Numerical Modeling of Seawater Intrusion: Implication for Sustainable Coastal Aquifer Management

ABSTRACT

Aim: To examine thenumerical modeling of seawater intrusion and show its implication for sustainable coastal acquifer management.

Problem Statement: The global rise in the world population has necessitated the essentiality of water which also has linkage with power and agriculture. However, arid and semi-arid regions occupy almost one-third of the global land surface which makes many regions to be under harsh and rising water stress. The intrusion of seawater into some sections of aquifers has been one of the major problems contributing to water scarcity, especially during the dry season.

Significance of Study:A numerical model is a reasonably accurate and economical tool to simulate and predict the head and quality of groundwater in coastal aquifers if it is properly calibrated using the available measurements of heads, pumping rates, and boundary conditions. The calibrated geo-hydrological parameters can then be used to validate the model for another set of measured data. Thus, it is imperative to predict seawater intrusion into coastal aquifer using numerical modeling tools for water management and sustainability purpose.

Methodology: This review article was compiled using references from previous literatures addressing seawater intrusion into coastal aquifer. Cited cases were referenced from different relevant journals.

Discussion: This article has presented the fundamental principles and mechanisms of seawater intrusion into coastal aquifer. It was observed that seawater intrusion may arise as a result of moderately lower groundwater withdrawal in dry seasons during which the intrusion of seawater is considerably much when compared with the rainy season. The major influencing factors are temperature, rainfall, abstraction rate and evaporation. However, abstraction rate is the most vital variable in relation to rise in population because the saline water migrates more inland due to water over-extraction from the subsurface without adequate replenishment in either semi-arid or arid regions. Different applicable mathematical models for seawater intrusion into coastal aquifer stated in this review are visual MODFLOW, MT3DMS routines, SEAWAT-2000 routines and FEFLOW routines. The applications of these models in the numerical modeling of coastal aquifers in some countries are stated and with their respective influence on the objectives of the study and the results obtained.

Conclusion: In conclusion, the use of numerical modeling in studying the nature of seawater intrusion is imperative to achieve sustainable coastal aquifer management.

Keywords: Seawater Intrusion, Numerical Modeling, Coastal Acquifer, Abstraction Rate, Groundwater Management

1. INTRODUCTION

A permeable rock which is layered and adequately conductive in nature in order to enhance an appreciable volume of water to flow is called an aquifer. The groundwater available in the cracks and which is easily accessible via a borehole or well is called phreatic. It is referred to as “freshwater” when it is in good condition for consumption [1]. However, as a result of extreme freshwater pumping, the tide and deficient aquifer replenishment, large volumes of seawater inland are being observed in numerous coastal regions. In this case, intrusion of seawater into some sections of the aquifer is experienced due to this phenomenon. It is essential to abandon the pumping wells when the freshwater becomes frequently salty due to the interface of seawater/freshwater which may act as a pollution source. Seawater intrusion is currently among the constraints hindering groundwater management in numerous coastal aquifers. Many coastal areas around the world are known for high populations such that 70% of the global population (within 60 km of the shoreline) and 8 among the 10 largest cities around the globe are situated along the coastline [2].

Coastal aquifers overexploitation is now a usual scene in which numerous coastal regions experience the intrusion of seawater which causes harsh decline in the quality of ground freshwater. Seawater intrusion is a big challenge in some coastal areas. Seawater intrusion is defined generally as saline water encroachment into fresh groundwater domains in a coastal aquifer formation. This is observed when the existing natural equilibrium condition formed between seawater and freshwater is hindered due to artificial or natural effects. This adversely causes worsening of freshwater resources troubling animals, agriculture, human and industrial resources within the polluted areas [3]. Several severe environmental cases have been reported due to intrusion of seawater in the coastal zones.

