A Review on Modelling of Seawater Intrusion in Coastal Aquifer

Bhavin Prajapati and Nayankumar Soni

December 9, 2020

A Review on modelling of Seawater Intrusion in Coastal aquifer

Prajapati Bhavin S.[1], N.P.Soni[2]

[1]*M.E.(Water Resources Engineering), Gujarat Technological University, Rajkot, Gujarat-360002, India*
[2]*Assistant prof. SSEC Bhavnagar, Bhavnagar, Gujarat-364001, India*
Email: *bhavinp380@gmail.com*
Telephone/Mobile No.: +91 9033194195

Abstract

The Groundwater is major source for the people who works in different parts of works like irrigation, Domestic & Industrial parts, etc. So specially in coastal regions, there are some effects on the Groundwater due to sea water intrusion. Now a days, SWI is major environmental issue all over the world. These salinity concentration in groundwater may harmful for plants and animal that use it. Present study aims to analyses the Previous Literatures published by different authors with the. Different methods can be used to study how much effects should be done on the ground water by the nearer Sea water course. There are many reasons of SWI, but major factor is increasing the rate of pumping water from groundwater and decreasing rate of groundwater recharge. The aquifer zone in the region are essential contributor sources of drinking water and irrigation water for agriculture needs. For the study GW sample should be collected from the different parts in the region so the we will check that Sea water effects in how many areas from cost line and will gives the exact picture of sea water intrusion in coastal aquifer. Numerical model is used for the creating, running and processing of based model. There are some models available for GW modelling like MODFLOW, MT3DMS, FEFLOW, SEAWAT, SUTRA, FloPy etc. These all are a modular finite difference flow model to solve Groundwater flow equations and detailing of Ground water. After literature study it is concludes that, Numerical model gives more clear pictorial view of model rather than other methods of study. It is easy to apply and versatile, also it can be adopted to the specific hydrological setting of the area of interest.

Keywords: *Geophysical, Numerical model, Seawater Intrusion, Coastal aquifer, Unconfined aquifer.*

1. Introduction

In last few years, the use of surface water is increased in different purposes like domestic, industrial, agricultural sectors as an agreeable source of water as well as its lower cost and ease of accessibility. [Mohammad and Akbar, 2015] The rapid pace of development in the country of India in line with the high population growth, land use change and heavy urbanization, is expected to require clean water to rise sharply. [Mohammad, 2015; Purwanto, 2014] Due to these factors, pressure is increased on the surface water source to the extent that it has led to use of alternative sources like ground water to satisfy the need. Also, the ground water is a major source of fresh water. [Mohammad and Akbar, 2015]

But, the problems arise in the ground water which is nearer to coastal line. Because, coastal zones are highly sensitive and it is influenced by human activities, some activities which requires large quantity of water, climate change and corresponding rise of sea level. [Nerantzis, 2019] So, because of such factors coastal aquifers are currently in critical situation throughout the world. These quifers are important source of freshwater for more than 40% of world’s population, which is living in the coastal areas. [Beshad and Marwan, 2019]

So, from these factors, the salinization of coastal aquifer, because of overexploitation, is a common and major phenomenon. So, seawater intrusion is a major environmental issue, which affects 80% of world’s population lives in coastal areas. Also, seawater intrusion degrades the quality of coastal aquifer groundwater, which causes reduction in crop yield efficiency, reduce the sources of ground water and soil fertility. Also the seawater intrusion has been considered a global issue. Any changes in coastal aquifer results in the movement of seawater from sea side towards the aquifer, which is known as seawater intrusion (Seawater intrusion). [Nerantzis, 2019; Ratnakar and Ratnalu, 2020; Mahdi and Hojjat, 2019; Rachid and El-Fadel, 2017]

From the previous study it concludes that the two major reasons of seawater intrusion is over-exploitation of coastal aquifer and sea level rise due to the climatic change. The India is not a land locked country, but the coastal areas are there at east, west and south part in India. So, the effective monitoring of groundwater is required to save the drinking water resources. Also, the preventive measures are requiring in the area which is saline affected. [Ratnakar and Ratnalu, 2020] The costal line length of the India is around 6031km which includes 9 coastal states and 2 union territories having 66 coastal districts. [nccr.gov.in]

