

Studying the vulnerability factors of coastal aquifers due to sea saline water intrusion

Abstract

The coastal aquifers and controlling of vulnerability caused by saline water intrusion into these aquifers are considered as important issues from an environmental point of view in addition to their importance in water resource planning and management. This research is performed by a descriptive-analytic method and focuses on the evaluation of aquifer vulnerability through respective indicators to determine the groundwater withdrawal policies in coastal areas. According to the results, the most important factors affecting the intrusion of sea water are divided into three classes. Firstly, the level of freshwater in the aquifer above the sea level and the horizontal distance of the aquifer to the coastline have the most significance. Secondly, the hydraulic control of the porous medium and the thickness of the aquifer are effective in the amount of saline water intrusion. Third, the type of aquifer affects its vulnerability extent. Therefore, coastal aquifers withdrawal requires the evaluation of aquifer vulnerability, by which in different aquifer status, aquifer improvement approaches could be applied.

Keywords: vulnerability, intrusion, GALDIT index, aquifer management

Introduction

In most coastal areas, groundwater is considered as one of the most important resource of usable water supply for agriculture, drinking and industry. In these areas, the fresh water resources are exposed to salt and saline water, which has caused some concerns in these areas.¹ The interference and intrusion of saline water in coastal aquifers occurs due to groundwater level drop and the lateral or vertical transitions of salt and saline water which lead to degradation of groundwater quality.² The management of fresh water resources in the coastal aquifers requires identifying groundwater geochemical evolution as well as the dynamics of the flow system.³ The salinity of groundwater resources in coastal areas can be controlled by complex geochemical processes such as inter-aquifer interference, saline water flow, water-soil interactions, and human made pollutants.⁴ The amount of saline water and fresh water interaction depends on a variety of factors such as topography, substrate hydraulic characteristics, rainfall time variations, local patterns of groundwater flow, waves variations in coastal and estuarine, low intrusion and sharp drop in surface groundwater levels.⁵

The significant difference in the chemical composition between saline groundwater caused by saline water intrusion and replacement can be considered as an important factor in determining the source and mechanism of salinization and damage to the groundwater in coastal aquifers.⁴ The concept of vulnerability has first been introduced in 1960 to raise awareness about the groundwater contamination.⁶ Various methods such as WESPA, EPIK, AVI, GODS, PI, SI, SINTACS, DRASTIC, GALDIT, PESTICAIDE and IRISH MAIA have been presented to investigate vulnerability, each of which can be examined with its own parameters.⁷ The first research on saline water and fresh water on the coasts was separately initiated by Ghyben⁸ and Herzberg⁹ in Europe which has resulted in the Ghyben-Herzberg relation as the first equation for the interaction of saline water and fresh water. This relation is taken as the basis for studies by other researchers to study the front status of saline and fresh water as well as damages to aquifers. The term vulnerability refers to the potential of degradation degree with a given risk.¹⁰ For groundwater issues, Lobo-

Ferreira & Cabral¹¹ have defined vulnerability as the susceptibility of the groundwater quality to the aquifer contamination in terms of the inherent characteristics of aquifers. As a result, the aquifer vulnerability through the interference of saline water with the coastal aquifer has become a subject matter for researchers in various fields.

The vulnerability evaluation of saline water interference in coastal aquifers has been first performed by Chachadi & Lobo-Ferreira¹² on the Montenegro Coast of Portugal, and it has been called the GALDIT model. In this respect, Najib et al.¹⁰ has studied the vulnerable areas in the coastal regions of Morocco by using GALDIT model where their results represent high risk of interference on the margins of coastal areas and regions close to the boundaries of the Er-Rbia River which also penetrate into three kilometers depth inside the coast. In addition, this method has been applied successfully over the Montenegro Coast of Portugal.¹³ Bardis aquifer coasts.¹⁴ Gibbison & Randall¹⁵ first have studied the spatial and temporal variation of ions in the southeastern Georgia by using co-level maps. Then, they have proved the saline water intrusion into coastal aquifer by hybrid diagrams. Similarly, Mona et al.¹⁶ has evaluated the vulnerability of coastal aquifer in Tunisia by GALDIT index.

