Groundwater Vulnerability Risk Maps Using GIS and DRASTIC Index Method for Jeddah City, Western Saudi Arabia

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Abstract. Jeddah city, located in western Saudi Arabia along the Red Sea coast, is highly developed and has been showing rapid expansion in land use for the past 3 decades. The exponential expansion does not meet the city planning for the services such as water supply and sewage network systems. Soil and natural groundwater are subject to contamination on the basis of hydrogeological and anthropogenic factors. This study presents a new approach to produce soil and groundwater vulnerability and risk maps for Jeddah city using GIS and DRASTIC index. The seven factors of this model were collected, analyzed and manipulated using Kriging techniques. The final vulnerability risk maps of soil and groundwater were produced utilizing GIS system for the city. The results in the form of DRASTIC index map show potential for groundwater pollution at high to very high risk in the whole area, (e.g. high nitrate concentrations. Adding more anthropogenic and land-use factors to the model might help in the future planning and the development of Jeddah.

Keywords: Groundwater vulnerability. DRASTIC index. GIS, Jeddah. Saudi Arabia
Introduction

Vulnerability, from environmental point of view, is generally referred to the sensitivity or the potential for groundwater to be contaminated as a result of hydrogeological and anthropogenic (human) factors. Aller et al., (1987) developed a vulnerability assessment technique depending on the readily available information about the sites or aquifers. DRASTIC method is the most widely used technique for groundwater contamination mapping, which is an overlay technique coupled with geographic information systems (GIS) (Bartels and Beurden, 1998; Ducci, 1999; Awawdeh and Jaradat, 2009; and Baalousha, 2010). Each letter in “DRASTIC” refers to one of the seven factors utilized in the rating system. These are, (D) Depth to groundwater, (R) net Recharge, (A) lithology of the Aquifer, (S) Soil texture, (T) Topography, (I) Impact of vadose zone, and (C) hydraulic Conductivity of the aquifer.

With the help of vulnerability maps, especially in urban areas, planners and decision makers can appropriately suggest the location of new projects such as; sewage treatment plants, housing, commercial sites and recreation areas in appropriately low risk hazard zones. Jeddah is one of the most important cities, located in western Saudi Arabia. It is a site of attraction for human and economic development since the 20th century. Due to the rapid increase in urban areas as a result of the exponential growth of population, several private and public residences and commercial buildings, housings, industrial sites, as well as associated infrastructures are being built. The construction of utility services (water supply, sewage/rainstorm networks) and soil saturation due to extreme rainstorms has resulted in the rise of groundwater levels and flash floods. Therefore, the city became under serious environmental quality problems (Bayumi et al., 2000; Al-Sefry and Şen, 2006; Qari, 2009; Subyani et al., 2009).

The main purpose of this study is to develop the vulnerability maps of groundwater and soil contamination and areas subject to higher flood risk in the city of Jeddah through a modified DRASTIC method combined with GIS and Kriging techniques.

Geologic and Geographic Setting

Jeddah city, located between latitudes 21° 20’ and 21° 30’ N and Longitudes 39° 06’ and 39° 25’ E, covers an approximate area of about
450 km². Geologically, it is comprised of two distinctive units, namely Precambrian basement rocks, and Quaternary coastal plain (called Tihamah) (Fig. 1).

**Fig. 1: Geology and Location map of the study area.**

The Precambrian basement rocks lie in the eastern part of the city as mountains and pediments of medium altitude. They consist of volcanic and layered rocks intruded by plutonic rocks. The Tertiary sediments and lavas are recorded to the east and north of Jeddah. The Quaternary unit
(Tihamah) includes the recently emerged marine deposits and corals, wadi alluvium, sabkha deposits and aeolian sands along the coastal plain and mountain pediments (Moore and Al-Rehaili, 1989; Qari, 2009).

The mountains, located in the eastern part of Jeddah, rise to between 60 m and 350m above sea level; steep-sided wadis dissect the mountains region, many of which are strongly controlled by series of tectonic events. The main courses of these wadis flow in the westerly directions towards the city of Jeddah.

The study area is predominately arid desert type, with hot summer and cooler winter seasons. The mean temperature ranges from 24°C to 46°C in the summer and from 15°C to 25°C in the winter. Rainfall is sporadic, characterized by moderate to high variations in space and time. Rainfall often occurs as thunderstorms of very high intensity during local storms, causing frequent flash floods. The mean annual rainfall ranges from 30 mm in the coastal plain to around 60 mm in the mountainous inland areas. The rainy season is from October to April (Şen, 1983; Bayumi et al., 2000; Subyani et al., 2009).