In various part of India, salinization of coastal aquifers has been studied by various authors: Digha, West Bengal(Choudhary et al., 2001), Godavari region(Surinaidu et al., 2014), Chennai(Nair et al., 2016), Gujarat (Desaai et al., 1979, Rina et al., 2013). Also, various methods are used to study the problem such as Geophysical method, numerical method and hydro-chemistry approach. [Parul and Rina, 2018] Coastal length of the Gujarat state constituting 14 coastal districts and 2 union territories having 2542 villages is measured to be approximately 1701km from 2016 satellite imagery. [nccr.gov.in]

1.1 Factors affecting Seawater Intrusion

Most of the coastal areas in the India are economic hub due to easy accessibility of natural resources and navigational facilities as well as supporting the population needs. Indiscriminate withdrawal of ground water from the aquifer to meet the people demands for different purposes leads to decrease in water level and it causes Sea water Intrusion. [Parul and Rina, 2018] Reason behind over exploitation from the ground water is limited availability of surface water and it makes groundwater highly vulnerable. So, groundwater is only source of potable drinking in this coastal region. [Parul and Rina, 2018] Seawater intrusion caused because of changes in coastal aquifer condition resulting from water extraction, climate drivers, sea-level rise, oceanic over topping events, and land use change. [Mahdi and Hojjat, 2019] Besides the dense population on coastal aquifers, extreme storm surges and tropical storms area among the main indirect effects to coastal aquifers. In practice coastal areas and coastal aquifers are highly vulnerable environments and may experience impacts from storms [Saber and Hocine, 2017]

The seawater intrusion is a natural disaster which causes the biggest impact on the agriculture practices in many regions all over the world. The sea level rise will likely pose the risk of further penetration of salt water with more severe intensity in coastal areas. [Tran and Phu, 2018] Also, Higher seawater density than freshwater density which is available in the aquifer cause the seawater intrusion. The law of nature states that object with higher density flows towards the object with lower density. Thus, the sea water which is having higher density than the fresh water will flow towards the fresh water area i.e. coastal aquifer.

2. Methods of study Seawater Intrusion

The selection of methods to study SWI is the first step towards decision-making whereby different methods are studied and assessed against clear criteria. The methods consisted of a comprehensive analytical approach which includes: Review and selection of methods generally used in study, fieldwork of aquifer properties and testing in laboratories, evaluation of the effectiveness of tested methods based on predefined criteria, development of a SWI numerical model. [Rachid and El-Fadel, 2017] Following are some methods which used to study Seawater intrusion in coastal aquifer:

2.1 Hydro-Chemistry method [Ratnakar and Ratnalu, 2020]:

Ground water samples are collected from the southwest coast of India in polyethylene containers from 49 different shallow and deep wells during the pre-monsoon period of may 2013 and one surface water sample from the perennial stream and one seawater sample. The physical (pH, EC and TDS) and chemical (Na^+, Ca^{2+}, K^+, Mg^{2+}, Cl^-, F^-, SO_4^-, HCO_3^-, NO_3^-) parameters and oxygen isotopes ($\delta^{18}O$) are determined. pH was measured using a digital pH meter, Electrical conductivity and TDS were estimated with HANNA EC and TDS analyser. Sodium and potassium ions were analysed by flame photometry using CL-345 flame photometer of ELICO. Sulphate was measured by turbidity method using the UV-vis spectrophotometer at 425 mm wave length and fluoride concentration was measured by colorimetric method using UV-vis spectrophotometer at 570mm wavelength. Nitrate was estimated using UV-vis spectrophotometer at 220 nm wavelength and standard titration methods were used to analyse the bicarbonate, calcium and chloride ions. Oxygen isotopes ($\delta^{18}O$) were analysed in a stable Isotope Ratio Mass Spectrometer (GV Instruments Ltd., Isoprime).