According to the research results in the field of chemical processes, this factor can be considered as an important indicator in determining the source and mechanism of groundwater salinization in the coastal aquifers through the significant difference in the chemical composition between the salinized groundwater caused by saline water intrusion and saline water replacement.⁴ One of the suitable hydro-geochemical indexes that can be used to investigate the saline water intrusion into coastal aquifers is the chloride to bromide ions ratio. The weight ratio of these two ions in sea water is about 300 and their molecular weight is about 655.¹⁷ In the study of groundwater around the sea coasts, if this ratio is about the given amount, it indicates the saline water intrusion into coastal aquifer. In this type of research, the reason why these ratios be used is that halogens are relatively stable and unchanged and the halogen ratios are within the common tracer group. In this regard, we can mention the researches performed by Mandilaras et al.,¹⁸ Katz et al.¹⁹ and Warner et al.²⁰ Regarding the importance of the coastal

areas, the role of aquifer in supplying drinking water and developing these areas, the evolution of aquifer salinization process and the effective factors on the intrusion of saline water into coastal aquifer and how to determine the extent of vulnerability for management practices have been studied in this research with the aim of identifying and measuring the vulnerability of coastal aquifers to protect them.

Materials and methods

This research has studied the aims by using interdisciplinary knowledge via a descriptive-analytical method so that the hydro-chemical facies evolution process has been analyzed during saline water intrusion and then the factors affecting the saline water intrusion in to the coastal aquifer have been studied. And to evaluate the vulnerability of the aquifer, the parameters of the GALIT index presented by Chachadi & Lobo-Ferira¹² have been investigated.

Groundwater hydro-chemical facies evolution during saline water intrusion

Hydro-chemical facies evolution diagram (HFE) that has been presented by Giménez-Forcada²¹ to classify water in the coastal regions only considers the percentage of original cations (Ca^{2+} and Na^+) and anions (HCO_3^- and SO_4^{2-}) which determine the dynamics of saline and salty water intrusion (1941). Revelle has defined

$\frac{\text{Cl}}{(\text{HCO}_3 + \text{CO}_3)}$ as a criterion to detect the saline water intrusion into coastal aquifer where chloride is the most abundant iodine in the sea while its amount in groundwater is very low. Facies are determined as a function of Ca^{2+} and HCO_3^- cations percentages and HCO_3^- , SO_4^{2-} and Cl^- anions percentages over total cations and anions. Once the cation or anion ratio is less than 0.5 and on the other hand it is higher than any other cation or anion, facies are called Mix. The triangular diagrams are the commonly used graphical method to represent the hydro-chemical facies where ions concentration is in terms of meq/l and is given as the total percent of cation and anion contents. To represent hydro-chemical facies in the central section, it is necessary that the right handed vertices of the triangular (Cl^- and SO_4^{2-}) and the left handed ones (Ca^{2+} and Mg^{2+}) are integrated. Therefore, the central range represents ($\text{Cl}^- \% + \text{SO}_4^{2-} \%$ $\text{HCO}_3 \%$ and ($\text{Ca}^{2+} \% + \text{Mg}^{2+} \%$) against ($\text{Na}^+ \% + \text{K}^+ \%$)

(Ghiglieri et al, 2012). As Figure 1 shown, the HFE diagram has solved some complexities and problems by using the major processes occurring during the intrusion of saline and fresh waters into coastal areas.²¹ In this diagram, the longitudinal axis is the difference in the percentages of Na^{2+} and Ca^{2+} in terms of meq/l which shows the base-exchange reactions (values are calculated in terms of total cations such as Mg^{2+}). The vertical axis represents anions where $\text{Na}-\text{HCO}_3$ percent shows the saline water, while the fresh water is introduced by bicarbonate percentage (or sulfate) (according to the dominant ion in the fresh water). In the saline water intrusion step, the aquifer is affected by two simultaneous processes which is called increasing salinity (path I) and leads to beginning of reverse exchange reactions (path II). The result of this process is generation of $\text{Ca}-\text{Cl}$ facies. Then, the groundwater tracks path (III) towards the saline water ($\text{Na}-\text{Cl}$). During the desalination process, freshwater supply results in direct exchange reactions (paths I' and II') and production of $\text{Na}-\text{HCO}_3$ facies. Finally, water moves along path (III') towards freshwater synthesis and aquifer restoration.²¹