The existing closest pumping wells to the coast turn saline as a result of upconing as the intrusion of seawater evolves and thus become abandoned. Coastal aquifers management in situations like this is a dangerous task which needs special and quick intervention in order to reduce seawater wedge movement into aquifers and control seawater up-coning close to the pumping stations [4]. The most common and prevailing type of groundwater pollution in coastal aquifers is the salinization whose potential origins are different including halite dissolution, seawater intrusion, natural saline groundwater, oil and gas-field brine. Of these origins, the intrusion of seawater occurs naturally as a result of differences in the densities of freshwater and seawater. Other influencing factors include evapotranspiration, regional hydrogeological states and change in climate. The rise in population growth together with the global economic development has necessitated the need for large volume of groundwater. It is recommended that the abstraction rate in pumping wells must not go beyond the allowable sustainable yield along the coastal areas [5]. The critical nature of salinization prevention necessitates the comprehensive description of coastal aquifers and the corresponding remediation in order to safeguard the coastal aquifers from intrusion of seawater.

Arid or semi-arid occupies almost one-third of the global land surface which makes many regions to be under harsh and rising water stress as a result of rise in water usage, speedy urbanization, increasing population and constrained availability of water resources. The global population has risen approximately four times beyond in the last 150 years with the possibility of being quadrupled in thirty years to come [6]. The surface water and groundwater quality has significantly deteriorated in numerous regions around the world. Monitoring surface water quality in water bodies and open channels is not often difficult to undertake unlike groundwater quality monitoring, this in turn makes groundwater remediation an enormous task [4].

A typical example of a place where seawater intrusion normally occurs is the Arabian Peninsula's where exploitable fossil aquifer systems ranging between small to medium size may attain maximum depletion by 2050 [7]. Also, in the next sixty to ninety years to come, there is a high likelihood of the occurrence of complete groundwater supplies depletion in all aquifer systems [7]. Thus, all hands must be on desk by the government, researchers, citizens, NGOs and others to tackle this menace because there is direct linkage existing between water, food and energy in order to prevent worsening of the country's social and economic development. In countries and areas like this, the management and exploration of groundwater is imperative to attain sustainable development. Where there is paramount water supply shortage, the problems are heightened by the anticipated temperature increase and the deterioration in precipitation, which would decrease the volume of recharge for renewable water supplies [8].

Despite this, seawater intrusion may arise as a result of moderately lower groundwater withdrawal during the dry season. During this period, the intrusion of seawater chances is considerably much when compared with the rainy season. From among the factors (temperature, rainfall and evaporation) affecting seawater intrusion, abstraction rate is the most vital variable in relation to rise in population because the salinity water migrates more inland as a result of water over-extraction from the subsurface without adequate replenishment in either semi-arid or arid regions. This stresses the necessity for the mitigation of the environmental impact [8]. Figure 1 is a typical conceptual model of Wadi Al Jizi groundwater flow system showing the locations for the bed rock; alluvium; direct recharge to bed rock; pumping for water supply and agriculture; seepage from Wadi channel; runoff; evapotranspiration; and freshwater water discharge to sea.

The existing natural steady state between salt- and freshwater is often hindered as a result of coastal aquifer overexploitation. This occurs when the seawater and freshwater boundary migrates towards inland together with the succeeding salinization of areas formerly situated within low freshwater. During this course, the level of freshwater is drawn down as a result of pumping excessively. Factors used in characterizing seawater intrusion include usual dynamic changes, its invisibility, tasking management, impossible reversibility and harmful effects. Additionally, intrusion of seawater has become significant and tagged among the most prevailing processes leading to water quality degradation because it increases freshwater salinity to concentrations above the maximum allowable drinking standards [9]. This is an essential area calling for serious investigations by researchers around the world. This has equally prompted the numerical modeling of the mechanism of seawater intrusion due to its practical significance and thus, has gained noteworthy attention in the field of water resources.

