Evaluation vulnerability of coastal aquifer via GALDIT model and comparison with DRASTIC index using quality parameters

Hamid Kardan Moghaddam\textsuperscript{a}, Fatemeh Jafari\textsuperscript{b} & Saman Javadi\textsuperscript{a}

\textsuperscript{a} Department of Water Engineering, College of Aburaihan, University of Tehran

\textsuperscript{b} Water Research Institute, Ministry of Energy, Tehran, Iran

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Evaluation Vulnerability of Coastal aquifer via GALDIT model and comparison with DRASTIC Index using Quality parameters

Hamid Kardan Moghaddam¹, Fatemeh Jafari², Saman Javadi³*

¹- Ph.D. student, Department of water engineering, College of Aburaihan, University of Tehran
²- M. Sc Graduated in Hydrogeology, Water Research Institute, Ministry of Energy, Tehran, Iran
³- Assistant Prof., Department of water engineering, College of Aburaihan, University of Tehran
(* Corresponding Author). Email: Javadis@ut.ac.ir

Abstract: In recent years, environmental assessments of groundwater resources have resulted in development of models that help identify the vulnerable zones. The aquifer is investigated by both GALDIT and DRASTIC indices. The GALDIT model is developed to determine the vulnerability of coastal aquifers in terms of saltwater intrusion; whereas, the DRASTIC model is generally applicable to all aquifers. Having compared the results of both GALDIT and DRASTIC models by quality parameters, salinity models prove to be more appropriate in identifying the vulnerability of coastal aquifers. The results show Pearson’s correlation coefficients between TDS and GALDIT vulnerability map is obtained 58% while the corresponding values for DRASTIC index are 48%.

Key words: Coastal Aquifer; DRASTIC; GALDIT; vulnerability; Quality parameters

1. INTRODUCTION

The development of societies, followed by industrial and agricultural activities has resulted in environmental pollution and water resources contamination (Rahamm 2008). Groundwater resources are specifically important in arid regions where surface water is scarce. In some regions, groundwater is the only drinking water resource, so protecting them from contamination is critical. Identification of contaminated groundwater zones is a practical solution to establish appropriate groundwater extraction practices. Evaluation of aquifers by vulnerability indices is one of the key elements in decision making and it is considered a multi-criteria decision making tool in river basins and wastewater management systems (Kholghi 2001). Unconfined aquifers have a high potential to be polluted from near surface activates; therefore, precise scientific methods are required to obtain reliable results in vulnerability investigation. Vulnerability is a relative, non-dimensional and immeasurable factor that depends on aquifer characteristics, as well as geology and hydrogeological conditions of the aquifer (Antonakos and Lambrakis 2007). In other words, vulnerability defines the ease of surface pollution penetration into groundwater. A greater value of vulnerability indicates a higher potential to receive and transfer surface pollution into aquifer.
Coastal aquifers however, in addition to surface pollution, are vulnerable to saltwater intrusion from seawater. Moreover, groundwater extraction increases saltwater intrusion by disturbing the balance of saltwater-freshwater interface (Karanth 1987). According to Ghyben–Herzberg relation, if the water table in an unconfined coastal aquifer is lowered by 1 meter, the salt-water interface rises by 40 meters. Thus, the groundwater level head of freshwater close to the sea becomes lower, due to extraction of groundwater, and the transition zone rises to attain a new equilibrium, governed by the quantity of groundwater extracted (Bear and Verruijt 1987). Hence, extraction of freshwater from a zone above an underlying saltwater body must be accomplished by creating very small drawdown, if saltwater is to be prevented from upcoming into the freshwater wells (McWhorter and Sunada 1977).