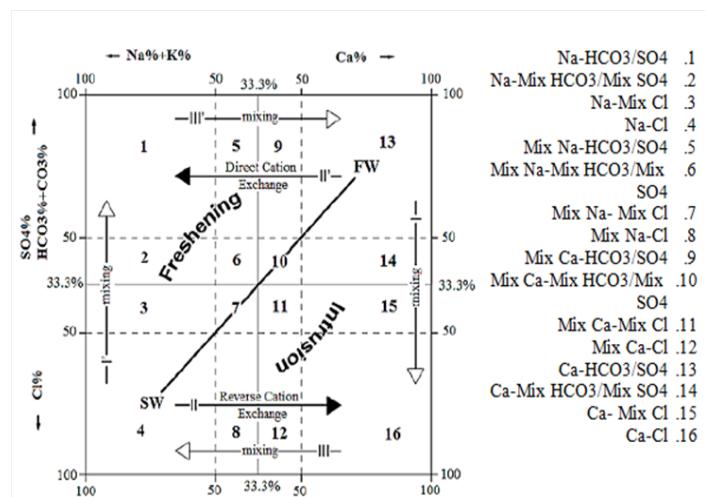


Figure 1 HFE diagram.

Studying the factors affecting the intrusion of saline water into the aquifer

Groundwater surface height above sea level

The groundwater surface level over the mean sea height is considered as one of the most important parameters in assessing the susceptibility to sea saline water intrusion. According to equations (1) and (2) and Figure 2, driven by Ghyben- Herzberg relation, the saline water surface arises about 40m per one meter withdrawal from the freshwater stored above the mean sea height. In this equation, s_p is the special mass of saline water, f_p is the special mass of fresh water, z is the height of the saline water column or the depth from the sea level on an intersection point and $h_f + z$ is the height of the fresh water column or the depth of groundwater level on an intersection point. The left side of this equation is the hydrostatic pressure of saline water at a point to the depth z under sea level and its right side shows the hydrostatic pressure of fresh water at the same point to the depth $z + h_f$ under groundwater fresh water level.

$$\rho_{\text{sea}} g z = \rho_{\text{fresh}} g (h_{\text{fresh}} + z) \quad (1)$$

$$Z = \frac{\rho_{\text{fresh}}}{\rho_{\text{sea}} - \rho_{\text{fresh}}} \cong 40 h_f \quad (2)$$

Horizontal distance of the aquifer from the seacoast

The greater the horizontal distance of aquifer to the coast, the lower the tension from seawater, and the aquifer vulnerability decreases. Also, that part of the aquifer areas closer to the coast is more vulnerable (Figure 3). According to this index, the aquifer vulnerability increases based on the horizontal distance to the coast from very small ranges for long distances and also for distances near to the vulnerability.

Hydraulic control

This parameter is estimated based on the flow velocity in the aquifer layers and represents the capability to transfer water within the aquifer which is the result of effective porosity in sediments and aquifer constituents. It is estimated through dividing the transfer coefficient (T) by aquifer thickness (T).²² Eq. (3) is true for the pressurized aquifer and eq. (4), (5) are true for free aquifer where K is the hydraulic control; B is the thickness of saturation area; q is the flow rate; ρ is the water density and W is the natural supply. In fact, there is

a direct relation between hydraulic control and aquifer vulnerability, so that the more the hydraulic conductivity is, the faster the saline water intrusion occurs and the aquifer will be more vulnerable.