From the results and graphs, it represents three majot water types: freshwater, mixed water and saline water. The fresh water belongs to the Ca^{2+}, Mg^{2+}, -HCO_3^- type, mixed water belongs to the Ca^{2+}, -Mg^{2+}, Cl^- type, and saline water belongs to Na^+, Cl^- type. About 60% of samples belongs to freshwater and they show no major ions dominance. Around 30% of the samples belong to the saline type with dominance of strong alkalis (Na^+) and strong acid (Cl^-). About 10% of the samples were mixed water. This distribution of samples suggest that the groundwater compositions were governed by hydrogeochemical processes, influxes from recharge, seawater intrusion, and salinization process in the aquifer regime.

2.2 Numerical method (SEAWAT) [Mehdizadeh and Sinohel, 2017]:

In layered aquifers, vertical leakage through layers makes the intrusion mechanism different compared to homogeneous one. Seawater intrude more appreciable into bottom layer rather than the upper one. For the upper layer seawater intrude toward land at early times but then naturally driven back to almost its original position (called as overshoot). It weaker matched with SEAWAT result for lower permeability(K^0) scenario where it cannot successfully predict the correct amount of freshwater upward leakage. So, in this study used the finite-difference model SEAWAT (Version 4.00.05) to simulate three-dimensional, variable density, transient groundwater flow in porous media.

From the results, it was concluded that, two different three-horizontally layered aquifers were defined by changing middle layer conductance. The first scenario contained an aquitard with hydraulic conductivity (K^0: L/T) of 0.01 m/d and the second one had lower permeable aquitard with K^0. In first scenario lower layer can leaks upward to the upper layer and no overshoot occurs for both ISLR and GSLR at the bottom aquifer. For the second scenario almost no freshwater leaks upward, therefore the freshwater inflow at the lower layer can easily push the salt wedge back toward the sea.

2.3 Numerical method (Sutra) with ArcGIS [Mohammad and Akbar, 2015]:

Seawater intrusion (SWI) is assessed using a 3D finite element (FE) model. The numerical model is developed based on available hydrogeological data in real scale. model is subjected to a management strategy involving surface recharge of the aquifer with treated wastewater. In the study there are two points are there, first one is recharging the aquifer using treated wastewater and second one is general impacts from multiple ponds in recharge. In the numerical model they used Darcy's law and mass balance equation. To prepare the 3D simulation model of the aquifer with the irregular geometry, the elevation maps and all the other information layers are prepared in the field scale using ArcGIS platform and in shape file formats and then imported into graphical interface of the SUTRA code.

From the conclusion, in order to control the negative impacts of SWI, the system was subjected to management scenarios of artificial recharge using ponded treated wastewater in two different schemes and the results were compared with the no management scenario. It has been shown that a considerable reduction in salinity levels occurs throughout the aquifer owing to the application of the artificial recharge scenarios. Consequently, a higher level of efficiency and a long-term sustainability of the system would be guaranteed by designing several surface recharge basins in different locations of the study area.

2.4 Geophysical method [Hesham El-Kaliouby, 2020]:

- Time Domain Electromagnetic (TDEM) method has been widely used in mapping and assessment of groundwater resources and sea water intrusion along coastal alluvial plains. TDEM data were used to map the depth to the interface between freshwater and saline-water along the coast. TDEM method was used to differentiate between fresh, brackish, and saline water. TDEM responses of the earth due to a primary signal from a large wire square- loop laid on the ground surface yield information about the variations of the electrical conductivity with depth. The conductivity of soils and rocks are controlled by mineralogy, clay content, water content, salinity, and porosity. Changes in the conductivity of soils and rocks produce variations in the electromagnetic signature. TDEM made by transmitting input current into square loops of insulated wire deployed on the land surface. The transmitter loop current consists of equal periods of time - on and time- off, which produce an electromagnetic field near the loop of wire. electromagnetic field in the ground underneath Journal applied geophysics loop in accordance with Faraday's Law. This resultant field instantly begins to decay, generating additional eddy currents that spread downward and outward into the subsurface. These eddy currents then produce a secondary magnetic field that is recorded as voltage measurement by a receiver positioned in the centre or at an off - set distance from the transmitter loop. voltage magnitude received from the eddy currents at specific times and depths is determined by the overall conductivity of subsurface rock units and fluids. From these voltage measurements, apparent resistivity values can be calculated. A Geonics Protem-47 system using a square transmitter (Tx) loop was used to collect the TDEM soundings.