### Methodology

DRASTIC method consists of two major elements: the hydrogeological setting and the superposition of a relative rating system for pollution potential. As mentioned in the introduction the seven subjective layers or parameters have ratings from 1 to 10, where the ratings will then be multiplied by a suitable relative value that ranges from 1 to 5. The most significant factors are given the weight of 5, and the least significant are given the weight of 1 (Aller, 1987; Boughriba et al., 2009). According to the sensitive situation of Jeddah city, the quantitative parameters such as water Depth, Recharge, Topography and Conductivity should be restricted in rating and weighting. Other quantitative parameters, Aquifer media, vadose zone Impact and Soil media are dependent on the degree and sensitivity of the risk mapping in urban areas. All these parameters could be modified in a manner that does not follow exactly what is proposed in DRASTIC methodology (Table 1). These factors are adjusted by rating and weighting factors and summed to calculate the risk or pollution potential or DRASTIC index as applied by (Aller et al., 1987).
Table 1. DRASTIC rating and weighting values for the various hydrogeological parameter settings (Aller et al., 1987).

<table>
<thead>
<tr>
<th>Depth to Water (m)</th>
<th>Recharge (mm)</th>
<th>Aquifer Media</th>
<th>Soil Media</th>
<th>Topography(%)</th>
<th>Impact of vadose zone</th>
<th>Conductivity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>Rating</td>
<td>Range</td>
<td>Rating</td>
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<td>Rating</td>
<td>Range</td>
</tr>
<tr>
<td>0-1.5</td>
<td>10</td>
<td>0.0-50.8</td>
<td>1</td>
<td>Massive Shale</td>
<td>Thin or absent</td>
<td>10</td>
</tr>
<tr>
<td>1.5-4.57</td>
<td>9</td>
<td>50.8-101.6</td>
<td>3</td>
<td>Metamorphic/igneous</td>
<td>Gravel</td>
<td>10</td>
</tr>
<tr>
<td>4.57-9.14</td>
<td>7</td>
<td>Weathered Metamorphic/igneous</td>
<td>4</td>
<td>Sand</td>
<td>9</td>
<td>6-12</td>
</tr>
<tr>
<td>9.14-15.24</td>
<td>5</td>
<td>Glacial till</td>
<td>5</td>
<td>Peat</td>
<td>8</td>
<td>12-18</td>
</tr>
<tr>
<td>15.24-22.86</td>
<td>3</td>
<td>101.6-177.8</td>
<td>6</td>
<td>Bedded SS and LS</td>
<td>Shrinking clay</td>
<td>7</td>
</tr>
<tr>
<td>22.86-30.48</td>
<td>2</td>
<td>177.8-254</td>
<td>8</td>
<td>Massive SS</td>
<td>Sandy loam</td>
<td>6</td>
</tr>
<tr>
<td>&gt;30.48</td>
<td>1</td>
<td>&gt;254</td>
<td>9</td>
<td>Massive LS</td>
<td>Loam</td>
<td>5</td>
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<td></td>
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<td></td>
<td></td>
<td>Sand &amp; Gravel</td>
<td>Silty loam</td>
<td>4</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Basalt</td>
<td>Clay loam</td>
<td>3</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Karsts LS</td>
<td>Muck</td>
<td>2</td>
</tr>
</tbody>
</table>

Weight: generic = 5
Weight: generic = 4
Weight: generic = 3
Weight: generic = 2
Weight: generic = 1
Weight: generic = 5
Weight: generic = 3
DRASTIC Index = \( D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \) (1)

Where, the subscripts \( r \) and \( w \) refer to the rating and weighting factors, respectively.

DRASTIC method is an easy model with seven parameters to compute the vulnerability index, which ensures the best representation of the hydrogeological characteristics of an area in numerical rating and weights. The first step for vulnerability mapping of Jeddah city is to divide the area into a grid of cells within the GIS environment with grid cell size of 1x1 km\(^2\) (Fig. 2). The second step will be to interpolate the numerical parameters using Kriging technique into grid layers, and finally the vulnerability index is calculated for each grid cell. Finally, GIS based technique will be used to produce a risk zonation map by integration of the seven parameters for Jeddah city.