$$L = \frac{K \cdot B^2}{2q\delta} \quad (3)$$

$$q = \left[\frac{KB^2}{2L} \right] \cdot \left[\frac{1+\delta}{\delta^2} \right] - \frac{WL}{2} \quad (4)$$

$$L = 0.0257 \left[\frac{KB^2}{2q} \right] \text{ if } W = 0 \quad (5)$$

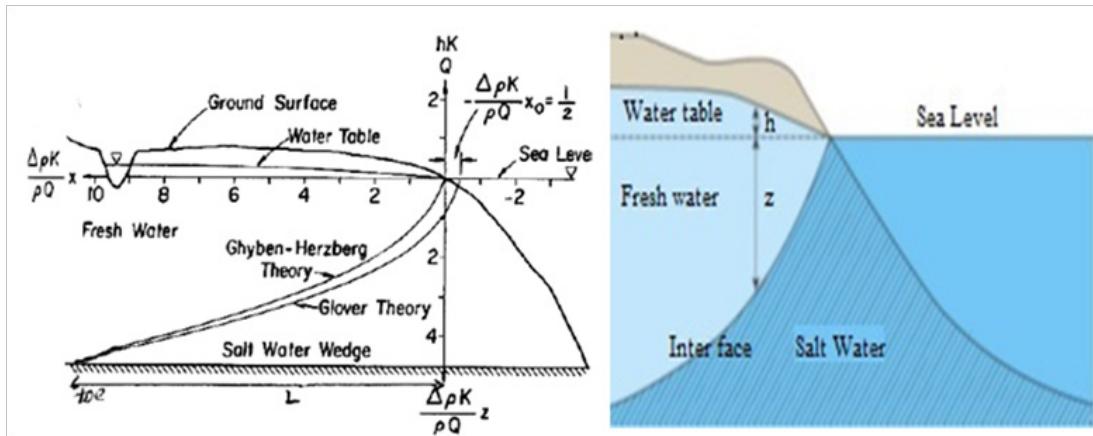


Figure 2 Saline water intrusion into coastal aquifer.

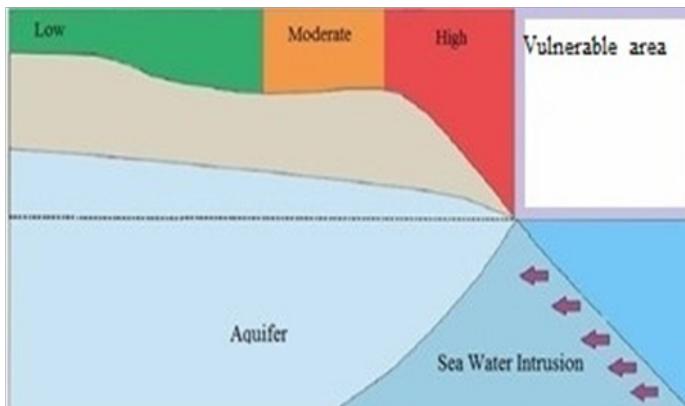


Figure 3 Vulnerability in different areas of the aquifer.

Aquifer thickness

The thickness or saturation area of the aquifer refers to the contour between the stationary surface and the impermeable layer which is used to estimate the intrusion of sea water into coastal areas as one of the model parameters. Based on this, the vulnerability index is divided into four high, medium, low and very low classes. Due to this factor, the greater the aquifer thickness, the less its vulnerability is.

Aquifer type

Table 1 Index calculation by each factor's weight and GALDIT ranking

Index	Weight	Rating importance range			Scores range		
		Min	Medium	Max	Min	Medium	Max
Aquifer type (free, enclosed, leakage)	1	2.5	5-7.5	10	2.5	5-7.5	10
Aquifer hydraulic control	3	2.5	5-7.5	10	7.5	15-22.5	30
The groundwater height higher than sea level	4	2.5	5-7.5	10	10	20-30	40
Horizontal distance of aquifer to coast	4	2.5	5-7.5	10	10	20-30	40
The qualitative effect of sea water intrusion on the coastal strip	1	2.5	5-7.5	10	5	5-7.5	10

Various types of aquifer include free, enclosed, leakage and bounded where the vulnerability in the free aquifer is more important and it has less importance for the bounded aquifer.