There are different methods for identifying groundwater vulnerability such as: DRASTIC, SINTACS, SI, PI, GODS, AVI, EPIK, WESPA, IRISH, MAIA, PESTICIDE, GALDIT each developed for specific conditions and based on different data sets. DRASTIC is one of the most popular models and was developed by the American Environmental Protection Agency (Aller et al 1987). DRASTIC index has been used in several places including the USA (Plymale and Angle 2002), China (Yuan et al 2006), Jordan (El Naqa et al 2006), Morocco (Ettazarini 2006) and Iran (Javadi et al 2011). DRASTIC index, composed of seven independent influencing hydrogeological parameters, was used to assess the vulnerability of aquifers by intrinsic characteristics. The application of DRASTIC model, although common for identifying the vulnerability of aquifers, associates with limitations. Therefore, many researchers have used different techniques such as sensitivity analysis, AHP and correlation with quality parameters. For instance, Calibrated the weigh factors of DRASTIC model was investigated by applying the AHP method to Nitrate concentrations (Hailin et al 2011). In similar research, the application of AHP method was applied to improve the DRASTIC model, result showed that contaminated zones have the highest pollution potential because of water and geological conditions (Tirkey et al 2013). In another study, for identifying the risk of pollution and vulnerable zones of KufrinJa aquifer in Jordan was investigated by applying the DRASTIC index (Rakad et al 2013). The DRASTIC index is most appropriate for non-coastal aquifers, so other indices such as GALDIT are more suitable for coastal aquifers. GALDIT based investigations have been performed in several coastal strips belts like in Greece (Kallioras et al. 2011). Vulnerability to seawater intrusion was also quantified for various stress situations, including sea-level rise (Werner and Simmons 2009; Marfai and King 2008), change in recharge due to climate change and change in seaward discharge (Lobo-Ferreira et al. 2005; Werner et al. 2012). While the DRASTIC method has been widely used for local scale assessments, GALDIT method with six hydrogeological parameters has been mostly used to perform large-scale assessments of seawater intrusion. In a study, the GALDIT model was applied to identify vulnerable zones along Morroco’s coastlines (Najib et al 2012). The results show high vulnerability along the coastline as well as areas close to bank of Er-Rbia River. In another study, the GALDIT index was employed to identify the inherent vulnerability of coastal particles to saltwater intrusion (Recinos and et al 2014). In similar study, the DRASTIC and GALDIT indices were applied to determine the groundwater vulnerability to contamination from anthropogenic activities and seawater intrusion (Kura and et al 2014). The result of mentioned study showed both models indicate that the areas are likely to be affected by anthropogenic pollution and seawater intrusion are within the alluvial deposit at the western part of the island. GALDIT and AVI were applied to study an aquifer in Tunisia by Saidi et al (2013). Their study showed that GALDIT can be reliable method for coastal aquifers and had close results with AVI.

The aim of this study is to investigate the impact of rising seawater levels as well as saltwater intrusion resulted by over drafting in a coastal aquifer in north of Iran. In this
research, the GALDIT model was developed to obtain a vulnerability zoning distribution map for coastal aquifer. Finally, the output map of GALDIT model were compared with the DRASTIC index by some quality parameters.

2. MATERIALS AND METHODS

2.1 STUDY AREA

To evaluate the proposed methods and compare the results, Astaneh-Koochesfahan Aquifer was selected. It is a coastal aquifer and some evidences of saltwater intrusion have been observed in supply wells close to the shoreline. Astaneh-Koochesfahan region, with an area of 2835 km², is located in the sub basins of Sefidrood and Talesh-Talab Anzali in northern Iran, just south of Caspian Sea. The aquifer is located between 49° 32' and 50° 05' eastern longitude and 37° 07' and 37° 25' northern latitude (Figure 1). The highest altitude in the area is 2705 meters while the lowest is only 25 meters below sea level. The length of the coastal strip is 63 kilometers, receiving an average annual rainfall of 1300 millimeters.

The aquifer is mainly unconfined with the exception of small part in the west. The general slope of the ground surface in the area is from south to north ranging from 25 percent in south to 2 percent in north. Topographical heights are located in the southern and northwestern parts. The plain area with slope less than 1% starts from central parts to the sea. Geological formation is known from Precambrian till quaternary and they consist of varies types of rocks and deposits. They are more likely to be originated from limestone, shale, sandstone, conglomerate, igneous volcanic rocks and coastal sediments.

Fig. 1 Location of aquifer and piezometric wells in the Astaneh-Koochesfahan region

2.2 GALDIT MODEL

The contamination of groundwater resources, as a result of sea water intrusion, has tremendously increased during the past two decades. Groundwater levels have decreased due to over-drafting which itself, has led to serious water quality degradation for seawater intrusion. Therefore, it is specifically important to monitor the saltwater/freshwater interface level and control groundwater extraction in coastal aquifers. The overall impacts of seawater rise on aquifers are observed as the erosion of the coastal strip, saltwater intrusion, increased flooding and higher temperatures. The GALDIT model was first evaluated by Chachadi and Lobo-Ferreira in 2001 for the coastal regions of India and Portugal. This model was applied to coastal regions, most significantly the Mediterranean Sea, as a tool for vulnerability assessment. High concentrations of TDS in saline water cause non-organic variations in coastal aquifers that consequently disrupt with the everyday life of local residents. The intrusion of saltwater decreases freshwater storage volumes and increases TDS and ion concentrations. Thus, it is more difficult overtime to meet drinking water quality standards in the region. The six components of GALDIT model are defined:

- **G**: Groundwater occurrence (aquifer type: unconfined, confined and leaky confined)
- **A**: Aquifer hydraulic conductivity
- **L**: Depth of groundwater level
- **D**: Distance from the coastline (distance inland perpendicular from shoreline)
- **I**: Impact of existing status of seawater intrusion in the area
- **T**: Thickness of the aquifer

Aquifer Type: In nature, groundwater generally occurs in the geological layers which may be confined, unconfined, and leaky confined or limited by one or more boundaries. The
extent of seawater intrusion is dependent on this basic nature of groundwater occurrence. In unconfined aquifers, the natural condition of the bottom layer has a significant influence on the mixing interface of saltwater and freshwater. Confined aquifers are however, more sensitive because of higher depression levels of water table during well water pumping.

Hydraulic conductivity: Hydraulic conductivity is the ability of the aquifer to transmit water. Groundwater recharge can occur in several ways, including infiltration of rainfall, river recharge, flooding, inter-aquifer leakage, return irrigation flows, leaky drains and artificial recharge. Hydraulic conductivity has an important role in aquifer recharge. High values of conductivity associate with wider depression cones during well pumping, resulting in more significant saltwater intrusion and thus higher vulnerability to contamination. The extent of seawater penetration into the aquifer is highly dependent on the aquifer’s hydraulic properties.

Depth of groundwater level: Groundwater level is one of the most important parameters in evaluating the aquifer’s vulnerability to contamination. The deeper groundwater table in an aquifer, the more vulnerable it is to become saline. The famous Ghyben-Herzberg (1901) relation shows that, for every one meter rise of fresh water above mean sea level, a freshwater column of 40 meter is created below it down to the interface.

Distance from the shore: The impact of tidal movements becomes less with distance. The farther away from the shore, the less vulnerable the aquifer becomes to saline contamination. Equation (2) shows the relation between saline water zone spread (L) and freshwater flow towards the sea (q), as illustrated in Figure 2. There is a major difference between freshwater flow towards the sea and the natural recharge of aquifer, based on which BEAR and VERRUJIT relations were developed in 1987. In a confined aquifer:

$$L = \frac{K B^2}{2q \delta} \quad L > B$$  \hspace{1cm} (1)

$$\delta = \frac{\rho_{\text{fresh}}}{\rho_{\text{sea}} - \rho_{\text{fresh}}} = 40$$  \hspace{1cm} (2)

In a confined aquifer:

$$q = \left[ \frac{K B^2}{2L} \right] \left[ 1 + \frac{\delta}{\delta^2} \right] - \frac{W L}{2}$$  \hspace{1cm} (3)

If W=0 then:

$$L = 0.0257 \left[ \frac{K B^2}{2q} \right]$$  \hspace{1cm} (4)

Where \( K \): Hydraulic conductivity (m/day), \( B \): Thickness of the aquifer (m), \( \rho \): Density of water (kg/m³), \( W \): Recharge (mm)

**Fig. 2** Length of seawater g intrusion in the coastal aquifer

Impact of existing status of seawater intrusion in the area: If surface conditions were stable and stress less, saltwater and freshwater gradients would have established a balanced hydraulic gradient. Groundwater extraction however, has led to saltwater movement towards the coast and thus, increased TDS concentrations. Revelle (1941) recommended the ratio of Cl / [HCO₃+ CO₃] as a criterion to identify the extent of seawater intrusion into coastal
aquifers (equation 5). Chloride (Cl) is the dominant ion in the seawater and it is only available in small quantities in groundwater while bicarbonate (HCO3), which is available in large quantities in groundwater, occurs only in very small quantities in seawater.

\[
I = \frac{Cl^-}{[CO_3^{2-} + HCO_3^-]} \tag{5}
\]

Thickness: Aquifer thickness or saturated thickness of an unconfined aquifer plays an important role in determining the extent and magnitude of seawater intrusion in coastal areas. This parameter, also a parameter of the GALDIT model, is used to estimate the amount of seawater penetration into coastal aquifers. Increased thickness of the saturated zone results in lower saltwater levels and thus, decreased vulnerability.