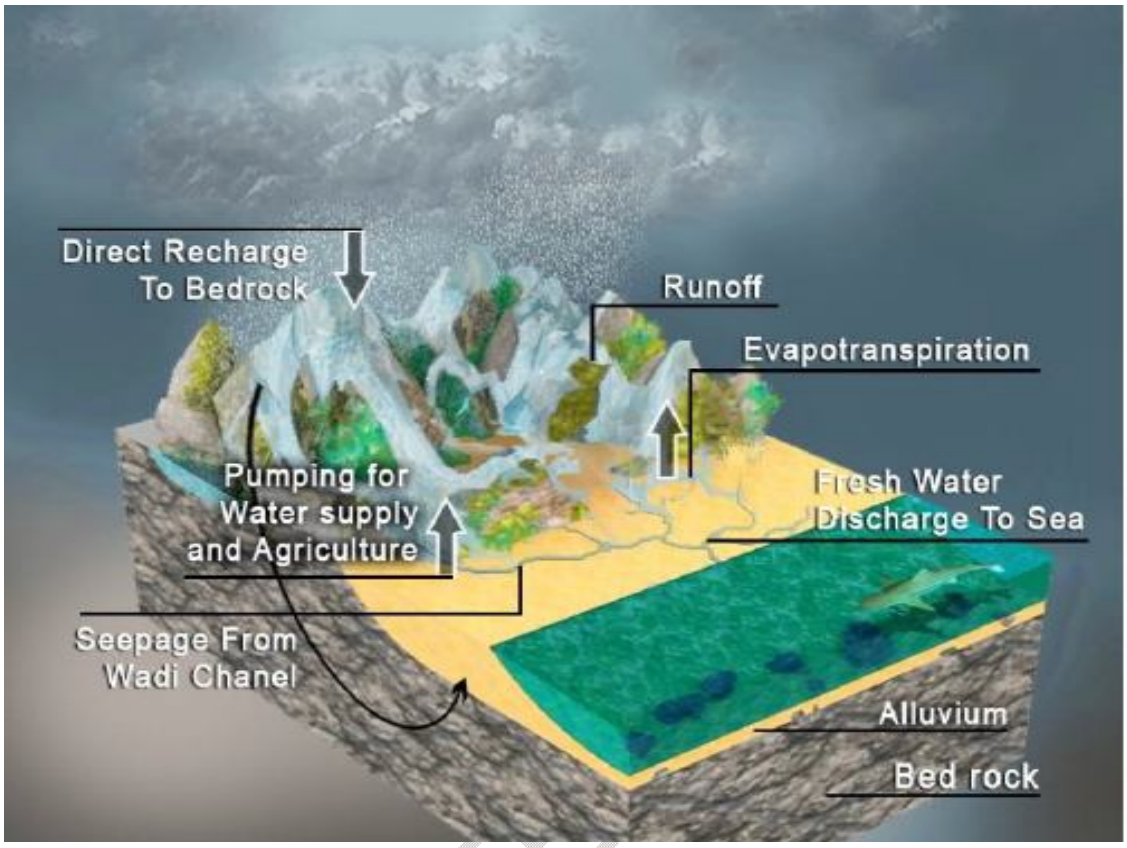

Figure 1: Typical conceptual model of Wadi Al Jizi groundwater flow system [7]

In order to model intrusion of seawater in a coastal aquifer, a combination of salt transport groundwater and density dependent flow model is required. The groundwater velocity field from flow modeling computes the simulated salinity while the water density is determined by the salinity which in turn influences the flow field simulation. Seawater intrusion has been investigated using numerous variable-density numerical models which were developed by previous researchers [11]. Examples are FEFLOW, SUTRA, SEAWAT and so on. However, the most widely applicable and adopted density-dependent model is SEAWAT and it tackles flow equations using finite difference technique and related equations of transport using three major classes of numerical methods. It should be noted that many of the applicable variable-density models are complex numerically and computationally expensive [12]. This is because they need implicit procedure and smaller timestep to solve transport and flow equations iteratively several times in each stagewise step. This review article presents the fundamental principles and mechanisms of seawater intrusion into coastal aquifer. The numerical modeling was considered for the sustainable management of the process.