The influence of the penetrated saline water spread

If the studied area is fixed and non-stressed, a balanced hydraulic gradient would be in the aquifer between the saline water and the fresh water. However, due to the water withdrawal and intrusion of saline water into coast area, this balance has been disturbed and the concentration of the salt materials has been increased. Chachado & Loborieriera¹² have proposed Revelle²² relation presented in the first section to determine this parameter. According to this relation, the aquifer vulnerability index is classified into high, medium, low and very low classes.

Evaluating the coastal aquifer vulnerability by GALDIT index

GALDIT index values are calculated by dividing the total scores by total weight of used parameters in the model, as Table 1 and the vulnerability evaluation is performed by eq. (6). Therefore, the vulnerability of the coastal area to saline water intrusion and interference with the fresh water of the coastal aquifer is estimated based on the amount of GALDIT index. And according to Table 2, the vulnerability is classified into three high, medium and low classes.

$$GALDIT = \frac{\sum_{i=1}^6 W_i R_i}{\sum_{i=1}^6 W_i} \quad (6)$$

Table Continued....

Index	Weight	Rating importance range			Scores range		
		Min	Medium	Max	Min	Medium	Max
Aquifer thickness	2	2.5	5-7.5	10	5	10-15	20
Total scores					40	75-112.5	150
GALDIT index					2.5	5-7.5	10

Table 2 Determining the classes of vulnerability by using weight and GALDIT values

No.	GALDIT range	Vulnerability class
1	>7.5	High
2	5-7.5	Medium
3	<5	Low

Conclusion

The specific importance of the coastal areas and the role of its aquifers in supplying freshwater resources to the deployment and development of these areas make groundwater resources protection necessary. One of the most important threats to the coastal aquifers is the intrusion of saline water into the aquifer. According to the obtained results, the most important factor in moving the saline water towards the coastal aquifer is by disturbing the balance between the sea water and the aquifer through the withdrawal of the aquifer and decreasing the groundwater level which makes the withdrawal management necessary and the most important physical factor affecting the acceleration of saline water intrusion into the aquifer include the level of fresh water in the aquifer which is higher than sea level and the horizontal distance between the aquifer to the coastline. Increasing these two factors reduces the intrusion of the saline water into the aquifer. Secondly, the hydraulic control of the porous medium and its thickness are effective on the saline water intrusion so that reducing the hydraulic control and increasing the aquifer thickness reduces the sea water intrusion into the aquifer. Third, the type of coastal aquifer is important in saline water intrusion. The intrusion into height-constrained bounded aquifers is less than other aquifers. The intrusion depth of saline water can be determined in order to identify and specify the extent of damage to the aquifer by collecting water specimens at different intervals from the coast and determine the amount of chloride in the specimens. And the aquifer's vulnerability can be evaluated based on the amount of damage incurred by the studied indexes in this research. In addition, regarding the amount of vulnerability, the operational policies or necessary practices to supply the aquifer and also management and engineering approaches such as dike construction, coastal walls or tidal valves can be applied to prevent saline water intrusion and restrain fresh water at the last river outlet for the aims like coastal washing and restoration.

Acknowledgments

None.

Conflicts of interest

The author declares that there is no conflicts of interest.