Table (1) shows the parameters of GALDIT model along with their weighs and ranks (Chachadi and Lobo-Ferreira, 2001). As shown, groundwater table and closeness to the shoreline are most significant factors in determining the vulnerability of the aquifer to salinity. Therefore, it is important to estimate these two parameters with greater precision. Figure (3) shows the maps of GALDIT components introduced in Table (1).

| Table 1 GALDIT model parameters and weighs (Chachadi and Lobo-Ferreira, 2001) |

2.3 DRASTIC MODEL

DRASTIC index was developed by the American Environmental Protection Agency (Aller et al, 1987) for identifying groundwater vulnerability across the country. This model was based on the concept of a hydrogeological media. The hydrogeological media describes a complex situation of all geological and hydrological factors that influence the flow of groundwater at inflow, outflow and internal points of the aquifer. This model is composed of seven parameters: depth to groundwater table, gross recharge, aquifer material, soil type, topography, unsaturated zone and hydraulic conductivity. These parameters are used to determine the vulnerability of the aquifer. Table (2) shows the parameters of DRASTIC along with their weight and rank factors. The distribution map of each parameter which was developed by GIS is presented in Figure (4).

| Table 2 Original ratings and weights of the seven DRASTIC factors (Aller et al, 1987) |

2.4 DEVELOPING GALDIT INDEX

After determining the six weight values, the following relation was applied to estimate the value of GALDIT index.
Based on equation (6) GALDIT index values, ranging from 2.5 to 10 are classified as in Table 3.

\[ GALDIT = \frac{\sum_{i=1}^{6} W_i R_i}{\sum_{i=1}^{6} W_i} \]  

(6)

Where \( R = \) rating and \( W = \) weight

**Table 3** Vulnerability classification of GALDIT index

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### 2.5 IDENTIFYING THE DRASTIC INDEX

The DRASTIC value is obtained by Relation (7) for the parameters of Table (2). The vulnerability index is then determined based on the classifications of Table 4.

\[ DRASTIC = \frac{\sum_{i=1}^{7} W_i R_i}{\sum_{i=1}^{7} W_i} \]  

(7)

Where: \( R = \) rating and \( W = \) weight

**Table 4** Vulnerability classification of DRASTIC index

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### 2.6 SENSITIVITY ANALYSIS

Sensitivity analysis was carried out to evaluate reliability parameters of DRASTIC and GALDIT models. Several studies have been conducted to evaluate the importance of the parameters in vulnerability methods and tried to reduce the number of parameters (Rahman, 2008).

In this study, single-parameter sensitivity analysis developed by Babiker et al (2005) was used. This method has been made to evaluate the impact of each parameter in the vulnerability method and applied for DRASTIC method (Babiker et al, 2005; Javadi et al, 2011). To estimate the effective weight of each parameter, equation (8) was used:

\[ W = \left( \frac{P_r P_w}{V} \right) * 100 \]  

(8)

Where \( W = \) the effective weight of each parameter, \( P_r \) and \( P_w \) are the rating value and weight of each parameter, and \( V = \) the overall vulnerability index (babiker et al. 2005).

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### 3. RESULTS

#### 3.1 GALDIT MAP

GALDIT index can predict the aquifer's vulnerability to seawater intrusion by combining hydrogeological and morphological data. The data describes the state of the
aquifer under investigation and categorizes the data into different parameters which are rated and weighted accordingly. The data is, finally combined in the GALDIT equation. In this study, the final map of GALDIT index was developed and categorized after estimating the parameters based on table 3 as shown in Figure (5). Based on the estimated parameter values, hydraulic conductivity is the most significant factor in the overall vulnerability of the aquifer. The aquifer is confined at the western and southern zones, at which vulnerability is higher due to the fact that confined aquifers are generally more sensitive to groundwater contamination. Moreover, the aquifer is highly vulnerable to contamination because of saltwater intrusion resulted from over-drafting and its short distance to the coastline.

Fig. 5 Groundwater vulnerability of the Coastal aquifer using GALDIT method

3.2 DRASTIC MAP
The attribute layers of the seven DRASTIC parameters were assembled within a GIS format, the commercially available ArcGIS 10.2 Software being used to execute the necessary computations in raster format. After creating all the necessary layers, each pixel was classified and rated, then, multiplied by its weighting factor and the DRASTIC index calculated value. Finally, vulnerability maps were categorized based on table 4 as shown in Figure (6).