2. MODELING EQUATIONS FOR SEAWATER INTRUSION INTO COASTAL ACQUIFERS

The most prominent applicable modeling equations for seawater intrusion into coastal acquifers are visual MODFLOW, MT3DMS routines, SEAWAT-2000 routines and FEFLOW routines [13].

- **VISUAL MODFLOW**

Equation 1 represents a 3D numericalflow model for unsteady and steady conditions. It was expanded using Visual MODFLOW. The principle involves applying finite difference technique in Visual MODFLOW Flex with the incorporation of MODFLOW code. The modular finite difference is adopted in three-dimensional modeling to tackle the differential equation that controls the flow in a porous medium [14].

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)\pm W=S_s\times\frac{\partial h}{\partial t} \quad [1]$$

where K_{xx}, K_{yy}, and K_{zz} = K-values in the x, y, and z directions (L/T); h = hydraulic head (L); W = volumetric flux per unit volume (T^{-1}); S_s = porous medium specific storage (L^{-1}); and t = time.

- **MT3DMS ROUTINES**

Equation 2 represents the governing equation of solute-transport that uses MT3DMS routines.

$$\frac{\partial C}{\partial T}=\nabla\cdot(D\cdot\nabla C)-\nabla(vC)-\frac{qs}{\theta}Cs+\sum_{K=1}^{N}Rk \quad (2)$$

where D = coefficient of hydrodynamic dispersion ($L^2\ T^{-1}$); v = velocity of the fluid ($L\ T^{-1}$); C_s = solute concentration of water coming from sources or exiting vai sinks (ML); and R (k = 1, …, N) = solute production rate or decay in reaction k of N different reactions ($ML^{-3}\ T^{-1}$).

- **SEAWAT-2000 ROUTINES**

With SEAWAT-2000 routines, the seawater flow and transport are under different values of salt concentration within the coastal area as stated in Equation 3.

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(V_iC)-\frac{q_sC_s}{\theta}+\sum_{k=1}^{N}R_k \quad (3)$$

C = concentration of contaminant (ML^{-3}), x_i = position occupied in the cartesian coordinate axes (L), D_{ij} = coefficient of hydrodynamic dispersion ($L^2 T^{-1}$), V_i = velocity of fluid (LT^{-1}), q_s = flow per unit of length of injected or pumped aquifer, C_s = discharge or recharge flow concentration (q_s) (ML^{-3}), θ = porous medium porosity and R_k (k = 1, . . . ,N) is the rate of solute production or decay in reaction k of N different reactions ($M L^{-3} T^{-1}$).

- **FEFLOW ROUTINES**

FEFLOW is a finite element subsurface FLOW system. It is a modular 3D finite element groundwater flow model which possesses the ability to simulate processes that are either in steady state condition or in transient state in subsurface water resources [15]. It is the applicable governing equation (Equation 4) for a mixed variable density flow with reference to salt movement and freshwater head of a miscible seawater-freshwater aquifer.

$$\frac{\partial}{\partial x_i}\left[K_{ij}\left(\frac{\partial H}{\partial x_j}+\eta Ce_j\right)\right]=S_s\frac{\partial H}{\partial t}+\phi\eta\frac{\partial C}{\partial t}-\frac{\rho}{\rho} \quad [4]$$

where x_i, x_j (i, j = 1, 2, 3) = cartesian coordinates, K_{ij} = principal components of hydraulic conductivity along the x, y, and z axes, respectively, H = equivalent freshwater hydraulic head, η = coefficient of density coupling, C = solute concentration, S_s = porous medium specific storage, t = time, φ = porosity; and ρ = density of salt-fresh water.

3. CASES OF NUMERICAL MODELING OF SEAWATER INTRUSION INTO COASTAL ACQUIFERS

The incorporation of numerical modeling to understand the mechanisms behind seawater intrusion into coastal aquifer is essential and has been an effective tool in the analysis of the influencing factors and the fundamental conditions. Also, it has been so helpful in the management and protection of coastal aquifers from salinity intrusion. The visualization of transport phenomena and two- and three-dimensional flow; and real-time analysis can be provided by groundwater models [16]. The models can be easily utilized via user-friendly graphical interfaces.