References

1. Boluda-Botella N, Valdes-Abellan J, Pedraza R. Applying reactive models to column experiments to assess the hydrogeochemistry of seawater intrusion: Optimising ACUAINTRUSION and selecting cation exchange coefficients with PHREEQC. *Journal of Hydrology*. 2014;510:59–69.
2. Barlow PM, Reichard EG. Saltwater intrusion in coastal regions of North America. *Hydrogeology Journal*. 2010;18(1):247–260.
3. Matiatos I, Alexopoulos A, Godelitsas A. Multivariate statistical analysis of the hydrogeochemical and isotopic composition of the groundwater resources in northeastern Peloponnesus (Greece). *Science of the Total Environment*. 2014;476–477:577–590.
4. Han DM, Song XF, Currell MJ, et al. Chemical and isotopic constraints on evolution of groundwater salinization in the coastal plain aquifer of Laizhou Bay, China. *Journal of Hydrology*. 2014;508:12–27.
5. Mondal NC, Singh VS, Puranik SC, et al. Trace element concentration in groundwater of Pesarlanka Island, Krishna Delta, India. *Environmental Monitoring and Assessment*. 2010;163(1–4):215–227.
6. Vrba J, Zoporozec A. *Guidebook on Mapping Groundwater Vulnerability*. IAH International Contribution for Hydrogeology, Hannover7 Heise. 1994;16:131.
7. Antonakos AK, Lambrakis NJ. Development and testing of three hybrid methods for the assessment of aquifer vulnerability to nitrates, based on the drastic model, an example from NE Korinthia, Greece. *J Hydrol*. 2007;333(2–4):288–304.
8. Ghyben WB. *Nota in verband met de woorgenomen putboring nabij Amsterdam*. Tijdschrift van Let Koninklijk Inst. Van Ing. 1889.
9. Herzberg A. Die Wasserversorgung einiger Nordseeba der. *J Gasbeleucht Wasserversorg*. 1901;44:815–819.
10. Najib S, Grozavu A, Mehdik, et al. Application of the Method GALDIT for the Cartography of Groundwaters Vulnerability: Aquifer of Chaouia Coast (MOROCCO). *Geography series*. 2012; 58(2).
11. Lobo-Ferreira JP, Cabral M. Proposal for an Operational Definition of Vulnerability for the European Community's Atlas Groundwater Resource. In: *Meeting of the European Institute for Water, Groundwater Work Group, Brussels*. 1991.
12. Chachadi AG, Lobo-Ferreira JP. Sea water intrusion vulnerability mapping of aquifers issuing GALDIT method. In: *Proc. Workshop on Modeling in Hydrogeology, Anna University, Chennai*. 2001;143–156.
13. Lobo-Ferreira JP, Chachadi AG, Diamantino C, et al. Assessing aquifer vulnerability to seawater intrusion using GALDIT method: Part 1 – Application to the Portuguese Aquifer of monte Gordo. *The forth Inter-Celetic colloquium on the hydrology and management of water resources, Guimaraes, Portugal*. 2005;1–20.
14. Chachadi AG, Lobo-Ferreira JP, Noronha L, et al. Assessing the impact of sea-level rise on salt water intrusion in coastal aquifers using GALDIT model. *COASTIN newsletter*. 2002;7:27–32.
15. Gibbison A, Randall J. The salt water intrusion problem and water conservation practices in southeast Georgia, USA. *Water and Enviro J*. 2006;20(4):271–281.
16. Mona G, Nabila A, Ikram J, et al. Sensitivity analysis for the GALDIT method based on the assessment of vulnerability to pollution in the northern Sfax coastal aquifer, Tunisia. *Arabian Journal of Geosciences*. 2016;9(416):1–15.
17. Alcala FJ, Custodio E. USE of the Cl/Br ratio as a tracer to identify the origin of salinity in some coastal aquifers of Spain. *18 SWIM. Cartagena, Spain*. 2000;1–17.

18. Mandilaras D, Lambrakis N, Stamatidis G. The role of bromide and iodide ions in the salinization mapping of the aquifer of Glafkos River basin (northwest Achaia, Greece). *Hydrol Process*. 2008;22(5):611–622.
19. Katz BG, Eberts SM, Kauffman LJ. Using Cl/Br ratios and other indicators to assess potential impacts on groundwater quality from septic systems: A review and examples from principal aquifers in the United States. *Journal of Hydrology*. 2001;397(3–4):151–166.
20. Warner NR, Jackson RB, Darrah TH, et al. Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. *Proceedings of the National Academy of Sciences of the United States of America*. 2012;109(30):11961–11966.
21. Giménez-Forcada E. Dynamic of seawater interface using hydrochemical facies evolution diagram. *Ground Water*. 2010;48(2):212–216.
22. Revelle R. Criteria for recognition of sea water in ground-waters. *Trans of American Geophys Union*. 1941;22:593–597.