Fig. 6 Groundwater vulnerability of the Coastal aquifer using DRASTIC method

3.3 ASSESSMENT OF VULNERABILITY INDICES BY QUALITY PARAMETERS
Coastal aquifers are subject to higher levels of vulnerability, thus it is necessary to assess the obtained values of vulnerability indices in terms of quality parameters. Therefore, 18 samples of Quality parameters measured in August 2013 were used to calculate correlation factor (Figure 7). However, the estimated vulnerability level of both methods were compared in terms of TDS, Na, NO3 and Cl using statistical and regression analysis. Salinity is a parameter related to the dissolved chemical components. In this research, one cation and one anion including sodium and chloride were selected to represent salinity. In addition, TDS was selected to present the total salinity. Nitrate is a parameter which usually reaches groundwater from the surface. Therefore, this parameter in agricultural lands can be an indicative of how easy contamination can reach groundwater which is the main concept behind vulnerability assessment.

Based on the results shown in Table 5, both indices have the same relations for quality parameters, such that both are least correlated to Nitrates and Na. Besides, both methods are closely related to TDS values, with a higher correlation for GALDIT.

Fig. 7 Quality sampling locations and distribution of TDS concentrations in the study area

Table 5 Correlation between quality parameters and GALDIT and DRASTIC indices
3.4 SENSITIVITY ANALYSIS

Effective weights for both GALDIT and DRASTIC models were estimated using the proposed method by Babiker et al (2005). The new vulnerability index for DRASTIC in Figure (8) and for GALDIT in Figure (9) are shown. Based on these new maps, depth to groundwater has the most effective weight in both models with 74% in GALDIT and 40% in DRASTIC method. Topography and impact of seawater intrusion parameters showed the lowest effectiveness in DRASTIC and GALDIT methods, respectively.

Fig. 8 Sensitivity Analysis Results for DRASTIC Method

Fig. 9 Sensitivity Analysis Results for GALDIT Method

4. CONCLUSION

Seawater intrusion is a major environmental threat for groundwater resources, and since a large portion of global population is located within the coastal zone, this phenomenon has also social and economic dimensions. This case study indicates that over drafting of wells, resulting in sea water intrusion has caused a critical situation for coastal aquifers. Therefore, application of vulnerability models that do not include groundwater salinity factor is not effective in the study area. In this study, while introducing the new model of GALDIT for investigating the vulnerability of a coastal study, an effort has been made to compare this method with the popular DRASTIC model. The GALDIT model was developed by six input parameters. Validation was performed based on the high regression between the results obtained from the model and TDS, as a water quality parameter. The outputs of GALDIT model indicate a 58% regression between vulnerability index and TDS concentration. Results consequently reveal that more than 50 percent of the aquifer is vulnerable, to the greatest degree, to saltwater intrusion and only 30 percent of the aquifer falls within the safe zone. The outputs of the model also introduce hydraulic conductivity and distance to sea as the most significant parameters in GALDIT model. The evaluation of this index at the coastal strip can lead to action plans for groundwater extraction as well as prohibition plans for well drilling. The results obtained for Astaneh- Koochehsfahan Aquifer show the importance of management plans to prevent saltwater intrusion.

5. REFERENCE


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Table 2 Original ratings and weights of the seven DRASTIC factors (Aller et al, 1987)

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### Table 3: Vulnerability classification of GALDIT index

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### Table 4: Vulnerability classification of DRASTIC index

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### Table 5: Correlation between quality parameters and GALDIT and DRASTIC indices

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</tbody>
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Fig. 1 Location of aquifer and piezometric wells in the Astaneh-Koochesfahan region

Fig. 2 Length of seawater intrusion in the coastal aquifer
a. Groundwater occurrence (G)  
b. Aquifer hydraulic conductivity (A)  
c. Groundwater Level (L)  
d. Distance from the coastline (D)
e. Impact of seawater intrusion (I)

f. Thickness of the aquifer (T)

**Fig. 3** Six GALDIT maps to compute the vulnerability to seawater intrusion
a. Depth to groundwater parameter

b. Recharge parameter

c. A parameter

d. Soil type parameter
Fig. 4 Seven DRASTIC maps to compute the vulnerability index
Fig. 5 Groundwater vulnerability of the Coastal aquifer using GALDIT method
Fig. 6 Groundwater vulnerability of the Coastal aquifer using DRASTIC method
Fig. 7 Quality sampling locations and distribution of TDS concentrations in the study area
**Fig. 8** Sensitivity Analysis Results for DRASTIC Method

**Fig. 9** Sensitivity Analysis Results for GALDIT Method