- In this method different loop size were used for study for example 20m, 30m, 50m, etc. and from the results it is conclude that, the Large loop cannot resolve details in a freshwater-saturated zone, while small loop could resolve it clearly. On the other hand, Large loop could resolve the limits of saltwater- saturated zone at depth, where smaller loop could not penetrate to that depth.

3. Status of Seawater Intrusion in India

About 6632km long shoreline distributed among nine coastal state and two union territories. Coastal erosion has become one of the most serious problem in varying pockets along the Indian coast.

The shoreline analysis shows that 34% of coast is eroding, 28% is accreting and 38% is in stable state. The state wise analysis suggests that in the West Bengal (63%) and Pondicherry (57%) coast erosion exceeds more than 50%, followed by Kerala (45%) and Tamil Nadu (41%). Odisha (51%) is the only coastal state which is having more than 50% of accretion, followed by Andhra Pradesh (42%). Considering the maximum and minimum values of the shoreline change rate, the shoreline is divided into seven categories as low erosion, moderate erosion, high erosion, stable, low accretion, moderate and high accretion which is shown in figure. (nccr.gov.in)

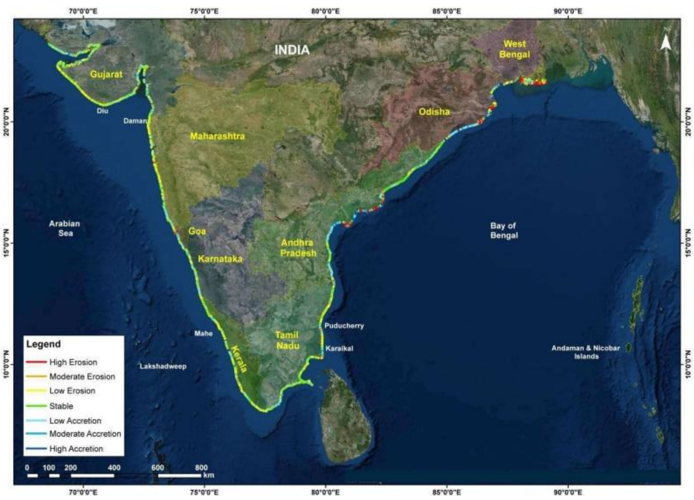

Figure 1 Shoreline of India

It can be seen that the coastal states of Gujarat, Andhra Pradesh, Odisha and West Bengal have undergone drastic change in the past 26 years. Land gain of greater than 60 sq. km is observed along the states of Gujarat and Odisha. (nccr.gov.in)

The costal state of Gujarat is on the western end of Indian peninsula. It is longest coastline with geomorphic features, and based on the varied physiographic features, coastal processed and river discharge the coast can be broadly classified into five regions (1) The Rann of Kachchh (2) Gulf og Kachchh (3) The Saurashtra coast (4) Gulf of Khambhat and (5) The south Gujarat coast. The 1990-216 shoreline change assessment result shows that 43% of the coast is stable, 31% is eroding and remaining 26% is accreting which shown in figure. (nccr.gov.in)