- **MODFLOW AND MT3DMS NUMERICAL MODELING TECHNIQUES**

One of the most prominent three-dimensional models for flow groundwater under transient and steady flow conditions is MODFLOW usually adopted in the saturated zone in unconfined or confined aquifer systems. Another numerical modeling tool that could be employed for the simulation of solute and advection transport is MT3DMS which is also a three-dimensional multi-species transport model. These have been successfully applied and adopted in the construction of a regional representative 3D numerical solute transport and groundwater flow mode [17]. These were adopted for the study of groundwater head fluctuations and intrusion of salinity into Salalah plain aquifers and Al Batinah aquifer. These were purposely for the execution, calibration, and validation of MT3D for seawater intrusion and MODFLOW for groundwater flow in the aquifers of the aforementioned two regions.

Also, multifaceted multi-layer aquifer situated in the Wadi Samail area within Al Batinah region was simulated using a 3D groundwater model (MODFLOW). The heterogeneous multi-layer aquifer was represented by a four-layer conceptual model. A main influence of unregistered pumping wells on groundwater levels was revealed by the study while insisting on the maintenance of the records of numerous pumping wells for adequate water management [15]. Nonetheless, climate change impact on Jamma aquifer and Samail aquifer, both situated in Oman within the Al Batinah region, was investigated using both MT3DMS and MODFLOW simultaneously. A defy in the seawater intrusion by the watershed was noticed which was maintained by flowing groundwater towards the sea. However, the Jamma aquifer became vulnerable to intrusion of saline water, harshly affected and stressed at the same time [9].
The pattern of seawater and groundwater intrusion was examined via these numerical modeling tools in the Eastern Al Batinah coastal region. Both MT3DMS and MODFLOW were run as models to duplicate both the transient and steady-state conditions for the given data set. In addition, the calibrated model has been utilized in the simulation of two cases where seawater intrusion was reduced. These include lowering of pumping rate and recharging of treated wastewater artificially via pumping continuously. The outputs of the model runs' revealed that an effective management strategy could be achieved in the Eastern region of Al Batinah coastal purposely to move against seawater intrusion via the alteration of pumping rate and artificial recharge [14].

Suggestion was made from the results obtained from simultaneous groundwater modeling (using MT3DMS and MODFLOW) and chemical results for aquifer wells located within Salalah plain that there may be significant contraction of the freshwater zone as the year progresses if increase in both domestic and irrigation abstractions continues. Decline in the freshwater outflow to the sea is often experienced as a result of the deficient annual rainfall which gives room for seawater intrusion into inland by additional 2 km. The insufficiency has been anticipated to rise in the years to come [18].

Furthermore, a GMS (Groundwater Modeling System) incorporated with MT3DMS and MODFLOW was utilized in the representation of solute transport and 3D groundwater flow in Salalah region of Oman. The intrusion of seawater in another 15 years was predicted to determine both the future and current groundwater quality states. The results were resourceful in the prediction of aquifer responses under different water management techniques [19]. In support of this, stoppage of saline water intrusion via the introduction of cleaned sewage effluents artificially to the Salalah plain aquifer, Oman was proposed and investigated. It was noticed that the implementation of sewage treatment after collection could put an end to seawater intrusion. The results proved treated wastewater artificial recharge as being effective in combating seawater intrusion and pushing back the saline front by 700 meters [20].

