by 3.0 m near the western boundary and would shift the interface by 0.5 km towards the coast compared to the same in 2008 (Table 4). Salinity in 0.6 km^2 could be brought under the safe limit.

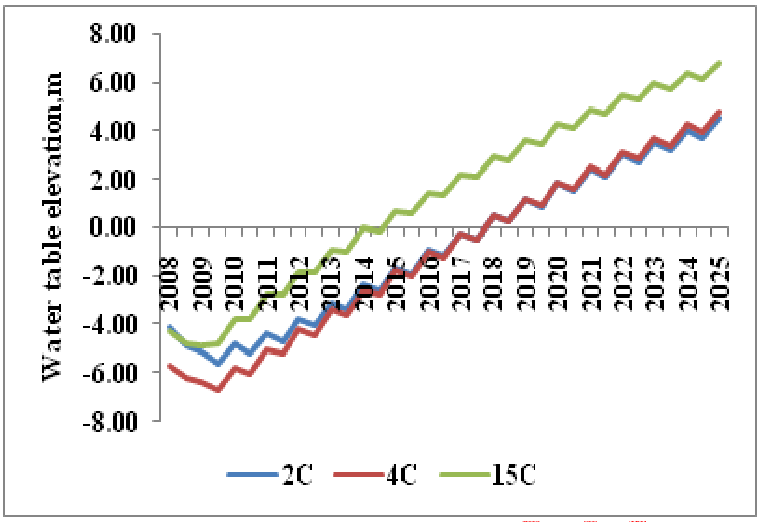

Figure3. Water level in observation wells under the scenario III

<u>Scenario IV: Reduction in pumping by 25% from semi confined aquifer and increase in pumping by 25% from unconfined aquifer combined with scenario II.</u> Since it is difficult to impose restrictions on pumping rate followed by farmers, it was decided to reduce pumping rate by 25% from semi confined aquifer and increase the pumping rate by 25% from unconfined aquifer along with the scenario II. Figure 4 shows the effectiveness of this measure in reversing the hydraulic gradient in unconfined aquifer. The water table would reach above MSL by the year 2025. Interface movement of 1.0 km towards coast would be achieved in unconfined aquifer. By the end of simulation period, groundwater

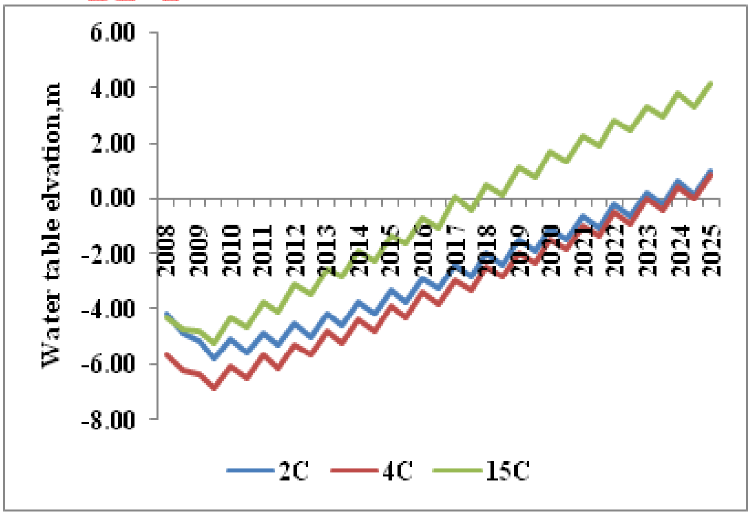

Figure 4. Water table in observation wells under the scenario IV

salinity in 10.2% (15.3 km^2) of the study area could be reduced to less than 2.0 kg/m^3 by adopting this measure (Table 3). This scenario would also result in improvement in piezometric head by 3.0 m (Figure 5) and an interface movement of 1.5 km towards the coast in semi confined aquifer. Consequently, water quality would improve in 8.25 km^2 area (Table 4). There is good scope for improving water level and water quality in both the aquifers by implementing this measure. This will also ensure the water supply level to that of 2008 by maintaining nearly same level of total pumping.

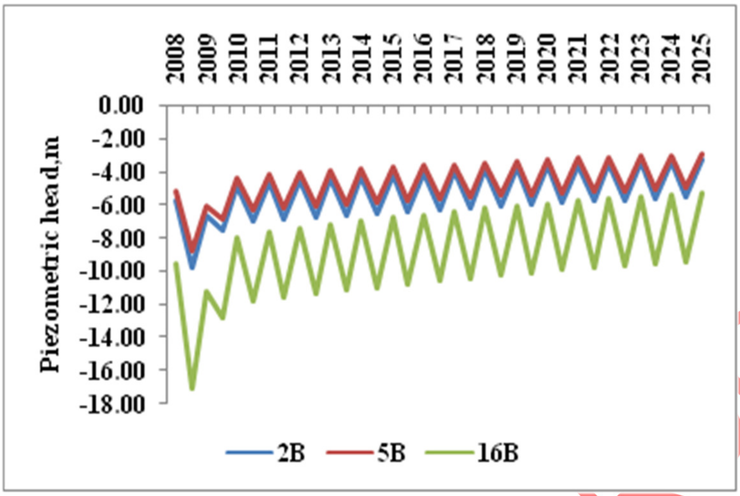

Figure 5.Piezometric head under the scenario IV

Evaluation of management scenarios to control seawater intrusion

Interface position and area under different TDS classes were determined under various scenarios at the end of simulation period. Appropriate management strategies were suggested based on their ability to restrict the interface movement and control salt affected areas. In the case of unconfined aquifer, scenario IV exhibited lowest area having TDS > 2.0 kg/m^3 in unconfined aquifer. In case of semi confined aquifer also, scenario IV was found to be effective in preventing the advancement of interface towards landside.The scenario I would also help in restricting the advancement of interface in unconfined aquifer. However, effectiveness of this scenario in reducing the affected area in semi confined aquifer was far behind compared to other scenarios.