Figure 2 Shoreline of Gujarat

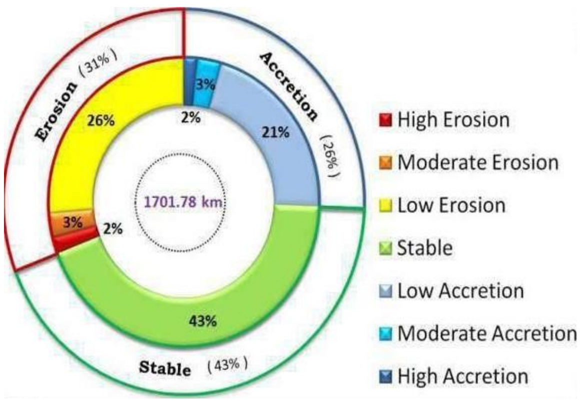

Figure 3 Shoreline changes in %

References

1. Abd-Elhamid, H.F., Javadi, A.A., 2011. A density-dependent finite element model for analysis of saltwater intrusion in coastal aquifers. J. Hydrol. 401, 259e271. http://dx.doi.org/10.1016/j.jhydrol.2011.02.028.
2. Abourida, A., Errouane, S., Bahir, M., Olivera de Silva, M., Cheggour, A., 2004. Contribution des isotopes de l'aquifere Mio-Plioquanternaire du Haouz de Marrakech (Maroc). Estud. Geol. 60, 161–167.
3. Allouche, N., Maanan, M., Gontara, M., Rollo, N., Jmal, I., Bouri, S., 2017. A global risk approach to assessing groundwater vulnerability. Environ. Model. Softw. 88, 168–182. https://doi.org/10.1016/j.envsoft.2016.11.023.
4. Barlow, P.M., Reichard, E.G., 2010. Saltwater intrusion in coastal regions of North America. Hydrogeol. J. 18, 247e260. https://doi.org/10.1007/s10040-009-0514- 3.
5. Brunner, P., Simmons, C.T., 2012. HydroGeoSphere: a fully integrated, physically based hydrological model. Ground Water 50, 170e176. https://doi.org/10.1111/ j.1745-6584.2011.00882.
6. Ciriello, V., Federico, V.D., Riva, M., Cadini, F., Sanctis, J.D., Zio, E., Guadagnini, A., 2013. Polynomial chaos expansion for global sensitivity analysis applied to a model of radionuclide migration in a randomly heterogeneous aquifer. Stoch. Env. Res. Risk Assess. 27, 945–954. https://doi.org/10.1007/s00477-012-0616-7.
7. Fausey, N.R., Brown, L.C., Belcher, H.W., Kanwar, R.S., 1995. Drainage and water quality in great lakes and cornbelt states. J. Irrigat. Drain. Eng. 121, 283e288. https://doi.org/10.1061/(ASCE)0733-9437(1995)121:4(283).
8. Guevara Morel, C.R., van Reeuwijk, M., Graf, T., 2015. Systematic investigation of nonBoussinesq effects in variable-density groundwater flow simulations. J. Contam. Hydrol. 183, 82–98. https://doi.org/10.1016/j.jconhyd.2015.10.004.
9. H. Abd-Elhamid and A. Javadi, A Cost-Effective Method to Control Seawater Intrusion in Coastal Aquifers. Water Resources Management, 25:11 (2011) 2755-2780.
10. Hadi, S.P.(2013), Manusia dan Lingkungan (Human and Environmental). Text Books Semarang : Badan Penerbit Universitas Diponegoro, 979-9156-69-6.
11. Homma, T., Saltelli, A., 1996. Importance measures in global sensitivity analysis of nonlinear models. Reliab. Eng. Syst. Saf. 52, 1–17. https://doi.org/10.1016/0951- 8320(96)00002-6.
12. Jerbi, C., Fourno, A., Noetinger, B., Delay, F., 2017. A new estimation of equivalent matrix block sizes in fractured media with two-phase flow applications in dual porosity models. J. Hydrol. 548, 508–523. https://doi.org/10.1016/j.jhydrol.2017.03. 028
13. Ketabchi, H., Mahmoodzadeh, D., Ataie-Ashtiani, B., Simmons, C.T., 2016. Sea-level rise impacts on seawater intrusion in coastal aquifers: review and integration. J. Hydrol. 535, 235–255. https://doi.org/10.1016/j.jhydrol.2016.01.083.
14. Konakli, K., Sudret, B., 2016. Global sensitivity analysis using low-rank tensor approximations. Reliab. Eng. Syst. Saf. 156, 64–83. https://doi.org/10.1016/j.ress.2016.07. 012.
15. M. Papadopoulou, G. Karatzas, M. Koukadaki, and Y. Trichakis, Modeling the saltwater intrusion phenomenon in coastal aquifers–A case study in the industrial zone of Herakleio in Crete. Global NEST J, 7:2 (2005) 197-203.
16. M.S. Hussain, A.A. Javadi, A. Ahangar-Asr, and R. Farmani, A surrogate model for simulation–optimization of aquifer systems subjected to seawater intrusion. Journal of Hydrology, 523:0 (2015) 542-554
17. McCall, R.T., Masselink, G., Roelvink, D., Russell, P., Davidson, M., Poate, T., 2012. Modelling overwash and infiltration on gravel barriers. In: Coastal Engineering Proceedings. Santander, Spain, p. 34. https://doi.org/10.9753/ icce.v33.currents.34.
18. Miller, K.L., Berg, S.J., Davison, J.H., Sudicky, E.A., Forsyth, P.A., 2018. Efficient uncertainty quantification in fully-integrated surface and subsurface hydrologic simulations. Adv. Water Resour. 111, 381–394. https://doi.org/10.1016/j.advwatres. 2017.10.023
19. . Mohammadi, A., Manteghian, M.(2011), Numerical Solution of One-dimensional advection-diffusion Equation Using Simultaneously Temporal and Spatial Weighted Parameter, Australian Journal of Basic and Applied Sciences, 5(6): 1536-1543,ISSN 1991-8178
20. Oberle, F., Swarzenski, P., Storlazzi, C., 2017. Atoll groundwater movement and its response to climatic and sea-level fluctuations. Water 9, 18. https://doi.org/ 10.3390/w9090650.