In Qatar, MODFLOW 2000 was adopted as a numerical model to examine the northern karst aquifer. In the model calibration results, the positions, number and pilot point's distribution were investigated and it was revealed that the pilot points performed excellently more than the arbitrarily placed points despite the same number of uniform placement and points [8]. In Saudi Arabia, visual MODFLOW was adopted in investigating groundwater depletion level of the Saq aquifer situated around Qasim area [11]. The model results obtained, stressed that the restoration and storage of previously wasted runoff in an already existing pond as a result of artificial recharge could be achieved. This was envisaged to be helpful to boost the life of the aquifer by 3%. A drop in the water head within the region far away by 65 meters in the next 30 years is possible if pumping continues and no preventive measure is taken [19]. Same in Saudi Arabia, modeling of groundwater of the Saq aquifer was executed with the aid of MODFLOW. A continuous increase in the demand for water has been experienced in

Buraydah area resulting in groundwater pumping and increase in drilled wells number to a distressing situation. This has led to water head depletion by 1.10 meters with a year. A depletion in water table by 33.5 m in the next 27 years was predicted if there is rise in the present pumping rate by 10% in 10 years period [21].

- **FEFLOW AND SUTRA NUMERICAL MODELING TECHNIQUES**

In Taiwan, saltwater encroachment in various multilayer aquifer system layers located in Pingtung Plain region was numerically modeled using FEFLOW. It was shown that all the aquifer layers were hindered by the intrusion. However, the bottom and top regions were more hindered than the middle section [13]. In UAE, brackish water pumping from the intrusion zone was perfectly modeled using FEFLOW purposely to control the intrusion of seawater into the Wadi Ham aquifer. In order to attain optimum pumping rates at different locations, various simulation cases were run. An increase in the salinity of groundwater was observed in non-pumping case as compared with the pumping case.Also, the prominent FEFLOW was used in the simulation of seawater intrusion in Wadi Ham aquifer under unsteady state conditions [6]. It was proved that 50% reduction in pumping rates will have significant impact and will also aid reduction of saltwater intrusion and improve groundwater quality. Conversely, the rate of salinity intrusion would be enhanced via increasing water abstraction rate causing further deterioration of groundwater quality [12].

In another study, an analytical solution called “Dupuit–Forchheimer” and a numerical model called “SUTRA” were both adopted in the examination of seawater intrusion located around Eastern Al-Batinah regions and their unconfined aquifers within Sultanate of Oman. It was noticed that mitigation of seawater intrusion could be achieved via pumping of saltwater from the intruded section of the aquifer. Equally, saltwater and fresh water flow within unconfined aquifers was successfully simulated with the aid of a numerical scheme and a software called “OpenGeoSys” [22]. Model validation was done in contrary to a laboratory experiment conducted on saltwater intrusion. In order to simulate saltwater intrusion in a coastal aquifer, additional calibration was executed for a heterogeneous and multi-layered regional-scale model. In UAE, in the lower alluvial plain around Wadi Ham region located within Fujairah Emirate, a finite element-based flow and solute transport model called SUTRA was employed in modeling seawater intrusion. In this study, artificial recharge was utilized in the management of seawater infiltration into coastal aquifer systems in order to curb additional groundwater quality deterioration [18]. In South Korea, climate change effect was studied using SUTRA model while the intrusion of salinity within the coastal groundwater system was investigated simultaneously using SLR. It was shown and concluded that it is imperative to take both the Sea Level Rise (SLR) and freshwater recharge rates into account to achieve perfect evaluation of the impacts of climate change on the intrusion of seawater in groundwater systems of coastal regions [4].

- **SEWAT-2000 NUMERICAL MODELING TECHNIQUE**

In India, a 3D multi-species transport and unsteady density subsurface water flow was simulated in a coastal aquifer in Karnataka using SEWAT-2000 which is a paired MT3DMS 5.2 and MODFLOW-2000 model [23]. The result revealed an excellent correlation between the computed and observed values. The calibrated parameters were utilized for the model prediction and it was noticed that the degree ofseawater intrusion induced by the tides affected the concentrations and groundwater levels near the coastal aquifer. In Nile Delta, SEWAT program was also employed to get the comprehensive mechanism of saltwater intrusion into the aquifer scheme which was simulated using data collected from the aquifer’s

hydrochemistry and heterogeneity [24]. The result proved SEWAT program to be a robust and effective tool for examining transport processes and variable-density flow. However, future studies should investigate large-scalenumerical dispersion.In Wadi Ham, this same technique was adopted in modeling groundwater flow and analyzing seawater intrusion cases and proposed prospective mitigation methods [16]. The result proved significant but further improvement regarding groundwater development and implementation of aquifer management measures were recommended.