Fig. 2. Cells of the study area.
Results and Discussion

Groundwater occurs within the highly permeable unconfined aquifer in Jeddah city, which is made of surficial soil, sandy gravel and coralline limestone. From field study in years 2000 and 2008, the depth to water table was very shallow (less than 8 m), decreasing gradually from the east near the Precambrian outcrops to less than 0.5 m. at the shoreline in the west. According to the DRASTIC rating for depth to water as in Table 1, the rating ranges from 5 to 10 (Fig. 3). The recharge contribution from rainfall to groundwater is very small. However, the average annual rainfall is as low as 35 mm (Bayumi et al., 2000; and Subyani et al., 2009). Only a small portion of this water infiltrates into the ground due to impervious infrastructures such as houses, asphaltic roads, pavements and saturated surficial soils in many locations in the city. On the other hand, the low amount of rainfall may produce swamps and depressions causing many problems to the infrastructure of the city. Rating value of net recharge is 1, which indicates that Jeddah has generally very low net recharge.

Fig. 3. Water depth in the study area.
According to the geological framework of Jeddah city (Fig 1), three distinctive units could be indicated, namely Precambrian basement rocks in the east, alluvial sand and gravel of the wadis deposits in the middle, and coralline limestone in the west with rating values 3, 8 and 10, respectively. Soils in Jeddah city have mainly 3 classifications, silty-sand, loose sand, and calcareous sand (Al-Quahtani, 1979). Based on Table 1 of soil texture, Figure 1 shows the soil ratings are 4, 5 and 6. Sandy loam of rating 6 covers a huge area in the city. Topography or surface slope is very important factor to the vulnerability index. The flatter the topography, the more vulnerable is the aquifer (Bayumi et al., 2000). Figure 4 shows the topography map displaying a low variation in slope with ratings of 1,3 and 5. The high slope rating 1 occurs in the mountains area in north-eastern parts of the city, while the slight slope is in the hilly areas in the south. The flat slope areas rating of value 5 covers the greatest area of the city, where most of the land uses are located.

Fig. 4. Topographic map of study area.
The vadose zone and hydraulic conductivity in Jeddah city were determined from field work and from different technical reports (Bayumi et al., 2000). Generally, vadose zone has only one class of sand and gravel with silt and can be given a rating of 6. The water-bearing aquifer is characterized by 3 classes of hydraulic conductivity with rating values of 2 in the south, 4 in the east and 8 in the west and the northwest of the city (Fig. 5). By applying Eq. 1, Table 2 was generated that summarizes the numerical values of the DRASTIC index in Jeddah.

DRASTIC Index of Study Area

The integration of the six maps through the use of Equation 1 provides the DRASTIC index map of the degree of vulnerability to pollution in Jeddah city (Fig. 6). The results show that the area can be
subdivided into four classes or risk zones, low (from 100 to 120), moderate (from 121 to 140), high (from 141-160) and very high ( > 160). The zones of low and moderate risk to pollution appear in the eastern areas of the city, where the alluvial fan deposits are located within high slopes. The southern part of the city also falls within the moderate zone, because this area is well developed in regards to infrastructure with rainstorm and sewage networks. The middle area of the city falls within high vulnerability risk due to its high population, shallow water depth, flat slopes and various incomplete network services (i.e. leakage from septic tanks and water pipes). The western and northwestern parts of city are subject to very high pollution risk, due to the highly permeable area with coralline formation, very shallow water depth and depressions.

Fig. 6. Vulnerability index map.
The seven parameters of original DRASTIC method may be adequate for application on natural groundwater aquifers. However, in the case of Jeddah, accelerative expansion of urban areas and exponential population growth (present population is more than 3 millions) have contributed to a series of groundwater quality problems. Among these is the accumulation of huge quantities of wastewater from residences, due to the lack of sanitary sewage network in many parts of the city, thus septic tanks are used. They allow seepage of sewage water to reach groundwater within short time. Pollutants seepage is dynamic and continuously affecting the water quality.

Nitrate concentration can be used also to validate groundwater vulnerability assessment. In Jeddah, nitrate measurements from groundwater samples analysis show high concentrations in most of the places (Bayumi et al., 2002; and Subyani et al., 2009). Figure 7 shows the increase of nitrate concentration from the south to the north. This resulted in the deterioration of natural groundwater.

![Nitrate concentration](image)

Fig. 7. Nitrate concentration (mg/l).
Table 2. DRASTIC parameters of Jeddah city.