In semi confined aquifer, reduction in pumping rate by 25% was found effective in improving the water quality during initial simulation. But this scenario would not bring any improvement in water quality in unconfined aquifer. Moreover, it is very difficult to impose any restriction in pumping done by farmers immediately. It is expected that increase of abstraction from unconfined aquifer by 25% and compensating this by increased level of recharge in unconfined aquifer would bring groundwater salinity under desirable limits. From simulation conducted in a coastal basin of Orissa, Rejani *et al.*[6] suggested reduction in pumping by 50% from 2nd aquifer and increase of pumping by 150% from 1st and 2nd aquifers at potential locations as a promising strategy for containing seawater intrusion. In view of this, a combination of various scenarios which would improve water level, water quality and interface movement towards sea in both the aquifers were considered. Among these, scenario IV, which would bring substantial reduction in the area where TDS is >2.0 kg/m^3 in both aquifers, was recommended for implementation. This may be followed by scenario III.

The results of simulation showed that the affected area cannot be reclaimed fully by 2025, even after implementing the best scenario which is a combination of various measures like reduction in pumping by 25% from semi confined aquifer, increase in pumping by 25% from unconfined aquifer and recharging the aquifer by increasing stage of flow in rivers. However, the simulation results can be accepted considering the severity of the seawater intrusion problem in the affected area.It may be noted that water quality deterioration due to seawater intrusion in the area started as early as in the 1960s. Ganesan [24] reported that even by recharging aquifer using the optimal recharge of 8.1 MCM/year in confined aquifer, the interface could be shifted by 2.9 km in 24 years in a seawater intruded coastal aquifer.It was also found that by imposing 28% reduction in the pumping rate, the interface would be moved only 1.5 km in 24 years. From the results of numerical modelling of seawater intrusion, Narayan *et al*.[43] reported that by adopting control measures like reduction in pumping and increased recharge rates, the salt water –freshwater interface would move about 3.5 km in 40 years in Burdekin delta irrigation area, Queensland.

Simulation results also highlighted the fact that in unconfined aquifer a substantial increase in water table could be achieved by implementing scenarios I, III, and IV. In most of the cases, water table would reach above MSL and seaward hydraulic gradient would be created by the end of simulation. But, the maximum movement of interface would be only 1.25 km under scenario I. The result is on par with the findings reported by Ganesan [24], where the interface would be shifted by 1.5 km and 2.9 km towards the coast in 24 years under two promising scenarios. The reason for this slow rate of reclamation could be attributed to the fact that salt transport in groundwater is governed not only by advection, but also by dispersion and diffusion.

CONCLUSIONS

The Minjur coastal aquifer system in Tamil Nadu is seriously affected by seawater intrusion due to over exploitation of ground water. In this study, the response of the coastal aquifers to various seawater intrusion control measures was analysed using calibrated and validated groundwater flow model MODFLOW and solute transport model MT3D. Predictability of models was assessed using statistical measures like Mean Error (ME), Mean Absolute Error (MAE), Mean Percent Error (MPE), Root Mean Square Error (RMSE), Coefficient of determination (R^2) and Nash-Sutcliffe Efficiency Index (E) after calibration and validation. The various statistical parameters obtained during calibration and validation of hydraulic head and groundwater salinity revealed a good agreement between simulated and observed hydraulic head and salinity. Various seawater intrusion management scenarios like groundwater recharge, reduction in pumping, relocation of pumping wells in higher recharge zone and a combination of recharge and reduced pumping were simulated using calibrated validated models. The performance of various management scenarios were evaluated by their effectiveness in increasing groundwater level, interface movement and changes in the area falling under different TDS classes. Model simulation with various management scenarios showed that salinity in unconfined aquifer can be reduced considerably by enhancing the natural recharge. The semi confined aquifer was found to be responsive to pumping rate. Considering the improvement in groundwater quality in both the aquifers, the scenario which combines recharge of groundwater from rivers and reduction of pumping rate from semi confined aquifer by 25% and increase of pumping rate from unconfined aquifer by 25% was found to be a more promising scenario.This would result in shifting the interface towards the coast by 1.0 km in unconfined aquifer and 1.5 km in semi confined aquifer by the year 2025. The study indicated that the once the coastal aquifer is affected by seawater intrusion, the rate of restoration is very slow.The simulation procedures used in this study can be used to simulate the seawater intrusion in space and time, and evaluate the impact of various possible management strategies for controlling it in coastal aquifers.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to the officials of Groundwater Division, State Public Works Department, Department of Economics and Statistics and Department of Agriculture, Government of Tamil Nadu for providing necessary data and assistance in field investigations. The first author wishes to acknowledge the financial support in the form of fellowship provided by Indian Agricultural Research Institute, New Delhi.

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