4. CONCLUSION

The global rise in the world population has necessitated the essentiality of water which also has linkage with power and agriculture. However, arid or semi-arid regions occupy almost one-third of the global land surface which makes many regions to be under harsh and rising water stress.As a result of extreme freshwater pumping, the tide and deficient aquifer replenishment, large volumes of sea water inland are being observed in numerous coastal regions. In this case, intrusion of seawater into some sections of the aquifer is experienced due to this phenomenon. A numerical model is a highly significant tool for the simulation and prediction of groundwater head and its quality in coastal aquifers. To achieve this, its adequate calibration is needed using the existing measurements of heads, pumping rates, and boundary conditions. Finally, predictions of the groundwater elevations and quality can be made for any anticipated situation occurring in the future. This article has presented the fundamental principles and mechanisms of seawater intrusion into coastal aquifer. Different applicable mathematical models for seawater intrusion into coastal aquifer stated in this review are visual MODFLOW, MT3DMS routines, SEAWAT-2000 routines and FEFLOW routines. The applications of these models in the numerical modeling of coastal aquifers in some countries are stated and with their respective influence on the objectives of the study and the results obtained. In conclusion, the use of numerical modeling in the studying the nature of seawater intrusion is imperative to achieve sustainable coastal aquifer management.

REFERENCES

1. ELHamidi, M.J.; Larabi, A.; Faouzi, M. Numerical Modeling of Saltwater Intrusion in the Rmel-Oulad Ogbane Coastal Aquifer (Larache, Morocco) in the Climate Change and Sea-Level Rise Context (2040). Water 2021, 13, 2167.

2. Praveena, S.M.; Aris, A.Z. Groundwater resources assessment using numerical model: A case study in low-lying coastal area. Int. J. Environ. Sci. Technol. 2020, 7, 135–146.

3. McDonald, M.G.; Harbaugh, A.W. A Modular Three-Dimensional Finite Difference Groundwater Flow Model Technique of Water Resources Investigations of United States Geological Survey; U.S. Geological Survey: Denver, CO, USA, 1988; Volume 6, p. 586.

4. Shammas, M.I.; Thunvik, R. Predictive simulation of flow and solute transport for managing the Salalah coastal aquifer, Oman. Water Resour. Manag. 2019, 23, 2941–2963.

5. Al-Hashmi, S.; Gunawardhana, L.; Sana, A.L.; Baawain, M. Application of groundwater flow model in assessing aquifer layers interaction in arid catchment area. Int. J. Environ. Sci. Technol. 2024, 17, 4577–4588.

6. Al-Maktoumi, A.; Zekri, S.; El-Rawy, M.; Abdalla, O.; Al-Wardy MAl-Rawas, G.; Charabi, Y. Assessment of the impact of climate change on coastal aquifers in Oman. Arab. J. Geosci. 2023, 11, 501.

7. Akhtar, J.; Sana, A.; Tauseef, S.M.; Tanaka, H. numerical modeling of seawater intrusion in Wadi Al-Jizi coastal aquifer in the Sultanate of Oman. Hydrology 2022, 9, 211.

8. Dibaj, M.; Javadi, A.A.; Akrami, M.; Ke, K.-Y.; Farmani, R.; Tan, Y.-C.; Chen, A.S. Modelling seawater intrusion in the Pingtungcoastal aquifer in Taiwan, under the influence of sea-level rise and changing abstraction regime. Appl. Hydrogeol. 2024, 28, 2085–2103.