<table>
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<th>Range</th>
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<tbody>
<tr>
<td>0-1.5</td>
<td>10</td>
<td>0.0-50.8</td>
<td>1</td>
<td>Metamorphic/Igneous</td>
<td>3</td>
<td>Sandy loam</td>
<td>6</td>
<td>6-12</td>
<td>5</td>
<td>Sand &amp; Gravel /silt</td>
<td>6</td>
<td>4.716x10^4-1.41x10^4</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5-4.57</td>
<td>9</td>
<td></td>
<td></td>
<td>Loam</td>
<td>5</td>
<td>12-18</td>
<td>3</td>
<td></td>
<td></td>
<td>1.41x10^4-3.3x10^4</td>
<td>4</td>
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<tr>
<td>4.57-9.14</td>
<td>7</td>
<td></td>
<td></td>
<td>Silty loam</td>
<td>4</td>
<td>&gt;18</td>
<td>1</td>
<td></td>
<td></td>
<td>4.716x10^4-9.43x10^4</td>
<td>8</td>
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<td>9.14-15.24</td>
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<td>4.716x10^4-9.43x10^4</td>
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</table>
Conclusion

DRASTIC method can be used for regional scale of groundwater quality assessment. It estimates groundwater vulnerability of aquifer systems based on the hydrogeological factors of the study area. Anthropogenic (human) impact factors should also be taken into consideration for the vulnerability assessment, especially in urbanization areas where the potential impacts of anthropogenic activities are more significant.

In the city of Jeddah, DRASTIC index was used according to the rating and weights of the hydrogeological characteristics of the study area. The resulting maps of the seven DRASTIC parameters were obtained utilizing GIS environment. The final DRASTIC index map has been classified into four major classes of low, moderate, high and very high vulnerability representing 32%, 35%, 25% and 8% of the study area, respectively. Nitrate concentrations were used to validate qualitatively the final results. Most of the study area is subject to very high contamination vulnerability.

DRASTIC method application reveals some advantages for decision makers and future planners to help protect groundwater and soil from contamination. On the other hand, application of this method in urban areas has some drawbacks. Accordingly, several anthropogenic parameters should be considered and included to modify the DRASTIC method. Among such parameters are land use, exfiltration of cesspools and septic tanks, landscape irrigation, leakage from sewage and water supply networks. Using these anthropogenic parameters in addition to the traditional hydrogeological factors in such a developing city like Jeddah would help in avoiding future contamination of groundwater and will help in planning for new infrastructure in the city.

References


خرائط قابلية المخاطر للمياه الجوفية باستخدام نظم المعلومات الجغرافية وطريقة مؤشر دراستك (DRASTIC) لمدينة جدة، غرب المملكة العربية السعودية

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المستخلص. تقع مدينة جدة على الساحل الغربي للمملكة العربية السعودية وتتميز بالتطور والانتشار السريع يومًا بعد يوم. ولا يتوافق هذا الانتشار مع خطط الخدمات العامة مثل شبكات إمدادات مياه الشرب والصرف الصحي وتصريف الأمطار. وواقع الحال أن التربة والمياه الجوفية لمدينة جدة تتعرض للملوثات نتيجة العوامل الهيدروجيولوجية الطبيعية أو بتأثير الإنسان.

وهذه الدراسة تعتبر تطبيقًا أساسيًا لإنتاج خرائط لتعيين درجة قابلية المخاطر للمياه الجوفية في مدينة جدة باستخدام نظم المعلومات الجغرافية وطريقة مؤشر دراستك.

ومؤشر دراستك (هـكلمة عبارة عن جمع الحروف الأولى) لسبعة مؤشرات هيدروجيولوجية هي عمق الماء الجوفي، التغذية D، التركيب الصخري للخزان المائي A، نسيج التربة S، طبوغرافية R، المنطقة T، تأثير نطاق التهوية I، قيمة التغذية C يخذل بعضين
الاعتبار هذه السبعة ميؤشرات لتحديد مدى قابلية التربة والمياه الجوفية لمخاطر التلوث.

أظهرت النتائج الميدانية للنموذج أن مدينة جدة ذات قابلية كبيرة لتلوث المياه الجوفية بها بعد إضافة مؤشر تركيز النترات في المؤشر. ويمكن إضافة مؤشرات أخرى مثل استخدامات الأراضي ومناطق الفيضانات ومؤشرات هندسية وبيئية أخرى بحيث يمكن أن تساعد في الخطط المستقبلية لتطوير مدينة جدة.

الكلمات الدالة: قابلية المخاطر للمياه الجوفية، مؤشر دراستك، نظم المعلومات الجغرافية، جدة، المملكة العربية السعودية