21. Perriquet, M., Leonardi, V., Henry, T., Jourde, H., 2014. Saltwater wedge variation in a non-anthropogenic coastal karst aquifer influenced by a strong tidal range (Burren, Ireland). J. Hydrol. 519, 2350–2365. https://doi.org/10.1016/j.jhydrol.2014.10. 006.
22. Rajabi, M.M., Ataie-Ashtiani, B., Simmons, C.T., 2015. Polynomial chaos expansions for uncertainty propagation and moment independent sensitivity analysis of seawater intrusion simulations. J. Hydrol. 520, 101–122. https://doi.org/10.1016/j.jhydrol. 2014.11.020.
23. Ramasomanana, F., Fahs, M., Baalousha, H.M., Barth, N., Ahzi, S., 2018. An Efficient ELLAM implementation for modeling solute transport in fractured porous media. Water Air Soil Pollut. 229, 46. https://doi.org/10.1007/s11270-018-3690-8.
24. Riva, M., Guadagnini, A., Dell'Oca, A., 2015. Probabilistic assessment of seawater intrusion under multiple sources of uncertainty. Adv. Water Resour. 75, 93–104. https://doi.org/10.1016/j.advwatres.2014.11.002.
25. Werner, A.D., Bakker, M., Post, V.E.A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T., Barry, D.A., 2013. Seawater intrusion processes, investigation and management: Recent advances and future challenges. Adv. Water Resour. 51, 3–26. https://doi.org/10.1016/j.advwatres.2012.03.004.
26. Werner, A.D., Bakker, M., Post, V.E.A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T., Barry, D.A., 2013. Seawater intrusion processes, investigation and management: Recent advances and future challenges. Adv. Water Resour. 51, 3–26. https://doi.org/10.1016/j.advwatres.2012.03.004.
27. Younes, A., Fahs, M., Ahmed, S., 2009. Solving density driven flow problems with efficient spatial discretizations and higher-order time integration methods. Adv. Water Resour. 32, 340–352. https://doi.org/10.1016/j.advwatres.2008.11.003.