9. Sowe, M.A.; Sadhasivam, S.; Mohamed, M.M.; Mohsen, S. Modeling the mitigation of seawater intrusion by pumping of brackish water from the coastal aquifer ofWadi Ham, UAE. Sustain. Water Resour. Manag. 2022, 5, 1435–1451.

10. Nofal, E.; Amer, M.; El-Didy, S.; Fekry, A.M. Delineation and modeling of seawater intrusion into the Nile Delta Aquifer: A new perspective. National Water Research Centre. Water Sci. 2019, 29, 156–166.

11. Chun, J.A.; Lim, C.; Kim, D.; Kim, J.S. Assessing Impacts of Climate Change and Sea-Level Rise on Seawater Intrusion in a Coastal Aquifer. Water 2022, 10, 357.

12. Baalousha, H.M.; Fahs, M.; Ramasomanana, F.; Younes, A. Effect of Pilot-Points Location on Model Calibration: Application to the Northern Karst Aquifer of Qatar. Water 2024, 11, 679.

13. Akhtar, J.; Sana, A.; Tauseef, S.M. Using MODFLOW to Investigate the Effect of Persistent Water Deficit in Al-Jizi Coastal Aquifer, Sultanate of Oman. Arab. J. Geosci. 2024, 15, 1448.

14. Mondal, N.C.; Singh, V.S. Mass transport modeling of an industrial belt using visual MODFLOW and MODPATH: A case study. J. Geogr. Reg. Plan. 2009, 2, 001–019.

15. Ranjbar, A.; Cherubini, C.; Saber, A. Investigation of transient sea level rise impacts on water quality of unconfined shallow coastal aquifers. Int. J. Environ. Sci. Technol. 2020, 17, 2607–2622.

16. Yang, Y.; Song, J.; Simmons, C.T.; Ataie-Ashtiani, B.;Wu, J.;Wang, J.;Wu, J. A conjunctive management framework for the optimal design of pumping and injection strategies to mitigate seawater intrusion. J. Environ. Manag. 2023, 282, 111964.

17. Chang, Q.; Zheng, T.; Zheng, X.; Zhang, B.; Sun, Q.; Walther, M. Effect of subsurface dams on saltwater intrusion and fresh groundwater discharge. J. Hydrol. 2024, 576, 508–519.

18. Shen, Y.; Xin, P.; Yu, X. Combined effect of cutoff wall and tides on groundwater flow and salinity distribution in coastal unconfined aquifers. J. Hydrol. 2022, 581, 124444.

19. Abdoulhalik, A.; Ahmed, A.A. The effectiveness of cutoff walls to control saltwater intrusion in multi-layered coastal aquifers: Experimental and numerical study. J. Environ. Manag. 2017, 199, 62–73.

20. El Hamidi, M.J.; Faouzi, M.; Larabi, A.; El Gaatib, R. Spatial and temporal modelling of the vulnerability to pollution of groundwater of Rmel-Oulad Ogbane (NW-Morocco). Tech. Sci. Methodes 2018, 113.

21. Eissa, M.A.; Mahmoud, H.H.; Shouakar, S.O.; El-Shiekh, A.; Parker, B. Geophysical and geochemical studies to delineate seawater intrusion in Bagoush area, Northwestern coast, Egypt. J Afr Earth Sci 2016, 121:365–381.

22. Lin, J.; Snodsmith, J.B.; Zheng, C.M.; Wu, J.F. A modeling study of seawater intrusion in Alabama Gulf Coast, USA. Environ Geol 2019, 57:119–130.

23. Hussain, M.S.; Elhamid, H.F.A.; Javadi, A.A.; Sherif, M.M. Management of Seawater Intrusion in Coastal Aquifers: A Review. Water 2019, 11, 2467.

24. Sherif, M.; Al-Mulla, M.; Shetty, A. Seawater Intrusion Assessment and Mitigation in the Coastal Aquifer of Wadi Ham. In Groundwater in the Coastal Zones of Asia-Pacific, Coastal Research Library 7; Springer: New York, NY, USA, 2018.